NUREG/CP-xxxx

Proceedings of the

Conference on Vessel Penetration Inspection, Crack Growth and Repair

Held at Gaithersburg Marriott at Washingtonian Center
Gaithersburg, Maryland
September 29 – October 2, 2003

U. S. Nuclear Regulatory Commission

Office of Nuclear Regulatory Research

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Held at Gaithersburg Marriott at Washingtonian Center
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ABSTRACT

These two volumes of proceedings contain the visual projections (in Volume I), and the contributed manuscripts (in Volume II) from the Conference on Vessel Head Penetration, Crack Growth and Repair, held at the Gaithersburg Marriott at Washingtonian Center on September 29 – October 2, 2003. The conference was co-sponsored by the U. S. Nuclear Regulatory Commission and Argonne National Laboratory. Over two hundred attendees were provided with 45 presentations, divided into five sessions: (I) Inspection Techniques, Results, and Future Developments, (II) Continued Plant Operation, (III) Structural Analysis and Fracture Mechanics Issues, (IV) Crack Growth Rate Studies for the Disposition of Flaws, and (V) Mitigation of Nickel-Base Alloy Degradation and Foreign Experience. The conference opened with a plenary session including presentations giving the overview from the NRC Office of Regulatory Research, and an overview of nickel-base alloy cracking issues worldwide. The conference closed with a panel session consisting of industry representatives and NRC management discussing the prognosis for future issues in this area of concern.

EXECUTIVE SUMMARY

The purpose for this conference was to examine the current state of technology for vessel head penetrations with respect to inspection, cracking, and repair. This subject is being examined because of penetration cracking which has been occurring for over a decade. The first reactor head penetrations to show signs of leakage occurred in France in the early 90's at Bugey 3. After this incident the French inspected a large number of their penetrations and reported that roughly 3% of their inspected nozzles had some type of indication. Because of the cracking in France, many power plants in the US and elsewhere started to examine penetrations and found ultimately that a large number were similarly cracked. The next leakage from a vessel head penetration occurred in the United States at Oconee 3 in 2000. Following Oconee there have been many other plants with cracked or leaking penetrations. This type of degradation led to one of the most serious nuclear incidents in the U.S. at Davis Besse. A crack in a vessel head penetration, possibly combined with the presence of substantial boric acid deposits, led to corrosion of the low-alloy steel, and the formation of a large cavity in the reactor head. Another significant event included the first leaking bottom mounted instrument penetrations discovered at the South Texas Project Plant in the United States. These instances of failure are a concern to the public, industry, and regulators. Knowledge gained from this conference will help reduce future incidents from occurring. The five sessions listed below were held at the conference and covered several topical areas.

Session I: Inspection Techniques, Results, and Future Developments
Session II: Continued Plant Operation
Session III: Structural Analysis and Fracture Mechanics Issues
Session IV: Crack Growth Rate Studies for the Disposition of Flaws
Session V: Mitigation of Nickel-base Alloy Degradation and Foreign Experience

The first session examined the area of inspection techniques for the vessel head penetrations. This is important research, since inspection capability is one of the first lines-of-defense against vessel head penetration leakage. A range of topics were discussed including how nondestructive examination (NDE) has evolved over time. Advancements in NDE were examined which included Phased Array Ultrasonic Testing and Eddy Current Testing Arrays. With regards to the area of NDE testing tools, cracked penetration mockups and performance demonstrations were discussed. This included examining new techniques for developing realistic flaws. The issue of reliability of NDE data was another topic of concern. This led into presentations about in-service inspections (ISI). One main area of discussion for ISI is the frequency of inspections. One question that was raised asked what should be the bases for determining the inspection frequency. Should the ISI be based on avoiding any leakage at a plant or should it be based on avoiding core damage? The discussion of inspection techniques carried over to the next session of Continued Plant Operation.

The second session examined Continued Plant Operation, and one of the first presentations examined the analytical and repair approaches for continued plant operation. Included in this session was a description of the cracking which occurred at South Texas Project in the bottom mounted instrument (BMI) nozzles. The repair techniques for these bottom mounted nozzles were discussed in detail. With regards to upper head penetrations, there is an understanding that evaluation methods are being developed and will be included in section XI of the ASME code sometime in 2004. The French discussed the initial leak at Bugey and investigations which followed. In France it was determined that the best choice of action was to replace the vessel heads with Alloy 690 nozzles and Alloy 152 weld material. The subject of how power plants in the United States have reacted to the nickel-based material cracking issues was similarly covered. In examining how to operate after repair or mitigation, taking into consideration cost and downtime, the optimum solution to this problem was to reduce the reactor vessel head temperatures. There were two repair techniques presented, which included embedded flaw repair and weld overlay

repair. In determining the acceptable usage for these two repair techniques, structural analysis must be taken into consideration, a discussion which provided a segue into the next session.

Structural Analysis and Fracture Mechanics Issues was the title of session three. The initial presentations focused on using probabilistic analysis to determine the probability that the head penetrations will either leak or be ejected. It seems that through this type of analysis, in conjunction with reasonable inspection plans, the top heads meet the safety limit for nozzle ejection. However, there are conservatisms still inherent in these calculations. The next topic focused on residual stresses present in the nozzle and how they may affect cracking. There are different variables that need to be considered to determine accurately the hoop and axial residual stresses. Some of these variables are nozzle thermal properties, welding procedure, joint configuration, and mechanical properties. The research presented suggests that residual hoop stresses are larger then the residual axial stresses. In the peripheral nozzles the stresses will depend upon the location in the nozzle, with respect to the downhill or uphill side. It was described that as the weld height increased the axial stresses decreased while the hoop stresses increased. Therefore it was recommended that some type of medium weld height might be used in order to achieve a balance between both hoop and axial residual stresses. Another area examined in this session was the subject of ductile-dip-cracking, which seems to be a much larger problem for alloys 152/52 then it was for alloy 182/82. There was also some examination of the leak before break (LBB) concept. Initial LBB calculations utilized cracks which were more characteristic of fatigue cracks rather than PWSCC cracks. A reanalysis of LBB using PWSCC crack geometries leads to some new results. It was presented that LBB is difficult to satisfy using the PWSCC crack geometries. Another feature is that PWSCC could result in long circumferential surface cracks which are more likely to break than a through wall circumferential crack. The LBB screening criteria is not satisfied by this type of circumferential cracking. Finally, the last subject in this session examined the subject of predicting first failure. The way this was to be accomplished was to create an all inclusive equation. This equation would predict failure by using past experience as a guide. There would be auxiliary equations that would take into consideration variables such as temperature or stress, which affects failure. These small individual equations would be combined to create an overall cracking equation. However, this work is still in the beginning phase of development.

The fourth session of the conference was titled Crack Growth Rate Studies for the disposition of flaws. This is a very important subject because crack growth rates can be used to predict when an identified crack will lead to leakage of reactor coolant solution. Initially there was discussion of the history of Alloy 600 cracking at plants in the United States and France. Following the history of Alloy 600, there were presentations describing new testing techniques for stress corrosion cracking growth rates (SCCGR). Included in these discussions were details about compliant, self-loaded compact tension (CT) specimens and accelerated crack growth tests with a clearly-defined acceleration factor. With regards to SCCGR evaluation procedures, there was discussion about using a maximum or average SCCGR. There was also discussion about the pros and cons of periodic unloading for more continuous crack tip activation. The next subject covered examined the SCCGRs for the materials such as Alloy 600, 182, 152, 132, 82, and 52. From these discussions it was concluded that SCCGR for Alloy 182 is larger then Alloy 82. Alloy 132 has a SCCGR on the order of Alloy 182 SCCGR. The crack growth rates in the heat affected zone (HAZ) in Alloy 600 may be 30 times larger then the non-HAZ material. Alloy 52M has been tested but no cracking was found in this material. In service, an Alloy 182 with 5-10 effective full power years (EFPY) cracked. Alloy 600 showed cracking in a material with 6-13 EFPY. There was much discussion about the effect of dissolved hydrogen on SCCGRs in this session. There was agreement that the SCCGRs are maximized when exposed to electrochemical conditions around the Ni/NiO equilibrium line on a Pourbaix diagram. Another subject covered was models for SCCGRs. The physical and mechanical-chemical models discussed are useful tools that can be utilized to examine the SCCGR inter-workings. The combination of models with the SCCGR data should provide a more accurate assessment of SCCGR curves.

The final session for the conference examined Mitigation of Nickel-Base Alloy Degradation and Foreign Experience. During previous sessions the experiences from both the United States and France had been presented. This session allowed other countries affected by the same degradation to present the issues occurring in their country. This foreign experience included presentations from Belgium, Germany, Sweden, and Japan. In Belgium, a proactive approach has been taken to repair, replace, or mitigate any alloy 600 cracking before leakage occurs. In Germany, the Obrigheim power plant is the only plant in that country which contains Alloy 600 in the reactor vessel head penetrations. It was decided to use leakage detection systems at Obrigheim. In Japan, reactor heads were replaced in older plants, while newer plants have lowered the reactor vessel head temperature. Minor indications in the bottom mounted instrument nozzles have also been discovered in Japan. In Sweden it was decided to replace the reactor vessel heads. The next subject of this session was mitigation techniques for nickel-based alloy degradation. One of the main directions industry is headed is to replace Alloy 600 parts with Alloy 690. Other then replacing the material, there are three ways to alleviate degradation. These mitigation strategies are mechanical surface enhancement, environmental barriers or coatings, or changes to the environment. Which of these mitigation strategies to chose is dependant upon the geometry of the equipment. One type of mitigation technique that has been employed is to reduce the head temperature of the vessel. This has the effect to reduce the rate of increase of effective degradation years. Another mitigation technique which is being tested is low-level zinc additions to the primary coolant. There has been some evidence that zinc reduces the initiation time for PWSCC. However, there is less evidence that zinc additions reduce the PWSCC crack growth rate. A final mitigation technique which was presented was the mechanical stress improvement procedure (MSIP). MSIP has been demonstrated on thick walled PWR piping. The results from this demonstration show that compressive stresses are formed in the inner weld region and that the profile of the pipe after MSIP is still acceptable for in-service inspections.

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FOREWORD

Stress-corrosion cracking of nickel-base alloys used in vessel penetration components, including both wrought and welded products, has been an increasing and worldwide challenge for the nuclear industry and regulatory authorities since the middle 1980s. Leaks and cracks were discovered initially in components fabricated from alloys 600 and 182 exposed to higher temperatures - pressurizer heater sleeves and nozzles. With time, cracks and leaks have been discovered in components operating at lower temperatures, including vessel head and bottom-mounted instrumentation penetrations. This conference provided a four-day forum for presentations and discussion of the inspection, stress analysis, flaw evaluation, and mitigation of stress-corrosion cracks in vessel penetrations.

Forty-five technical presentations provided a wide-ranging perspective on this issue. The contributed presentations were prepared by researchers involved in computational and laboratory studies of the cracking phenomena, as well as by reactor component vendors and utility representatives describing plant response related to component degradation, structural integrity evaluation, repair or the mitigation of cracking. The complete conference proceedings package consists of CDs containing copies of all the presentations, and all the available manuscripts, plus printed copies of the same material.

The conference brought together much of the worldwide expertise in the area of nickel-base alloy cracking. Many utility, vendor and regulatory participants described various observations of cracking incidents, problems encountered and solutions developed. Scientists involved in crack growth rate studies and non-destructive inspection described the difficulties and successes with various aspects of testing and inspection procedure development. Several presentations discussed the stochastic nature and statistical analysis of cracking incidents, the predictive algorithms for this type of degradation, and the prognosis for the future, including discussions of head replacement strategies, mitigation of the cracking process, and the likelihood of an increased resistance to cracking of the replacement materials, alloys 690 and 152.

Convocations such as this one provide a forum for the concentrated and focused presentation of recent findings on cracking in nickel-base alloys. Additionally, this conference was an opportunity for participants from several venues - regulatory, research and plant operations - to meet face-to-face, and to formally and informally exchange data and concepts with the individuals who are at the forefront of the issue of nickel-base alloy cracking. Several presentations described the approach of non-domestic institutions, providing contrasts and different approaches to the same problem. The wide, public distribution of the proceedings of the conference ensure that the presentations will be subject to a maximum amount of scrutiny and accreditation. The NRC believes that participants and readers of these proceedings will be able to develop an overview of the current status of inspection technology and crack growth rate studies and to understand the reactor safety and economic impact of this degradation of nickel-base alloys on plant operation. These proceedings offer the industry documentation of recent events and their solution, suggesting avenues that may improve opportunities for continued improvement in plant operations. They offer the NRC many helpful insights on the characteristics of service-induced cracking and the challenges of inspection and repair of the affected components.

Carl Paperiello, Director
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission

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The bulk of the arrangements for this conference were handled by the Conference Office at Argonne National Laboratories. Ms. J. Brunsvold of that office negotiated with the lodging and conference staffs at the Marriott/Gaithersburg – Washingtonian Center, and arranged for a trouble-free four days of conferencing. The assistance of the staff at the Conference Center was managed by K. Natesan, Argonne National Laboratory, who is the program manager for several NRC-funded programs. Speaking for all the attendees, we appreciate the hard work of both Ms. Brunsvold, and Mr. Natesan.

Actually, Ms. Brunsvold and Mr. Natesan planned the logistics for this conference twice. The conference was originally scheduled for September 24, 2001, which turned out to be less than two weeks following the attacks of Sept. 11. The conference was successfully postponed, thanks to the efforts of the Argonne staff and the gracious understanding of the Marriott-Gaithersburg conference office staff. All participants were successfully contacted; not one person showed up at the venue expecting a conference to actually take place.

The organization of the sessions and contributing authors was handled by Ms. Karen Gott, Swedish Nuclear Power Inspectorate (SKi), who was participating in a rotational assignment at the NRC in the months preceding the original conference. We appreciate her hard work; her diligence in this effort was extremely helpful in getting this conference off the ground successfully. At the rescheduled conference, Dr. T. Mintz was indispensable in his seemingly effortless handling of the audiovisual logistics during the course of the conference, and with his able assistance in the preparation of the proceedings. The registration and logistics table at the conference site was staffed by Ms. Brunsvold, together with Ms. C. Briggs and Ms. E. Miller, both of the NRC's Office of Nuclear Regulatory Research. Their contribution is much appreciated. T. Mintz also assisted in the compilation, tabulation and electronic linking of the written and electronic versions of the proceedings.

W. Cullen, NRC Program Manager

Section 1:
Opening Session

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A Review of Alloy 600 Cracking in Operating Nuclear Plants: Historical Experience and Future Trends

Warren H. Bamford

John F. Hall

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Introduction

- Small Bore Piping in Combustion Engineering Plants
- RV Head Penetration Cracking
  - Base Metal - Upper Head Penetrations
  - J-Groove Attachment Welds - Upper Head
  - Bottom Mounted Instrumentation Penetrations
- R. V. Outlet Nozzle Safe End Regions
- Steam Generators
- Pressurizers
- Summary and Discussion

Introduction

- Cracking in Alloy 600 and Alloy 182/82 is not new for either BWR or PWRs
- Review of Cracking Experience Reveals some Interesting Trends
  - There is generally a significant incubation time
  - Base metal cracks long before weld metal
  - Small bore tubes and pipes crack earlier
- We will review
  - Reactor Vessels
  - Steam Generators
  - Pressurizers
- We will identify past experience and predict future trends

Small Bore Piping in CE Plants

- In CE designs, the main loop piping is carbon steel
- Therefore there are few large diameter Alloy 600 lines and Alloy 182 welds, but many small areas
- Examples:
  - PZR Instrument Nozzles
  - PZR Heater Sleeves
  - SG Primary Head Instrument Nozzle
  - Hot Leg Piping Sampling Nozzles
- The first cracking was in the base metal of the first two listed, after 1-5 years service
- The earliest failures were at the hottest locations
- Cracks occurred in pipes with yield strength as low as 35 ksi , the minimum, value permitted.
- Flaws were always stable,always axial, and detected by leakage

Reactor Vessel Head Penetrations

- First observed as a leak at Bugey 3, 1991, after 12 years service.
- This led to a surge of inspections worldwide
  - 100% of EdF heads have at least one crack
  - 100% of B&W designed & manufactured heads have at least one crack
  - Percentages are much smaller with other manufactures
- After Bugey 3, no further leaks were found until 2000, when Oconee 3 had serious cracking.
- Most cracks have been axial, but, circumferential cracks have been found in at least six units.
- There are now at least 8 other units with leaks.
- In Spring of 2002, Davis Besse reported severe boric acid corrosion degradation of the head due to head penetration leakage.

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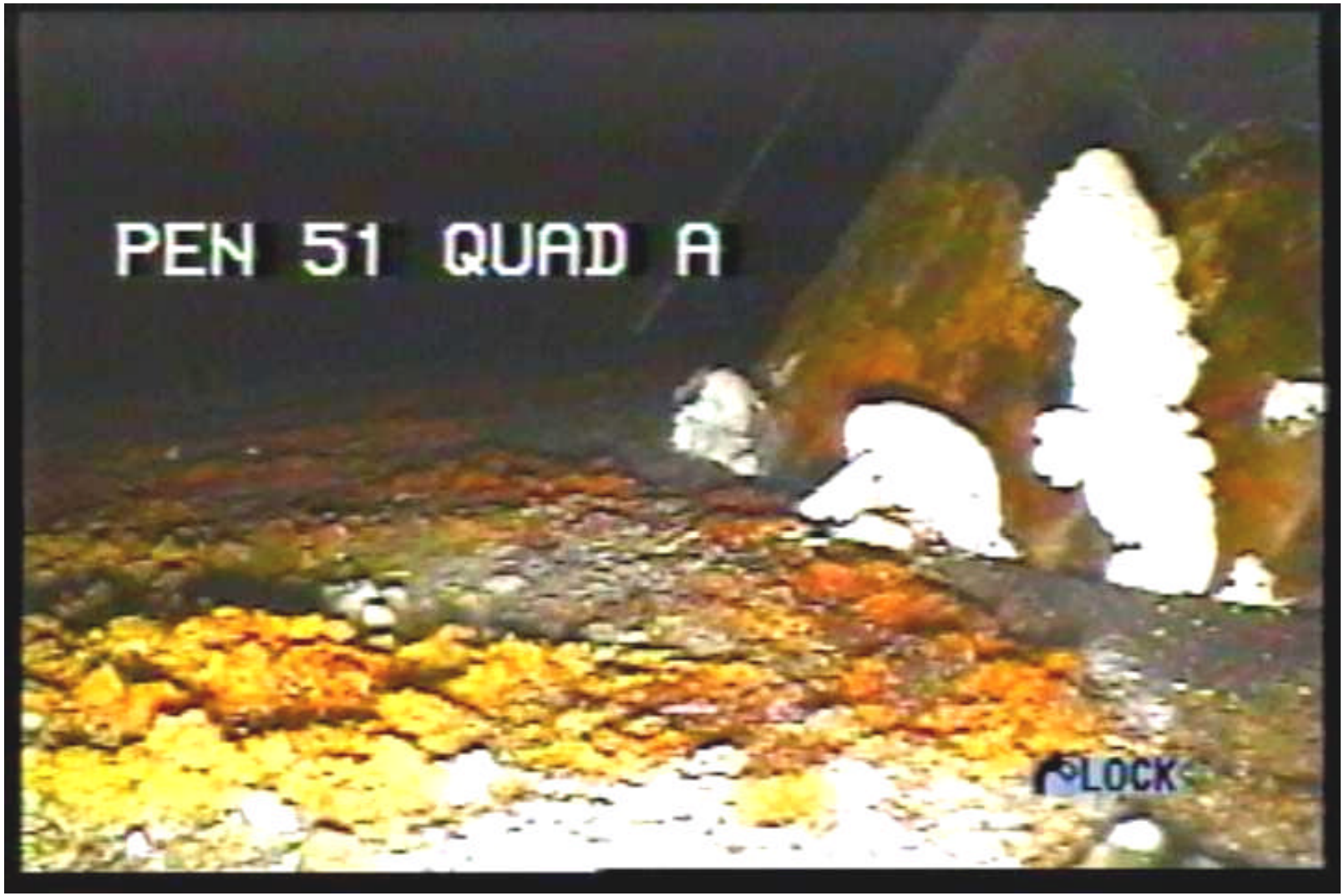
North Anna Unit 2



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Surry Unit 1

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Crystal River #3

Head Penetration J-Groove Attachment Welds

- In 1992 Ringhals 2 found extensive lack of fusion in their J-Groove weld regions - repairs implemented.

- To date(spring 2003), inspections are complete on about 350 J-groove welds, with the following results:
  - Rotterdam Dockyard: ~85% cracked (70 inspected)
  - Combustion Engineering: 0% cracked (242 inspected)
  - Chicago Bridge and Iron: 0% cracked (10 inspected)
  - Babcock and Wilcox: ~70% cracked (31 inspected)

- EdF reported that 11 reactor vessels heads were inspected after replacement, about 754 welds, with no cracking found

Bottom Mounted Instrumentation Penetrations

- EdF has inspected 17 units (~900 tubes), with no indications
- Ringhals has inspected one unit, no findings
- Doel has inspected 2 units, no findings
- MHI has inspected 4 units, no findings except one possible scratch with no measurable depth
- South Texas found two leaking BMIs in April 2003; these have been repaired, and the cause is still under investigation

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RV Outlet Nozzle Safe End Regions

- Ringhals 3 found small cracks in June 2003, and left them in service for a period of one year, before repair
- Ringhals 4 found small cracks in July 2003, repairing them by removing appropriate boat samples
- VC Summer identified a through-wall leak in October 2000
- All flaws were axially oriented, and limited to the weld width, no more than two inches
- All flaws were in hot leg nozzle welds
- Two of the three were in heavily repaired welds

Steam Generators

- Conditions:
  - Temperatures range from 550 to 610F
  - De-oxygenated water
- Divider Plates
  - EdF Inspections of replaced units:
    - 42 hot sides, 26 cold sides
    - Only one had any cracking
    - Shallow cracking associated with dents from a loose part
  - No known inspections to date elsewhere in the world
- Bowl Drains
  - Catawba Unit 2 had a leak in the base metal in 2001
  - No other known cracking,
  - Not all Steam Generators have bowl drains

Pressurizers

- Conditions:
  - Temperature 653F
  - De-oxygenated water
- Heater Sleeves/Small Bore Nozzles
  - First cracking found after about one year service, San Onofre Unit 3
  - Since then, multiple instances, nearly all in base metal
- Safe-end Regions
  - Tihange Unit 2 had a significant surface indication, Nov. 2002
  - Re-inspected in May 2003, no change
  - Mitigation planned for Fall 2003
- Inspections: ASME requires Safe-end inspections every 10 years

Summary and Discussion

- Alloy 600 and Alloy 182/82 will crack
- Base metal cracks before weld metal
  - Alloy 600 requires > Six years
  - Alloy 182 requires > ten years
- Weld repairs are often associated with cracking
- Cracking leads to leaks, not breaks, due to high ductility
- High temperature increases the probability of cracking
- Low temperature does not guarantee no cracking (South Texas BMI)
- Material supplier seems to affect the likelihood of cracking, but the reasons are not entirely clear yet
- Most Alloy 600 materials have been in service long enough that cracking is increasingly likely, so be prepared for future occurrences

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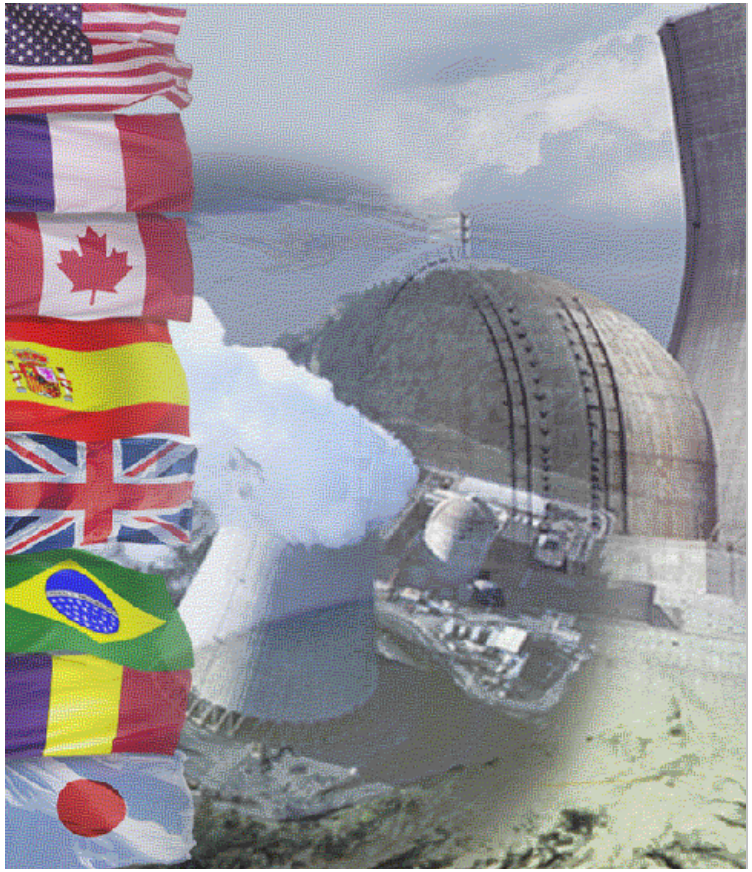
Section 2:
Session 1: Inspection Techniques, Results, and Future Developments



NDE of Austenitic Materials A Review of Progress and Challenges

Frank Ammirato

Senior Technical Manager-NDE

EPRI Nuclear Sector

Charlotte, NC, USA

Conference on Vessel Head Penetration Inspection, Cracking, and Repairs

September 29-October 1, 2003

Gaithersburg, MD

EPRI

Outline

- NDE issues associated with austenitic materials
  - Piping Butt welds
  - Vessel head penetrations
- Activities in progress to address the issues
  - Technology development
  - Mockup considerations
  - Demonstration/Qualification

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NDE Issues Associated with Austenitic Materials

- Ultrasonic techniques (UT) are used extensively for volumetric examination
- Austenitic weldments have particular characteristics that challenge UT
  - Coarse dendritic grain (scattering/attenuation/noise/beam steering)
  - Configuration (accessibility/interfering geometric features)
- Other NDE issues
  - Cost & availability of inspection resources
  - Qualification of procedures & personnel
  - Dose

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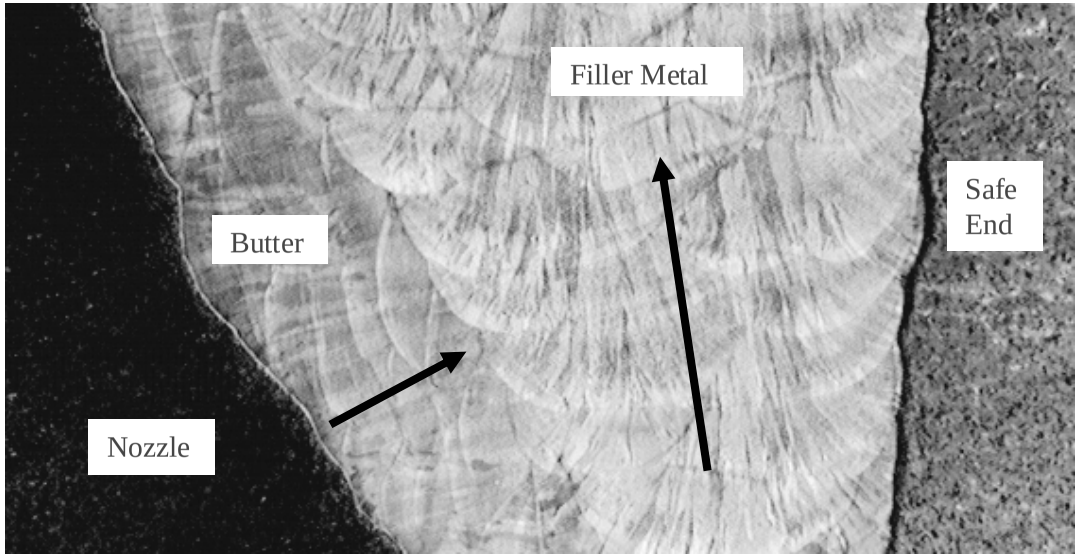
Typical Austenitic Weld Structure-Nozzle-to-Safe End

- Interpretation
- Probe Contact
- Attenuation
- Scattering
- False calls



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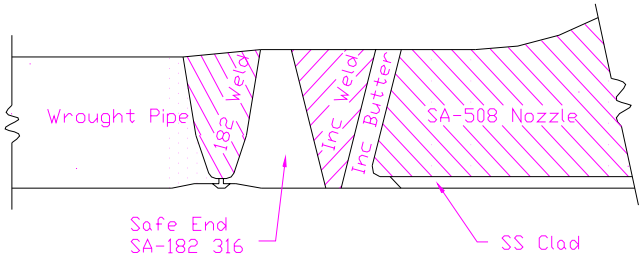
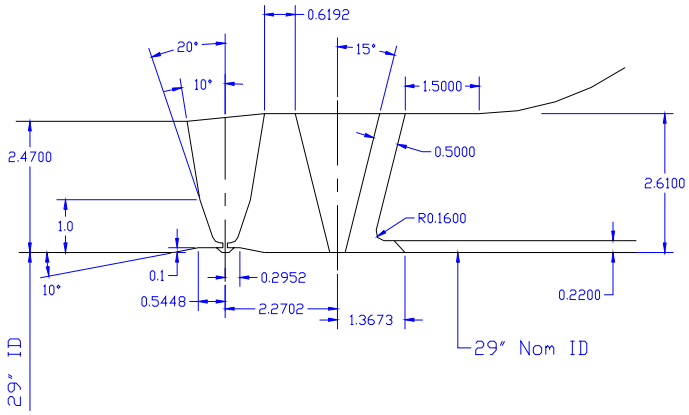
Dissimilar Metal Butt Weld Configurations



Some UT examinations are performed from Inside surface



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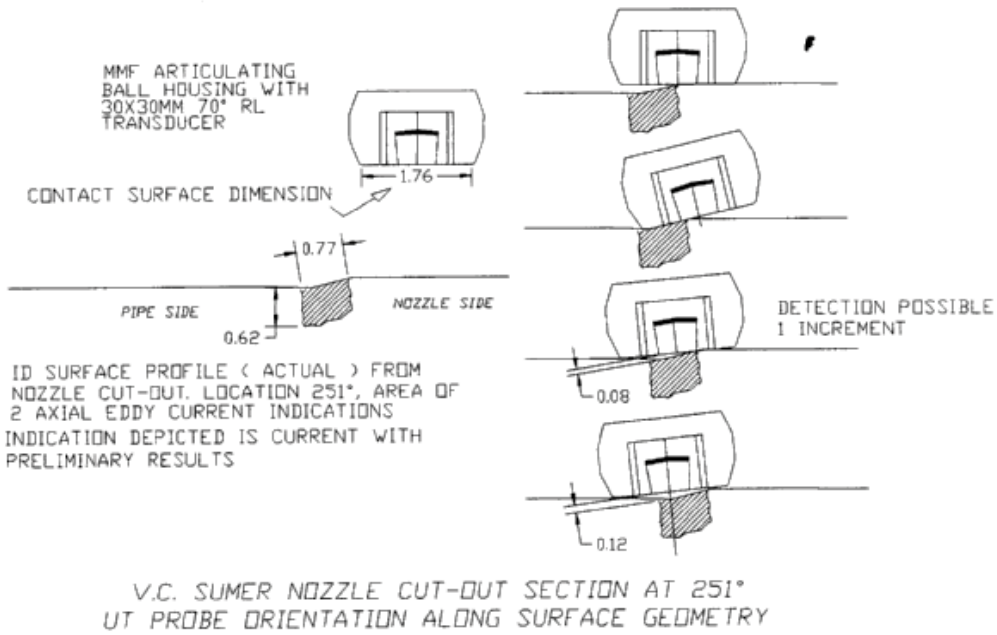
Inside Surface Effects

- Detection of short axial cracks limited due to poor UT probe contact on inside surface



Source; Wesdyne presentation at VC Summer Public Meeting 12/6/2000

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IGSCC Examination Approach

Extensive BWR NDE experience is helpful for PWR application, but not entirely transferable

	IGSCC	Dissimilar Metal Welds
Flaw Location	Heat affected zone	Weld metal (typical)
Detection Method	Shear waves	RL waves
Ultrasonic Responses	Root (typical)	ID surface contour
	Austenitic weld metal	Numerous metallurgical interface(s)
		Complex configurations
Flaw Sizing	Flaws located in base metal	Flaws located in weld metal

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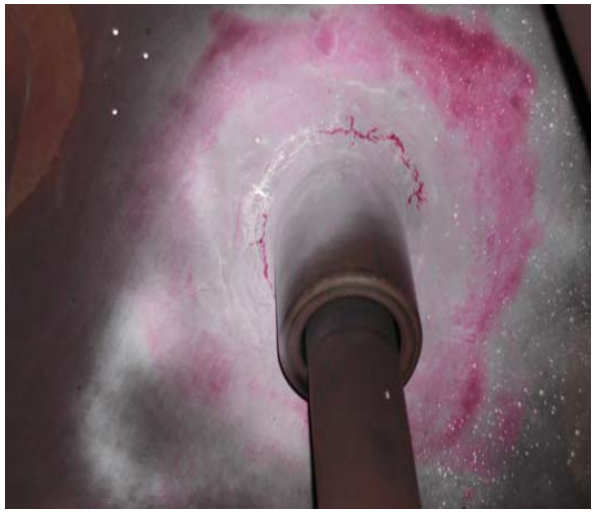
VHP Penetration, J-Groove Weld Cracking, & BMI Leak



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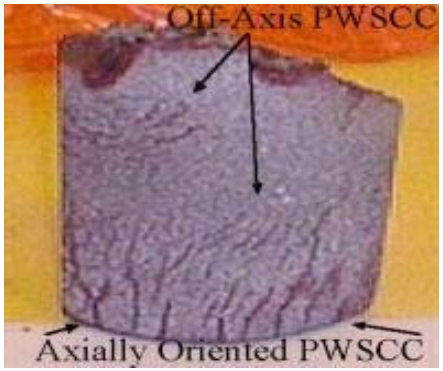
Cracking in CRDM Penetrations



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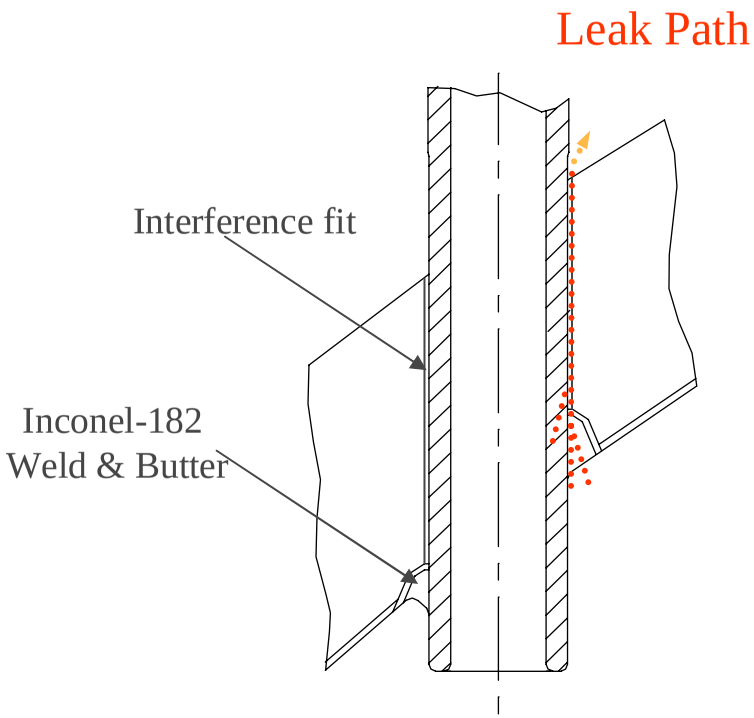
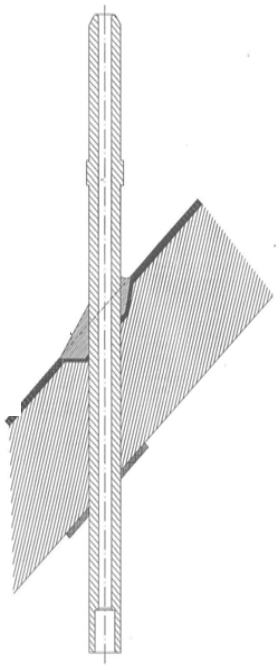
Leak Paths

Consider leak path through base metal or through weld



Top Head



Bottom Head

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NDE Effectiveness & Productivity Improvement

- Modify butt weld ID transducer sled for more flexibility
  - Smaller probes for better contact on inside surface
- ID Profiling to improve sizing accuracy for butt welds
- Evaluate productivity improvements
  - Eddy Current array probes
  - Phased array UT
- Qualify procedures & personnel
  - Realistic Mockups
  - Realistic flaws
  - ASME Appendix VIII for butt welds , including dissimilar metals
  - MRP Program for VHPs

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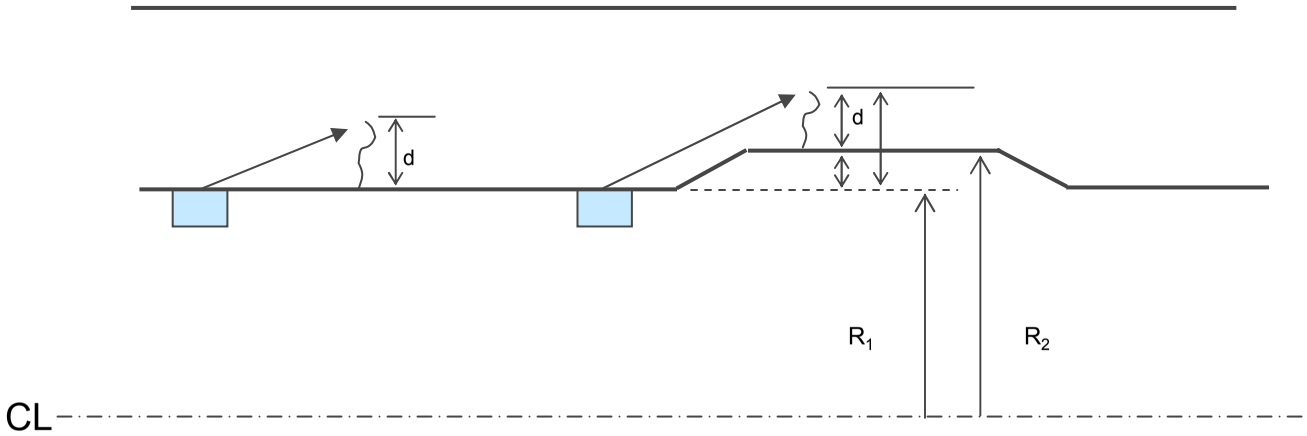
Flaw Depth Sizing-Compensation for Butt Weld Contours



Profiling techniques can improve accuracy of depth sizing when the probe is not on the same surface as the crack

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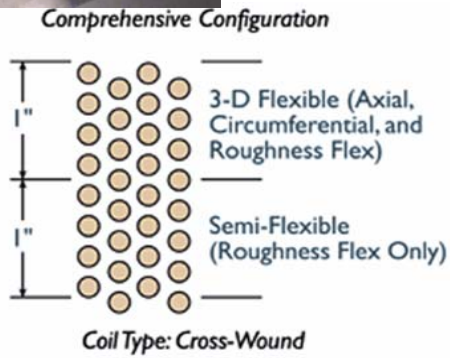
Eddy Current Array Probe for VHP J-Groove Welds

Advantages

- Speed
- Flexible membrane to accommodate contours
- Multi-directional sensitivity



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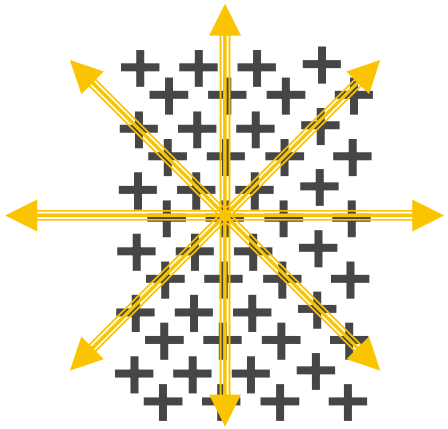
Eddy Current Array Probe Configuration



Array configuration allows switching between modes for multi-directional coverage at high speed

- Cross wound impedance mode for 0º, 90º directions
- Driver-pickup mode for ± 45º directions

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NDE Mockup Considerations

- Mockups are used extensively
  - Technique development & demonstration
  - Training of personnel
  - Qualification of capability
- Mockup criteria
  - Realistic configuration
  - Sufficient number of intentional flaws with controlled & well known features
    - Size
    - Location
    - Shapes
  - Realistic flaw responses
    - Consistent with NDE techniques being used (UT techniques, ET, combination)
  - No “signposts”

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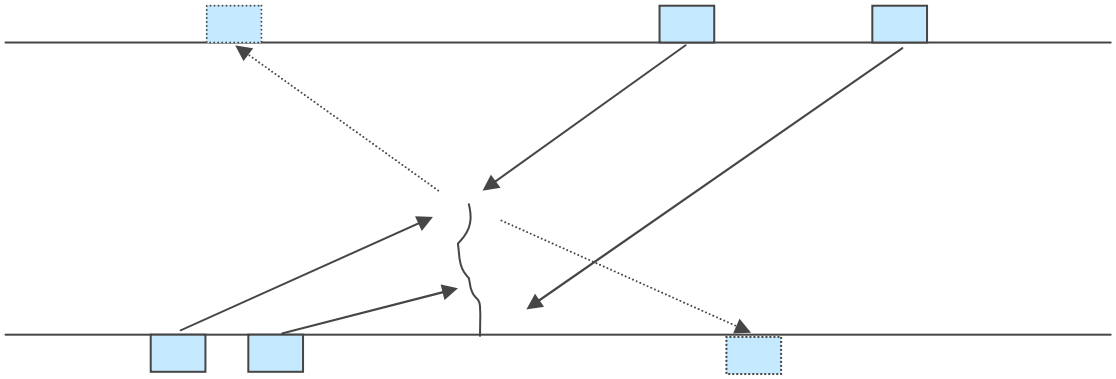
NDE Mockup Considerations

Intentional flaws in mockups must have realistic NDE responses that reflect & challenge the techniques being applied

- Tip response
- Corner response
- Face response
- Examination surface



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Mockup/Flaw Making

- Several methods can be used to produce flaws in mockups, e.g.:
  - Fatigue (mechanical & thermal)
  - Implantation
  - Weld contamination
  - Machining
  - Isostatic processing (HIP or CIP)
  - Combinations
- No one particular method addresses all the criteria
- Qualification of Mockups & flaws
  - Manufacturing surveillance
  - Comparison of responses with field removed samples
  - ISI experience

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Qualification of Inspection

- Dissimilar metal butt welds
  - New requirement took effect November 22, 2002 for qualification of DM weld procedures/personnel
  - Applicable to all units-PWR and BWR
  - Applies to UT performed from inside or outside surface
  - Procedures & personnel being qualified through PDI program
- Vessel head penetrations (top head and BMI)
  - MRP inspection demonstration program
    - Volumetric Examination of base material
    - Examination of wetted surfaces
  - Demonstrations continuing
  - Tracking field results

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Qualification of Inspection-DM Butt Welds

- Demonstration of Performance according to Supplement 10 of ASME SXI Appendix VIII
- Industry experience has indicated a need for improving inspection methods for dissimilar metal butt welds
  - Missed detections at VC Summer & Hope Creek
  - Appendix VIII qualification experience (supplement 10)
- VC Summer experience showed influence of ID contour on UT conducted from the inside surface
  - ID contour caused intermittent contact of the UT probe
- First attempts at qualification to Appendix VIII Supplement 10 identified some limitations for:
  - Detection of axial defects from ID
  - Depth sizing
  - Manual examination

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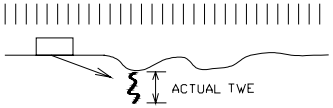
Status of Qualifications for DM Butt Welds

- Large effort by vendors and EPRI to improve capability
  - Closure weld (field weld) ID configurations added to qualification program to address ID contour problem identified at VC Summer
  - Vendors have made improvements such as more flexible ID transducer sleds, used smaller footprint probes, developed ID profiling
  - EPRI NDE Center evaluated essential joint parameters to design comprehensive mockup sets
  - Practice program initiated through PDI at the NDE Center to refine procedures and prepare personnel for qualification
  - Intense effort to qualify



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Status of Qualifications for DM Butt Welds

- Considerable progress has been made, although some limitations still remain
- Qualifications to Supplement 10 have been achieved for some conditions:
    - Detection & length sizing of circ & axial defects from OD in range of wall thickness up to ~5”
    - Detection & length sizing of circ & axial defects from ID in configurations typical of shop welds, that is, no ID geometry
    - Detection & length sizing of circ defects from ID in configurations typical of closure welds with ID geometry
    - Depth sizing from OD in thicknesses up to ~2”

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Status of Qualifications for DM Butt Welds

- Remaining limitations
  - Manual depth sizing
  - Detection of axial defects from ID in configurations with ID geometry (root, counterbore, etc)
  - Detection of defects from OD in configurations with OD tapers or limited scan surfaces
  - Depth sizing from ID surface (thick nozzle-safe end welds)
    - Sizing error is measurable, but exceeds code criterion
      - Some vendors have achieved errors ~ 8 -10% of wall thickness, but exceeding 0.125” (0.125” is ~ 2-5% of wall thickness)
- Efforts are continuing to eliminate or minimize limitations

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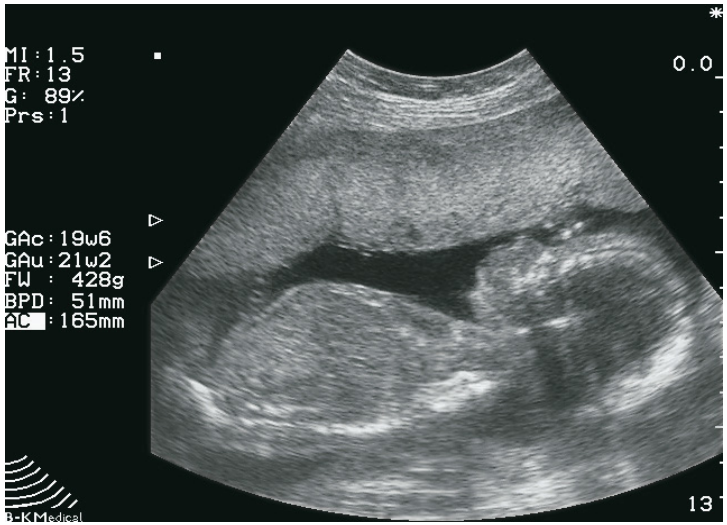
Phased Array UT Technologies for Nuclear Pipe Inspection Productivity and Reliability



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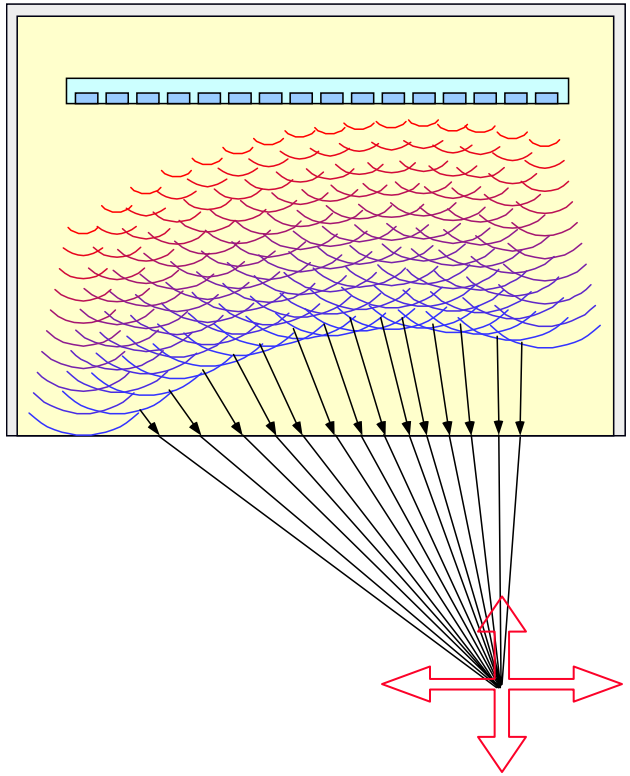
Phased arrays - Principles

Focused Angle Beam Mode



- Can focus & sweep the beam

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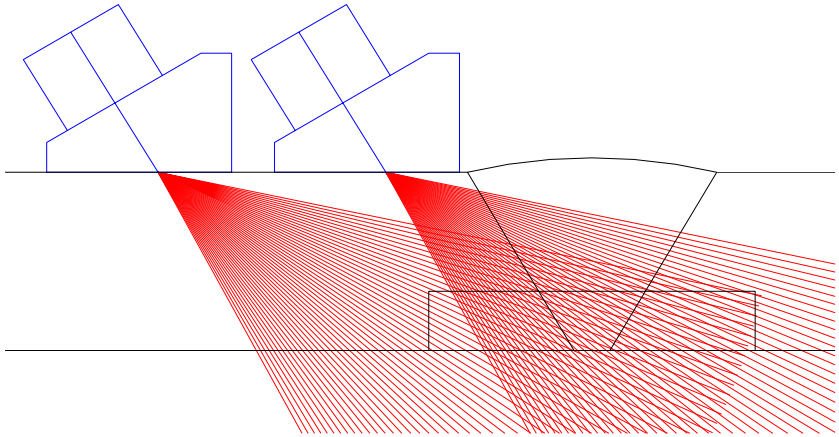
Phased arrays - principles

- Many angles produce a “sector scan” in milliseconds
- Provides good coverage from just one or two probe positions



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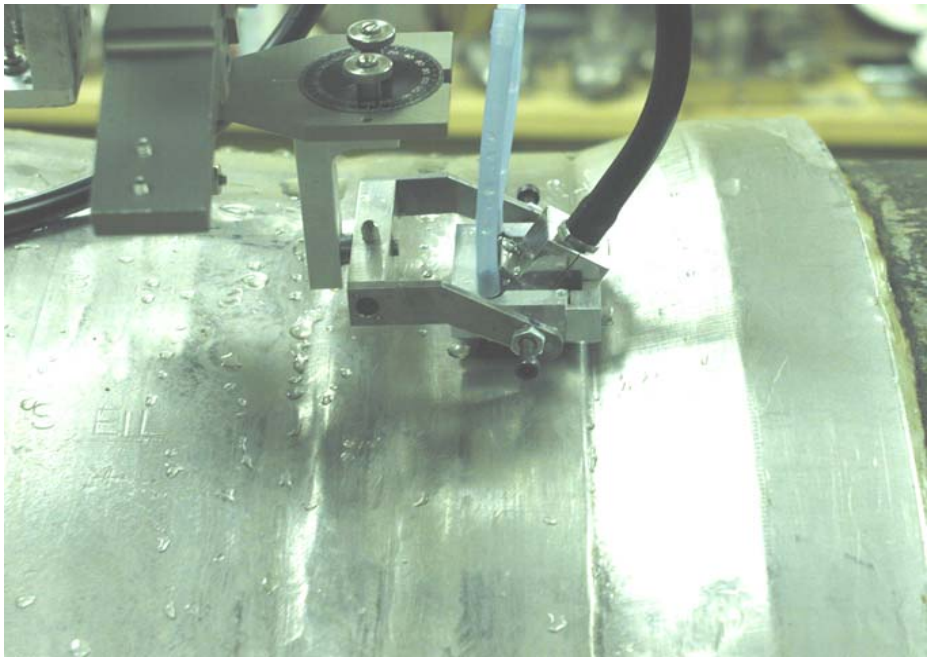
Good Coverage with Poor Access

- Scanning a field-removed IGSCC specimen – only enough room for one stroke, but still get excellent data



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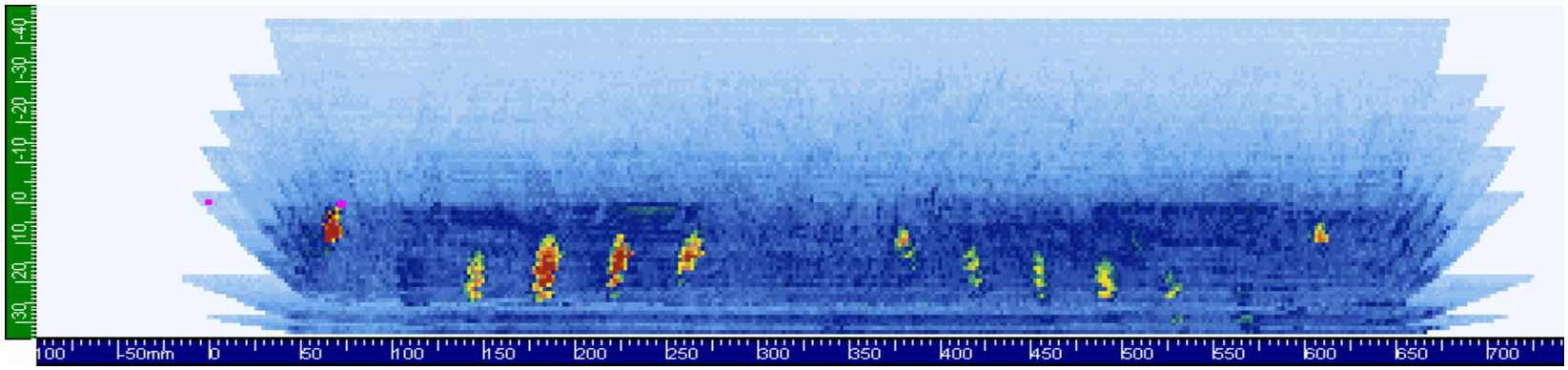
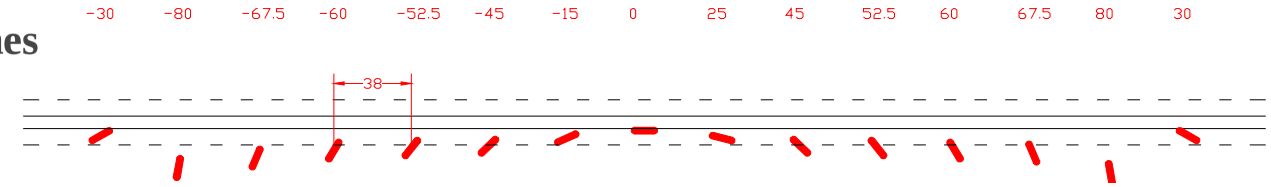
Next Step: Do It All with one 2D Array Probe



EDM notches

10mm long

5mm deep



SS pipe
30 mm
thick

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Summary

- Events in US and foreign plants highlighted NDE issues and focused industry attention on improving inspection technology & increasing productivity
  - PWSCC in Alloy 182 butt welds
  - Dissimilar metal welds
  - RPV head penetrations
- Complex configurations and materials associated with austenitic materials challenge NDE practitioners
- Considerable progress has been achieved in previous 12 months through demonstrations of capability
  - MRP
  - Appendix VIII
- New techniques & processes have been developed and are now being demonstrated to improve NDE performance & productivity
- Array probe technology shows promise for improving the reliability, effectiveness, and cost of inspection (UT and ET)
- Qualification has been achieved for many situations, with some limitations remaining to be addressed

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Inspection Reliability of Reactor Vessel Head Penetrations

Presented by

Steven R. Doctor, PNNL

NRC Conference on VHP

September 29-October 2, 2003

Battelle

Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Acknowledgements

- Work being conducted under NRC programs
  - Y6534 – Carol Moyer NRC Program Manager
  - Y6604 – Debbie Jackson NRC Program Manager
  - Y6909 – Bill Cullen NRC Program Manager
- PNNL staff supporting work
  - George Schuster
  - Al Pardini
  - Randy Thornhill
  - John Abrefah

Presentation Outline

- Background
- History of degradation in high nickel alloys
- PWSCC in head penetrations
- NDE strategies for detecting PWSCC
- Programs addressing NDE effectiveness
- Conclusions

Background

- Inconel Alloy 600 selected because of its high strength, ductility and corrosion resistance
- Used in many applications: steam generators, pressurizer heater sleeves, instrumentation and sampling nozzles, head penetrations and DM piping welds – Alloy 600 historical failure experience addressed in paper by Bamford and Hall 2003
- PWSCC is a complex process that is not understood - many factors affect initiation and crack growth rate: environment (temperature), stresses (grinding or weld repairs) and susceptible microstructure

Historical Data

- NRC Lessons Learned Task Force – addressing the degradation of Davis-Besse Nuclear Power Plant
- Appendix E – Licensee Event Reports 1986-2002
- 89 LERs
  - 17% were CRDM leaks (most since 2000)
  - 15% were RCS instrumentation nozzle leaks
  - 10% were pressurizer instrumentation nozzle leaks
  - 8% were pressurizer heater penetration leaks
  - Remaining 50% from a variety of components and locations

Example of Early Leak

- San Onofre Unit 3 – leak detected February 27, 1986
  - Initially detected by subtle rise in radiation levels based on manually trending data
  - Sent staff member in to search for source of leak
  - No boric acid deposits found
  - Staff member perplexed and was trying to figure out what to look for when he heard hissing sound
  - Audible acoustic emission detection
  - Leak on pressurizer instrumentation nozzle, 0.15-0.2 gpm (0.57-0.76 lpm)
  - Confirmed to be PWSCC

CRDM Leak

- Bugey 3 – 9/1991during 10 year hydrotest - leak detected by acoustic emission with leak rate 0.003 gpm (0.7 L/h)
- Two through wall ID axial cracks confirmed by destructive testing (DT) to be PWSCC
- Two circumferential cracks on OD confirmed by DT
  - One located in the weld – hot crack created during fabrication
  - Other in the base metal and connected to the axial through wall crack on downhill side of nozzle just above the weld
- PT test of 754 J-groove weld crowns and buttering from 11 replaced heads – no cracks found (Amzallag et.al. 2002)

Overview of Degradation in Inconel – VHP

- Vessel head penetrations started to become a significant problem in the USA with the CRDM degradation in Oconee
- Ten plants have had cracking requiring repair based on data from 11/2000 to 2/19/2003
- Oconee Unit 1
  - 3 CRDMs requiring repair and 5 thermocouple nozzles
- Oconee Unit 2
  - 19 CRDMs requiring repair with one circumferential crack above the J-groove weld

Overview of Degradation in Inconel – VHP Cont'd

- Oconee Unit 3
  - 14 CRDMs requiring repair with four having circumferential cracks above J-groove weld
- ANO 1
  - 8 CRDMs requiring repair
- Surry 1
  - 6 CRDMs requiring repair
- North Anna 2
  - 14 CRDMs requiring repair and 6 with circumferential cracks – Head replaced

Overview of Degradation in Inconel – VHP Cont'd

- Davis-Besse
  - 5 CRDMs
  - 2 nozzles with significant wastage in ferritic head
- Three Mile Island 1
  - 6 CRDMs and 8 thermocouple requiring repair
- Crystal River 3
  - 1 CRDM with a circumferential crack
- Millstone 2
  - 3 CRDMs requiring repair

Overview of Degradation in Inconel – VHP Cont'd

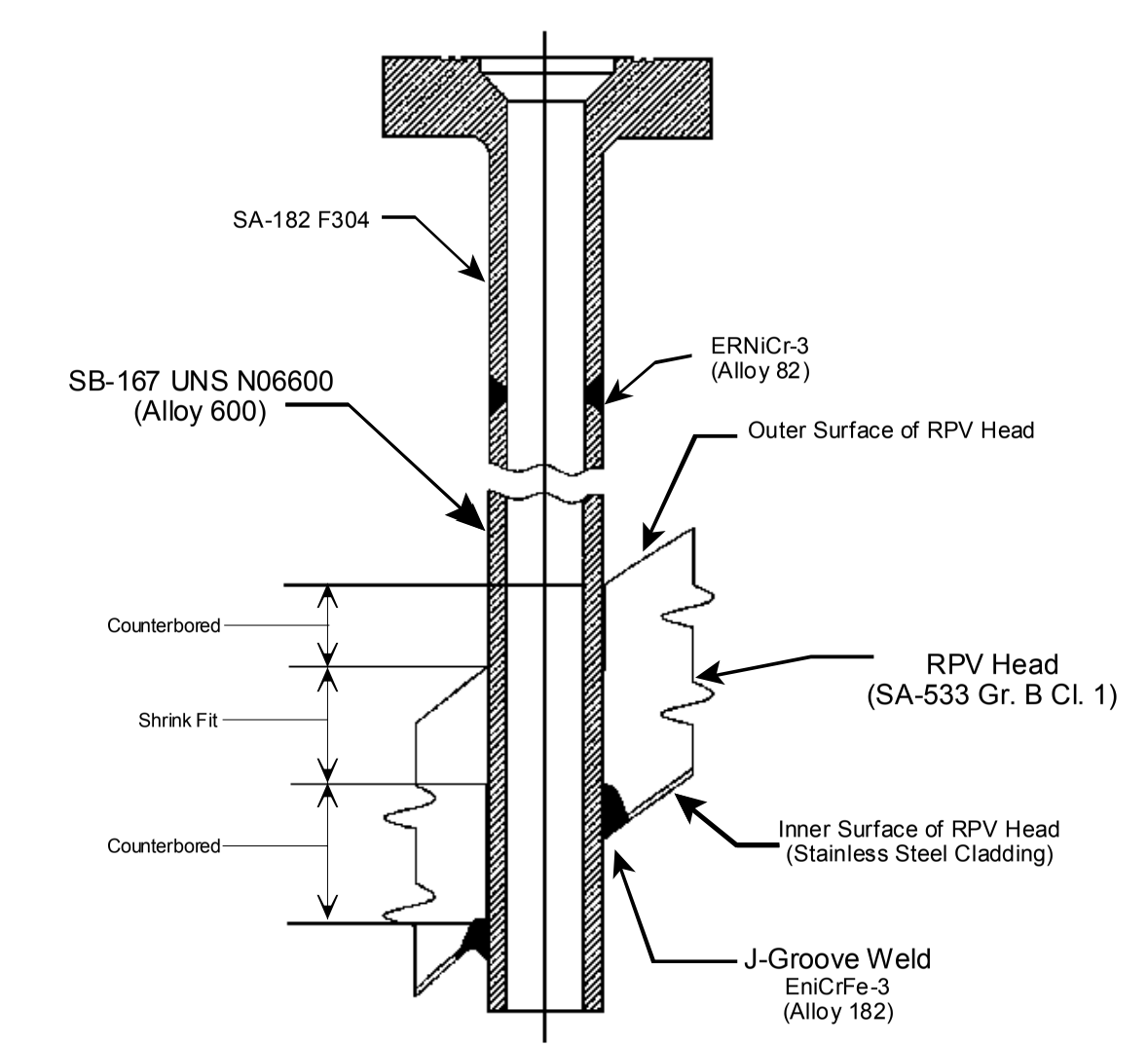
- LOWER HEAD PROBLEM
  - South Texas Project
    - 2 Bottom Mounted Instrument penetrations – visual detection of small boric acid deposits (3 mg and 150 mg)
    - Boric acid deposits were estimated to be 3 – 5 years old
    - Cracking along fusion zone of penetration tube and J-groove weld and into the penetration tube wall
    - Cracks confirmed by UT, ET and Helium Bubble Test
    - Boat samples taken
    - Not expected to crack because of low temperature

CRDM Degradation Locations

- Over time the problem has changed and NDE program has adapted to improve detection at each new location
  - Initially cracking was on ID of penetration tube
  - Cracking on OD of penetration tube at fusion zone of J-groove weld
  - OD initiated circumferential cracking above J-groove weld
  - Cracking in J-groove weld
  - Next had cracking associated with buttering
  - Large cavities in the ferritic steel
  - What is Next?

WNP-1

Design of B&W CRDM



NDE Methods - Visual Testing

- VT is conducted of the vessel head region to detect boric acid deposits
  - Need good access to the bare metal of the head in order to perform an effective examination
  - Other sources of leakage can obscure VHP leaks
  - Will not prevent leaks but only detects leakage
  - The goal of NDE should be to prevent leaks and VT should be used as back up in case degradation is missed by other NDE inspections

NDE Methods – Eddy Current Testing

- Is sensitive to the presence of surface breaking cracks on surface being inspected
- Provides crack length information
- If crack is near to the surface, the eddy current technique can still be effective
- Does not require coupling media but must be in contact with the surface for best test sensitivity
- Inspection of the J-groove weld crown and buttering is more challenging because of the curvature and surface preparation
- Inspection of the ID of the penetration tube is more reliable because of machined conditions

NDE Methods – Ultrasonic Techniques

- Primarily used for inspection from ID of the penetration tube testing for OD and ID flaws
- Most of the implementations use time-of-flight diffraction method
- Since flaws of interest are cracks – TOFD works well for detecting tips and perturbations of the surface signals (lateral wave and back surface)
- Over the fusion zone of the J-groove weld, there are no OD surface signals
- Works well for both axial and circumferentially oriented cracks
- Provides detection, length and depth sizing

NDE Methods – Penetrant Testing

- Primarily used for detection/confirmation of cracks on the crown of the J-groove weld or buttering
- Is an enhanced visual test
- Can be very effective but surface conditions and tight cracks degrade detection capability
- If done manually – high radiation exposure
- If cracks only break the surface in a limited number of locations, crack length will be undersized

Other NDE Methods

- Acoustic Emission for crack growth or leak detection
- Phased Arrays for detecting and characterizing wastage
- Helium Bubble test

Programs Addressing NDE Effectiveness

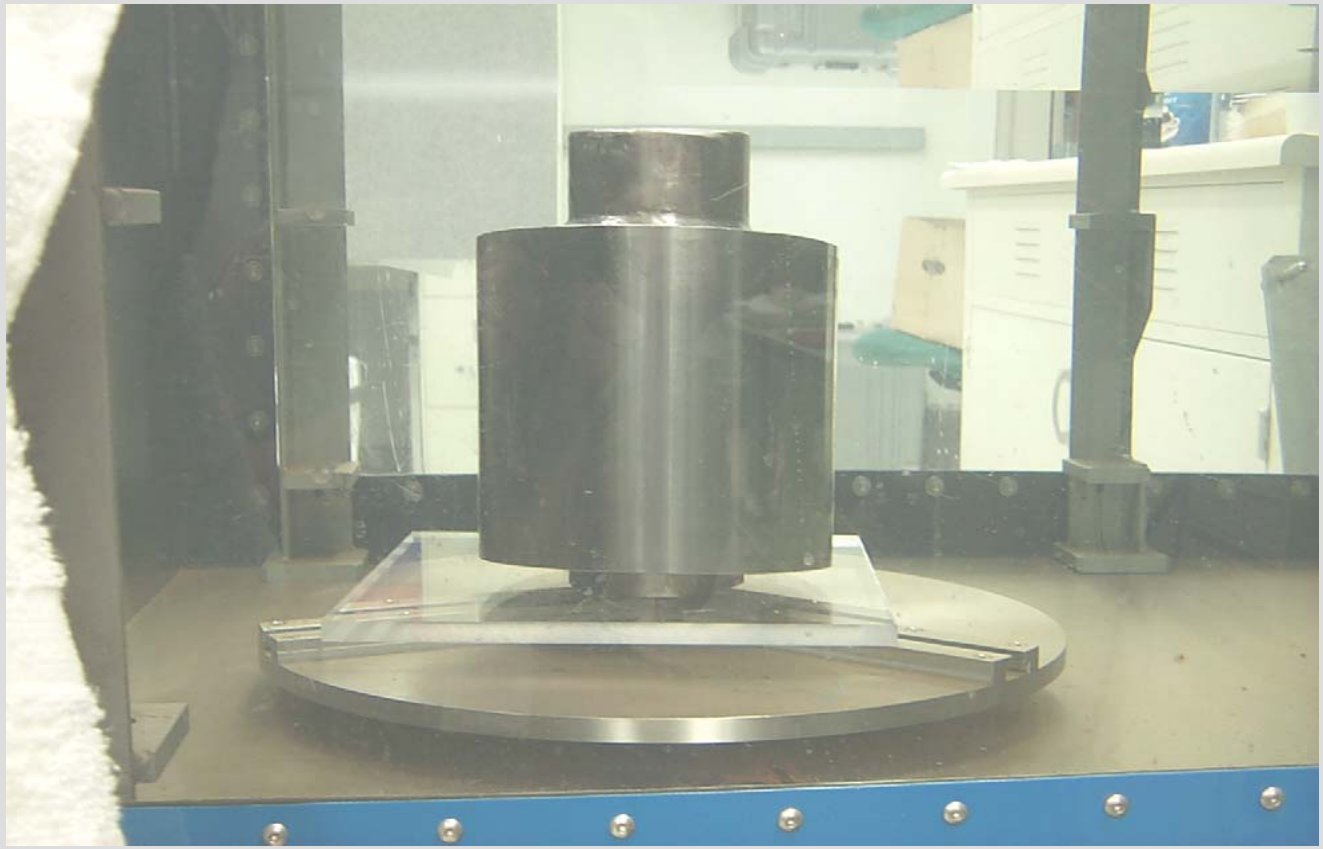
- NRC NDE programs
  - JCN Y6604
  - JCN Y6534
  - JCN Y6909
- EPRI/MRP
  - Developed mockups for NDE demonstration
  - Other research activities
- International Activities
  - Electricity de France
  - Sweden
  - JRC – Petten

NRC Program JCN Y6604

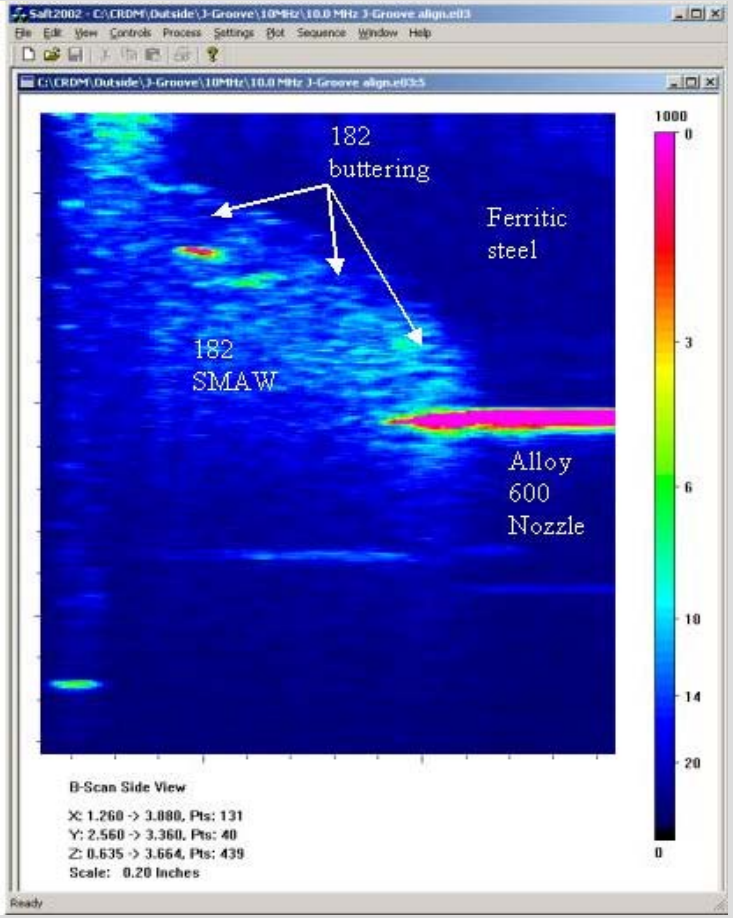
- Studies conducted on a Midland CRDM specimen
- Initial focus of work - detection of fabrication flaws in the J-groove weld and buttering
- Can detect fabrication flaws (1-2 mm)
- Can not effectively detect fabrication flaws on far side of J-groove weld
- Future work will quantify what can be detected

Midland CRDM Nozzle – Head Segment

CRDM prepared for Inspection



SAFT-UT Images from the Outside Machined Surface: 10 MHz



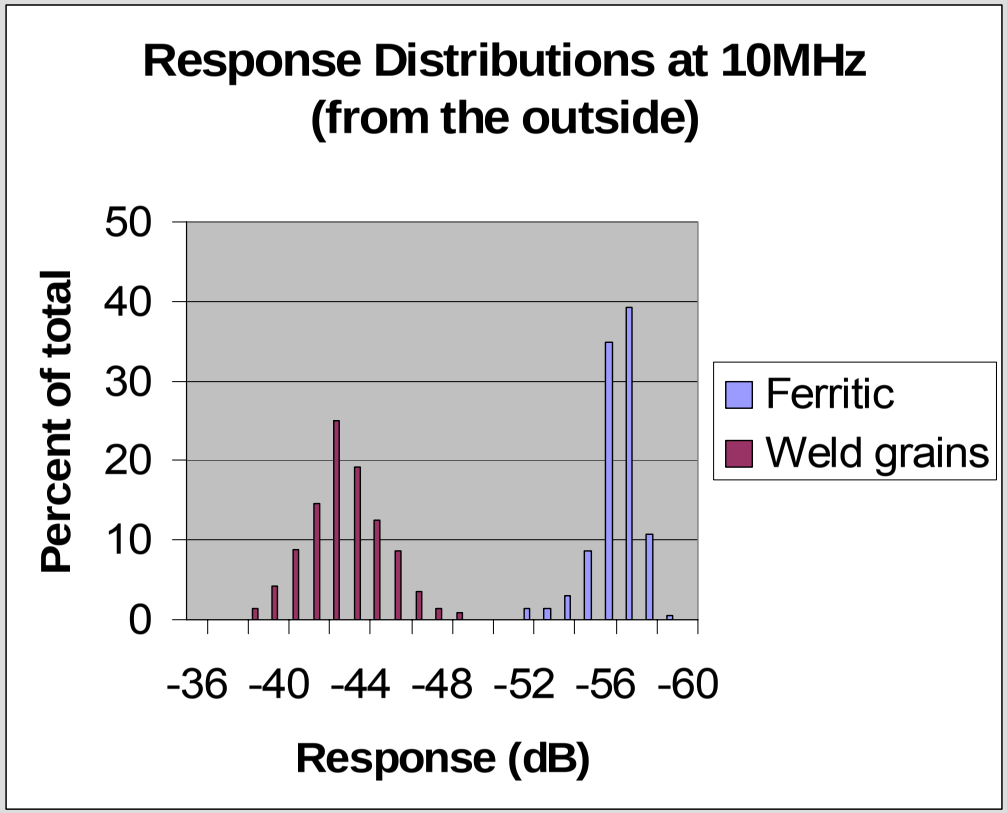
Normal incidence using 10MHz spherically focused, F8

Image is SAFT processed using a shallow processing angle

Four product forms are imaged

- Ferritic steel
- 182 buttering
- 182 Shielded metal arc weld (SMAW)
- Alloy 600 nozzle

Comparison of Response Distributions



NRC Program JCN Y6534

- International Cooperative on PWSCC and NDE of DMW and Nickel Base Alloys
  - Carol Moyer is leading this effort
  - Produce an atlas of metallography documentation on PWSCC cracks and NDE responses
  - Organize and conduct round robin study to assess nondestructrive evaluation (NDE) techniques for detecting and characterizing PWSCC
  - Other options being considered such as modeling, assessing conditions affecting NDE effectiveness, etc.

NRC Program JCN Y6909

- North Anna 2 CRDMs containing real cracks
- Joint program with EPRI/MRP
- 7 nozzles flame cut from head – Shipped to PNNL
- Being decontaminated for study – Note extreme care being taken to keep cracks pristine
- ISI vendors to conduct NDE inspections
- Will provide an assessment of what was and was not detected and how accurately characterized
- Destructive validation and study of cracking process planned – PWSCC or Hot Tears?

North Anna 2 Nozzle #51

NRC Program JCN Y6909 Cont'd

- Davis-Besse material received at PNNL
  - Some of this material is being destructively characterized under a DOE program by Stephen Bruemmer at PNNL
  - Remaining material to be studied during FY 04 and 05

Davis Besse Head Degradation

Conclusions

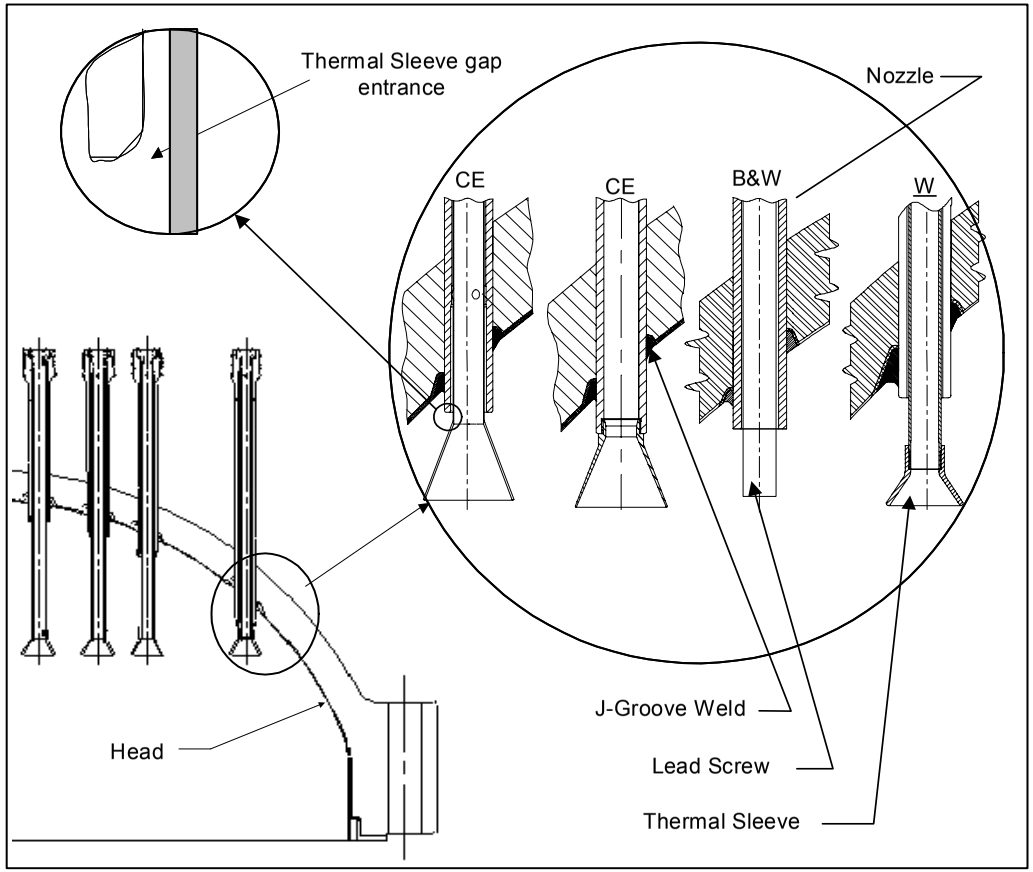
- Failure of Alloy 600/182/82 is a generic problem
- Dominant failure mode is PWSCC
- Most cracking has been detected by leakage because of ISI strategy - that is how areas of potential failure are located
- Goal of NDE program should be to prevent leaks
- How effectively can the J-groove weld be inspected? Classic coarse grained ISI problem
- Overall effectiveness of NDE is unknown
- A number of studies and programs (NRC, industry, international) are in progress or are being planned to address these issues and should bring closure to some of them

The Evolution of Inspection and Repair Approaches for Reactor Vessel Head Penetrations

D. Schlader

FRAMATOME ANP

Typical CRD Nozzle Configurations



FANP RV Head Inspection Experience

RVH Inspection Experience at Westinghouse Designed Plant

Utility Name Station Name	Date Insp.	Nozzle Types (#)	Bare Head By	UT [1]	PT [2]	ET [3]	Contact
RG&E Ginna	March 1999	CRDM (36) Vent Line (1)	Utility	1 BUT	0	28 BET 5 RET	Brian Flynn (716) 771-3734
FirstEnergy Beaver Valley 1	Fall 2001	CRDM (65)	FANP	0	0	0	Tim Heimal (724) 682-5470
Dominion Surry 2	Fall 2001	CRDM (60)	FANP	0	0	0	Dean Price (804) 237-2684
FP&L Turkey Point 3	Fall 2001	CRDM (65) ICI (8) Vent Line (1)	FANP	0	0	0	John Manso (305) 246-6622
Dominion Surry 1	Fall 2001	CRDM (60)	FANP	26 BUT	16 MPT	0	Dean Price (804) 237-2684
FP&L Turkey Point 4	Spring 2002	CRDM (65) Vent Line (1)	FANP	0	0	0	John Manso (305) 246-6622
FirstEnergy Beaver Valley 1	Spring 2002	CRDM (65)	FANP	0	0	0	Tim Heimal (724) 682-5470
Wisconsin Electric Point Beach 2	Spring 2002	CRDM	Utility	0	0	0	Tim Olson (920) 755-7435
British Energy Sizewell B	Spring 2002	CRDM	FANP	0	0	0	
Southern Company Farley 2	Fall 2002	CRDM (69) Vent Line (1)	Utility	69 BUT 1 RUT	0	0	David Gambrell (205) 992-6480
Wisconsin Electric Point Beach 1	Fall 2002	CRDM (49) Vent Line (1)	Utility	33 BUT 20 RUT 1 RUT	0	0	Tim Olson (920) 755-7435
Dominion North Anna 2 (Baseline for new head)	Fall 2002	CRDM (65) Vent Line (1)	NA	65 BUT 1 RUT	66 MPT	0	
Dominion North Anna 1 (Baseline for new head)	Fall 2002	CRDM (65) Vent Line (1)	NA	65 BUT 1 RUT	66 MPT	0	
Dominion Surry 1 (Baseline for new head)	Fall 2002	CRDM (65) Vent Line (1)	NA	65 BUT 1 RUT	66 MPT	0	
FP&L Turkey Point 3	Spring 2003	CRDM (65) Vent Line (1)	FANP	65 BUT 1 RUT			John Manso (305) 246-6622
TVA Sequoyah 1	Spring 2003	CRDM (6)	Utility	6 BUT	2 MPT		Tommy Hale (423) 365-3538

FANP RV Head Inspection Experience (cont'd)

RVH Inspection Experience at CE Designed Plants

Utility Name Station Name	Date Insp.	Nozzle Types (#)	Bare Head By	UT [1]	PT [2]	ET [3]	Contact
Consumer Power Palisades	May 1995	ICI (8)	Utility	0	0	8 RET	Anand Gangadharan (616) 764-8913
FP&L St. Lucie 2	Fall 2001	CEDM (66)	FANP	0	0	0	John Manso (305) 246-6622
BG&E Calvert Cliffs 1	Spring 2002	CEDM (65) Vent Line (1)	FANP	0	0	0	Joe Richards (410) 495-6575
Dominion Millstone 2	Spring 2002	CEDM (69) ICI (8) Vent Line (1)	FANP	69 RUT 8 RUT 1 RUT	4 MPT	0	Tim Petit (860) 447-1791 x0509
FP&L St. Lucie 1	Fall 2002	CEDM (69) ICI (8) Vent Line (1)	FANP	69 BUT 8 RUT 1 RUT	0	0	John Manso (305) 246-6622
BG&E Calvert Cliffs 2	Spring 2003	CRDM (65) ICI (8) Vent Line (1)	FANP	65 BUT 8 RUT 1 RUT			Tim Lupold (410) 495-2283
FP&L St. Lucie 2	Spring 2003	CEDM (91) ICI (10) Vent Line (1)	FANP	91 BUT 10 RUT 1 RUT	0	0	John Manso (305) 246-6622

RVH Inspection Experience at B&W Designed Plants

Utility Name Station Name	Date Insp.	Nozzle Types (#)	Bare Head By	UT [1]	PT [2]	ET [3]	Contact
Duke Energy Oconee 2	Oct. 1994	CRDM (69)	Utility	2 BUT	2 MPT	69 BET 3 RET	Barry Millsaps (864) 885-3667
Duke Energy Oconee 2	April 1996	CRDM (2)	Utility	0	2 RPT	2 RET	Barry Millsaps (864) 885-3667
Duke Energy Oconee 2	Fall 1999	CRDM (8)	Utility	0	0	8 RET	Barry Millsaps (864) 885-3667
Duke Energy Oconee 1	December 2000	CRDM (17)	Utility	16 RUT	0	17 RET	Barry Millsaps (864) 885-3667
Duke Energy Oconee 3	Spring 2001	CRDM (18)	Utility	18 RUT	0	18 RET	Barry Millsaps (864) 885-3667
Entergy ANO – 1	Spring 2001	CRDM (1)	Utility	1 RUT	0	1 RET	Terry Windham (501) 858-4355
Duke Energy Oconee 2	Spring 2001	CRDM (4)	Utility	4 RUT	0	4 RET	Barry Millsaps (864) 885-3667
Florida Power Crystal River 3	Fall 2001	CRDM (9)	Utility	9 RUT	0	0	Jeff Hecht (352) 795-6486 x3478
Duke Energy Oconee 3	Fall 2001	CRDM (51)	Utility	9 RUT 42 BUT	9 MPT	0	Barry Millsaps (864) 885-3667
Exelon Three Mile Island 1	Fall 2001	CRDM (12)	Utility	12 RUT	9 MPT	0	Brad Oliver (267) 253-5685
FirstEnergy Davis-Besse	Spring 2002	CRDM (69)	FANP	69 BUT 6 RUT	0	0	Rich Chesko (419) 321-7580
Duke Energy Oconee 1	Spring 2002	CRDM (4)	Utility	4 RUT	0	0	Barry Millsaps (864) 885-3667
Duke Energy Oconee 2	Fall 2002	CRDM (69)	Utility	65 BUT 15 RUT	7 MPT	0	Barry Millsaps (864) 885-3667
Entergy ANO – 1	Fall 2002	CRDM (31)	Utility	31 BUT	0	0	David Bauman (479) 858-4461
Total FANP Inspections To Date			**14 BHV by FANP**	**738 BUT 318 RUT**	**247 MPT 2 RPT**	**97 BET 66 RET**	

[1] BUT = Blade UT; RUT = Rotating UT
[2] RPT = Remote PT; MPT = Manual PT
[3] BET = Blade ET; RET = Rotating ET

US RV Head Repair Experience

NPP	INTERVENTION DATE	TYPE OF REPAIR	VENDOR
DC COOK 2	1994	Local excavation and manual weld of 1 nozzle	W
MILLSTONE 2	1995	Local excavation and manual weld of 1 nozzle	W
OCONEE 1	11/00	Manual excavation & manual weld of 1 nozzle and 8 T/C's	FANP
ANO-1	03/01	Manual excavation & manual weld on 1 nozzle	FANP
OCONEE 3	03/01	Manual excavation & manual weld of 9 nozzles with remote machine weld overlay of 5	FANP
OCONEE 2	05/01	Remote ID TemperBead Process on 4 nozzles	FANP
CRYSTAL RIVER 3	10/01	Remote ID Ambient TemperBead Process on 1 nozzle	FANP
TMI 1	10/01	Remote ID Ambient TemperBead Process on 6 nozzles and manual repair of 8 T/C's	FANP
SURRY 1	11/01	Remote ID Ambient TemperBead Process on 6 nozzles	FANP
NORTH ANNA 2	11/01	Local excavation and machine weld of 3 nozzles	W
OCONEE 3	12/01	Remote ID Ambient TemperBead Process on 7 nozzles	FANP
MILLSTONE 2	3/02	Remote ID Ambient TemperBead Process on 3 nozzles	FANP
OCONEE 1	4/02	Remote ID Ambient TemperBead Process on 2 nozzles	FANP
DAVIS-BESSE	4/02	Remote ID Ambient TemperBead Process on 5 nozzles	FANP
POINT BEACH 1	9/02	Cut 3 Guide Sleeves in support of Inspection efforts	FANP
ST. LUCIE 2	10/02	Cut 2 Guide Sleeves in support of Inspection efforts	FANP
NORTH ANNA 2	10/02	Cut 12 Guide Sleeves in support of Inspection efforts	FANP
OCONEE 2	11/02	Remote ID Ambient TemperBead Process on 15 nozzles	FANP
ANO -1	11/02	Imbedded Flaw Process on 2 nozzles	W
ANO -1	11/02	Remote ID Ambient TemperBead Process on 6 nozzles	FANP
BEAVER VALLEY 1	4/03	Local Excavation and overlay of 4 nozzle lower stubs	W
ST. LUCIE 2	5/03	Remote ID Ambient TemperBead Process on 2 nozzles	FANP

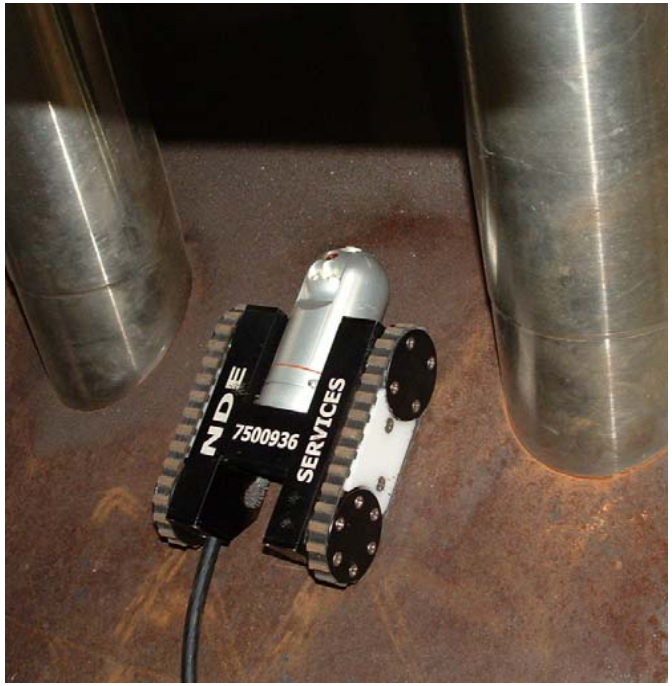
FANP has repaired 84 of the 93 RV head penetrations in the last three years.

Nozzle Inspection Techniques

- Visual Inspection - With and Without Crawler
- Rotating / Blade Ultrasonic Inspection of CRDM Nozzles
  - Penetrations with or without Thermal Sleeves/Lead Screws
  - Rotating UT - Large Cylindrical Probe Inserted in Nozzle
  - Blade UT - Flexible Blade Inserted in the Narrow Gap
  - Axial and Circumferential Crack Detection and Sizing
  - Enhancements
    - Examination of Nozzle and J Weld (Leak Path Verification)
    - SumoROCKY Delivery
- Surface Inspection of J-groove Weld
  - Penetrant Testing - Remote and Manual
  - Eddy Current Testing - Remote

Inspection Techniques - VT

- Bare Head Visual Inspection
- Mirror type insulation or removed insulation
  - Remote Crawler
  - Pole
- Contoured insulation
  - Video probe/snake



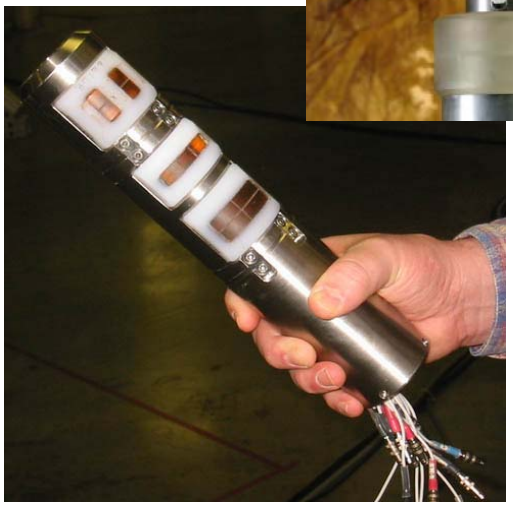
Inspection Techniques - ET

RV Head Remote ET

J-Groove Weld and Nozzle Stub Scanning

Inspection Techniques - UT

- ***Ultrasonic Inspection***
  - ***Rotating UT***
    - ***Penetrations without Thermal Sleeves/Lead Screws***
    - ***Circumferential and Axial Crack Detection and Sizing***
    - ***Initial Inspection of CRDM Nozzles and Inspection of IDTB Repair***
    - ***Leak Path Detection***
  - ***SumoROCKY delivery***



Inspection Techniques - UT

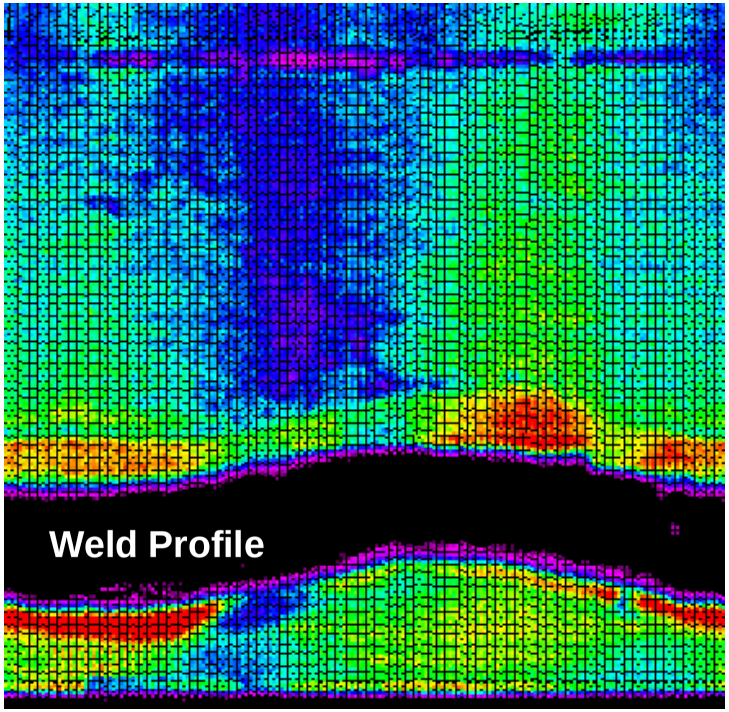
- ***Ultrasonic Inspection***
  - ***Circumferential Blade UT***
    - ***Penetrations with Thermal Sleeves/Lead Screws***
    - ***Flexible Blade Inserted in the Narrow Gap***
    - ***Detection and Sizing of all Circumferential Cracks and Most Axial Cracks***
    - ***Leak Path Detection***
  - ***Range of Axial Blade Probes Available, If Needed***
  - ***SumoROCKY Delivery***

UT Blade Probe with SumoROCKY Manipulator

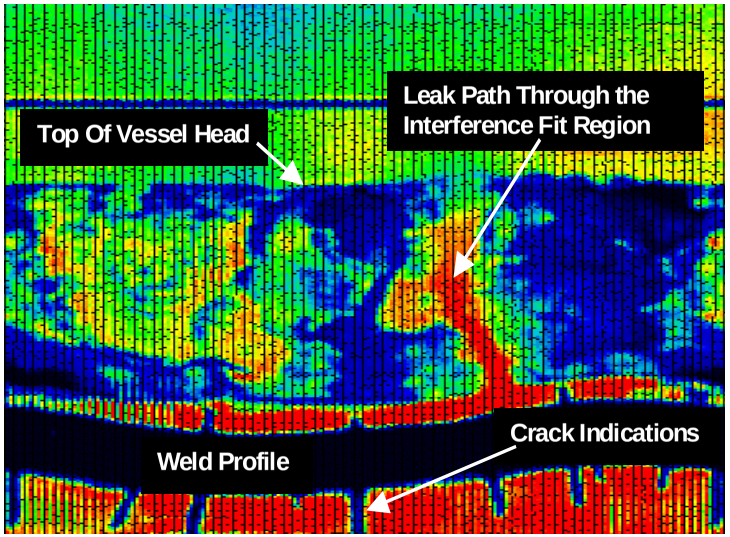
Leak Path Detection

- ***What is it?***
  - ***UT Image of the Amplitude Profile Resulting From Changes in Reflectivity of the Nozzle Backwall in the Interference Fit Region of the Nozzle***
  - ***Sees Changes in the Geometry of the Interference Fit Caused by Erosion/Corrosion of Head Material***
  - ***Patterns Form in the C-scan Image Indicative of a Leak Path***
- ***How Reliable is it?***
  - ***NRC Order (EA-03-009) identified technique as underhead inspection option with UT of the nozzle***
  - ***Database includes over 1000 nozzle scans***

Leak Path Detection
Typical Response for Normal Interference Fit



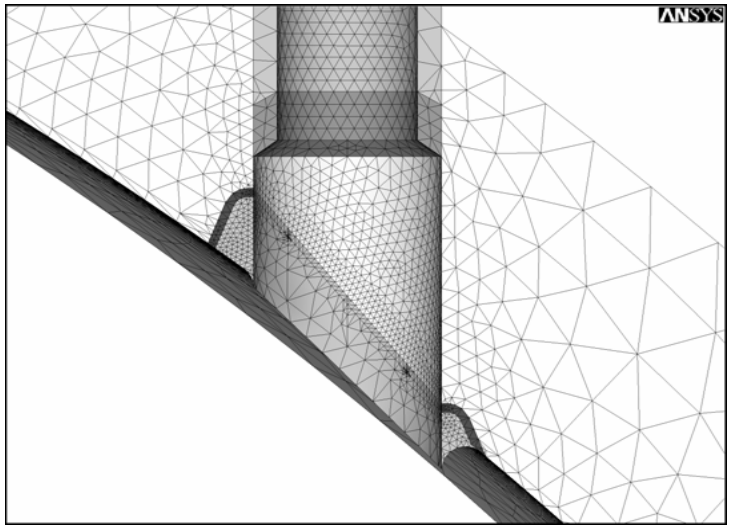
Without Leak



With Leak

Framatome ANP Repair Approaches

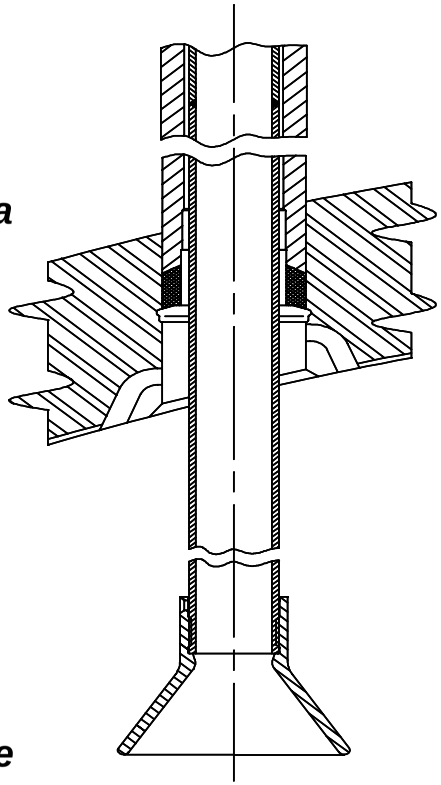
- ***Remote ID Temper Bead (IDTB) Process - Recommended***
  - ***Good contingency approach to be prepared for any failure event***
    - ***Structural Weld Defects***
    - ***Nozzle ID Defects***
    - ***Nozzle OD Defects***
    - ***Multiple Defects in Nozzles With Multiple Failure Modes***
    - ***Maximizes Repair Life Due to Remediation of Weld HAZ***
    - ***Not Flaw Dependent***
    - ***Remote Application***
    - ***Full Nozzle Replacement Possible***



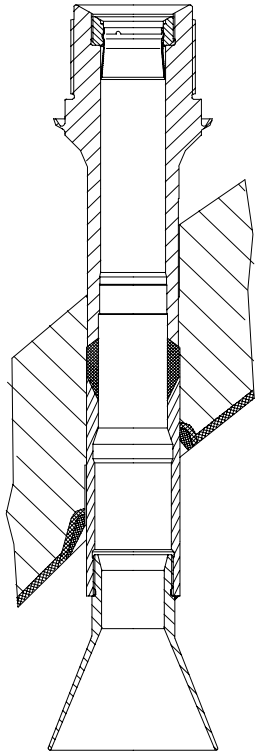
Framatome has repaired 84 RV Head Penetrations in the US over the last 30 months on B&W, W, & CE designed Units.

Remote ID Temperbead CEDM/CRDM Repair Process

- Remove Guide Sleeve
- Base Line NDE
- Roll Nozzle in Repair Region
- Machine Weld Prep & PT Prep Area
- Grind Original Structural Weld Chamfer
- Perform Structural Weld
  - Ambient Temperature Temper Bead
- Prepare Welded Surface For NDE (Grinding / Boring)
- Perform Post-Repair UT & PT
- Remediate Rolled and Repaired Areas With Abrasive Water Jet
- Install Replacement Guide Sleeve
- Fully Analyzed to meet ASME Code

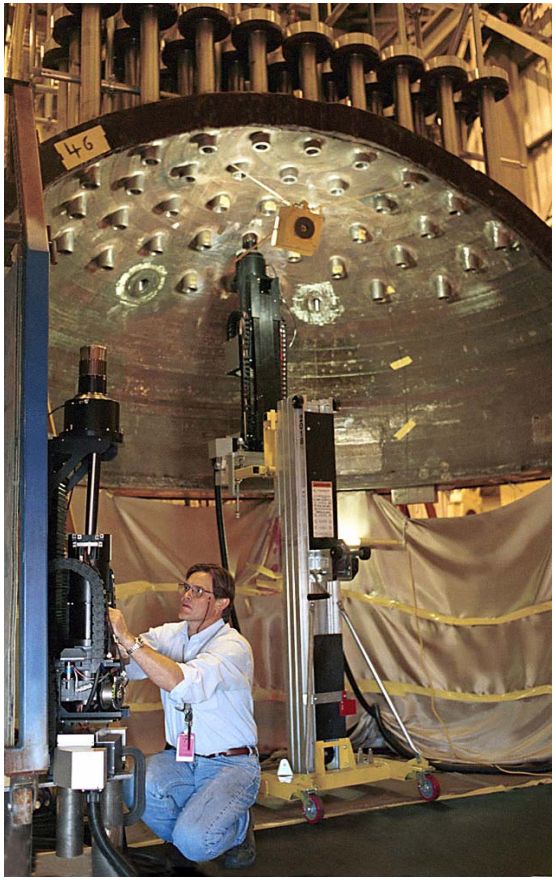


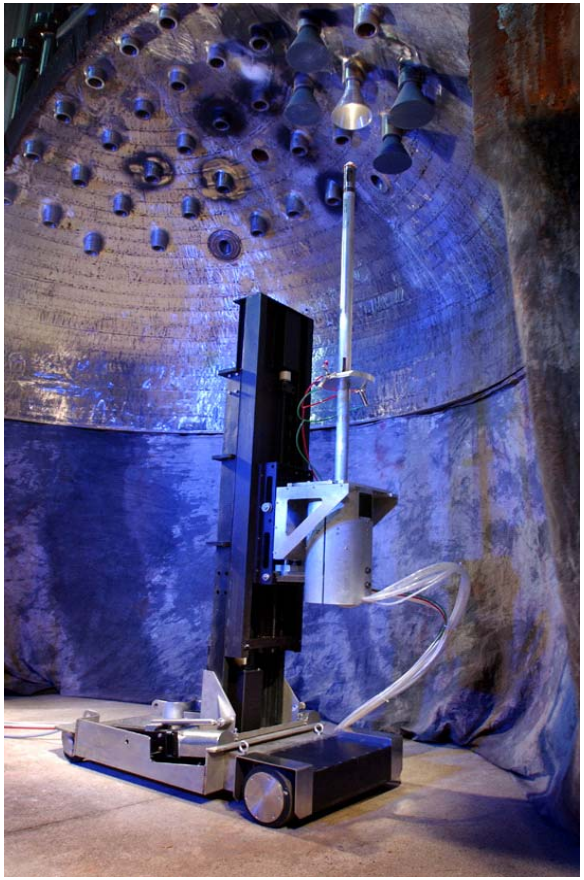
W



CE

Head Mockups





FRAMATOME ANP

Summary of U.S. PWR Reactor Vessel Head Nozzle Inspection Results

U.S. Nuclear Regulatory Commission
Argonne National Laboratory

Conference on Vessel Head Penetration Inspection, Cracking, and Repairs

September 29 – October 2, 2003
Marriott Washingtonian Center
Gaithersburg, Maryland

G. White, DEI
N. Nordmann, DEI
L. Mathews, SNOC
C. King, EPRI

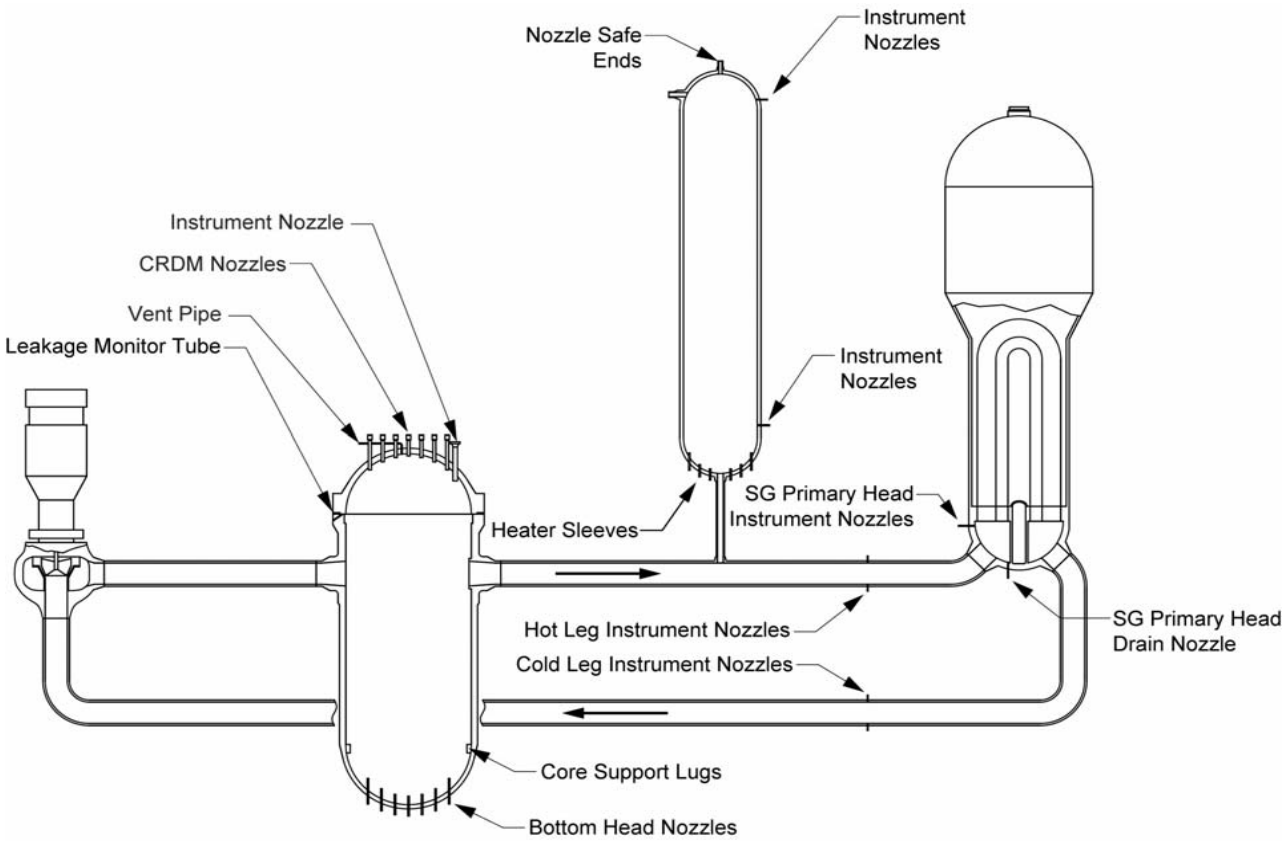
Topics

- Uses of Inspection Summary Statistics
- Introduction
  - Penetration types
  - Materials Reliability Program (MRP) database
  - Inspection techniques
  - Inspections performed to date
- Cracking Detected
  - Leakage and boric acid wastage
  - Circumferential nozzle cracking
  - J-groove attachment weld cracking
- Subpopulation Statistics
  - By EDY group
  - By head fabricator
  - By nozzle material supplier
- Planned Head Replacements and Inspections

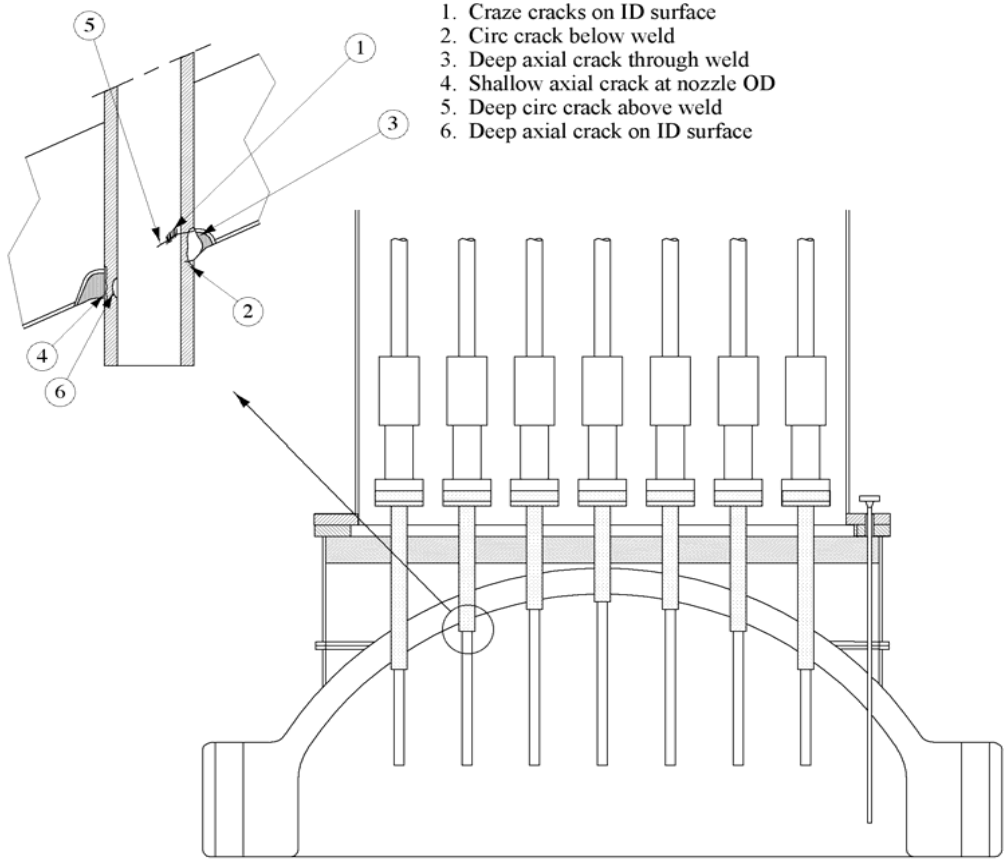
Uses of Inspection Summary Statistics

- Verify use of time at temperature (EDYs) as a susceptibility indicator
- Reveal cracking trends for fabrication and materials groups
- Support safety analysis assessments
  - Weibull statistical modeling of crack initiation or leakage
  - Check of crack growth rates developed using laboratory test data
  - Crack location and orientation assumptions
  - Low alloy steel wastage assessments
- Facilitate periodic evaluations of industry inspection plan
- Support responses to NRC questions

Introduction
Locations of Thick-Section Alloy 600

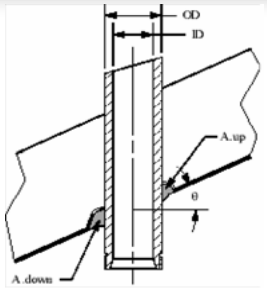


Introduction
Typical PWR RV Head Nozzle PWSCC

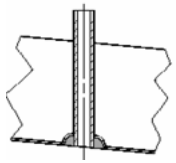


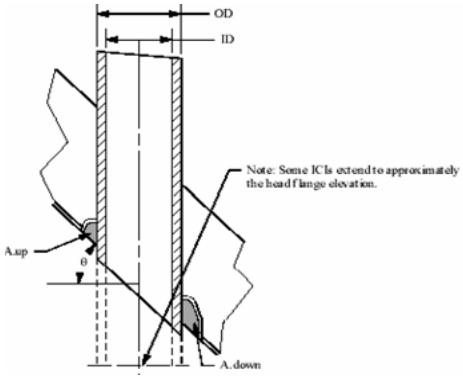
Introduction
Penetration Types

- 69 operating PWR units in the U.S.
- J-groove nozzle designs (all Alloy 600)
  - 3871 CRDM nozzles (55 units)
  - 1090 CEDM nozzles (14 units)
  - 94 in-core instrument (ICI) nozzles (11 units)
  - 59 vent line nozzles (59 units)
  - 16 small-bore thermocouple nozzles (2 units)
  - 8 auxiliary head adapters nozzles (2 units)
  - 2 de-gas line nozzles (2 units)
- Nozzle designs without J-groove welds
  - 3 full penetration weld vent line nozzles (3 units)
  - 6 internals support housing nozzles (2 units)
  - 20 auxiliary head adapters nozzles (5 units)



Basic CRDM/CEDM nozzle design


J-groove vent nozzle design



Typical ICI nozzle design

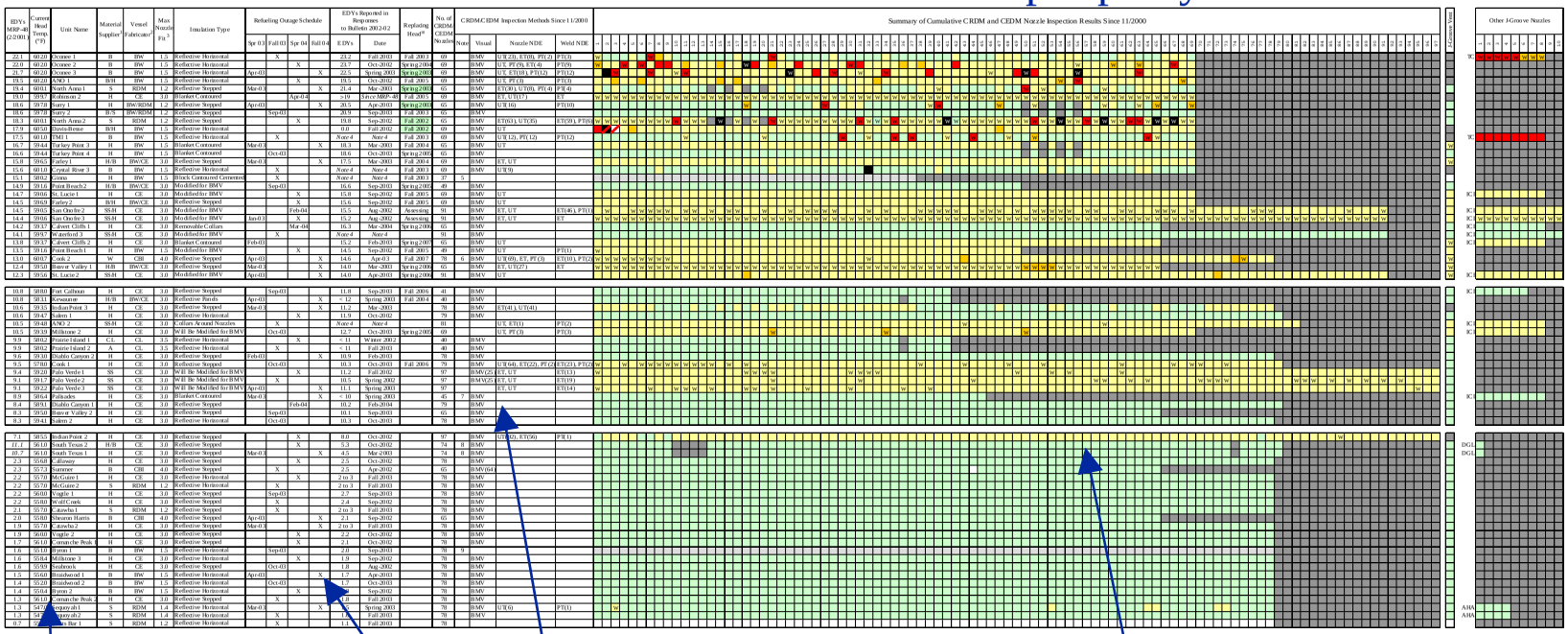
Introduction
MRP Database

- The Materials Reliability Program (MRP) collects inspection results data and updates the summary statistics each outage season
  - Data are collected on the individual flaw level
  - Summary statistics are generated from the detailed level
- The key parameters table graphically shows:
  - The extent to which the fleet has been inspected
  - The extent of detected cracking, leakage, and wastage correlated with effective degradation time (EDYs) and position on the head
  - Key operating and design data
  - Refueling outage schedule and current head replacement plans

Introduction
Key Parameters Table

Toward head periphery →

EDYs →



Notes

1. Key for Material Suppliers: B = B&W Tubular Products, H = Huntington, S = Sandvik, SS = Standard Steel, W = Westinghouse (Huntington), CL = C.L. Imphy, A = Aubert et Duval
2. Key for Vessel Fabricators: BW = B&W, CBI = Chicago Bridge & Iron, CE = Combustion Engineering, RDM = Rotterdam Dockyard, CL = C.L. Imphy
3. Maximum Specified Diametral Interference of Fit (mils).
4. Not reported in Response to Bulletin 2002-02 (e.g., because of head replacement).
5. Because of cemented head insulation, performed special inspections in spring 2002:
   100 % visual above insulation, removed insulation in two suspect areas, no evidence of leakage;
   100 % visual of seal weld joint between CRDM adaptor and CRDM, no indications; and
   UT at some of the and and four instrument port penetration locations, through thickness direction of head to assure no voids similar to Davis-Besse experience.
   Also 100% inspection of ID surface of all head penetrations by ET in 1999 with no recordable indications.
6. Axial crack detected on ID of Nozzle 75 in October 1994.
7. ET for all JCI nozzles in 1995.
8. Modification to EDY calculation based on re-evaluation of head temperature.
9. Visual inspection in the area of the head vent nozzle (but not BMVI); roughly 20% of the head surface was examined.
10. Green = Head Replaced.

Inspection Status Code

- No nozzle associated with this location
- Not yet inspected (since first CRDM leakage was discovered in December 2000)
- Visual test meeting 100% BMV requirements (e.g., = 100% nozzle inspected by BMV, insulation not removed or lifted)
- Bare Metal Visual (BMVI) inspection with no leaks
- Non-visual inspection (UT or ET) of nozzle base metal with no leaks or cracks (indications having detectable depth)
- Non-visual inspection (UT, ET or PT) of nozzle base metal with cracks requiring repair
- Leaking nozzle (according to BMV but not including masked nozzles found not to be leaking by UT/ET)
- Circumferential crack above or near top of J-groove weld
- Significant wastage of low alloy steel head material
- Weld inspected by PT or ET

Other J-Groove Nozzle Code

AHA = Auxiliary Head Adapter
DGL = De-Gas Line Nozzle
JCI = In-Core Instrument Nozzle
TC = B&W Thermocouple Nozzle

MRP-48 EDYs, head temp., unit name, and basic design info

Outage schedule, BL 2002-02 EDYs, and head replacement plans

Types of inspections performed

Color-coded nozzle-by-nozzle inspection results (CRDM/CEDM, vent, other)

Introduction
NRC Chart for Tracking Insp. Results[1]

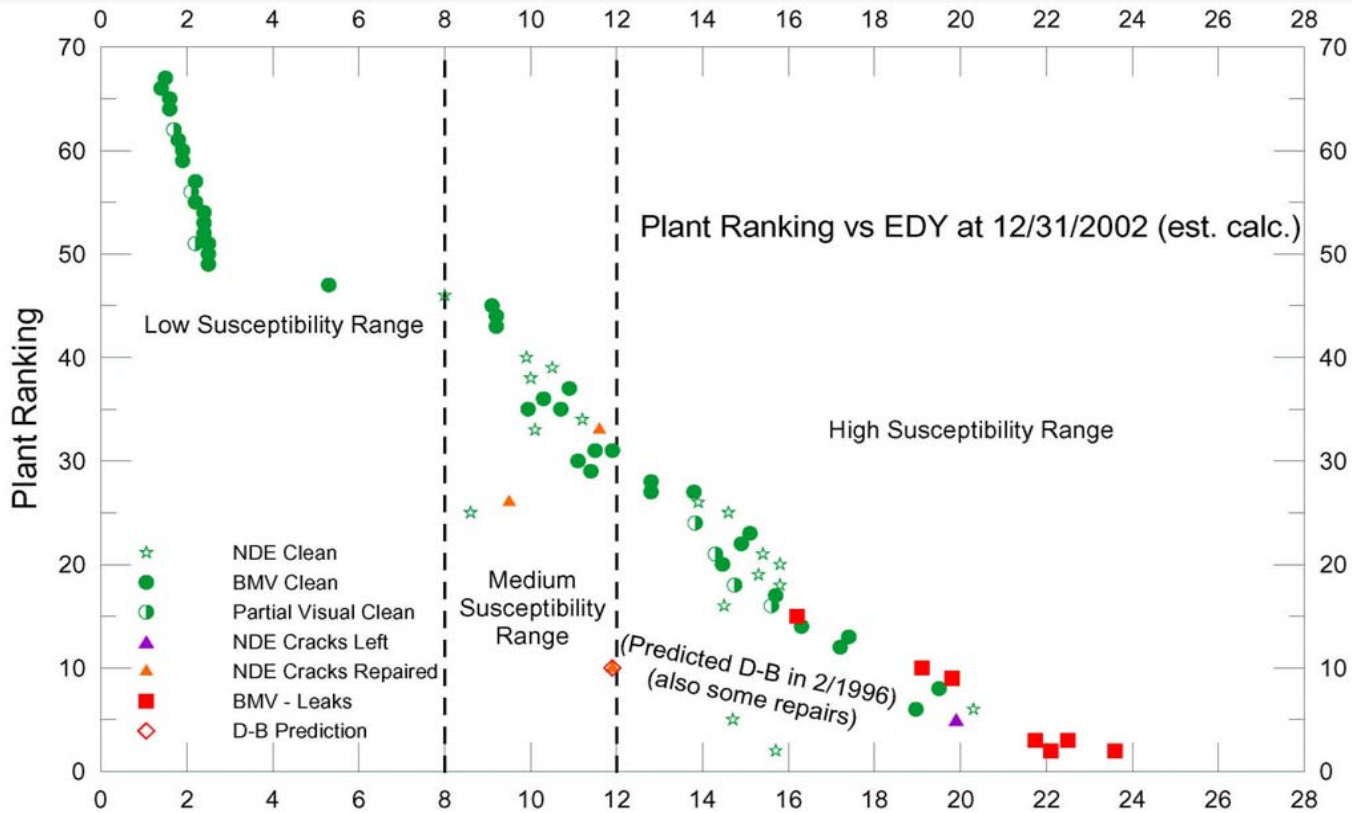
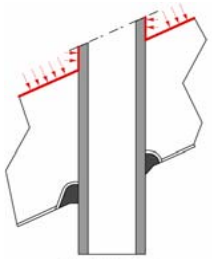


Figure 1. Ranking of domestic plants according to the EDY formula, showing results of inspections, evidence of leakage, and repairs. Many plants are shown with multiple symbols, indicating a "clean" inspection at inspection opportunity, followed by a different finding at a subsequent inspection (e.g., Oconee 2: clean NDE @ EDY=15.7, leaks and circ. flaws @ 22.1)

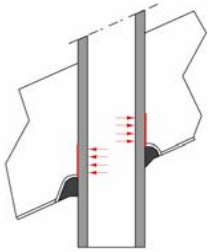
[1]Attachment to Memo, L. Marsh, "Use of the 'EDY' Formula – Susceptibility Model Critique," NRR-2002-018 User Request & LLTF Recommendations Action Plan, July 14, 2003

Introduction
Inspection Techniques

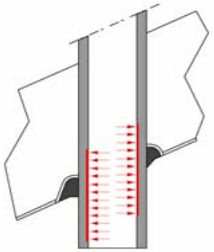
- Inspection techniques include visual inspections for leaks and surface and volumetric NDE of the nozzle,
  J-groove attachment weld, and interference fit zone



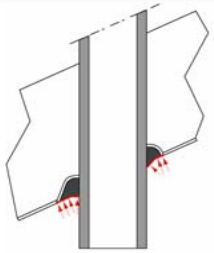
Bare Metal Visual
(Leak Detection)



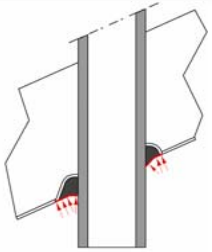
Leak-Path UT
(Leak Detection)



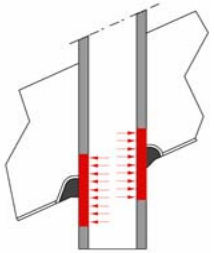
ET-ID
(Tube)



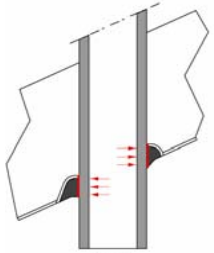
ET
(Weld)



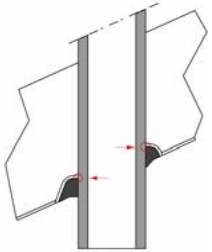
PT
(Weld)



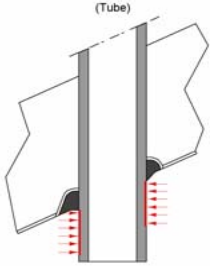
UT
(Tube)



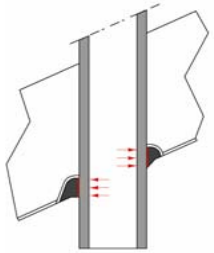
UT-ID
(Weld)



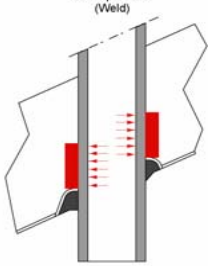
UT-Triple Point
(Weld)



ET-OD
(Tube)



UT-Lack of Fusion
(Tube-Weld)



LF ET-Wastage
(Head)

Introduction
Inspections Performed to Date

- From December 2000 through spring 2003, bare metal visual (BMV) and/or nonvisual NDE examinations have been performed on 96% of CRDM and CEDM nozzles
- From December 2000 through spring 2003, nonvisual NDE examinations have been performed on:
  - 40% of all CRDM and CEDM nozzles (UT and/or ET)
  - 68% of the CRDM/CEDM nozzles in heads having > 12 EDYs
  - 47% of the CRDM/CEDM nozzles in heads having 8-12 EDYs
  - 501 J-groove attachment welds (ET or PT)
- In addition, 5 heads have already been replaced

Cracking Detected
Plants with Detected Cracking

Number	Unit	EDYs thru Feb. 2001 (@ 600°F) (MRP-48)	Current Head Temp. (°F)	NSSS Supplier	Vessel Fabricator (Note 1)	Nozzle Material Supplier (Note 2)	No. of CRDM or CEDM Nozzles on Head	Number Cracked Penetrations Detected (Note 3)			Notes
								Tube and/or Weld Cracked	Tube Cracked	Weld Cracked	
1	ANO 1	19.5	602.0	B&W	BW	B/H	69	8	7	2	
2	Beaver Valley 1	12.4	595.0	W	BW/CE	H/B	65	4	4	0	
3	Cook 2	13.0	600.7	W	CBI	W	78	3	3	0	
4	Crystal River 3	15.6	601.0	B&W	BW	B	69	1	1	1	
5	Davis-Besse	17.9	605.0	B&W	BW	B/H	69	5	5	0	
6	Millstone 2	10.5	593.9	CE	CE	H	69	3	3	0	
7	North Anna 1	19.4	600.1	W	RDM	S	65	6	6	1	
8	North Anna 2	18.3	600.1	W	RDM	S	65	42	8	42	
9	Oconee 1	22.1	602.0	B&W	BW	B	69	3	3	2	4
10	Oconee 2	22.0	602.0	B&W	BW	B	69	19	18	4	
11	Oconee 3	21.7	602.0	B&W	BW	B	69	14	14	2	
12	St. Lucie 2	12.3	595.6	CE	CE	SS/H	91	2	2	0	5
13	Surry 1	18.6	597.8	W	BW/RDM	H	65	6	0	6	
14	TMI 1	17.5	601.0	B&W	BW	B	69	8	7	4	4
							Unique Penetration Totals	124	81	64	

NOTES:

1. Key for Vessel Fabricators: BW = B&W, CBI = Chicago Bridge & Iron, CE = Combustion Engineering, RDM = Rotterdam Dockyard, CL = C.L. Imphy
2. Key for Material Suppliers: B = B&W Tubular Products, H = Huntington, S = Sandvik, SS = Standard Steel, W = Westinghouse, CL = C.L. Imphy, A = Aubert et Duval
3. The totals reflect nozzles that were found to have cracks requiring repairs.
   Other than the 16 small-diameter B&W thermocouple nozzles at two plants, all the cracked nozzles detected are either CRDM or CEDM nozzles.
4. Also all 8 small-diameter B&W thermocouple nozzles were found to be cracked.
5. The CEDM nozzle material at this plant was supplied by Standard Steel, and the ICI nozzle material was supplied by Huntington Alloys.

Cracking Detected
Plants with Detected Cracking (cont'd)

- Cracking has been detected at 14 units:
  - 58 CRDM penetrations at 7 B&W plants having B&WTP material
    - mostly tube cracking but also some weld cracking
  - 54 CRDM penetrations at 3 Westinghouse plants having heads fabricated by Rotterdam Dockyards
    - mostly weld cracking
  - 12 additional CRDM and CEDM penetration tubes
    - 4 nozzles fabricated from a B&WTP heat of material at a Westinghouse plant
    - 3 nozzles fabricated from a heat of material processed by Westinghouse in a Westinghouse plant
    - 3 nozzles fabricated from Huntington Alloys material in a CE plant
    - 2 nozzles fabricated from Standard Steel material in a CE plant
  - 16 of 16 small-diameter thermocouple nozzles at periphery of head in 2 plants

Cracking Detected
Leakage and Boric Acid Wastage

Inspection Number	Unit	NSSS Supplier	Approx. EDYs at Insp.	Insp. Date	No. of CRDM Nozzles on Head	Number Leaking Penetrations (Note 1)			Repair Technique (Note 2)	Repair Method Would Likely Have Detected Significant Wastage?	Notes
						Total	Due to Tube	Due to Weld			
1	ANO 1	B&W	19.6	Mar-2001	69	1	1	0	Embedded flaw	No	3
2			21.1	Oct-2002	69	1	1	0	ID temper-bead	Yes	4
3	Crystal River 3	B&W	16.2	Oct-2001	69	1	1	0	ID temper-bead	Yes	
4	Davis-Besse	B&W	19.2	Apr-2002	69	3	3	0	Replaced head	Yes	5
5	North Anna 1	W	21.4	Mar-2003	65	1	0	1	Replaced head	No	
6	North Anna 2	W	19.0	Nov-2001	65	3	0	3	Weld overlay	No	
7			19.7	Sep-2002	65	6	0	6	Replaced head	See Note 7	6, 7
8	Oconee 1	B&W	21.8	Nov-2000	69	1	0	1	Weld overlay	No	8
9			23.2	Mar-2002	69	1	0	1	ID temper-bead	Yes	
10	Oconee 2	B&W	22.2	Apr-2001	69	4	4	0	ID temper-bead	Yes	
11			23.7	Oct-2002	69	10	7	3	ID temper-bead	Yes	
12	Oconee 3	B&W	21.7	Feb-2001	69	9	9	0	ID temper-bead	Yes	
13			22.5	Nov-2001	69	5	5	0	ID temper-bead	Yes	
14	Surry 1	W	19.1	Oct-2001	65	2	0	2	ID temper-bead	Yes	
15	TMI 1	B&W	18.1	Oct-2001	69	5	1	4	ID temper-bead	Yes	9
					Unique Penetration Totals	51	31	20			

NOTES:

1. No CEDM, ICI, or other types of reactor vessel head nozzles have been found to be leaking (other than the B&W thermocouple nozzles at the two units that have this type of nozzle).
2. The "ID temper-bead" repair method for leaking nozzles involves cutting out the lower section of the nozzle, which makes the surface of the penetration hole in the head shell visible.
3. Although the 2001 repair of this nozzle would not have revealed the presence of low-alloy steel wastage, the subsequent repair in 2002 likely would have.
4. The leaking nozzle that was repaired in March 2001 was found to be leaking again in October 2002.
5. Detailed destructive examinations of the original Davis-Besse head have been performed to characterize the extent of wastage.
6. One of the leaking nozzles that was repaired in late 2001 was found to be leaking again in September 2002.
7. Several leaking nozzles have been extracted from the original North Anna 2 head and are expected to be examined for signs of wastage of the low-alloy steel shell material, among other tests.
8. Also 5 of the 8 small-diameter B&W thermocouple nozzles were found to be leaking.
9. Also all 8 small-diameter B&W thermocouple nozzles were found to be leaking.

Cracking Detected
Orientation/Location for Tube Cracks

		No. of Indications on the Nozzle ID	No. of Indications on the Nozzle OD	*Total*
No. of Axial Tube Indications		112	224	*336*
No. of Circumferential Tube Indications	**Above Weld**	0	7	*7*
	Weld Elevation	0	12	*12*
	Below Weld	6	10	*16*
	Total	*118*	*253*	*371*

Note: Craze cracking and other shallow indications with no depth detectable by UT are not included.

Cracking Detected
Circumferential Nozzle Cracking

Circumferential Nozzle Cracking Above or Near the Top of the Weld

Unit	NSSS Design	Nozzle ID	Nozzle Angle (°)	Inspection Results							
				Date	Approx. EDYs	OD/ ID	Axial Location	Circ. Angle (°)	UH/DH Side	Depth (in)	TW Depth (%)
Crystal River 3	B&W	32	26.2	Oct-01	16.2	OD	above weld	91	DH	0.29	47%
Davis-Besse	B&W	2	8.0	Mar-02	19.2	OD	above weld	34	DH	0.31	50%
North Anna 2	W	15	19.8	Sep-02	19.7	OD	≥1.12" below root	5	DH	0.23	36%
		41	33.1			OD	≥0.52" below root	46	DH	0.10	16%
		54	38.6			OD	≥0.04" below root	79	UH	0.23	36%
						OD	≥0.28" below root	32	DH	0.16	25%
		59	40.0			OD	≥0.31" below root	76	DH	0.15	24%
						OD	≥0.32" below root	50	UH	0.15	24%
		65	42.6			OD	≥0.32" below root	72	DH	0.15	24%
						OD	≥0.20" below root	30	UH	0.08	12%
		67	42.6			OD	≥0.80" below root	44	DH	0.09	15%
Oconee 2	B&W	18	18.2	Apr-01	22.2	OD	above weld	36	DH	0.07	11%
Oconee 3	B&W	11	16.2	Feb-01	21.7	OD	over weld	153	DH	0.36	57%
						OD	over weld	113	UH	0.25	40%
		23	23.2			OD	above weld	66	DH	0.22	35%
		50	35.1			OD	above weld	165	UH	0.62	pin holes
		56	35.1			OD	above weld	165	UH/DH	0.62	100%
		2	8.0	Nov-01	22.5	OD	above weld	48	DH	0.18	29%
		26	24.7			OD	over weld	44	DH	0.07	11%

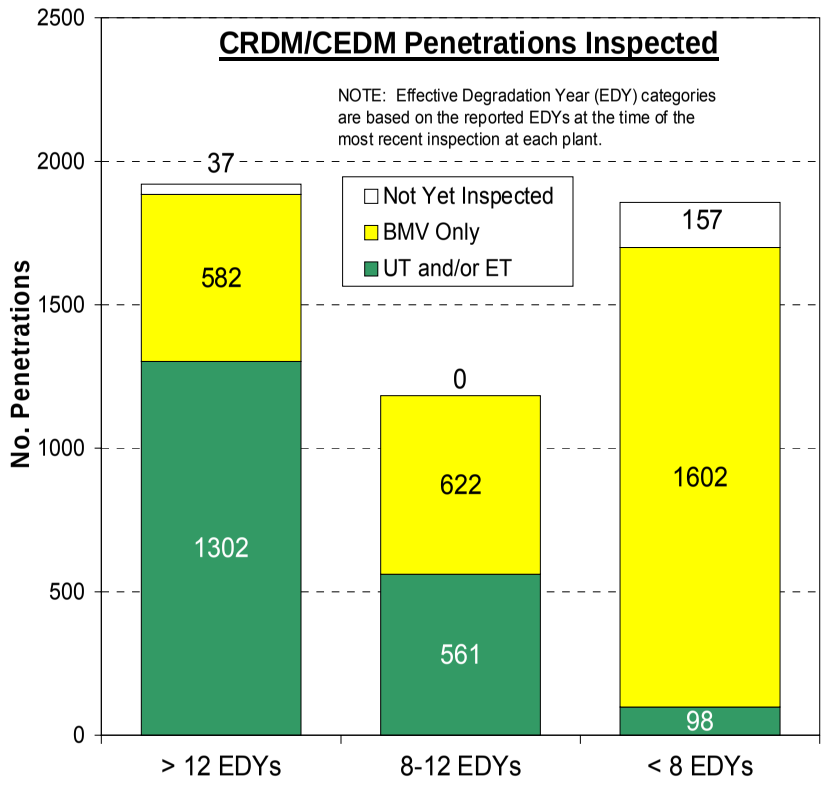
Cracking Detected
Summary

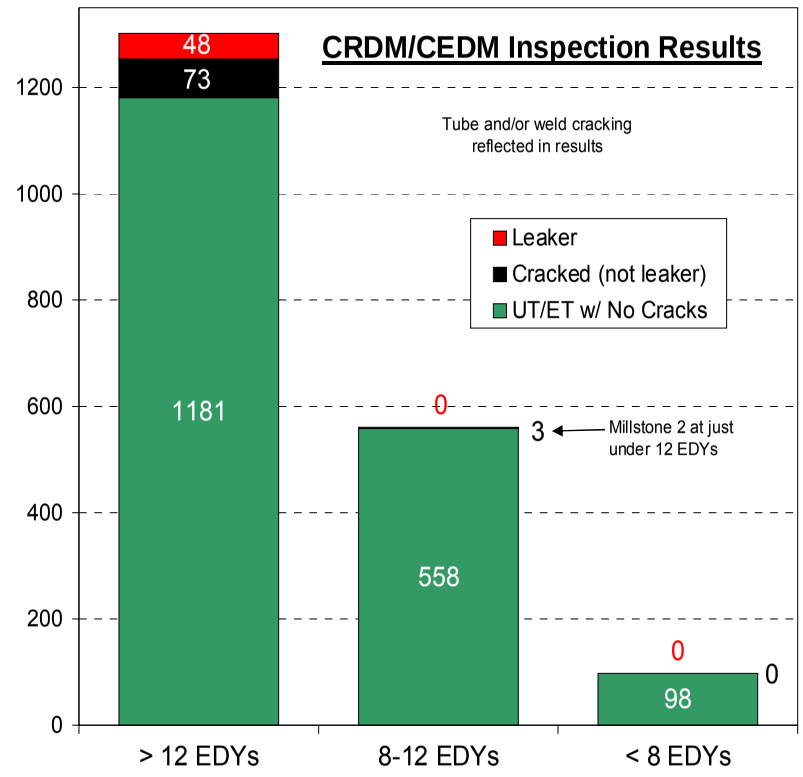
- About 51 CRDM nozzles have been found to be leaking:
  - All in the "> 12 EDY" category
  - 40 of 483 (8.3%) CRDM penetrations in 7 B&W plants
  - 11 CRDM penetrations in 3 heads fabricated by Rotterdam Dockyards, all due to weld cracking
- Little or no wastage has been detected except for the Davis-Besse experience
  - 42 of the leaking CRDM nozzles were repaired in a manner such that if significant boric acid wastage had occurred, it would likely have been detected
- As expected based on the welding residual stress analyses, the nozzle cracking is primarily axial
  - 35 of 371 detected nozzle flaws are circumferential
  - Only 2 circ flaws above or near top of weld are through-wall

Subpopulation Statistics *Introduction*

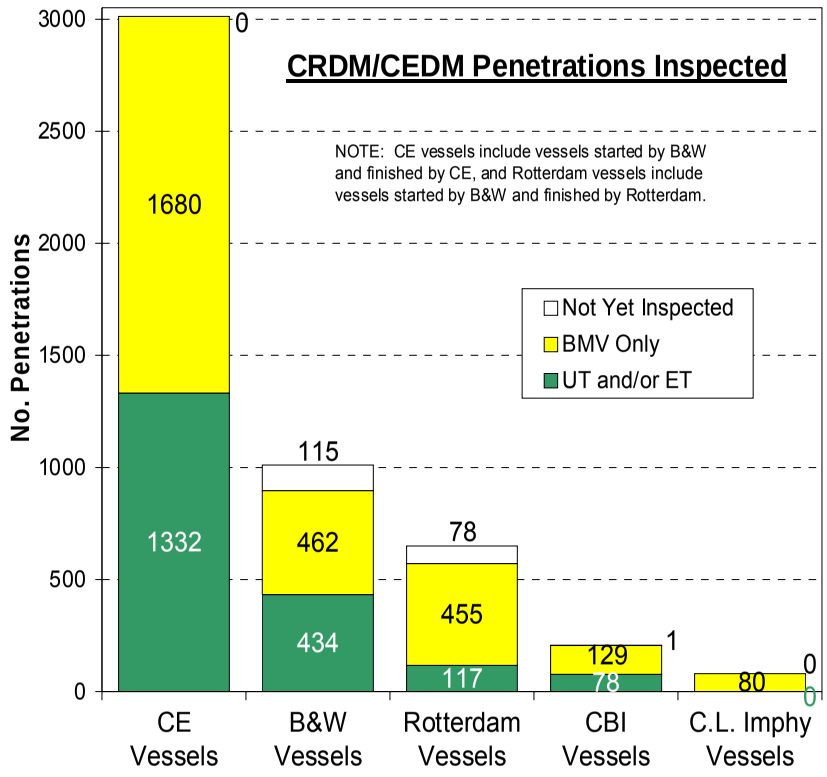
- The summary statistics on the following slides are for inspections performed over the period from December 2000 through August 2003
  - Following first leak detected late 2000
  - After awareness of nozzle cracking originating on the nozzle OD below the weld and of weld cracking
- The left bar chart on each slide indicates the inspection status totals
  - Some nozzles in the 5 heads already replaced were never inspected by a nonvisual technique
- The right bar chart on each slide indicates the result totals for the nonvisual NDE inspections
  - All nozzles found to be leaking were also inspected using a nonvisual technique

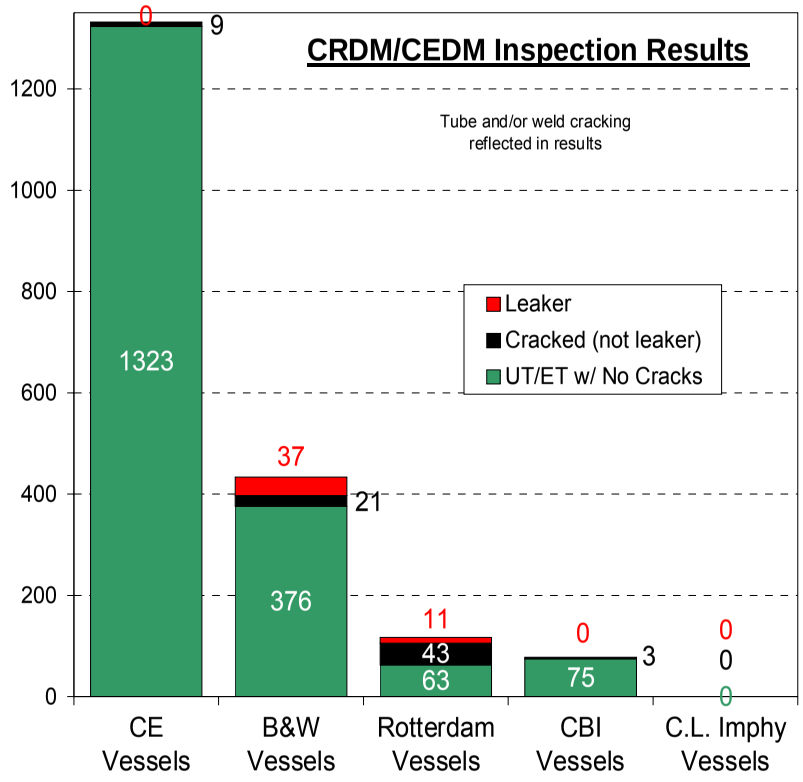
Subpopulation Statistics
By EDY Group



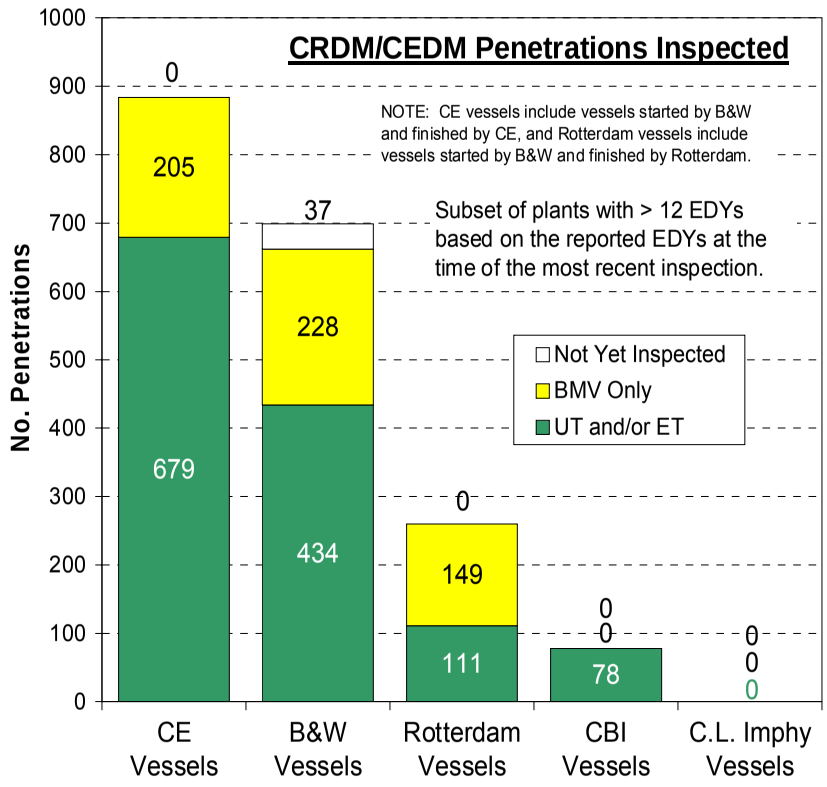


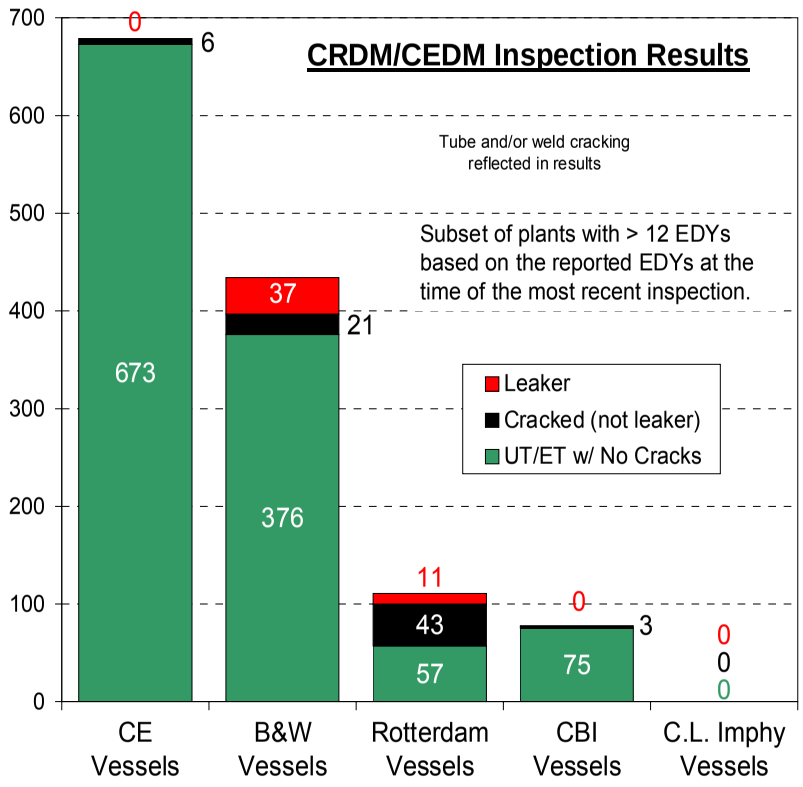
Subpopulation Statistics
By Head Fabricator (All EDY)



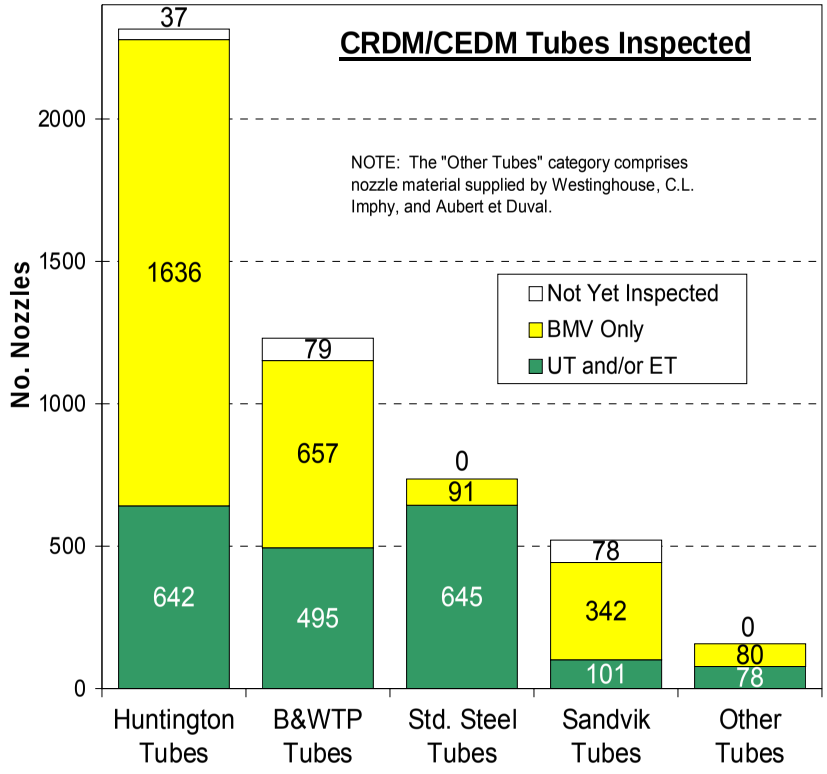


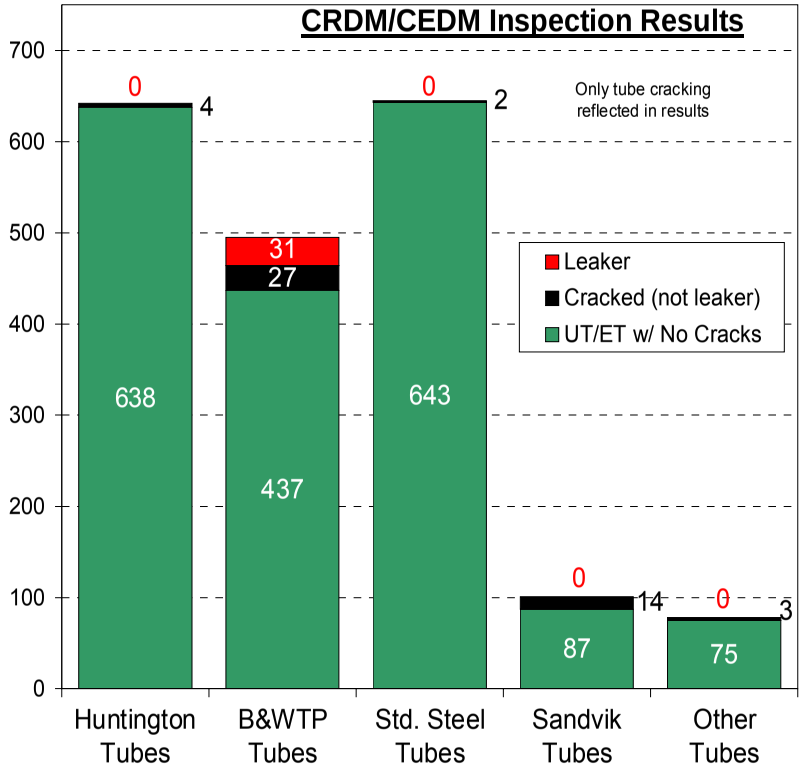
Subpopulation Statistics
By Head Fabricator (>12 EDYs)



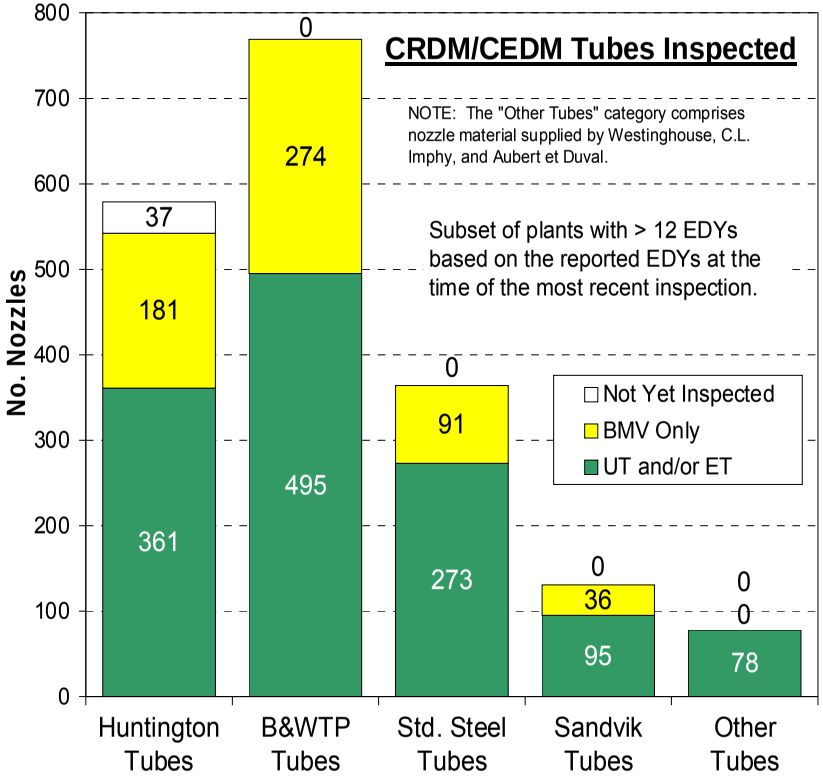


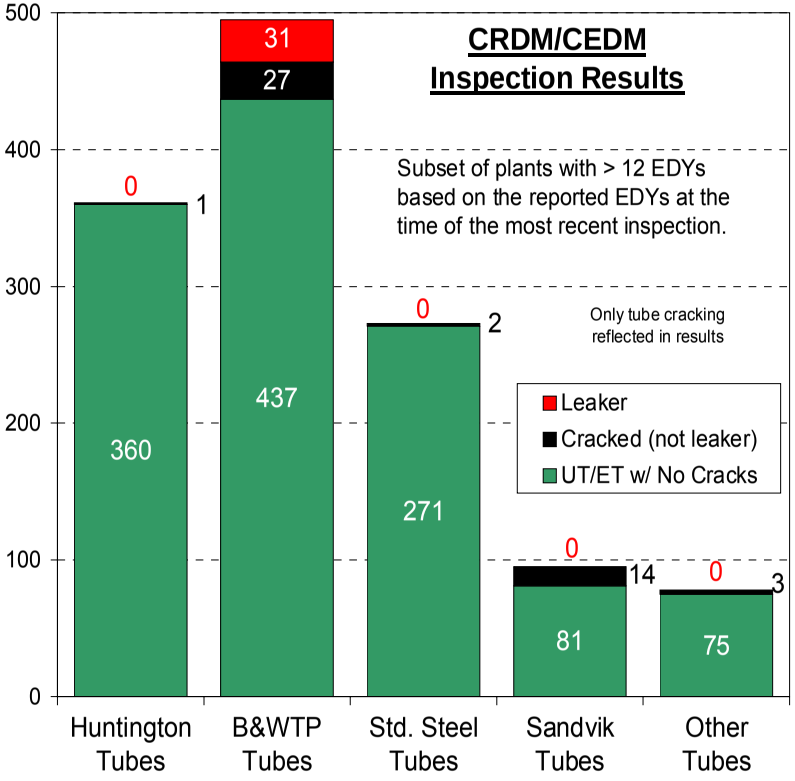
Subpopulation Statistics
By Nozzle Mat'l Supplier (All EDY)





Subpopulation Statistics
By Nozzle Mat'l Supplier (>12 EDYs)





Subpopulation Statistics
Summary

- The 51 leaking CRDM penetrations and all but 12 of the 124 cracked penetrations detected are from the 15 highest ranked units on the basis of time at temperature
- Incidence of cracking in heads fabricated by CE is relatively low:
  - 9 of 1332 (0.7%) penetrations in CE-fabricated heads inspected nonvisually have shown cracking
  - 58 of 434 (13%) penetrations in B&W-fabricated heads inspected nonvisually have shown cracking
  - 54 of 117 (46%) penetrations in Rotterdam-fabricated heads inspected nonvisually have shown cracking
  - Comparisons for EDY groups show that these differences reflect more than just EDY differences

Subpopulation Statistics *Summary (cont'd)*

- Incidence of cracking in nozzle tubes fabricated from material supplied by Huntington Alloys or Standard Steel is relatively low
  - 6 of 1287 (0.5%) nozzles in this category inspected nonvisually have shown cracking
  - 58 of 495 (12%) nozzles fabricated from B&W Tubular Products material inspected nonvisually have shown cracking
  - Comparisons for EDY groups show that these differences reflect more than just EDY differences
- Detected weld cracking has been limited to vessels fabricated by Rotterdam Dockyards and B&W-designed units

Planned Replacements & Inspections
Announced Head Replacements

Announced Head Replacement Plans as of September 2003				
Status	**Year**	**Season**	**No.**	**Unit Name**
Already replaced	2002	Fall	1	Davis-Besse
			2	North Anna 2
	2003	Spring	3	North Anna 1
			4	Oconee 3
			5	Surry 1
Replacing next refueling outage		Fall	6	Crystal River 3
			7	Ginna
			8	Oconee 1
			9	Surry 2
			10	TMI 1
	2004	Spring	11	Oconee 2
		Fall	12	Farley 1
			13	Kewaunee
			14	Turkey Point 3
Replacing after next refueling outage	2005	Spring	15	Millstone 2
			16	Point Beach 2
			17	Turkey Point 4
		Fall	18	ANO 1
			19	Farley 2
			20	Point Beach 1
			21	Robinson 2
			22	St. Lucie 1
	2006	Spring	23	Beaver Valley 1
			24	Calvert Cliffs 1
			25	St. Lucie 2
		Fall	26	Cook 1
			27	Fort Calhoun
	2007	Spring	28	Calvert Cliffs 2
		Fall	29	Cook 2

Planned Replacements & Inspections *Summary*

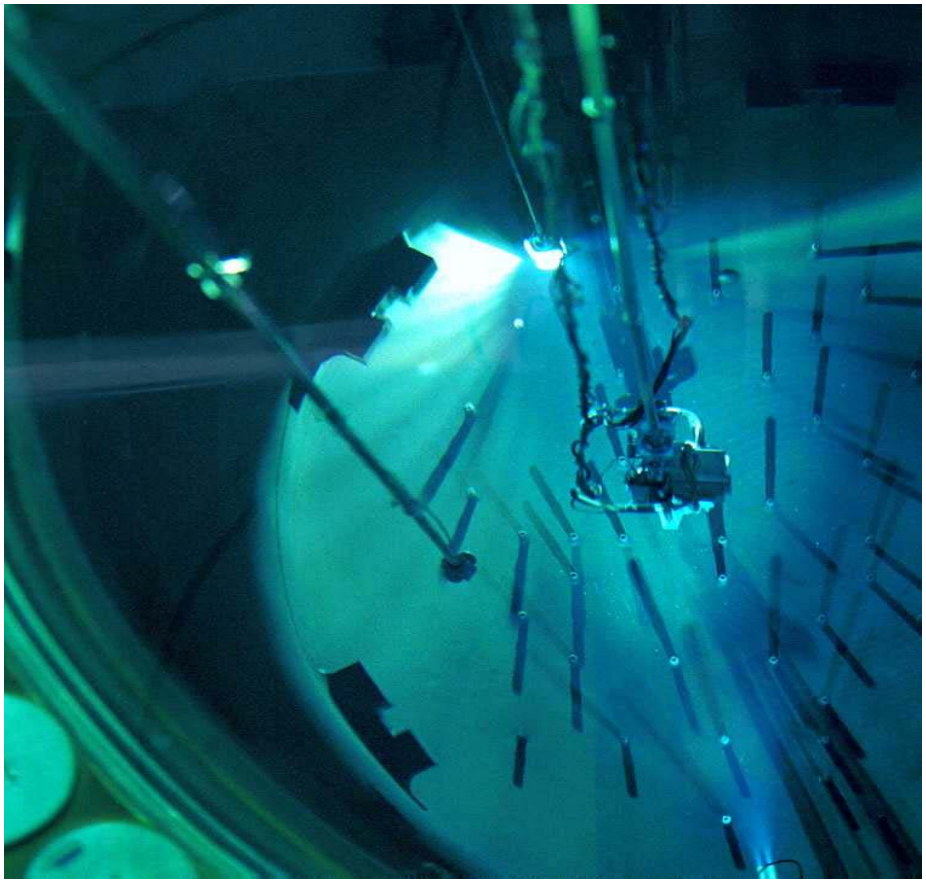
- 27 units have refueling outages this fall:
  - 5 will replace their heads with new heads having Alloy 690 material
  - About 6 plants in the “8-12 EDY” and “> 12 EDY” categories are expected to perform nonvisual inspections of all nozzles
- After fall 2003, it is expected that:
  - BMV and/or nonvisual NDE examinations will have been performed on all RV head nozzles
  - 28 of the 29 plants in the NRC’s high susceptibility category (> 12 EDYs or detected cracking) will have completed baseline nonvisual examinations or head replacement
  - 6 of the 16 plants in the NRC’s moderate susceptibility category (8-12 EDYs) will have completed baseline nonvisual examinations
- After fall 2005, all 46 plants with > 8 EDYs are expected to have completed baseline nonvisual examinations or head replacement

Conclusions

- Time at temperature is an important susceptibility factor
- The head fabricator and nozzle material supplier are also significant factors
  - Relatively little nozzle cracking has been detected in heads fabricated by CE using nozzle material supplied by Huntington Alloys or Standard Steel
  - No weld cracking has been detected in heads fabricated by CE
  - The reasons for these effects are not clear but likely are associated with material and fabrication processing parameters such as:
    - Annealing temperature, cooling rate, and effect on microstructure
    - Straightening practices during nozzle fabrication
    - Machining practices, surface cold work, and fabrication-related defects
    - Welding procedure details

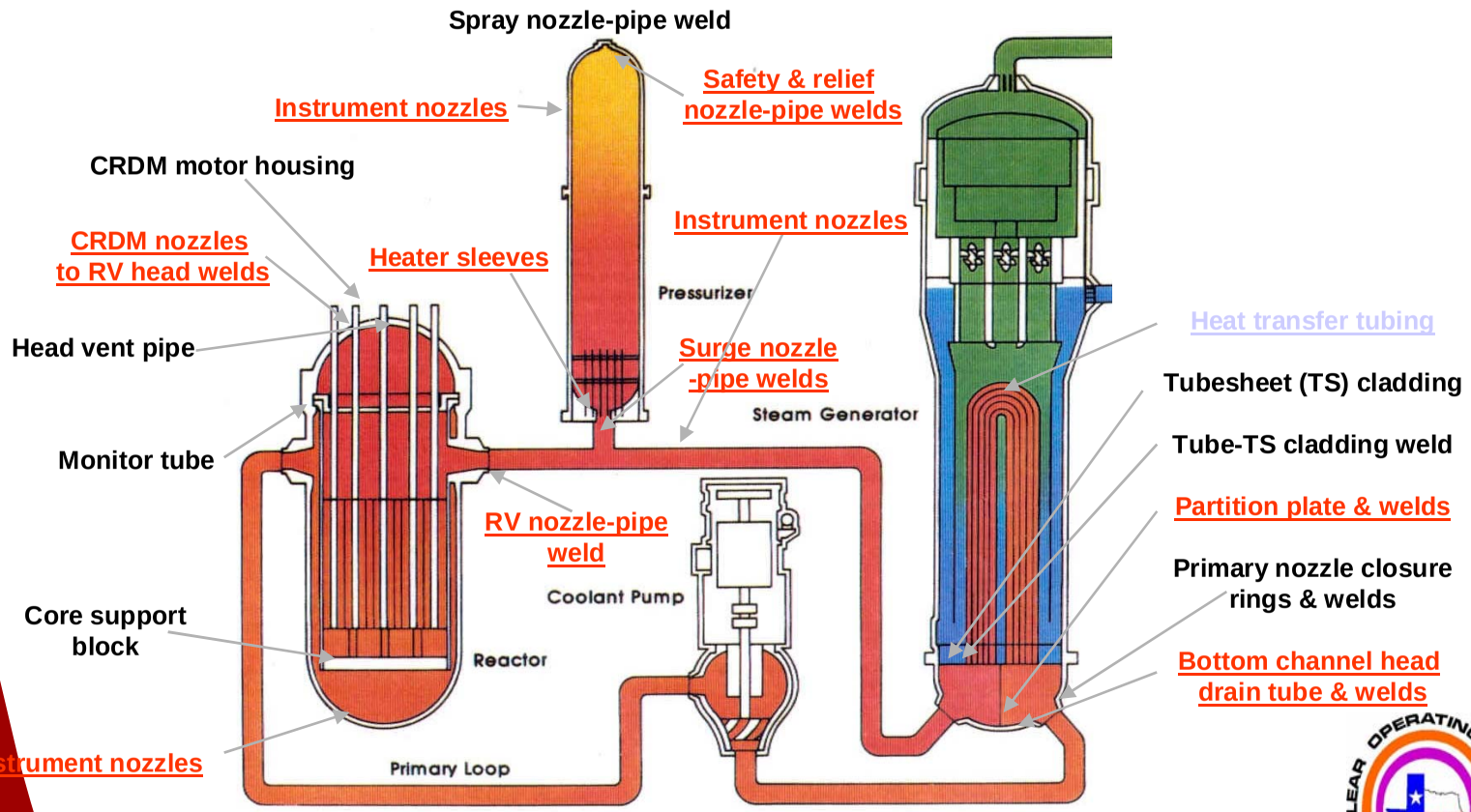
Inspection Technology for BMI Penetrations

M. S. Lashley, South Texas Project, R. F. Cole, and S. W. Glass, Framatome ANP Inc.



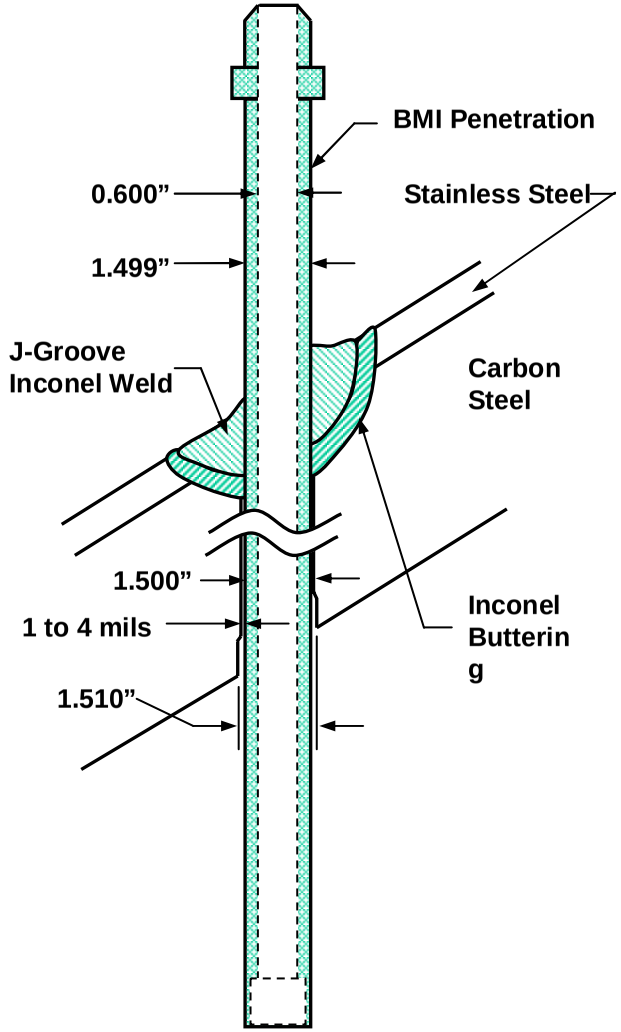
FRAMATOME ANP

Typical Alloy 600 locations



* Represents locations that have experienced cracking and or leakage at other PWRs are highlighted in red.

BMI Guide Tube Penetration



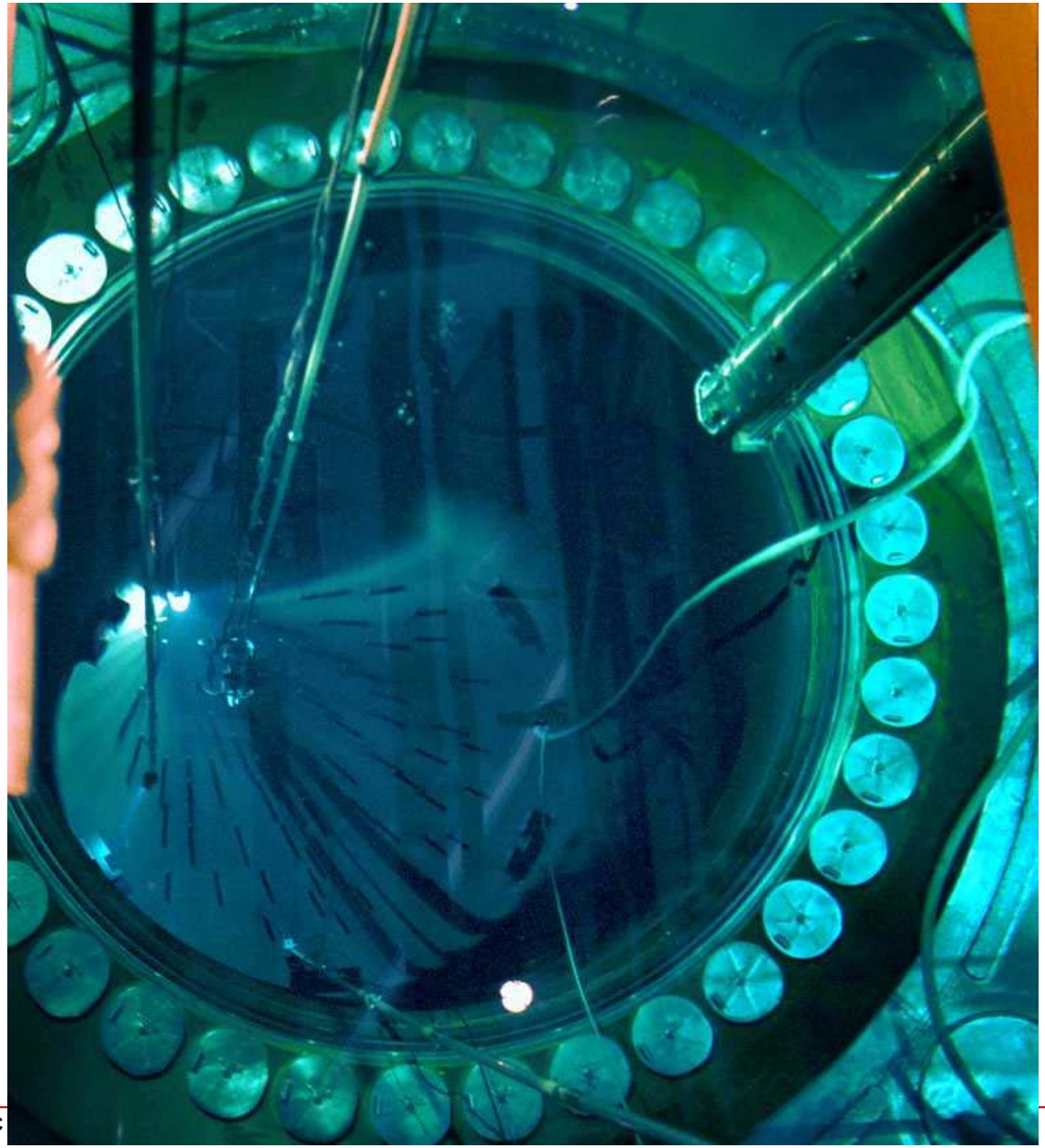
In France, EDF commissioned development of BMI ultrasonic inspection methods and has performed more than 500 examinations since 1992. Framatome has participated in all of these examinations. The 4 columns represent the type of UT examinations performed. Until the South Texas project, no confirmed leaking tubes had been detected.

Plant - Unit	*TOFD C*	*TOFD L*	*OL 0° base*	*OL 0° Comp.*
TRICASTIN 1	***49***	***22***		
BUGEY 3	***50***	***50***		
FESSENHEIM 2	***50***	***50***		***11***
BUGEY 2	***50***	***50***		***16***
NOGENT 1	***58***	***58***		***26***
BLAYAIS 3	***50***	***50***		***22***
BUGEY 3	***50***	***50***	***50***	
TRICASTIN 2	***50***	***50***	***50***	
GRAVELINES 4	***50***	***50***	***50***	
PALUEL 1	***58***	***58***	***?***	***?***
FLAMANVILLE 1	***58***	***58***		***13***
GRAVELINES 1	***50***	***50***		***3***
SOUTH TEXAS 1	***58***	***58***	***58***	
Total	*681*	*654*	*208*	*91*

Comprehensive Examination Performed Using Industry Experts

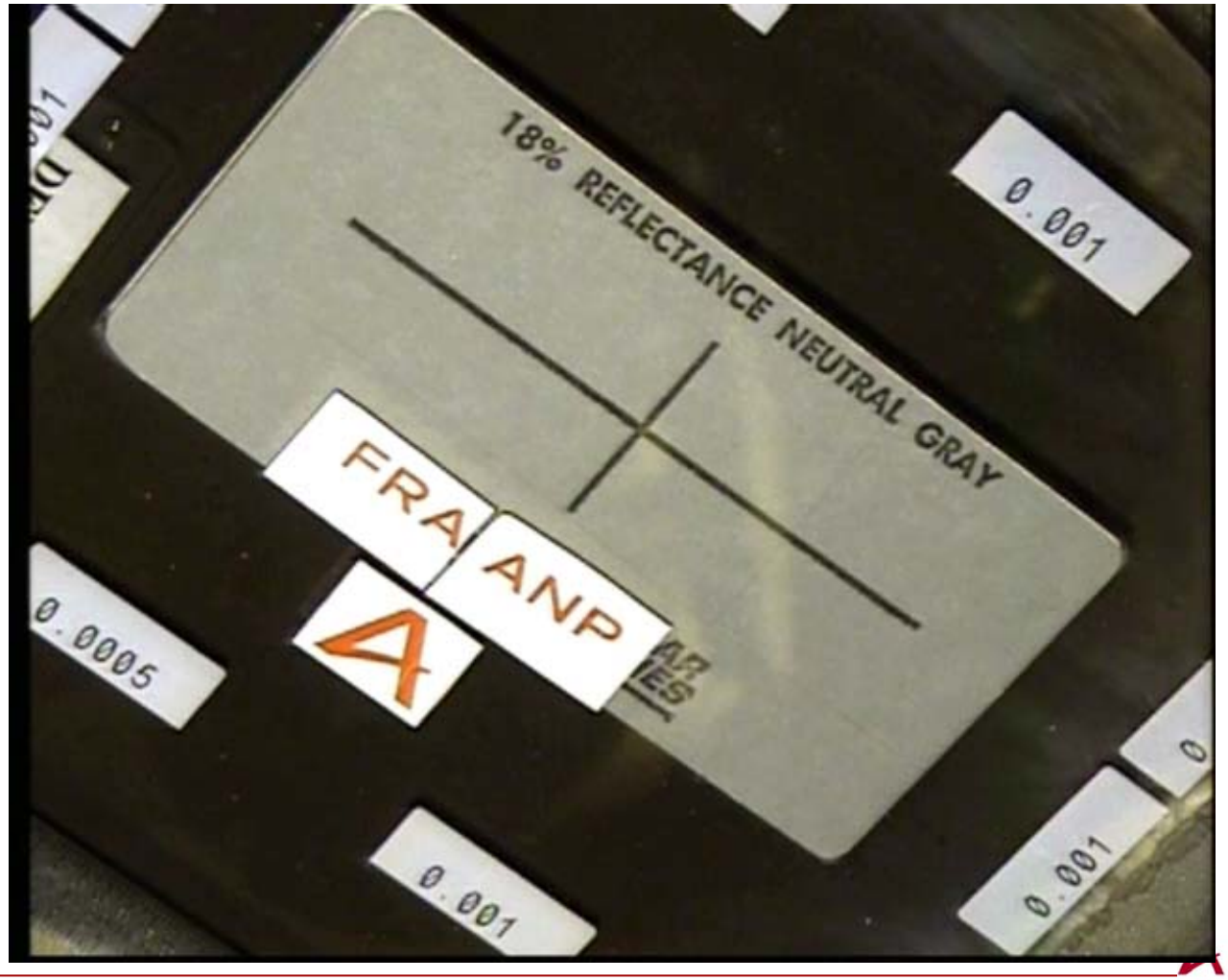
- UT from penetration tube ID
- Enhanced visual exam of J-groove weld surface
- Volumetrically interrogate vessel base metal for wastage
- ET from penetration tube ID
- ET of J-groove weld surface
- Profilometry
- Borescope examinations
- Helium tests
- Metallurgical analyses of removed nozzle remnants
- Boat sample analyses

Unit 1 Reactor Vessel Bottom Head



Penetration Overview

Enhanced Visual

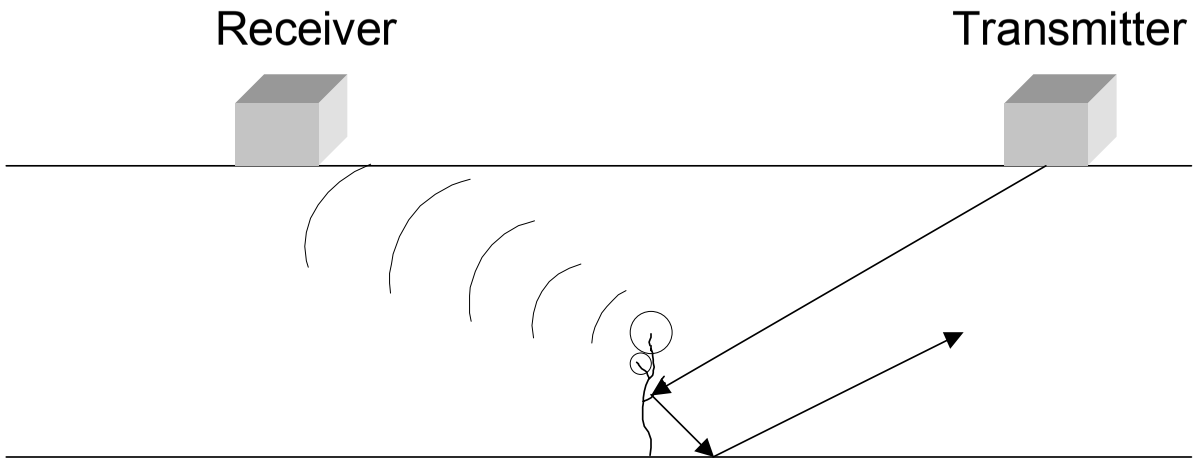


The South Texas project BMI inspection was performed with THE French tool. Subsequently, the US division has developed a second tool that incorporates improvements dictated by experience with the French tool.

French UT Probe Delivery Tool

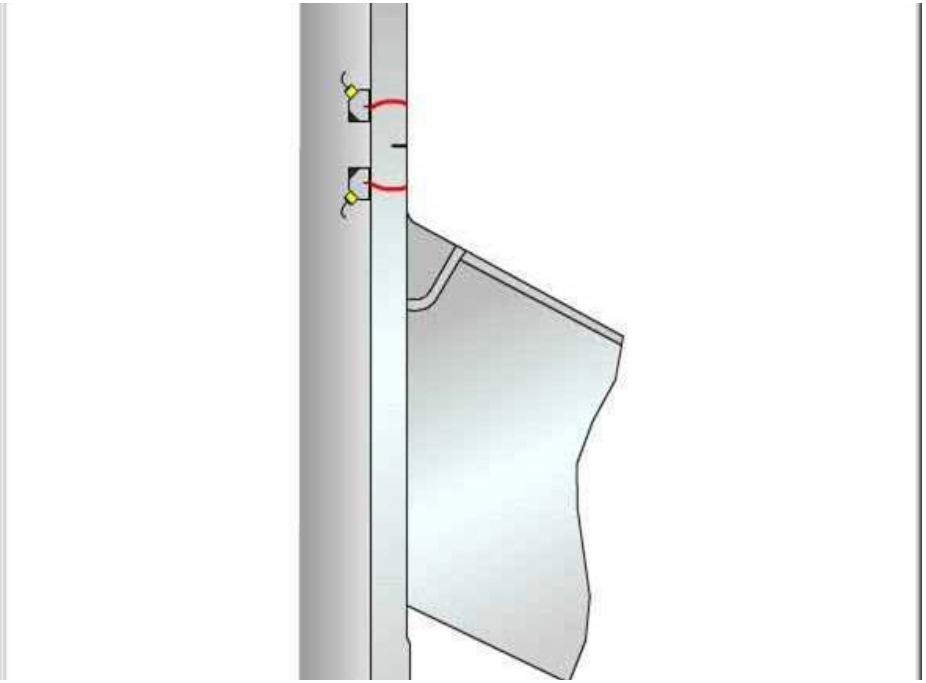
US UT Probe Delivery Tool

Time of Flight Diffracted (TOFD)



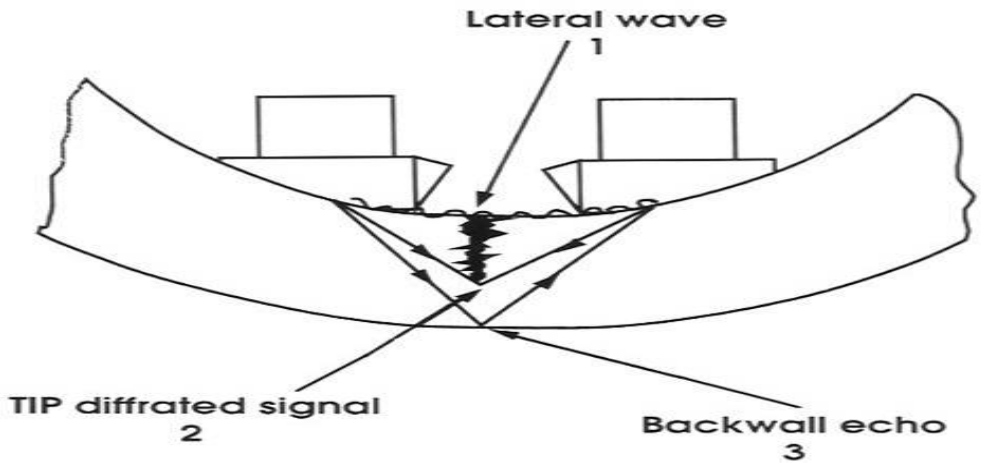
Low-amplitude, secondary wave generated by excitation of flaw

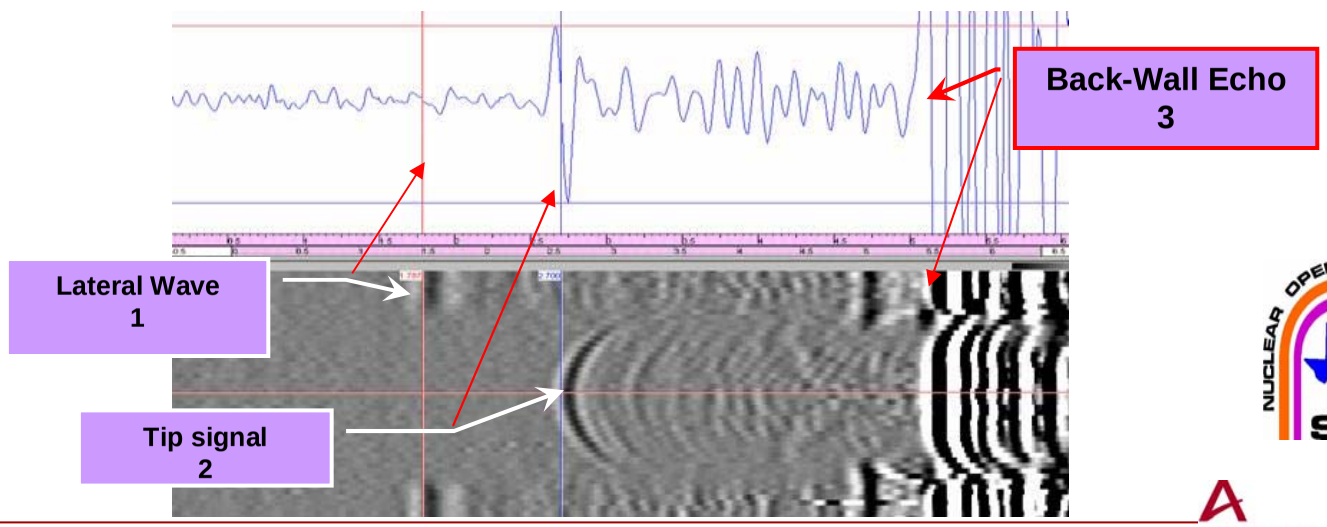
TOFD Animation



Double click in box to start animation when in "slide-show-presentation mode", accept warning, then enlarge by dragging corner to display full screen

TOFDT (Time Of Flight Diffraction Technique)





Demonstration Protocol

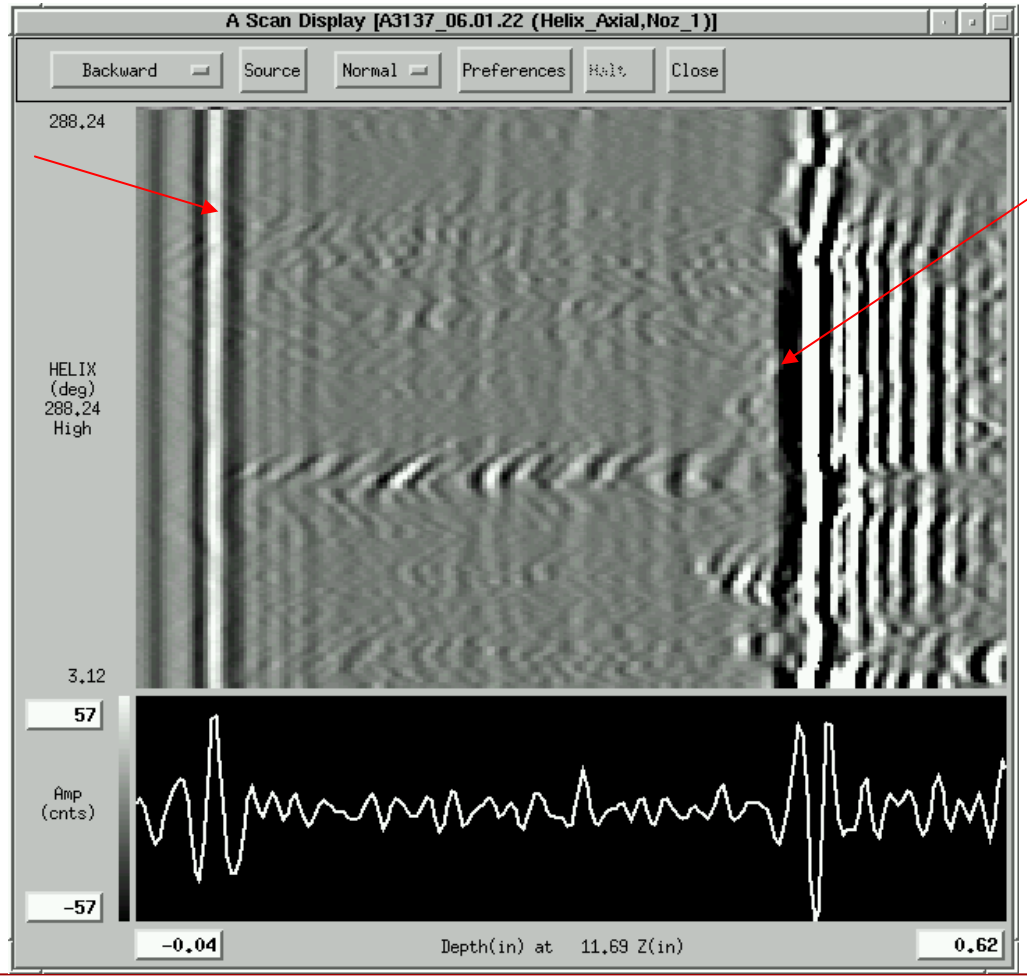
- Scope
  - Detection and sizing of axial and circumferential flaws in the tube
    - » Isolated flaws
    - » Axial and circumferential flaws in conjunction
    - » ID and OD flaws
  - Discrimination of flaws from sources of false calls
  - Flaw locations relative to component geometry

Demonstration Protocol (cont'd)

- Process - follows MRP process for VHP demos
  - Phase 1 (open/non-blind)
    - » Allow refinement of procedures under realistic, controlled conditions
    - » Allow analysis of results to determine and improve capabilities of individual techniques within the procedure
      - Detection, sizing, location
  - Phase 2 (monitored/blind)
    - » Demonstrates capability
      - Detection, sizing, location

Penetration #1 Axial Probe

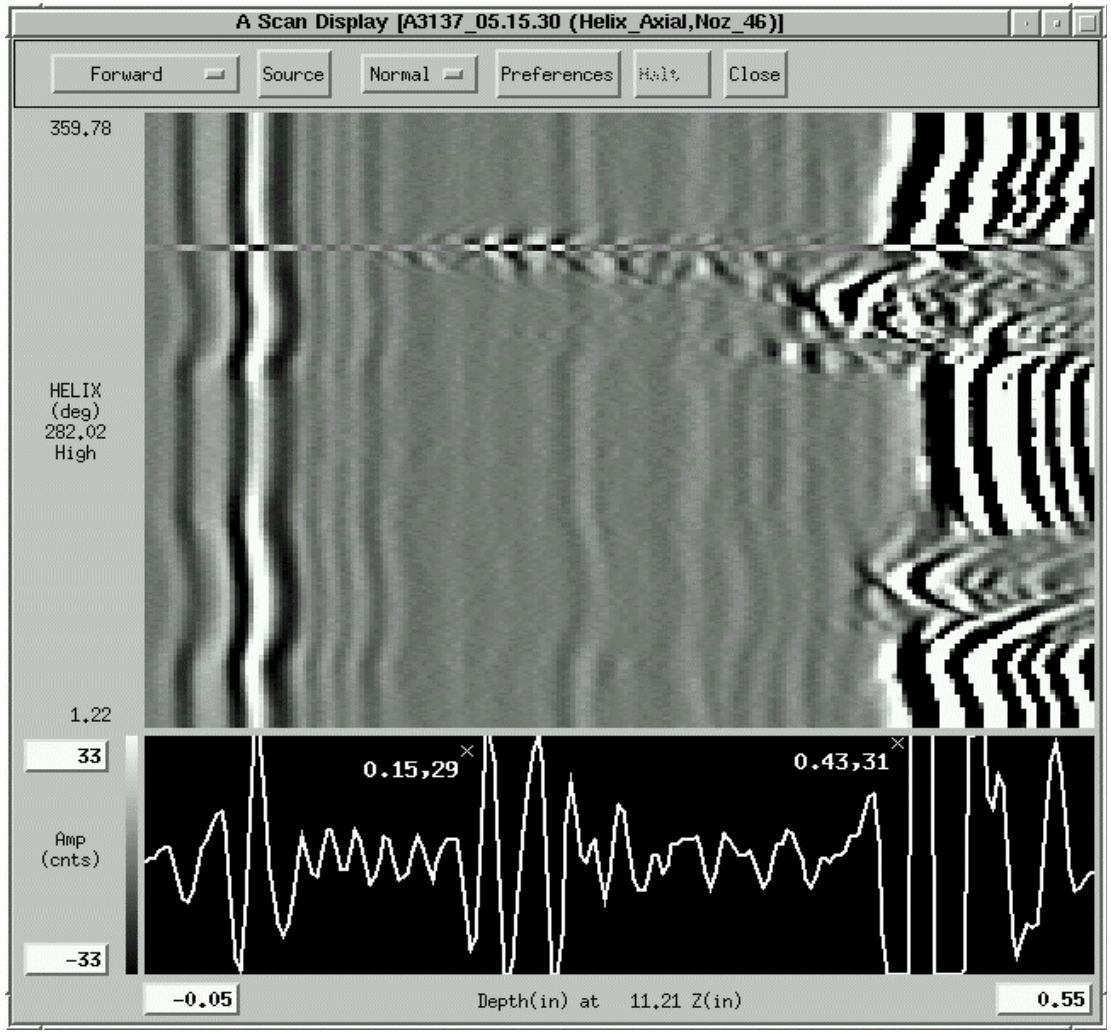
Tube ID



Tube OD

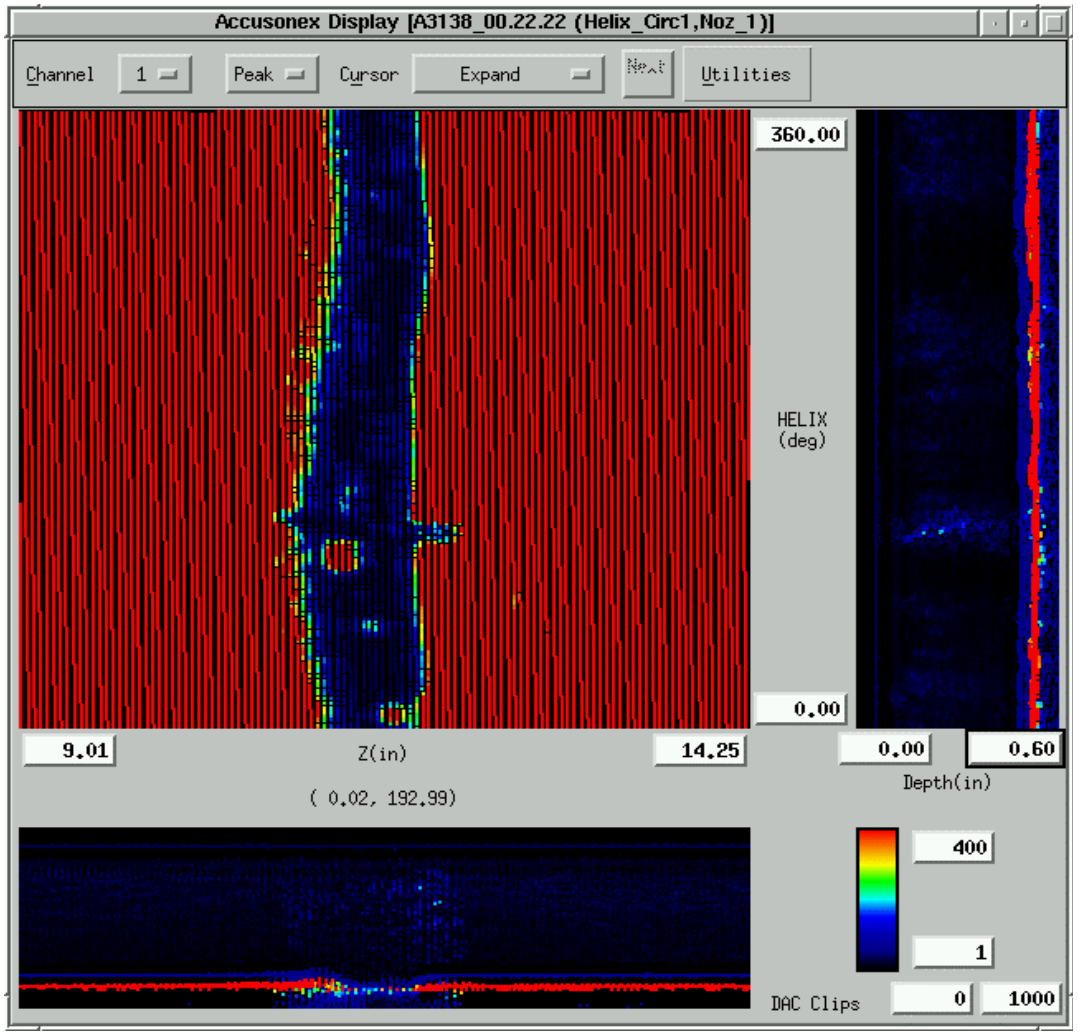
FRAMATOME ANP

Penetration #46 Axial Scan



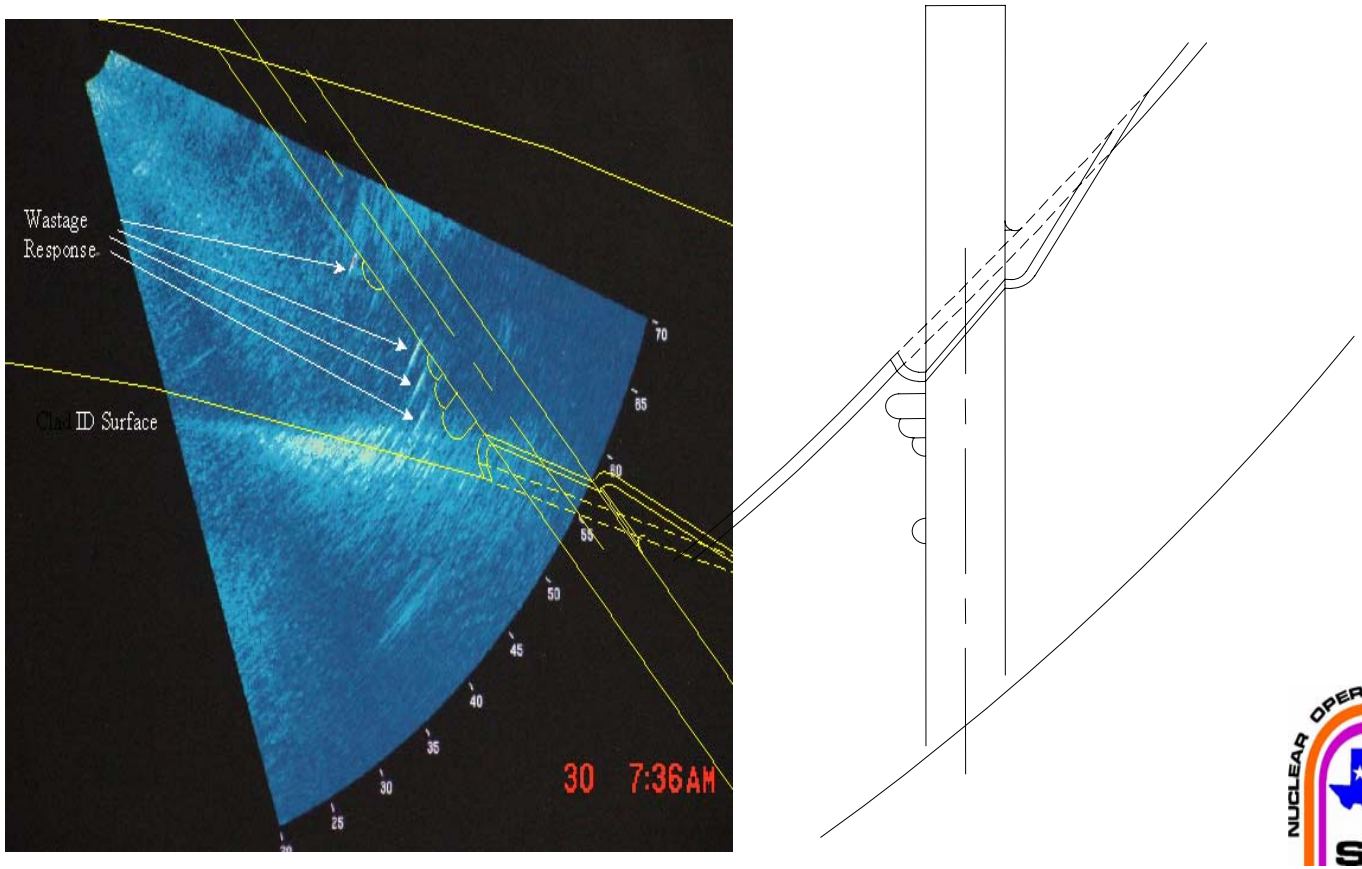
FRAMATOME ANP

Penetration #1 Weld Profile



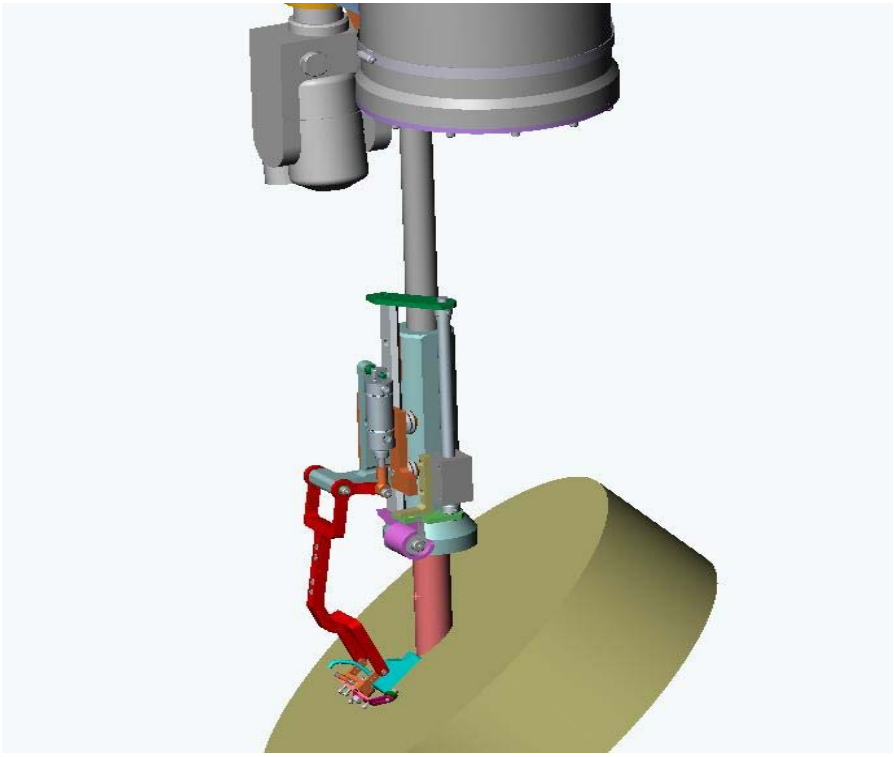
FRAMATOME ANP

Phased Array UT to Identify Wastage



Eddy Current J-Groove Probe

Incore J-Groove Eddy Current



Examination Matrix

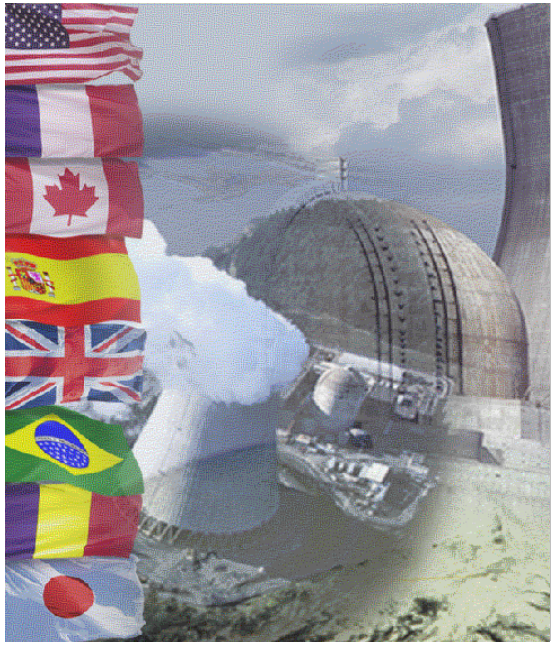
Techniques	Benefits
UT - circ	Most beneficial tool to detect and size flaws of different depths, lengths, and orientation.
UT - axial	Very beneficial to detect and size flaws
UT - 0	Good tool to discriminate between weld defects and cracks
EVT-1	Beneficial to detect surface indications with 0.0005 inch opening
UT - PA	Very beneficial to interogate complex geometry of the annulus
ET - J groove	Beneficial to detect and length size surface breaking flaws, can be limited due to surface contour and fillet region
ET - bobbin	Benficial to detect and length size surface breaking flaws
ET - profilometry	Technique limited to detecting tube deformation
VT - borescope	Minimum benefit
He leak test	Good test to confirm location

Framatome Continuing Development for BMI Nozzle NDE

- Improved UT probes for
  - combined circ and ax inspection
  - multiple probe designs developed, optimized, and tested for various tube IDs and wall thickness
  - improved fabrication techniques for lower cost and higher reliability
- Lessons learned improvements in EC tool and probe.
- Improved bare-metal examination tools & methods - particularly for difficult-to-remove insulation.
- Additional tools fabricated to be better prepared for emergent examinations should they be required.
- Planning begun for integrated 10-year ISI and BMI examination.

Summary of NDE

- Technology exists
- Limited quantity of tools
- TOFD is a highly capable technique
- Advancements have been made to interrogate the J groove surface and the annular region
- Framatome Development continues to assure tools are ready to meet additional BMI inspection challenges should the need arise



EPRI MRP Alloy 600 RPV Head Penetration Inspection Demonstration Program

Tom Alley, Duke Energy

E. Kim Kietzman

Frank Ammirato

EPRI

Conference on Vessel Head Penetration Inspection, Cracking, and Repairs

September 29-October 1, 2003

Gaithersburg, MD

CRDM Head Penetration NDE Background

- Original (97-01) demonstrations addressed cracks initiating on the inside surface of the penetration only
- Discovery of tube OD and weld cracking and BMI leakage identified the need to modify & extend the NDE demonstration program
  - Inspection technology required rapid development, deployment and field adaptation of existing inspection equipment
- First phase of MRP demonstrations was available to support fall 2001 inspections
  - Detection of “safety-significant” flaws in the tube
  - Qualify delivery devices
- Second phase performed to support fall 2002
  - J-groove weld flaws
  - More base metal flaws to evaluate depth sizing
  - Increase number of mockups available for training/practice
  - Extended into 2003
- BMI nozzle NDE demonstration program initiated

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MRP Visual Examination Guidance

- EPRI MRP Inspection Committee Task
  - Develop visual inspection training package for fall 2001
    - Published as TR report
  - Updated TR was published for spring and Fall 2002 inspections
  - Will be updated to incorporate results/lessons learned from Fall 2003 BMI visual inspections, false call data

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MRP Approach to NDE Demonstrations

- Head Penetration WG defines NDE objectives using analytical evaluations and service experience:
  - Identify relevant flaw mechanisms
  - Define inspection locations & volumes (e.g., OD, ID)
  - Define ranges of flaws to address (depth, length, orientation)
- Inspection WG develops demonstration program
  - Approach
  - Mockup design & procurement
    - Specifications for flaws in mockups
    - Realism of mockups (geometry, distortion, clearance, access, scratches, magnetic deposits, etc.)
  - Demonstration protocol & schedules (blind/non-blind, scope, result reporting process)
  - Publish results
  - Interpret results

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MRP Approach to Demonstrations, cont.

- All VHP NDE demonstrations since 1994 have had common characteristics:
  - Blind
    - Supported by non-blind preparation phases
  - Procedure only,
    - no personnel qualifications
  - Capability measurements only
    - no acceptance (pass-fail) criteria

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MRP Approach to Demonstrations, cont.

- Demonstration protocol
  - Vendor collects data on mockups & reports findings to NDE Center
  - NDE Center evaluates measured -vs.- true values
    - Detection (# detected/total flaws)
    - Location with respect to pressure boundary
    - Sizing
    - False call performance
    - Coverage
  - NDE Center documents procedure essential variables
  - Decision logic must be captured in the procedure and used during the demonstration
  - Results are published &n communicated to utilities who are required to protect vendor proprietary information

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MRP Demonstrations – Results

- Complex examination volume
- Vendor procedures include many technique options and probe combinations, examples:
  - Rotating probes
  - Blade probes
    - Probes are designed to accomplish specific objectives:
      - Specific volumes
      - Flaw orientations
      - Detection technique, e.g.., corner trap or tip diffraction
      - Sizing technique
- MRP Demonstrations document performance of individual probes/scans
  - More than one probe may be required to examine the specified inspection volume to detect/size specified flaw locations and orientations

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MRP Activities - Volumetric Examination Demonstration Program

- Fall 2001 demonstrations
  - Focus - Detection of "Safety-Significant" flaws in the tube base metal
  - Three vendors participated
    - Wesdyne
      - Blade-probe and Open-tube UT and ET
    - Framatome
      - Blade-probe and Open-tube UT and ET
    - Tecnatom
      - Blade-probe and Open-tube UT and ET

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2001 Demonstration Description

- Mock-ups
  - Field-removed- Oconee CRDM Penetration Samples
    - Demonstrate flaw detection
    - Good range of flaw sizes and orientation
      - OD Circumferential (up to 45 degrees off-axis),
      - OD Axial
      - ID Axial
  - Full-scale mock-up
    - Demonstrates effects of weld & capability to address geometry
    - Important examination considerations
      - Flaw location relative to weld
      - Flaw clusters
      - Triple-point indications

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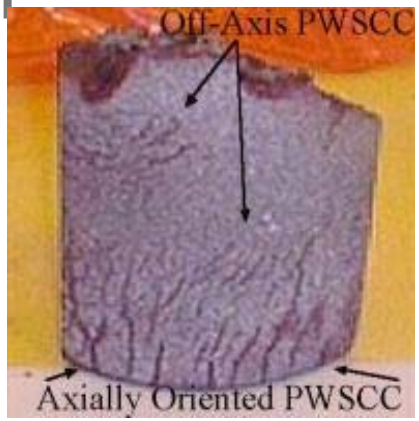
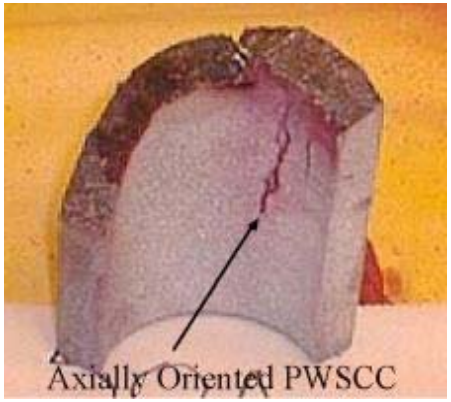
Oconee Specimens



- Specimen #56
  - OD-initiated PWSCC
    - Range of sizes & locations
  - Off-axis flaws (~45 degrees) are representative of circumferential flaw in outermost penetration



- Specimen #50
  - ID-initiated PWSCC

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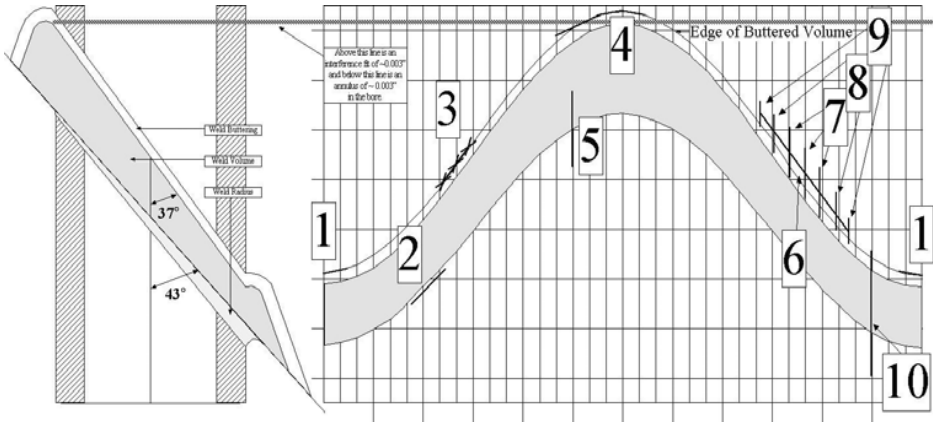
2001 Full-Scale Mock-up



- #1 & 4 – Circ. above weld. Corner trap one direction only. Min. skew angle. This circ position exhibits maximum distortion during fabrication, affecting UT contact.
- #2 – Circ. Below weld. No corner trap when UT oriented down. Near max skew angle.
- #3 – Circ. flaw at max skew. Cross-hatch simulates PWSCC affecting corner-trap
- #5 & 10– Axial flaw. Corner-trap lost over weld. Maximum distortion.
- #6,7, 8, 9 – Circ. & axial combination.

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2001 Demonstration Results

- Results distributed periodically by MRP
- Results summarize the capability of numerous probe types
  - Blade probes of various types, focal depths, frequencies, probe sizes & scanning directions
  - Rotating probes
  - Probes are designed to accomplish specific objectives:
    - Specific volumes, e.g, tube ID, OD or mid wall
    - Flaw orientations (Axial/Circumferential)
    - Detection technique, e.g., corner trap or tip diffraction
- In most cases, multiple demonstrations were supported
    - changing inspection requirements
    - equipment modifications and updates

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Example Results

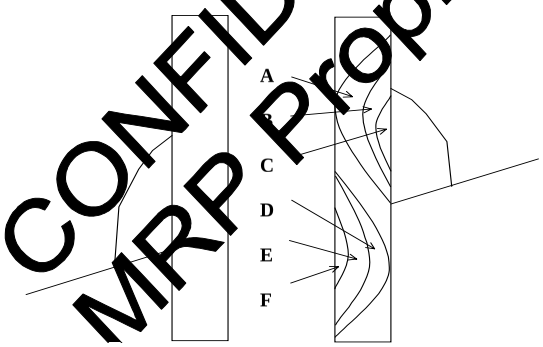
Example Detailed Summary Table

Summary of Detection Techniques	A OD to ID	B OD to mid-wall	C Shallow OD-initiated	D ID to OD	E ID to mid-wall	F Shallow ID-initiated	Weld Mapping	Procedure # & Date	Demonstration Date
Oconee CRDM Demonstrations conducted for 97-01 (ID flaws).									
BP TOFD for Axial flaws (7 mhz)					D, S	D, S	M	EN 2.4.1 GEN 3 *(1)*	02/1994
BP TOFD for Circ Flaws (7 mhz)					D, S	D, S	M	EN 2.4.1 GEN 3 *(1)*	02/1994
BP ID ET					D, S	D, S	N/A	*(1)*	02/1994
RP TOFD for Axial Flaws (7 mhz)					D, S	D, S	M	EN 2.4.1 GEN 3 *(1)*	02/1994
RP ID ET					D, S	D, S	N/A	*(1)*	02/1994
RP TOFD for Axial (7 mhz)					D, S	D, S	M	EPRI MRP-062 *(2)*	12/1996
RP ID ET					D, S	D, S	N/A	EPRI MRP-061 *(2)*	12/1996
BP TOFD for Axial flaws 10 mhz PCS 10 w/RD-Tech System					D, S	D, S	M	PB 447, Rev. 3 05/08/2000 *(3)*	05/2000
BP TOFD for Axial flaws 6 mhz PCS 18 w/RD-Tech System					D, S	D, S	M	PB 447, Rev. 3 05/08/2000 *(3)*	05/2000
BP TOFD for Circ flaws 10 mhz PCS 10 w/RD-Tech System					D, S	D, S	N/A	PB 447, Rev. 3 05/08/2000 *(3)*	05/2000
BP TOFD for Circ flaws 6 mhz PCS 18 w/RD-Tech System					D, S	D, S	M	PB 447, Rev. 3 05/08/2000 *(3)*	05/2000
BP ID ET					D, S	D, S	N/A	*(3)*	05/2000
WesDyne CRDM Demonstrations conducted for MRP (OD flaws).									
BP TOFD for Axial flaws 6 mhz PCS 18 & PCS 24 w/RD-Tech System	*(4)*	*(4)*	*(4)*	*(4, 5)*	*(4, 5)*	*(4, 5)*	M	ISI-UT-002, Rev. 0, 09/2001 *(6)*	09/2001
BP TOFD for Circ flaws 6 mhz PCS 18 & PCS 24 w/RD-Tech System	*(4)*	*(4)*	*(4)*	*(4, 5)*	*(4, 5)*	*(4, 5)*	M	ISI-UT-002, Rev. 0, 09/2001 *(6)*	09/2001
BP PE for Circ flaws w/RD-Tech System	*(4, 7)*	*(4, 7)*		N/A	N/A	N/A	N/A	ISI-UT-002, Rev. 0, 09/2001 *(6)*	09/2001
BP TOFD for Axial flaws 6 mhz PCS 18 w/Intraspect System	*(4, 5)*	OR	OR	*(4, 5)*	*(4, 5)*	*(4, 5)*	M	ISI-UT-002, Rev. 0, 09/2001 *(6)*	01/2002
BP TOFD for Axial Flaws 6 mhz PCS 24 w/Intraspect System	OR	D	D	*(4, 5)*	*(4, 5)*	*(4, 5)*	M	ISI-UT-002, Rev. 0, 09/2001 *(6)*	01/2002
BP TOFD for Circ flaws 6 mhz PCS 18 w/Intraspect System	*(4, 5)*	*(4, 5)*	OR	*(4, 5)*	*(4, 5)*	*(4, 5)*	M	ISI-UT-002, Rev. 0, 09/2001 *(6)*	01/2002
BP TOFD for Circ Flaws 6 mhz PCS 24 w/Intraspect System	OR	D	D	*(4, 5)*	*(4, 5)*	*(4, 5)*	M	ISI-UT-002, Rev. 0, 09/2001 *(6)*	01/2002
RP TOFD (only 5 mhz PCS 24 demonstrated) w/Intraspect System	OR	D	D	*(4, 5)*	*(4, 5)*	*(4, 5)*	M	WD-UT-008, Rev. 0 01/2002 *(6)*	01/2002

Notes for Table:

BP: Blade Probe UT/ET.
TOFD: Time-of-Flight-Diffraction UT
PE: Pulse-Echo UT
D: Detected flaw successfully in Oconee specimens or EPRI 97-01 mock-ups. The 97-01 flaws were demonstrated to have similar ET and UT characteristics to PWSCC.
S: Sized flaw successfully in EPRI 97-01 mock-ups. The 97-01 flaws were demonstrated to have similar ET and UT characteristics to PWSCC. Sizing of OD initiated flaws not currently addressed by the MRP demonstration.
M: Weld mapping demonstrated with 97-01 mockups.
RP: Rotating Probe UT/ET.
OR: Outside depth range of probe design.

(1)



CONFIDENTIAL - MRP Proprietary
CONFIDENTIAL - MRP Proprietary

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Demonstrations for 2002

- Demonstration Scope
  - Flaw characterization capabilities
    - Depth sizing
    - Length sizing
    - Location with respect to weld
  - Increased population of flaws
  - Attachment weld flaws
    - Identification of flaws reaching triple-point
      - Creating leak path
  - Effect of Cluster flaws
    - Masking flaws in remaining tube volume

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2002 CRDM VHP Mockups

- Flaw types determined by MRP Inspection/Assessment Committees
  - Axial, circ, & off-axis tube flaws
    - Library of flaws spanning full range of depth/length
  - Cluster flaws in tube
    - Library of flaws spanning full range of depth/length
  - Axial & circ. attachment weld flaws
    - Library of flaws spanning full range of depth/length
    - Located at weld/head & weld/tube interface
      - Most challenging geometry
    - Flaws approaching & thru triple-point
      - Allowing leak point to annulus

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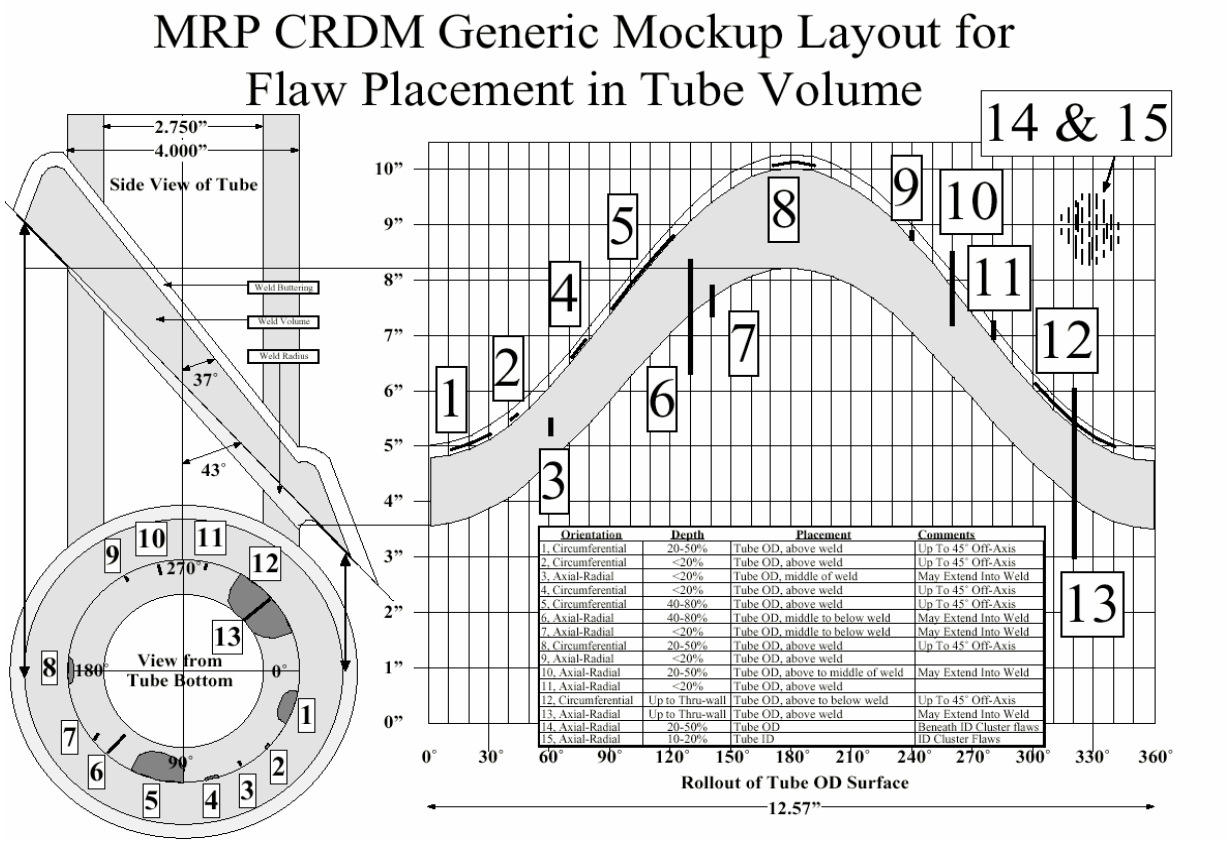
2002 Mock-up – Tube Flaws- Schematic



Orientation	Depth	Placement	Comments
1. Circumferential	20-50%	Tube OD, above weld	Up To 45° Off-Axis
2. Circumferential	<20%	Tube OD, above weld	Up To 45° Off-Axis
3. Axial-Radial	<20%	Tube OD, middle of weld	May Extend Into Weld
4. Circumferential	<20%	Tube OD, above weld	Up To 45° Off-Axis
5. Circumferential	40-80%	Tube OD, above weld	Up To 45° Off-Axis
6. Axial-Radial	40-80%	Tube OD, middle to below weld	May Extend Into Weld
7. Axial-Radial	<20%	Tube OD, middle to below weld	May Extend Into Weld
8. Circumferential	20-50%	Tube OD, above weld	Up To 45° Off-Axis
9. Axial-Radial	<20%	Tube OD, above weld	
10. Axial-Radial	20-50%	Tube OD, above to middle of weld	May Extend Into Weld
11. Axial-Radial	<20%	Tube OD, above weld	
12. Circumferential	Up to Thru-wall	Tube OD, above to below weld	Up To 45° Off-Axis
13. Axial-Radial	Up to Thru-wall	Tube OD, above weld	May Extend Into Weld
14. Axial-Radial	20-50%	Tube OD	Beneath ID Cluster flaws
15. Axial-Radial	10-20%	Tube ID	ID Cluster Flaws

NOTE: Flaw locations and sizes are shown only to describe typical types of flaws to be included in blind mockups. Actual flaw sizes and locations are confidential. Drawing is not to scale.

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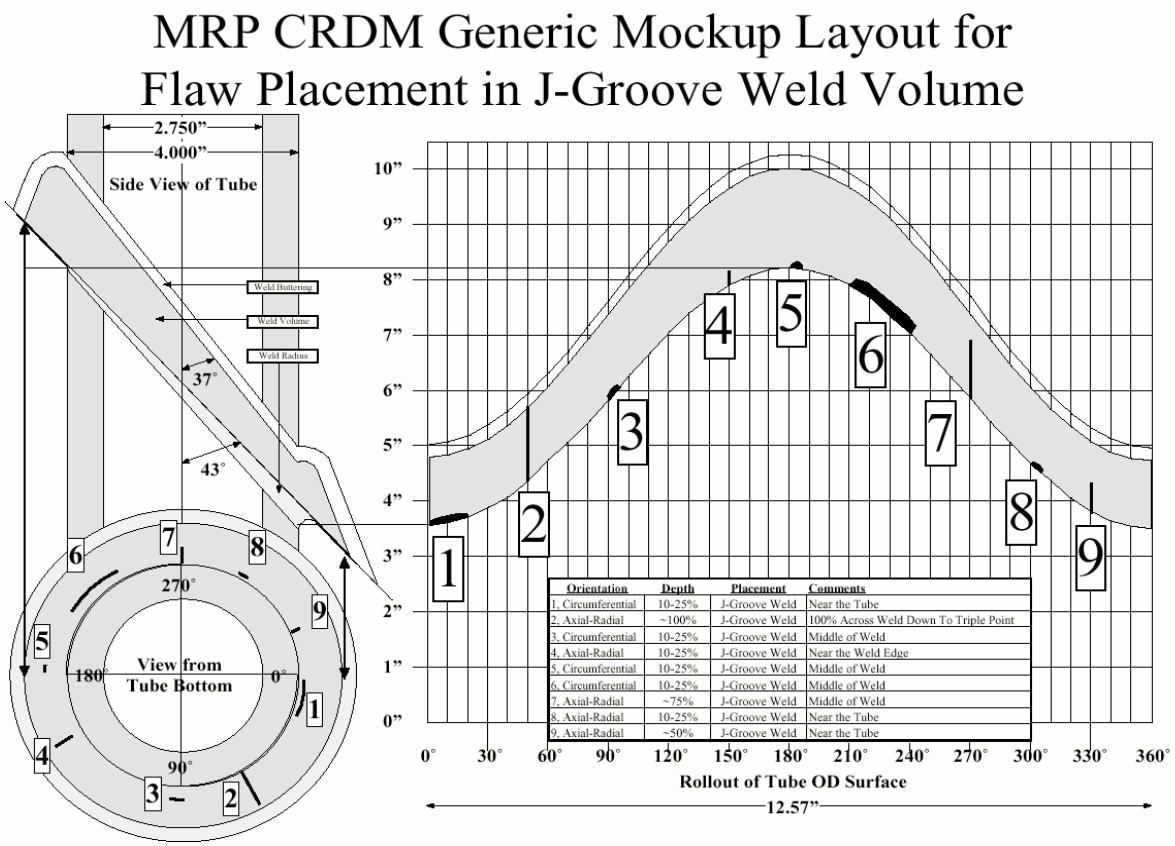
2002 Mock-up – Weld flaws-Schematic



Orientation	Depth	Placement	Comments
1, Circumferential	10-25%	J-Groove Weld	Near the Tube
2, Axial-Radial	~100%	J-Groove Weld	100% Across Weld Down To Triple Point
3, Circumferential	10-25%	J-Groove Weld	Middle of Weld
4, Axial-Radial	10-25%	J-Groove Weld	Near the Weld Edge
5, Circumferential	10-25%	J-Groove Weld	Middle of Weld
6, Circumferential	10-25%	J-Groove Weld	Middle of Weld
7, Axial-Radial	~75%	J-Groove Weld	Middle of Weld
8, Axial-Radial	10-25%	J-Groove Weld	Near the Tube
9, Axial-Radial	~50%	J-Groove Weld	Near the Tube

NOTE: Flaw locations and sizes are shown only to describe typical types of flaws to be included in blind mockups. Actual flaw sizes and locations are confidential. Drawing is not to scale.

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2002 Mock-up Selection Considerations

- Mock-up flaws must be representative and appropriate for the NDE Method(s) to be demonstrated
  - Need to provide representative responses for:
    - UT
      - Specular reflection, Tip-diffracted response, Corner-trap response
    - ET
      - Realistic electromagnetic properties, crack width
- Goal is realistic reproduction of Key detection or sizing variables
  - Any differences are monitored and considered during the demonstration
- Challenge: Numerous NDE methods are being applied & numerous flaw types/exam volumes to be considered

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2002 Mock-up Flaws Selected

- CIP
  - Appropriate for ET
    - Tight, no unrealistic electromagnetic features
  - Appropriate for UT,
    - Comparable tip response
      - Most important - primary method of detection
    - Best control of flaw dimension
    - Realistic irregularity of flaw face in 600 tube
    - Branching simulated by using multiple flaws
- Accelerated Corrosion Cracks
  - Combined with CIP, will provide range of crack widths
  - No unrealistic electromagnetic features

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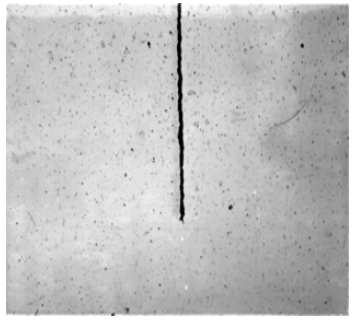
Manufactured Flaws - CIP

- CIP processed EDM notches, used in previous 97-01 demonstrations
  - Cold isostatic processing (CIP) “squeezes” notch
    - Sharpens tip
    - Reduce width to crack-like dimension
    - Induce crack-like faceting
  - Reduced temperature (< HIP) will not totally close flaw or alter electromagnetic properties that affect ET responses
  - Very good control of:
    - Flaw length, depth & position.
    - Width (affects UT & ET responses)
    - Photos show notch before and after CIP processing



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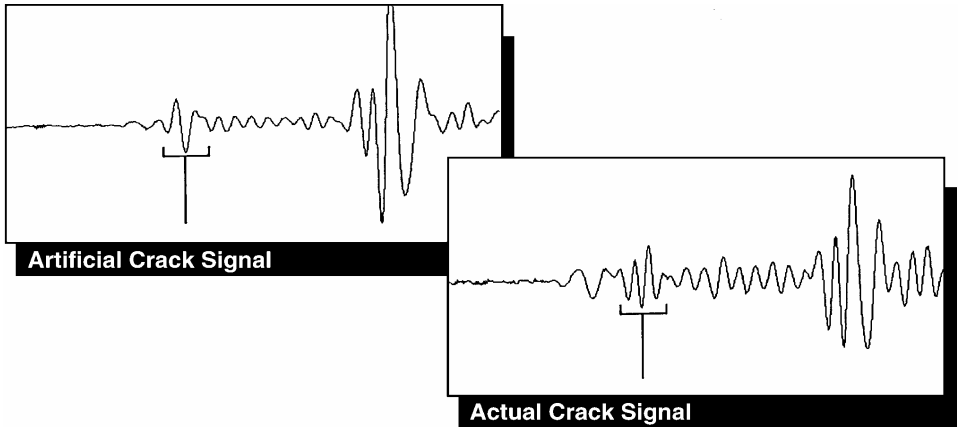
Manufactured Flaws – CIP cont..

- Demonstrated that UT and ET responses & dynamic characteristics were equivalent to flaws removed from Bugey VHP penetration



- Subsequent field data has confirmed equivalence

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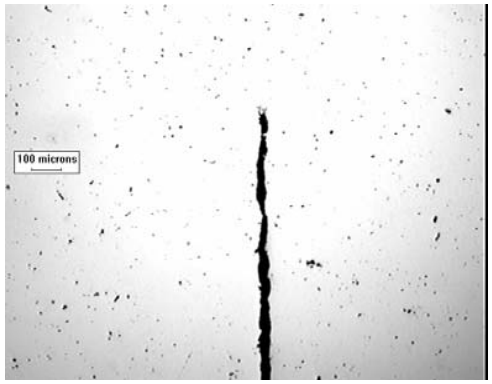
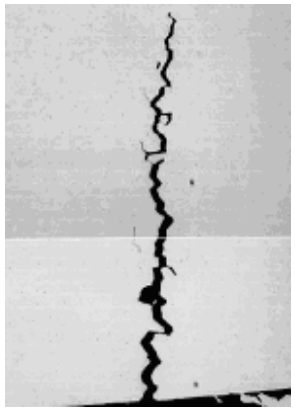
CIP Flaw Mock-ups – Technical Basis

- Photos show field-removed flaw (top) & CIP flaw
- Tip of CIP flaw has similar crack tip size
- Ultrasonic tip response equivalent to findings from several plants





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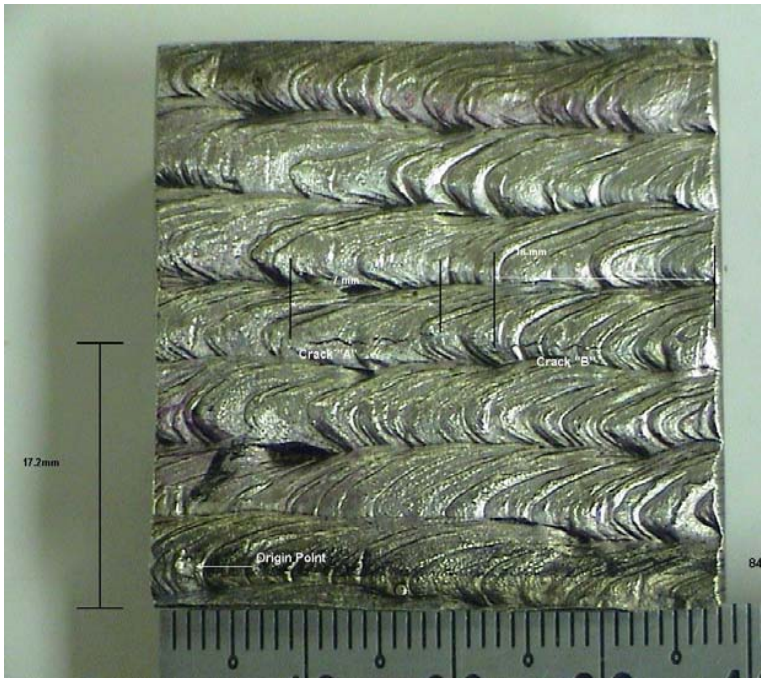
Stress Corrosion Weld Crack Specimens

- Laboratory-grown SCC
  - Three-point bend stress applied
  - Corrosive fluid applied to selected area only
- As-welded and ground surfaces
- Flaws vary in:
  - Length, width, orientation with respect to weld direction



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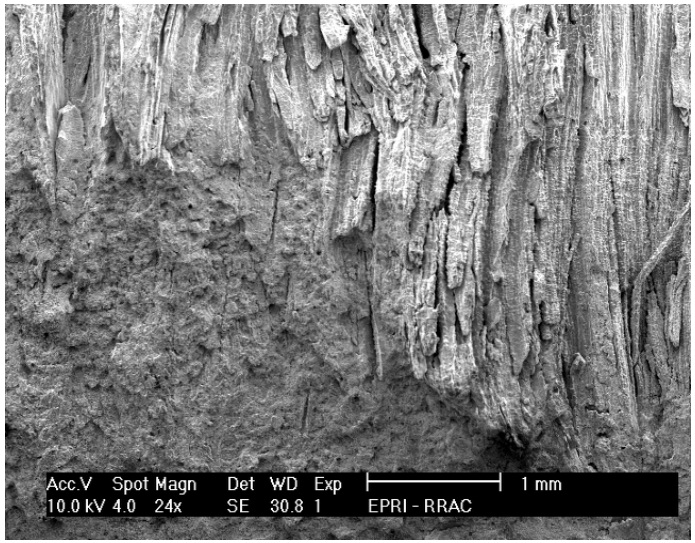
Stress Corrosion Weld Cracks

- SCC crack face showing interdendritic nature
- SCC crack grown, then specimen was broken apart
  - Upper right shows crack following weld dendrites
  - Lower left is ductile tear from break



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2002 Demonstrations

- Full-scale Tube Flaw Mock-up “J”
  - CIP manufactured flaws in tube volume
- Full-scale Weld Flaw Mock-up “K”
  - CIP manufactured flaws in volume of attachment weld
  - CIP flaws open to “wetted-surface”
- Full-scale Mock-up with SCC flaw Inserts “L”
  - Flaws open to “wetted-surface”

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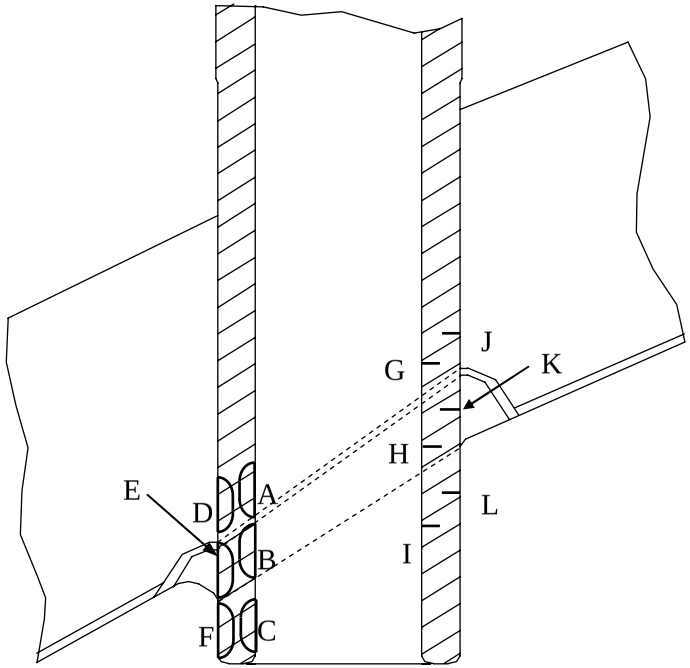
2002 Demo Tube Flaw mock-up “J”

- Full-scale mock-up with CIP flaws in tube



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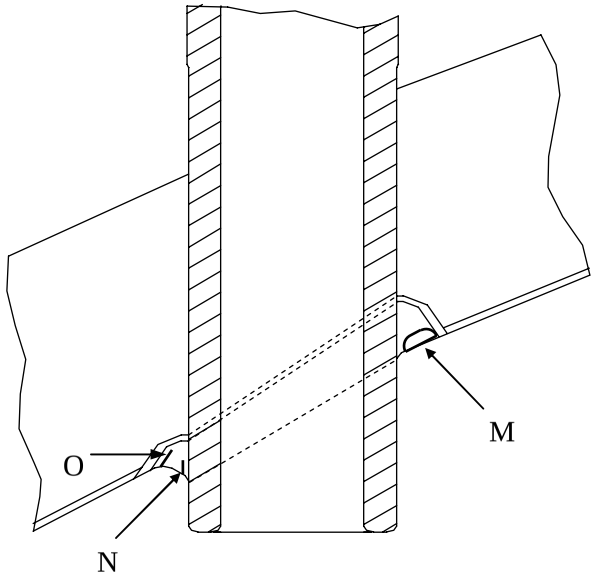
2002 Demo Weld Flaw Mock-up “K”

- CIP flaws for UT from inside surface of tube



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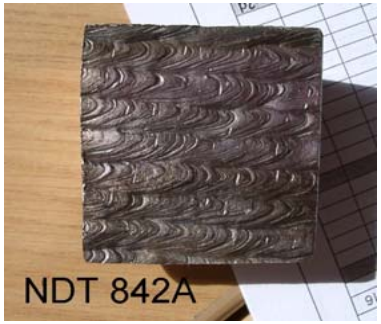
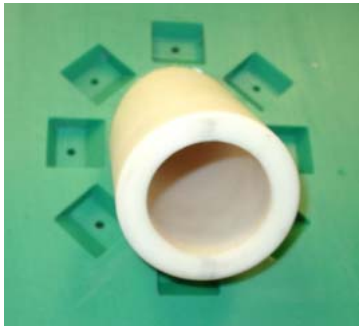
2002 Demo Weld Flaw Mock-up “L”

- Contains SCC flaw coupons for demo of ET on wetted surface

- Coupons contain cracks of varying
  - width
  - length
  - Orientation





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New Mock-ups

- Bottom Mounted Instrumentation nozzles
  - Incorporates South Texas Plant experience
  - Designed using same philosophy, methods, and criteria used for upper head penetration mockups
  - Representative of Westinghouse 2-, 3-,and 4-loop units and B&W designs
  - Currently under construction
- New upper head mockups under construction
  - Enables release of original mockups for training & practice

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NDE Center Funded Activities to Supplement MRP Inspection WG Tasks

- Flaw manufacturing technology for Alloy 600/182
- ET technology for inspection of attachment weld
- Industry liaison
  - Direct Utility & Owners groups Support
    - Inspection equipment or approaches
  - ASME task group support
  - Butt weld/dissimilar metal weld inspection technology & qualification

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Summary

- MRP has organized a comprehensive approach to address recent industry events
- Considerable progress has been made in a short amount of time
- Demonstrations underway
  - Extensive demonstration activity completed for upper head penetrations
  - BMI program initiated

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Action Items

- TR Report Production (Formal Status)
  - Report should field deployable techniques only
  - After possibly:
    - Tecnatom Demo
    - Fram ET Demo
  - Cut-off date for report content (Feb 28)
  - Report produced
    - May-June
- Visual Inspection Guideline

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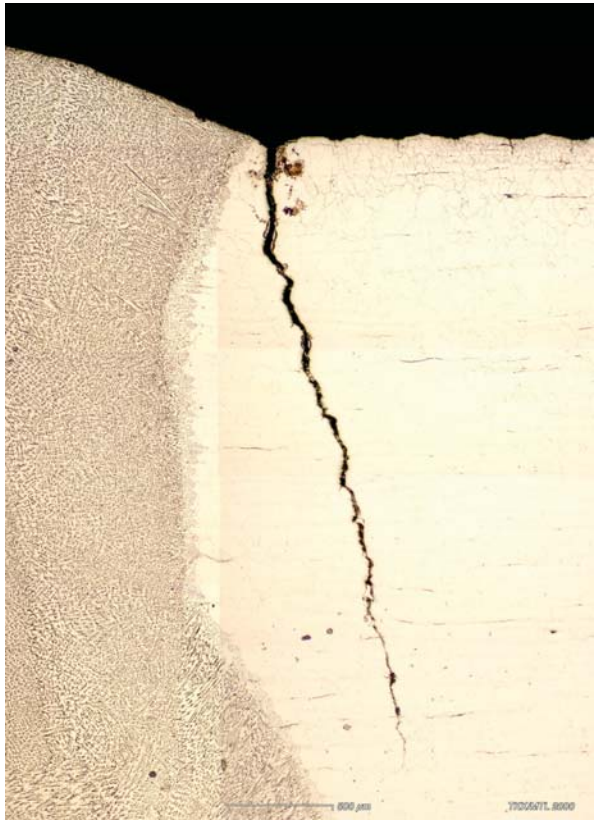
Production of realistic flaw in Alloy 600 for qualification purposes

Mika Kemppainen, Iikka Virkkunen, Jorma Pitkänen,
Kari Hukkanen and Hannu Hänninen
Trueflaw Ltd., Espoo, Finland
VTT Industrial Systems, Espoo, Finland
Teollisuuden Voima Oy, Olkiluoto, Finland
Helsinki University of Technology, Espoo, Finland

True damage mechanism for artificial flaws

- In-situ crack production
  - Real fatigue cracks
  - No additional welds
  - No microstructural alterations
- Controlled loading
  - Single and separate cracks
  - No specimen size limitations

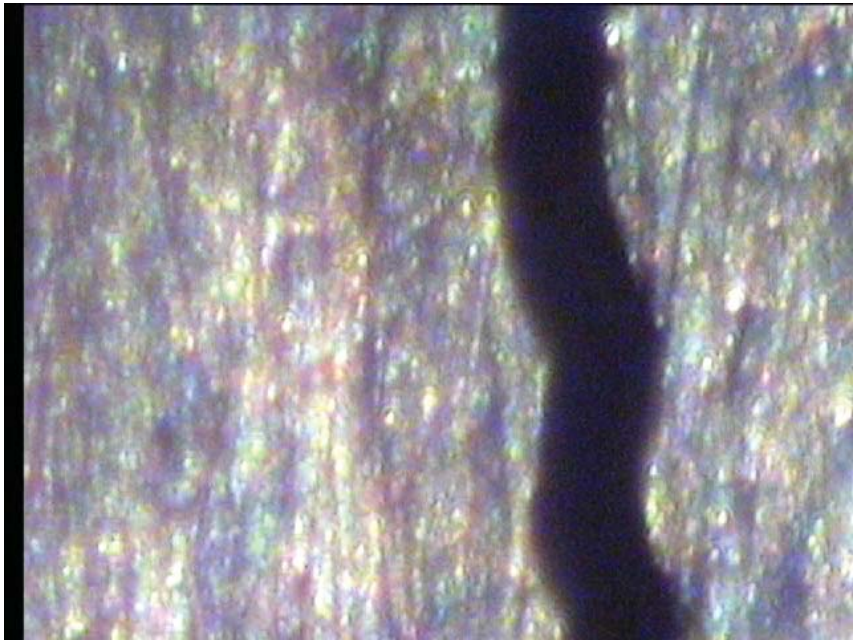
Controlled loading - controlled cracks



- Thermal fatigue offers:
  - Local loading
    - In situ production to full-size components
  - Highly controllable crack growth
    - Orientation
    - Size

Controlled loading - controlled cracks

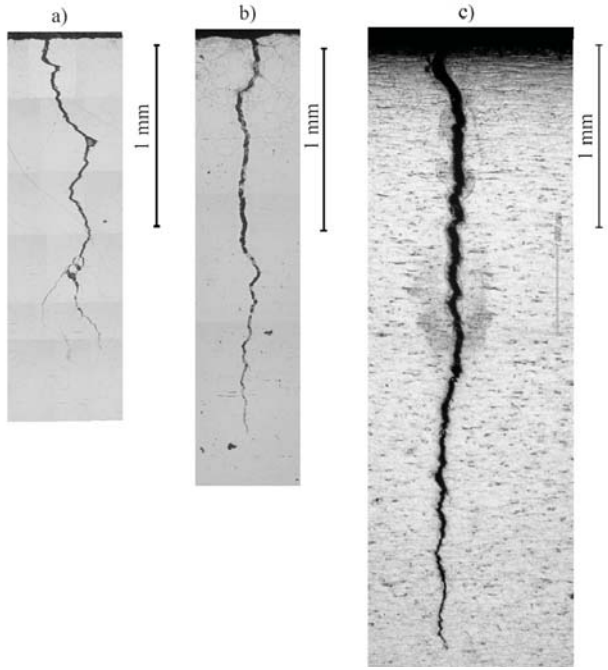
- Thermal fatigue loading
  - Crack closes during heating
  - Crack opens during cooling



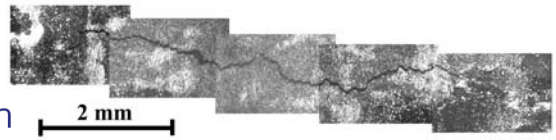
How does a True Flaw look like?

Austenitic stainless steel

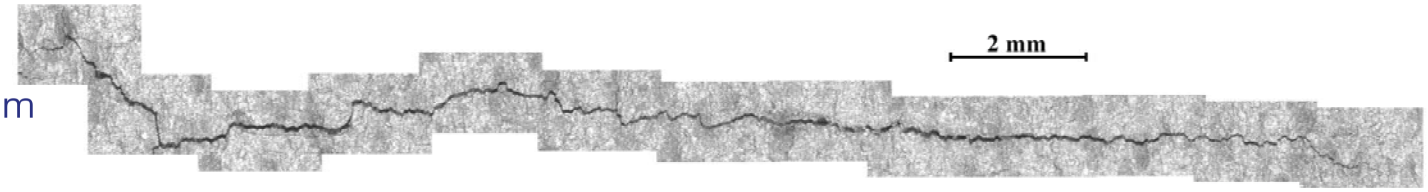
- Rough and tight crack in cross-section
- Tortuous surface propagation



L= 8 mm



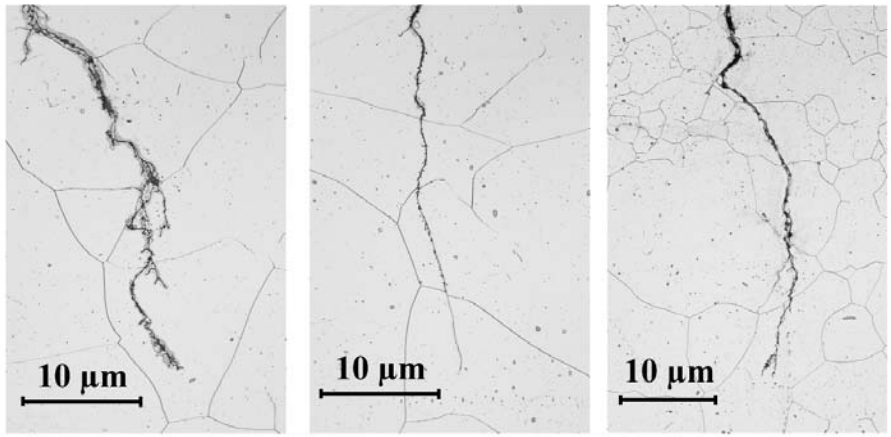
L= 20 mm

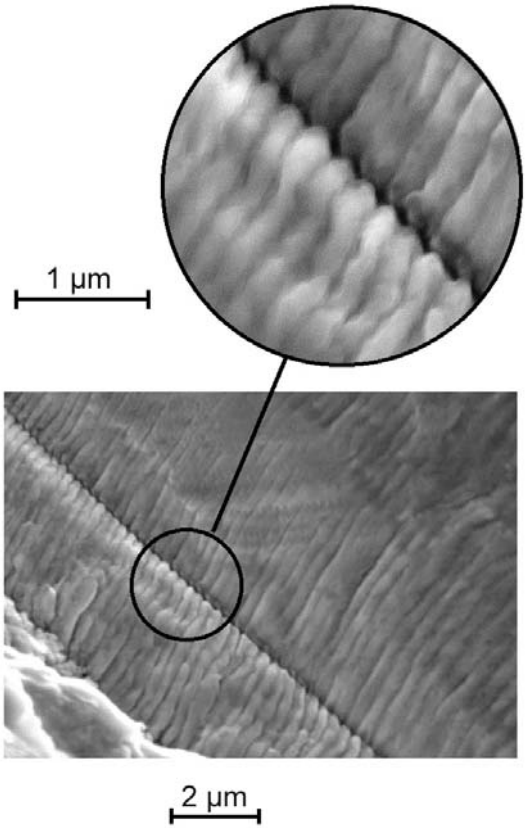


How does a True Flaw look like?

Austenitic stainless steel

- Tight crack tip
- Striations visible on the fracture surface
  - due to cyclic loading





True Flaw for Inconel 600

Core Spray Nozzle

- BWR type NPP
- Inconel 600 Safe-End
- Ready-made specimen for NDT qualification containing different flaws

True Flaw manufacturing

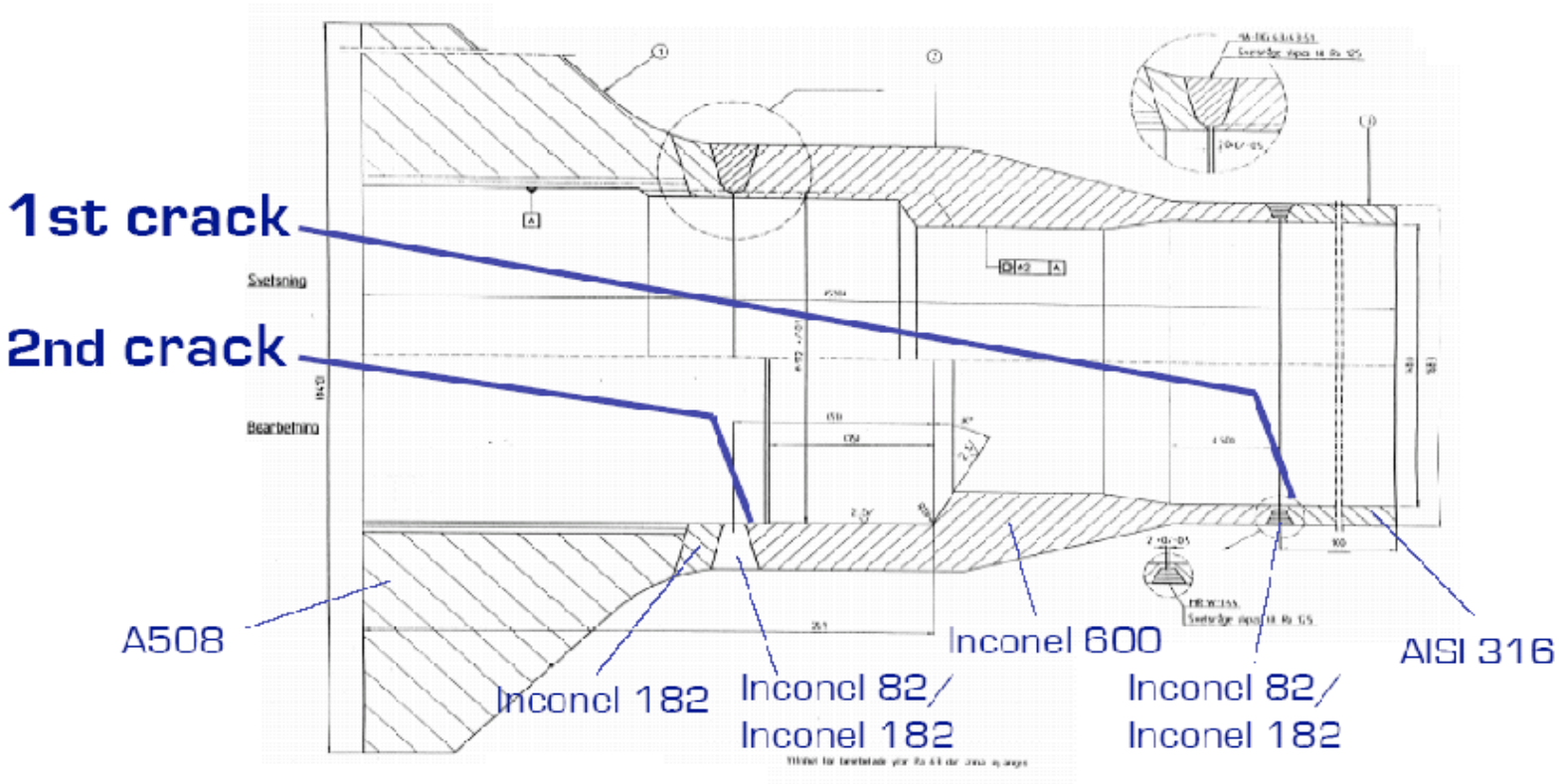
- To finished surfaces
- Without welding or machining
- Existing, previously made flaws do not affect flaw production

True Flaw for Inconel 600

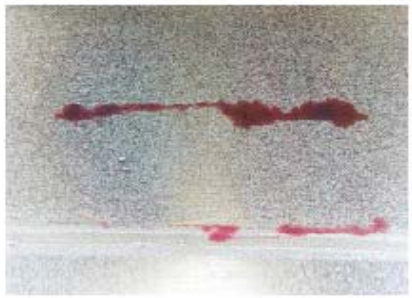
True crack production

- 2 cracks in the HAZ of welds
- At the inner surface of the nozzle
- 1st crack in AISI 316 vs. Inconel 600 weld
  - In AISI 316
- 2nd crack in Inconel 600 vs. A508 buttering weld
  - In Inconel 600

Locations of Manufactured Flaws



True Flaw in Inconel 600 Safe-End



Crack in AISI 316

- In HAZ of the joint weld
- 15,5 mm x 5 mm
- Size controlled by the process and confirmed by UT

Crack in Alloy 600

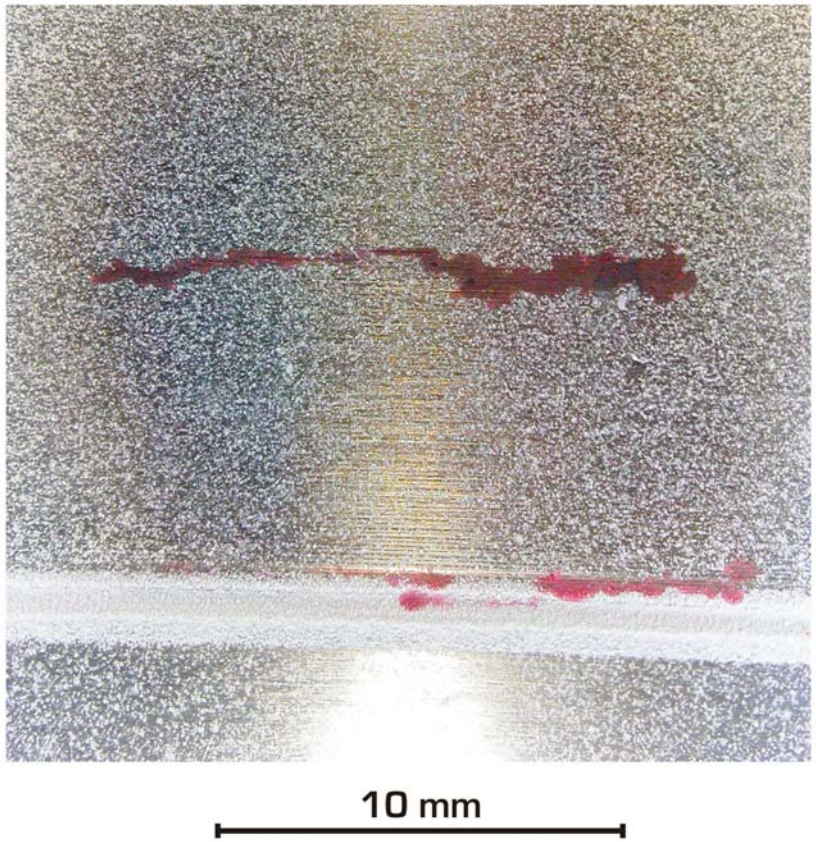
- HAZ of the buttering weld
- 14,2 mm x 5 mm
- Size controlled by the process and confirmed by UT

True Flaw in Inconel 600 Safe-End

Dye penetrant test

- Crack in the of Inconel 600

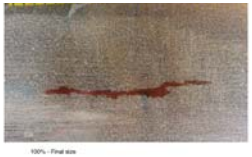
=> 14,2 mm x 5 mm



Arrangements for in-situ UT measurements

Two UT probes

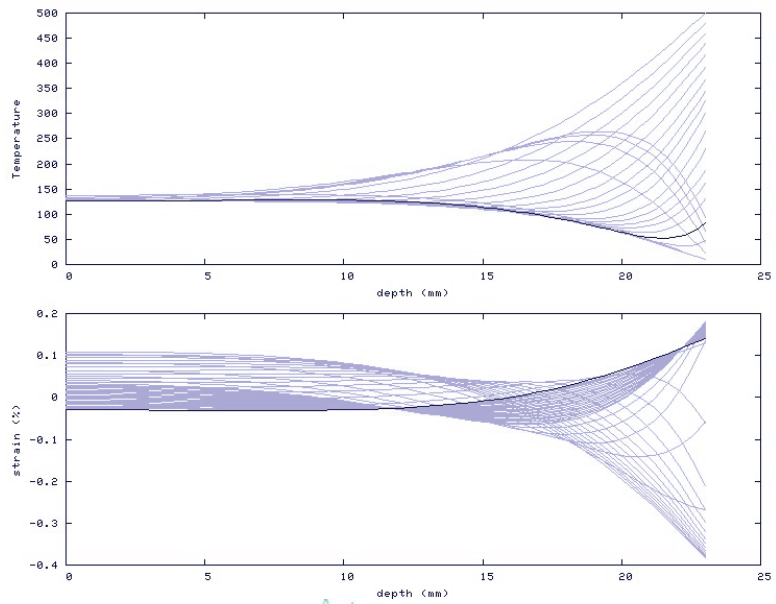
- Transverse wave
- 55° and 70°

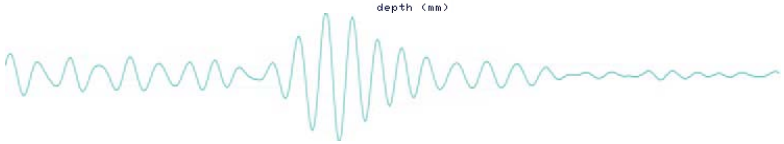


One UT probe

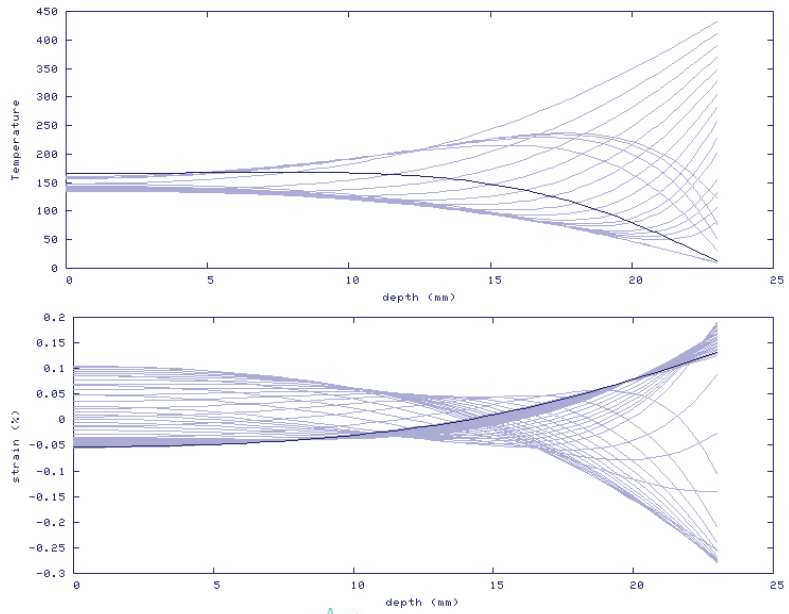
- Transverse wave
- 41°
- 1.5 MHz

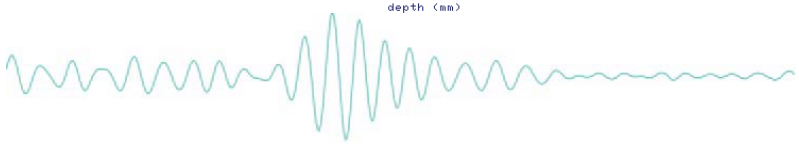
Applied loads - results





B1

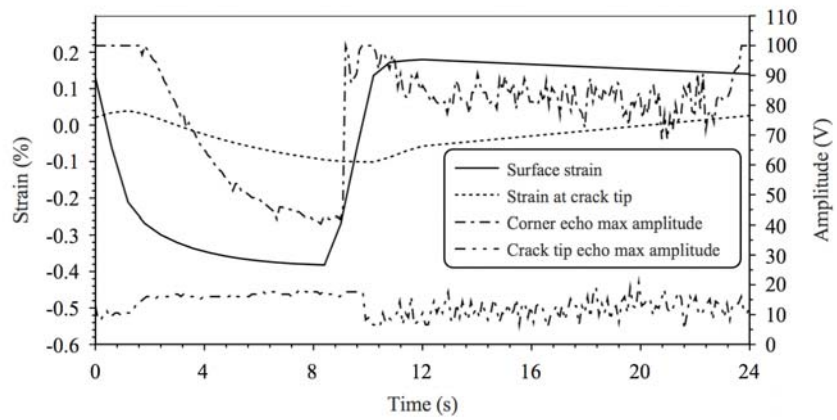


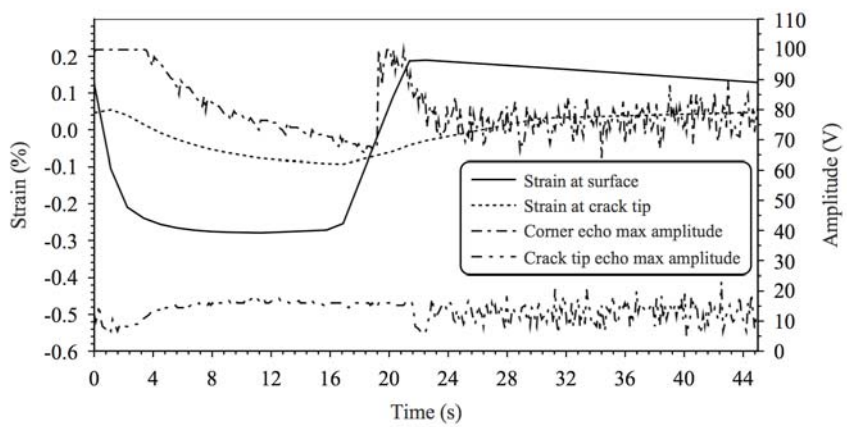


B2

Loading alters amplitude

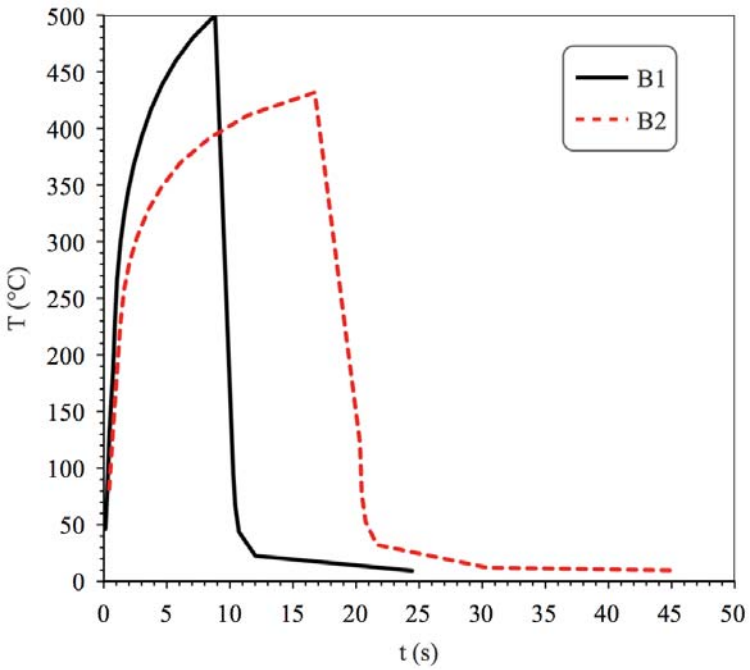
- Compression during heating decreases corner echo amplitude
- Tip echo amplitude increases during heating





Applied loads - analysis

- The applied loads were analyzed by FEM
  - 1-dimensional model
  - linear-elastic material
  - loaded by measured surface temperatures



Conclusions - True Flaw Production

Crack production is possible to

- Different materials including Alloy 600
- Ready-made components without welding or machining
- Offers for NDT qualification
  - Crack production method to new and old components and mock-ups
  - Use of realistic cracks

Westinghouse

A BNFL Group Company

CONFERENCE ON VESSEL HEAD PENETRATION INSPECTION, CRACKING AND REPAIRS
Gaithersburg, MD – Sept. 29-Oct. 2, 2003

Generic Guidance for an Effective Boric Acid Inspection Program for Pressurized Water Reactors WCAP-15988-NP

GUTTI RAO
Westinghouse Electric Company
SATYAN SHARMA
American Electric Power Company
DENNIS WEAKLAND
FirstEnergy Nuclear Operating Company

BNFL

Purpose

- To Provide A Generic Guidance to PWR Licensees to Aid in Developing Plant Specific Boric Acid Corrosion Control Programs (BACCP)

Objectives

- To Ensure that the implemented Plant Specific BACC Programs provide a reasonable assurance of compliance with the Regulatory Requirements specified in GL88-05, BL2001-01 and BL2002-02.

- To implement uniform BACC Programs/ Procedures throughout the industry.

Objectives

- To take advantage of the available tools, methods and procedures to detect, assess and remediate the BAC Issues and eliminate their recurrence.

- To ensure that the Plant BACC Programs incorporate and keep up with the industry experience.

Background and Basis (Drivers)

- Numerous leaks reported in the RCS and Borated Systems since Late ‘70’s
- GL88-05 in 1988 requiring Licensees to address small RCS Leaks
- CRDM Alloy 600, Alloy 82/182 Cracking experience of the past decade
- NRC IEB 2001-01, 2002-02 and Davis-Besse Incident
- Wide variations in the GL88-05 Plant Procedures and 60-Day Responses

WOG MSC Task Team

- WOG MSC Task Team Chartered to Develop 'Generic Guidance' (WCAP-15988-NP)
  - Ten Member Task Team representing PWR Owners Groups, INPO, NEI and EPRI
  - Issued Final Report WCAP-15988-NP in March, 2003
  - WCAP-15988, Rev. 1 is being developed to include Industry experience since March, 2003

WCAP-15988-NP

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WCAP-15988-NP

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WCAP-15988-NP

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Scope

- Sample Reviews of GL88-05 Procedures and 60-Day Responses
- Prioritization of Listing of Alloy 600/82/182 Locations (based on wastage/safety significance)
- Identification of Primary and Auxiliary System Potential Leak Locations and Related Wastage Potential
- Review of Industry Documented Leaks

Scope (cont'd.)

- Identification of Specific Improvements/ Enhancements to 88-05 Inspection Procedures
- Incorporation of Industry Experience (CRDM leaks and head wastage)
- Responsive to INPO Review Guidelines and Expectations
- On-Line Monitoring and Early Warning Indicators
- Lessons Learned from Davis-Besse Incident

Attributes Considered

- Attention to Procedures for Identification of Small RCS Leaks Below Tech Spec Limits
- Responsive to 88-01, 2001-01, BL2002-02 and BL2003-02 Requirements
- Incorporate EPRI Corrosion Handbook Procedures
- Lessons Learned from Davis-Besse
- Attention to Industry Documented Leaks
- Cycle Specific Inspection Reports
- Database for Trend Tracking
- Administrative Control and Program Ownership
- Attention to Early Warning Leak Detection Systems and Indicators
- Include All Pressure Boundary Alloy 600 and Alloy 82/182 Locations
- Primary and Auxiliary Systems Leak Susceptible Locations
- Leak Proximity to Carbon/Low Alloy Steel Components
- State-of-the-Art Detection Systems
- Personnel Qualification and Training Guidelines

Attributes Considered (cont'd)

- Coordination and Responsibility Flow Chart
- Coordinate Information from Parallel Programs
- Cycle Specific Reports and Trend Tracking
- Audits and Self-Assessments
- Other (cracking) susceptible Locations (IGSCC & IGSCC), including Plant Specific Material & Design and Component Considerations
- Continuous Improvement Program (self-assessments, audits, benchmarking, etc.)
- Data Collection and Recording Methods
- Criteria for the Removal of Insulation
- Inspection of Inaccessible Locations
- Methods of Gathering Information Prior to Removing Evidence (buildup)
- Corrective Actions to Prevent Recurrence of BAC
- Responsive to INPO Review Guidelines and Expectations

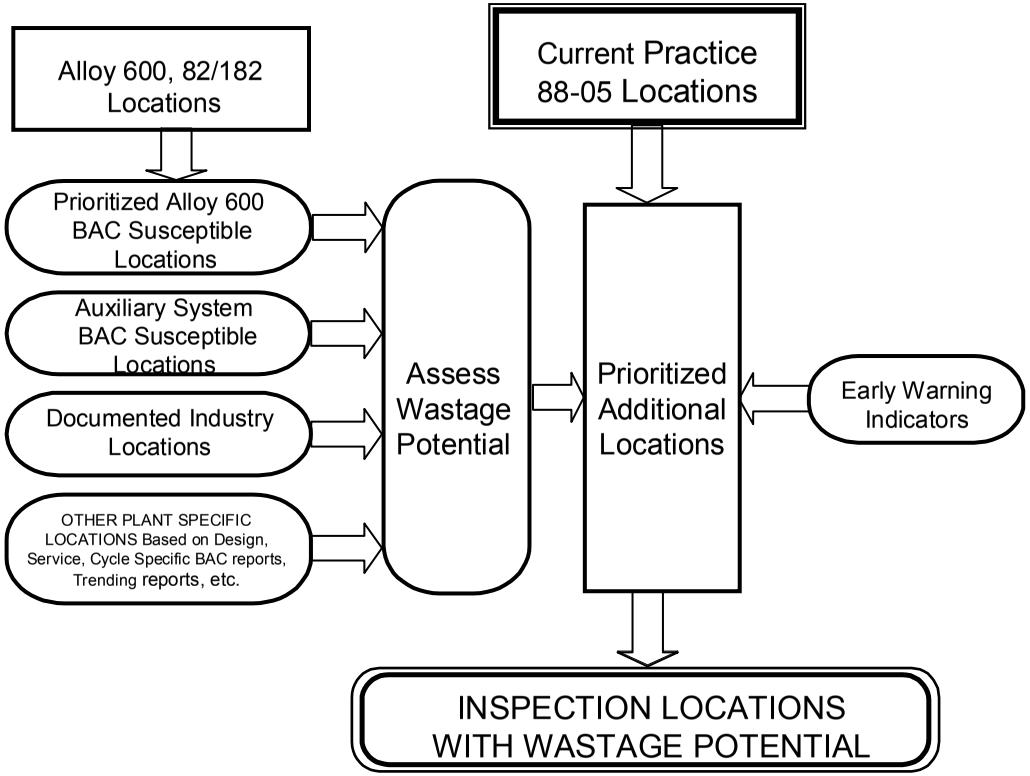
Inspection Locations

- Industry Documented Leaks
- 88 05 Locations
- Alloy 600/82/182 Locations
- Plant Specific Locations Based on Component Design, Material and/or Service History
- Other Locations Potentially Susceptible to IGSCC, TGSCC (based on field modifications and service history)
- Potential Leak Locations in the RCS and Auxiliary Systems Having Proximity to Carbon/Low Alloy Steel Components

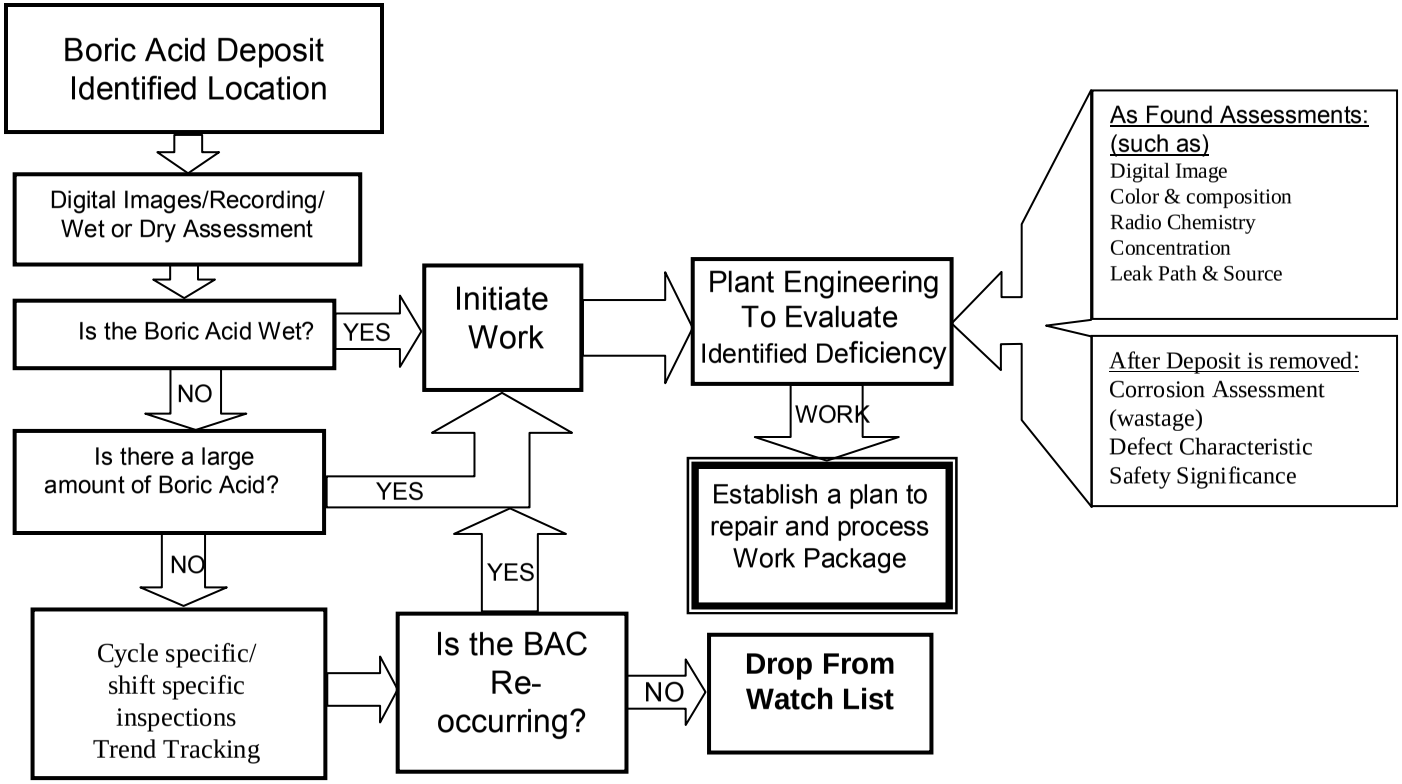
Examples of Systems Containing Boric Acid

- Reactor Coolant System
- Chemical and Volume Control System
- Safety Injection System
- Residual Heat Removal/Shutdown Cooling System
- Reactor Plant Sampling System
- Spent Fuel Pool Cooling and Purification System
- Containment Depressurization System
- Containment Spray System
- Reactor Plant Vent and Drain System
- Liquid Waste Disposal System
- Gaseous Waste Disposal System

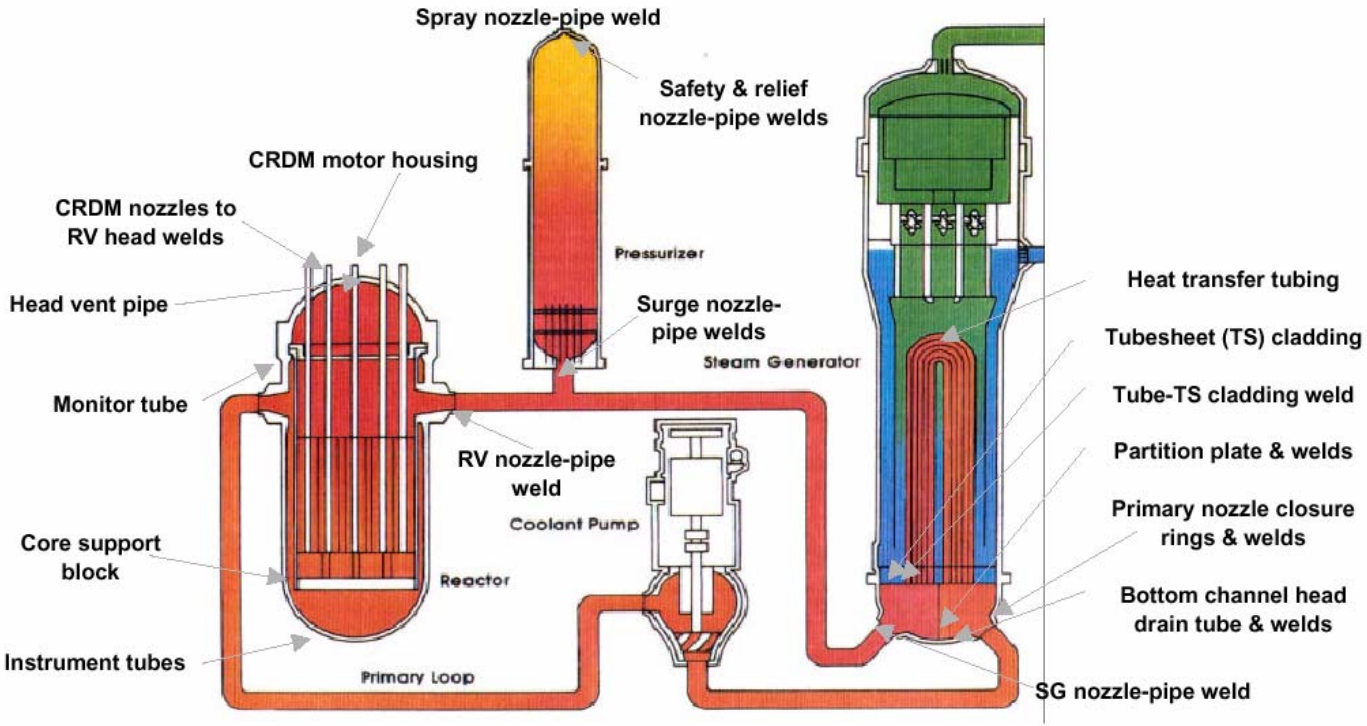
Identification of Inspection Locations with Wastage Significance



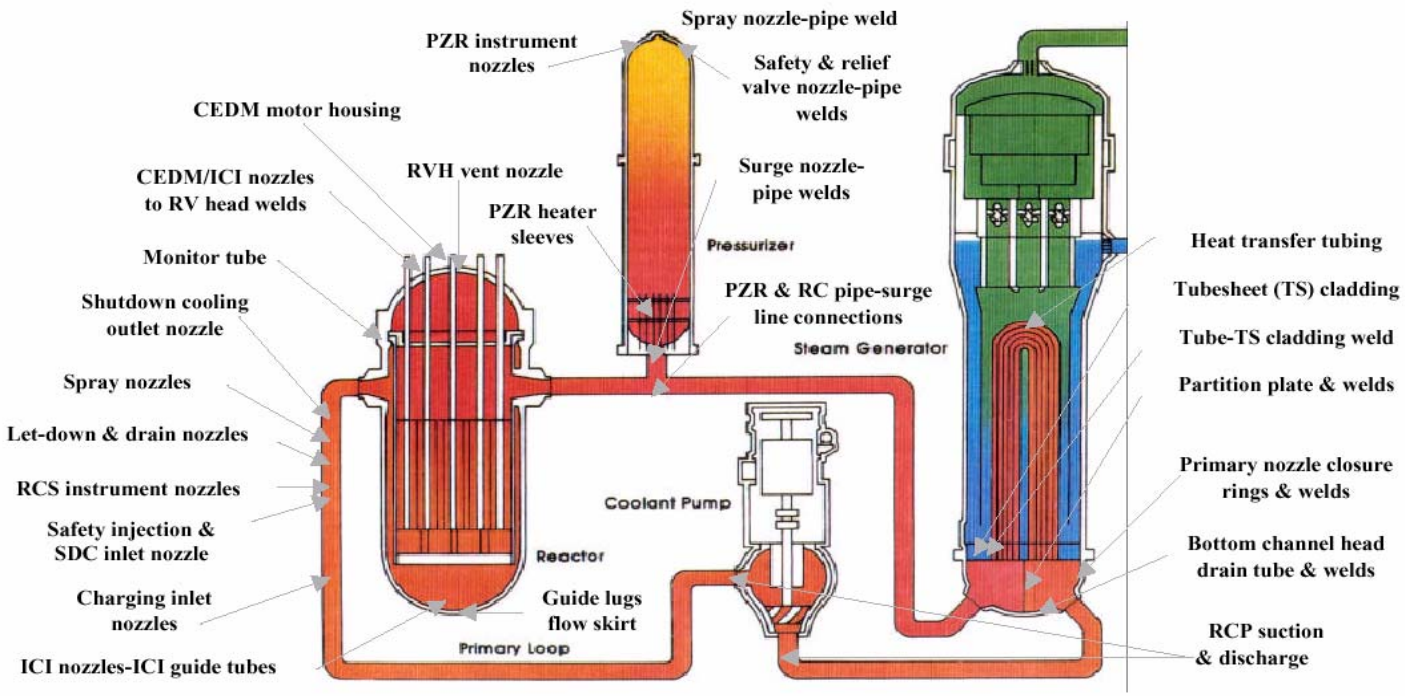
Criteria for Boric Acid Deposit Assessment



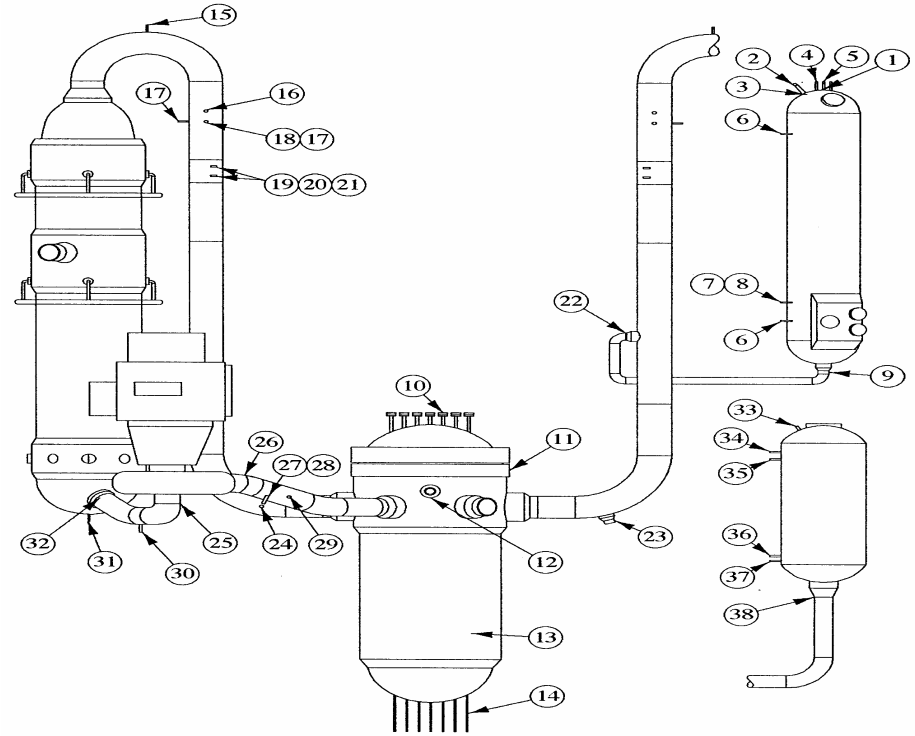
Alloy 600 and Alloy 82/182 Locations in the Primary Pressure Boundary Components of Westinghouse PWR Units



Alloy 600 and Alloy 82/182 Locations in the Primary Pressure Boundary Components of CE PWR Units



General Locations of Alloy 600 Type Materials in the B&W (177-FA Design) Reactor Coolant System (Prepared by DEI)



PROPOSED REVISIONS TO WCAP-15988

WCAP-15988 Will be updated to include:

- INPO findings from recent audits
- Update rankings for systems and components
- Impact of NRC order
- Definition of clean head
- Inspection procedures for BMI

PROPOSED REVISIONS TO WCAP-15988 (cont'd.)

WCAP-15988 Will be updated to include:

- Analytical procedures for thorough investigation of BA deposit prior to cleanup
- Industry experience since March, 2003
- Consistency with ASME Section XI Code requirements currently being developed by BAC Task Group

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Risk-Informed Evaluation of PWR Reactor Vessel Head Penetration Inspection Intervals

Vessel Head Penetration Inspection,
Cracking and Repair Conference

September 29 – October 2, 2003
Gaithersburg, MD

By:
Glenn White, Dominion Engineering, Inc.
Steve Hunt, Dominion Engineering, Inc.
Nicolas Nordmann, Dominion Engineering, Inc.

Dominion Engineering, Inc.
11730 Plaza America Dr.
Reston, VA 20190

Overview

- Purpose of Evaluation
- Evaluation Elements
- Flaw Tolerance Evaluation
- Nozzle Ejection Assessments
  - Deterministic Evaluations
  - Probabilistic Evaluation
- Boric Acid Wastage Assessments
  - Deterministic Evaluations
  - Probabilistic Evaluation
- Conclusions

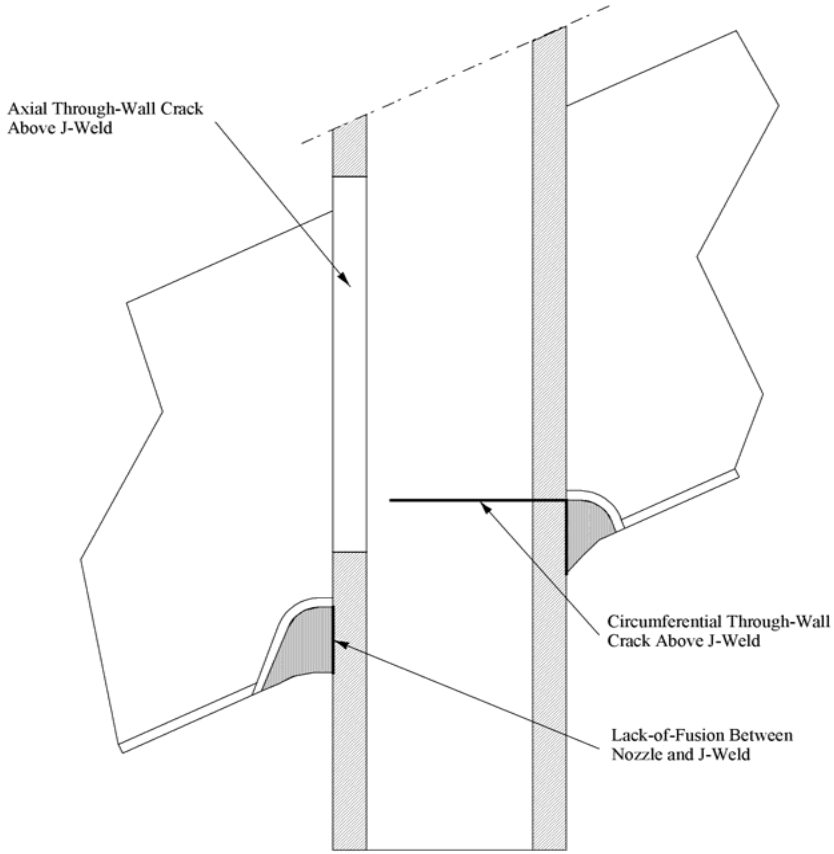
Purpose of Evaluation

- The purpose of the type of evaluation presented is to provide a rational basis for setting the re-inspection interval for nonvisual examination of reactor vessel (RV) closure head penetrations in PWRs
- Deterministic assessments show that nozzle ejection and significant head wastage are unlikely to occur given the indicated re-inspection interval
- Probabilistic assessments show that the requisite levels of nuclear safety are maintained given that the calculated increase in core damage frequency (CDF) due to the potential nozzle ejection and head wastage failure modes is within acceptable limits, i.e., 1×10^{-6} per year

Evaluation Elements

- Flaw and wastage tolerance calculations
- Review of subject plant design, materials, fabrication, and time at temperature
- Evaluation of visual and nonvisual inspection results at the subject plant
- Evaluation of expected inspection detectability limits and probability of detection (POD) curves
- Evaluation of industry inspection results including results for most similar material and fabrication groups
- Nozzle ejection and wastage evaluations
- Risk, consequential damage, and loose parts assessments

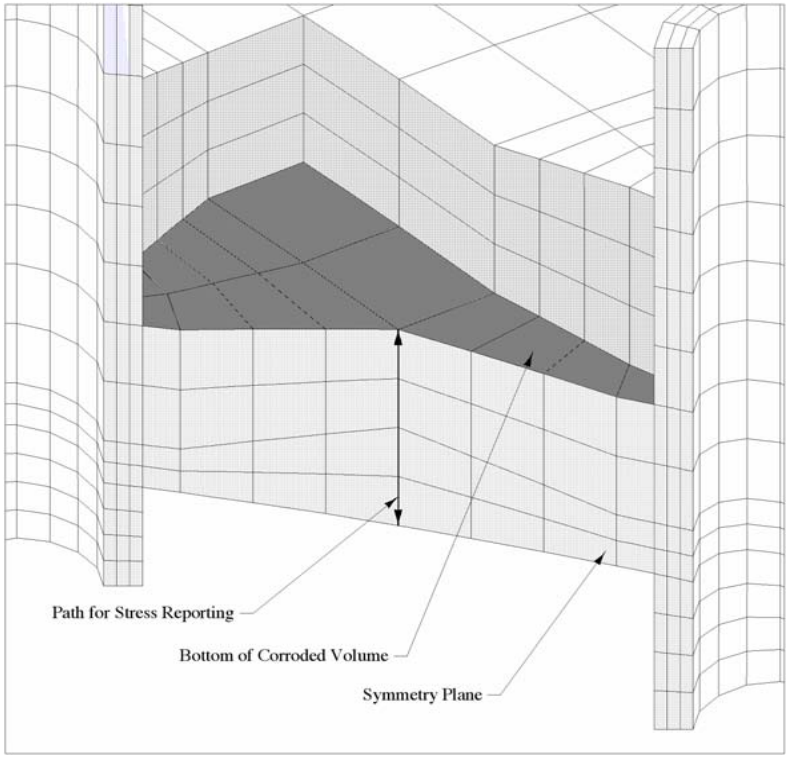
Flaw Tolerance Evaluation
Tolerance to Cracking



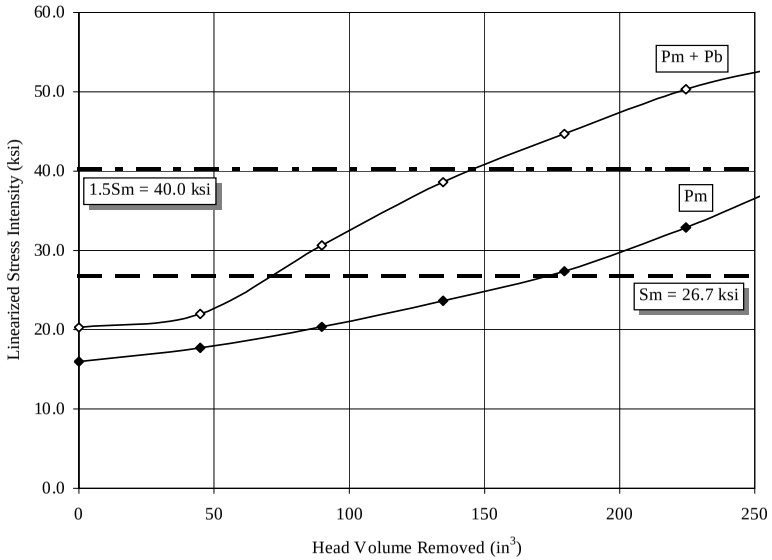
Typical Results for CRDM Nozzle

	2500 psi	6750 psi
Axial through-wall flaw in nozzle above J-weld	14.3 inches	5.3 inches
Circ. through-wall flaw above J-weld	330°	284°
Lack of fusion between nozzle and weld	327°	271°

Flaw Tolerance Evaluation
Tolerance to Boric Acid Wastage



Finite Element Model of Representative Head



Primary Membrane and Membrane Plus Bending Stress as Function of Wastage Volume

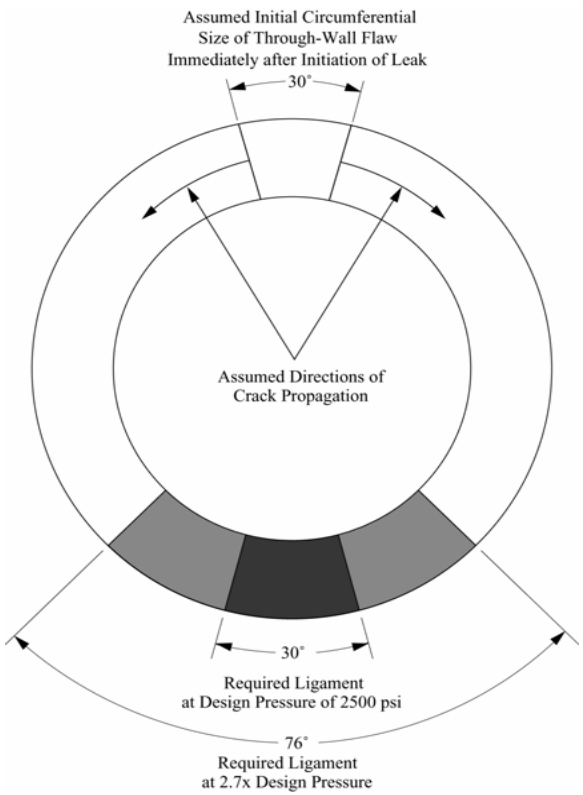
Flaw Tolerance Evaluation
Summary

- RV closure head nozzles are generally quite flaw tolerant
- The critical circumferential nozzle flaw size for nozzle ejection for CRDM nozzles is approximately 330°
- The critical flaw size for a “lack-of-fusion” type defect at the tube-to-weld interface is of similar magnitude
- Axial flaws leading to rupture of the CRDM nozzle are too long to be credible given the size of the high stress region
- The allowable wastage volume that maintains ASME Code allowable stresses in the head shell is about 150 in^3 for a representative head design

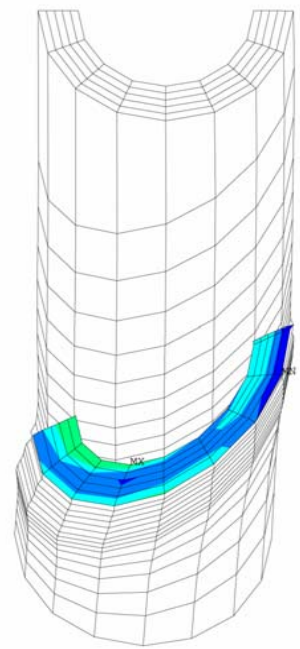
Deterministic Nozzle Ejection Assessments

1. Nozzle ejection due to the “lack-of-fusion” type flaw at the tube-to-weld interface is much less credible than nozzle ejection due to a large circumferential nozzle flaw
2. Conservatively assume a 30° through-wall circumferential nozzle flaw above the top of the weld upon restart from the initial nonvisual inspection
3. Calculate a stress intensity factor (SIF) as a function of circumferential crack size
4. Calculate the time to grow to the critical flaw size using the SIF curve and the deterministic MRP-55 crack growth rate (CGR) for Alloy 600 cracks in contact with the nozzle annulus environment with a safety factor on the pressure loading

Deterministic Nozzle Ejection Assessments
Calculation of Crack Growth Around Nozzle Circumference



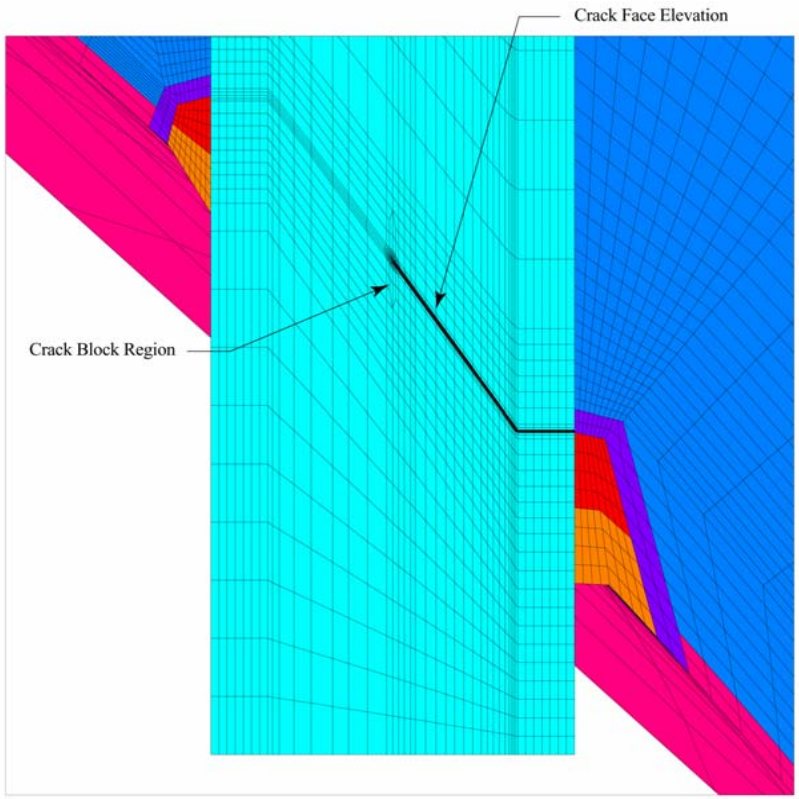
Typical Critical Flaw Size of 330°



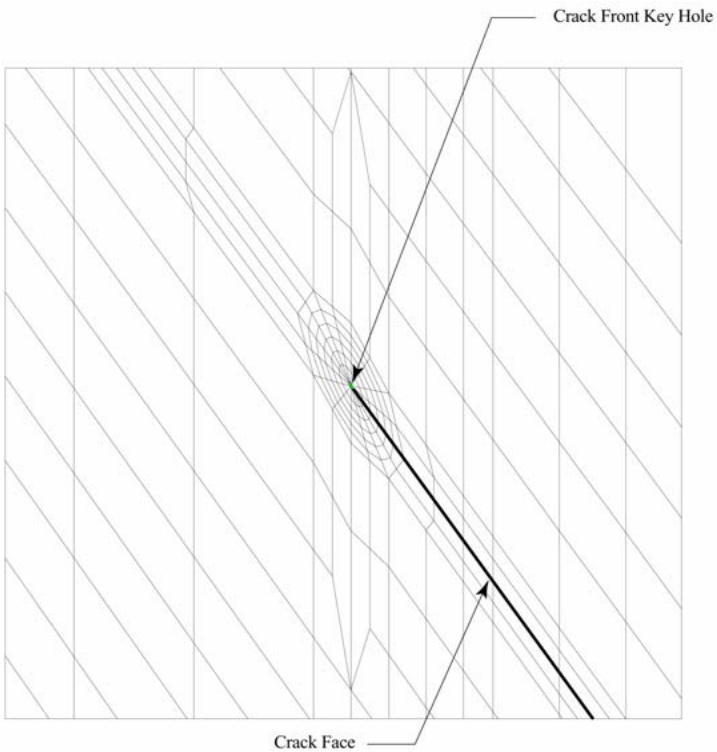
Example of Operating Stress Perpendicular to Circ Crack Plane

Stress Intensity Factor Calculation

Example Fracture Mechanics Analysis for Nozzle Circ Cracks

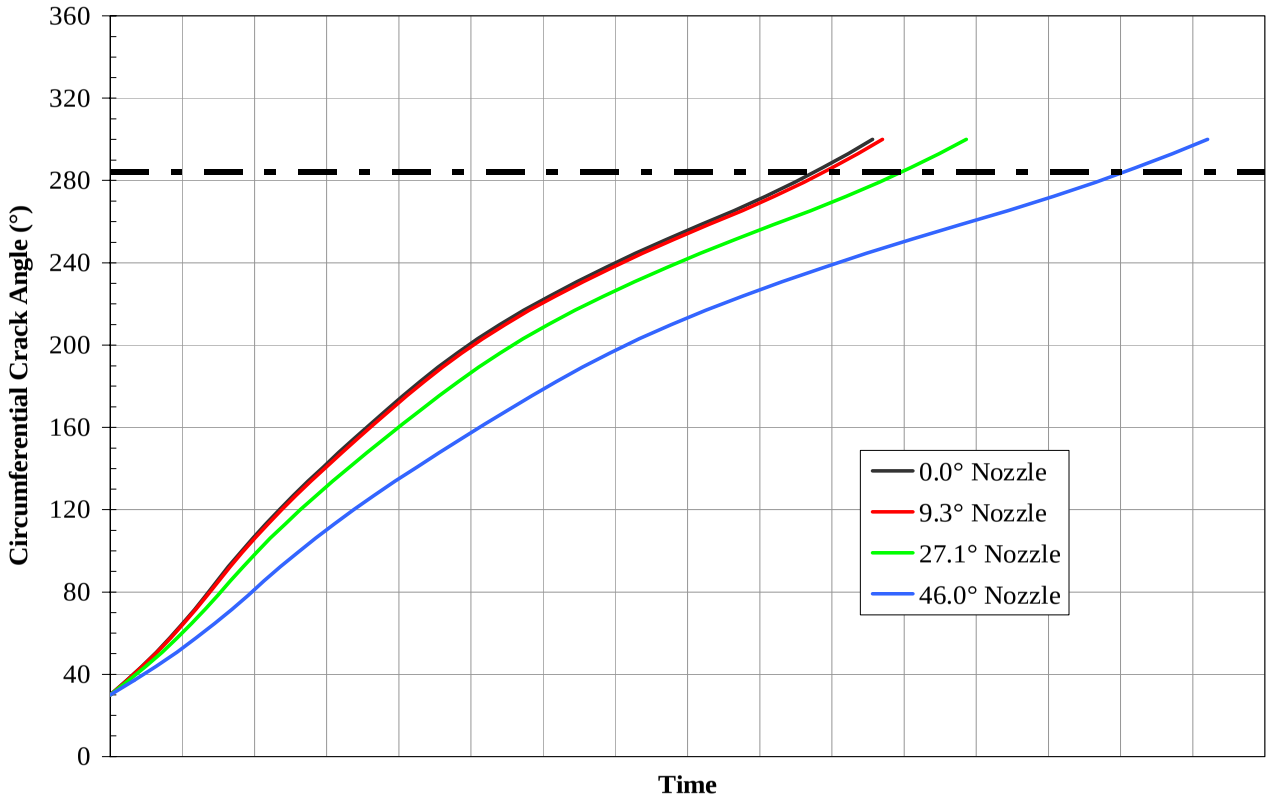


180° Downhill-Centered Crack

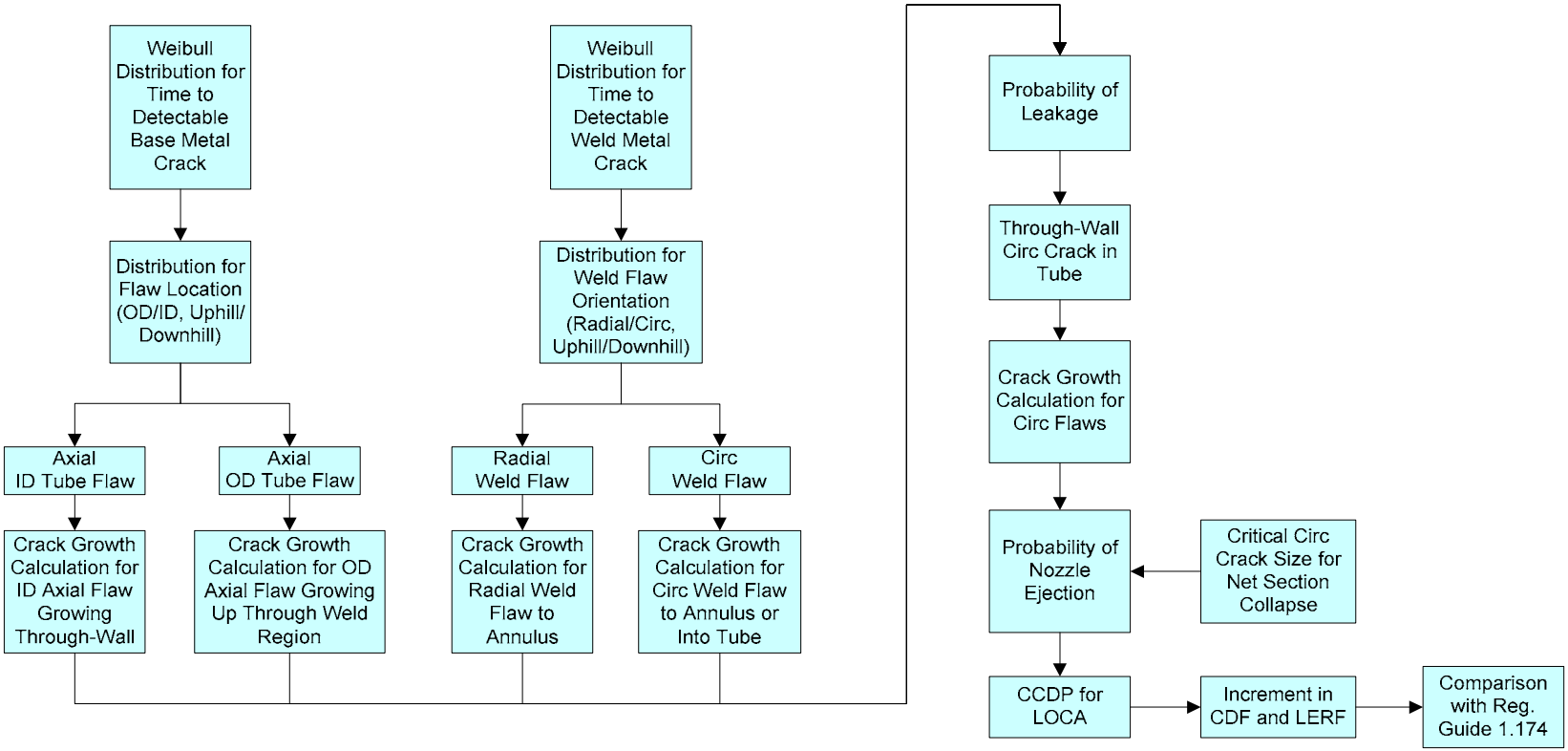


Crack Mesh Detail

Deterministic Nozzle Ejection Assessments
Example Results

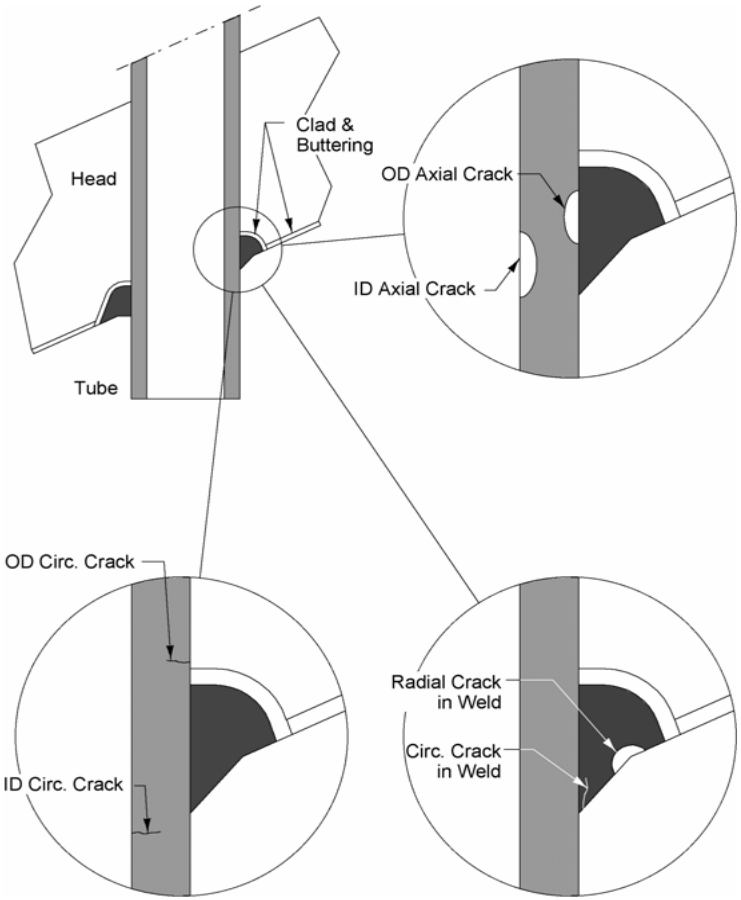


Probabilistic Nozzle Ejection Assessments
Simplified Simulation Model Flowchart



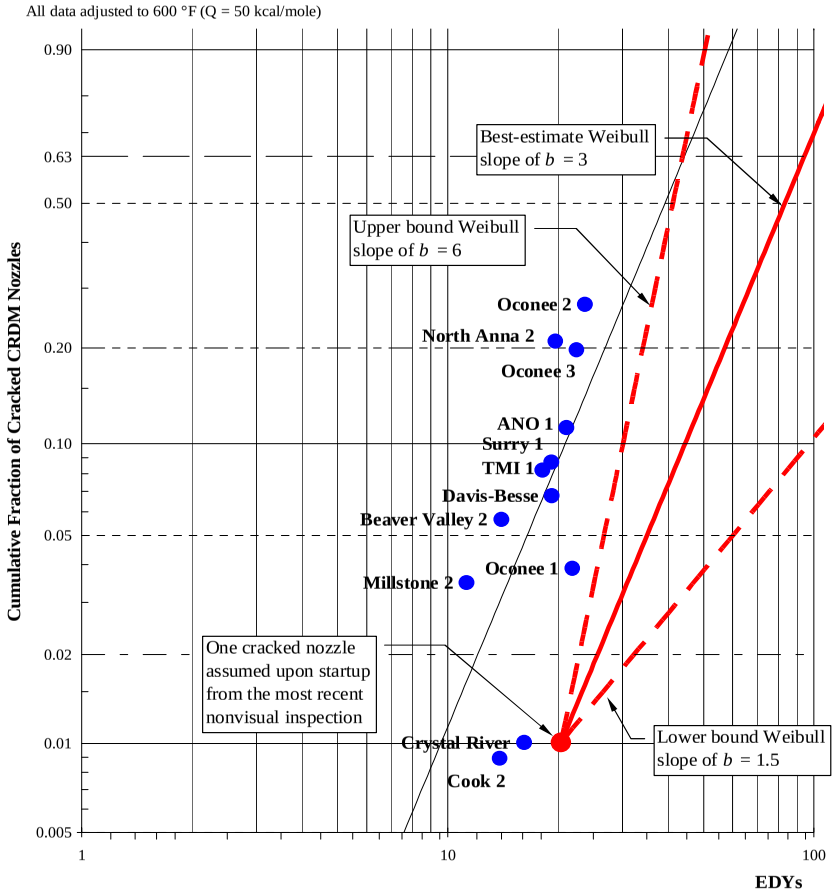
Probabilistic Nozzle Ejection Assessments
Modeled Flaw Geometries

- Cracking from the wetted surface to the nozzle annulus above the weld precedes circ cracking above weld
- Axial base metal cracking on nozzle ID and nozzle OD below the weld explicitly modeled
- Weld cracking to the nozzle annulus explicitly modeled



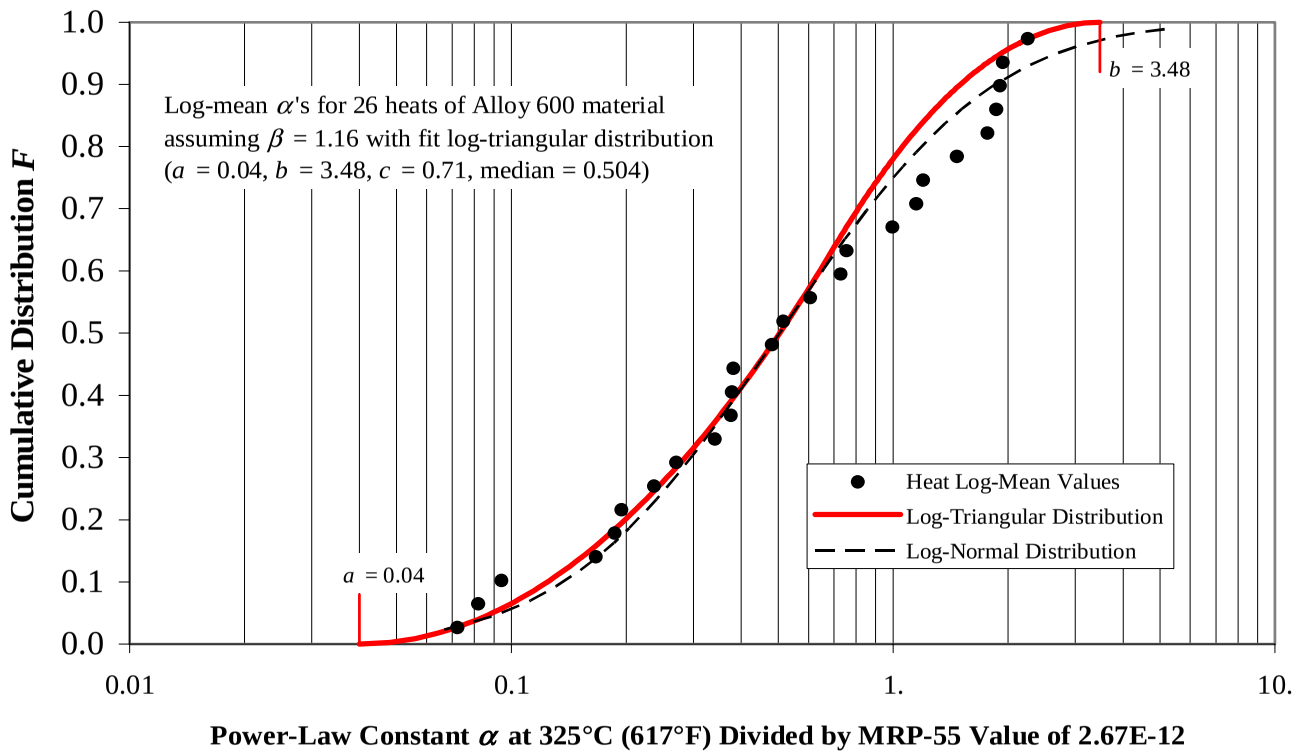
Probabilistic Nozzle Ejection Assessments
Weibull Statistical Modeling of Crack Initiation

- For plants that have performed a nonvisual inspection of all nozzles with no reportable PWSCC indications, it may be assumed that one nozzle immediately is cracked upon restart
- The rate of crack initiation in additional nozzles may be calculated assuming a range of Weibull slopes based on plant and laboratory test data



Deterministic Nozzle Ejection Assessments

Crack Growth Rate for Alloy 600 Based on Lab Data (MRP-55)

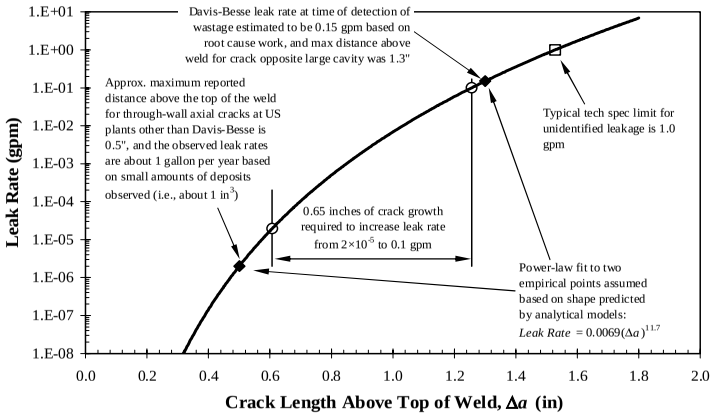


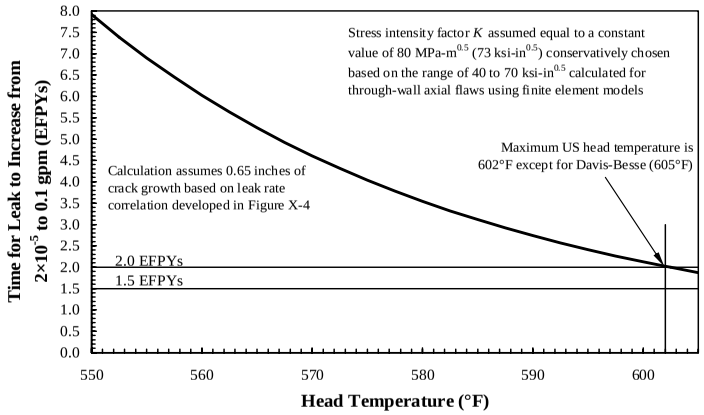
Probabilistic Nozzle Ejection Assessments
Assessment of Results

- The increase in CDF is calculated by multiplying the frequency of nozzle ejection times the conditional core damage probability (CCDP) for the appropriately sized loss of coolant accident (LOCA)
- The base case result is compared to the 1.0×10^{-6} per year criterion from Reg. Guide 1.174
- Sensitivity cases are also run to show that the results are not too dependent on the input assumptions and parameter distributions
  - POD curves
  - Crack geometry and location
  - Weibull crack initiation reference
  - Crack growth rate assumptions including weld CGR
  - Credit for bare metal visual (BMV) inspections to detect leak path flaws

Deterministic Boric Acid Wastage Assessments

- The methodology presented in Appendices C, D, and E of MRP-75 may be used to evaluate the potential for wastage
- The MRP is revising the MRP-75 wastage assessment on the basis of bare metal visual (BMV) inspections being performed each refueling outage
- The methodology is based on the time for the leak rate to increase to the point that cooling is sufficient to support a concentrated boric acid environment

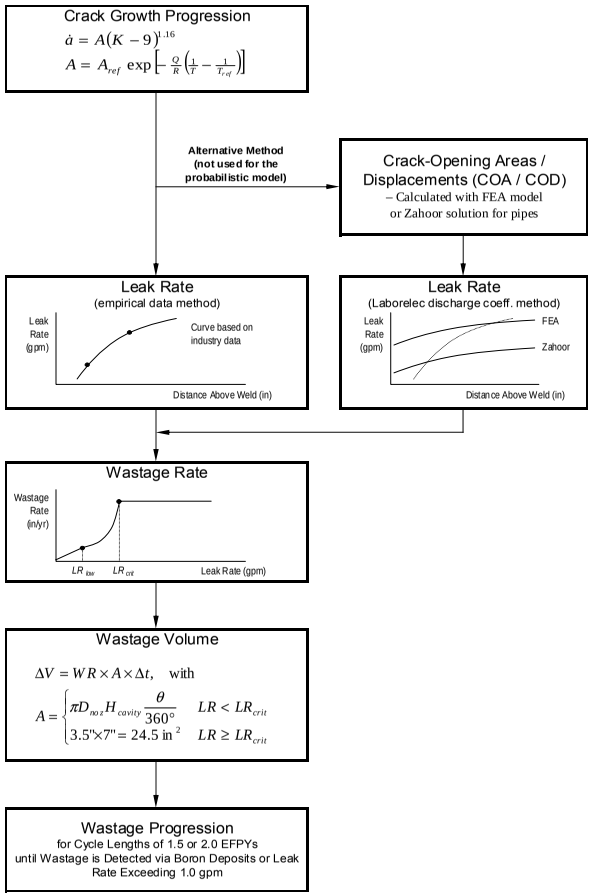




Risk-Informed Evaluation of PWR Reactor Vessel Head Penetration Inspection Intervals 17

Probabilistic Boric Acid Wastage Assessments
MRP Wastage Model (MRP-75)

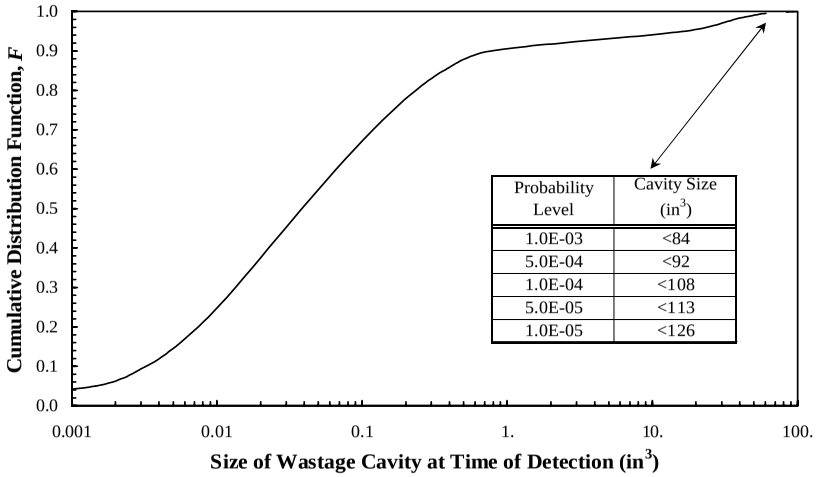
- The probabilistic wastage assessment of MRP-75 considers relatively wide tolerance bands for the key model parameters:
  - Point within operating cycle that wastage begins
  - Stress intensity factor driving crack growth
  - Crack growth rate distribution
  - Leak rate as a function of axial crack length
  - Wastage rate as a function of leak rate
  - Sensitivity of BMV inspection



Probabilistic Boric Acid Wastage Assessments
Typical Results

- Typical results shows that the probability of a leaking nozzle producing wastage greater than the typical 150 in^3 allowable volume is less than 1×10^{-4}

- The impact on the CDF may be estimated by multiplying the result of the probabilistic assessment by the probability of leakage from the nozzle ejection assessment and by the CCDP for the appropriately sized LOCA



Probability Level	Cavity Size (in^3)
1.0E-03	<84
5.0E-04	<92
1.0E-04	<108
5.0E-05	<113
1.0E-05	<126

Conclusions

- After consideration of additional factors such as the potential effects of loose parts, consequential damage, and the effect on the large early release frequency (LERF), the methodology forms a rational basis for setting the re-inspection interval
- Because RV head nozzles are quite flaw tolerant, typical results show that re-inspection every second or third operating cycle maintains the requisite level of nuclear safety

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Reactor Vessel Head Penetration Inspection Technology Past, Present and Future

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D. C. Adamonis

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RPVH Inspection Technology

- Initial Concern was ID Flaws in Nozzle
  - Eddy Current Testing for Detection
  - Ultrasonic Testing for Sizing
- Gapscanner sword probes used exclusively
- NDE Qualifications performed to Bulletin 97-01
- DERI Robotic Delivery System

RPVH Inspection Technology

- NRC Bulletins 02-02 and 03-02
  - Emphasis changes to Nozzle OD and Weld
  - Ultrasonic volumetric exam or wetted surface exams required
- Additional Inspection Equipment Required
  - Open Housing Scanner (ET and UT)
  - Weld and Nozzle OD Scanner (ET)

RPVH Inspection Technology

- Inspection Approach from ID
  - TOFD UT for OD Flaws and Sizing
  - Eddy Current Testing for ID Flaws
  - 0 Degree UT for Leak Path
- Inspection Approach from OD
  - Eddy Current Testing for Detection and/or confirmation of ID Results
  - Weld surface and Nozzle OD Coverage

Under the Reactor Vessel Head Inspection and Repair Equipment Delivery System

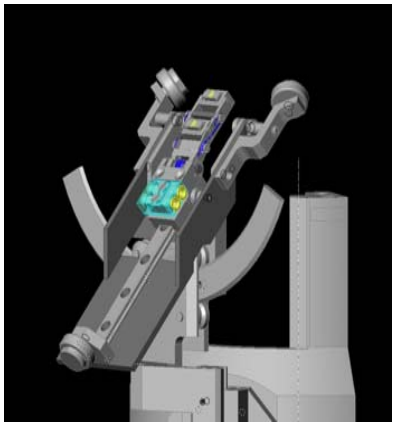
- End-effectors for under-head penetration inspection and repair are delivered by the “DERI” manipulator system
  - 5 systems available in the Westinghouse system
  - Over 140 RV Head inspections performed with the DERI/eddy current gap scanner
  - Change out of end effectors is performed remotely

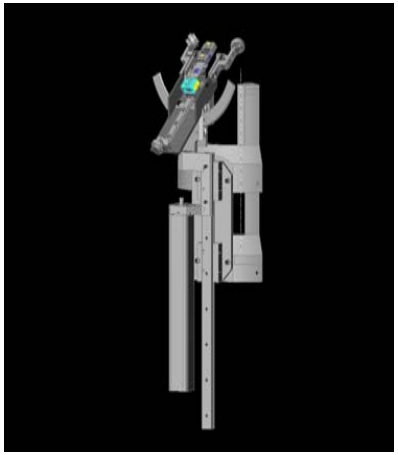
Open Housing Scanner Offers Eddy Current and TOF Inspection Capability

Gapscanners for Sleeved Penetrations

- Blade probes are delivered into the annulus between the the ID surface of the penetration and OD surface of the thermal sleeve, on the order of 0.125 inches
- The Gapscanner end effectors can be used with a variety of eddy current and ultrasonic blade probes for inspection and characterization
  - Eddy current probes
  - TOFD ultrasonic probes
  - Combination TOFD/ECT probes
  - Pulse-echo ultrasonic probes

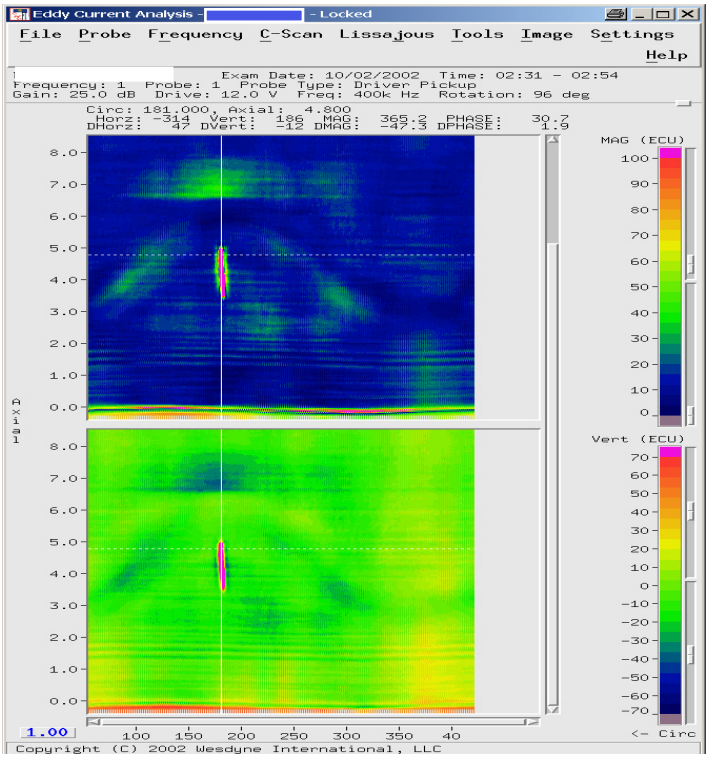
J-Weld and Penetration Tube OD EC Inspection

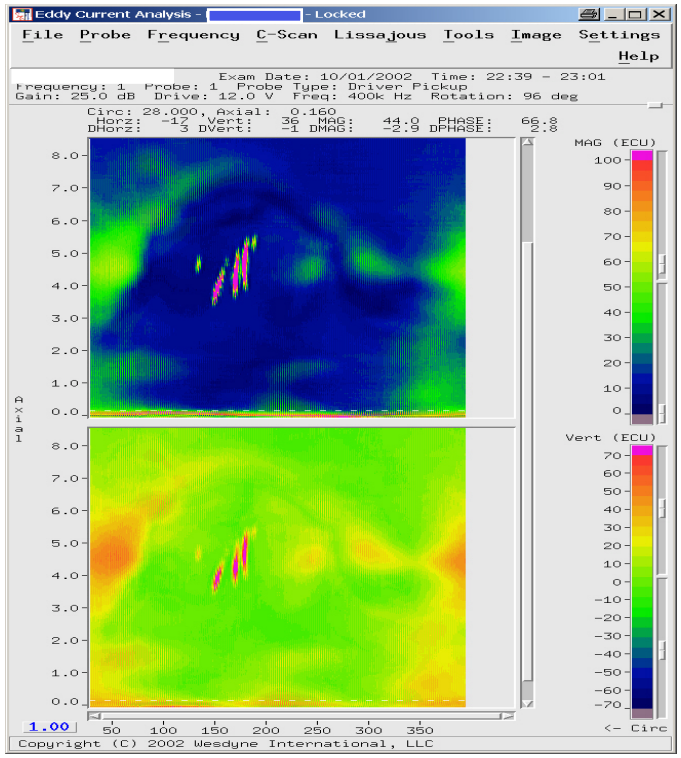




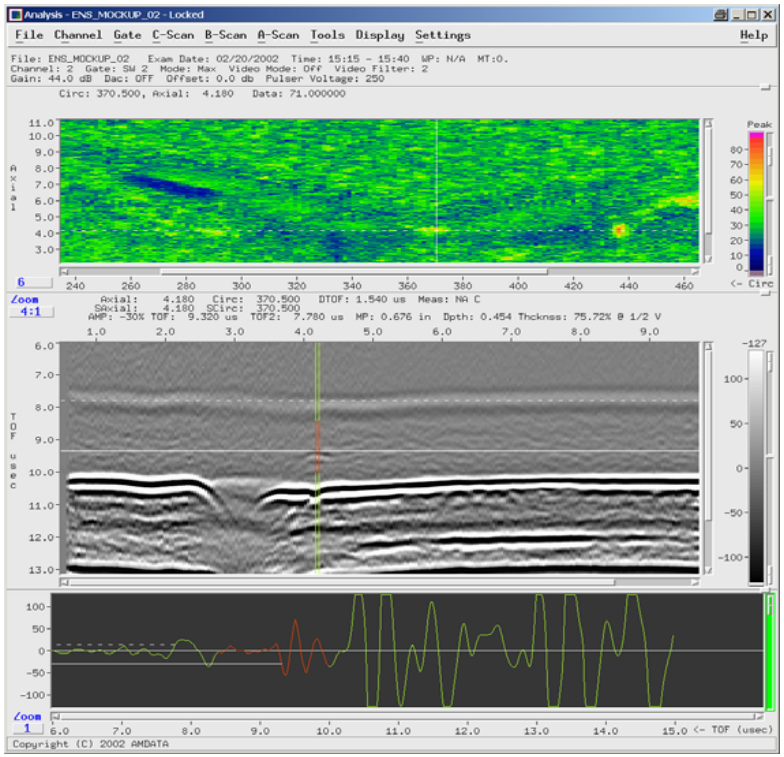
- “Grooveman” is used to perform eddy current inspections of the J-weld and penetration tube OD surface
- “Grooveman” has been used at North Anna Units 1 and 2, DC Cook Units 1 and 2, SONGS 2, H.B. Robinson Unit 2 and Palo Verde Units 1 and 2

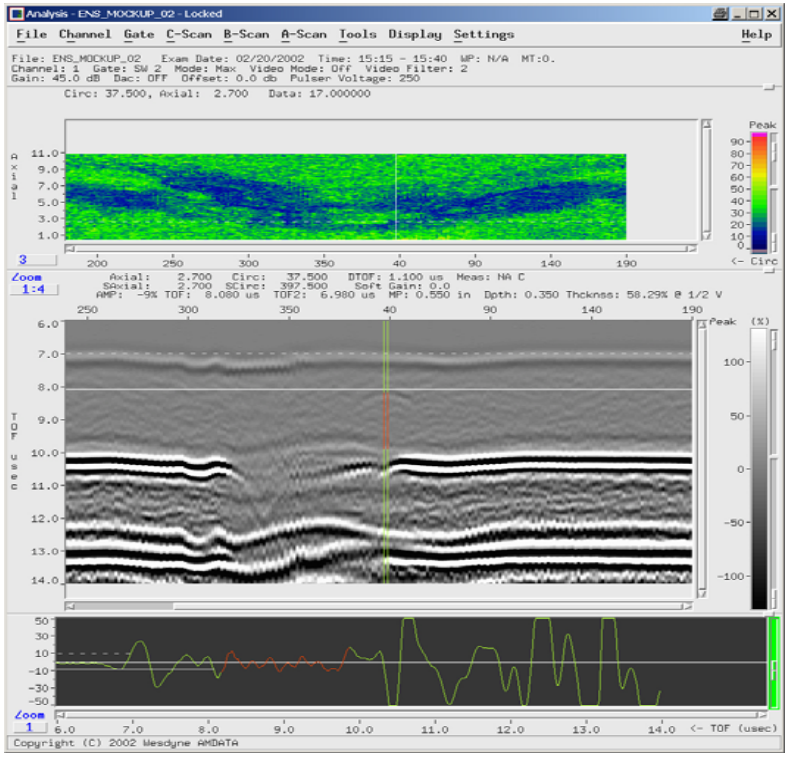
Penetration Tube ID Eddy Current Results



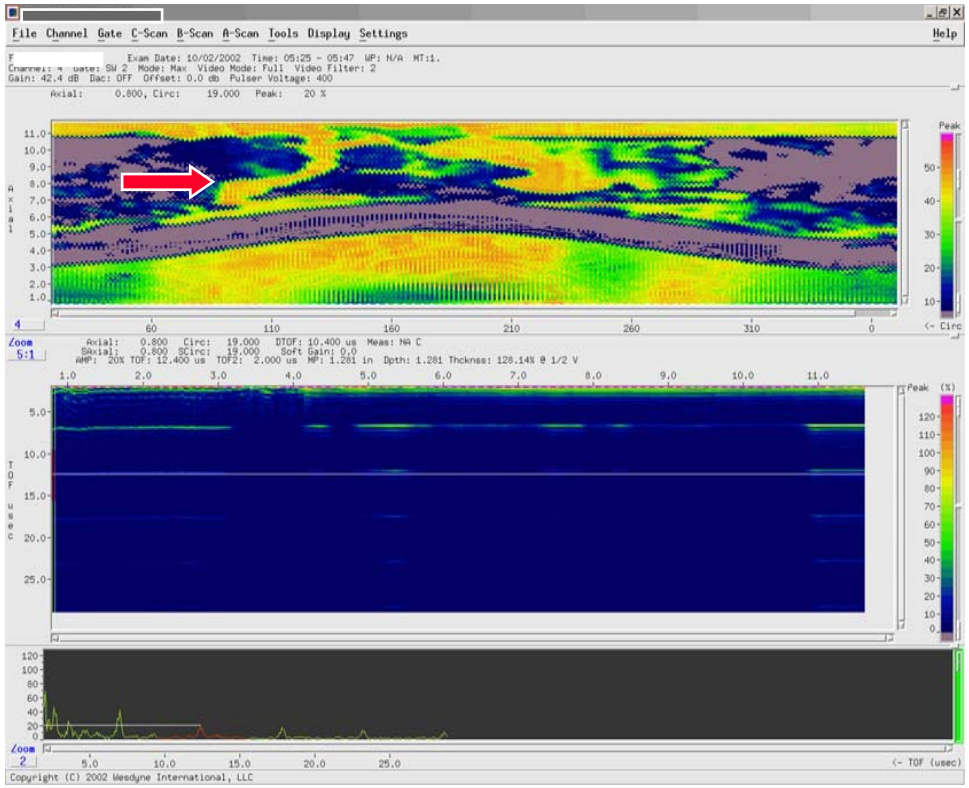


PCS24 TOFD UT Results



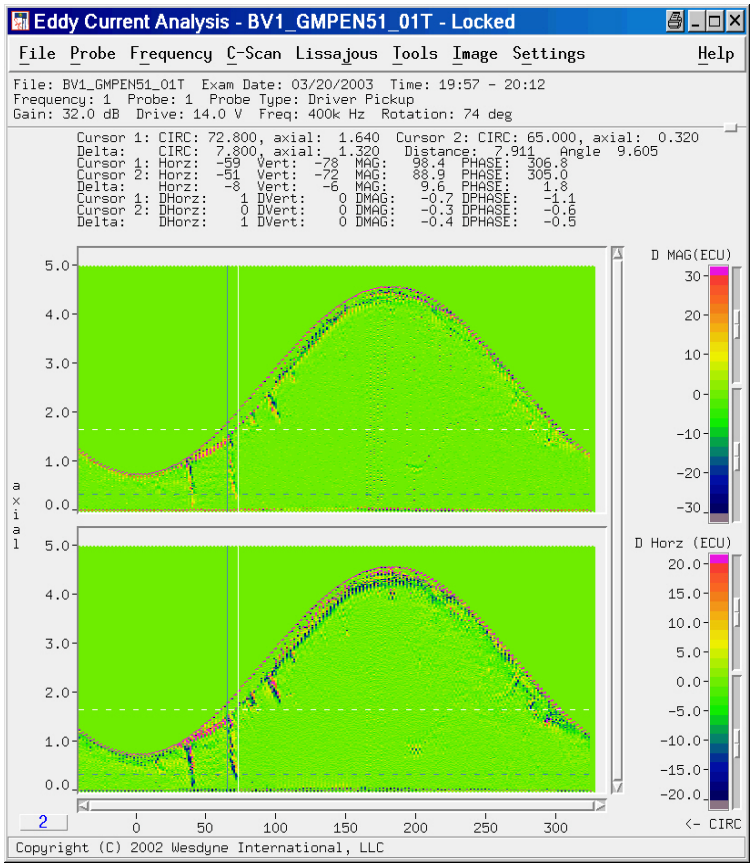


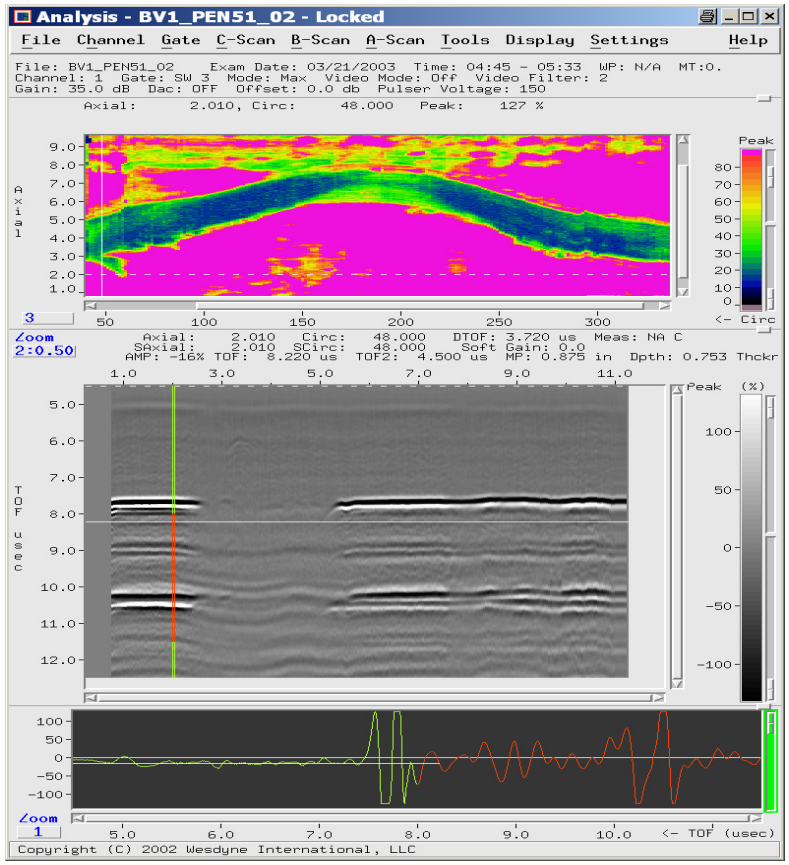
Leak Path Identification



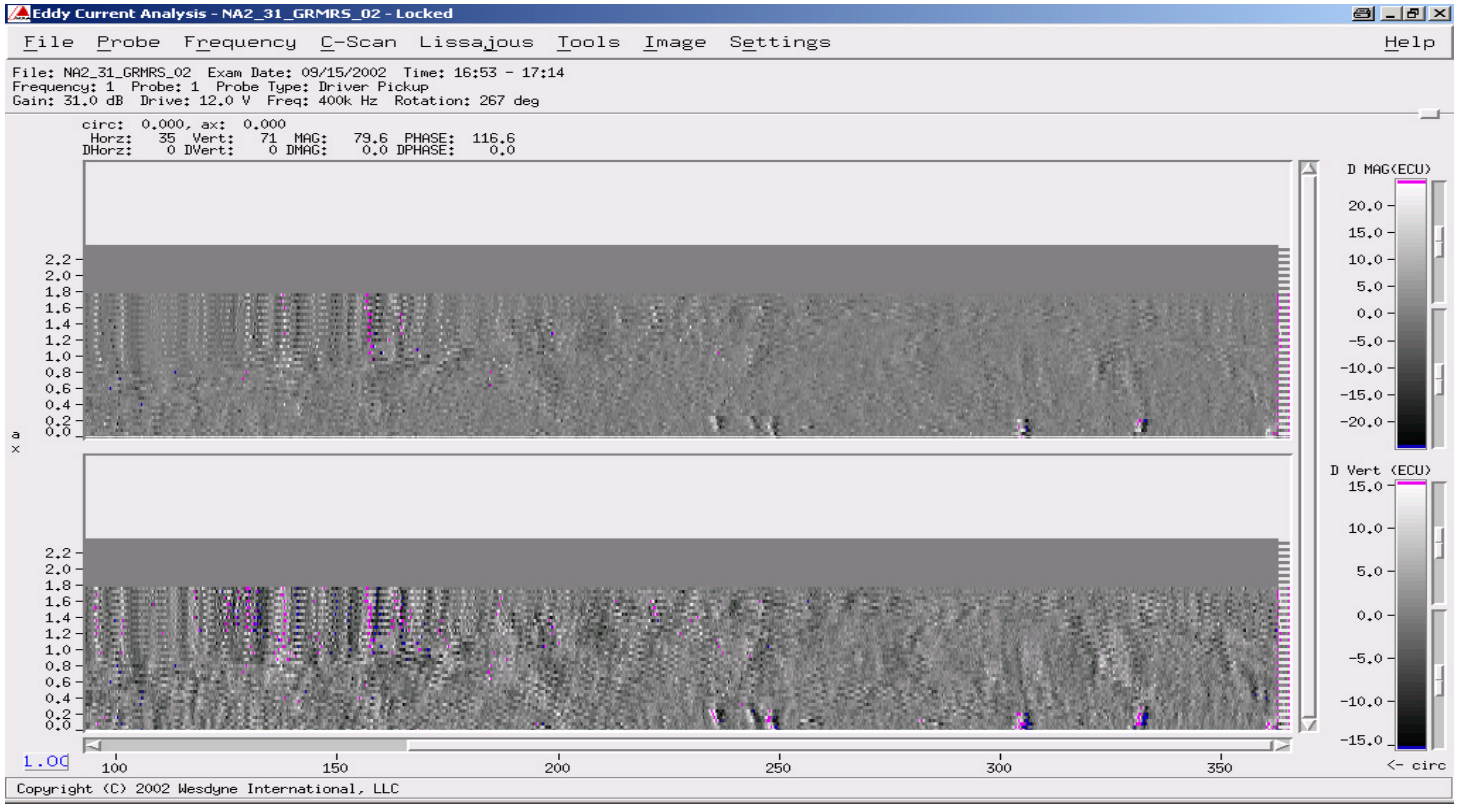
- Not applicable to BMI inspections
- Possible leak path identified with straight beam, high frequency ultrasonics
- Leak path leads to loss of shrink fit integrity and a resulting increase in reflectivity
- Diagnostic tool rather than a primary inspection method

Penetration Tube OD ECT and ID TOFD Results





J-Groove Weld ECT Results

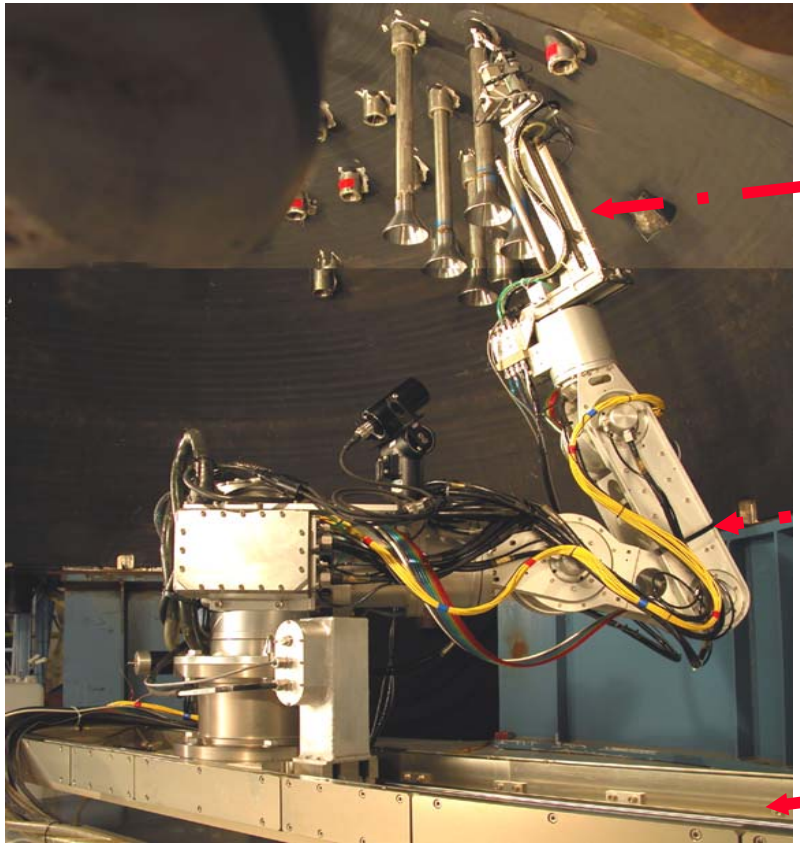


Reactor Vessel Head PT Results

RPVH Inspection Technology

- Next Generation Equipment
  - SUPREEM Based Robotics
  - Triple Sword Probe
    - TOFD
    - ET
    - 0 Degree
    - BMI Probes

Rapid Repositioning Accomplished with ROSA

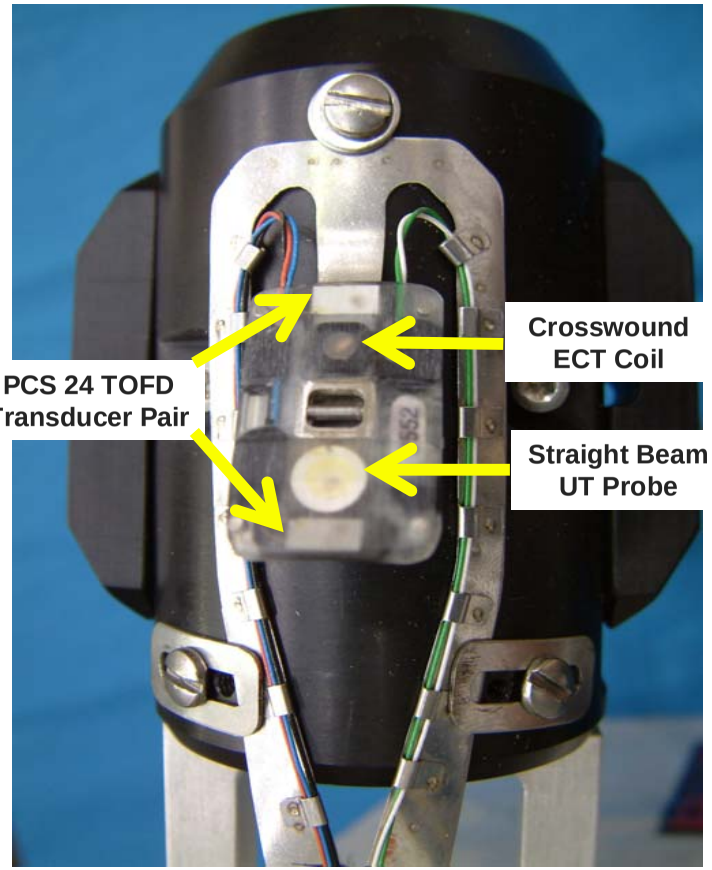


End Effector

Six Degrees of Freedom Robotic Arm

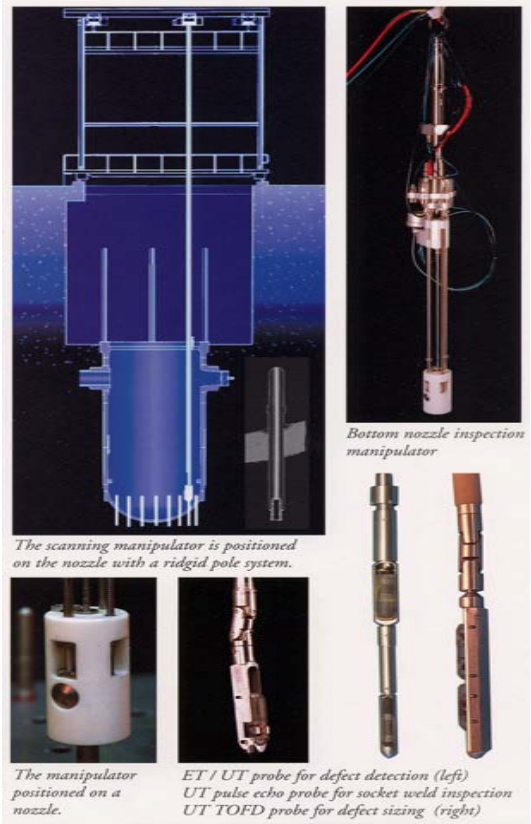
Positioning Track

Westinghouse Triple Combo Blade Probe



- Three examinations performed simultaneously:
  - PCS 24 TOFD ultrasonic examination of penetration tube
  - Eddy current examination of penetration tube ID surface
  - Straight beam ultrasonic examination for leak path identification

Bottom Mounted Instrumentation Inspection



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Section 3:
Session 2: Continued Plant Operation

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Background and Technical Basis: Evaluation of Upper Head Penetration Flaws in the ASME Code

Warren Bamford, Westinghouse Electric
and
Guy DeBoo, Exelon

BNFL

Westinghouse

Introduction

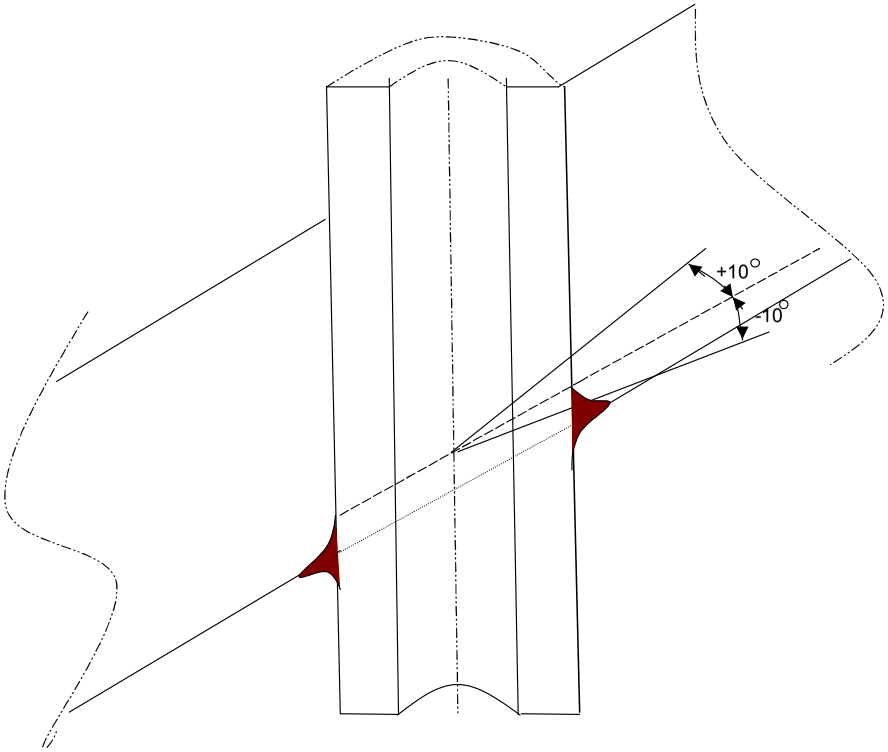
- A consistent and defendable evaluation process for the treatment of flaws in head penetrations has been developed
- The original work on these methods and acceptance criteria was done in the early 1990s, and reviewed and approved by NRC, but not codified
- In 2001, it was decided that the acceptance criteria should be expanded and put into the ASME code
- This work was completed in April of 2003, and will appear in the 2004 Edition of Section XI
- NRC endorsed this methodology in a letter to NEI published April 22, 2003

- Flaw Characterization
- Evaluation Process
- Stress Corrosion Crack Growth
- Example Results to Verify PWSCC Model
- Fatigue Crack Growth
- Flaw Acceptance Criteria
- Example Application

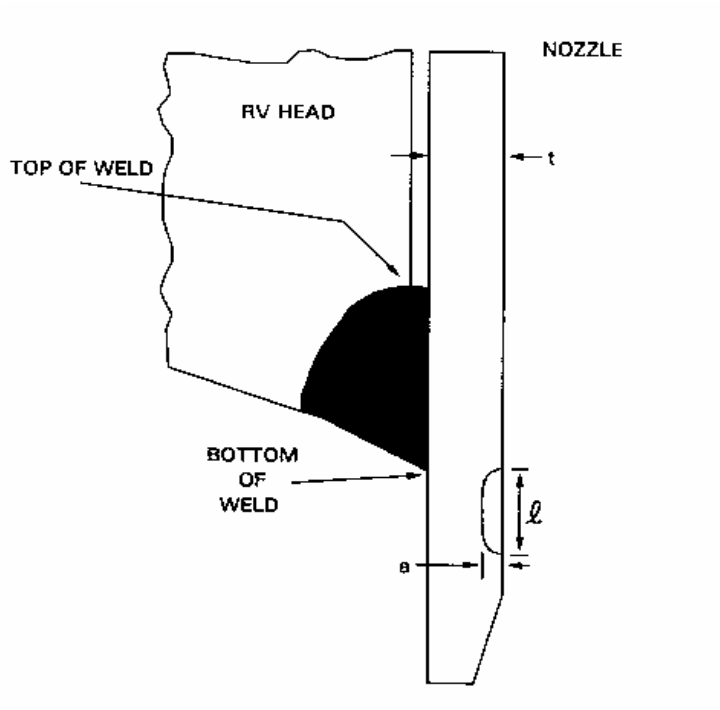
Flaw Characterization

- The approach already contained in Section XI, in IWA 3400-1 can be used directly.
- Flaws must be resolved into axial and circumferential components
- The location of the flaw relative to the attachment weld must be determined

Definition of “Circumferential”



Schematic of Head Penetration Geometry

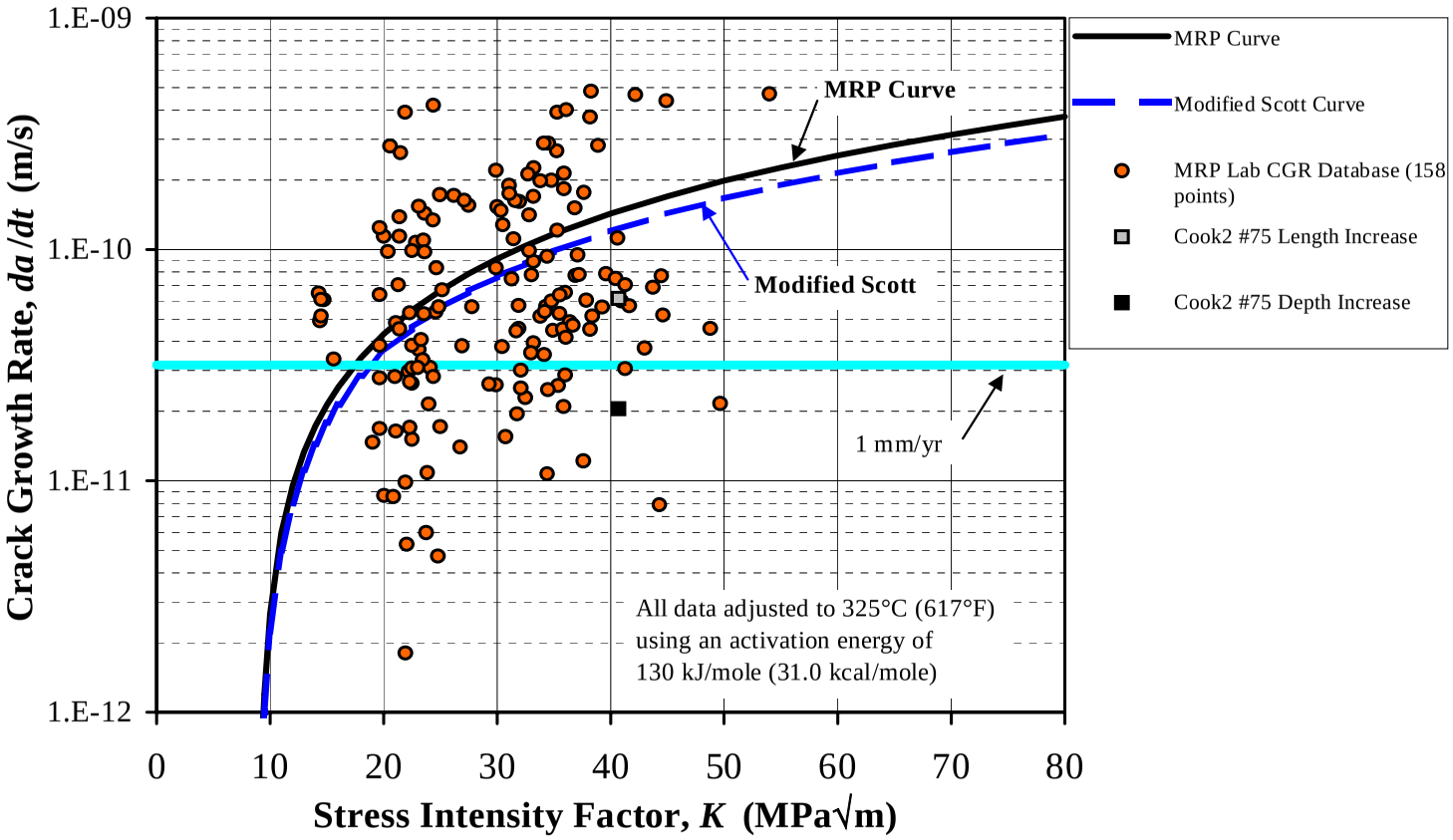


Evaluation Process

- Predict future growth due to
  - Fatigue
  - PWSCC
- Compare future growth with acceptance criteria to determine next inspection
- Process is similar to pipe flaw evaluation, already in Section XI, Appendix C

Stress Corrosion Crack Growth

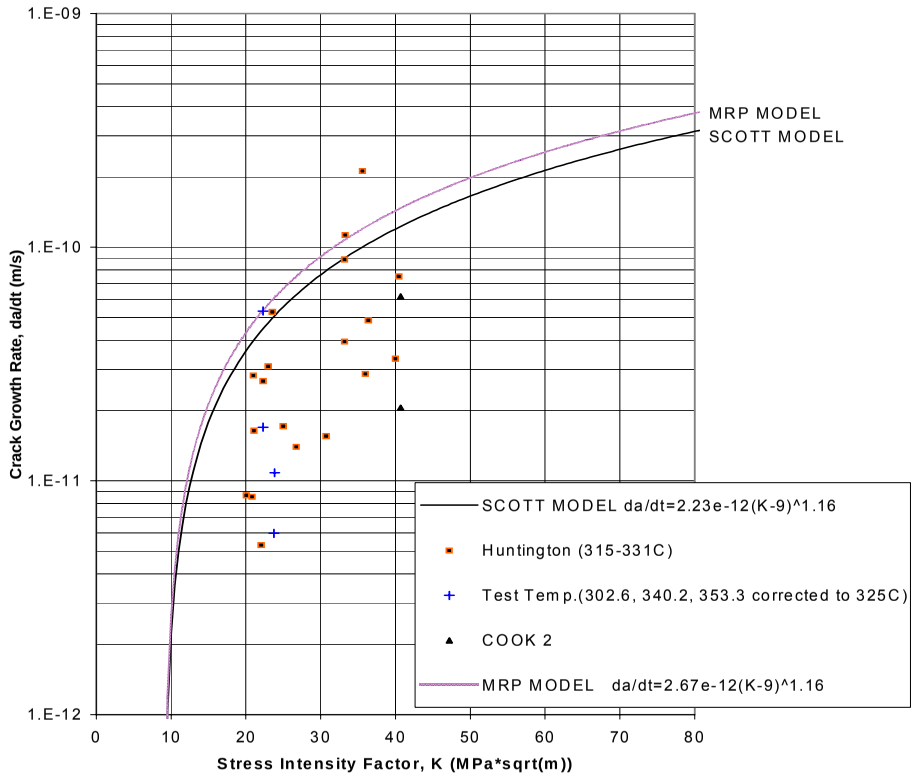
- Use EPRI MRP-55 Rev.A report as basis for growth model: Alloy 600 Base Metal
- Goal is a “Best Estimate” Prediction
- Model is higher than the mean, so it is conservative
- Additional conservations added in acceptance criteria


1.E-09
1.E-10
1.E-11
1.E-12
Crack Growth Rate, da/dt (m/s)
0
10
20
30
40
50
60
70
80
Stress Intensity Factor, K (MPa√m)
MRP Curve
Modified Scott
1 mm/yr
All data adjusted to 325°C (617°F)
using an activation energy of
130 kJ/mole (31.0 kcal/mole)
MRP Curve
Modified Scott Curve
MRP Lab CGR Database (158 points)
Cook2 #75 Length Increase
Cook2 #75 Depth Increase

Example Calculation to Verify SCC Growth Rate

- Inspections of D.C. Cook Unit 2 in 1994, 1996.
- Crack sizes determined with ECT, UT
- Crack growth was below predictions
- Flaw shape did not change

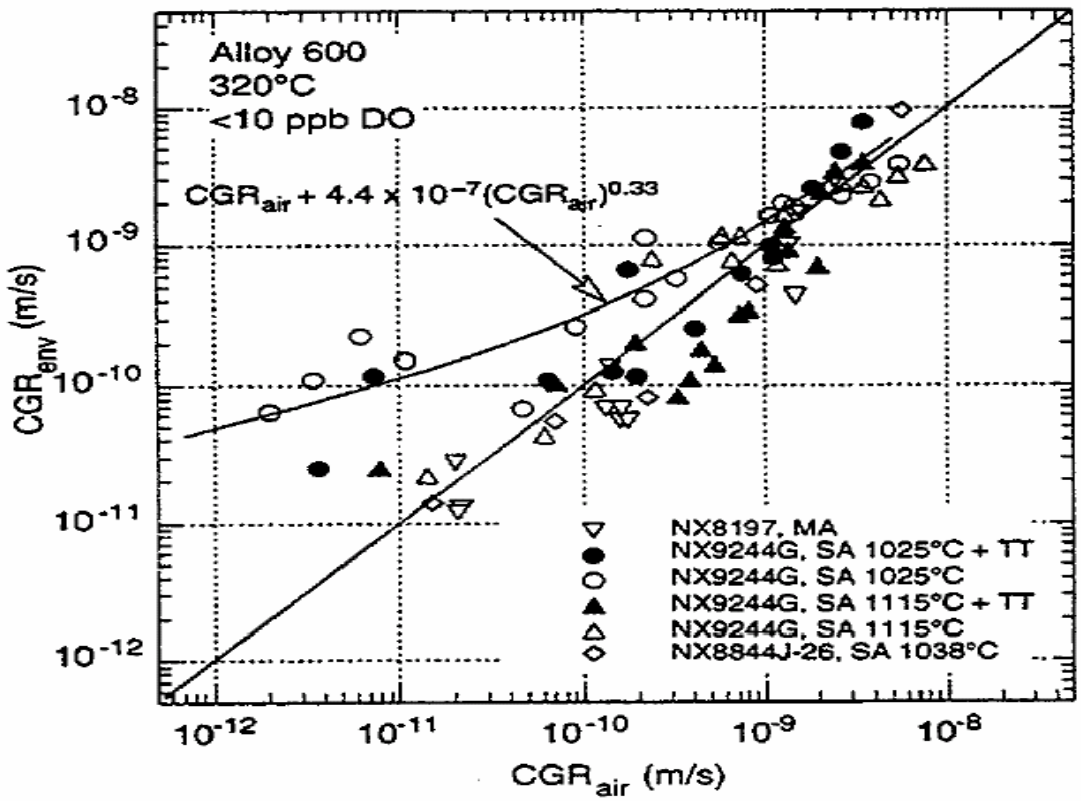
Service induced crack growth, compared with the PWSCC model



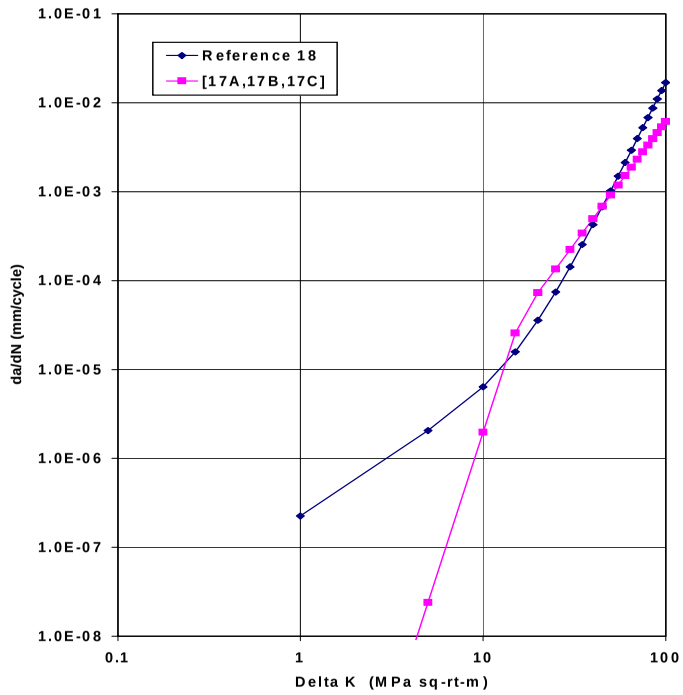
Fatigue Crack Growth

- Model obtained from literature: Argonne Report NUREG/CR-6721
- Several other references reviewed
- Contribution to total growth is negligible

Argonne Model, with Data



Comparison to other Fatigue Crack Growth Models



Flaw Acceptance Criteria

- Flaw acceptance standards (IWB 3500) may not be used for PWSCC
- Critical flaw size for head penetrations is very large, for both axial and circ. flaws
- Flaw acceptance criteria developed to protect against leakage, rather than taking a margin on the critical flaw size

Table IWB 3663-1: Summary of R.V. Head Penetration Acceptance Criteria				
Location	Axial		Circ	
	a_f	l_f	a_f	l_f
Below Weld (ID) (2)	t	No Limit	t	.75 Circ.
At and Above Weld (ID)	0.75 t	No Limit	(3)	(3)
Below Weld (OD) (2)	t	No Limit	t	.75 Circ.
Above Weld (OD)	(3)	(3)	(3)	*(3)

Notes:
(a) Surface flaws of any size in the attachment weld are not acceptable.
(2) Intersecting axial and circumferential flaws in the nozzle are not acceptable.
(3) Requires case-by-case evaluation and discussion with regulatory authority.

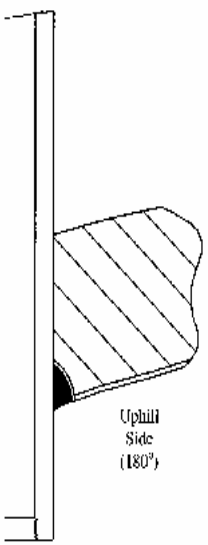
a_f = Flaw Depth as Defined in IWB 3600

l_f = Flaw Length

t = Wall Thickness of Head Penetration Nozzle

Example Application

Orientation	Vertical Location	Circumferential Location	Length	Depth
Axial-ID	At Weld	Uphill	0.283” (7.2mm)	0.047” (1.2mm)



ASME Code Actions

- This action was approved in principle at the Working Group level in December of 2002
- Subcommittee Section XI approved the action in February 2003
- The action will be published soon as an ASME Nuclear Code Case, and in the 2004 Edition of Section XI, as paragraph IWB 3660.
- NRC endorsed this methodology in a letter to NEI published April 22, 2003

Westinghouse

A BNFL Group Company

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MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE

François CHAMPIGNY (EDF – Nuclear Power Plant Operations)
François CHAPELIER (EDF – Nuclear Power Plant Operations – Liaison Engineer with INPO)
Claude AMZALLAG (EDF – Nuclear Engineering)
François VAILLANT (EDF – Research & Development)

CONTENT

- INTRODUCTION
- NON DESTRUCTIVE EXAMINATIONS, REPAIRS
- INVESTIGATION PROGRAM
- INSPECTION PROGRAM SINCE 1996
- EXPERIENCE FEEDBACK AND VESSEL HEAD REPLACEMENT
- OTHER INCONEL COMPONENTS
- CONCLUSION

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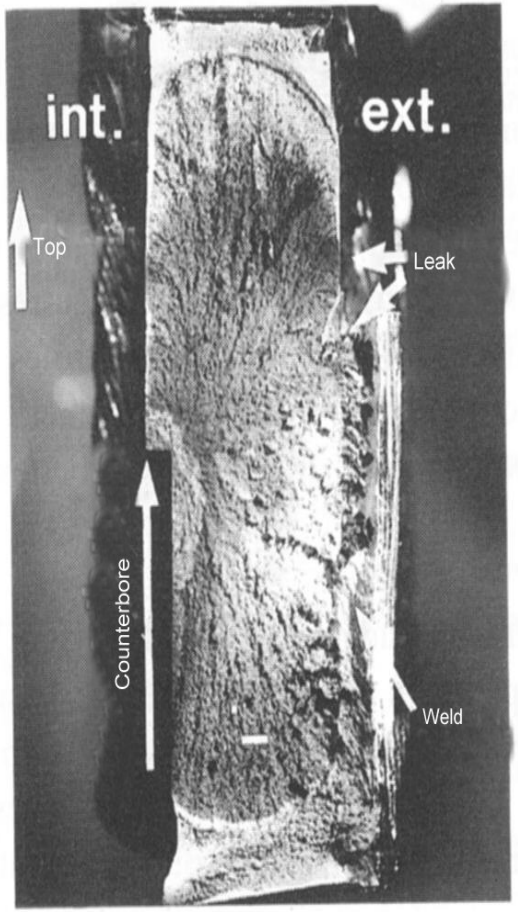
MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : Bugey Leak

- In France, on September 23, 1991, a leak occurred on the Bugey 3 T54 vessel head penetration;
- Leak was detected by acoustic emission during hydrotest (207 bar ⇒ 1.2 Pressure Design) and was estimated to 1l/h.
- After expertise, a mainly longitudinal crack from inside the penetration, through wall extent, was found.



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MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : Bugey results

- **NDE results**
  - First non destructive examinations, penetrant testing, Eddy currents, ultrasonic testing, revealed longitudinal cracks opposite to the weld in the tube part of the penetration.
- **Analysis of the crack morphology**
  - Primary water stress corrosion cracking (PWSCC),
  - No fatigue,
  - Orientation of the crack : mainly longitudinal
  - Azimutal location : 0° and 180°; most cracks were located at 180°,
  - Operating time : ~ 80 000 hours (BUGEY)

MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : 1st Investigations

- **NON DESTRUCTIVE EXAMINATION**
  - 1st NDE developments :ET
    - *Detection by Eddy current with a classical rotating probe but need to remove thermal sleeve*
  - 2nd NDE development : ET & UT
    - *Detection by Eddy current with « blade probe » without removing thermal sleeve*
    - *Characterization by ultrasonic « blade probe » using Time Of Flight Technique (TOFT)*
    - *Video probe*
- **Probes tested on mock-ups with artificial, realistic and real flaws.**
- **FIRST NDE RESULTS**
  - At the end of 1992 :
    - ✓*Five 900 MW vessel heads with cracked penetrations and four 1300 MW (after 30000 to 40000 hours operating).*
  - At the end of 1994 :
    - ✓*47 VHs had been inspected;*
    - ✓*33 VHs out of 47 with tiny indications and very few cracks in penetrations.*
- **Alternative methods**
  - Leak detection system using N^{13} installed on about 20 vessel heads with alloy 600 penetrations to prevent new leak.
  - No leak was detected since 1991,
  - Systems dismantled when vessel heads are replaced by Inconel 690.
- **Visual testing on vessel heads**

REPAIRS

- After vessel head penetration Bugey 3 T54 leak :
  - ✓ Repair solution tested,
  - ✓ Framatome achieved repairs,
  - ✓ Long time (~ 1 year),
  - ✓ High cost (> 1.5 M€).

REPLACEMENT

- Due to the homogeneous fleet of vessel heads and RPVs, **EDF decided to replace all vessel heads with alloy 600 penetrations at the beginning of 1993**. That decision concerned 54 VH out of 58, last four ones were equipped with alloy 690 penetrations.
- New vessel heads : base metal with alloy 690, welds with alloy 152.

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MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : Investigation program

- **A large investigation program is launched in 1992**
  - Operating temperature of the components in relation with thermal-hydraulics,
  - Susceptibility of the material to PWSCC, depending upon its microstructure and the manufacturing process,
  - Stress identification (residual and operating) and evaluation by measurements, mock-up corrosion tests and Finite Element Analysis (FEA),
  - Effect of surface finish on crack initiation,
  - Crack growth rate.

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MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : Investigation program

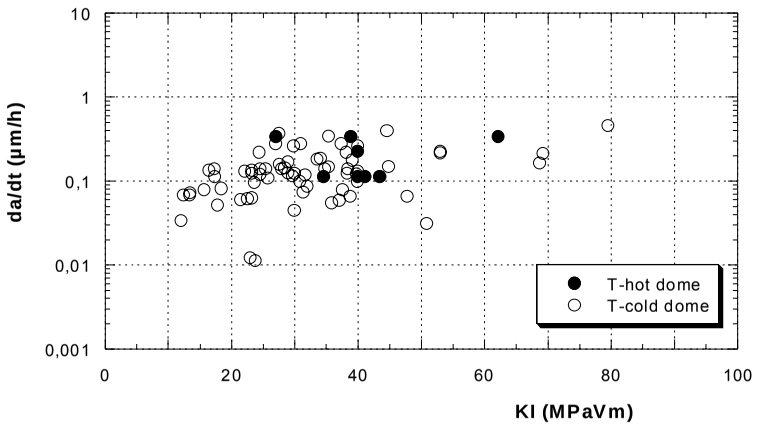
Best estimates of the temperatures at the penetration inner surface in front of the weld :

- in cold dome : **290°C,**
- in hot dome :**300°C.**

Difference of temperature between the T-hot dome and T-cold dome is close to **10°C**.

With the accuracy of the methods, it is not possible to singularize a particular plant or position of a penetration in the plant

Field data - T-hot dome data (300°C) and T-cold dome data (290°C)



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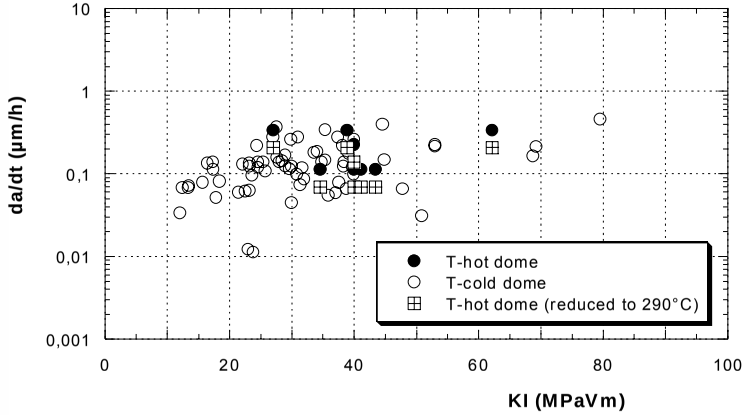
MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : Investigation program

Activation energy has been deduced from **laboratory data** obtained at EDF, Framatome, CEA and ETH, between 290°C and 360°C, for which a satisfactory agreement has been obtained **(Q = 130 KJ/mol).**

It is not possible to deduce an activation energy from **field data** since the scatter of data, for a given configuration (T-hot and T-cold), is greater than the difference of data converted with the activation energy of 130 KJ/mol.

Field data - T-hot dome data (300°C) reduced to 290°C with Q = 130 KJ/mol and T-cold dome data (290°C)



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Crack Propagation Laws

Alloy 600 :

Mean Curve - V.H. Penetrations (290°C) : $da/dt = 0.03 \times (K - 9)^{0,52}$

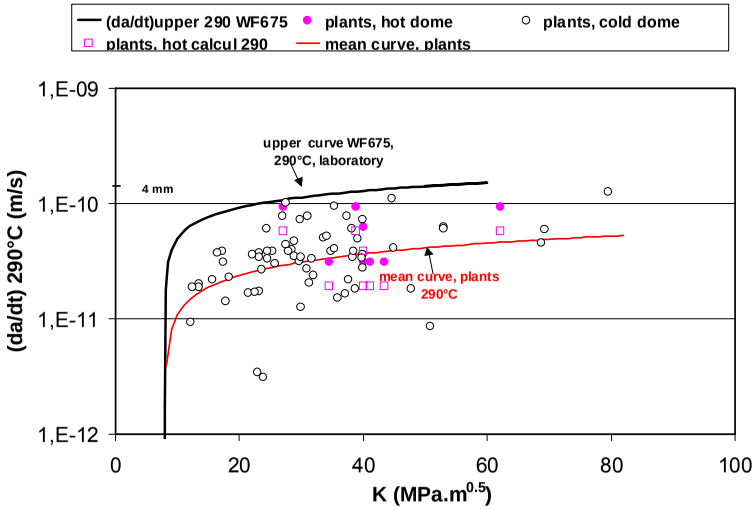
Upper bound (Field and Laboratory Data) (290°C) : $da/dt = 0.3 \times (K - 9)^{0,30}$

(da/dt in µm/h ; K in MPa√m)

Alloy 182 :

The upper bound of crack propagation rates measured in laboratory on Alloy 182 is equivalent to the upper bound (field and laboratory data) on Alloy 600.

Results



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Characteristic Values of Crack Growth Rates in Depth

Maximum crack growth rate of one crack : **0,46 µm/h**
(propagation of 3,5 mm measured over an operating cycle of 7661 hours),

Mean value of maximum crack growth rates observed on overall cracks ofoverall penetrations : **0,18 µm/h**

(propagation of 1,4 mm over a mean operating cycle de 8000 hours).

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EDF Electricité de France

❑ Effect of yield strength on Grain Boundary Coverage (GBC):

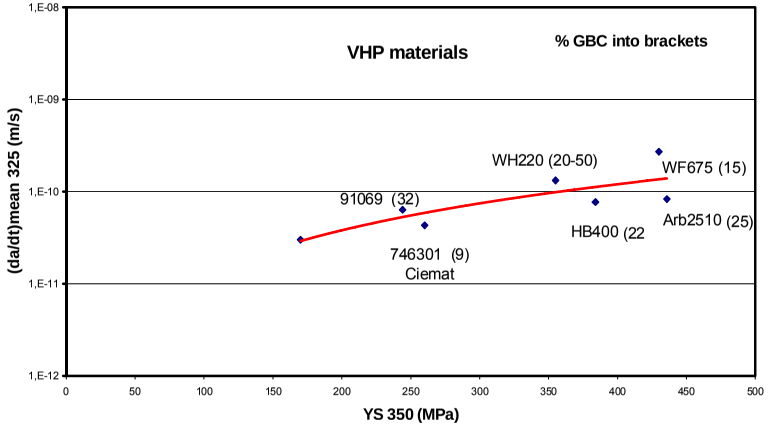
➢ Results : $(da/dt)_{mean} = f(YS, GBC)$

For VHPs, at 325°C:

➢ **detrimental influence of high YS_{350} , low GBC :**

➢ **$(da/dt)_{mean} = 6.10^{-15}\ YS^{1.66}$ but complex effects with GBC (+ intra)?**

Laboratory results (effect of the material)



MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : Maintenance strategy

EDF Electricité de France

Maintenance strategy is based upon safety criteria and a large anticipation.

After new probe developments, NDE inspection procedures were stabilized on the basis of fitness for service criteria discussed and approved by French regulators.

Safety criteria for 900 MWe
- Envelop kinetics : 3mm/year
- Minimum residual ligament : 4 mm

If safety criteria not met, a VH replacement can be decided by anticipation

Examination frequency (ET and UT) 900 MWe
- 3 years if no crack detected or crack < 3 mm
- 2 years if 3 mm < crack < 5mm
- 1 year if crack > 5 mm

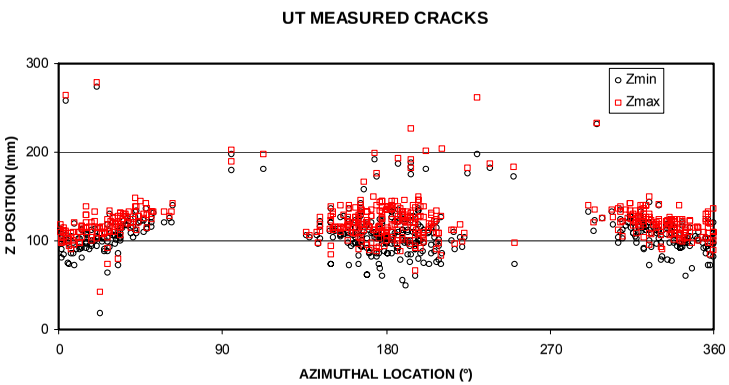
Vessel head replacement

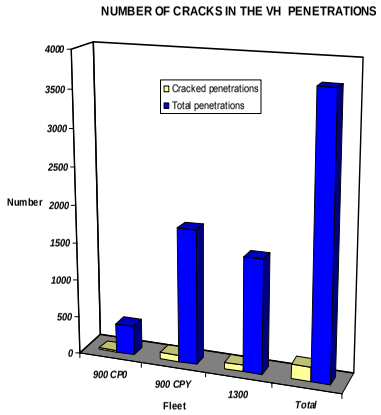
MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : NDE results

Results for VH penetrations NDE:

- Only longitudinal cracks from inside the penetrations and located at 0° (± 60°) or 180° (± 40°),
- Number of cracked penetrations versus total number of penetrations is less than 5%.
- Updated results on French fleet (mid 2003)
  - 1 VH without indications,
  - 6 VH with indications,
  - 3 VH with SCC defects (depth < 3 mm)
  - 2 VH with 3 mm < SCC defects < 5 mm
- Situation is considered under control.

Results





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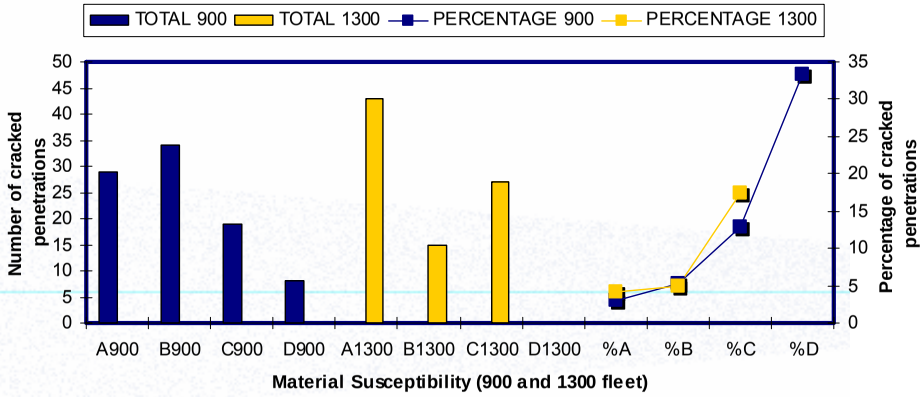
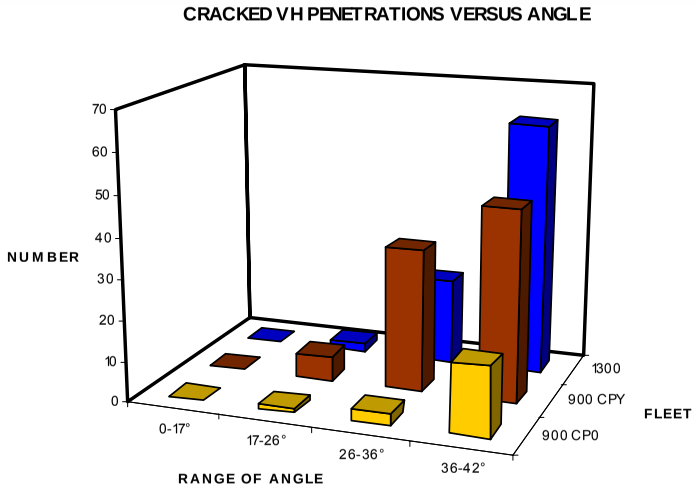
MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : Overall results

- Importance of the set up angle of the penetration,
- High angle = high stress level

- Importance of the susceptibility of materials to PWSCC

- Ranking in 4 classes show a clear effect of the material susceptibility





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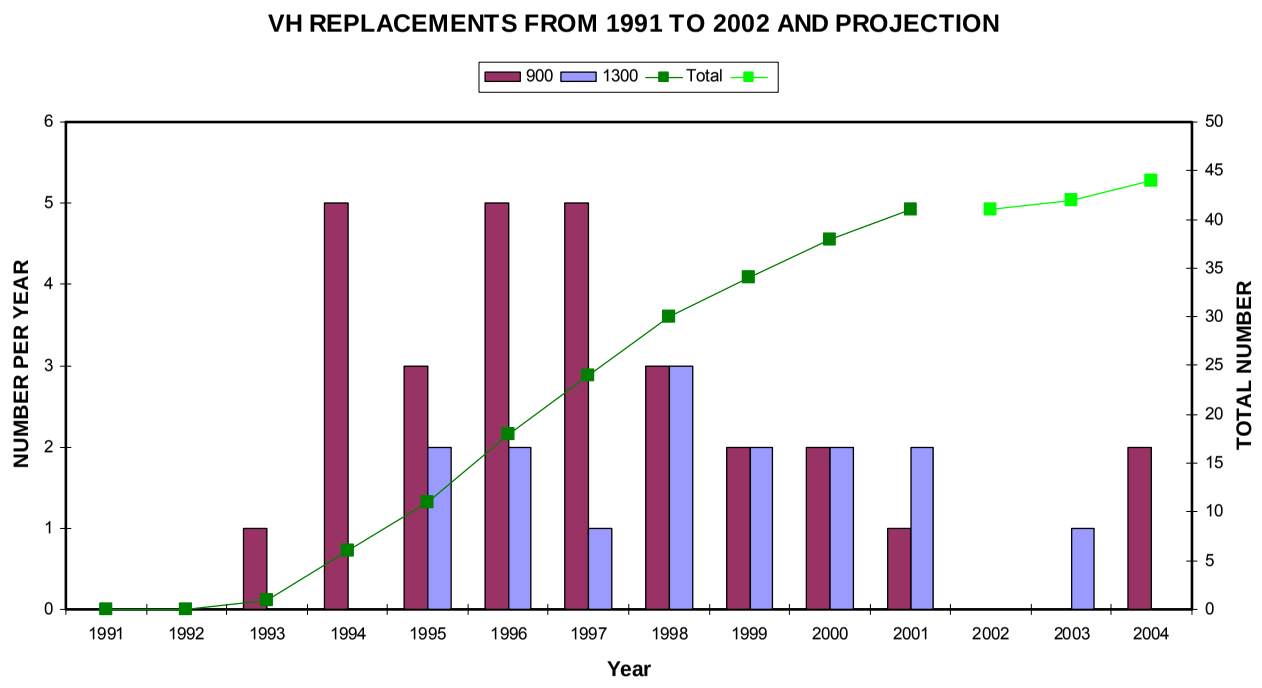
MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : Feedback experience

- **Complementary examinations of J groove welds**
  - Dye penetrant testing performed on 754 welds from 11 replaced VH
  - Results : no defect detected

- **Other examinations**
  - In order to prevent any leak with boric acid corrosion on top of vessel head, a video examination of Canopy welds is performed every 10 years.

- **VHP with alloy 690**
  - 3 VHP examined by ET technique with same kind of procedure than alloy 600 VHP;
  - Results : no SCC defects detected and characterized as expected from alloy 690 SG tubes follow up (performed since 1990).

MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : Overall results



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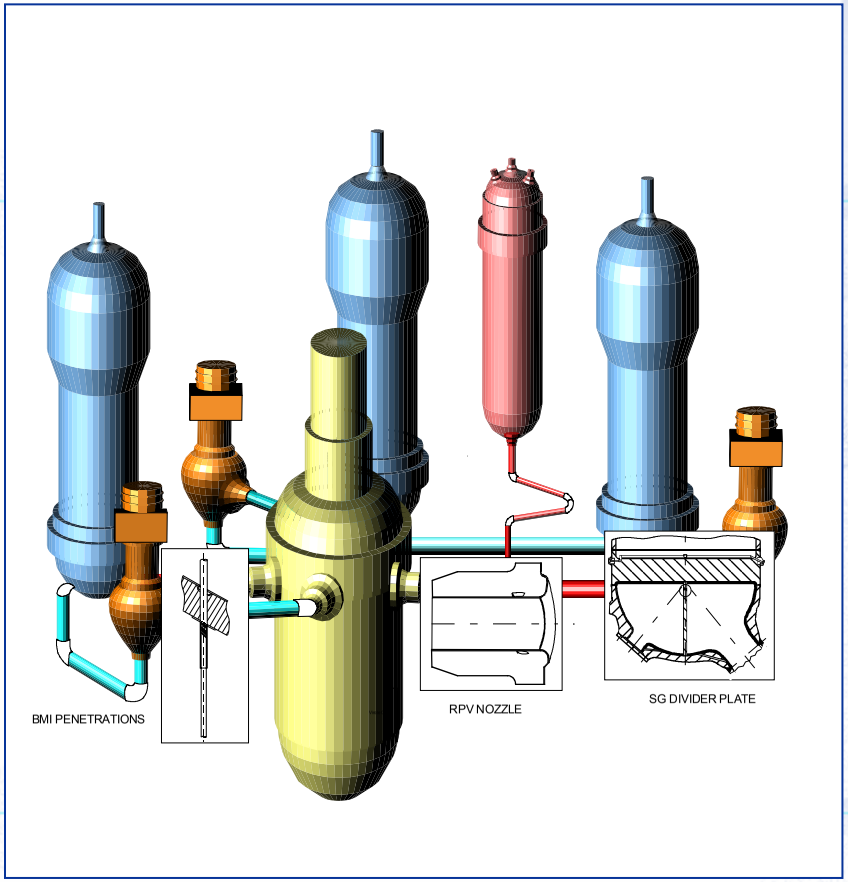
MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : Other components

IN PRIMARY SYSTEM

- **Following zones have to be inspected by sampling according to Regulators requirements**
  - Bottom head penetrations,
  - Steam generator partition plate (stub weld),
  - Repaired zones of RPV hot branch nozzles.



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MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : Overall results

EDF Electricité de France

- **NDE results at mid-2003:**
  - **From 1992 to mid 2003 : 48 NDE examinations of divider plates (hot branch or cold branch) by dye penetrant method,**
  - **From 1992 to mid-2003 : RPV bottom head penetrations of 15 plants by eddy current and ultrasonic methods,**
  - **From 1994 to 1996 : 17 reactor vessel nozzles, in hot branch, that contain repairs with alloy 182 (eddy current method),**
  - **From 1994 to 1999 : 754 welds of vessel head penetrations from 11 removed vessel heads (dye penetrant method).**

have been inspected

No crack indication has been found in these components.

- **Flaws have been found:**
  - **In steam generator tubes,**
  - **Pressurizer instrumentation nozzles in 1989 but were replaced within 2 years,**
  - **Vessel head penetrations,**
  - **Impacted area of the divider plate of a steam generator.**

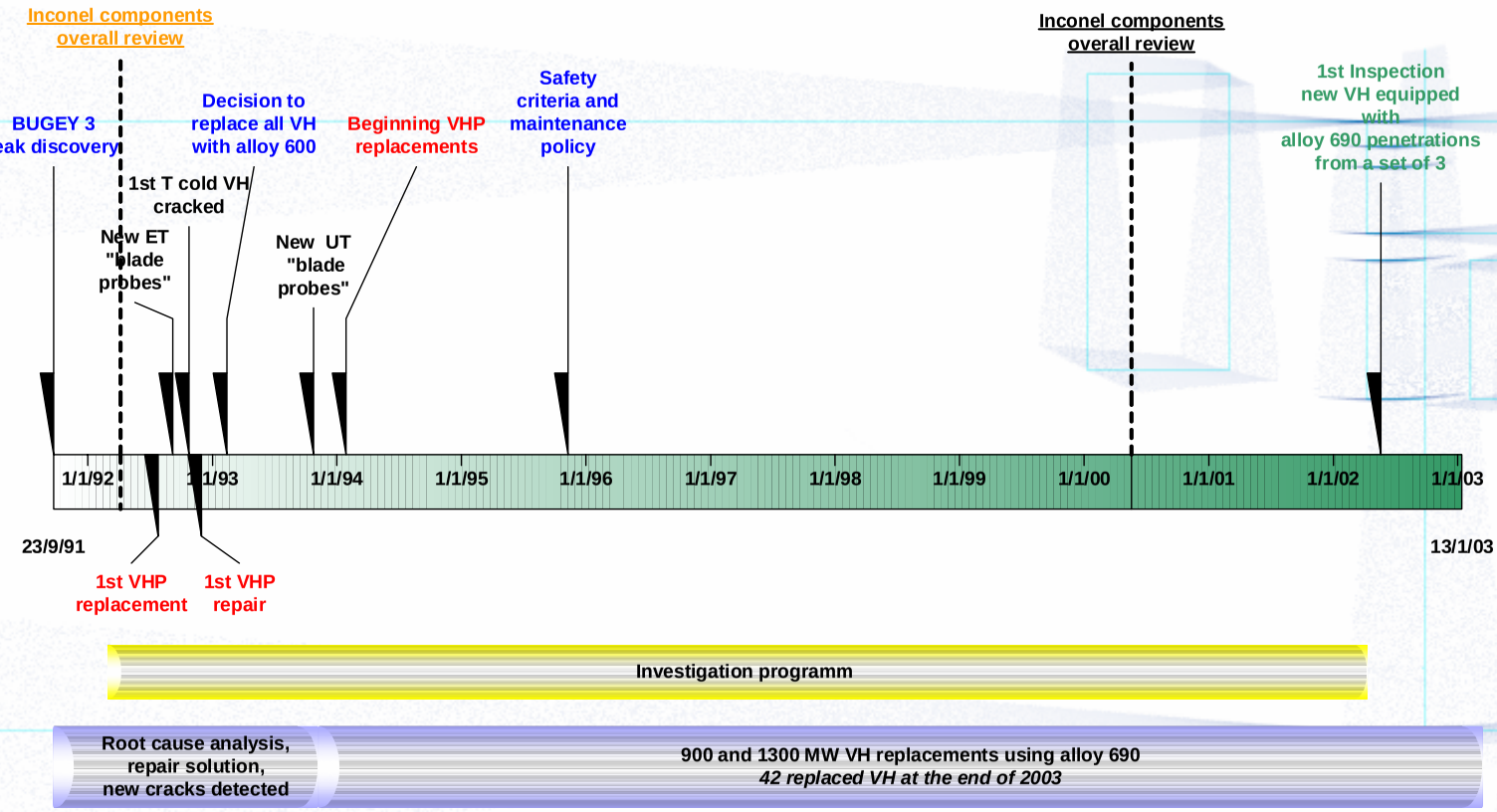
MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : Other components

- **Since 2001, a new program has been established following French regulator's decision :**
  - 26 SG partition plates (precursors) + 9 random to be inspected up to 2008,
  - 12 RPV bottom head penetrations to be inspected up to 2008,
  - RPV hot branch nozzles repaired zones (stress relieved during manufacturing) to be inspected with a qualified procedure at the third ten years visit (beginning 2009).

- **Examination results :**
  - 2 random SG and 1 precursor without SCC defects,
  - 2 new inspections of RPV BMI's but no SCC defects,
  - 4 Inconel repaired zones in RPV nozzles but no defects declared.

MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : Back to history

❑ Key milestones



MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : Summary and conclusions

- **In France, alloy 600 VH penetrations PWSCC is better known, since 1991.**
  - International cooperative laboratory studies benefit for a better control of the phenomenon, (lots of parameters studied),
  - EDF has anticipated potential degradations by a large NDE program.
- **In practice :**
  - Importance given to stress level and susceptibility of materials to PWSCC,
  - For VHP, inspection criteria based upon safety considerations,
  - Vessel head replacement policy since 1995 is fruitful :

    no new leak, no circumferential cracks detected, no surface breaking defects from J weld.
  - Before 2001 and from 1992, a NDE program had been established in order to inspect BMIs, SG partition plates, repaired zones in RPV nozzles. No SCC defects have been discovered.

MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : Summary and conclusions (contd)

- Since 2001, a new NDE program : NDE performed on SG partition plates, bottom head penetrations, repaired zones in RPV nozzles in accordance to French regulator's decision. Up to now, NDE results are blank (no SCC defects).
- 1st inspections on alloy 690 VHP's are blank (no SCC defects).

In conclusion, EDF has been proactive and has anticipated lots of studies.

but

EDF remains very careful to any new event on such material as it was shown in a recent past (dissimilar welds at VC Summer and Ringhals, VHPs cracking at Oconee, Davis-Besse, North Anna, and also BMIs at South Texas Project 1 and at Tsuruga on pressurizer…).

Strategic Planning for RPV Head Operation

Vessel Head Penetration Inspection,
Cracking and Repair Conference

September 29 – October 2, 2003
Gaithersburg, MD

By:
Steve Hunt, Dominion Engineering, Inc.
Glenn White, Dominion Engineering, Inc.

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11730 Plaza America Dr.
Reston, VA 20190

Contents

- Objective
- Background
- Inputs/Constraints
- Alternative Management Approaches
- Economic Evaluations
- Conclusions

Objective

- To review strategic planning alternatives for an example moderate susceptibility plant (8-12 EDY) which will
  - Ensure a low risk of leakage
  - Ensure an extremely low risk of core damage
  - Result in lowest net present value life cycle cost

Background
Potential Economic Consequences

- The economic consequences of managing RPV head PWSCC can be significant
  - EdF is replacing all vessel heads
  - Cracks and leaks in nozzles in several domestic plants have resulted in significant outage delays and costs
  - Boric acid wastage resulting from a PWSCC leak at Davis-Besse has led to over a 19 month outage
  - Cracks in large numbers of welds at North Anna 2 led to about a four month outage while the head was replaced
  - Industry findings and NRC guidelines/requirements have led to many expensive inspections
  - 29 plants in the US have announced plans to replace heads as of September 2003

Inputs/Constraints
Overview

- The optimum strategic plan should be established considering several constraints
  - Current condition of head as established by non-destructive examination of all nozzles (must be free of cracking to remain in moderate category)
  - Predicted future PWSCC based on industry experience
  - Inspection intervals to ensure low risk of leakage and very low risk of core damage
  - Planned outage durations including provisions for longer outages for SG replacement, 10 year ISI, etc.
  - Time and cost required for nozzle inspections and repairs
  - Time and cost required for replacement head procurement and installation
  - Potential remedial measures, including an assessment of their cost and effectiveness

Inputs/Constraints
Inspection Interval Requirements

- For plants in the Moderate category (greater than 8 EDY and less than 12 EDY) the NRC interim order requires that
  - Nondestructive examinations shall be performed at least every other refueling outage, and
  - Either a bare metal visual inspection or nondestructive examination shall be performed every refueling outage
- Risk-informed modeling work described in previous paper by White (DEI) has demonstrated that these requirements result in
  - A low risk of leakage
  - A very low risk of core damage as measured by Regulatory Guide 1.174 requirements

Inputs/Constraints
Outage Duration and Inspection/Repair Window

- A realistic assessment must be made of time available during outages for inspections, repairs, remedial measures and head replacement
  - Plants with short refueling outages will have less time available for inspections and repairs than plants with longer refueling outages
  - Long scheduled outages such as for steam generator replacement or 10 year ISI may provide an ideal opportunity for remedial measures or head replacement

Alternative Management Approaches
Overview

- Continue to inspect and repair as necessary at intervals necessary to ensure low risk of leakage and very low risk of core damage
- Perform remedial measures to reduce risk or possibly increase inspection intervals
- Replace head at the second outage after discovery of first PWSCC
- Replace the vessel head as quickly as possible and perform NDE every 4th outage

Alternative Management Approaches
Inspection and Repair Options

- Inspection options are currently available
  - Volumetric NDE of nozzle plus evaluation for leakage through annulus
  - Wetted surface examination of nozzle and welds
- Repair options are currently available
  - Embedded flaw repair
  - New nozzle structural weld

Alternative Management Approaches
Remedial Measures Options

- Several remedial measures have been proposed including
  - Modification of internals flange to increase bypass flow and thereby reduce the head temperature
  - Surface treatment of nozzle and weld surfaces (shot peening or water jet conditioning)
  - Nickel plating
  - Alloy 152 weld overlays
  - Roll expansion plus surface conditioning
  - Application of new structural weld
  - Mechanical stress improvement
  - Zinc injection

Alternative Management Approaches
Remedial Measures Effectiveness

- EPRI sponsored tests of several remedial measures
  - Results presented at 2002 Fontevraud conference
- Most Effective
  - Water jet conditioning
  - Electro mechanical nickel brush plating
  - Shot peening
- Intermediate Effectiveness
  - Electroless nickel plating
  - GTAW weld repair
  - Laser weld repair
- Least Effective
  - EDM skim cutting
  - Laser cladding
  - Flapper wheel surface polishing

Alternative Management Approaches
Remedial Measures Conclusions

- Modification of the internals to reduce temperature is the main remedial measure applied domestically
  - Lower head temperature should reduce the rates of crack initiation and growth
  - Experience in France suggests that the full predicted benefit of lower head temperature may not be achieved
- While remedial measures may reduce the rate of PWSCC initiation and growth, and thereby reduce the cost of future repairs, it may be difficult to take credit for the improvement in increased inspection intervals

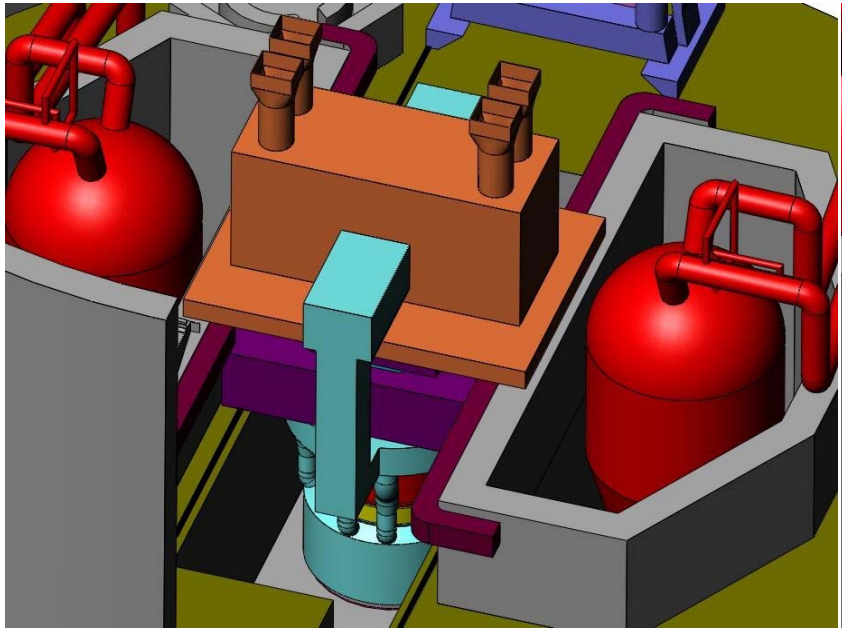
Alternative Management Approaches
Head Replacement

- Installation of a new head is a clear success path
- New heads will be more resistant to PWSCC
  - Alloy 690 nozzles
  - Alloy 52 J-welds
- Cost and replacement time is a function of containment building access
  - Will head fit through the equipment hatch
  - Will head fit through equipment hatch with CRDM drives preinstalled

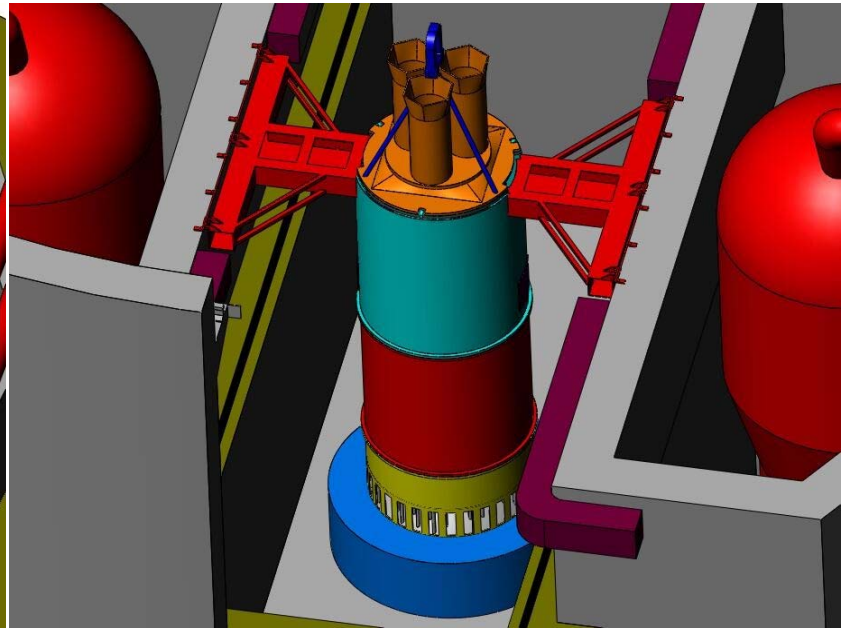
Alternative Management Approaches
Head Replacement - Service Structure Option

- Many domestic PWR plants have original-design head service structures that require significant time for disassembly and reassembly
  - Head insulation
  - Head cooling ducts
  - CRDM cables
  - Head cooling fans
  - Missile shields
- Head disassembly and reassembly time can impact critical path
- Head replacement provides an opportunity to incorporate an integrated head service structure

Alternative Management Approaches
Head Replacement - Service Structure Option



Typical Original Structure



Conceptual Integrated Structure

Alternative Management Approaches
Head Replacement - Service Structure Option

- An integrated head service structure can be developed for most plants
- Due to other constraints it may not be possible to demonstrate critical path savings for a normal outage
- Secondary benefits of an integrated head service structure may include:
  - Free up labor and crane time inside containment during normal outages
  - Cut several days off of the time to perform a rapid head disassembly/reassembly for leaking o-ring seal, slow rod drop, etc.
  - Reduce risk of personnel injury

Economic Evaluations
NPV Analysis Approach

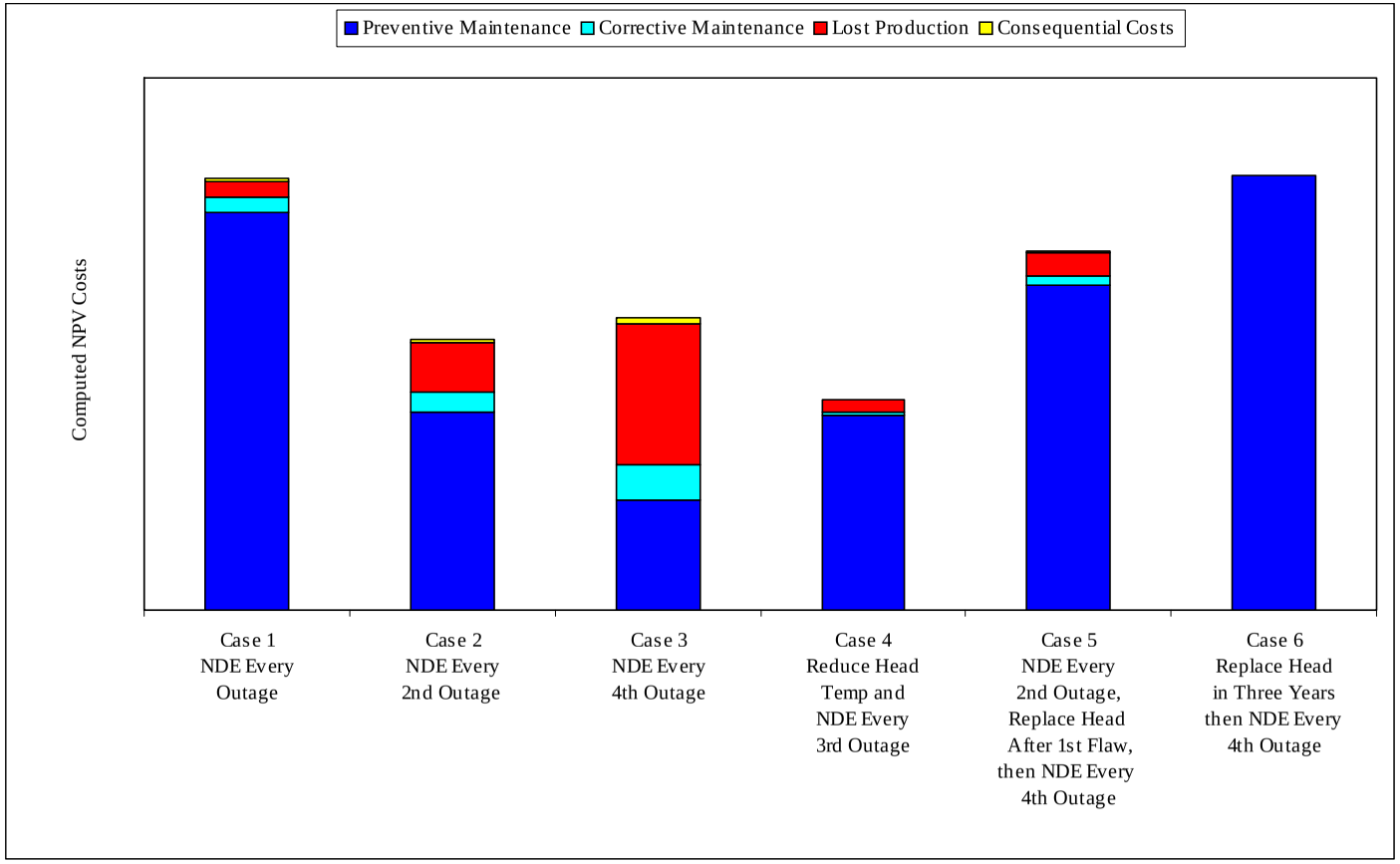
- Establish risk of future cracks/leaks for each alternative considered
- Establish consequences of leakage
- Estimate costs for each alternative
- Calculate Net Present Value (NPV) cost for each alternative assuming
  - Planned operating life, including life extension
  - Discount rate
  - Estimated value of lost production $/MWe

Economic Evaluations
NPV Analysis Software

- Probabilistic economic analyses can be performed using Monte Carlo methods
  - Results provide the range and probability of costs
- In most cases, decisions can be made using a simpler deterministic “best estimate” approach
  - One possibility is the LcmVALUE software prepared for EPRI Life Cycle Management Demonstration Project

Economic Evaluations

Typical Results for Moderate Susceptibility Plant



Conclusions

- For the case study presented, bare metal visual inspection every outage with volumetric examination every second refueling outage appears to be a reasonable approach
  - As future inspection data become available and predictive models are refined, there may be a technical basis for retaining inspections every second outage when the plant enters the high susceptibility category based on EDY's
  - Volumetric examination every outage and immediate head replacement appear significantly more expensive
  - Remedial measures such as reducing head temperature or waterjet conditioning may be attractive provided inspection intervals can be increased as a result of the effort
  - A reasonable longer term plan is to replace the vessel head the second outage after identifying PWSCC
- These results are plant specific and other plants may have different constraints that would affect the optimum solution

Reactor Vessel Bottom-Mounted Instrumentation (BMI) Nozzle Repair Development and Implementation at South Texas Project

D. Waskey

FRAMATOME ANP

RV Incore Nozzle FANP European History/ Experience/ Future

- **History**
  - *In 1991, EDF initiated a programmatic campaign to examine all I-600 sensitive areas including the in-core nozzles.*
- **Experience (to Date)**
  - *Surveillance of 18 EDF RPV (> 500 penetrations) since 1992, by Framatome.*
  - *To date, no indications of cracks have been found.*
  - *On-vessel time for complete inspection ~ one week*
  - *8 more EDF inspections planned through 2009*
  - *ECT and UT utilized*
  - *Circ and Axial probes being further developed (0°& 45° for characterization)*
  - *Nozzle Material and Weld fusion line inspected – not welds*
- **Future:**
  - *EDF plans to continue examinations of one or two plants per year through 2009.*

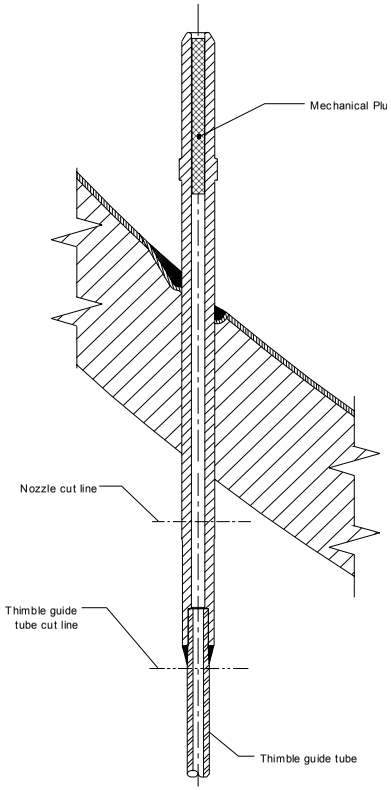
RV Incore Nozzle FANP Domestic History / Experience / Future

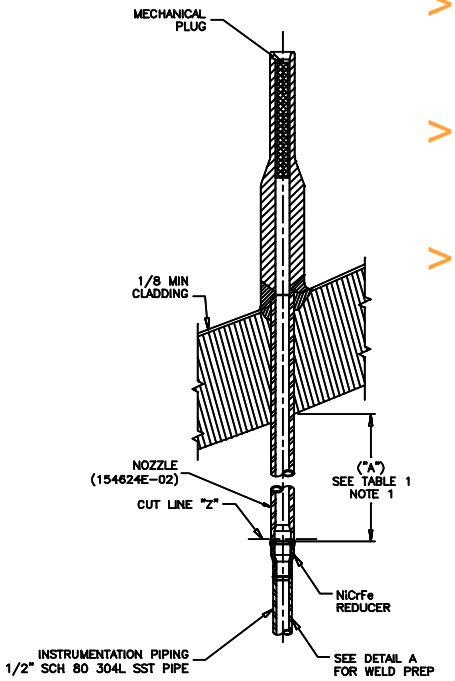
- History
  - During Hot Functional Testing of Oconee-1,iBMI nozzles broke.
  - Most B&W plants were field modified with thicker Alloy 600 nozzles and 182 filler material (Davis-Besse modified in shop).
- Experience (to Date)
  - Davis-Besse performed a bare head visual and found residue on lower RV Head.
  - PSC written by Framatome employee due to inconclusive evidence from Davis-Besse residue samples.
  - Oconee-2 & 3 performed visual inspection outside of insulation – no signs of boron.
  - ANO-1 performed visual inspection outside of insulation – dispositioned boron traces from other sources.
  - STP-1 performed bare head visual inspection and identified two leaking BMI nozzles.
    - FANP performed top down VT and UT on 100% of BMI nozzles. Eight BMI J-groove nozzles ET examined from top down.
  - FANP repaired two leaking BMI nozzles at STP-1 in June 2003.
  - Oconee-1 performed bare metal inspections in September 2003.
- Future
  - Davis-Besse will perform a bare metal after holding full temperature & pressure for one week.
  - CR-3 & TMI-1 will perform inspections outside insulation in 2003.
  - Many Inquiries from industry on inspection and repair services.
  - MRP recommended bare metal visual to Industry.
  - NRC Bulletin 2003-02 released August 21, 2003.
    - Perform Bare Metal Visual (BMV) on BMI/IMI nozzles at next refueling outage. If unable to perform BMV, describe actions planned to enable BMV during subsequent refueling outage.

Nozzle Repair Experience

- ***Over 500 small nozzle repairs performed since 1988 including repairs in last two years at the following units:***
  - ***St. Lucie 1 – Hot Leg Instrument Nozzles***
  - ***Oconee 2 – HPI Nozzle***
  - ***St. Lucie 2 – RCS RTD Nozzles***
  - ***Davis Besse – RCS RTD Nozzles and HPI Thermal Sleeve***
  - ***South Texas 1 – 2 BMI Nozzles***
  - ***Ringhals 4 – PZR Instrument Nozzle***

BMI Nozzle Repair – Step 1

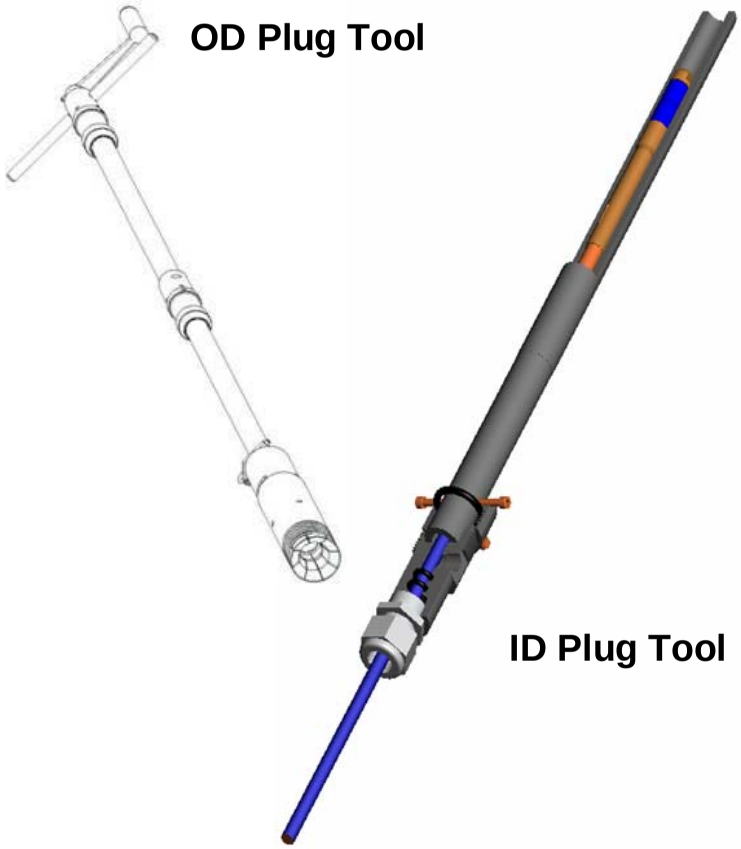




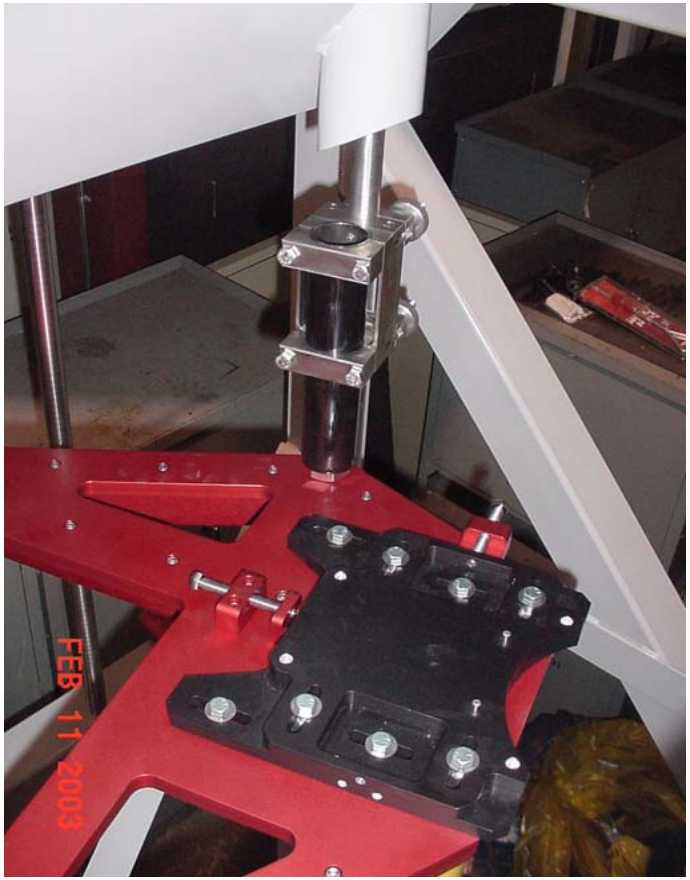
- > *Vessel Preparation*
  - *Remove fuel and internals*
  - *Retract/remove thimble*
- > *Install mechanical plug from top down*
- > *Make initial lower cut in thimble guide tube*
- > *Make second cut flush to RV Head*

Mechanical Plug

- ***Common Features***
  - ***Redundant seals constructed from rad-tolerant material***
  - ***Mechanically actuated to seal on nozzle surface (I.D. or O.D.)***
  - ***Provides shielding (external or internal)***
    - ***Rad-streaming concern after nozzle contents have been drained for below-vessel repair work***
- ***Option to remove I.D. Nozzle Plug from below vessel using freeze seals***

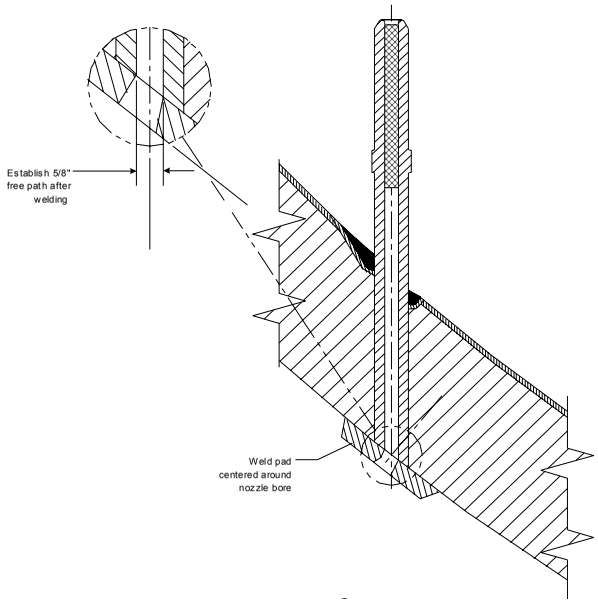


Tool Support Plate

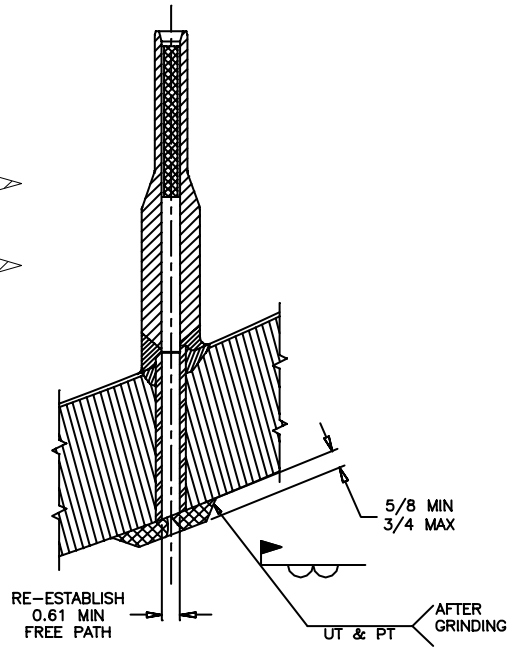


- *Lightweight components for rapid, one-man, assembly under the RV head*
- *Centering Plate with an alignment fixture allows for accurate alignment to nozzle bore*
- *Common interface for weld head, machine tool, and grinder*
- *Minimal tools required for installation and assembly*
- *Mounts from adjacent BMI nozzles. Custom Tool Support Plate required for each nozzle location*
- *Kicker Post reacts to floor below RV head to provide additional support where necessary*
- *New tooling platform designs shall be required for each repair location of the BMI nozzle configuration*

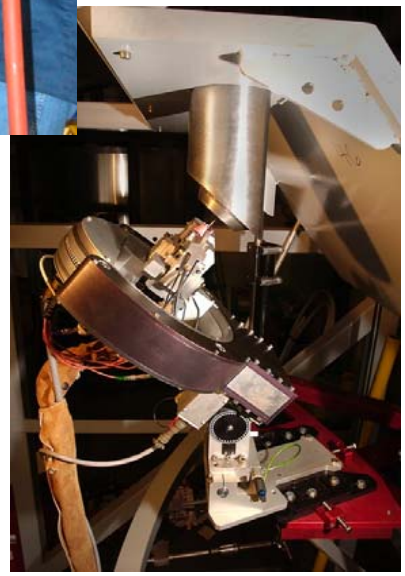
BMI Nozzle Repair – Step 2



- Deposit Alloy 52 weld pad
- Grind suitable for NDE
- Dimensionally inspect

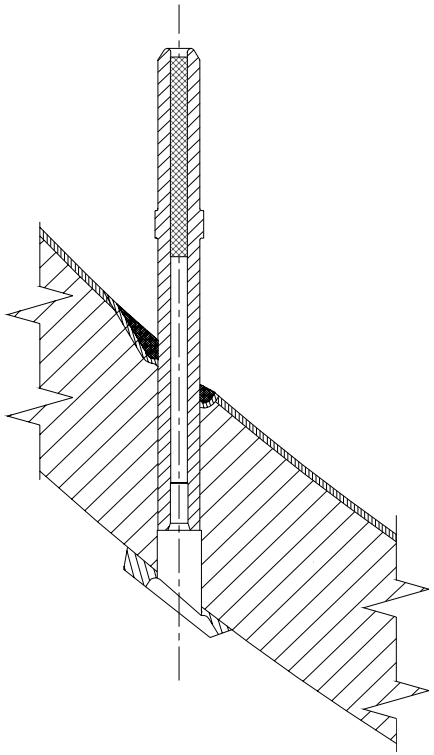


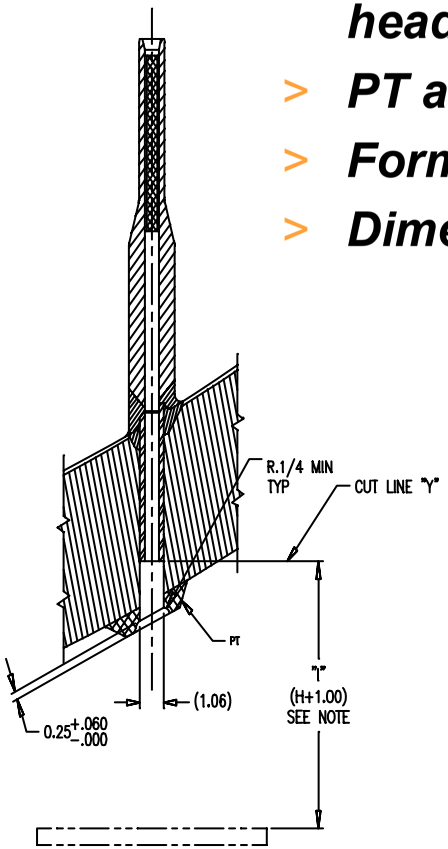
Weld Heads



- Field-hardened, proven design
- R-Θ motion control with AVC
- Machine vision of work point from remote operator's console
- Two-axis wire steer
- Water-cooled torch
- Scaled, digital read-out (DRO) of both R (inches) and Θ (degrees) axes
- Pivot mount for adjustment to RV head tangent angle

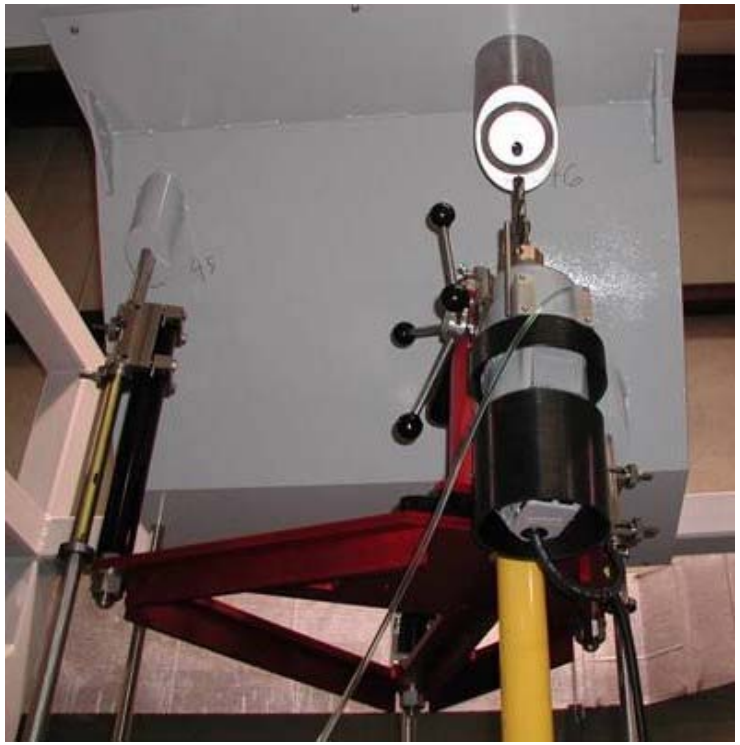
BMI Nozzle Repair – Step 3





- Bore nozzle into lower head
- PT and UT
- Form J Groove
- Dimensionally inspect

Drill Tool

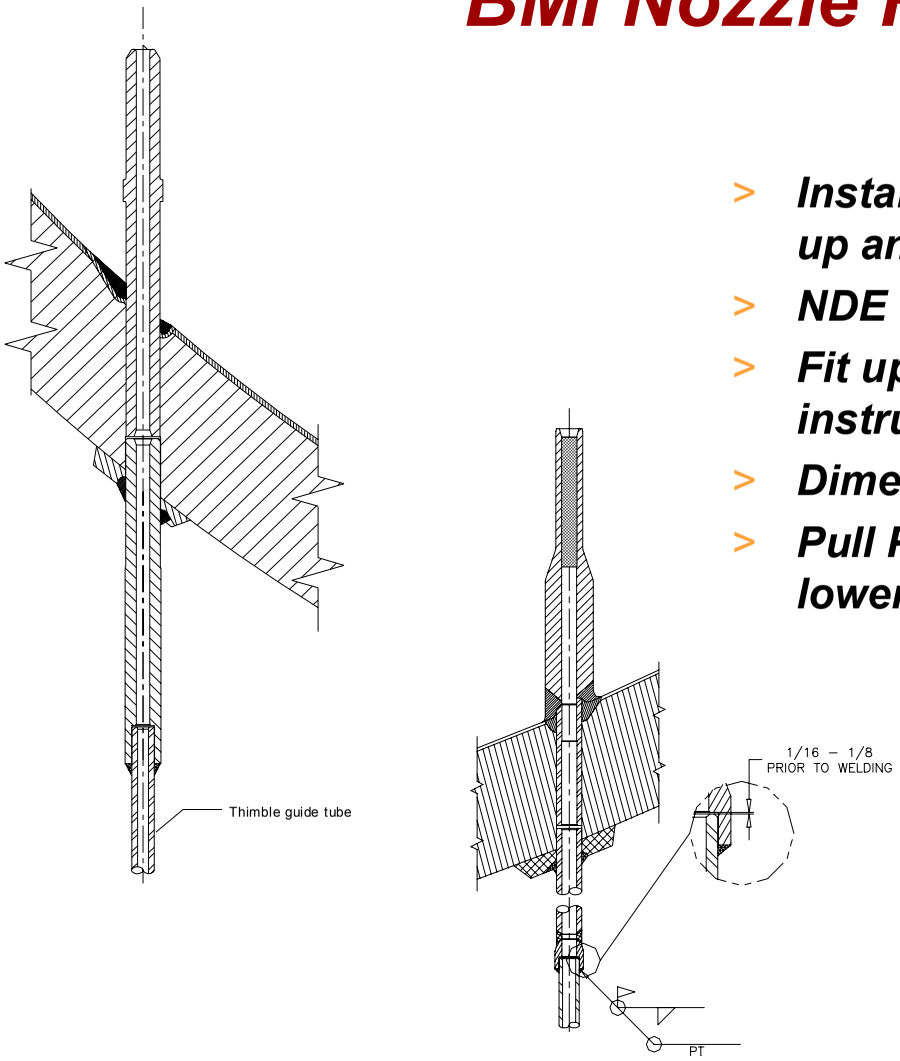


- Use of proven reliable Milwaukee electric drill
- Lightweight, one-man installation
- Integral cutting fluid injection operated remotely.
- Drill housing is "splash-resistant" to minimize the possibility of cutting fluid leakage into electrical components
- Cutters are 4 flute piloted core drills
- Drill can be used as-is for using an specific set of cutters

J-Prep Tool

- Proven reliable design used previously on pressurizer nozzles
- Lightweight, one-man installation
- Custom cam for each nozzle location to grind appropriate angle of J-prep
- Features a debris collection device with vacuum attachment to collect grinding flakes
- J-Prep tool can be used as-is for using an specific set of burrs and cams

BMI Nozzle Repair – Step 4



- Install replacement nozzle, fit-up and weld
- NDE weld with progressive PT
- Fit up and weld existing instrument guide tube
- Dimensionally inspect & PT
- Pull Plug (Can be pulled with lower intervals installed)

RV Lower Head Mockup

- *Originally designed for B&W Plant configuration, modified for Westinghouse design*
- *Includes features to hold removable coupons so that multiple repair trials can be performed at each location*
- *Used for machining and welding tool qualification and crew training*

BMI Repair at STP

Overall Schedule for Repair

Contract Award	05/02/03
Repair Crew Training	05/19/03
Repair Crew Deployment	06/01/03
Repair Crew on Site	06/02/03
On Site Mockup Demo	06/05/03 to 06/09/03

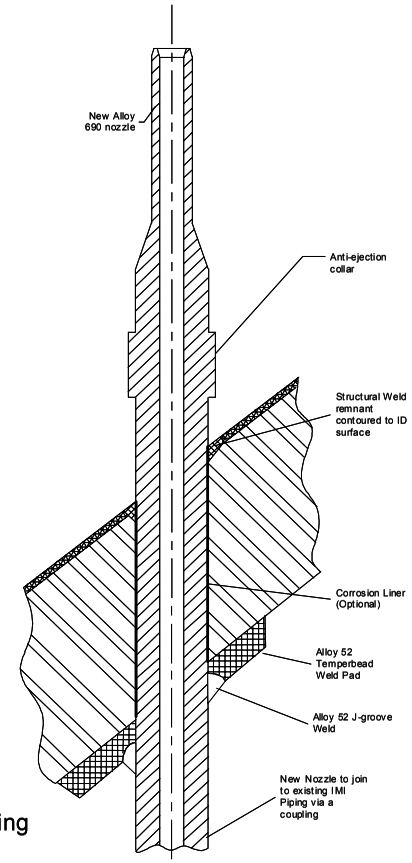
	Scheduled duration	**Actual duration**
Location 1	135 Hours	102 Hours
Location 46	135 Hours	104 Hours
Location 31	54 Hours	40.5 Hours

	Estimated Dose	**Actual Dose Received**
Nozzle 1 and 46 Repairs	19.000 R	11.709R
Location 31 Restoration	6.000R	5.025R

BMI Nozzle Repair Code Relief Requests

- *IWA-4610(a) – TCs & Recording Instruments for Preheat & Interpass Temperature Monitoring Not Used*
- *IWA-4611.1 – Original Weld/Nozzle Flaw NDE Characterization & Successive NDE Not Performed*
- *IWA-4633.2(c) - Code Case N-638 Temper Bead Welding Technique Used*
- *IWA-4610(a)/IWA-4633.2(d) – Elevated Preheat and Postweld Soak Not Used*
- *IWA-4610(b) – Section IX Max. IP PQ Temp. >100F Below 350 Max. IP Temp. During Welding.*

Full Nozzle Repair Concept

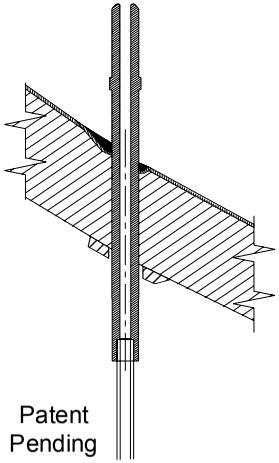


Patent Pending

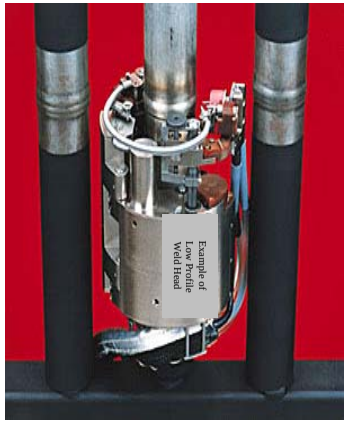
- ***Elimination of Alloy 600 Material***
  - ***Accomplished with RV in flooded condition by use of a double wall cofferdam deployed from above the RV.***
  - ***Completely eliminates all Alloy 600 from service.***
  - ***Optional corrosion liner to seal low alloy steel material***
  - ***Replaces existing BMI nozzle with new Alloy 690 nozzle***
  - ***Permanent repair solution***

BMI/IMI Nozzle Restoration Concept

- **Restore a full nozzle replacement nozzles using proven half-nozzle repair in a planned 1 or 2 outage campaign**
  - **Deposit weld pads with RV flooded**
    - **Parallel operation of four compact weld heads (opposite quadrants) - schedule efficiency**
    - **Significant reduction in weld volume (radial and thickness) - increases production rate**
    - **Air gap between pad and existing heater nozzle OD -ensures heaters are protected**
  - **Perform half-nozzle repairs after drain down or full nozzle replacement with drain down**
    - **Fillet weld in lieu of partial penetration weld for half nozzles (requires relief request with NB3200 supporting analysis)**
    - **No weld prep machining – increases production rate**



Patent Pending



FRAMATOME ANP

Bottom Mounted Instrument Penetration Condition Resolution

Penetration #1

Penetration #46

Sample Analysis

Samples contained boron and elevated concentrations of lithium

Samples did not contain any iron

Co-58 not present; therefore > 1 year old

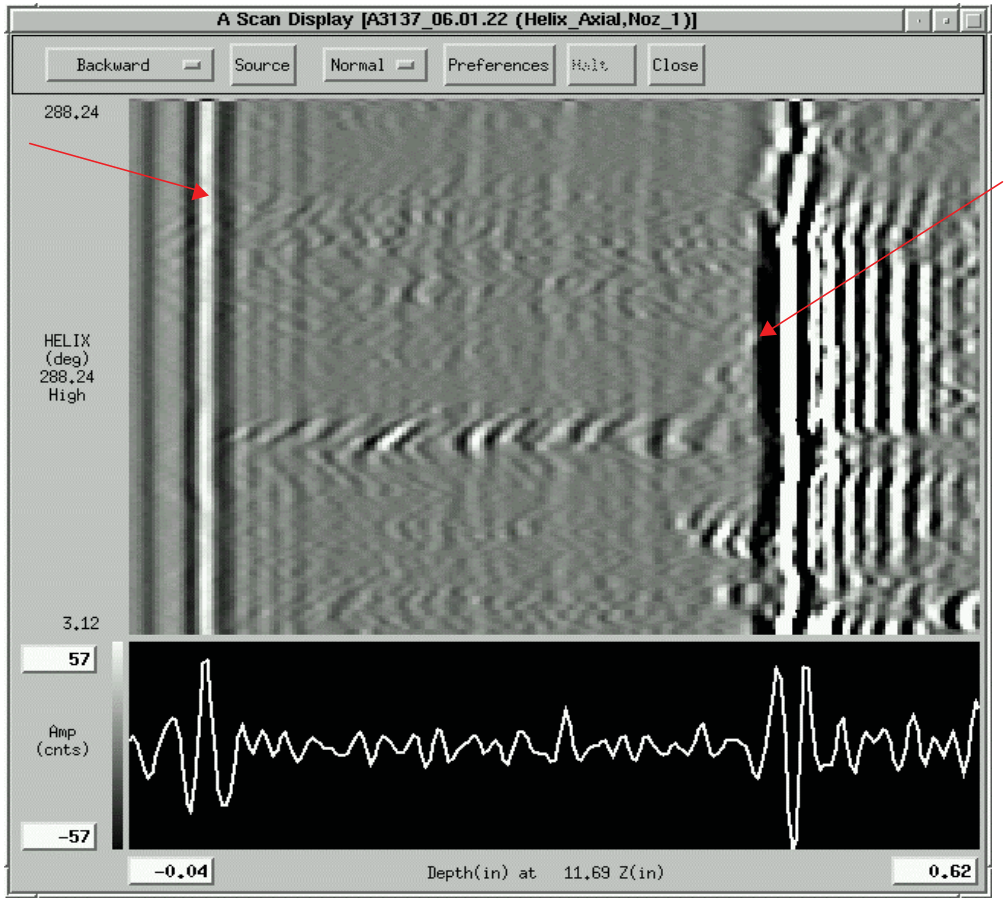
Ratio of Cs-134 to Cs-137 indicates 3 - 5 years

Comprehensive Examination

- UT from penetration tube ID
- Enhanced visual exam of J-groove weld surface
- Volumetrically interrogate vessel base metal for wastage
- ET from penetration tube ID
- ET of J-groove weld surface
- Profilometry
- Borescope examinations
- Helium tests
- Metallurgical analyses of removed nozzle remnants
- Boat sample analyses

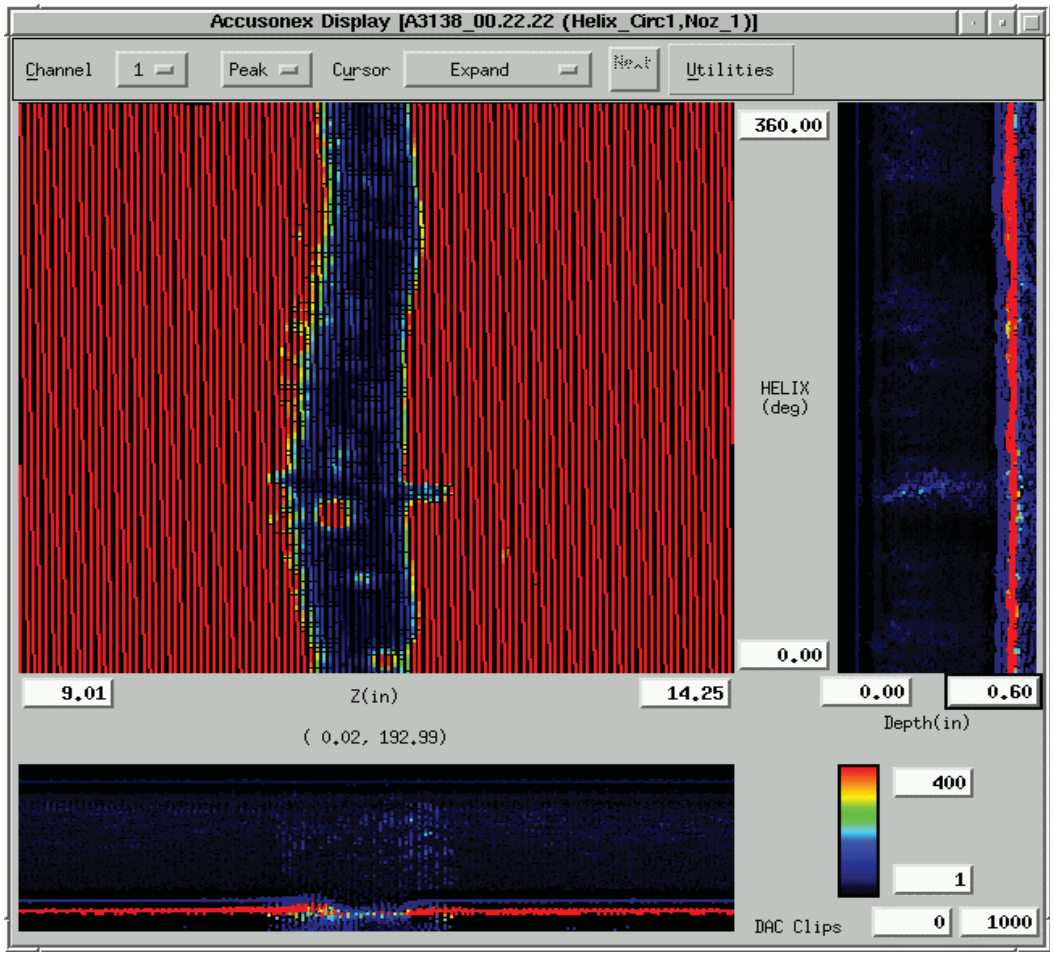
Penetration #1 Axial Probe

Tube ID

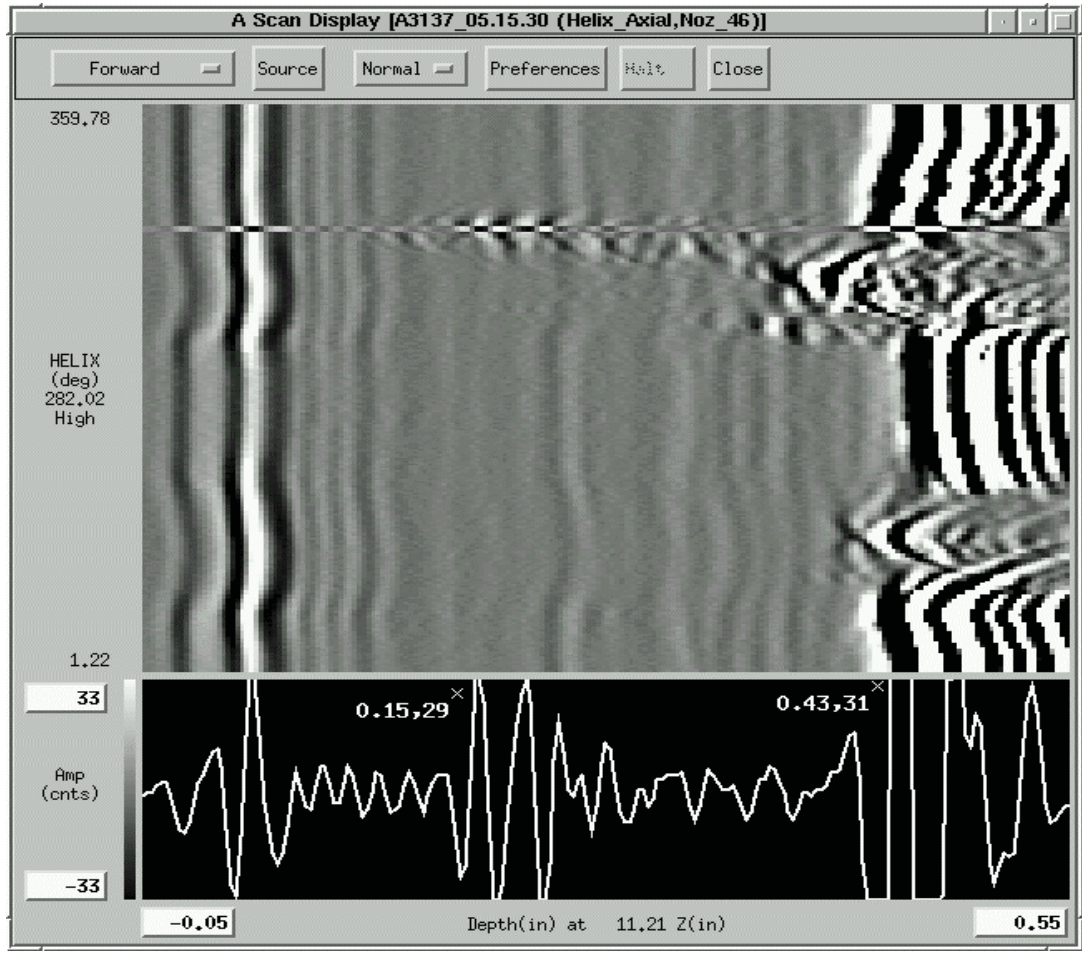


Tube OD

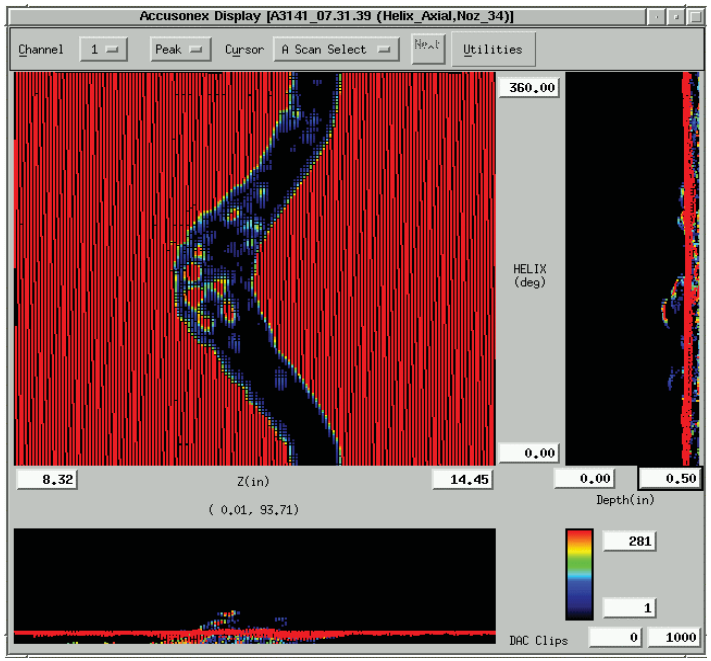
Penetration #1 Weld Profile

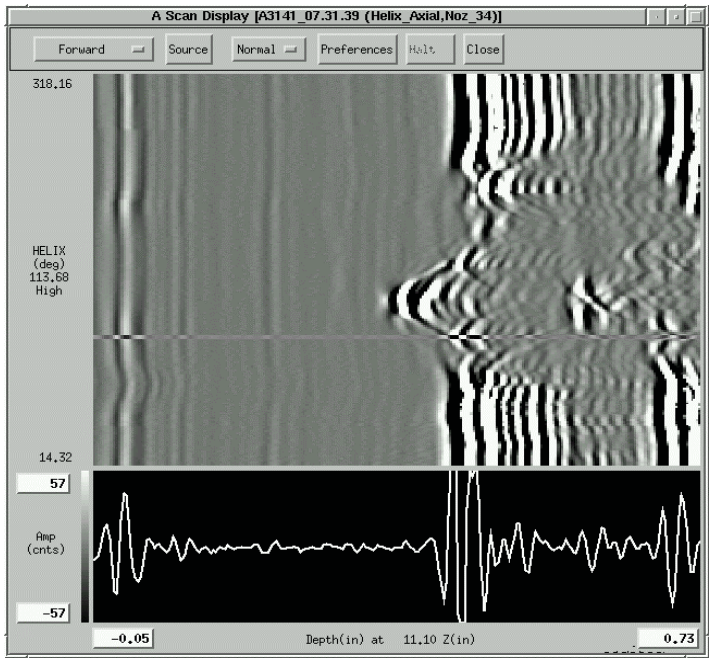


Penetration #46 Axial Scan

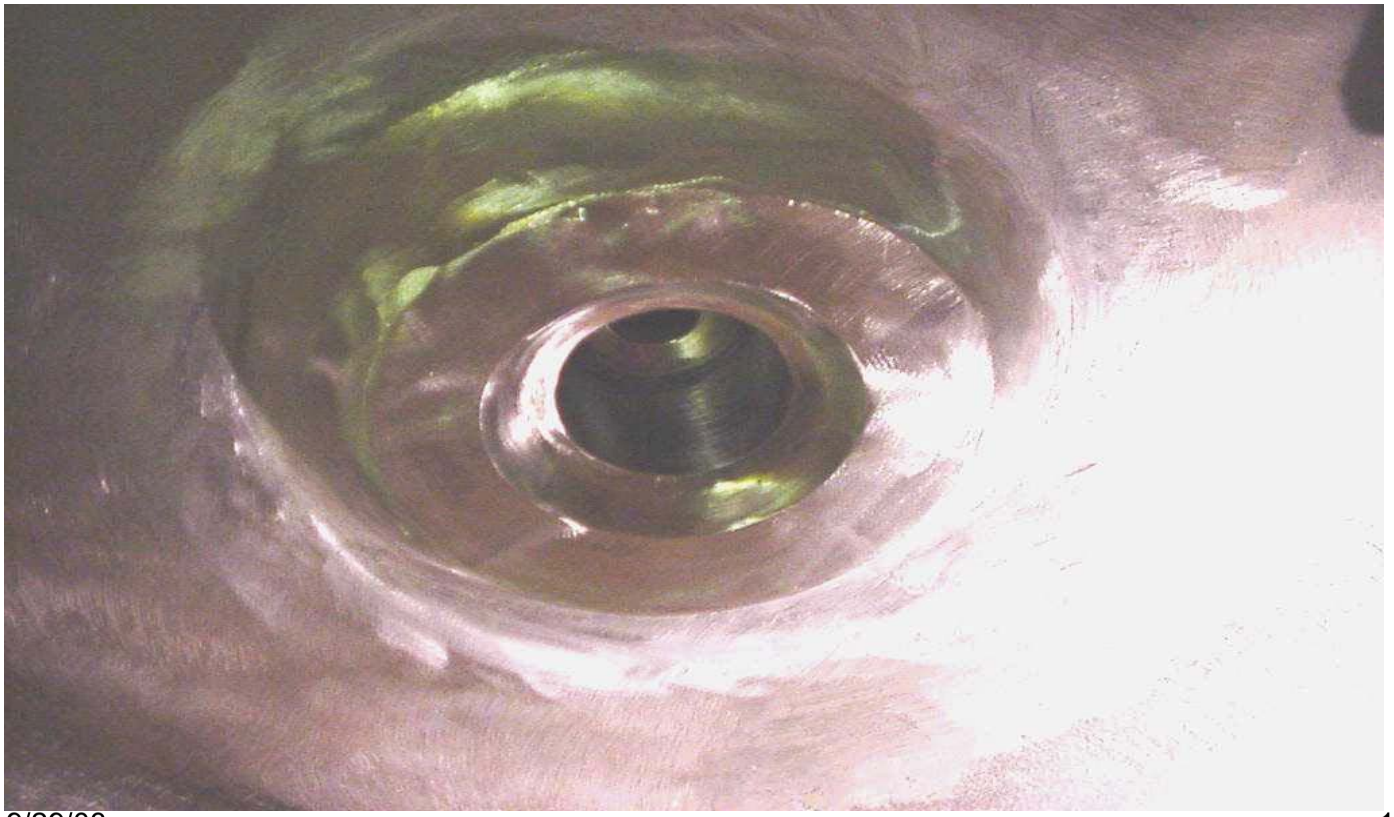


Penetration #34 Fabrication Discontinuity



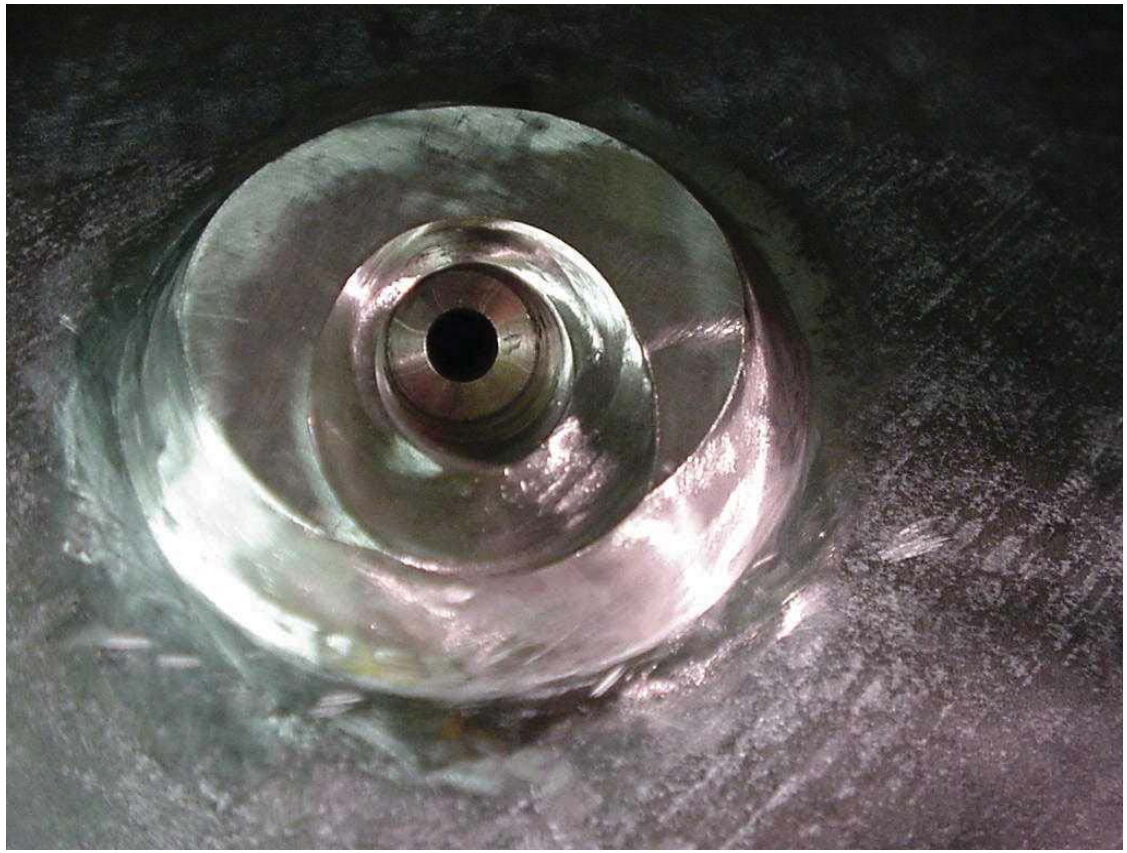


Penetration #1 Weld Pad



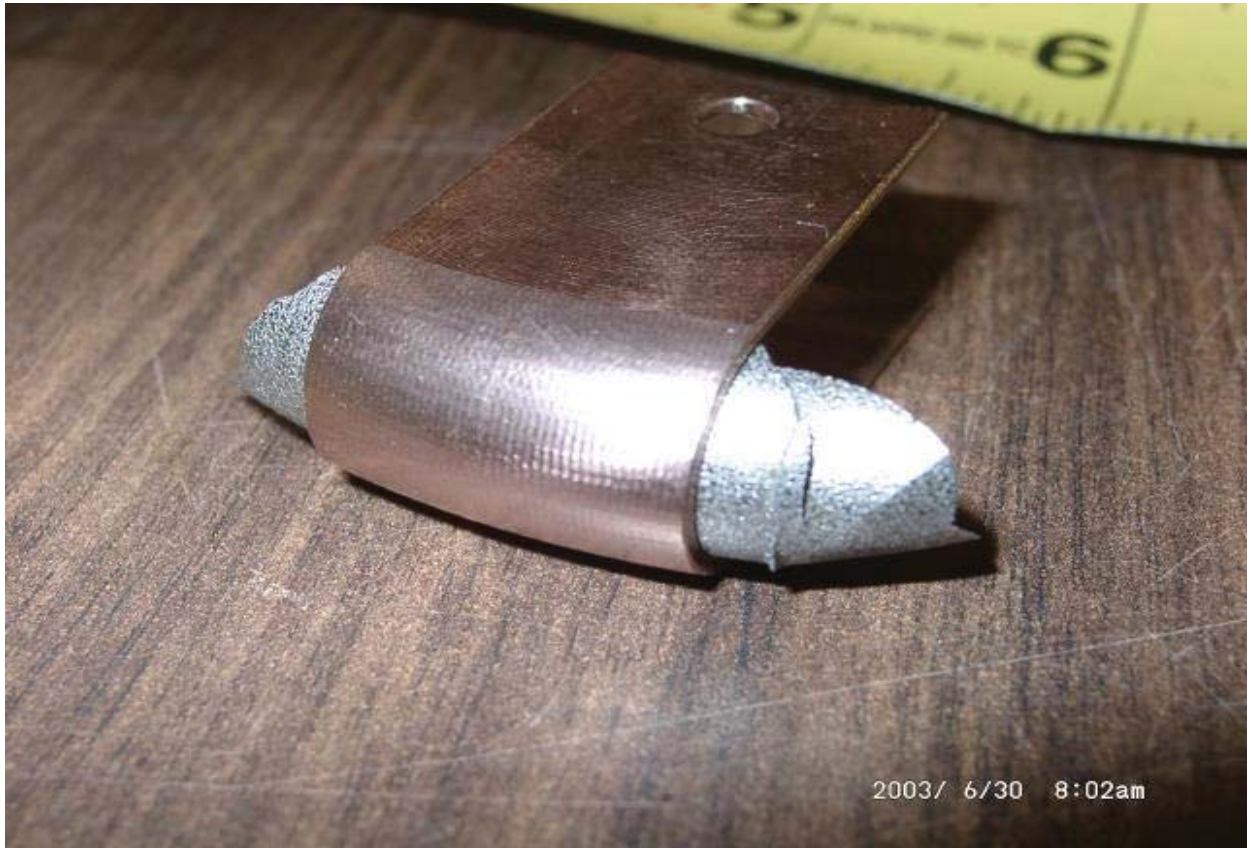
Penetration #1 Final Weld

Penetration #46 Weld Pad



Penetration #46 Final Weld

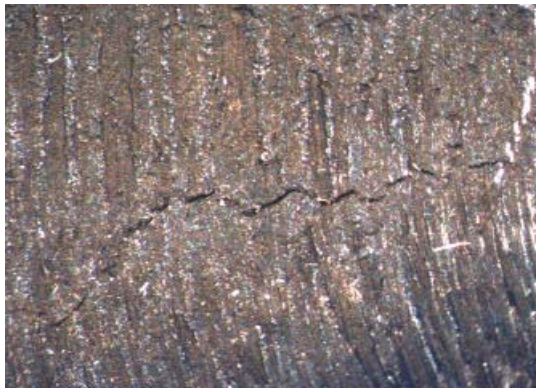
Boat Sample Electrode



Boat Sample Mockup

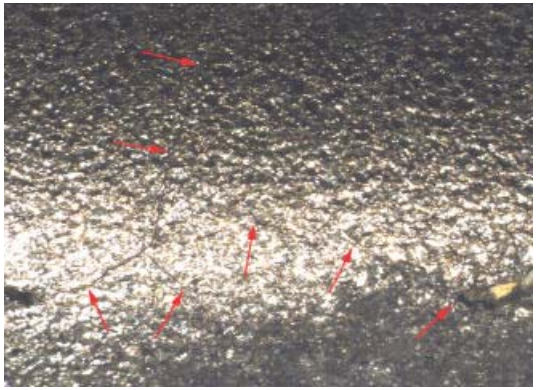
Penetration #1 Boat Sample

4X



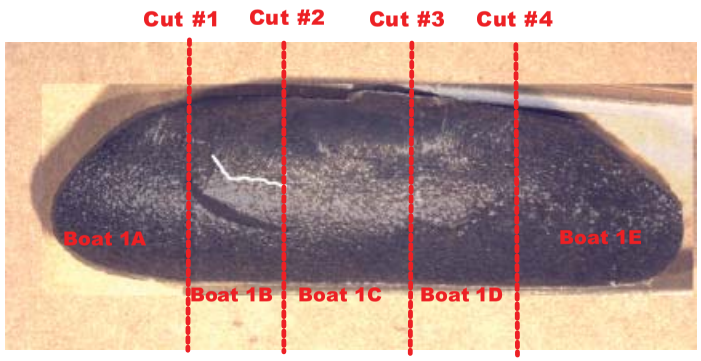
30X

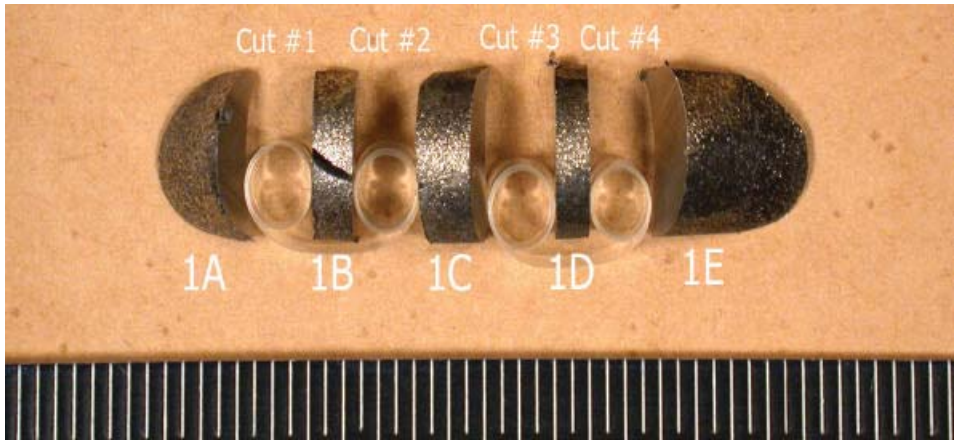
4X



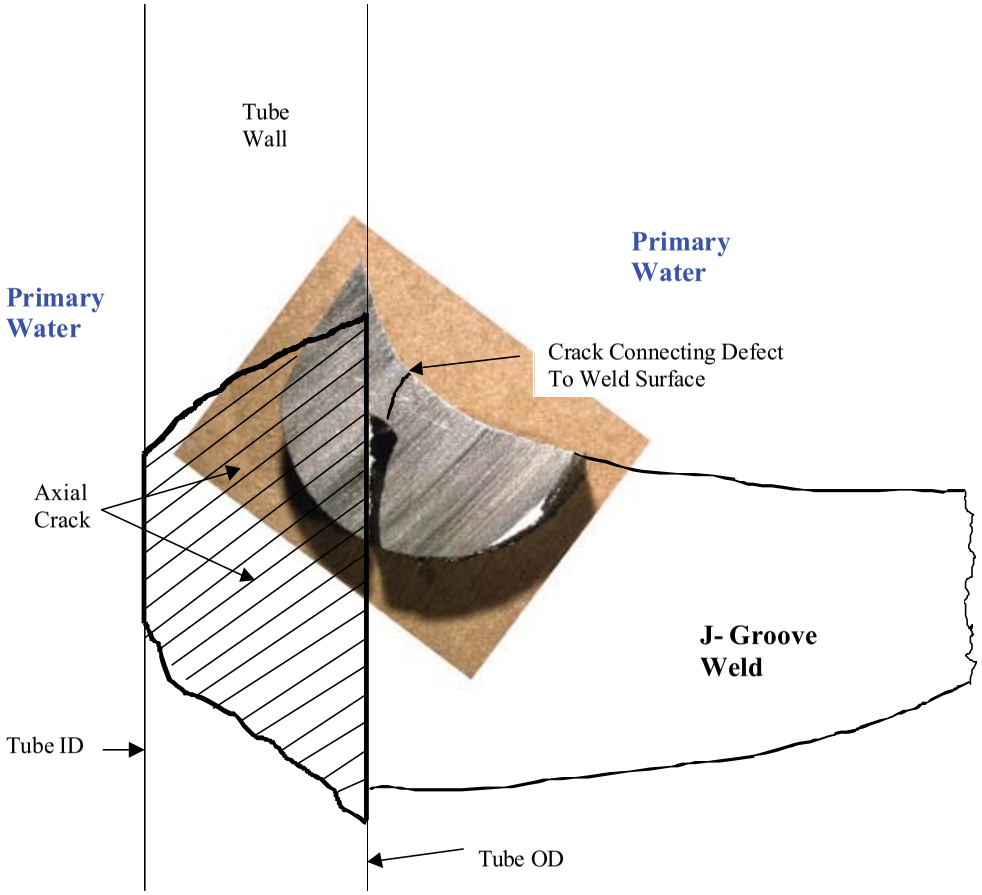
15X

Boat Sample Sectioning

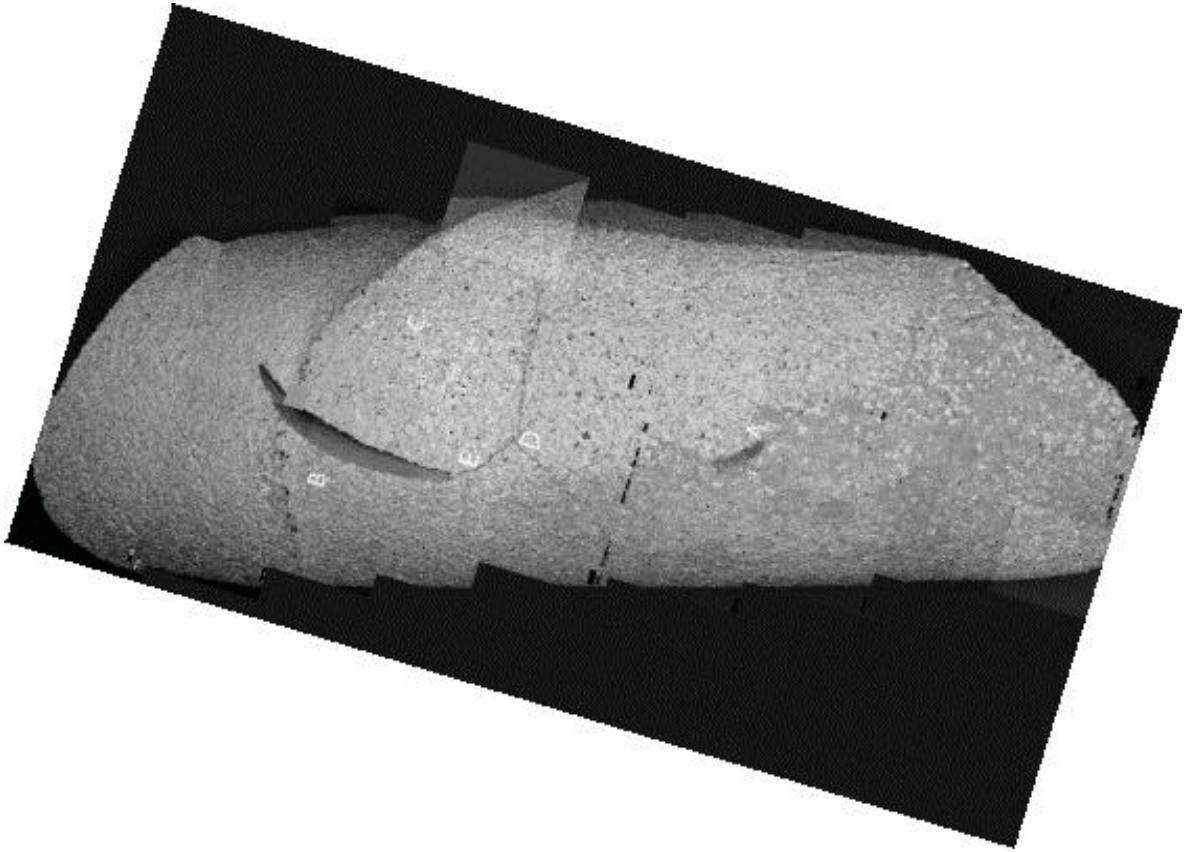




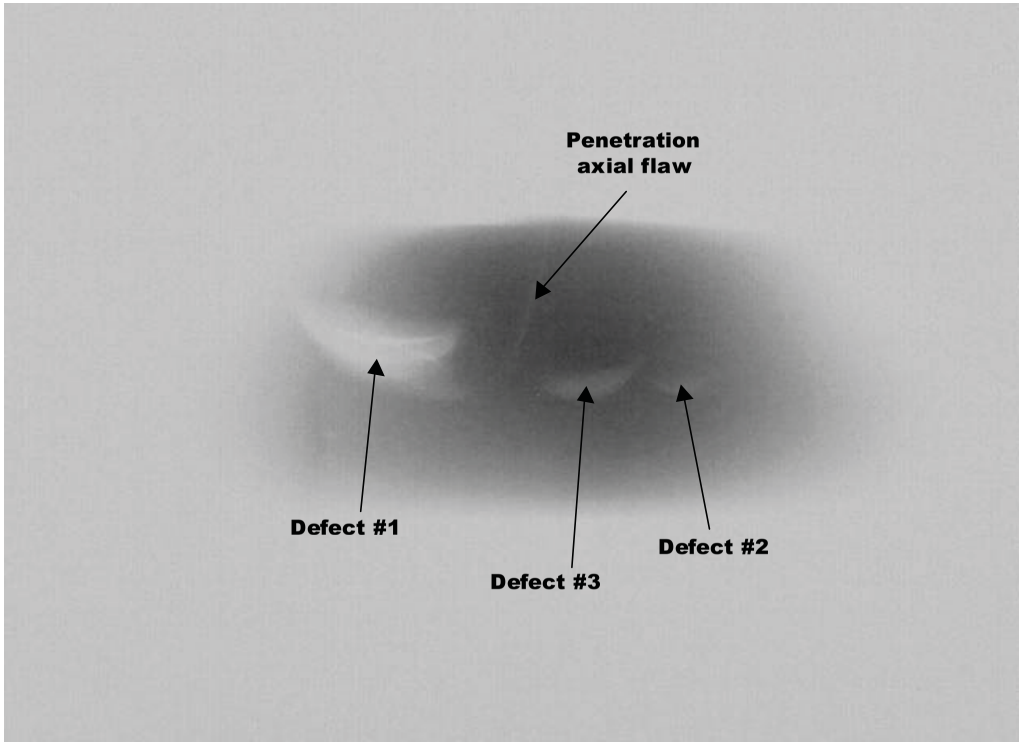
Boat Sample Analysis



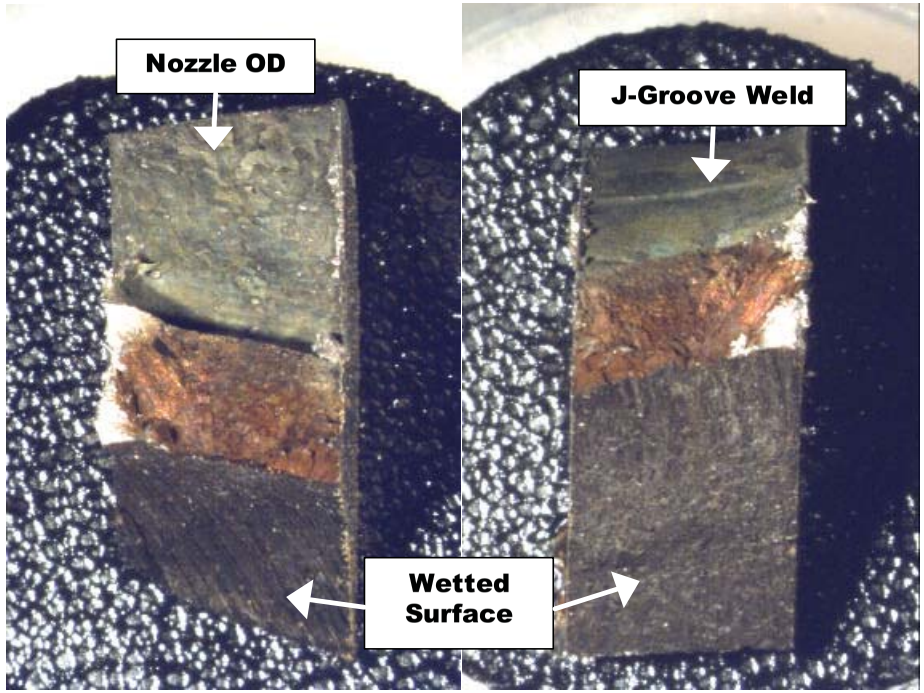
Boat Sample SEM/EDS As-Received



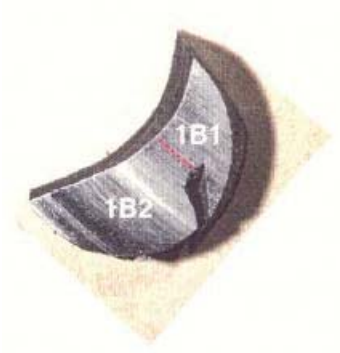
Boat Sample X-Ray Radiography



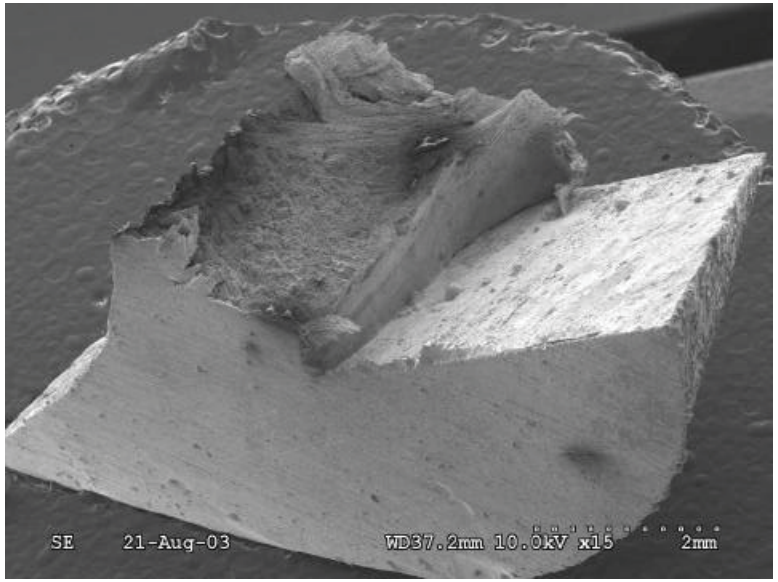
Boat Sample Open Crack - 1B1 & 1B2



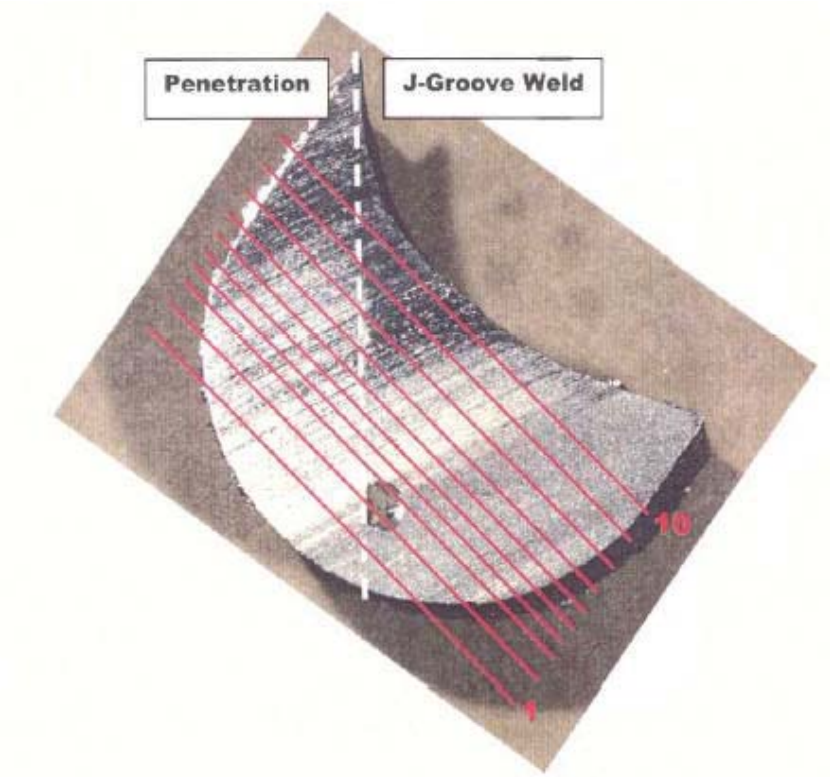
Piece 1B1 Piece 1B2



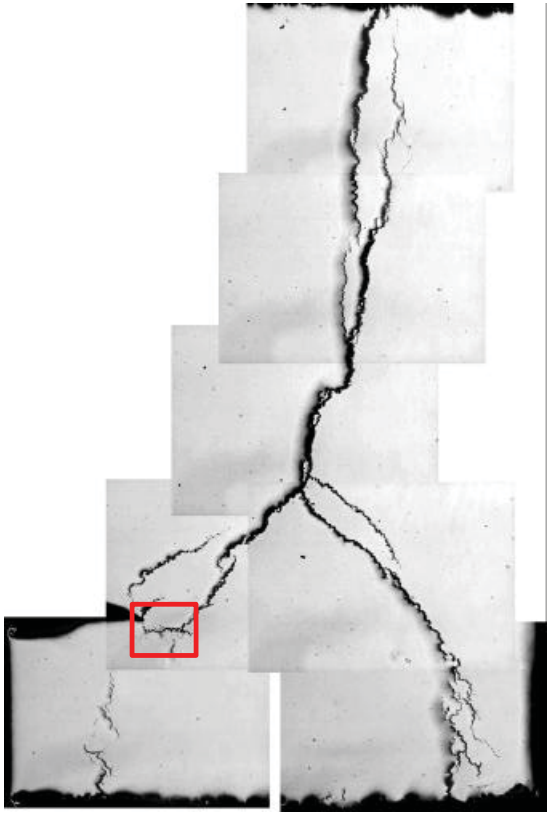
Boat Sample Open Crack - 1B1



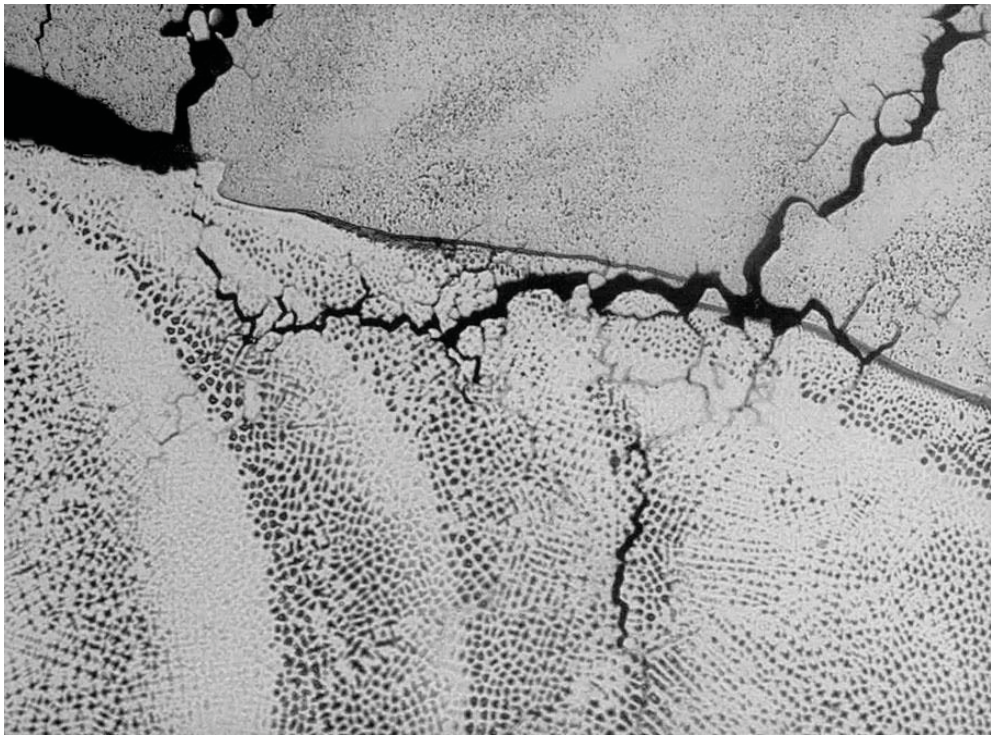
Boat Sample Progressive Grinds
1C & 1C2



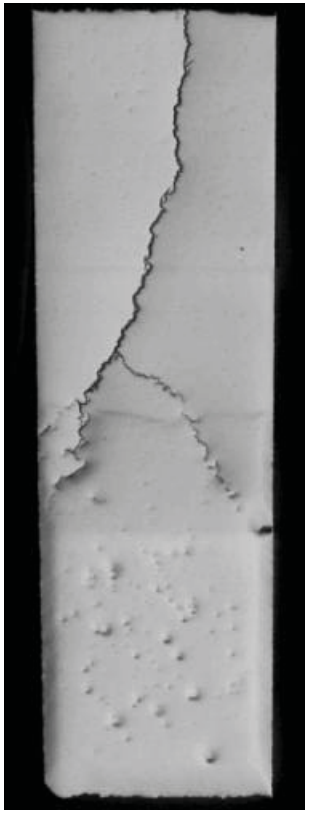
Face #1



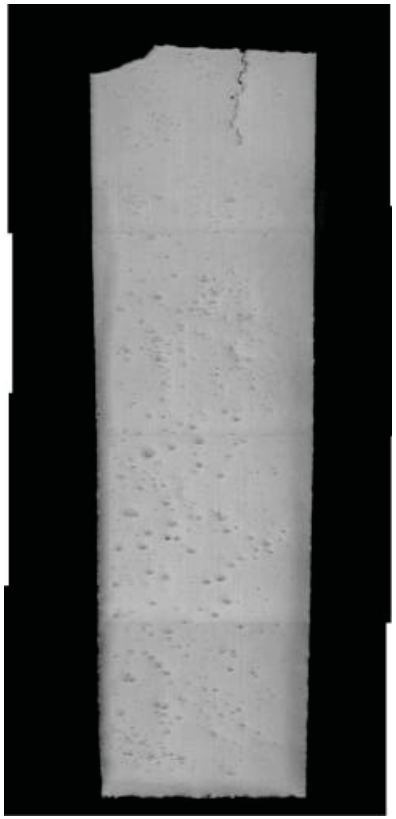
Intergranular Crack



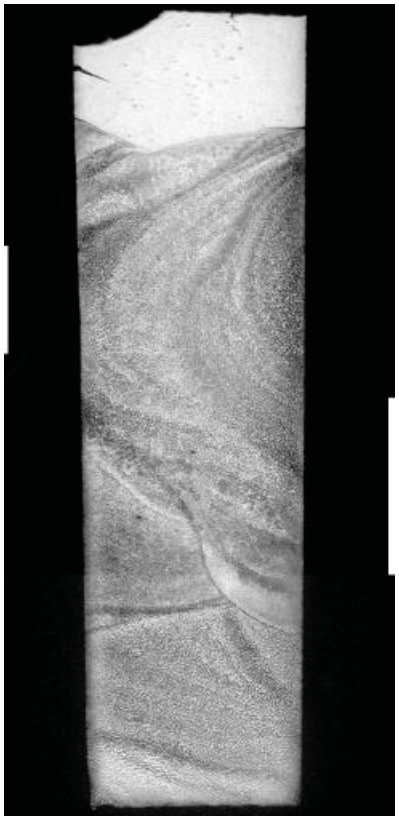
Face #3



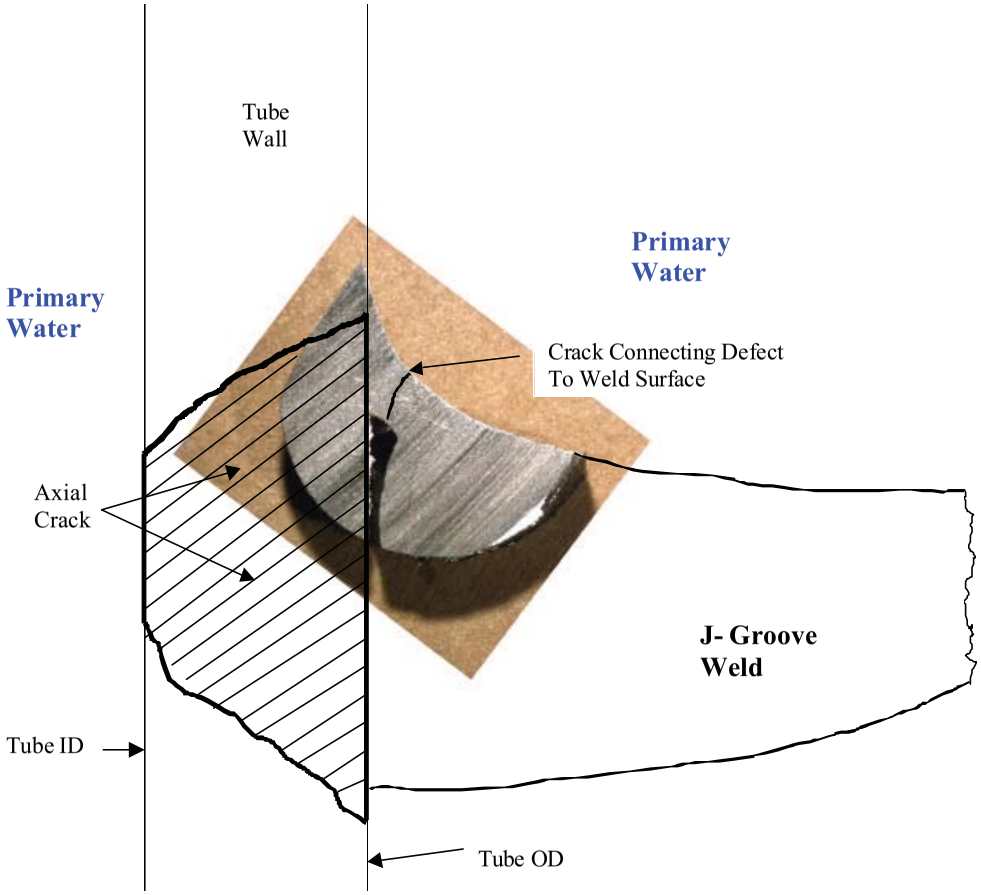
Face #9



Face #10



Boat Sample Analysis



Conclusions

- The Alloy 600 BMI nozzles are susceptible to PWSCC and will crack under the right conditions. PWSCC is possible even at T_{cold}.

- The SMAW process used to construct the J-groove welds is prone to leaving weld defects in service and creating high residual stresses.

- Visual bare metal examination of the BMI nozzles is an effective mechanism for detecting leakage long before flaws become structurally significant.

Future STP Inspections

- Bare metal inspections
- Volumetric examination of Unit 2 penetrations
- Follow-up volumetric re-examination of Unit 1 penetrations

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The Embedded Flaw Process for Repair of Reactor Vessel Head Penetrations

Warren Bamford

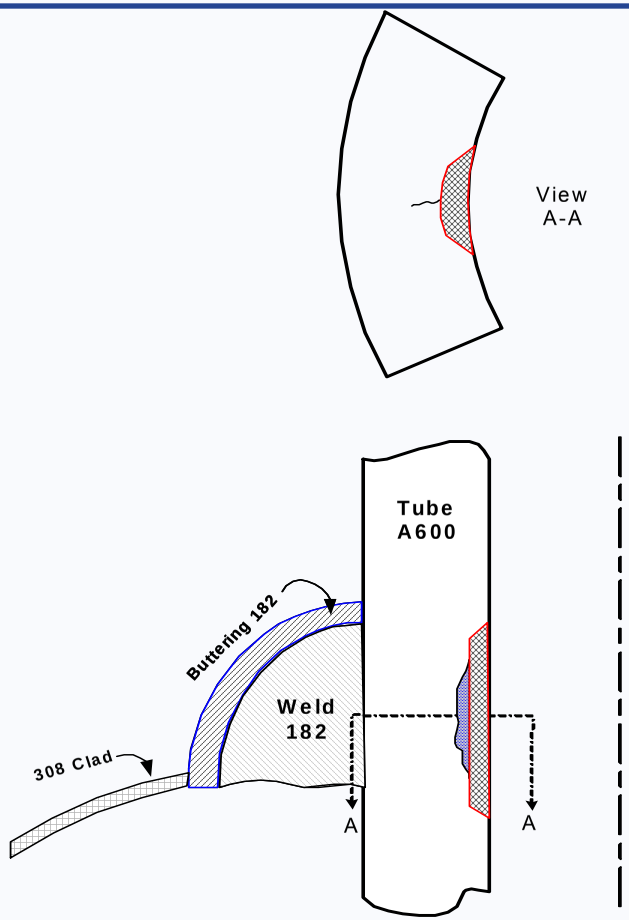
Paul Kreitman

Westinghouse Electric Company

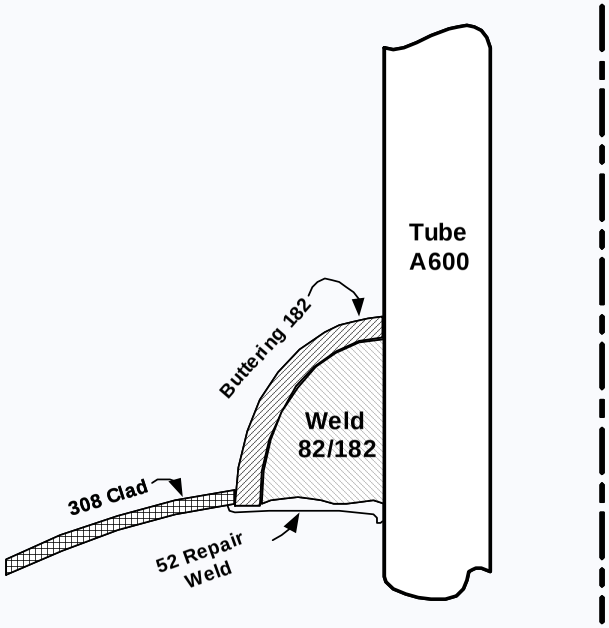
September 2003

- Introduction
- Attributes
- Basis for the embedded flaw concept
- Basis for selection of Alloy 52 for repair weld
- Experience with embedded flaw repairs
- Conclusions

Embedded Flaw Repair: Tube ID



Embedded Flaw Repair: J-Groove Weld



Introduction

- The Embedded Flaw repair was developed in 1993, and first implemented at DC Cook Unit 2 in the spring of 1996
- The next repair was at North Anna 2, in the spring of 2001
- The most recent repair was at Beaver Valley, in the spring of 2002
- Plant-specific relief requests were approved in each case
- On December 12, 2001, Westinghouse submitted a generic relief request for an embedded flaw repair that could be applied to CRDM/CEDM J-weld surfaces.
- NRC approved the process generically with an SER on July 3, 2003

Attributes

- Seals cracks from the environment, stopping PWSCC
- Small thickness minimizes weld residual stresses
- Welding can be done remotely
- Small amount of welding makes the repair timely
- Weld repair is not needed structurally , since critical flaw sizes are very large
- Embedded Flaw repairs are permanent repairs

Basis for the Embedded Flaw Concept
WOG Weld Repair Program Begun in 1993

- **Investigate and provide a local and 360° weld repair on flawed material.**
- **Provide a design that is consistent with rules of ASME Section XI**
- **Provide a weld process specification and repair design package**

Depth of Weldment for Embedded Flaw

- Section XI requirement for a flaw to be considered embedded:
  $S > 0.4a$

  where S = distance from flaw to surface

  a = half width of embedded flaw

- Set width of flaw (2a) equal to penetration thickness (0.625 in.)

- Weld thickness (S) is then 0.125 inches

- For smaller flaws the weld thickness can be smaller

WOG Program/Qualification Summary

- Local Repair
  - Performed with both uphill and downhill repairs
  - Residual stress levels of welded tube compared to unrepaired
  - Weld overlay on an EDM notch showed no cracks or indications generated in the surrounding area
- 360° repair - range of weld depths produced acceptable dimension change in the penetration tubes

Embedded Flaw Repair Process

- Welding Procedure Specification and Procedure Qualification Record Machine Gas Tungsten Arc Welding Process (Remote)
  - WPS 3-43/F43-B MC-GTAW and PQR 603, 677 and 694A was utilized.
  - ASME Section II, Part C, AWS Class. ERNiCrFe-7 (Alloy-52) was used for the overlay weld.
  - Standard ASME Section IX Groove Weld Procedure.
  - ASME Section IX Testing included Bends,Tensile, Hardness and ASTM-A262, Practice A Corrosion Testing.

Alloy 52

- Alloy 52 is the weld metal analog of Alloy 690; it is used for gas metal arc and gas tungsten arc deposition processes [Alloy 152 = shielded metal arc coated electrode version].
- The composition is very similar to that of Alloy 690 with slightly higher Cr [28-31.5 wt %] and controlled additions of Al and Ti [to 1.1-1.5 max combined]
- Developed to minimize issues related to hot cracking and SCC susceptibility of Alloys 182 and 82

Alloy 52 - SCC Resistance

- Owing primarily to high Cr content, Alloys 52/152 and 690 exhibit apparent immunity to primary water stress corrosion cracking (PWSCC)
- Service experience with Alloy 690 in SG heat transfer tubing, and mechanical tube plug applications, and Alloys 52/152 as buttering, cladding and weld filler materials has been exemplary, with no reported degradation, after more than 15 years of service
- Laboratory testing of each of these materials emphasizes the corrosion resistance - no known incidence of crack initiation or crack propagation in primary water environments

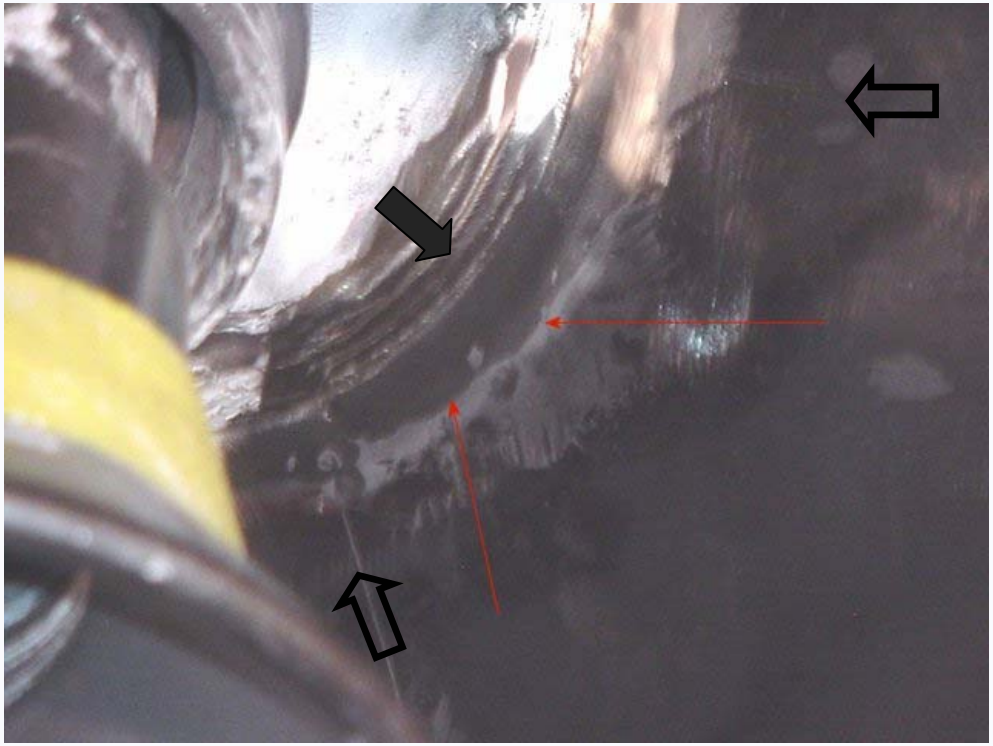
Embedded Flaw Service Experience: D C Cook Unit 2

- Pen. 75 found to have ID surface flaw in 1994
- Depth approx. 40 percent of wall thickness
- Embedded Flaw Repair implemented in 1996
- Repair re-inspected in Jan. 2002: No Indications on the weld repair

North Anna Implementation

- As a result of observed leakage on one of these penetrations in 2002, all three penetrations were re-examined. Evidence of flaws was observed
- An evaluation of these three repairs has been completed, with the following conclusions:
  - The weld repairs did not achieve full coverage of the Alloy 82/182 wetted surface
  - These exposed Alloy 82/182 surfaces are the location of indications found in 2002
- Lessons learned and corrective actions have been implemented.

Etched Region of Penetration 62



The Boundary Between the Repair and the Original Weld Buttering is Shown by the Solid Arrow. The Boundary Between the Buttering and the Etched Stainless Steel (Gray) is Shown by the Small Red Arrows. The Area of PT Indications is in the Buttering Between the Two Scribe Marks, Indicated by the Large Open Arrows.

SER on Embedded Flaw Repairs

- **Technical Basis submitted via WCAP 15987; to become 15987A**
- **SER issued July 3, 2003**
- **Approved a non-structural (seal) weld repair, of unspecified thickness**
- **Three layers of weld required on attachment weld repairs, and two layers for the tube ID or OD**
- **SER acceptance was based on Westinghouse application of current ASME Code fracture mechanics methods**
- **The SER states that the embedded flaw repair is approved for application to CE and Westinghouse designs**

SER on Embedded Flaw Repairs

- **At or Above the Weld**
  - The repair can be used for any flaws in the tube (ID or OD) that meet the ASME Section XI acceptance criteria, which were endorsed by the NRC by letter to NEI on April 11, 2003.
  - Larger flaws on the tube ID, are to be dealt with on a plant-specific basis
  - Circumferential flaws in the tube above the weld, regardless of size are treated on a plant-specific basis, consistent with previous NRC approaches
- **Below the weld**
  - Larger flaws on the tube below the weld are approved, regardless of size, provided their upper extremity does not reach the bottom of the weld
- **In the Weld**
  - The repair can be used for flaws of any type in the attachment weld

SER Requirements

- **Inspections are consistent with those for a structural weld, requiring both UT and surface exams in most cases**
- **Inspections must be performed by qualified inspectors**
- **Licensees must demonstrate that a plant-specific application is bounded by the WCAP (15987, Rev. 2), including the ASME Code fracture mechanics evaluation contained in Appendix C of the WCAP (see SER paragraph 3.6)**

Conclusions

- Embedded Flaw Repair process is now fully developed
- Implementation is qualified
- Good service experience
- SER received from NRC, July 2003

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Weld Overlay to Reduce Tensile Stresses in Alloy 82/182 Butt Welds

Vessel Head Penetration Inspection, Cracking and Repair Conference
September 29 – October 2, 2003
Gaithersburg, MD

by:
Steve Hunt, Dominion Engineering, Inc.
John Broussard, Dominion Engineering, Inc.
Stephen Ahnert, Dominion Engineering, Inc.
Patrick O'Regan, EPRI
Dana Covill, Progress Energy

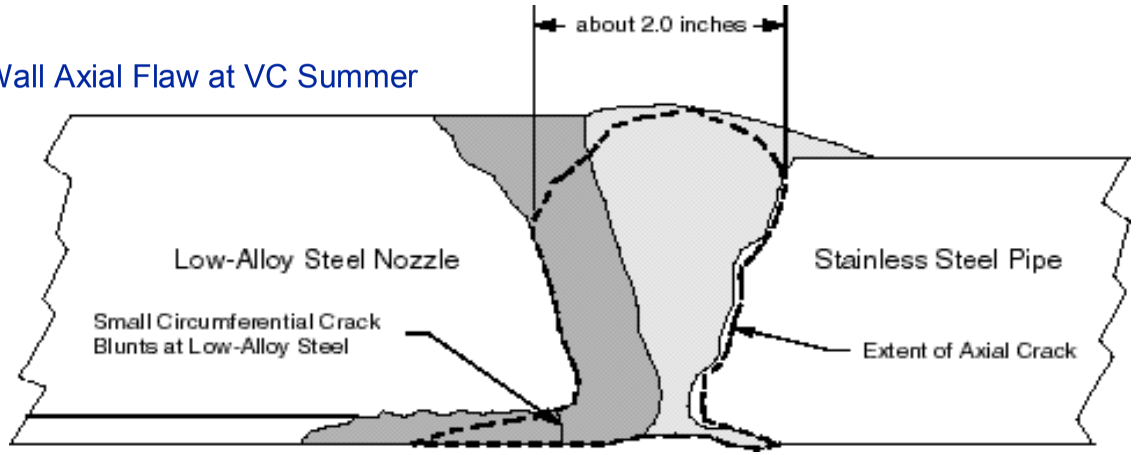
Contents

- Background
- Weld Overlay to Reduce Tensile Stress
- Finite Element Model
- Welding Residual Stresses
- Operating Stresses – As-Designed
- Operating Stresses – With Inside Surface Weld Repairs
- Operating Stresses – With Outside Surface Weld Overlay
- Summary of Results

Background

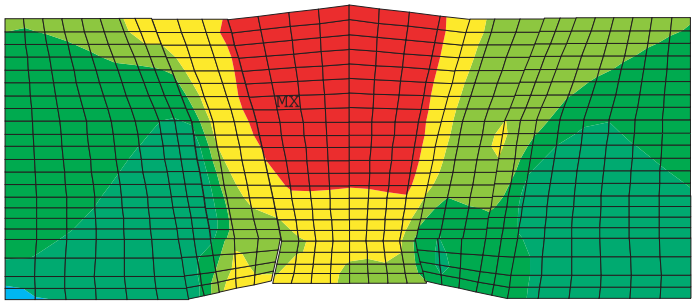
- PWSCC cracks have been discovered in RPV inlet and outlet nozzle to primary coolant pipe butt welds at VC Summer and Ringhals
  - Axial cracks in inlet and outlet nozzle butt welds at VC Summer, including one through-wall crack in an outlet nozzle butt weld that led to a leak
  - Part-depth axial cracks in outlet nozzle welds at Ringhals 3 and 4
  - A shallow circumferential crack in outlet nozzle cladding at VC Summer that arrested once the crack penetrated to the low-alloy steel nozzle

Through-Wall Axial Flaw at VC Summer

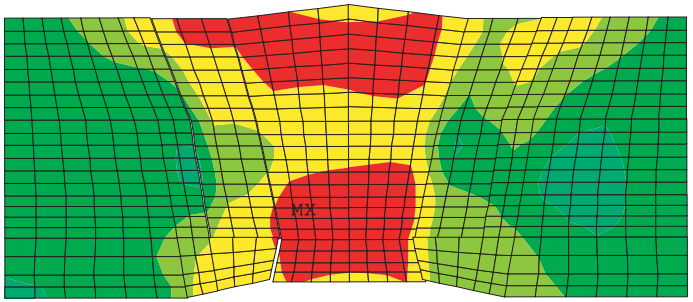


Background

- The outlet nozzle butt weld at VC Summer had been repaired from the inside surface
- Weld repair on the inside of a nozzle has been shown to produce high residual tensile stresses



Operating Hoop Stress – As Designed

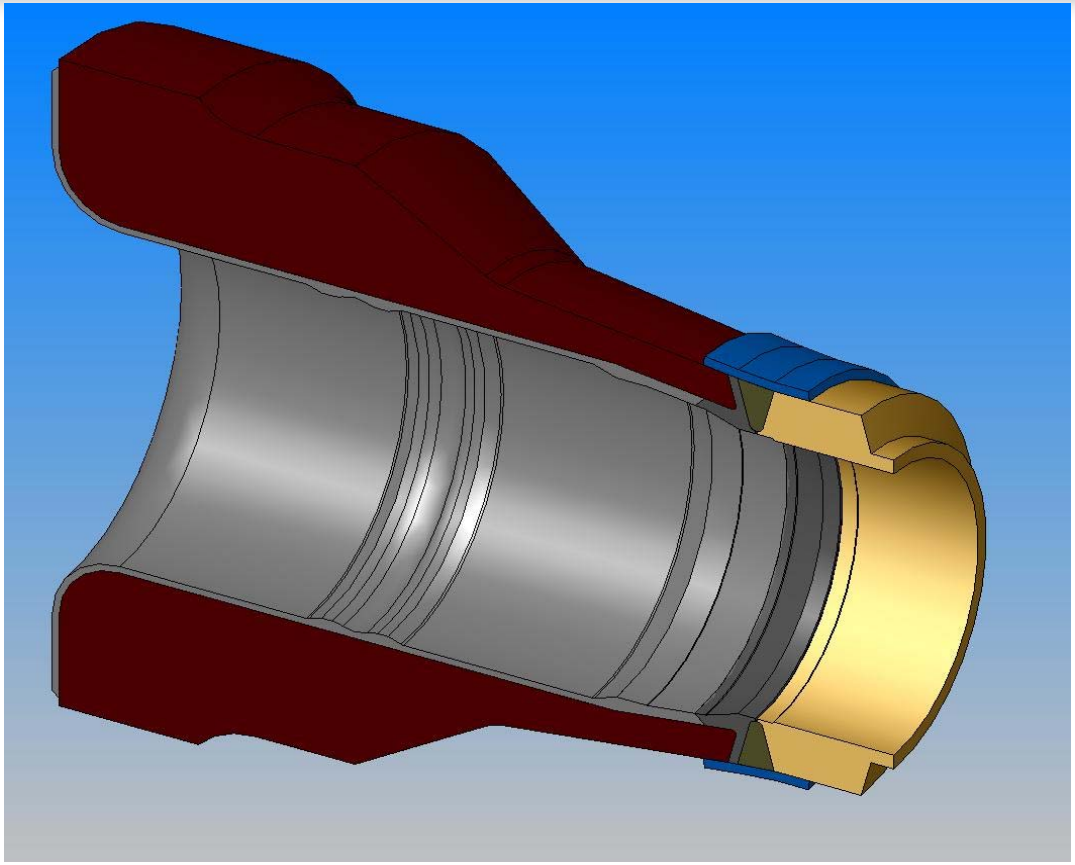


Operating Hoop Stress – With ID Repair

Weld Overlay to Reduce Tensile Stress

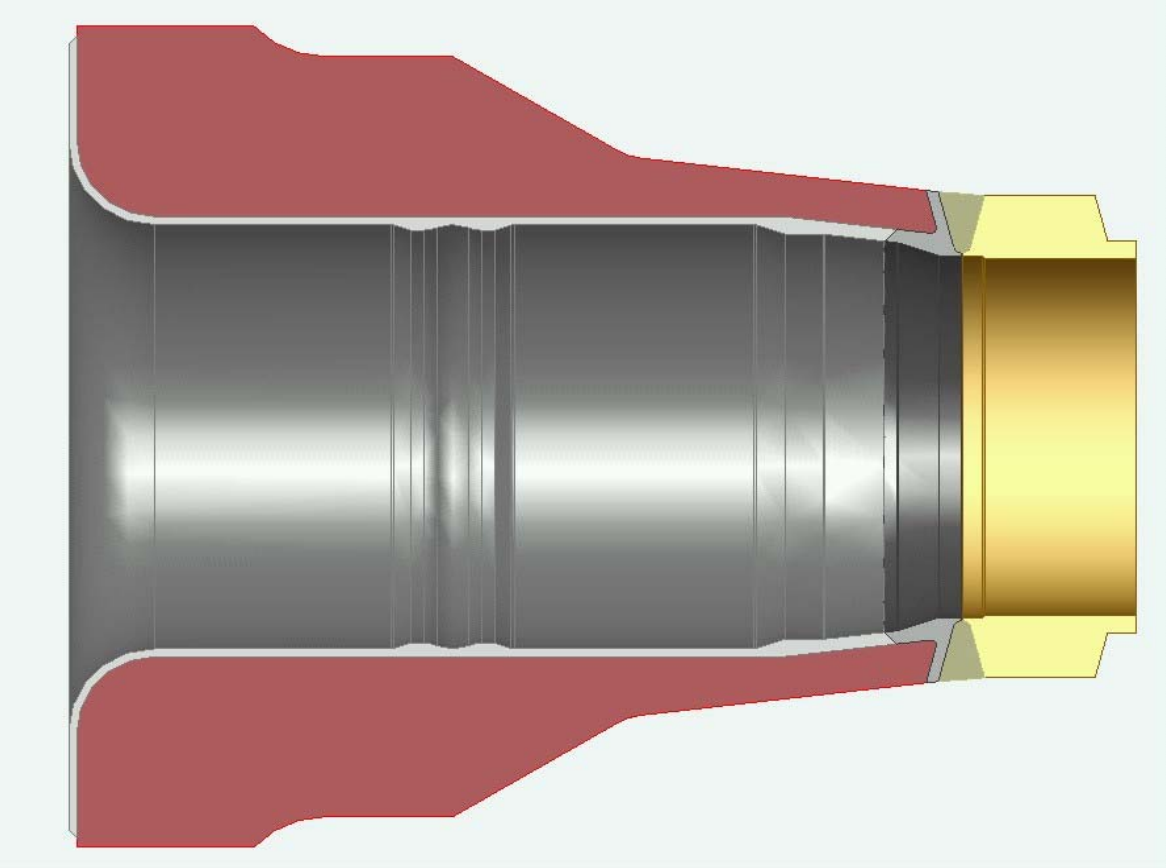
- A weld overlay applied to the outside of a nozzle/pipe at the butt weld will reduce tensile stresses on the inside surface of the weld
  - Weld shrinkage causes a reduction in nozzle/pipe diameter and a resultant reduction in tensile stress
  - Reduced tensile stresses will delay the time to PWSCC crack initiation and the growth rate of preexisting cracks
- A weld overlay can also be used to provide a redundant load path around a cracked weld, but this was not the objective of this evaluation

Weld Overlay to Reduce Tensile Stress

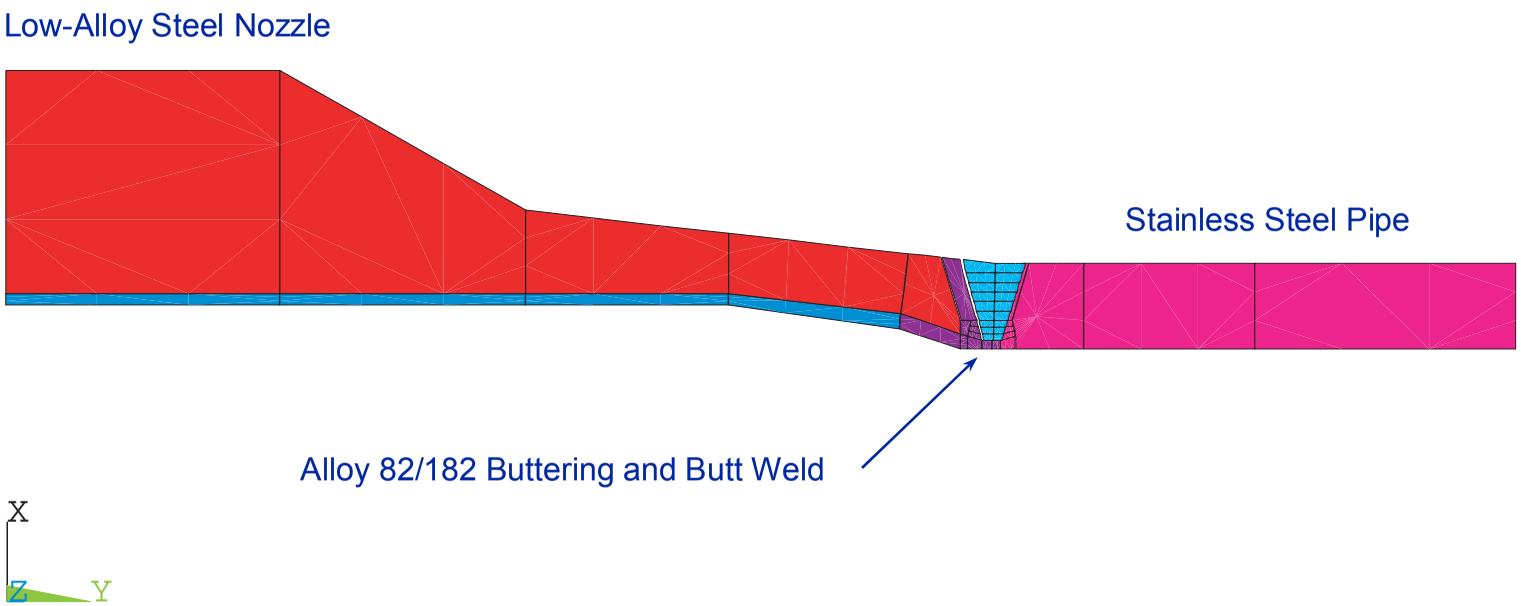


Weld Overlay Applied to Typical Pressurizer Surge Nozzle Butt Weld

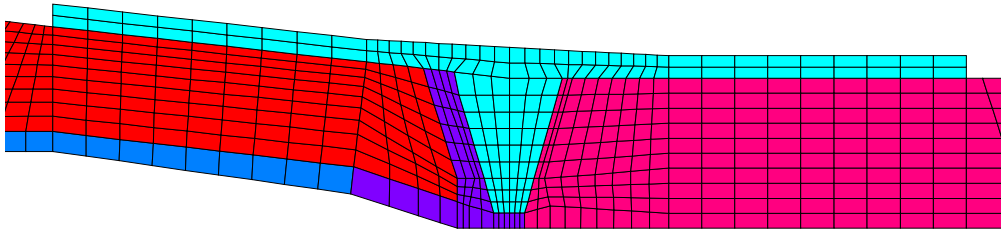
Finite Element Model
Typical Pressurizer Surge Nozzle



Finite Element Model
Overall Finite Element Model

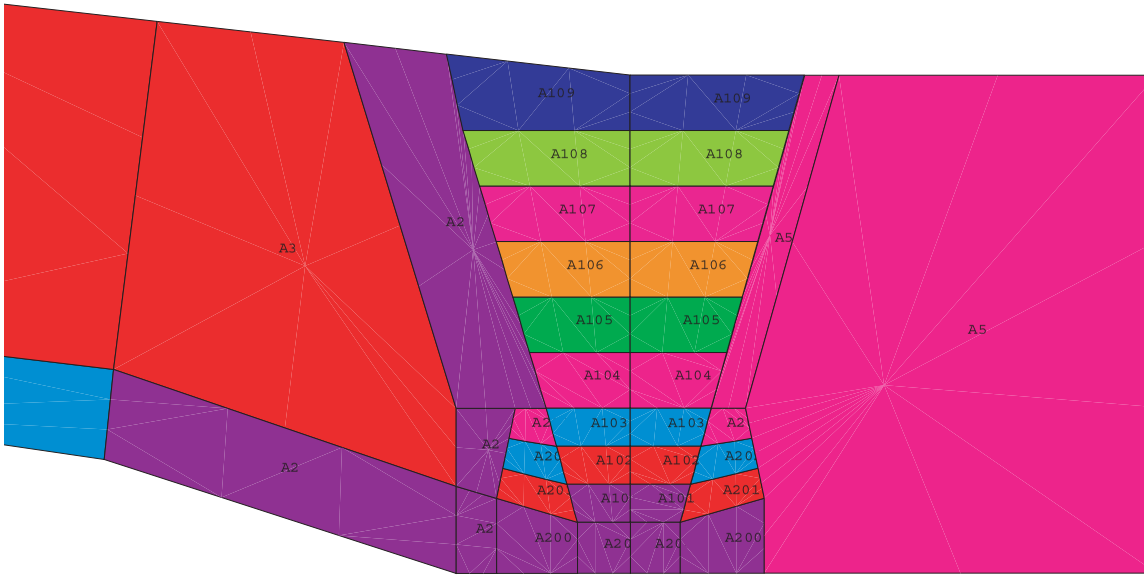


Finite Element Model
Finite Element Model with Weld Overlay



Overlay
t/T = 0.17, L/T = 5.5

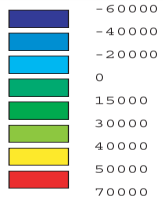
Finite Element Model
Weld Elements

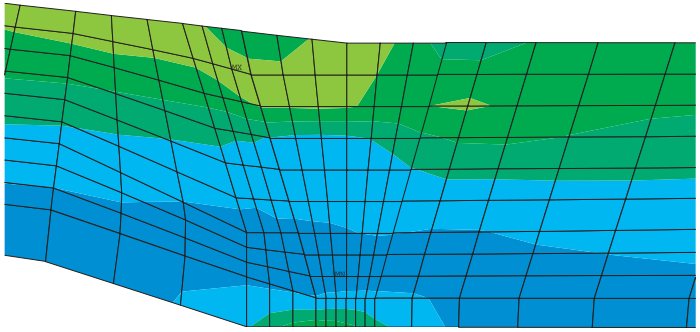


Finite Element Model
Analysis Approach

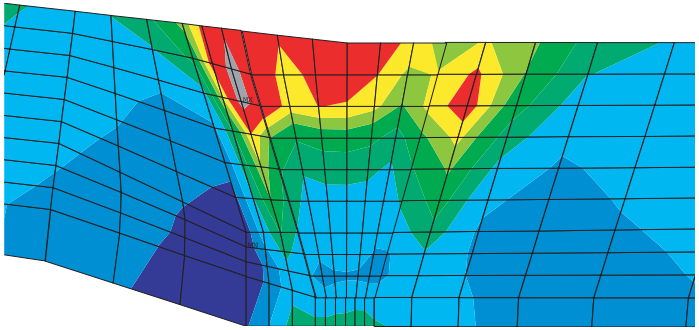
- Weld applied using methodology described in previous Dominion Engineering paper, *Welding Residual and Operating Stress Analysis of RPV Top and Bottom Head Nozzle*
  - Thermal and stress analysis of each pass
  - 6-11 passes applied depending on nozzle geometry
- Weld backgouged from the inside surface approximately 1/3 wall thickness
- Backgouged area weld repaired from the inside surface using 2-4 passes depending on nozzle geometry
- Completed joint subjected to hydrostatic test conditions (3,125 psi)
- Operating pressure (2,250 psi) and temperature (615°F) applied

Welding Residual Stresses
As-Designed



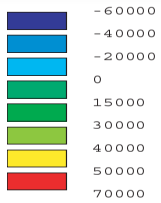


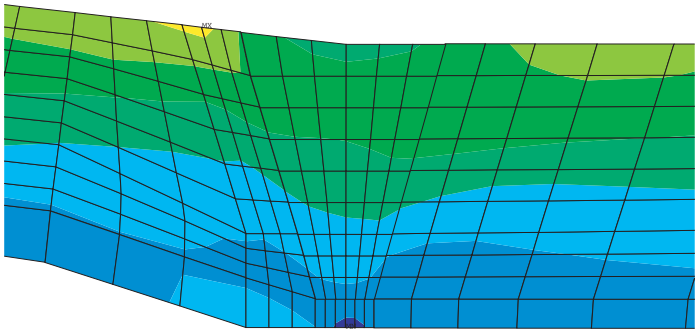
Axial Stress



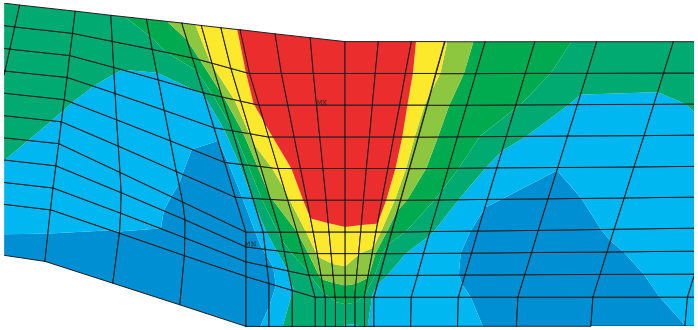
Hoop Stress

Operating Stresses
As-Designed





Axial Stress
(-2.7 ksi max)

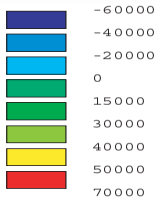


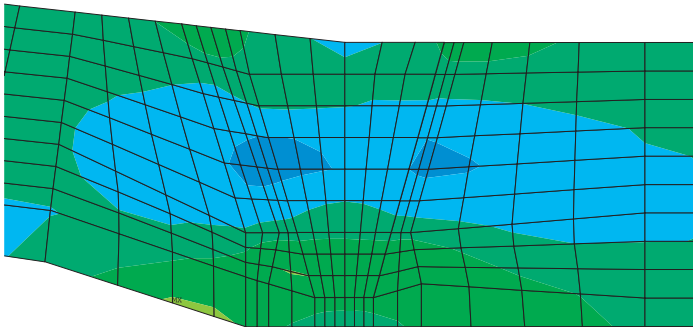
Hoop Stress
(9.0 ksi max)

Notes: For all cases:

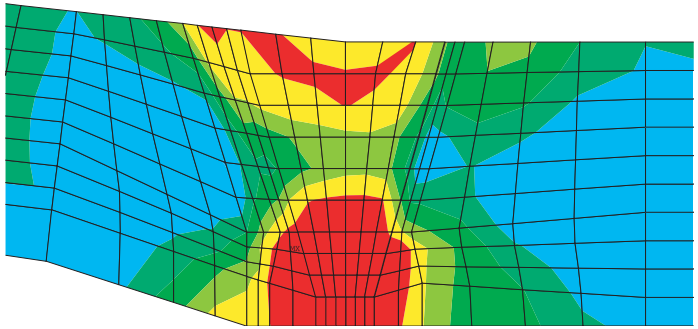
1) Operating stresses include pressure and temperature but not piping loads
2) Values reported for axial and hoop stresses are maximum stresses on wetted ID surface

Operating Stresses
With ID Weld Repair (360°)



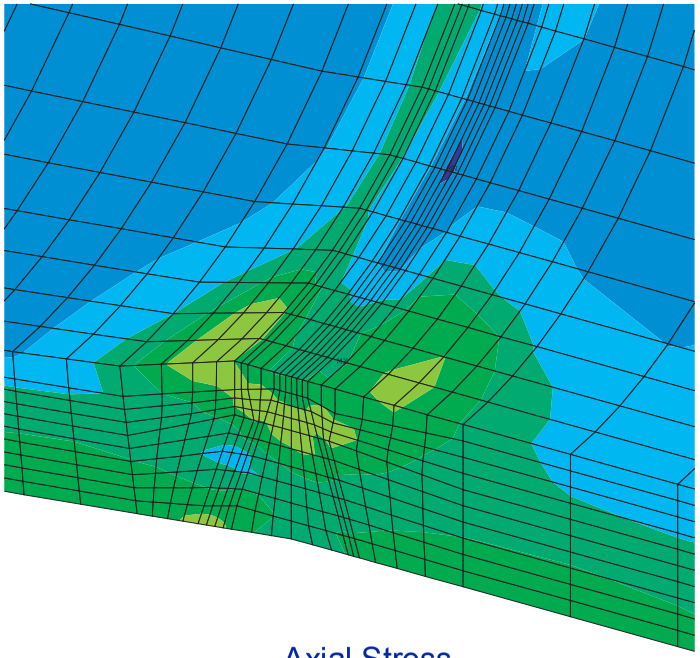


Axial Stress
(32.5 ksi max)

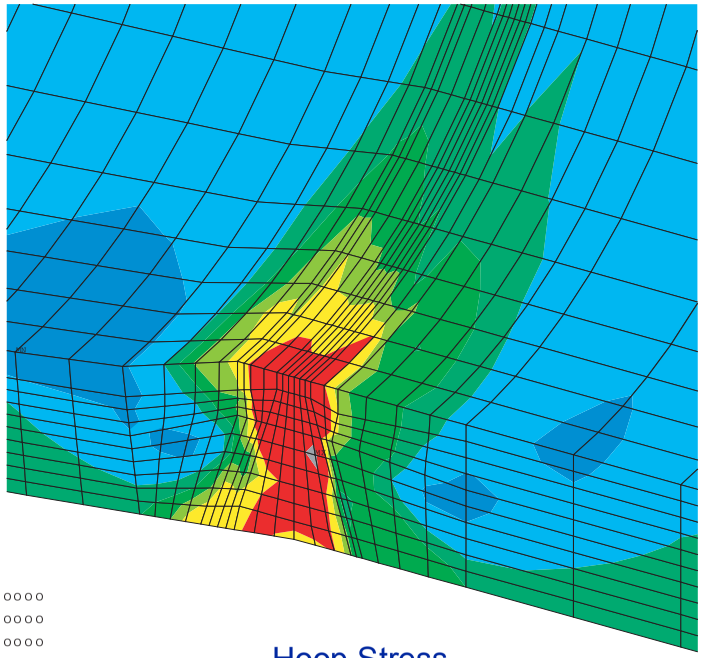


Hoop Stress
(52.8 max)

Operating Stresses
With ID Weld Repair (30° Arc)

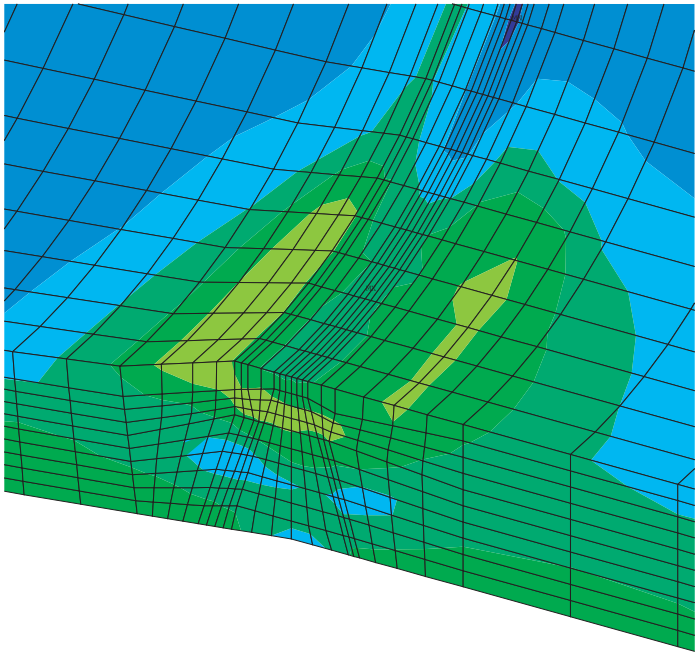


Axial Stress
(39.9 ksi max)

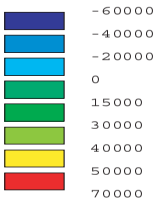


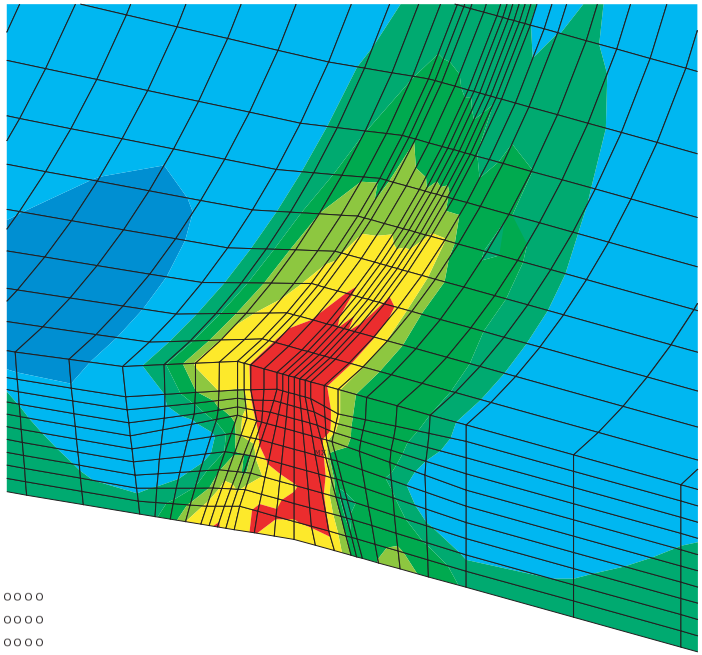
Hoop Stress
(54.6 ksi max)

Operating Stresses
With ID Weld Repair (60° Arc)



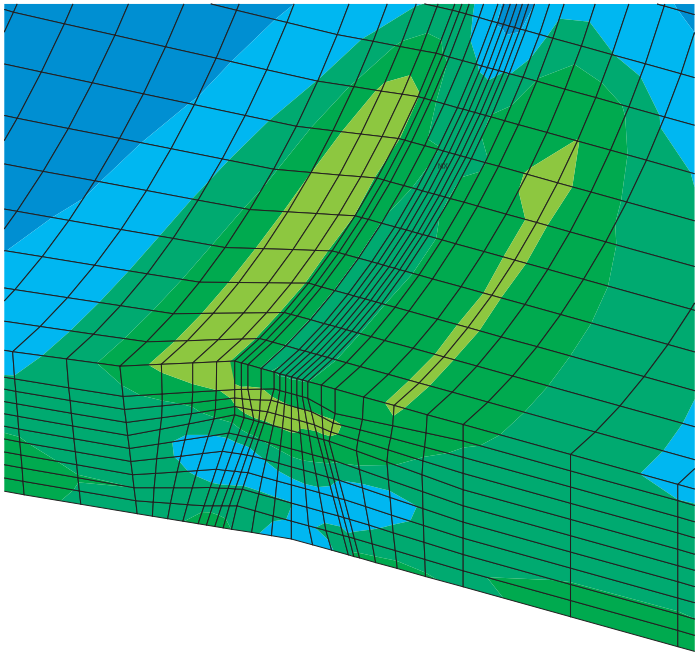
Axial Stress
(38.6 ksi max)



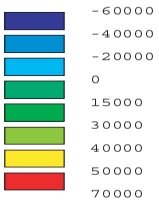


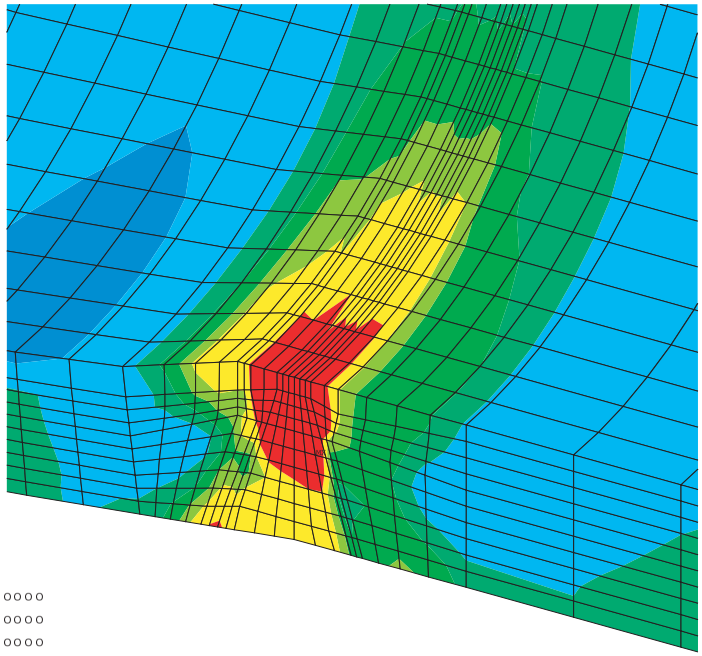
Hoop Stress
(52.6 ksi max)

Operating Stresses
With ID Weld Repair (90° Arc)



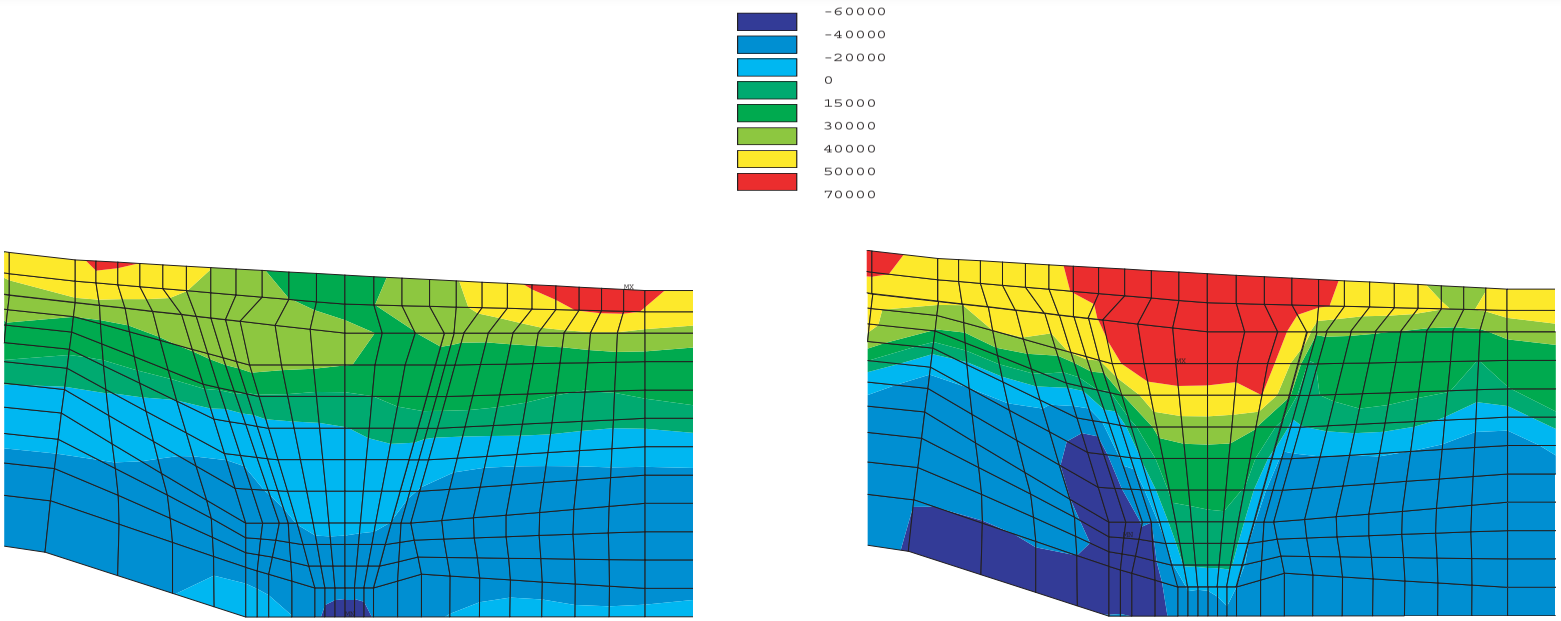
Axial Stress
(40.2 ksi max)





Hoop Stress
(72.0 ksi max)

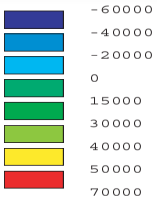
Operating Stresses
With Weld Overlay – As-Designed

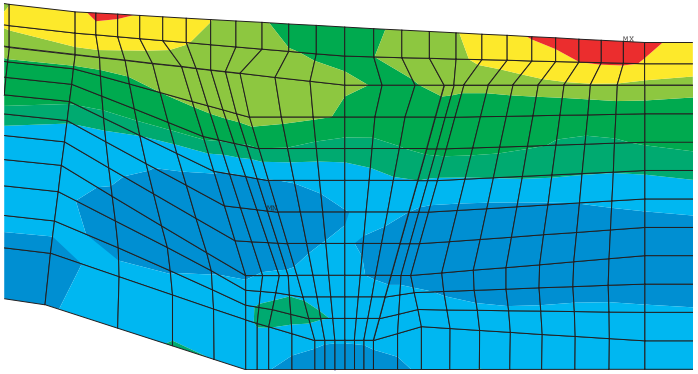


Axial Stress
(-8.6 ksi max)

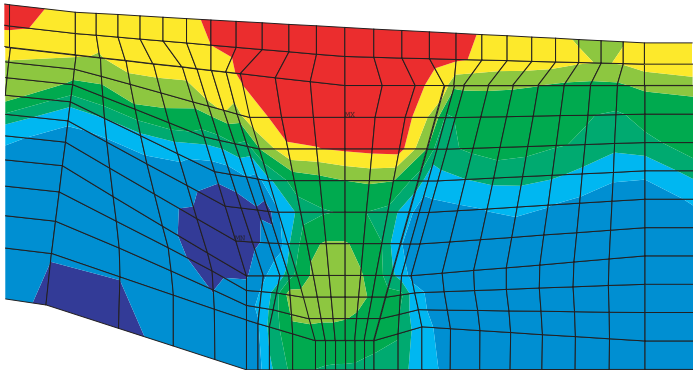
Hoop Stress
(-23.2 ksi max)

Operating Stresses
With Weld Overlay – 360° ID Repair





Axial Stress
(1.7 ksi max)



Hoop Stress
(19.9 ksi max)

Summary of Analysis Results
Operating Condition Stresses

- As-Designed (no weld repair)

Direction	No Overlay	Overlay
Hoop	9.0 ksi	-23.2 ksi
Axial	-2.7 ksi	-8.6 ksi

- With 360° ID Weld Repair

Direction	No Overlay	Overlay
Hoop	52.8 ksi	19.9 ksi
Axial	32.5 ksi	1.7 ksi

Conclusions

- Weld repairs to the nozzle ID after completing the through-wall weld produces high hoop and axial tensile stresses on the inside surface
- Partial-arc ID repairs also produce high hoop and axial stresses on the inside surface
- Weld overlay applied to the outside of the nozzle reduces the hoop and axial stresses on the nozzle ID surface
  - The weld overlay dimensions (thickness and length) can be selected to produce the desired stress reduction over the area of potentially high ID stresses
  - The axial length of the overlay deposits must be selected such that any increases in axial ID stress occurs in material that is not susceptible to PWSCC

Section 4:
Session 3: Structural Analysis and Fracture Mechanics Issues

Probabilistic Fracture Mechanics Analysis of RPV Top Head Nozzles

U.S. Nuclear Regulatory Commission
Argonne National Laboratory

Conference on Vessel Head Penetration Inspection, Cracking, and Repairs

September 29 – October 2, 2003
Gaithersburg, Maryland

Peter Riccardella, Nathaniel Cofie, Angah Miessi
Structural Integrity Associates
Sept. 30, 2003

EPRI

Structural Integrity Associates, Inc.

Project underway since Sept. 2001 under EPRI / MRP sponsorship

Objectives:

- **Develop generic methodology to determine probabilities of top head nozzle leakage and failure (ejection)**
- **Apply to assortment of U.S. PWRs in support of MRP Safety Assessment**
- **Use to define MRP inspection plan that provides acceptable level of quality and safety**

Elements of Analysis

- Monte-Carlo PFM model
- Applied stress intensity factors for circumferential cracks
- Weibull analysis of plant inspection data (time to leakage or significant cracking)
- Statistical characterization of laboratory PWSCC crack growth rates
- Effect of inspections (interval and probability of detection)

Monte-Carlo PFM Model

- **A time-dependent Monte Carlo analysis scheme**
- **Predicts probability of leakage and nozzle ejection versus time for a specific set of top head parameters:**
  - Deterministic Parameters
  - Statistical Parameters (Random Variables)
- **Two nested Monte Carlo simulation loops**
  - step through time for each nozzle in a head
  - and then for the total number of head simulations specified

Deterministic Parameters

- **Number of top head nozzles**
- **Angle of each nozzle with respect to the head**
- **Nozzle diameter and wall thickness**
- **Number of heats of nozzle material, and number of nozzles from each heat**
- **K-matrices for each of four nozzle angles into which nozzles are lumped**
  - K vs. Crack Length
  - Two Yield Strengths
  - Two Nozzle Interferences

Important Random Variables

- **Head operating temperature**
- **Weibull distribution of time to leakage or cracking (dependent on plant operating time and head temperature)**
- **Stress corrosion crack growth law distribution**
- **Correlation factor between time to crack initiation and crack growth law, and**
- **Critical crack size for each nozzle angle**

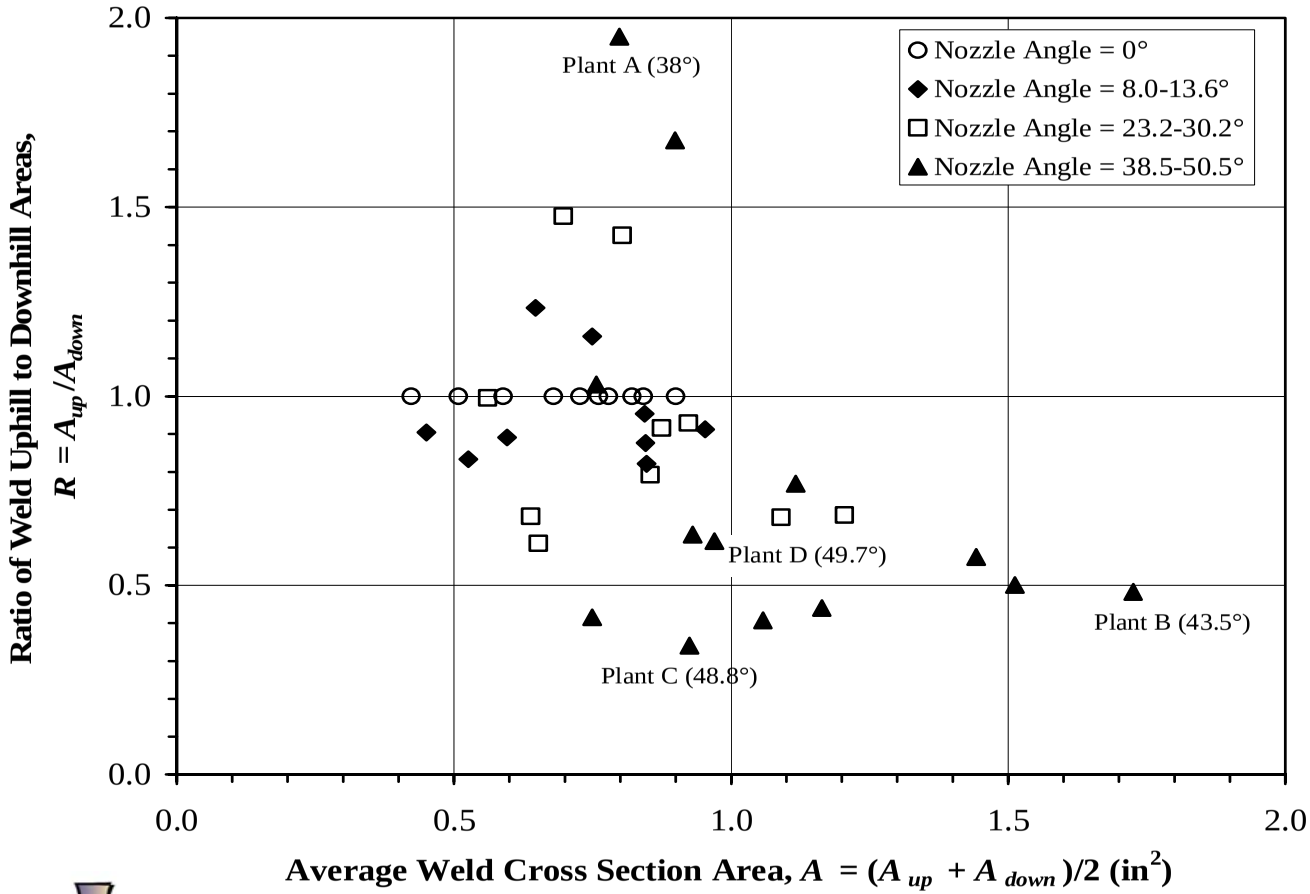
Input as distribution type (normal, triangular, log–normal, log-triangular, Poisson, Weibull, etc.) plus mean and variance

Stress Intensity Factor Calculations

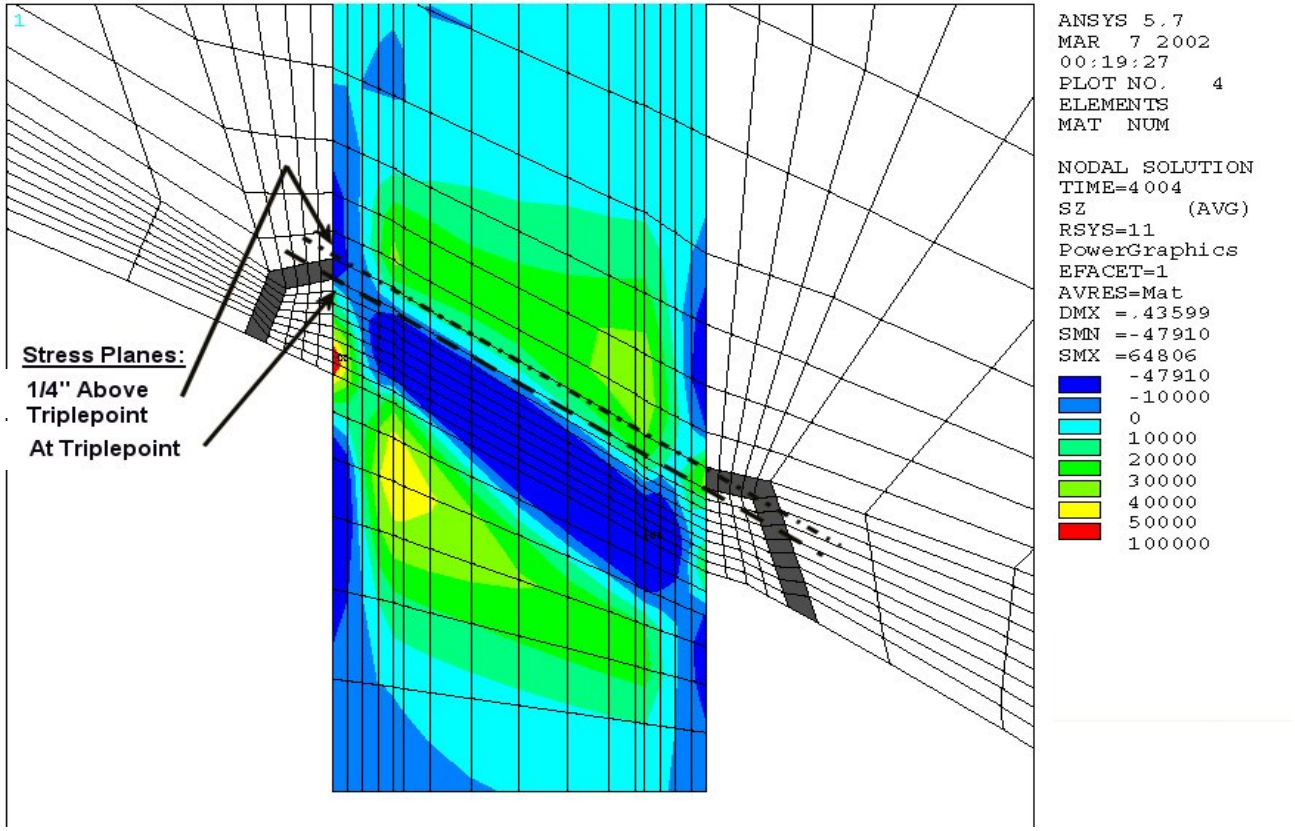
- **Analyses performed for four "characteristic plant types"**
- **Assume that cracking follows planes of maximum stress**
- **Assume through-wall cracks over entire propagation length (30º to 300º)**

	Plant A (B&W)	**Plant B (W 2-Loop)**	**Plant C (W 4-Loop)**	**Plant D (CE)**	
				CEDM	ICI
Top Head: ID (in.) thickness (in)	87.25 6.626	66.3125 5.75	86 7	86 7.6875	
Nozzle: OD (in.) thickness (in)	4.0 0.6175	4.0 0.625	4.0 0.625	4.05 0.661	5.563 0.4065
Total # Nozzles	69	37	96	91	10
Nozzle Angles Analyzed (º)	0, 18, 26, 38.5	0, 13.6, 30, 43.5	48.8	0, 7.8, 49.7	55.3
Nozzle Yield Strengths (ksi)	High:50 Low:37	58	63	High:59 Low:52.5	39.5

Geometric Comparison of Characteristic Plants



Residual + Operating Stress Analyses of Non-Cracked Nozzles



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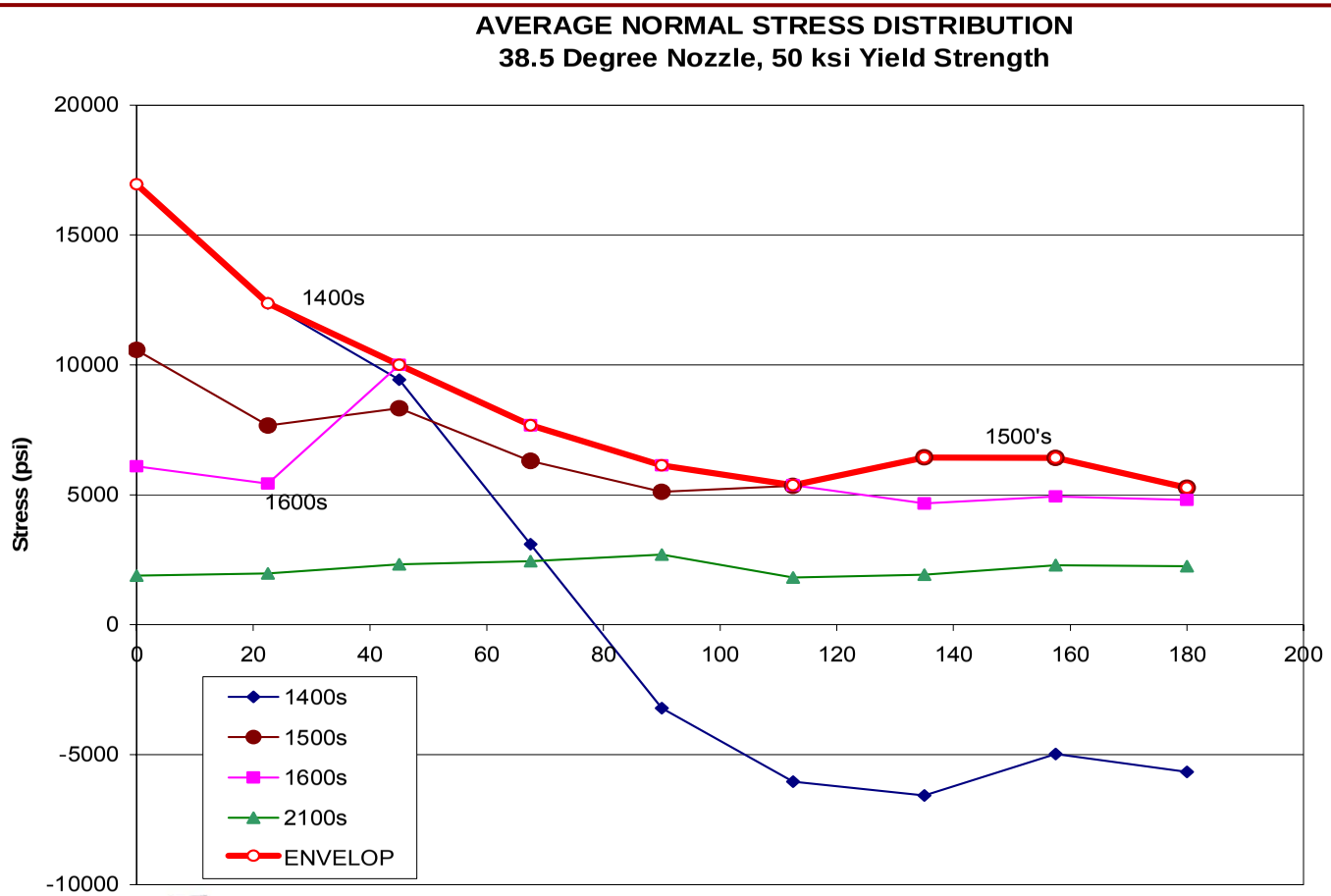
Stresses along Various Stress Planes – Plant A



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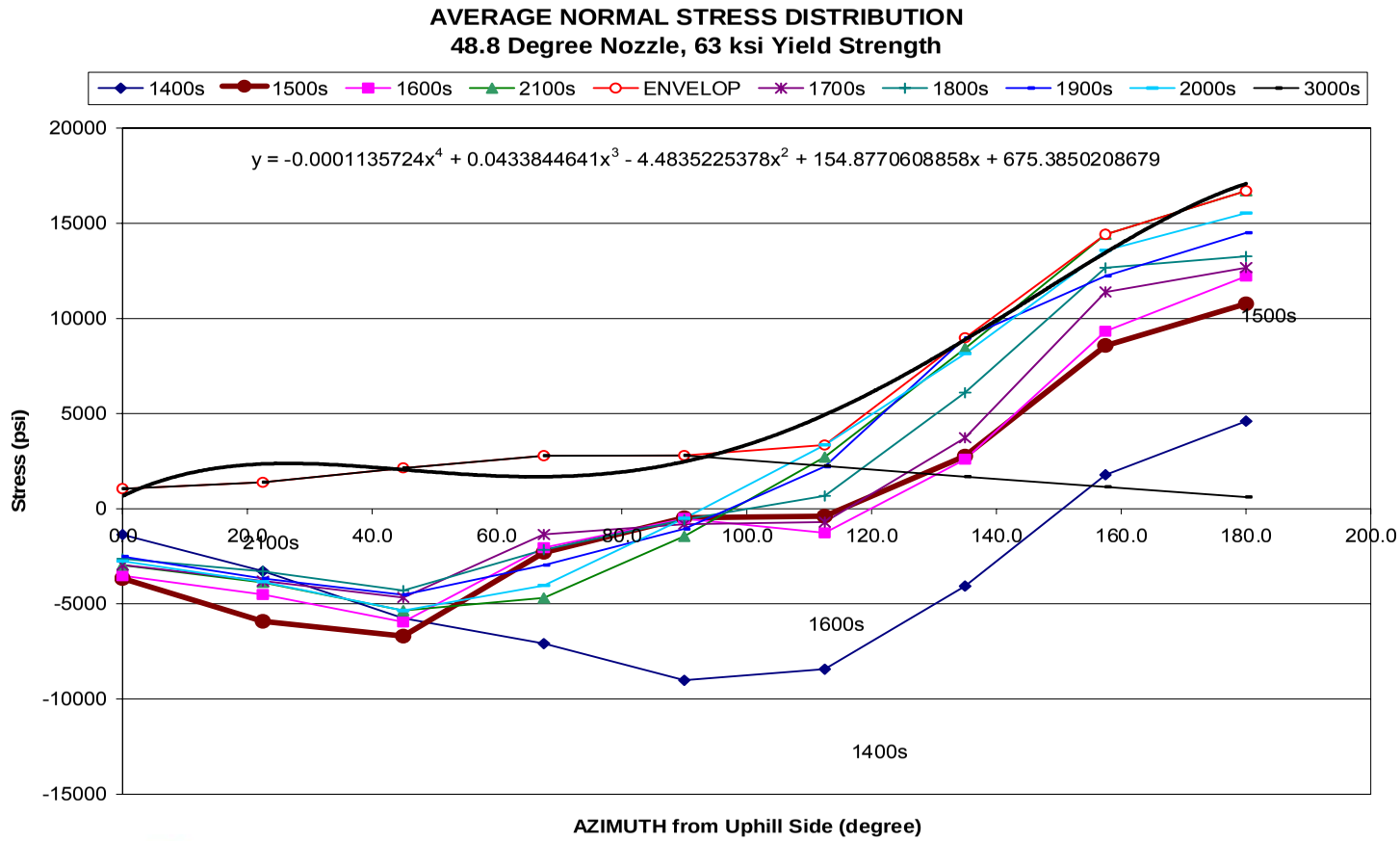
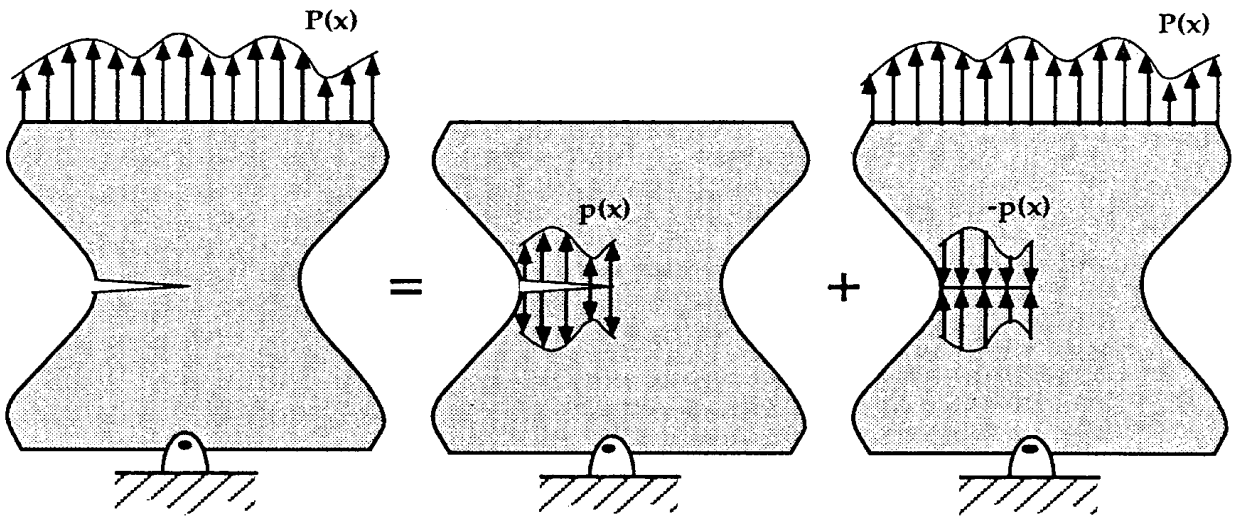
Stresses along Various Stress Planes – Plant C

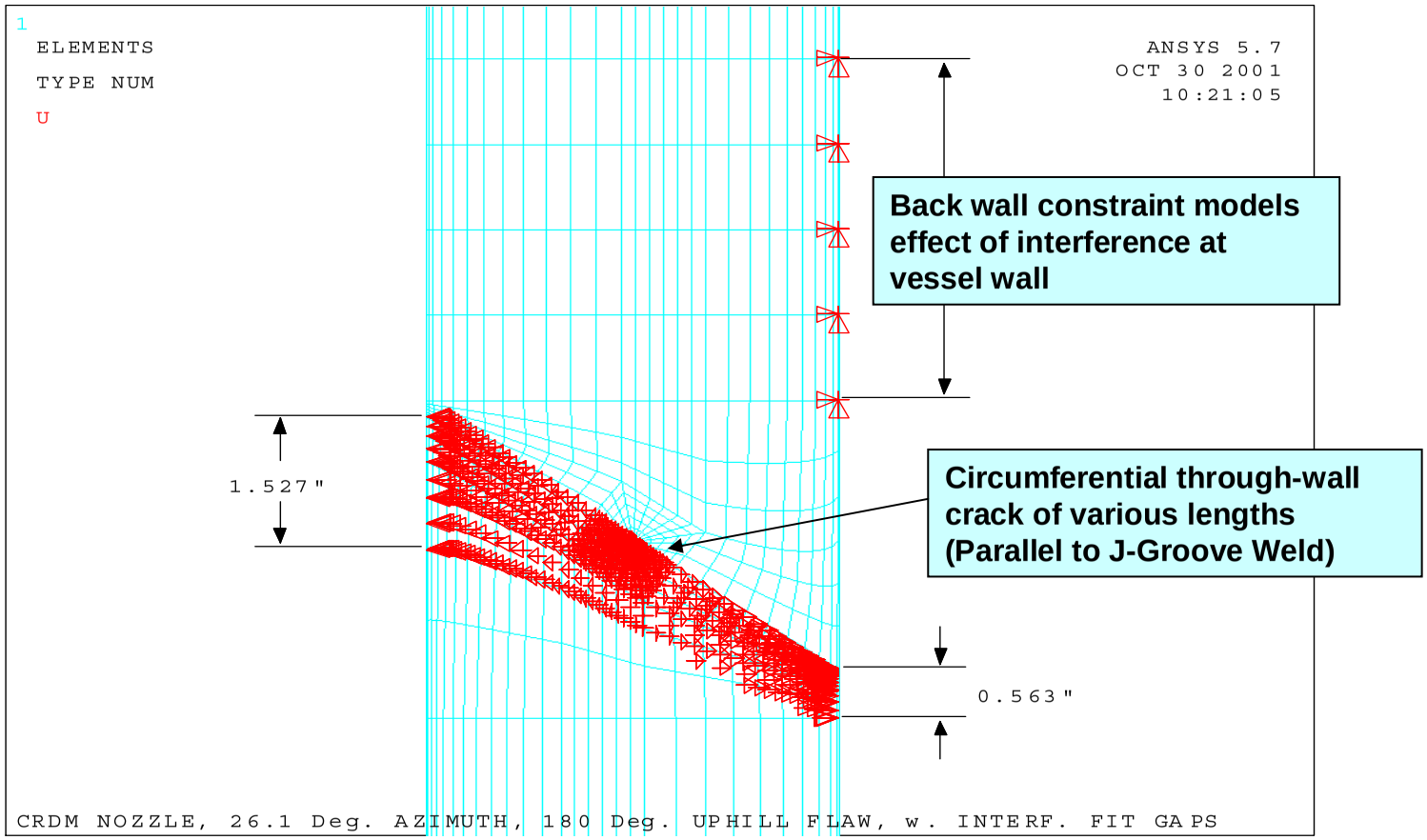


Superposition Approach for K Calculations



Fracture Mechanics

Through-Wall Crack Model



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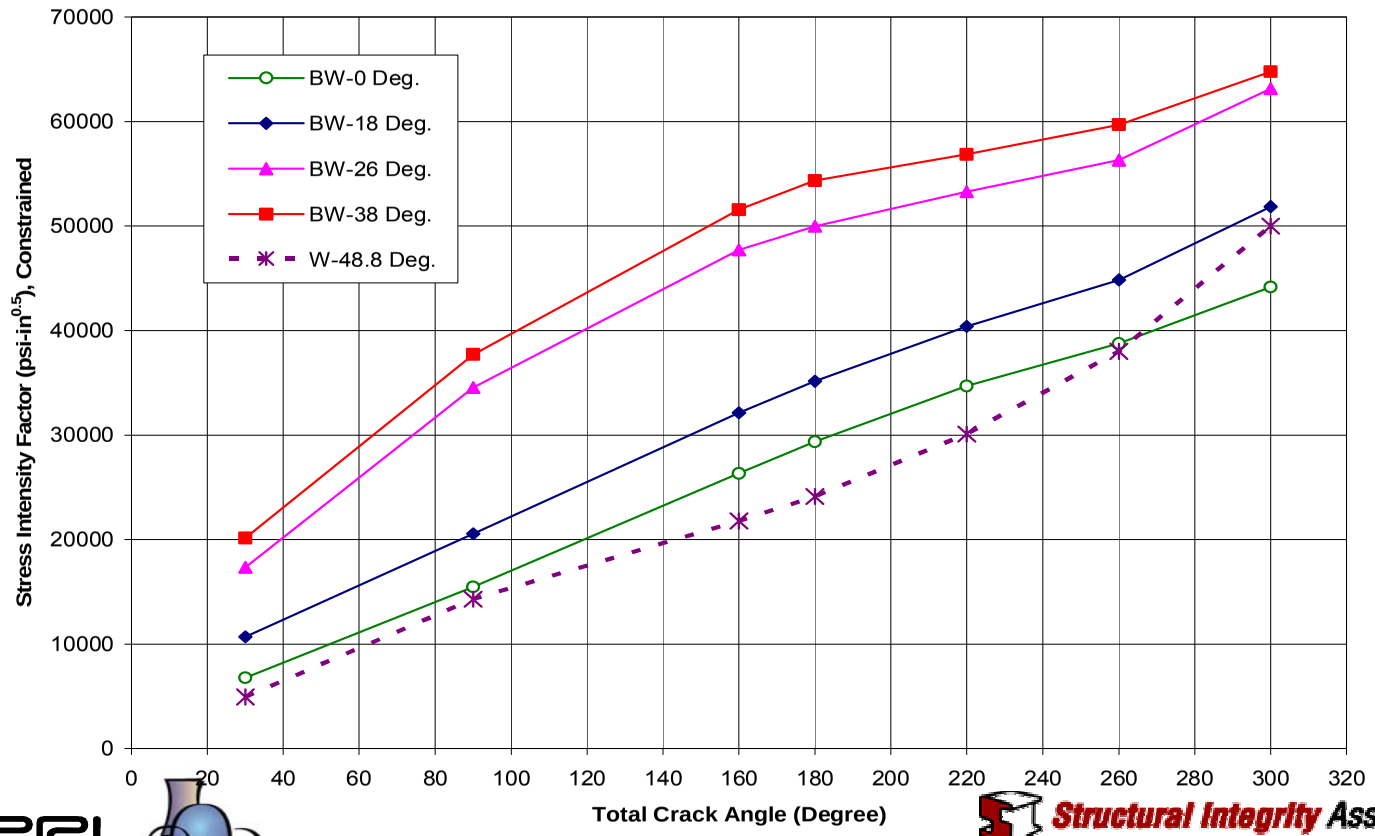
Stress Intensity Factors
Plants A & C - Uphill Cracking

Stress Intensity Factor Comparison - B&W vs. W Heads
Uphill Flaws; Envelop Stress



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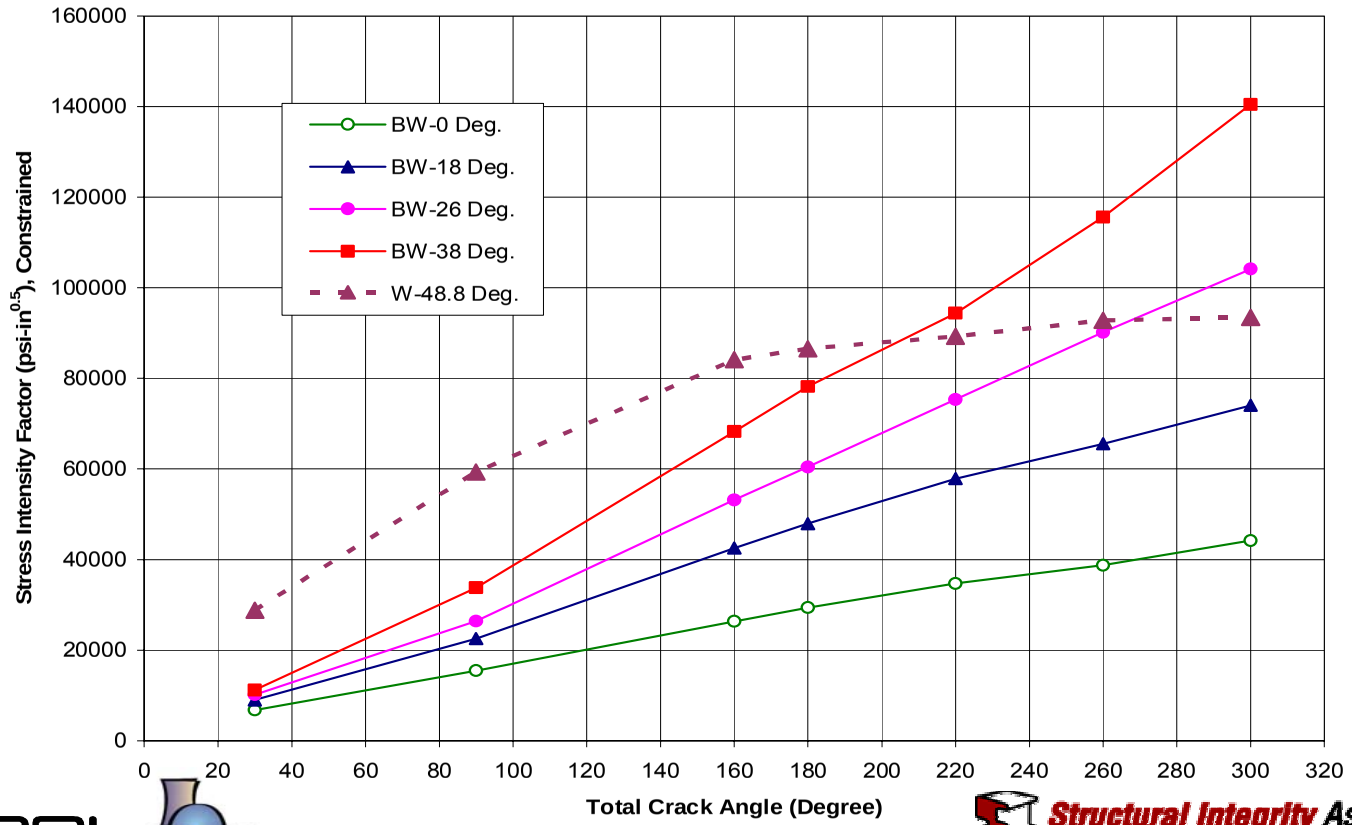
Stress Intensity Factors
Plants A & C - Downhill Cracking

Stress Intensity Factor Comparison - B&W vs. W Heads
Downhill Flaws; Envelop Stress



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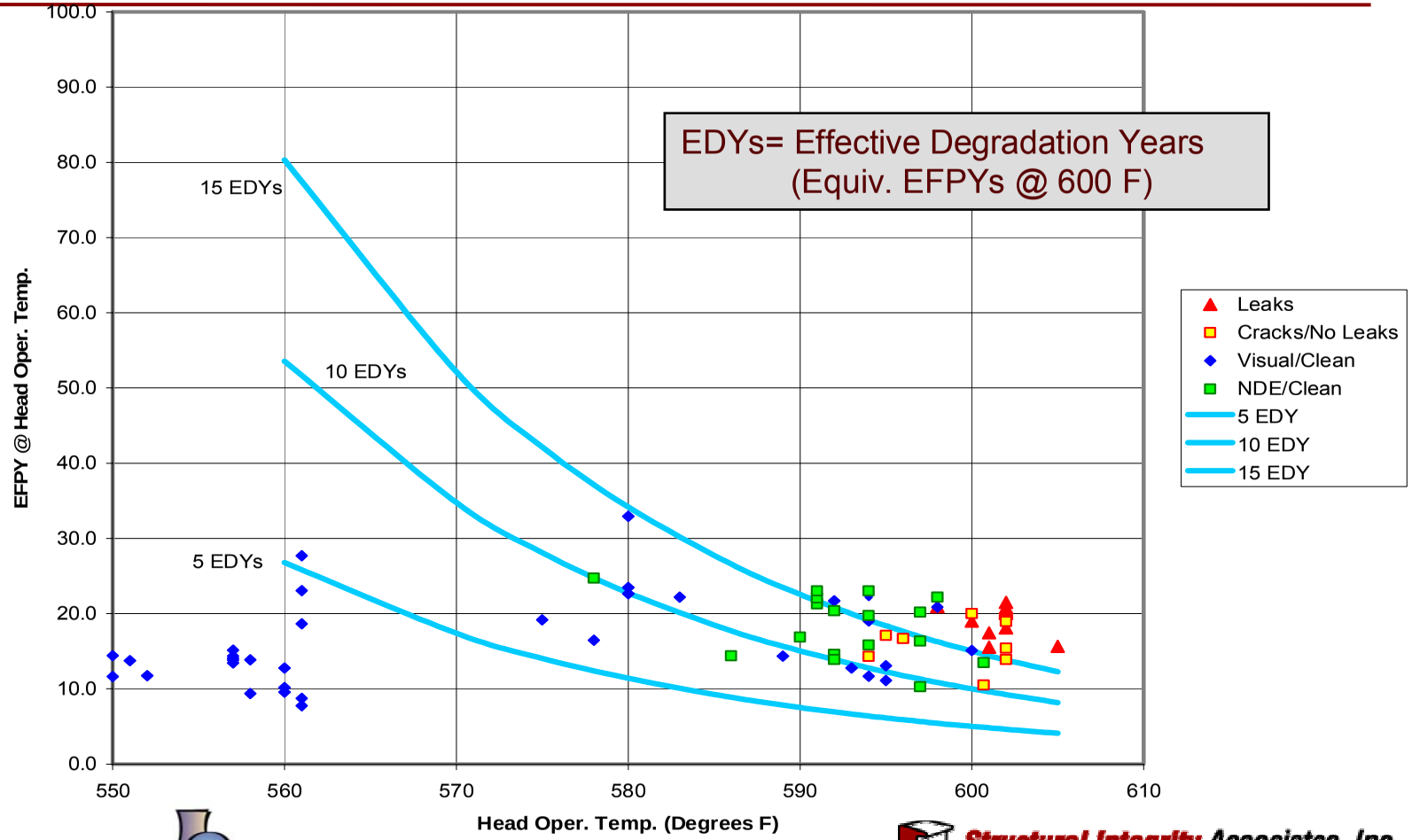
Weibull Model of Time to First Leakage or Cracking

- **"WEI-BAYES" analysis method***
  - Weibull Slope = 3.0 assumed from prior Alloy 600 experience
  - Determine best fit through field inspection results
- **Considers only plants that have performed non-visual NDE thru Spring-03**
  - Population = 30 plants
  - 12 had leaks or significant cracking
  - 18 inspected & clean treated as "Suspensions"
  - Plants that performed only visual examinations excluded
- **Plants w/ multiple cracked or leaking nozzles extrapolated back to time to first leak or crack**
  - w/ same assumed Weibull slope of 3

***R. B. Abernathy, "The New Weibull Handbook, Reliability and Statistical Analysis for Predicting Life, Safety, Survivability, Risk, Cost and Warranty Claims," Fourth Edition, Sept. 2000*

Summary of Inspections & Results (Thru Spring-03)



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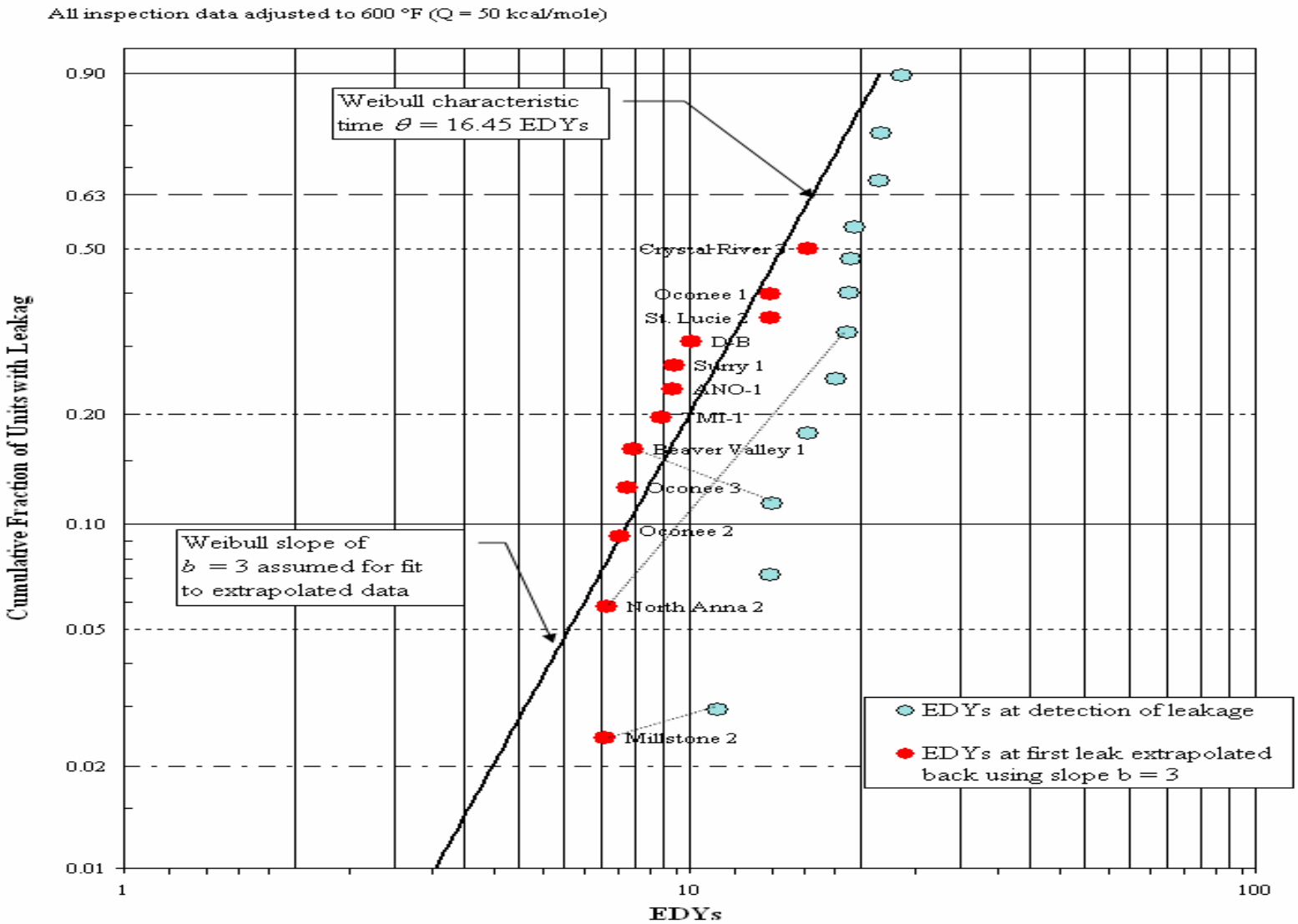
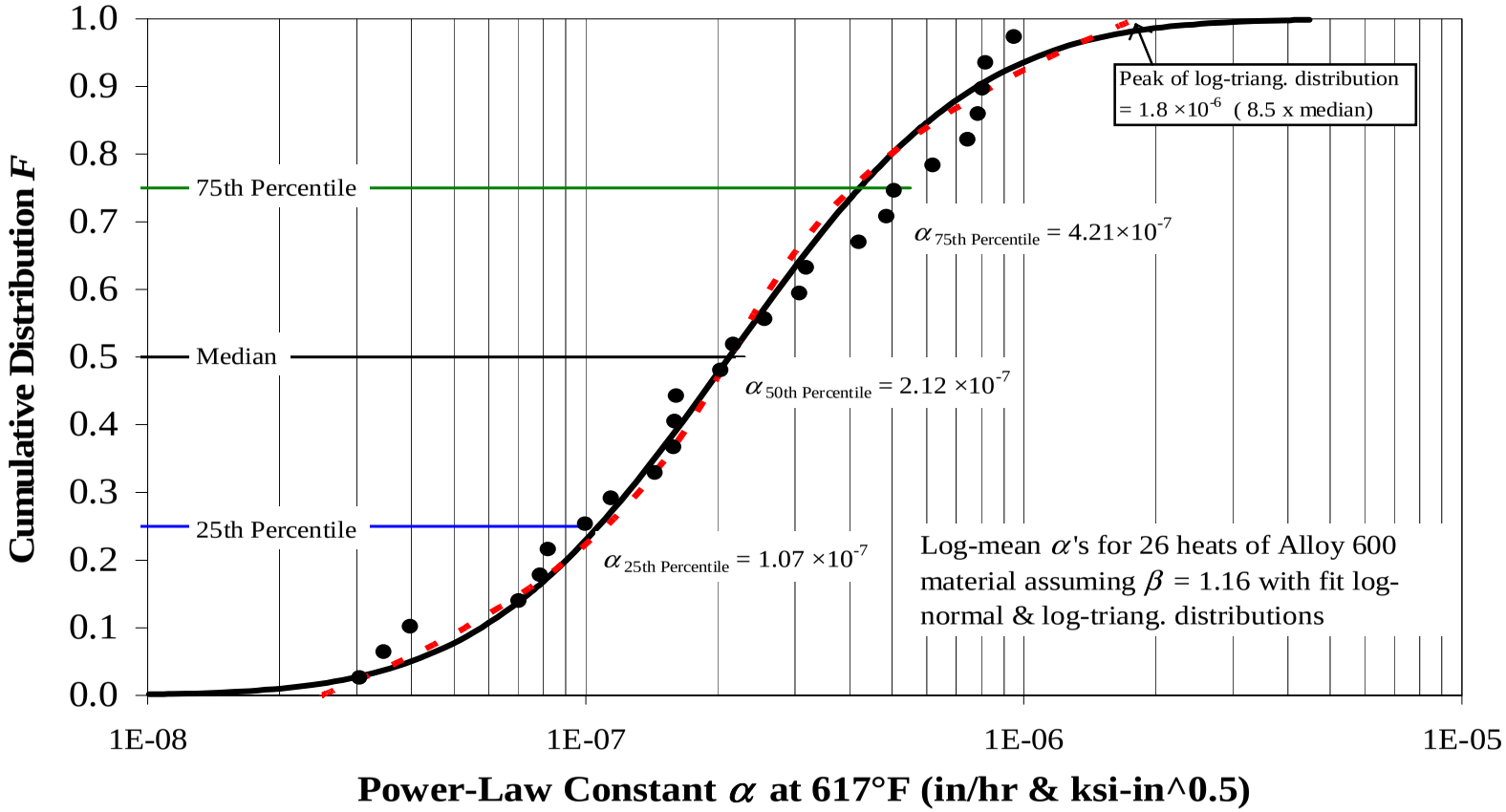

All inspection data adjusted to 600 °F (Q = 50 kcal/mole)
Weibull characteristic time θ = 16.45 EDYs
Weibull slope of b = 3 assumed for fit to extrapolated data
Crystal River 3
Oconee 1
St. Lucie 2
D/B
Surry 1
ANO-1
MI-1
Beaver Valley 1
Oconee 3
Oconee 2
North Anna 2
Millstone 2
EDYs at detection of leakage
EDYs at first leak extrapolated back using slope b = 3
Cumulative Fraction of Units with Leakag
0.90
0.63
0.50
0.20
0.10
0.05
0.02
0.01
1
10
100
EDYs

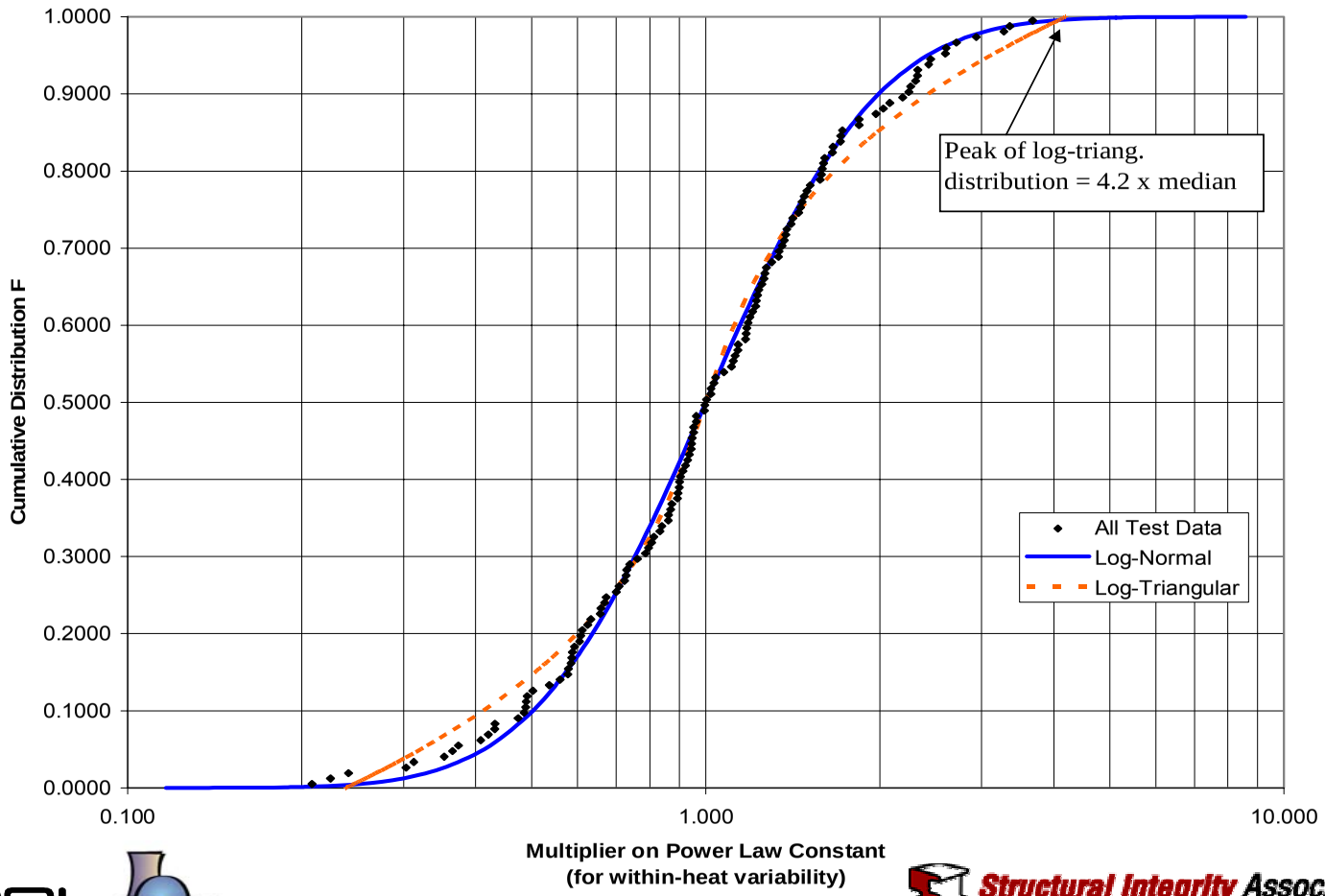
Material Crack Growth Rate Statistics

- **Crack growth statistics incorporate latest MRP-55 qualified data set**
  - 26 heats
  - 158 data points
- **Statistical distributions developed for heat-to-heat variation as well as for variability of CGR within a specific heat**
- **Statistical sampling of CGR for PFM analysis assumed to be correlated with Weibull statistics for time to leakage (I.e. nozzles which leak early tend to be sampled from high end of CGR distribution)**

CGR Distributions Based on Heat Data



Multiplier on CGR Distribution for Within-Heat Variability



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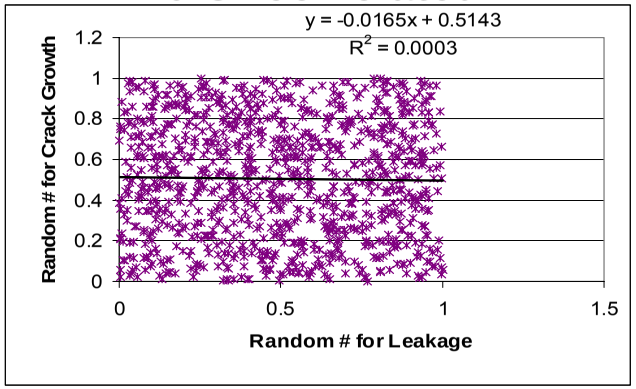
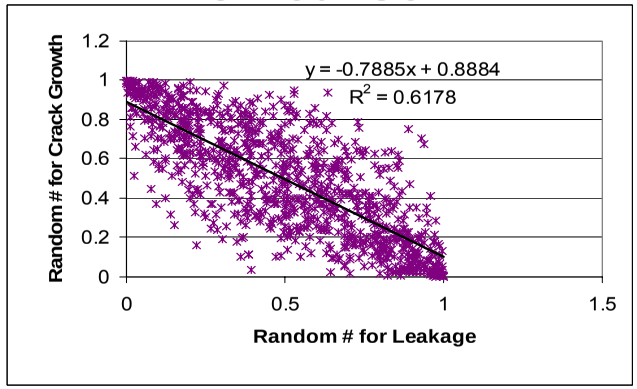
Correlation of CGR with Time-to-Initiation

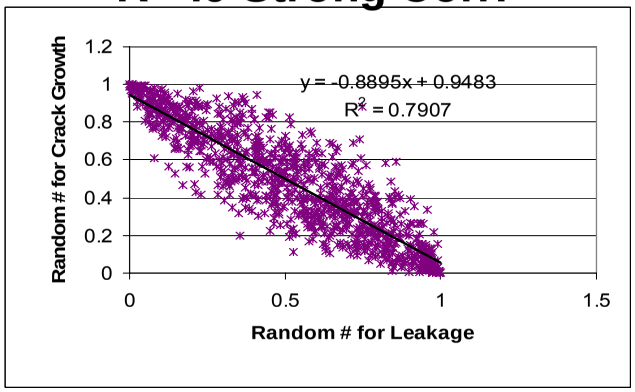
R=0 Uncorrelated



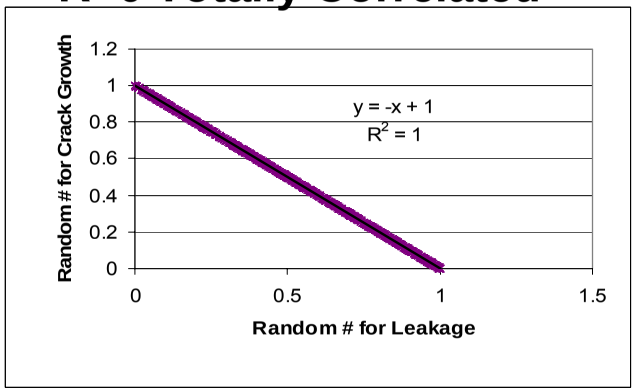
R=-.8 Mod. Corr.



R=-.9 Strong Corr.



R=0 Totally Correlated



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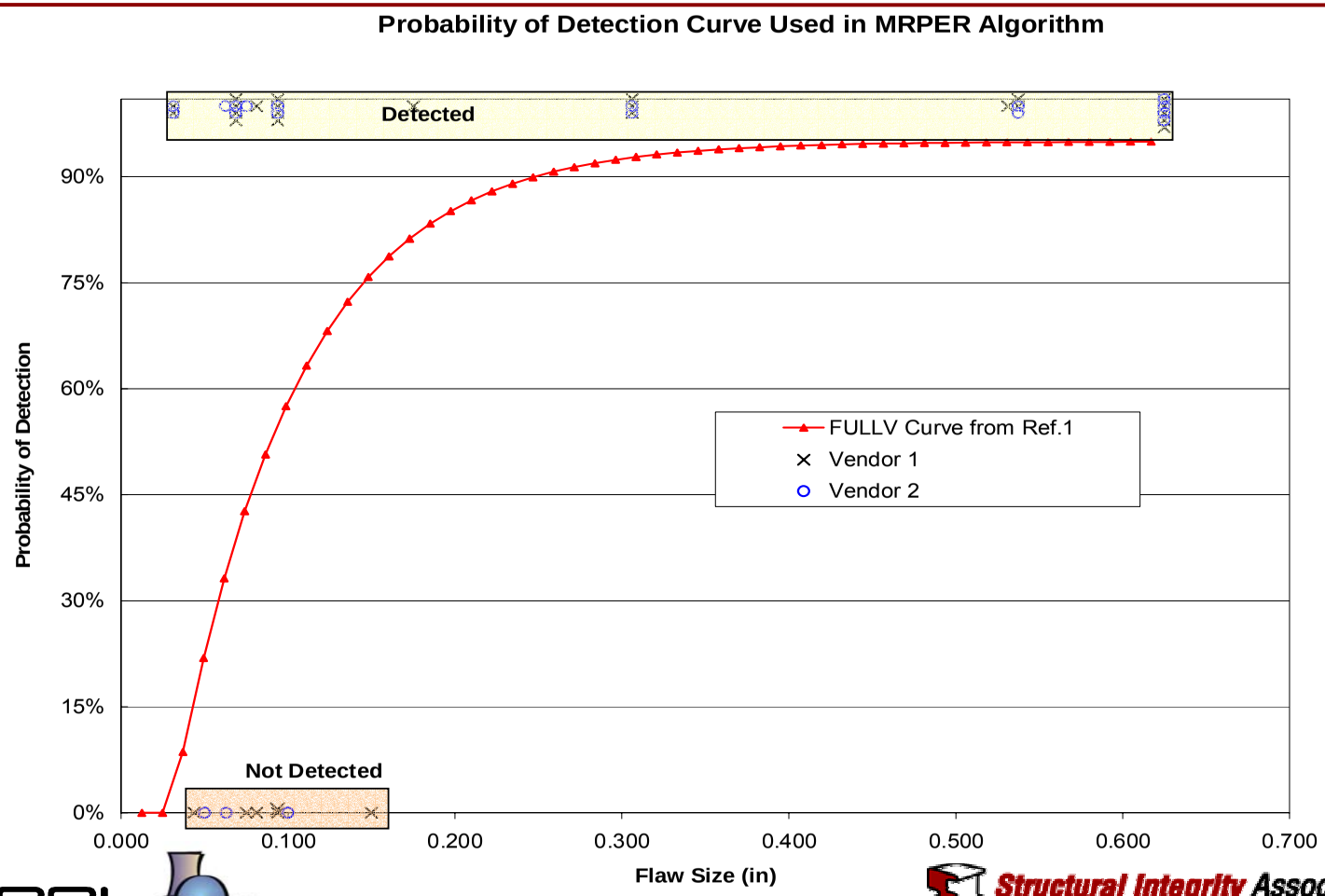
Inspection Interval Analysis
Probability of Detection for NDE

- **Non-Destructive Examinations (NDE)**
  - POD = f(crack depth) per EPRI-TR-102074[1]
  - 80% Coverage Assumed
- **POD Curve Compared to Vendor Inspection Demonstrations**

[1]Dimitrijevic, V. and Ammirato, F., "Use of Nondestructive Evaluation Data to Improve Analysis of Reactor Pressure Vessel Integrity, " EPRI Report TR-102074, Yankee Atomic Electric Co. March 1993

POD Curve for NDE (Illustrating Comparison to Vendor Demonstrations)



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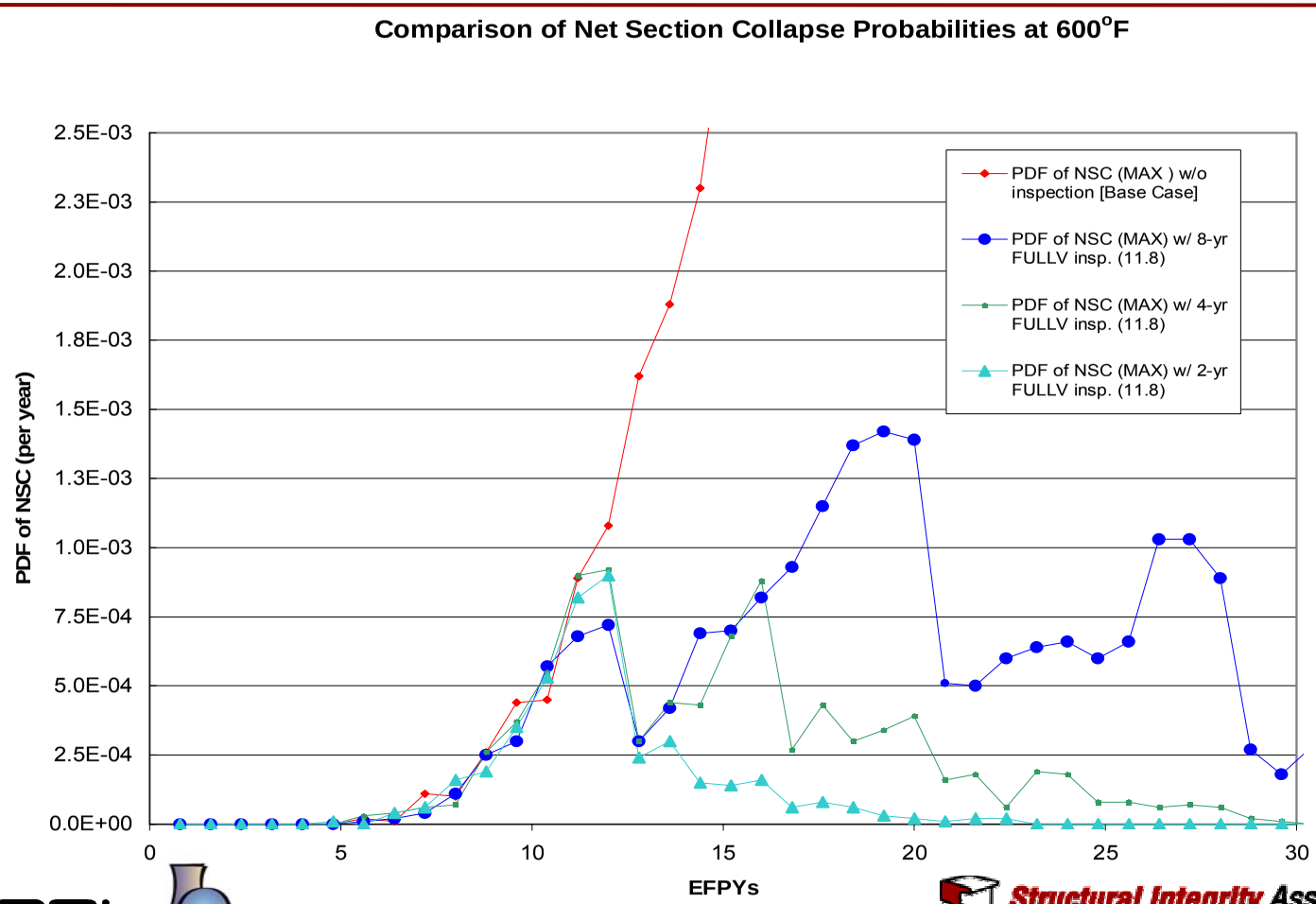
Effect of NDE on Prob. Nozzle Ejection

(Plant A, 600ºF Head, Various Inspection Intervals)



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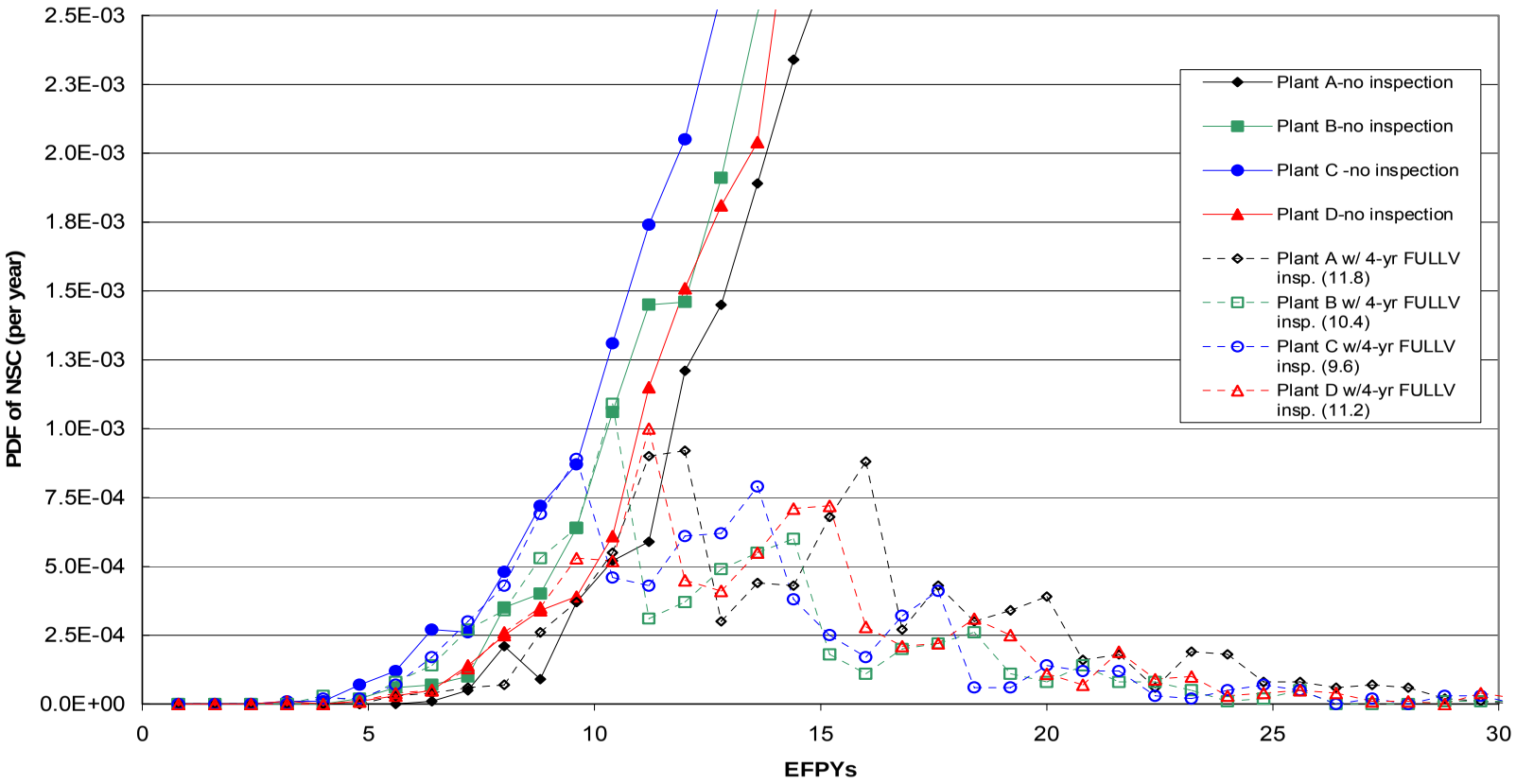
Summary of Results for Characteristic Plants

(Plants A,B,C&D, 600ºF Head, 4-Yr Inspection Intervals)



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Deterministic Crack Growth Analyses

- MRP-55 CGR correlations used - 75th percentile, with factor of 2 applied for OD connected circumferential flaws (severe environment effect)
- Stress Intensity Factors for envelope stress plane used to compute crack growth from 30° to ASME Section XI allowable crack length (~ 300°)
- Analyses performed for steepest angle (worst case) nozzles in Plants A - D
- Analyses run for various head temperatures using standard activation energy (31.05 kcal/mole) temperature adjustment on crack growth law
- Results Indicate that probabilistic-based inspection intervals are conservative

Deterministic Crack Growth Analysis Results (Plants A & B)

TEMPERATURE °F	UPHILL (EFPH)	UPHILL (EFPY)	DOWNHILL (EFPH)	DOWNHILL (EFPY)
580	218000	24.89	205000	23.40
590	168000	19.18	158000	18.04
600	131000	14.95	123000	14.04
602	125000	14.27	117000	13.36
605	116000	13.24	109000	12.44

Plant A – 38.5º Nozzle

TEMPERATURE °F	UPHILL (EFPH)	UPHILL (EFPY)	DOWNHILL (EFPH)	DOWNHILL (EFPY)
580	468000	53.4	149000	17.0
590	362000	41.3	115000	13.1
600	281000	32.1	90000	10.3
602	267000	30.5	85000	9.7
605	248000	28.3	79000	9.0

Plant B – 43.5º Nozzle

Deterministic Crack Growth Analysis Results (Plants C & D)

TEMPERATURE °F	UPHILL (EFPH)	UPHILL (EFPY)	DOWNHILL (EFPH)	DOWNHILL (EFPY)
580	no growth	no growth	126000	14.38
590	no growth	no growth	97000	11.07
600	no growth	no growth	76000	8.68
602	no growth	no growth	72000	8.22
605	no growth	no growth	67000	7.65

Plant C – 48.8º Nozzle

TEMPERATURE °F	UPHILL (EFPH)	UPHILL (EFPY)	DOWNHILL (EFPH)	DOWNHILL (EFPY)
580	215000	24.54	218000	24.89
590	167000	19.06	169000	19.29
600	130000	14.84	131000	14.95
602	123000	14.04	125000	14.27
605	115000	13.13	116000	13.24

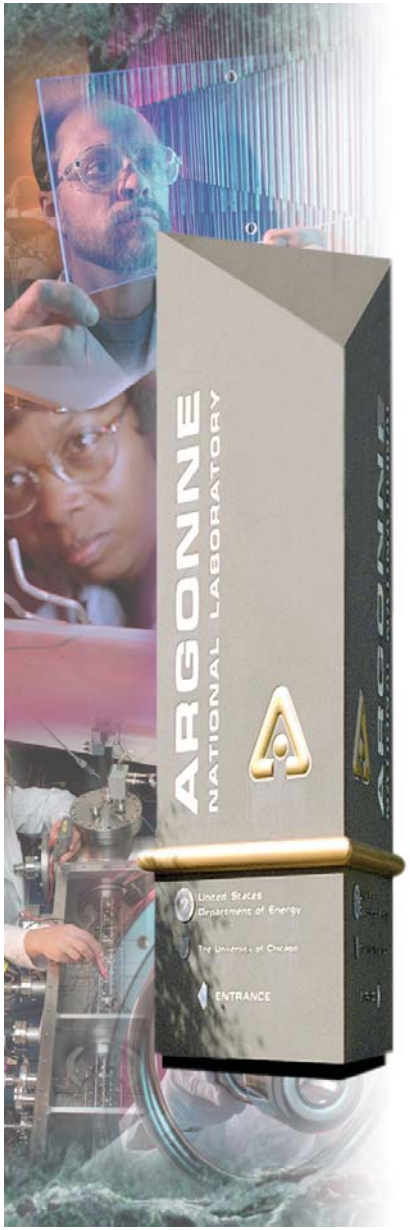
Plant D – 49.7º Nozzle

Highlights of Analysis

- Extensive finite element stress intensity factor computations for set of “characteristic plant types”
- Updated Weibull model of field inspection data including Spring-03 results
- Statistical characterization of latest laboratory PWSCC crack growth rate compilation
- Method to correlate CGRs with crack initiation – early crack initiation => more rapid crack growth
- Effects of inspection POD (correlated with inspection demonstrations) and interval evaluated

Conclusions

- **PFM demonstrates that RPV top head nozzles meet safety limit for nozzle ejection (< 10^{-3} per plant year) with reasonable inspection intervals**
- **Deterministic fracture mechanics analysis supports longer inspection intervals**
- **Several conservatisms in analysis**
  - Envelope stresses used to compute Ks
  - Entire fleet assumed to be from single Weibull population (even though data indicative of a batch effect, with worst heads being replaced)
  - Crack growth rates assumed correlated with time to crack initiation
  - Conservative POD curve assumed, with 80% coverage



Parametric studies of CRDM Head Failures

W. J. Shack

September 30, 2003

Argonne National Laboratory

Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Introduction

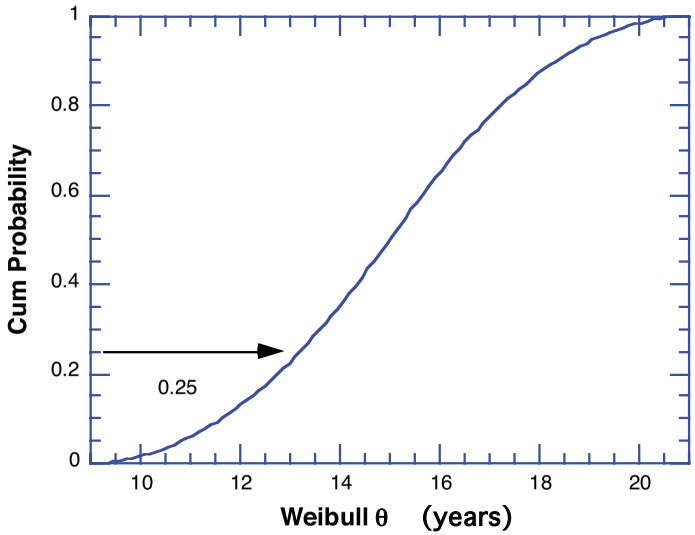
- Discuss three types of calculations
  - Distribution of the probability of failure (ejection) of a nozzle
  - Distribution of the probability of failure (nozzle ejection) of a vessel head
  - Expected numbers of leaks, large cracks, nozzle ejections for a population of plants with the same head temperatures, EFPYs, and numbers of nozzles as the 31 operating plants whose inspection data are used to estimate the statistical parameters describing leakage of the nozzles
- Distributions can be interpreted as describing the range of behavior expected in the whole population of nozzles or heads or as the uncertainty in the prediction of the failure of a specific Alloy 600 nozzle or head assuming that we know only its operating temperature and the number of EFPYs of operation
  - Distributions are broad — about 3 orders of magnitude at any given time
- Results are conservative — e.g., true 95th %tile of probability of failure is lower than the estimates presented here

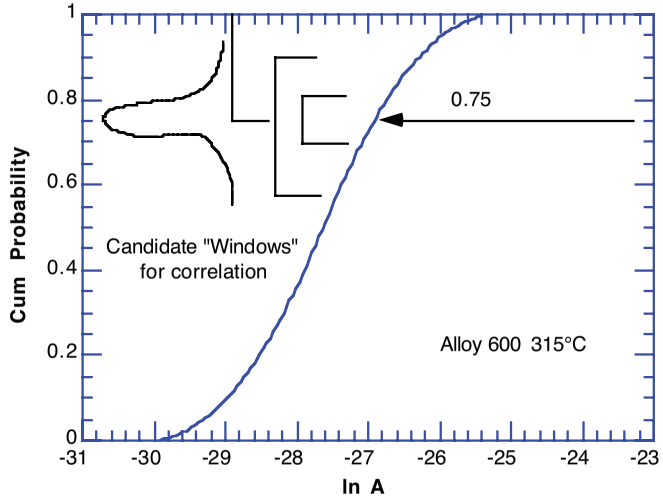
Primary Elements of Model for failure by SCC

- Weibull model for likelihood and initiation time determined from inspection results
  - Initiation assumed to result in a throughwall circumferential crack
  - More detailed modeling of initiation would have to account for growth by multiple initiation and linking and throughwall growth of part–through cracks. Current models assume growth is dominated by fracture mechanics growth of circ cracks.
- K solutions for circumferential cracks and data on crack growth rates used to predict growth
  - EMC^2 solutions for center and sidehill K
  - MRP-55 distribution for base metal (refit by log triangle) used to describe CGRs
- Time to initiation and CGR assume correlated (short initiation time correlated with high CGR); initiation and K uncorrelated

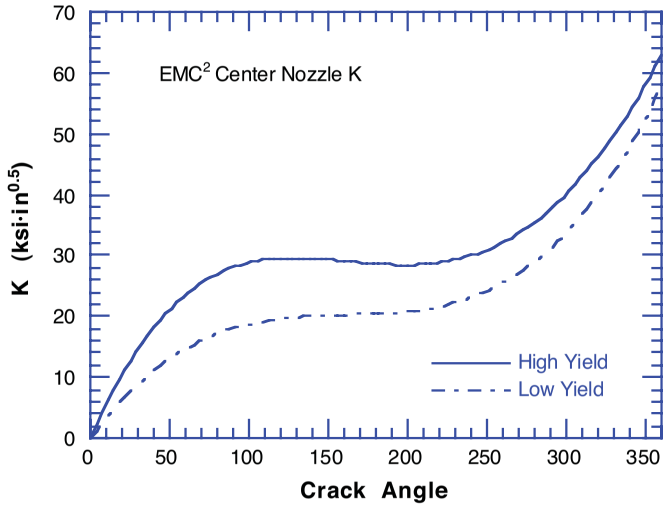
Correlation of Initiation and CGR and K values

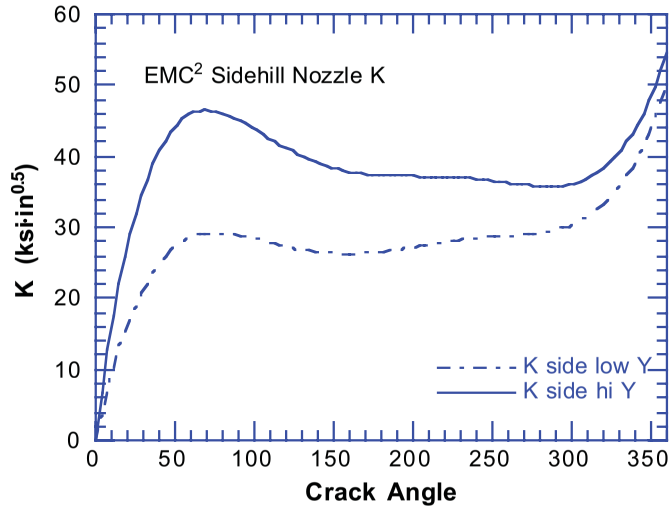
- Correlation between time to initiation and CGR





  - Susceptibility to initiation and CGR growth rate are expected to be correlated. Details of the correlation can have a strong impact on results depending on how much the impact of the “high” CGR tail is affected.
  - For specific cases, a conservative distribution for the scale parameter would lead to nonconservative estimates of the CGR (the 25th %tile value in the conservative distribution could be say the 10th %tile value in the realistic case)





- K values are dominated by welding residual stresses until circumferential cracks are very large
- EMC^2 solutions show strong dependence on yield stress.
- Random variable α used to sample K solutions $K = (1-\alpha)K_{low} + \alpha K_{high}$

Probabilistic initiation models

- Weibull distribution used to describe probability of initiation
  - Staelhe, Gorman et al. have popularized the use of empirical statistical models to describe initiation. Weibull cumulative probability is

$$F(t) = 1 - \exp\left[-\left(\frac{x}{\theta}\right)^{b}\right]$$

where θ is time until cumulative probability of a leak is 0.63 and b characterizes rate of acceleration with age

  - Typical applications of Weibull statistics assume we have data on failures at several times.

    Plot of lnln [1/(1-F)] vs ln t yields straight line from which slope and scale parameter can be determined

  - For CRDM prior knowledge have been used to select b = 3

    Lab data consistent with b = 3, PWSCC in SG tubes gives values ranging from 1.5 to 6 with a median value about 3

    Analysis of CRDM cracking data seems to suggest higher values, but for purposes of predicting initial failures 3 is a conservative choice

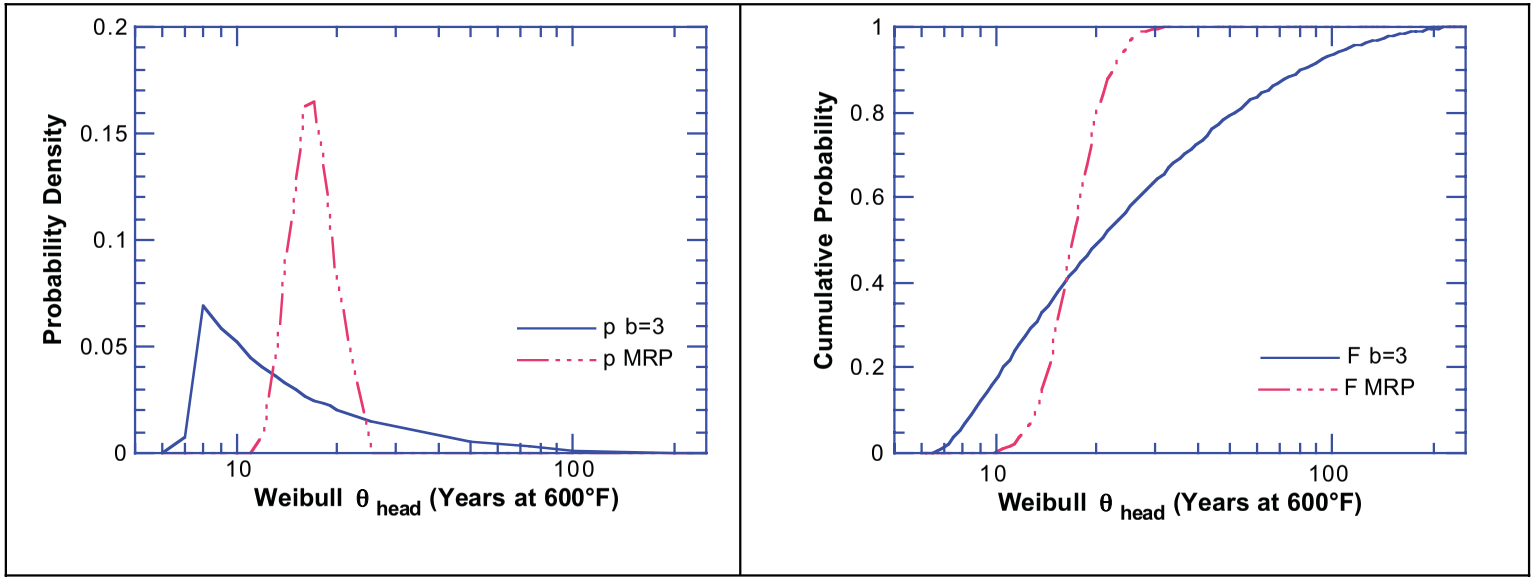
- Estimates of population bounds on Weibull scale factor
  - Consider the likelihood function L:

$$L = \prod_{i=1}^{N} \int_0^{\infty} p(\theta) \frac{N_i!}{n_{f_i}!(N_i - n_{f_i})!} \left\{ W(t_i,\theta)^{n_{f_i}} \left(1 - W(t_i,\theta)\right)^{(N_i - n_{f_i})} \right\} d\theta$$

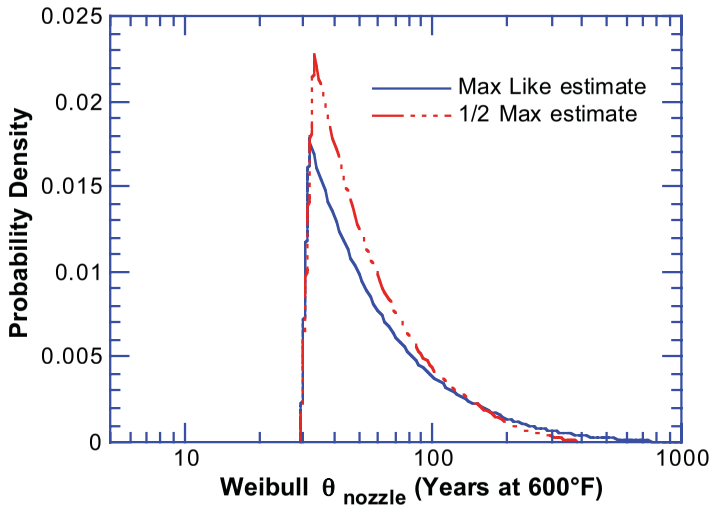
where $p(\theta)$ is the probability distribution function for θ, $W(t_i,\theta)$ is the Weibull cumulative function for time t_i and shape parameter θ, n_{f_i} is the number of leaking nozzles for plant i, N_i is the total number of nozzles for plant i, and N is the total of number of plants considered. The likelihood function is just the usual binomial probability for n_{f_i} items out of a collection of N_i items.

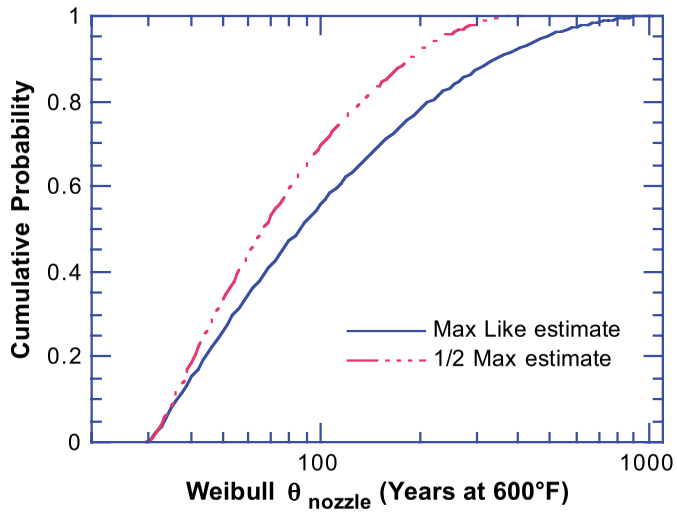
  - Triangular, log-triangular, Weibull, and lognormal distributions for θ were considered. The integrals were evaluated numerically and the distribution parameters varied to find the maximized solution.

Plant	Head Temp °F	EFPYs	EDYs	Nozzles	Leaks/Cracks
ANO 1	602	19.5	19.6	69	8
ANO-2	590	16.8	11.2	81	0
Beaver Valley 1	595	17.2	14.0	65	4
Calvert Cliffs 2	593.7	20.4	15.8	65	0
Cook 1	580	24.8	10.0	79	0
Cook 2	600.7	13.5	13.9	78	0
Crystal River 3	601	15.5	16.2	69	1
Davis-Besse	605	15.7	19.2	69	5
Farley 1	596.5	20.2	17.5	69	0
Farley 2	596.9	17.9	15.8	69	0
Indian Point 2	585.5	14.4	8.0	97	0
Indian Point 3	593.5	20.5	15.7	78	0
Millstone 2	593.9	14.3	11.2	69	3
North Anna 1	600.1	19.9	20.0	65	0
North Anna 2	600.1	19.9	19.0	65	14
Oconee 1	602	20.2	21.9	69	3
Oconee 2	602	21.9	23.7	69	19
Oconee 3	602	20.0	21.7	69	14
Palo Verde 1	592	14.6	10.6	97	0
Palo Verde 2	591.7	14.0	10.0	97	0
Point Beach 1	591.6	20.4	14.5	49	0
Robinson 2	598	22.0	20.3	69	0
San Onofre 2	590.5	22.5	15.3	91	0
San Onofre 3	590.6	22.4	15.3	91	0
Sequoyah 1	580	5.0	1.5	78	0
St. Lucie 1	590.6	23.1	15.7	77	0
St. Lucie 2	595.6	16.7	13.9	91	1
Surry 1	597.8	20.9	19.1	65	6
TMI 1	601	17.4	18.2	69	6
Turkey Point 3	594.4	23.0	18.3	65	0



- Calculations actually done to find scale factor for probability of leakage of a nozzle. Presented here in terms of scale factor for a head with 69 nozzles from the same heat. For Weibull distributions $\theta_{head} = \theta_{nozzle} / n^{1/b}$
- Maximum Likelihood Estimate is much broader than MRP 6-03 distribution which is essentially an estimate of an "average" value and the uncertainty on that estimate





- Maximum is very broad. Value of upper end can be varied significantly with minor effect on the value of likelihood. Physically reasonable. Experience can tell us a lot about the most susceptible nozzles/heads but less susceptible materials involve substantial extrapolation
- Sensitivity calculation was done to determine a distribution where the lower bound value was fixed and the other values adjusted to give a likelihood equal to 1/2 the peak value
- In the 31 plant sample 84 leaks (& large cracks) were observed. For a plant population with the same operating times, temperatures, and number of nozzles as the 31 plant sample, the expected number of leaks are

Weibull scale factor distribution	Expected number of leaks in population
Maximum Likelihood Estimate	55.3 ± 15.3
1/2 Maximum Estimate	69.7 ± 15.7
MRP 6-03	25.6 ± 2.5

- Baysian Updates
  - Use generic distributions as prior distributions to get updated distribution

    For a plant that has n_f / no failures at time t:

$$\overline{p}(\theta) = \frac{\left(1 - W(t,\theta)\right)^N p(\theta)}{\int_0^\infty \left(1 - W(t,\theta)\right)^N p(\theta)\, d\theta}$$

$$\overline{p}(\theta) = \frac{\left\{W(t,\theta)^{n_f}\left(1 - W(t,\theta)\right)^{(N-n_f)}\right\} p(\theta)}{\int_0^\infty \left\{W(t,\theta)^{n_f}\left(1 - W(t,\theta)\right)^{(N-n_f)}\right\} p(\theta)\, d\theta}$$

  - One could also develop a “Huntington” or “CE” distribution

$$\overline{p}(\theta) = \frac{\prod_{k=1}^{N}\left\{W(t_k,T_k,\theta)^{n_{f_k}}\left(1 - W(t_k,T_k,\theta)\right)^{(N-n_{f_k})}\right\} p(\theta)}{\int_0^\infty \prod_{k=1}^{N}\left\{W(t_k,T_k,\theta)^{n_{f_k}}\left(1 - W(t_k,T_k,\theta)\right)^{(N-n_{f_k})}\right\} p(\theta)\, d\theta}$$

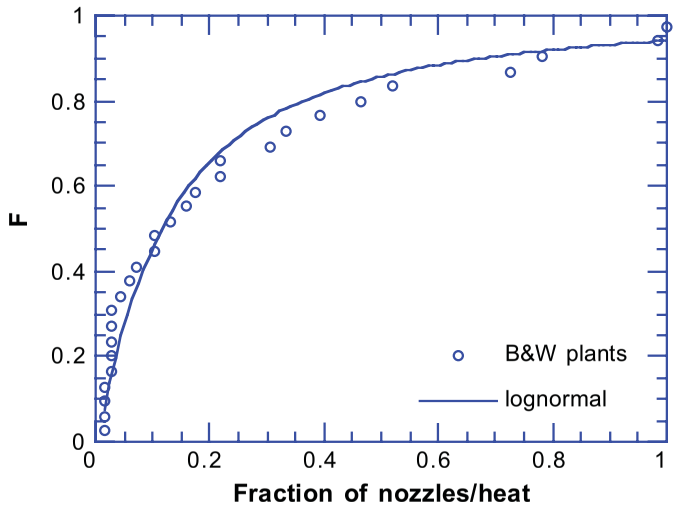
Probability of leakage for a head

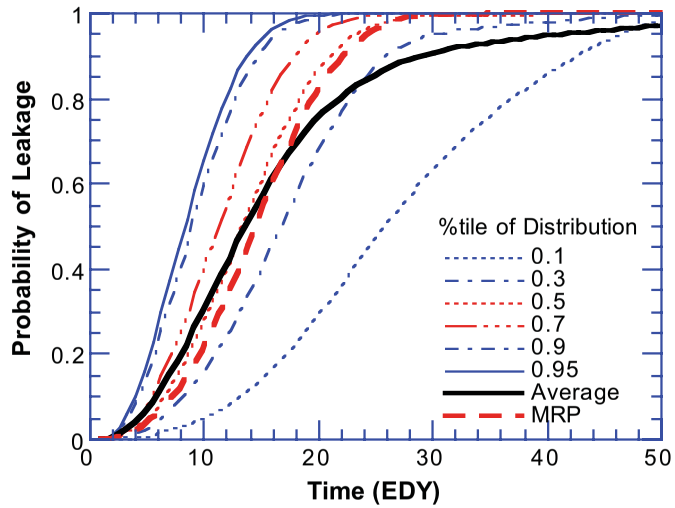
- Probablility of leakage from the head is computed from the probability of leakage for a nozzle. If all nozzles have the same susceptibility to leakage this is just

$$P_{leak} = 1 - (1 - P_{nozzle})^N$$

- Most plants appear to have multiple heats of material for nozzles. For the B&W plants the table shows the numbers of nozzles from different heats

ONS–1	ONS–2	ONS–3	ANO–1	Davis Bessie	TMI–1	CR–3
50	2	1	2	32	11	69
1	4	68	21	5	54	
15	27		7	23	1	
	15		36	9	2	
	7		1			
	12		2			
	2					





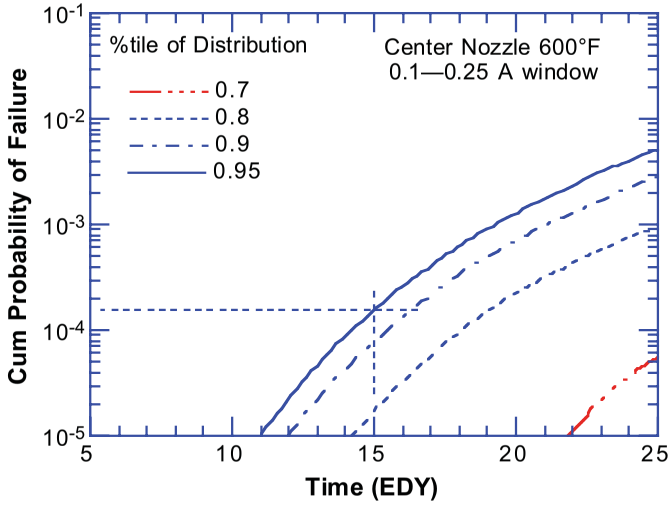
- Vessel head calculations are done assuming that the head contains from 1 to 7 heats of material and that the number of nozzles from a specific heat are distributed approximately lognormally.
- Results suggest a high probability of leakage for most plants after 10-15 EDY. MRP 6-03 Weibull scale factor is fairly close to the average value from the distribution.

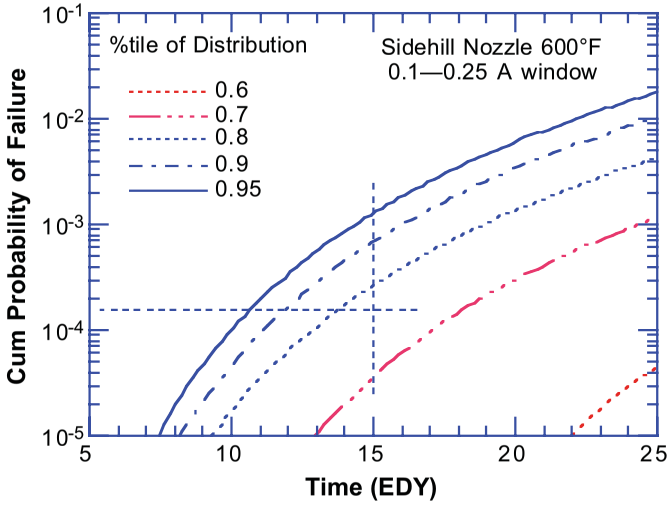
Probability of Failure of CRDM Nozzles

- Probability, $P(t_f < T)$, that a nozzle will fail at a time t_f less than T,

$$P(t_f < T) = \int_0^T p(t) P_c(t_f < T - t) dt$$

  - p(t) is the probability that a crack will initiate at a time t
  - $P_c(t_f < T - t)$ conditional probability a crack that initiates at t will fail at a time t_f less than T and is determined by fraction mechanics analysis.
- For a given choice of the Weibull scale factor [which determines p(t)] and stress intensity distribution [which together with the MRP-55 CGR distribution determines $P_c(t_f < T)$], integral gives a probability of failure for a nozzle
- Monte Carlo sampling from the distribution for the scale factor and for the parameter α to determine K gives distributions for the probability of failure of a nozzle

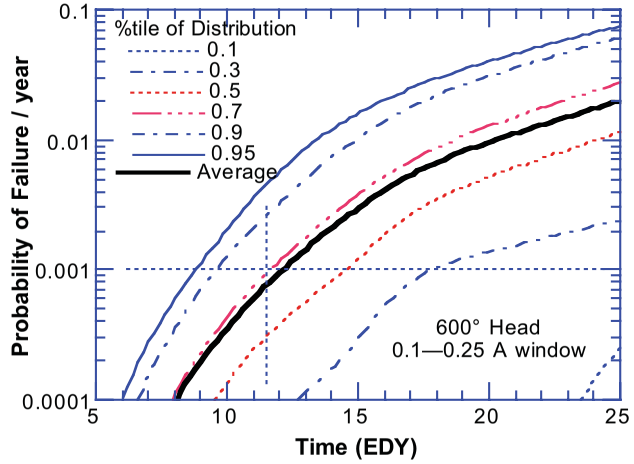


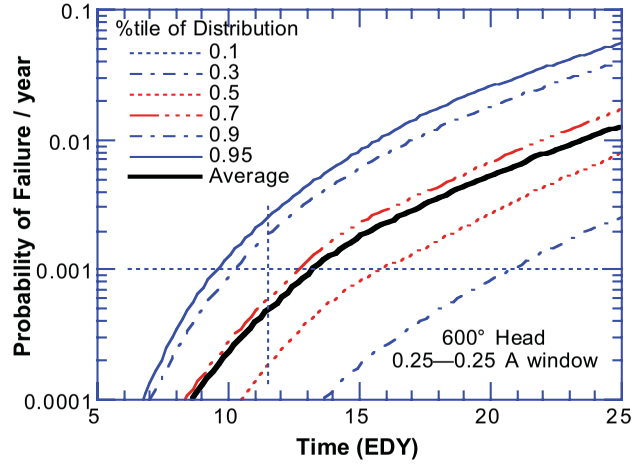


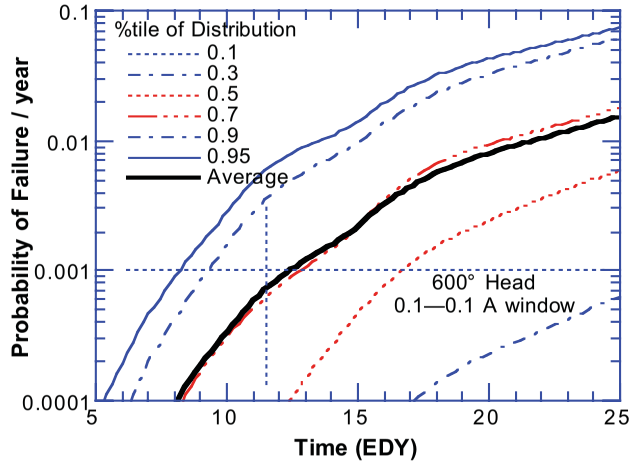
- Probability of failure depends strongly on temperature and choice of correlation window for CGRs
- Sidehill K from EMC^2 is for bounding sidehill angle. POF higher than for center nozzles because of higher K values, but there is overlap in the distributions; interpolation used for head calculations
- If all nozzles are from one heat of material then the POF for the head can be easily calculated from the probability of failure of the nozzles

$$P_{head} = 1-(1-P_{nozzle-c})^{N_c}(1-P_{nozzle-s})^{N_s}$$

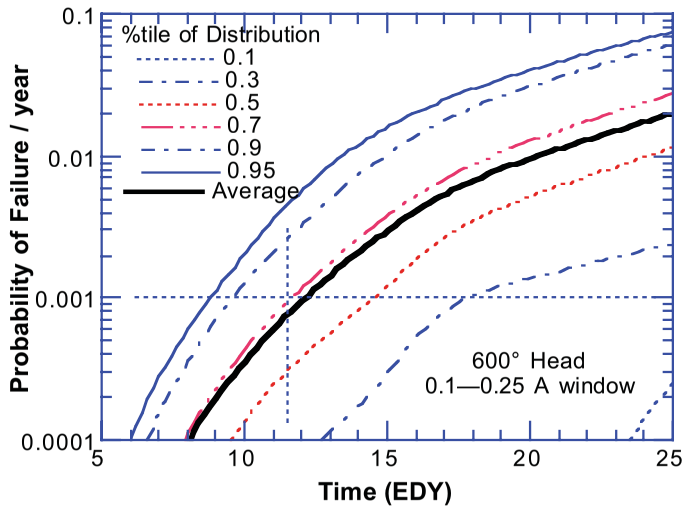
where N_c and N_s are the number of center and sidehill nozzles, respectively

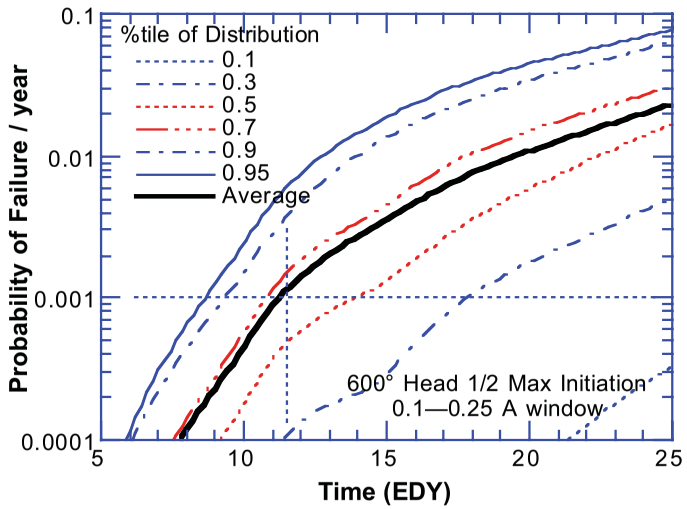




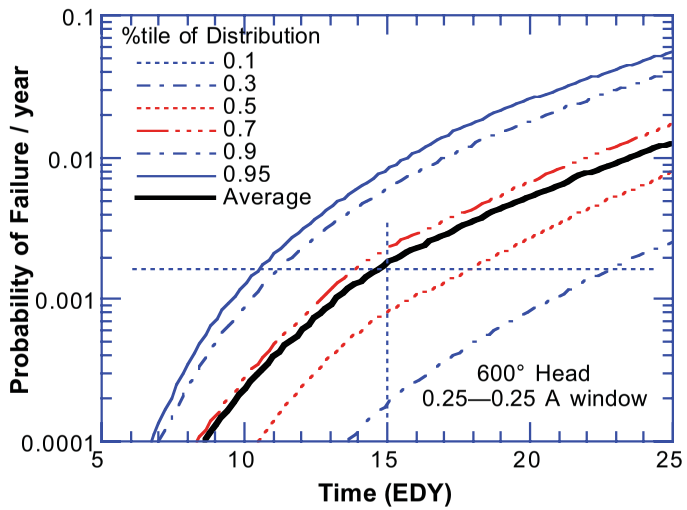


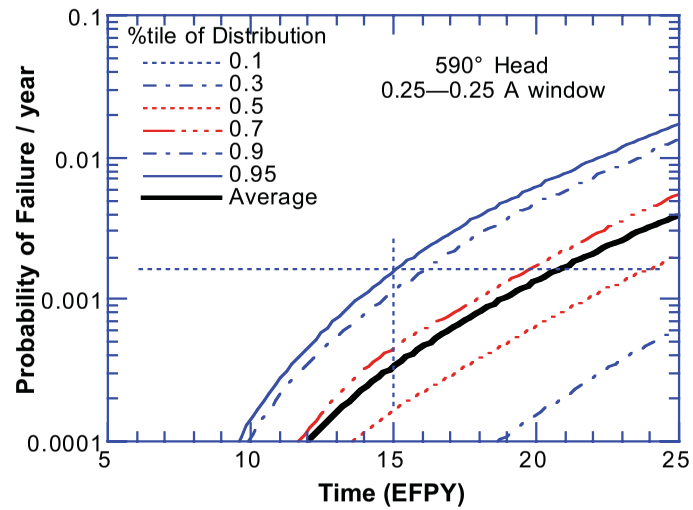
- Calculations for head use multiple heats based on B&W results
- MRP 6-03 POF bounds 70–80% of the population; represents average POF
- $POF_{95th\%tile} \approx 5 \cdot POF_{Average}$





- Using the more conservative 1/2 Maximum Likelihood distribution for the Weibull scale factor shifts the distributions only slightly





- Decreasing temperature does decrease POF significantly, but there is overlap in the distributions; $POF_{95\%tile}$ at 590°F is comparable to $POF_{average}$ at 600°F

Pioneering
Science and
Technology

Statistical Checks with operating experience

- For a plant population with the same operating times, temperatures, and number of nozzles as the 31 plant sample, we can compute expected number of large (165°) cracks and nozzle ejections

Model	165°Cracks	Nozzle Ejections
No Interpolation 0.1–0.25 A window	4.1 ± 1.0	1.1 ± 0.53
0.1–0.25 A window	2.8 ± 0.7	0.7 ± 0.33
0.25–0.25 A window	1.8 ± 0.6	< 0.7

- Statistical results suggest all the models are probably conservative. The statistical confidence is higher for the 0.1–0.25 window models.

Analysis of Weld Residual Stresses and Circumferential Through-Wall Crack K-solutions for CRDM Nozzles

D. Rudland [(1)], G. Wilkowski [(1)], Y.-Y. Wang [(1)], and W. Norris[(2)]

(1) Engineering Mechanics Corporation of Columbus

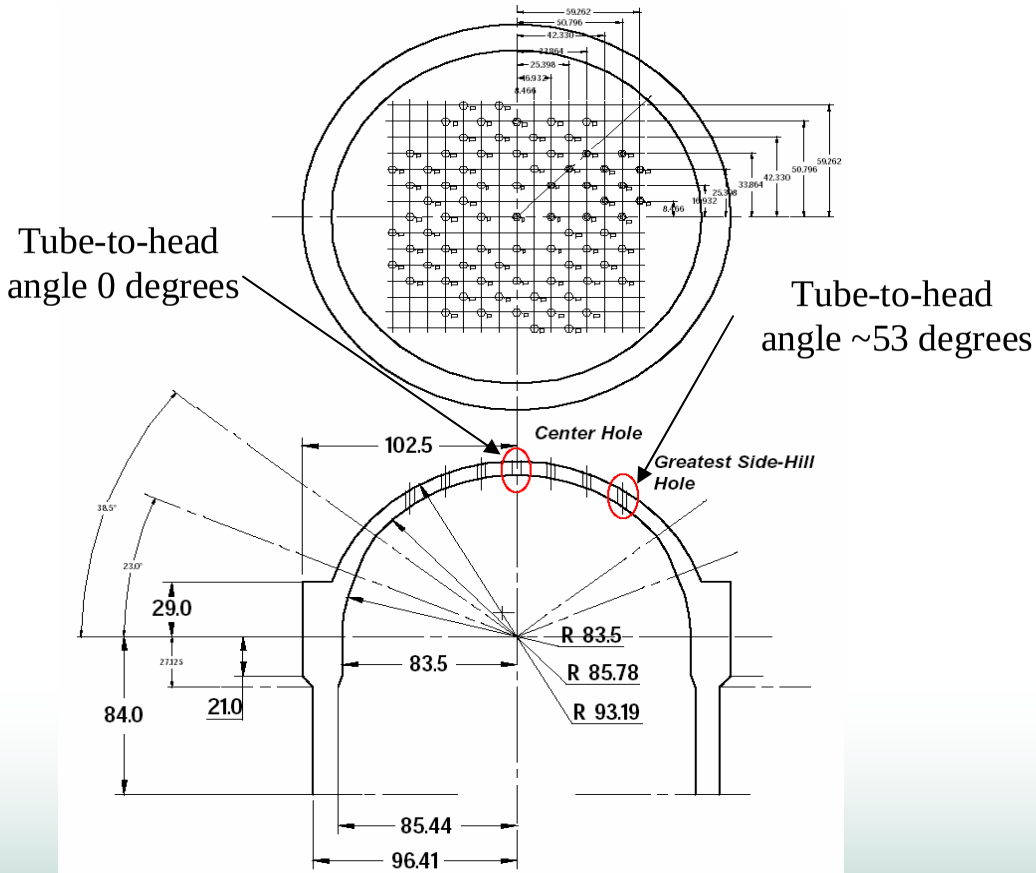
(2) U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Research

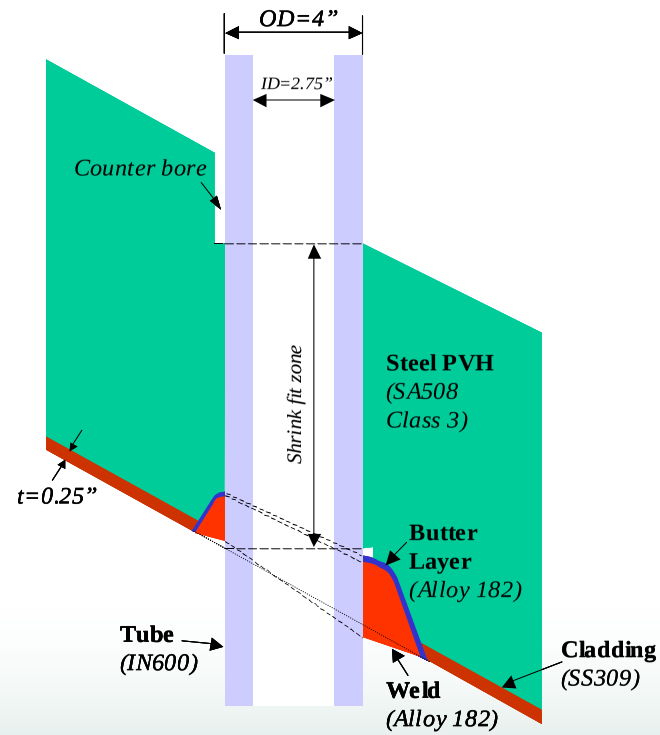
Objective of Program at Emc^2

- ***Main objective of the Emc^2 program is to develop a probabilistic computer code to predict the time from detection of leakage to failure for independent assessment of MRP/EPRI analysis.***
  - ***Residual stresses calculated and then circumferential through-wall crack inserted to determine crack-driving force.***
  - ***Dr. Sharif Rahman and B. N. Rao of Univ. of Iowa assisted Emc^2 in new Visual Fortran probabilistic code.***

- ***Numerous meetings with NRC staff and industry (significant amount of proprietary data).***

RPV Head Geometry Used in FE Analyses was a Westinghouse Design (PV-RUF drawings from ORNL)





Overall Modeling Strategy

- ***Weld Stress Analysis***
  - ***heat treatment for stress relieving***
  - ***installing tube into RPV head by shrinkage fit***
  - ***welding the J-groove***
  - ***hydro-testing***
- ***Stress Mapping***
  - ***Transferring all solution variables (stress tensor, strain tensors, displacement, BC) from weld stress mesh to a crack mesh***
- ***K-Solution Analysis***
  - ***Applying the service load (pressure and temperature)***
  - ***Unzipping the cracked mesh***
  - ***Calculation of K-solution***
  - ***Curve-fit for use in probabilistic code structure***

"Generic" CRMD Nozzle Fabrication Steps

- ***Rough drill the 4" diameter holes in the RPV head***
- ***Arc-gouge the groove area away and grind smooth***
- ***Butter the groove area with alloy 182 using SMAW process***
- ***Stress relieve the head at 1125F +/-25F***
- ***Finish machining the groove area***
- ***Finish reaming the main hole (interference area), and finish reaming the counter bore region***
- ***Install tube by shrinkage fit (tube submerged in liquid nitrogen)***
- ***Welding the J-weld with SMAW process and NDE at each 1/4 depth of weld***
- ***Hydro-test***
- ***Put into service at elevated temperatures***

The FE analyses followed the highlighted essential fabrication steps

Analyses Included Significant Factors Affecting The Crack-Driving Force Solutions

- ***Yield strength level of the tube***
- ***Interference fit***
- ***Weld bead layout sequence (using generic B&W design)***
- ***Weld size and number of weld passes (using generic B&W design)***
- ***Operating temperature of the reactor***
- ***Location of the nozzle penetrations***

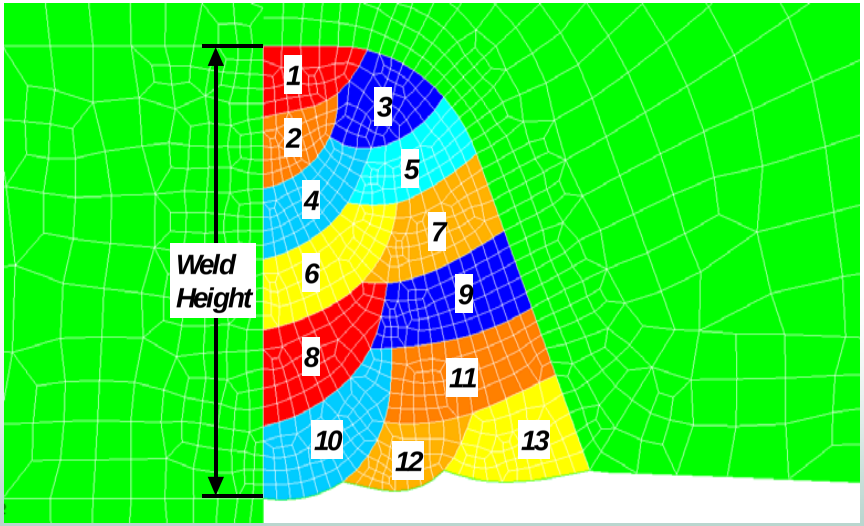
Analyses To Date Focused on Parametric Study of Center Hole and a Detailed 3D Model of The Steepest Side-Hill Nozzle

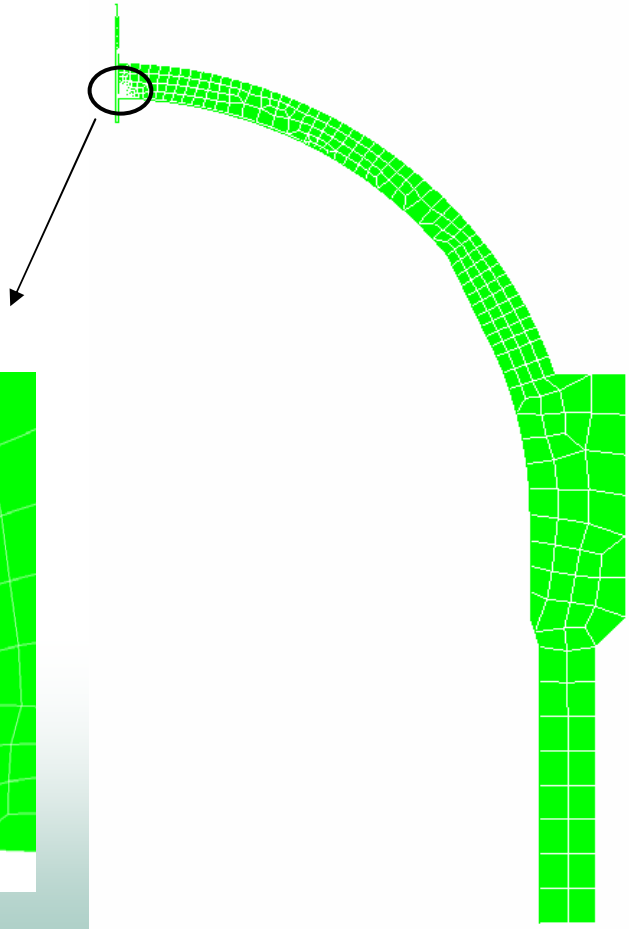
Case #	Interference fit, mm (mils)	Temperature, K (F)	Tube Yield Strength, MPa (ksi)	Weld Bead Layout Sequence	Nozzle Location	Weld Height, mm (in)	Number of Weld Passes
A	0 (0)	616.3 (605)	259 (37.5)	Tube-Head	Head Center	20 (25/32)	13
B	0.2286 (9)	616.3 (605)	259 (37.5)	Tube-Head	Head Center	20 (25/32)	13
C	0.0508 (2)	616.3 (605)	259 (37.5)	Tube-Head	Head Center	20 (25/32)	13
D	0.1143 (4.5)	616.3 (605)	259 (37.5)	Tube-Head	Head Center	20 (25/32)	13
E	0 (0)	566.5 (560)	259 (37.5)	Tube-Head	Head Center	20 (25/32)	13
F	0 (0)	616.3 (605)	259 (37.5)	Head-Tube	Head Center	20 (25/32)	13
G	0 (0)	616.3 (605)	444 (64.5)	Tube-Head	Head Center	20 (25/32)	13
H	0 (0)	616.3 (605)	259 (37.5)	Tube-Head	Head Center	28 (1.10)	20
I	0.2286 (9)	616.3 (605)	259 (37.5)	Tube-Head	Head Center	28 (1.10)	20
J	0.2286 (9)	616.3 (605)	259 (37.5)	Tube-Head	Head Center	36 (1.42)	27
K	0 (0)	616.3 (605)	259 (37.5)	Tube-Head	Greatest Side-hill	Variable	14

Base case analysis

FEM Mesh in Weld Analysis – Center hole

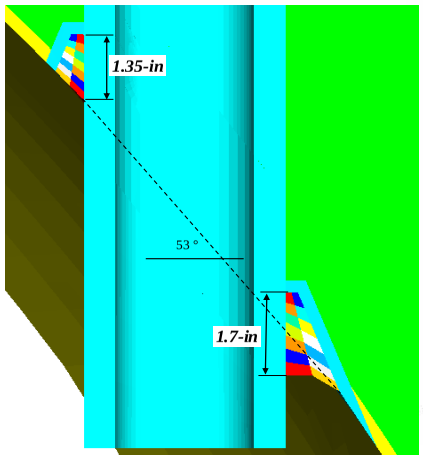
- *Axisymmetric weld analysis*
- *Solution revolved around tube axis for K-solution determination*
- *13 to 20 elements in each weld pass to deal with the temperature and stress gradients in the weld region*

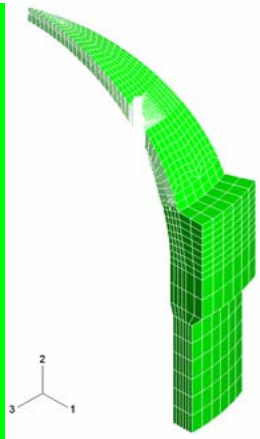


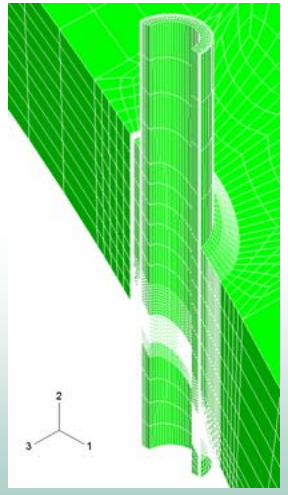


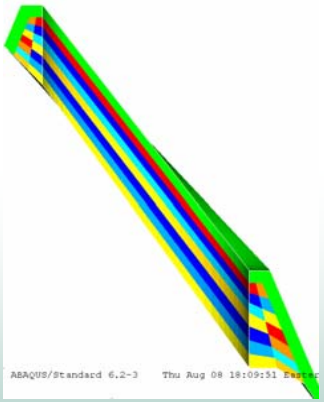
Side-Hill nozzle - Weld Geometry/Meshing

- *As with the centerhole, many factors went into deciding Sidehole geometry*
  - *Used steepest sidehill hole from previous drawing*
  - *Modeled 1/8 of head*
  - *Nozzle/weld details from various trips*
  - *Typical CRDM designs*
  - *Attempted to keep uphill and downhill area similar – Constant volume needed for weld analyses*
  - *Tried to keep some geometry (Bevel angle, etc) same between side-hill and center-hole models*



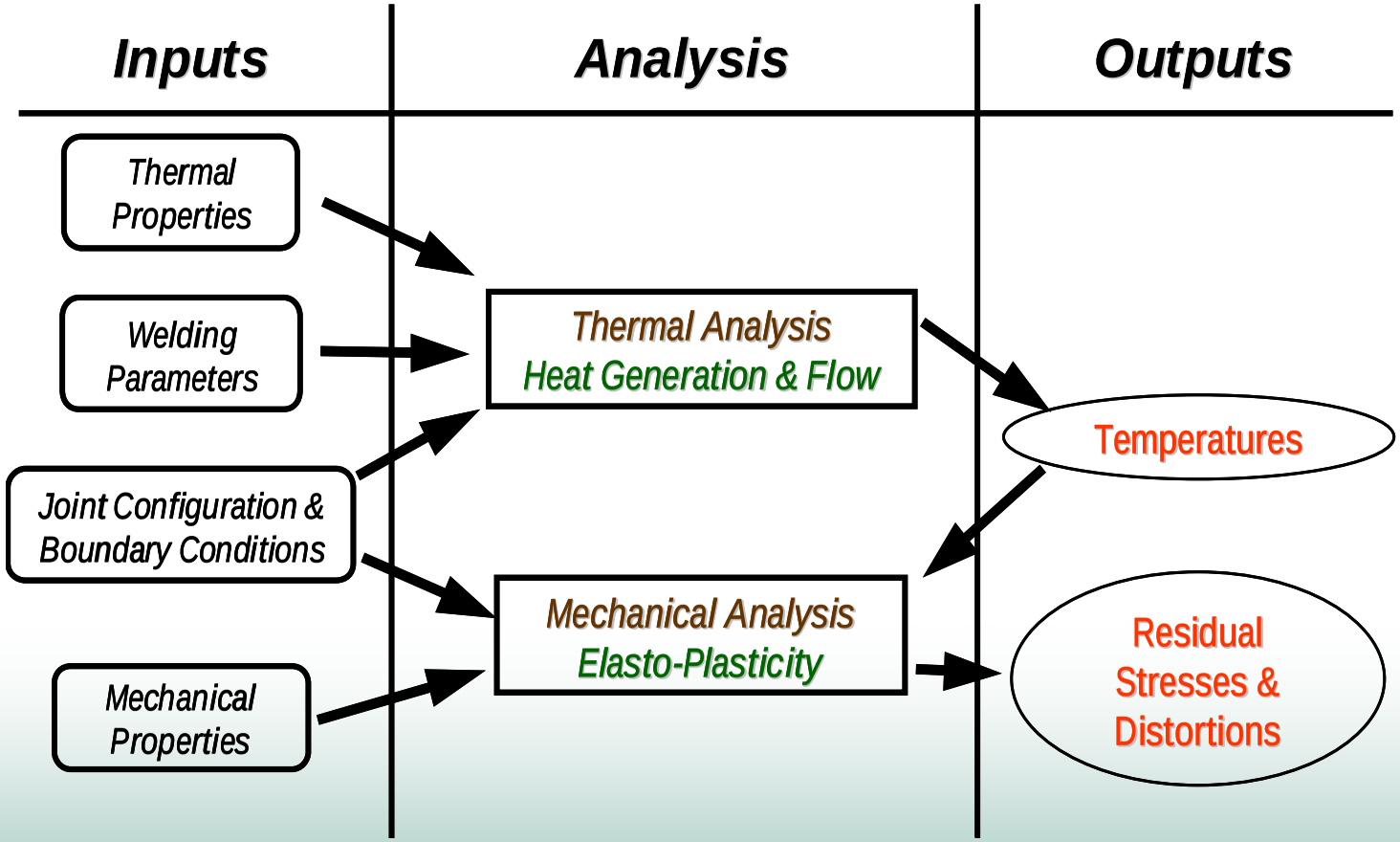






70,000 nodes and 64,000 8-node linear brick elements in the side-hill model.

Weld Analysis Procedure



Welding Stress Analysis Procedure (cont.)

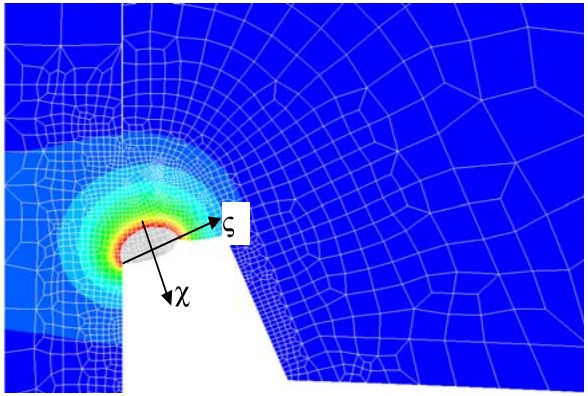
- ***Analysis was done using weld pass-by-pass procedure***
  - ***A weld pass is activated only when it is deposited***
  - ***Pass deposition followed the actual welding sequence***

- ***Heat input from the moving welding arc takes Gaussian distribution***

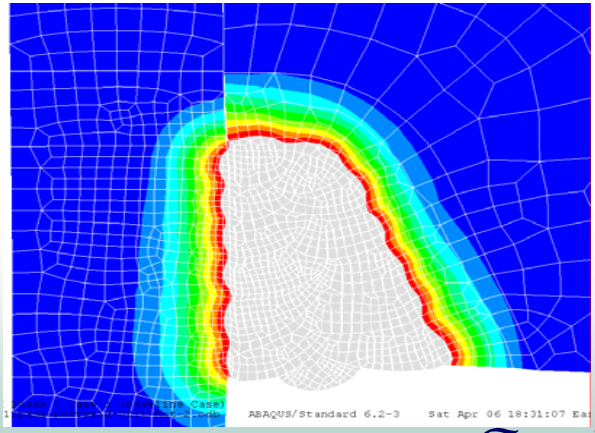
$$q = \frac{6\sqrt{3}\eta EI}{\pi\sqrt{\pi}abc} e^{\left[-3\left(\frac{(\chi-\chi_0)^2}{a^2}+\frac{(\varsigma-\varsigma_0)^2}{b^2}+\frac{(V(t-t_o))^2}{c^2}\right)\right]}$$

- ***Effect of weld solidification on materials constitutive behavior are properly treated with proprietary user subroutines***

- ***ABAQUS is the FE solver, enhanced with various user subroutines***



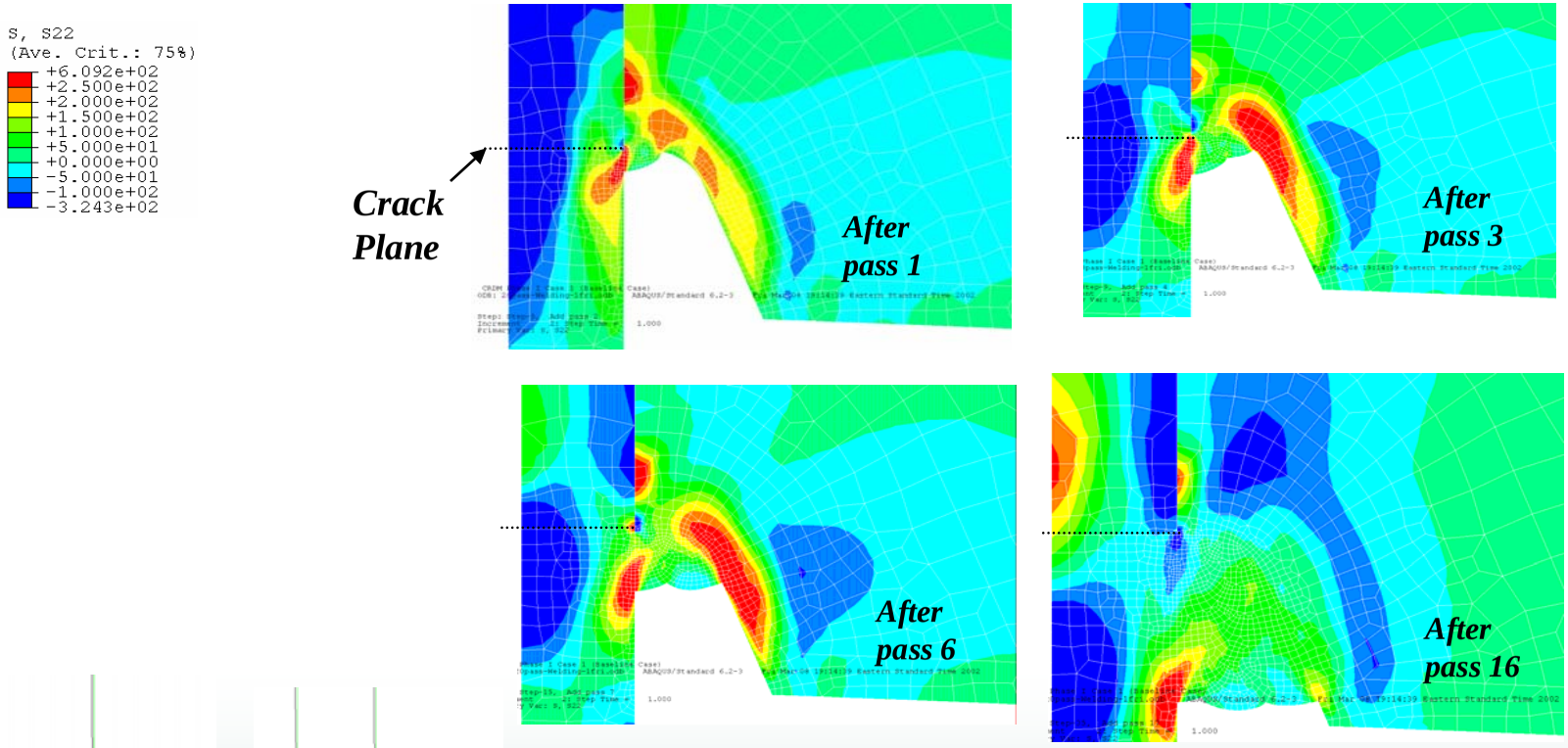
Peak temperature profiles

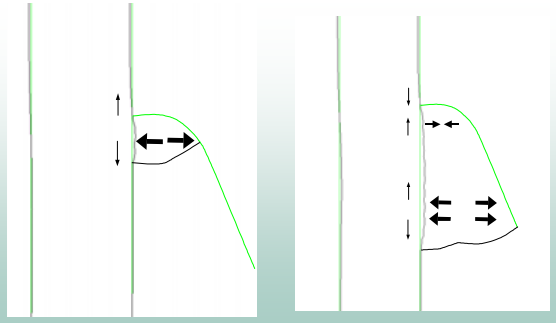


Material Properties

- *Analysis by Emc^2 involves weld simulation of each weld pass*
- *Base and weld metal stress-strain curves needed from room temperature to 1000C (cooling from molten conditions).*
  - *Since plastic strains for weld calculated in our analysis, the weld metal stress-strain curve should be from <u>annealed</u> weld metal, rather than from <u>as-welded</u> weld metal.*
  - *Speed of welding corresponds to an average strain-rate of 10^{-3}.*
  - *ORNL developed annealed Alloy 182 and A508 stress-strain curves at various temperatures and 10^{-3} strain rate. We used Alloy 600 data from literature (slower loading rate).*

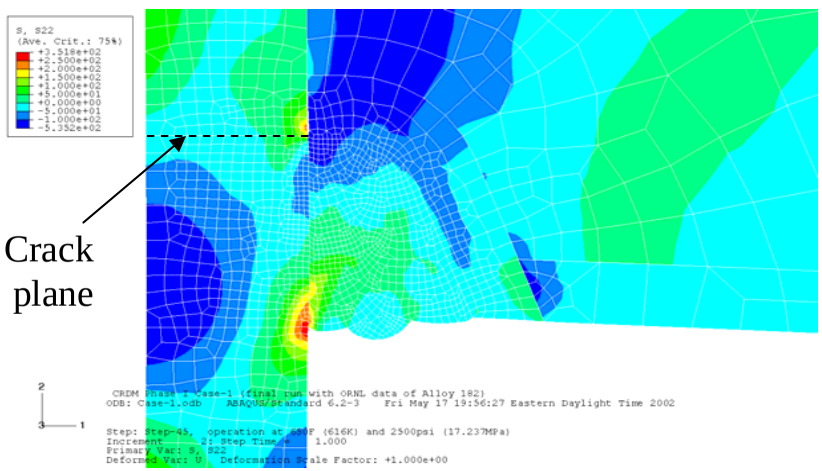
Axial residual stress development in a center-hole case – 20 weld passes max (Crack not present during weld simulation.)



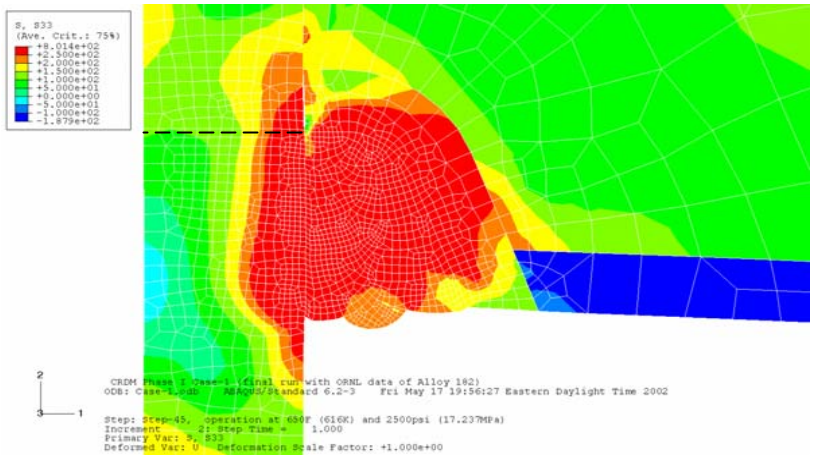


Weld Height Effects on Axial Stress Change is Attributed to "Hinging" Action around Initial Weld Beads

In-Service Stress Distributions of 13-pass J-weld (Design Conditions: 605F and 2,500psi)



Axial Stress, MPa

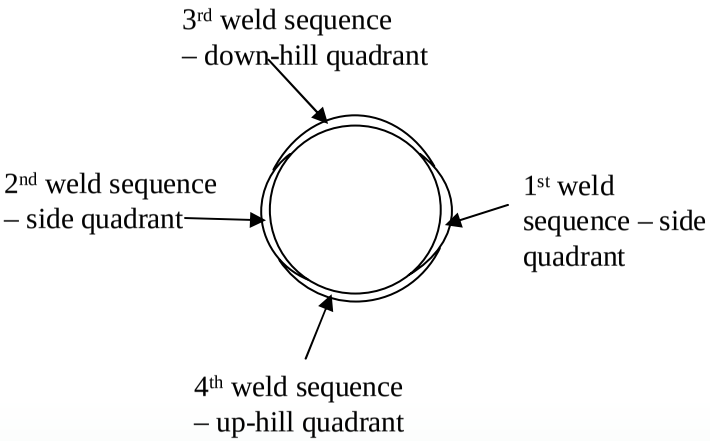


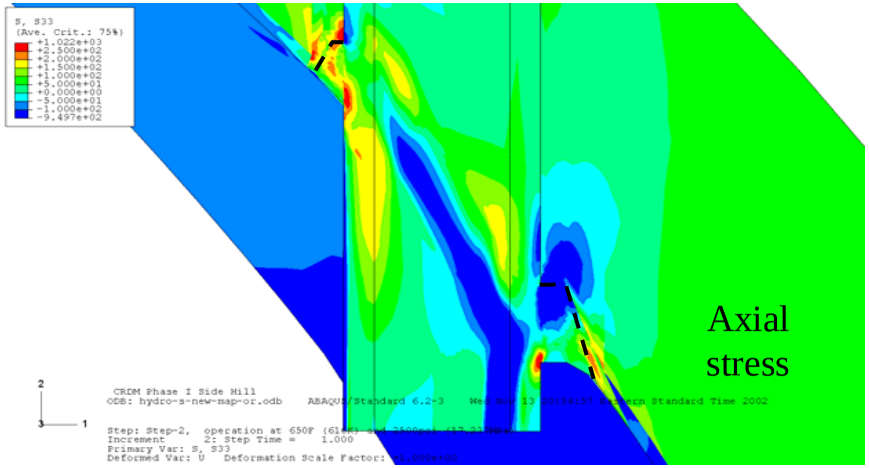
Hoop Stress, MPa

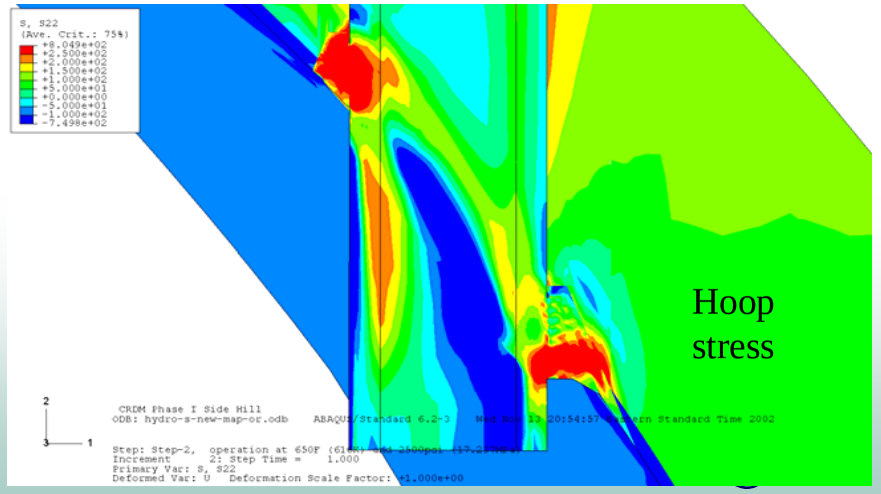
Center-hole model

Side-Hill Weld Residual Stress Model
(Design Conditions: 605F and 2,500psi)

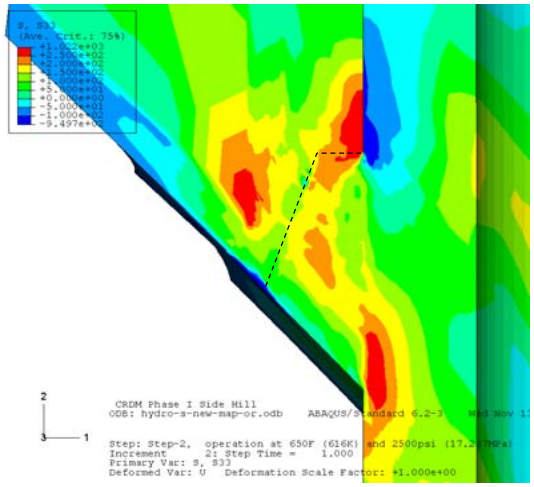
- ***Followed the welding sequence observed in actual fabrication***



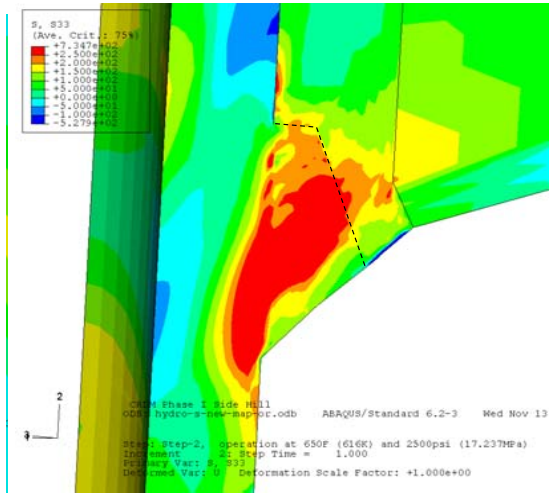




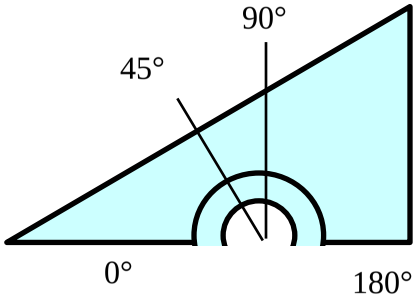
Sectional View of Axial Stresses

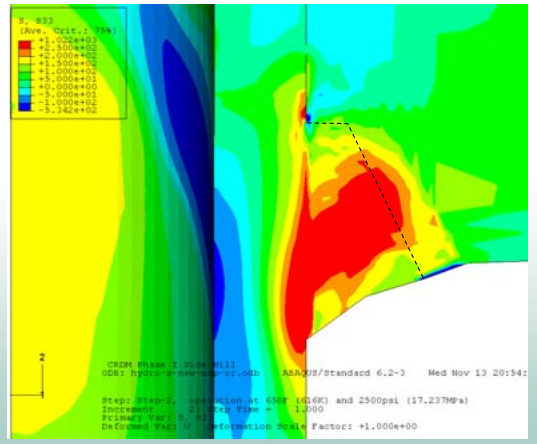


(a) 0-degrees

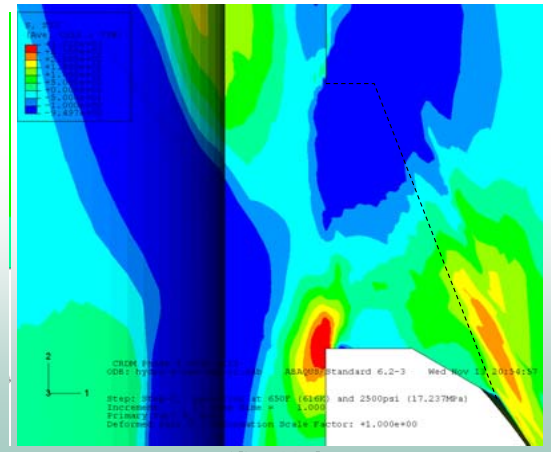


(b) 45-degrees





(c) 90-degrees



(d) 180-degrees

Observations of Weld Stresses

- ***The as-welded stress states are primarily dependent on the J-weld size, and the tube strength levels.***
  - ***(Nozzle angle is expected to be a primary factor as well, but the results are not yet available).***

- ***There are appreciable differences between the as-welded stress states and the in-service stress state caused by hydro-test and by the pressure and temperature loading from operation.***

- ***The hoop stresses in the tube next to the J-weld are high in tension, generally reaching the yield strength level of the tube on the OD and extending above and below the J-weld region.***

Observations of Weld Stresses

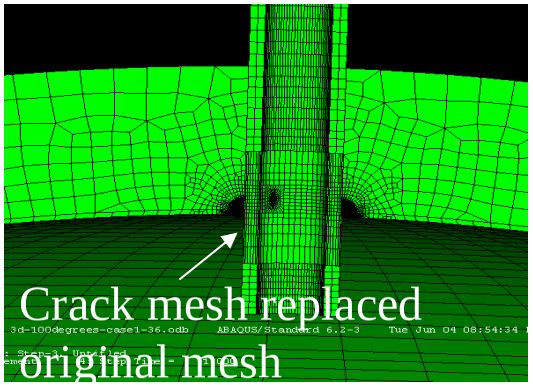
- ***The axial stress is highly sensitive to the weld height.***
  - ***A large J-weld tends to be beneficial for circumferential crack case as it creates compressive axial stresses at the root of the weld.***

- ***As the J-weld height increases, the hoop stresses on the ID surface of the tube increase and the axial stresses at the J-weld root decrease.***
  - ***There is probably an optimal weld height to minimize both stress components.***

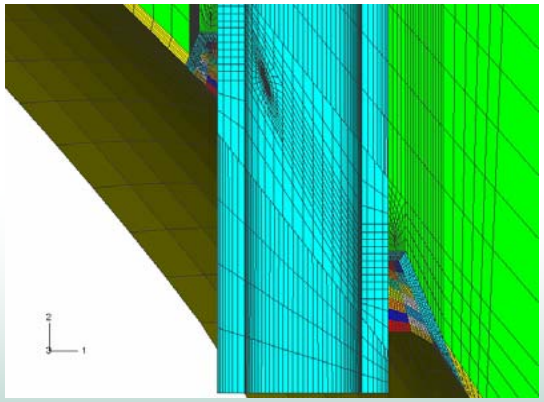
- ***The effects of other fabrication variables such as welding sequence and interference fit are secondary to the stress distribution in the J-weld region.***

Cracked Mesh

- ***Replaced original mesh at crack location with focused mesh (crack plane zipped)***
- ***Mapped residual stress solution onto "new" mesh***
- ***Added temperature and operating pressure***
- ***Released crack face restraints***
- ***Calculated K/J at crack tip through thickness***



Center hole

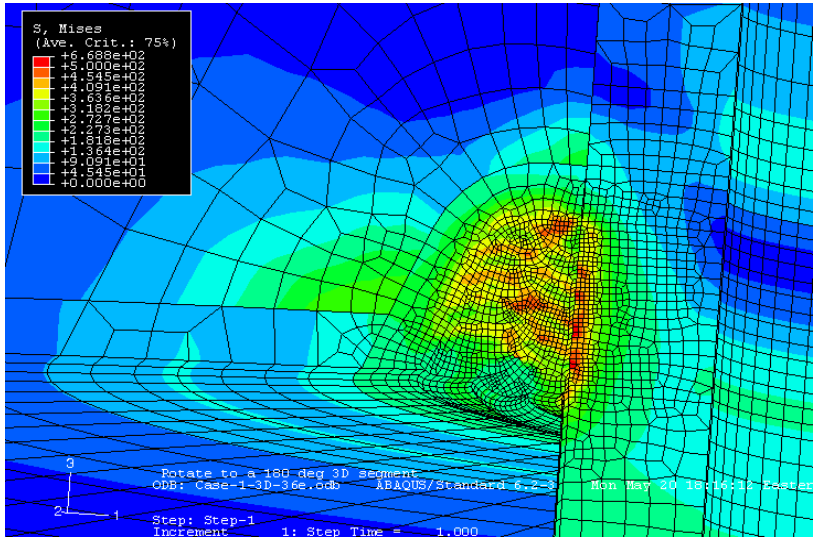


Steepest sidehill

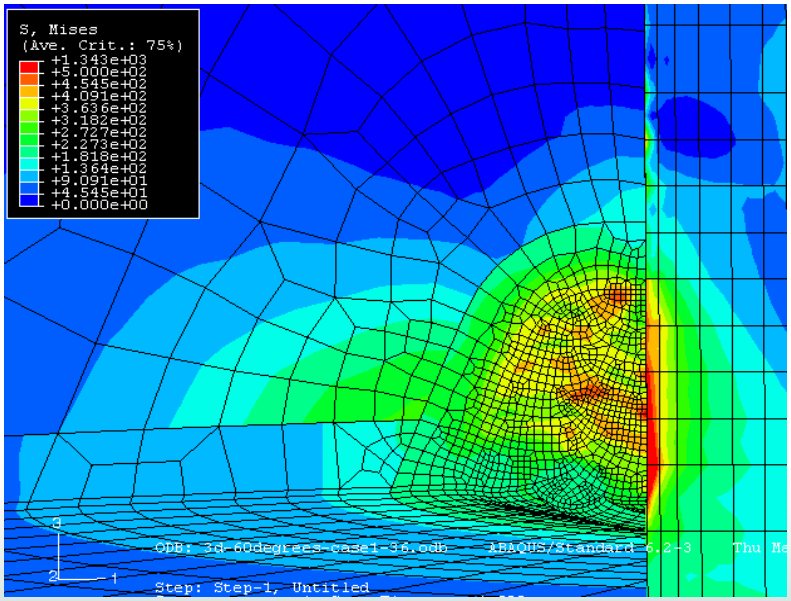
Parametric Analyses

- *10 circumferential through-wall-crack lengths: 40 to 320 degrees*
- *2 tube yield strengths: 37.5 ksi (258.6 MPa) for base case, and 64.4ksi (444 MPa)*
- *3 interference fits: 0, 2 (base case), and 4.5 mils (radial interference at room temperature and P = 0)*
- *Two operating temperatures: 605 F (base case) and 560 F*
- *One operating pressure: 2,500 psi*
- *Center-hole and largest side-hill angle*
  - *Most parametric work completed on center hole – Only baseline case run for largest side-hill angle*
- *Friction between tube and RPV hole included using friction factor of 0.1 (solid lubrication of boric acid crystals)*
  - *With circumferential crack, the tube tips in the hole and contacts the RPV head.*

Mapped Solution for Center-Hole Case

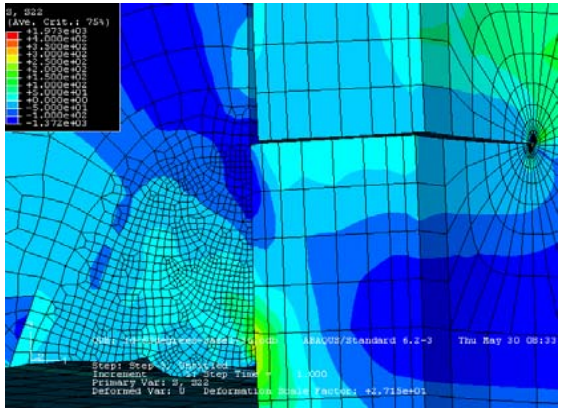


Original

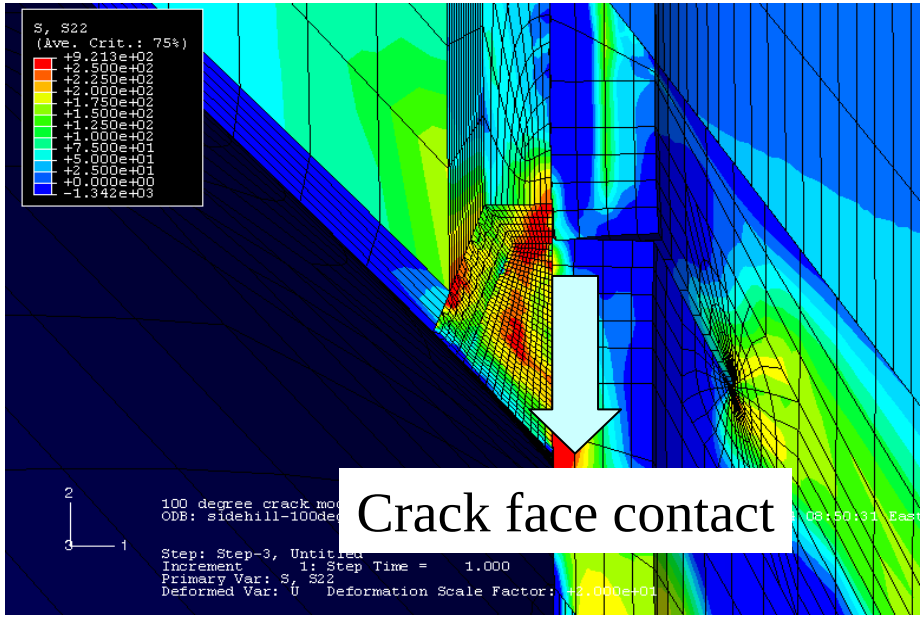


Mapped

Center-hole Cracked Case at Design Conditions



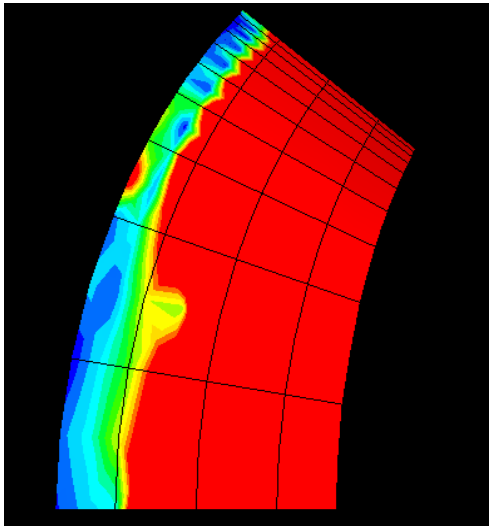
Mode III loading



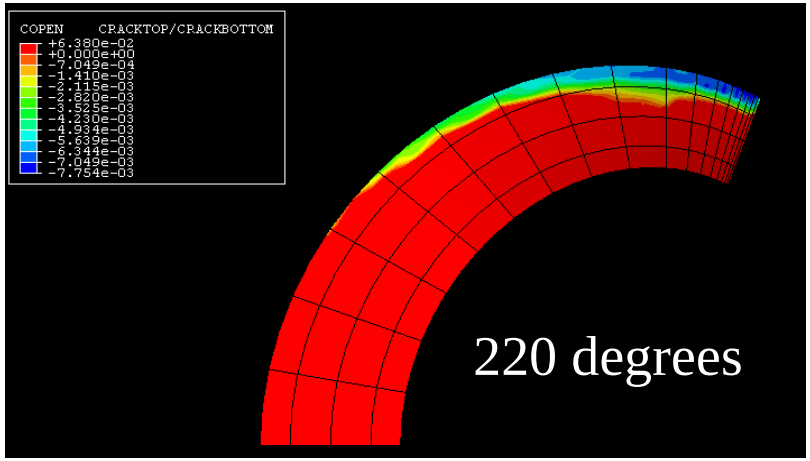
Crack face contact

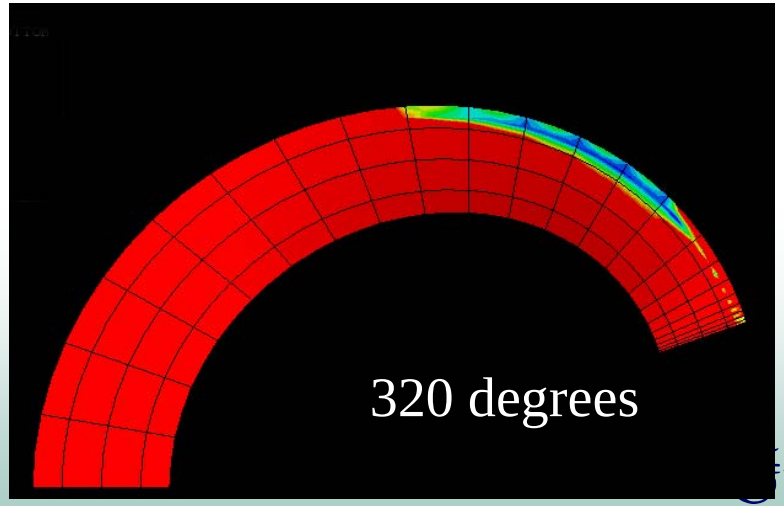
Trend suggests crack will not grow perpendicular to wall thickness – Angled crack growth through the thickness will be investigated in current program

Side-Hill nozzle – Crack face opening



60 degrees





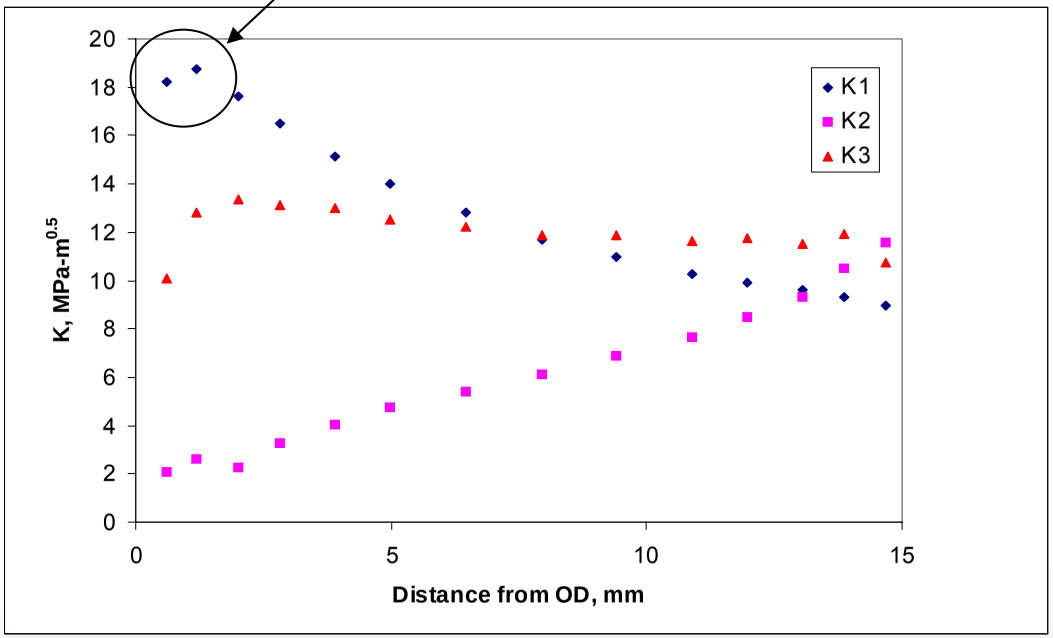
Crack closure exists at all crack lengths

Red – crack open
Other – crack closed

K-solutions from Center hole TWC Analyses

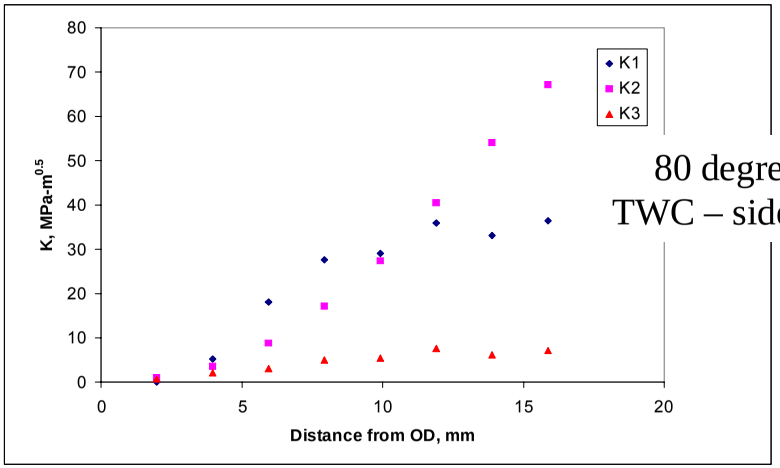
- ***With crack perpendicular to tube surface, large K_{III} and K_{II} component exists.***
  - ***Mode I = opening***
  - ***Mode II = in-plane sliding***
  - ***Mode III = out-of-plane sliding***
- ***Since subcritical cracks grow in maximum Mode I direction, crack angle through the thickness should not be perpendicular to tube surface.***
- ***K_{eq} was calculated from total J.***

Extrapolation technique used for path dependent J/K values

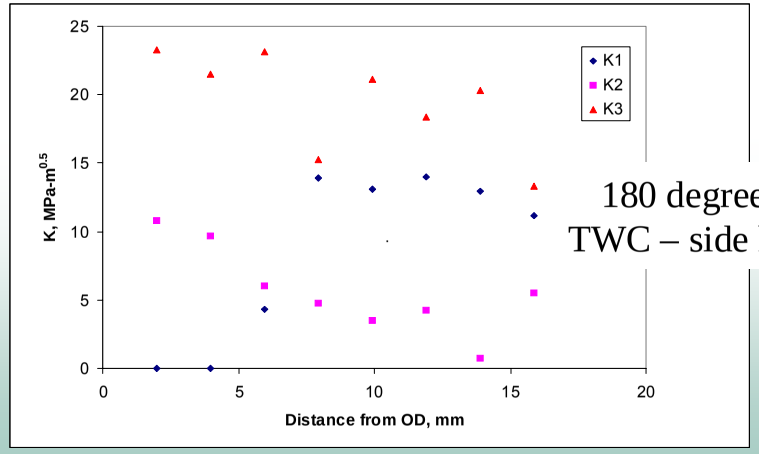


100-degree circumferential through-wall crack case

Side-Hill nozzle – J/K-solutions

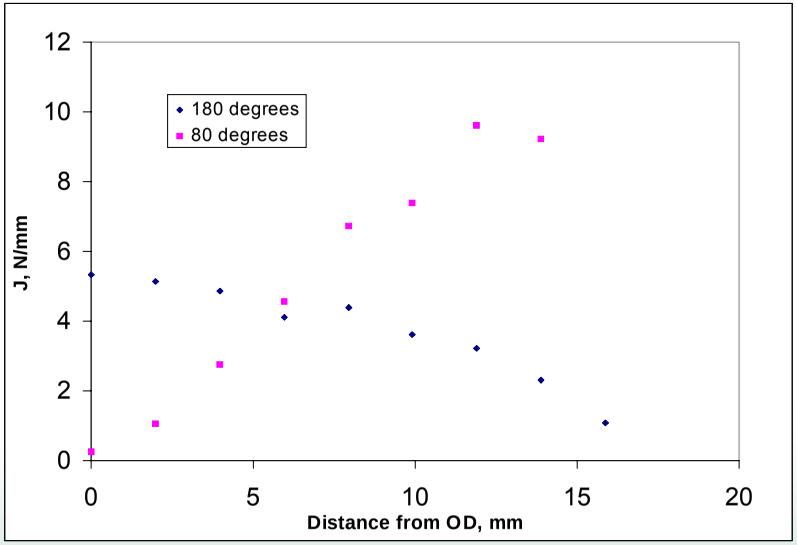


80 degree
TWC – side hill

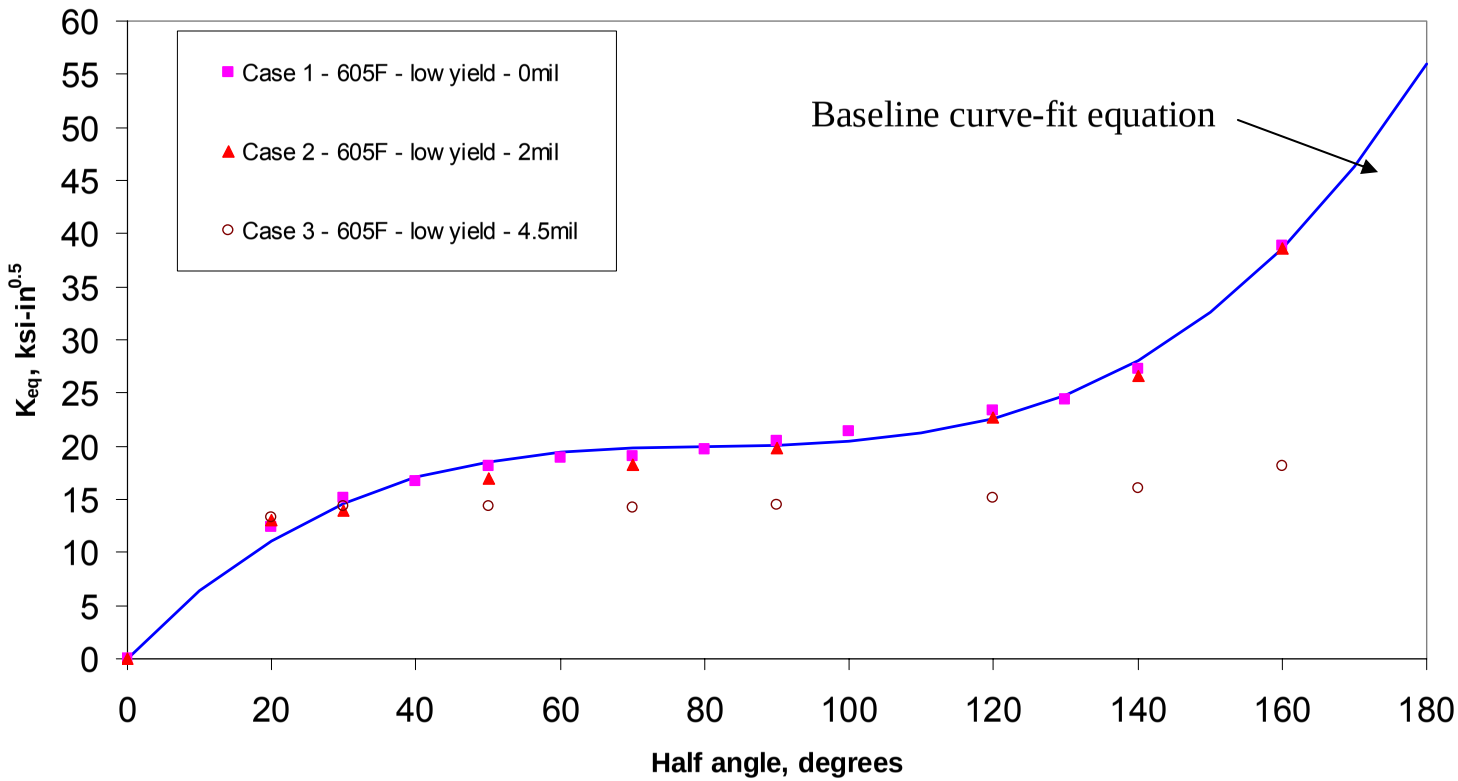


180 degree
TWC – side hill

Huge gradient due
to crack closure

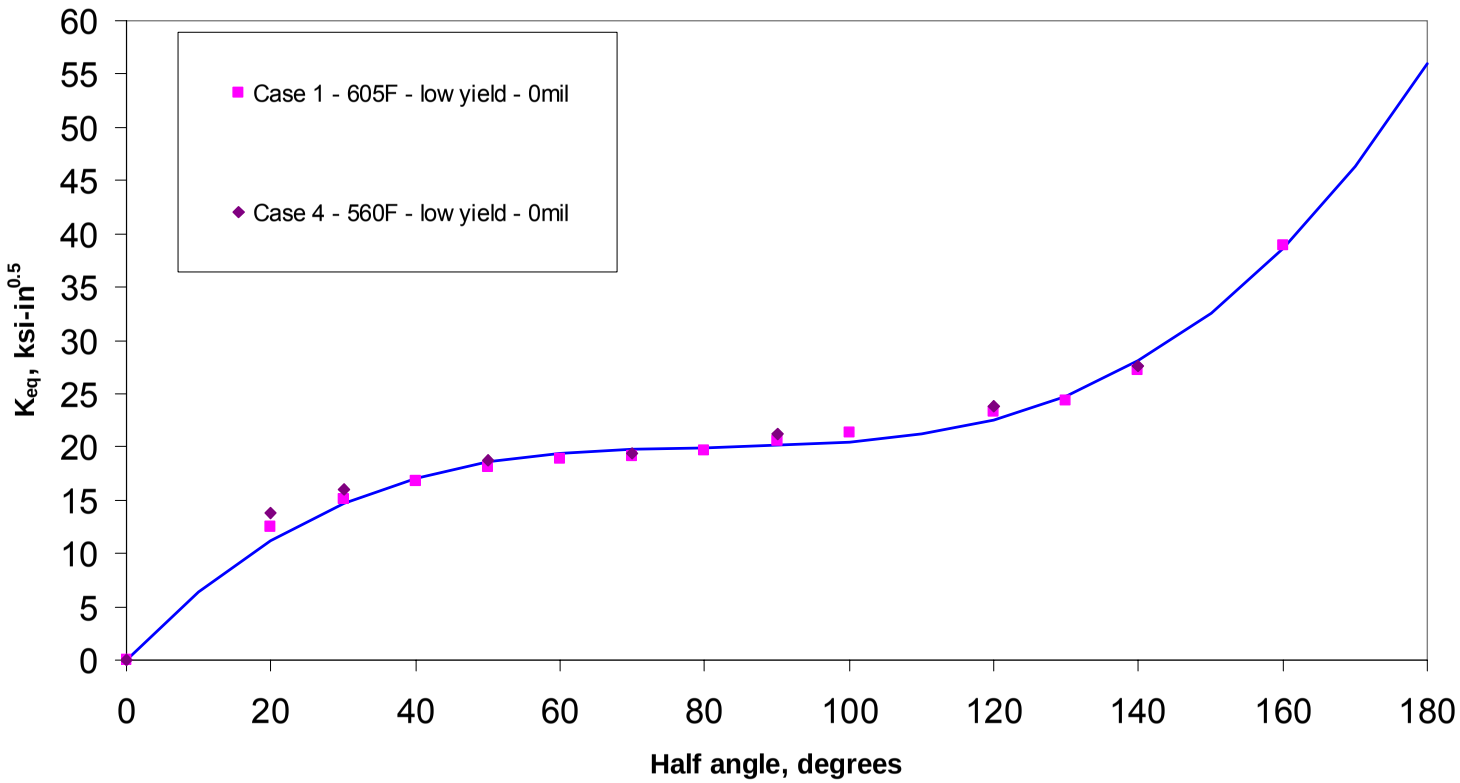


Center Hole $K_{J(average)}$ -solution Comparison



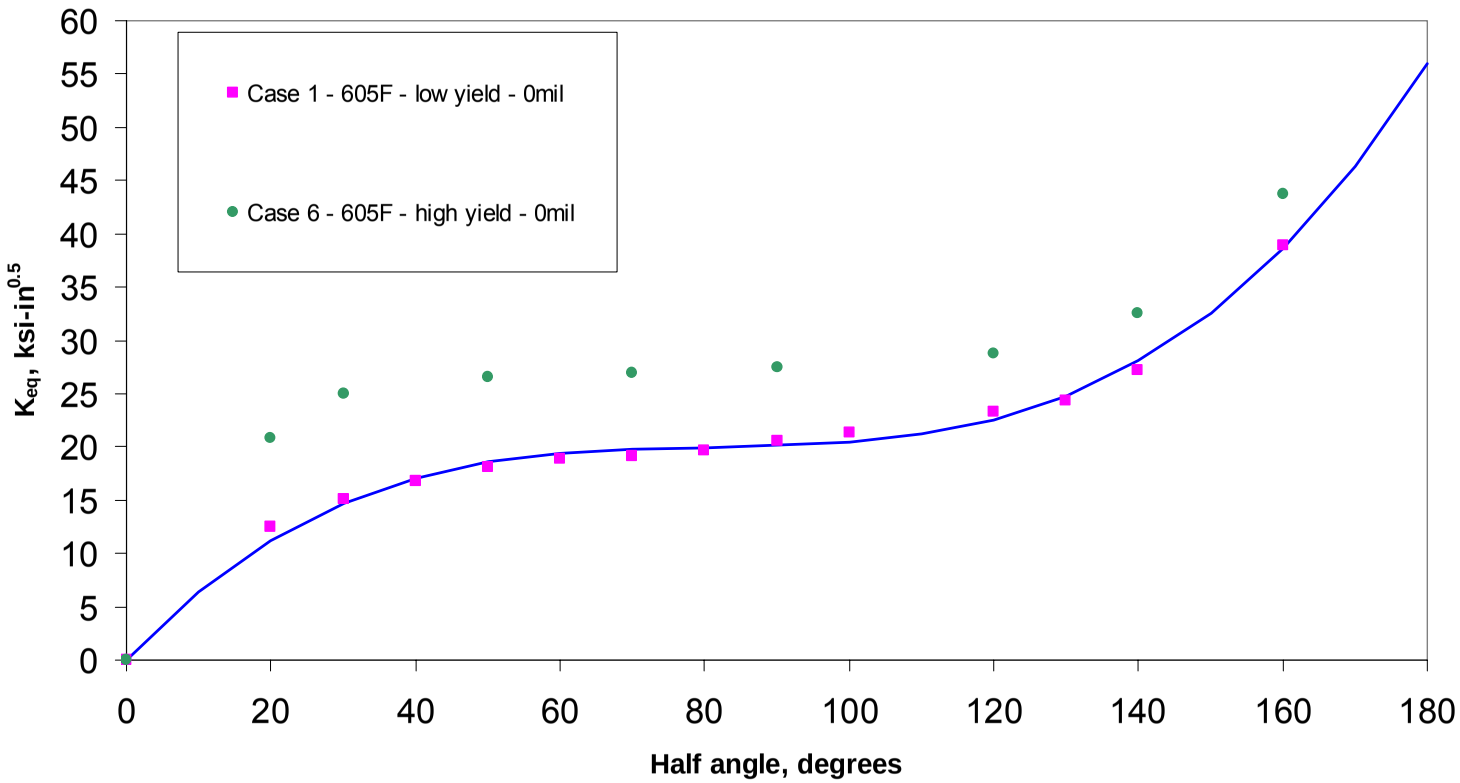
Center-hole circumferential though-wall cracks
(Effect of room temperature interference fit)

Center Hole $K_{J(average)}$ -solution Comparison



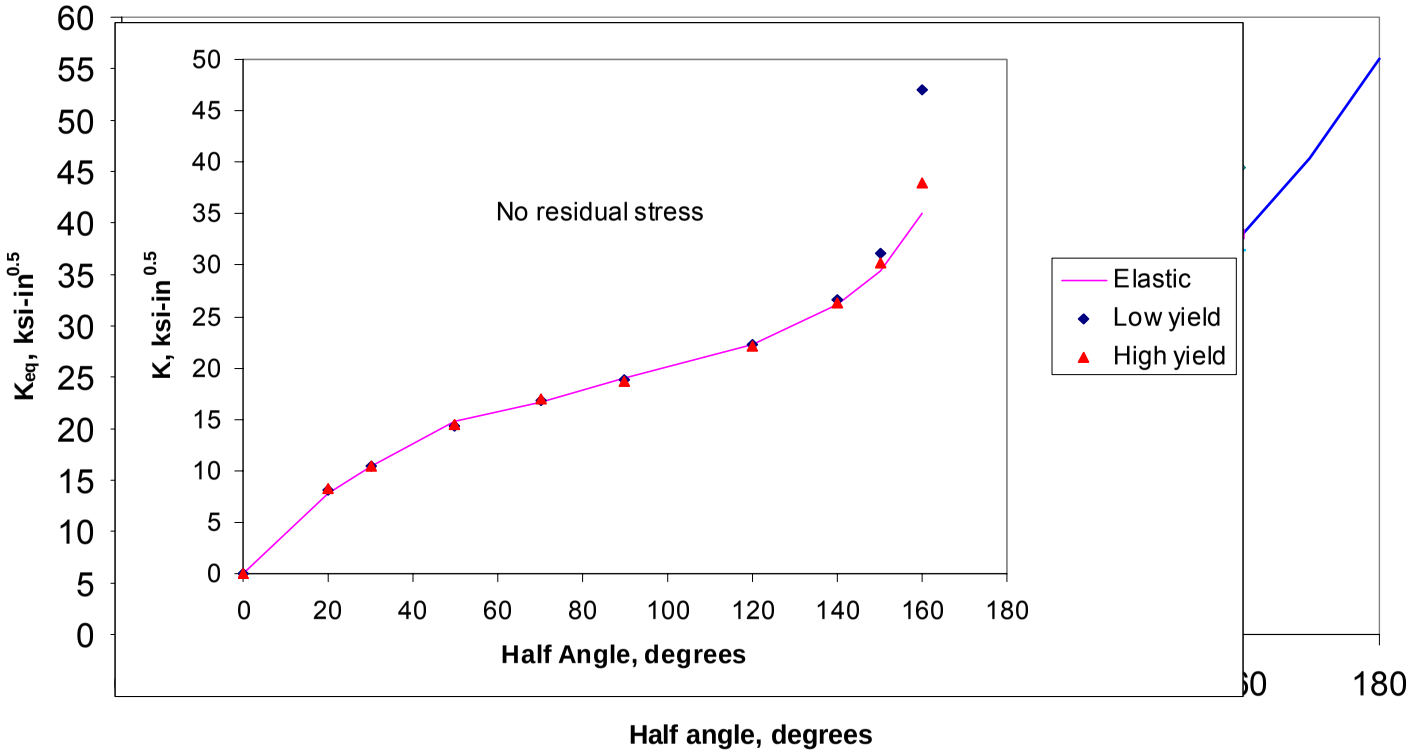
Center-hole circumferential though-wall cracks
(Effect of operating temperature)

Center Hole $K_{J(average)}$ -solution Comparison



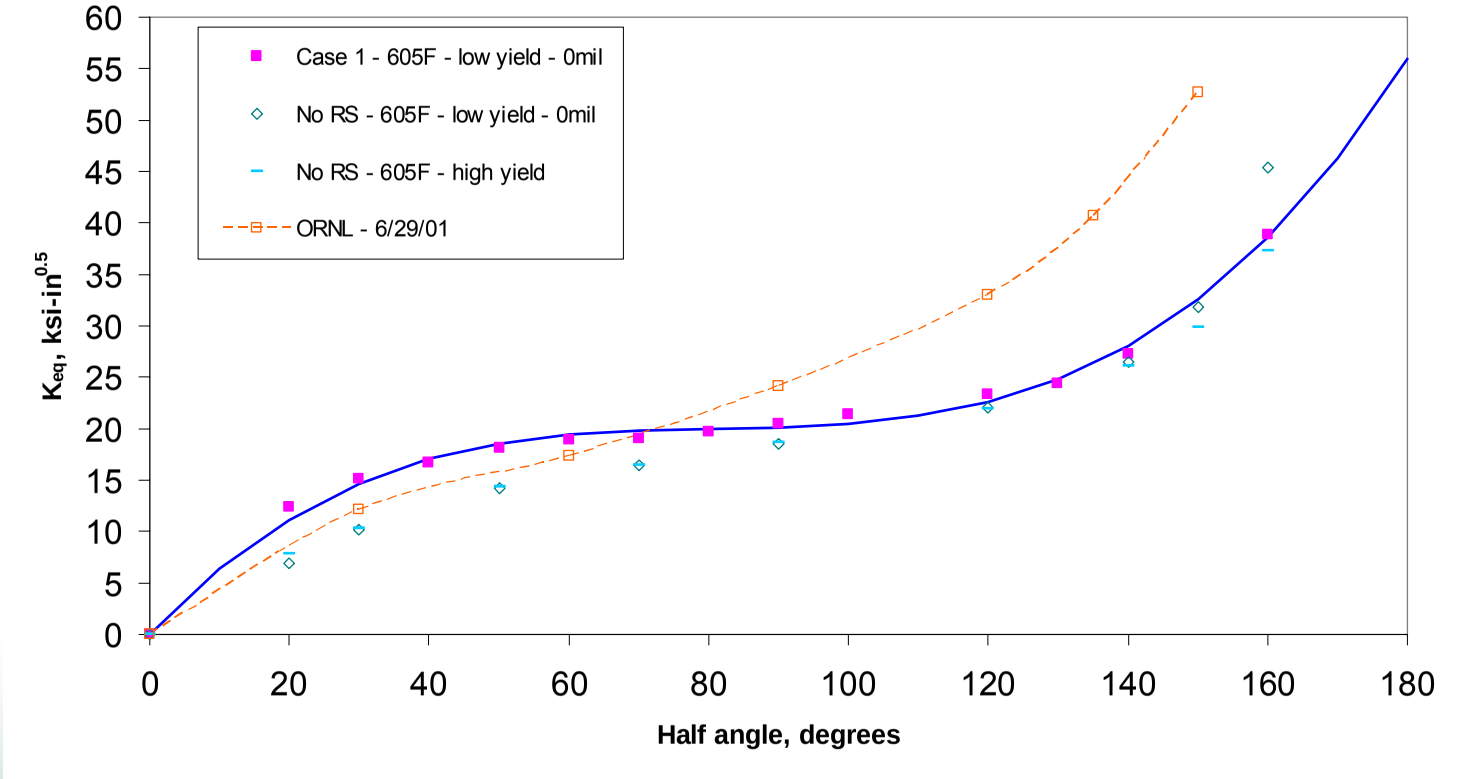
Center-hole circumferential though-wall cracks
(Effect of tube yield strength)

Center Hole $K_{J(average)}$ -solution Comparison



Center-hole circumferential though-wall cracks
(Comparison without residual stresses)

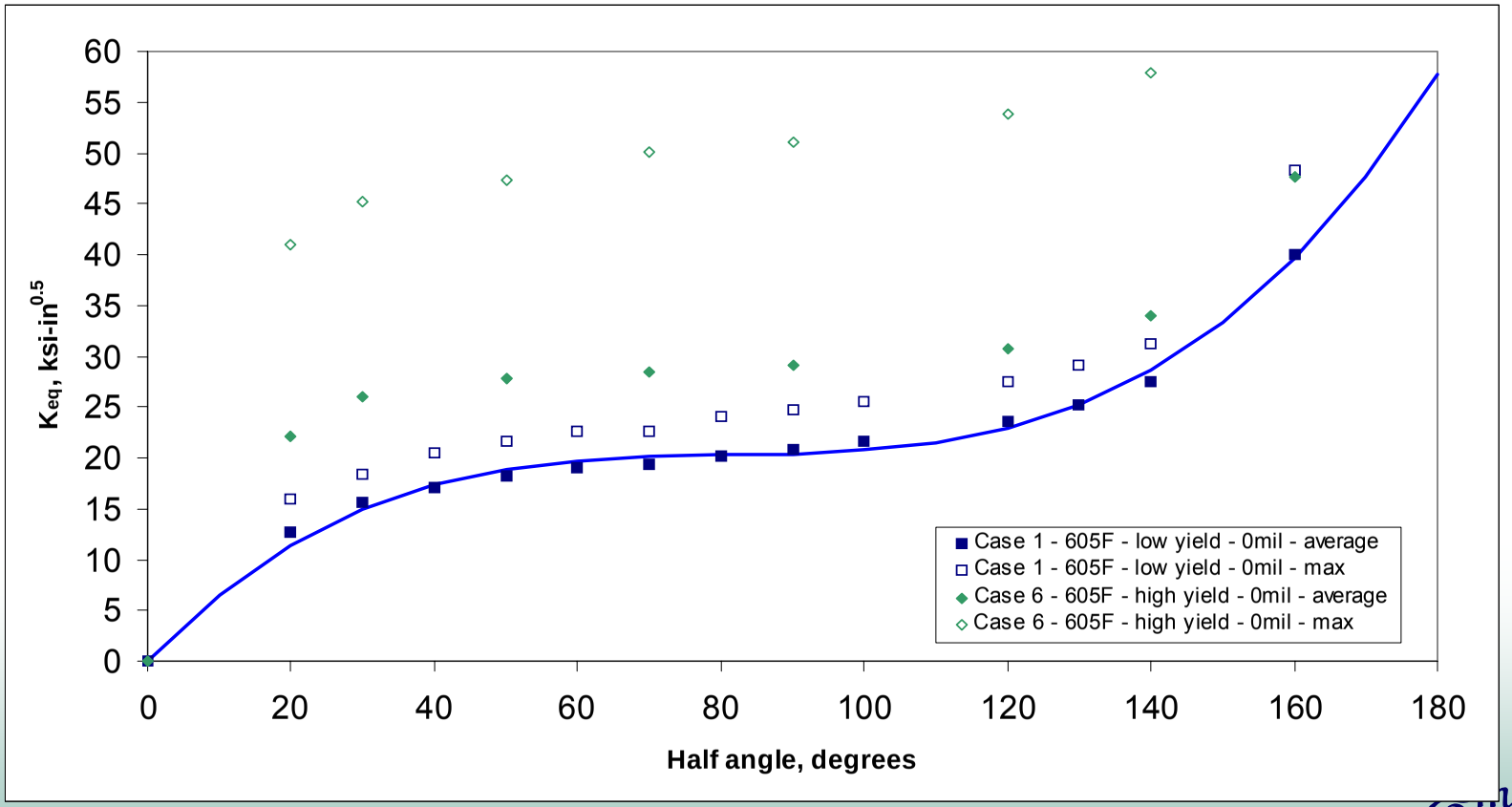
Center Hole $K_{J(average)}$ -solution Comparison



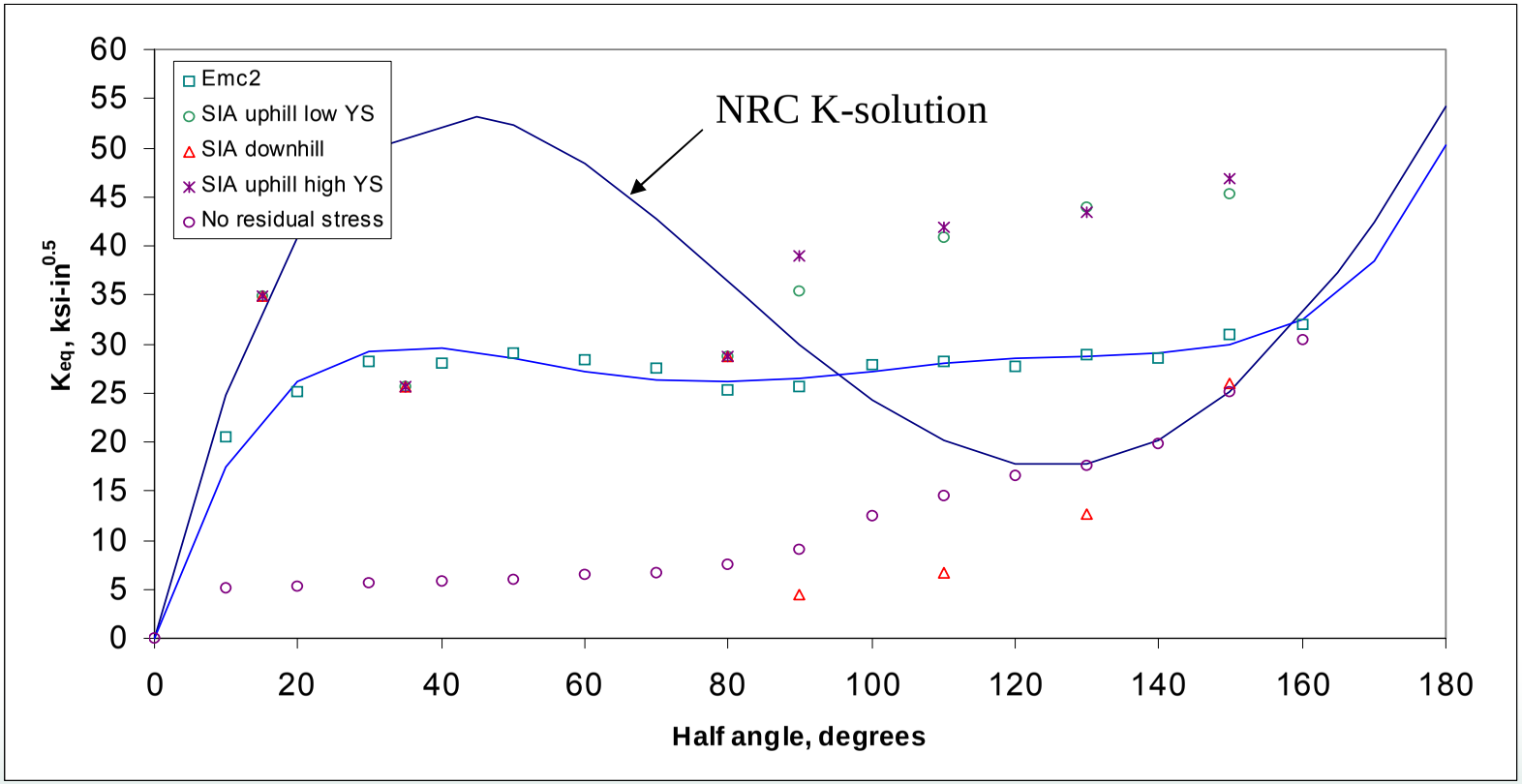
Center-hole circumferential though-wall cracks
(Comparison without residual stresses)

Center Hole $K_{J(average)}$ -solution

K_{max} versus K_{avg}



Side-Hill nozzle – $K_{J(average)}$ -solutions



Due to change in J-gradient through the thickness as a function of crack length, the K_{eq} is almost independent of crack length

K-solution Observations

- *Tube yield strength had large effect of K solution – high yield gave large J gradient through thickness.*
- *For low yield, residual stress made no difference in K for cracks greater than 180 degrees.*
- *Large interference fit decreased the K solutions, but intermediate interference fit (2 mil on radius) had no effect on K.*
- *The range of operating temperature considered (560F versus 605F) did not significantly affect the K-solution.*
  - *(Temperature affects the PWSCC crack growth rate, but not the crack driving force.)*
- *The overall results are consistent with past ORNL tube-only K values.*

General Significant Observations

- ***Residual stresses in hoop direction increase with increasing weld size, and stresses in longitudinal direction at J-weld root decrease with increasing weld size.***
  - ***There should be optimum design.***

- ***By mapping entire stress field, it can be seen that there are Mode I, II, and III components when keeping the crack perpendicular to the tube surface.***
  - ***PWSCC crack will probably grow in Mode I direction that would be angled through the thickness.***
  - ***Future work concentrating on optimal crack angle though thickness for maximum K_I contribution!!***

United States Nuclear Regulatory Commission

International Cooperative Project: PWSCC and NDE in Ni-Base Alloys and Dissimilar Metal Welds

Conference On Vessel Head Penetration Inspection, Cracking and Repairs

October 1, 2003

Carol E. Moyer, Materials Engineer
Office of Nuclear Regulatory Research
301-415-6764 cem3@nrc.gov

Objectives for Research Cooperative

- Document the range of locations and crack morphologies associated with PWSCC. Distinguish PWSCC cracks from similar-appearing features, such as weld hot tears.
- Identify, develop and assess NDE methods for accurately detecting, sizing and characterizing tight cracks such as PWSCC.
- Develop representative NDE mock-ups with cracks to simulate tight PWSCC cracks.

Project Organization

- Task 1 – Atlas of crack morphology for PWSCC
  - Compile existing work
  - Perform new fractography, metallography
- Task 2 – Round Robin of NDE techniques on PWSCC and simulated cracks
  - Assess techniques to detect and size cracks
  - Assess techniques to manufacture test blocks
- Other suggested topics: modeling, effects of surface condition, validation of structural integrity assessment, effects of weld repairs

What is Needed Next?

- People with common interests, resources
- Crack morphology information (reports, etc.)
- Set of relevant specimens
  - Cracks removed from plant components
  - Components from cancelled plants
  - Simulated or manufactured cracks
- Discussions to define project tasks

United States Nuclear Regulatory Commission

Welding Residual and Operating Stress Analysis
RPV Top and Bottom Head Nozzles

Vessel Head Penetration Inspection,
Cracking and Repair Conference

September 29 – October 2, 2003
Gaithersburg, MD

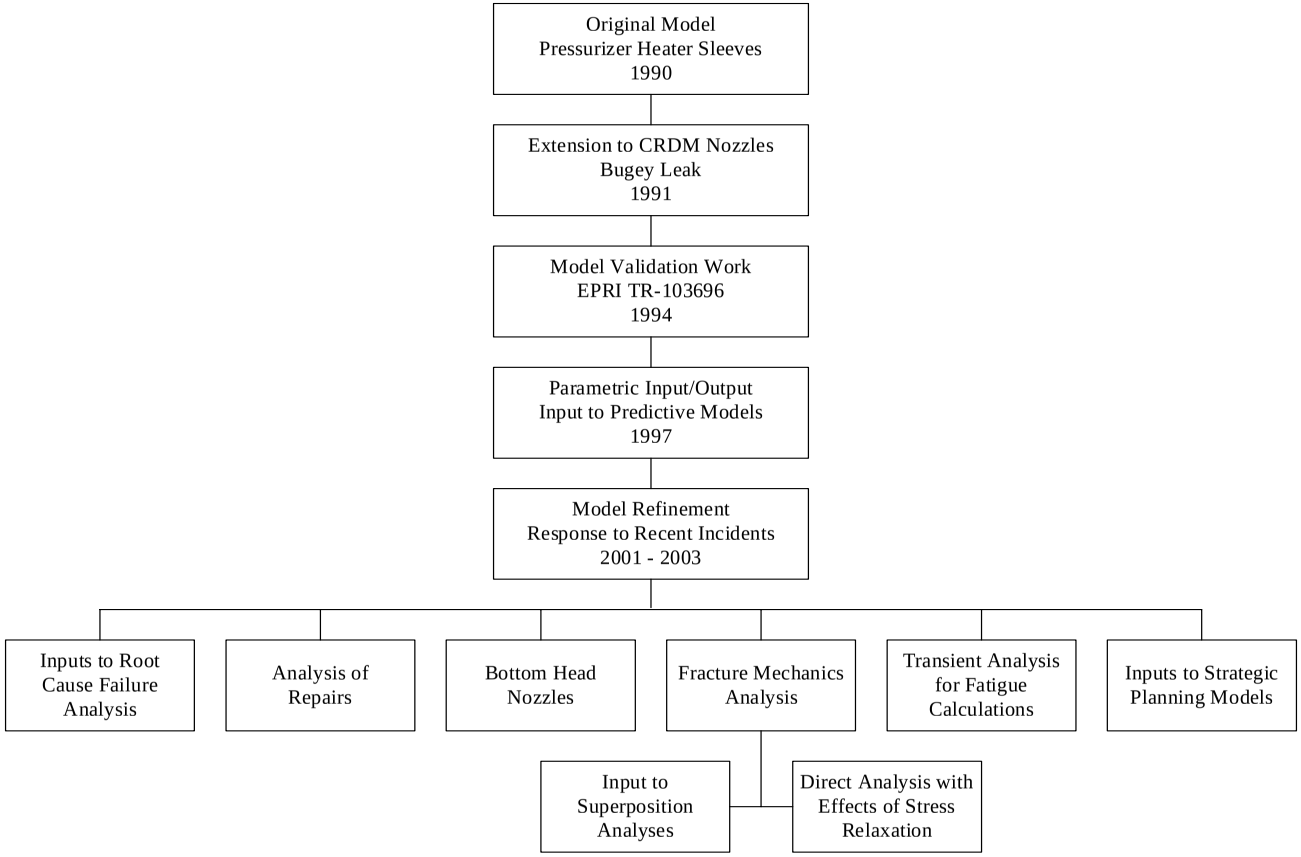
By:
John Broussard, Dominion Engineering, Inc.
David Gross, Dominion Engineering, Inc.

Dominion Engineering, Inc.
11730 Plaza America Dr.
Reston, VA 20190

Overview

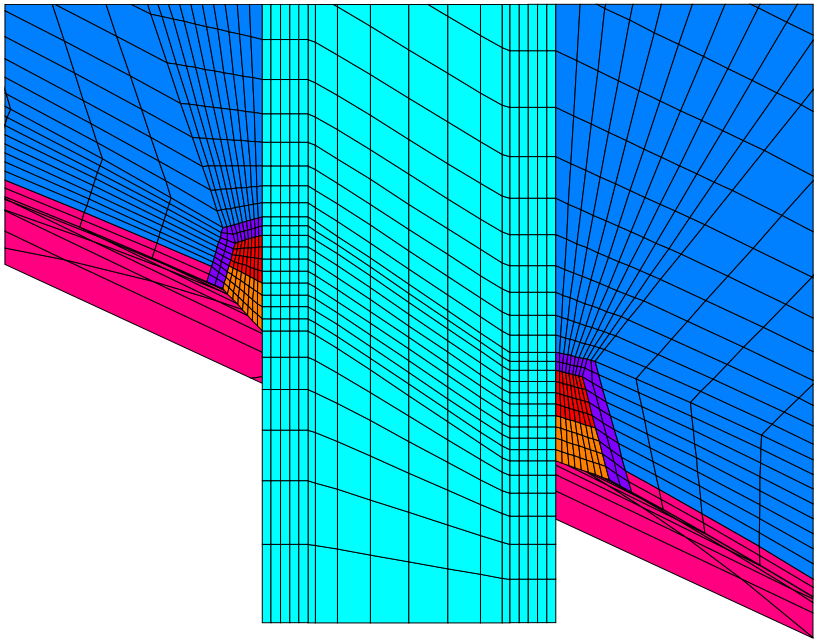
- Development of RPV Head Stress Analysis Model
- Model Description and Validation
- Results for RPV Top Head Nozzles
- Results for RPV Bottom Head Nozzles
- Transient Analyses for Fatigue Analysis
- Additional Weld Residual Stress Modeling
- Fracture Mechanics Modeling with Stress Relaxation

Development of RPV Head Nozzle Stress Analysis Model



Model Description and Validation
Description

- 3D FEA modeling
  - ANSYS FEA software
  - Parametric input/output modeling
- Multi-pass welding
  - Thermal analysis of each weld pass
  - Structural analysis during weld cooling
  - Alloy 600 tubes have strain hardening properties
  - Welds assumed elastic-perfectly plastic
- Analysis includes
  - Deposition and stress relief of buttering prior to making J-weld
  - Interference fit between nozzle and bore in vessel head
  - Counterbores at top and bottom of head
  - Hydrostatic test pressure
  - Operating pressure and temperature

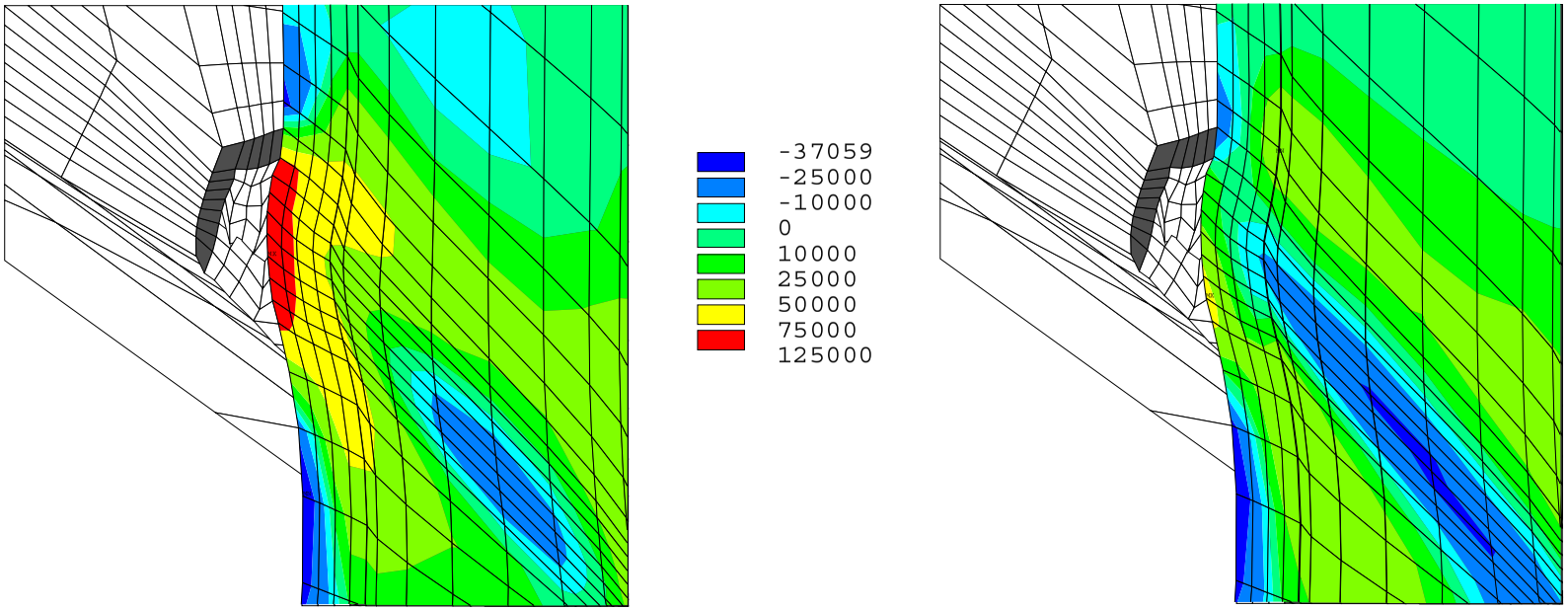


Model Description and Validation
Validation

- Nozzle lateral deflection and ovality
  - Pressurizer heater sleeves
  - CRDM nozzles
  - Bottom head nozzles
- Correlation with reported crack locations and orientations
  - Pressurizer heater sleeves
  - CRDM nozzles
  - Bottom head nozzles
- Correlation with x-ray and strain gauge hole drilling residual stress measurements
  - CRDM nozzle mockups
  - Pressurizer heater sleeve mockups
- Comparison to EMC^2 results
  - Material properties
  - Stresses
- Early validation work reported in EPRI TR-103696

Results for RPV Top Head Nozzles
Typical Hoop and Axial Stresses

- Typical hoop and axial stresses at uphill location



Hoop Stress **Axial Stress**

Results for RPV Top Head Nozzles
Correlation of Crack Orientation with Predictions

- Field experience consistent with typical analysis results
  - Over 90% of cracks have been axial
  - More cracks on the OD surface than on the ID surface
  - Circumferential cracks are more likely to initiate on the OD surface below the J-weld than on the ID surface

		No. of Indications on the Nozzle ID	No. of Indications on the Nozzle OD	*Total*
No. of Axial Tube Indications		112	224	*336*
No. of Circumferential Tube Indications	**Above Weld**	0	7	*7*
	Weld Elevation	0	12	*12*
	Below Weld	6	10	*16*
	Total	*118*	*253*	*371*

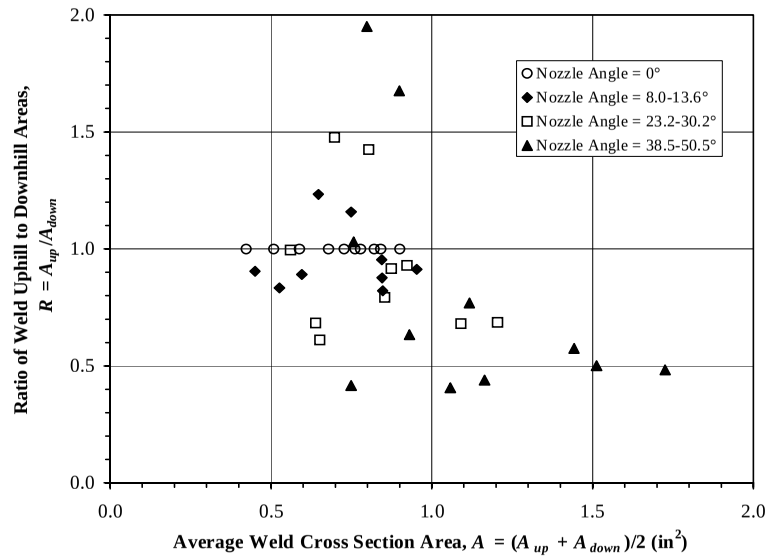
Notes
1. 498 Indications in the Database (as of 09/2003).
2. Craze Cracking/Shallow Cracks are not Included.

		% Indications on the Nozzle ID	% Indications on the Nozzle OD	*Total*
% Axial Tube Indications		30%	60%	*91%*
% Circumferential Tube Indications	**Above Weld**	0%	2%	*2%*
	Weld Elevation	0%	3%	*3%*
	Below Weld	2%	3%	*4%*
	Total	*32%*	*68%*	*100%*

Notes
1. 498 Indications in the Database (as of 09/2003).
2. Craze Cracking/Shallow Cracks are not Included.

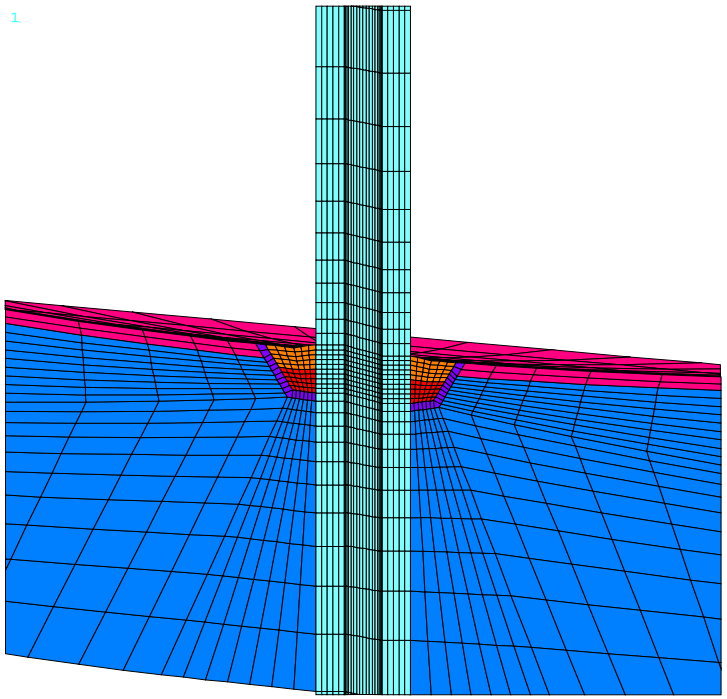
Results for RPV Top Head Nozzles
Range of J-Weld Geometries

- All J-welds are not the same design
  - Weld cross section areas vary
  - Ratio of uphill-to-downhill areas vary
- Analyses show differences in stress and stress distribution with J-weld geometry
- As-built weld sizes determined by UT inspections differ from design dimensions
  - Oversize downhill welds can reduce maximum OD stresses at weld toe due to lower restraint



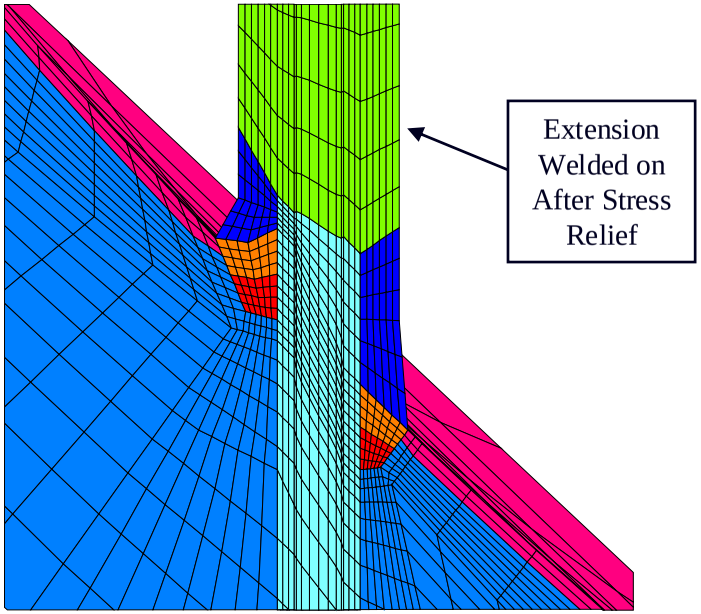
Results for RPV Bottom Head Nozzles
Typical Westinghouse BMI Nozzle

- Nozzles typically have lower D/T ratio than CRDM nozzles
- Typical results show
  - Ovalization is lower than in CRDM nozzles which have higher D/T ratio
  - Stresses are higher than in CRDM nozzles due to larger relative weld size
  - Hoop stresses in nozzle exceed axial stresses at high stress locations
  - Straightening the nozzle by plastic deformation does not increase total operating condition stresses



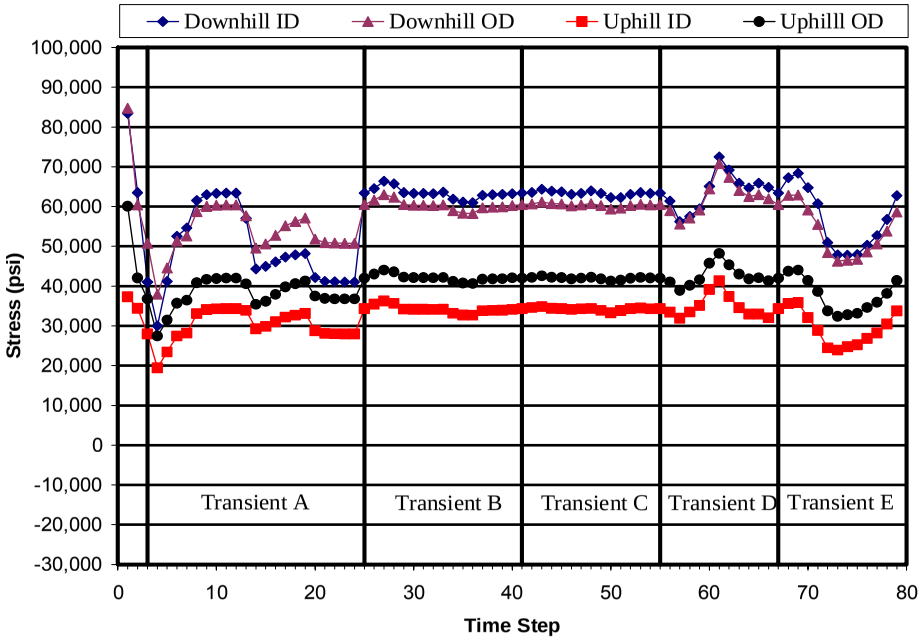
Results for RPV Bottom Head Nozzles
Typical B&W IMI Nozzle

- B&W IMI nozzles repaired
  - Original nozzles and J-welds stress relieved with vessel
  - Prior to plant operation the part of the nozzle inside the vessel was removed and replaced by larger diameter nozzle
- Typical results show
  - Peak stresses in nozzle are higher than in CRDM nozzles due to larger relative weld size
  - Hoop stresses in nozzle exceed axial stresses at high stress locations
  - Stresses in repaired part of nozzle trend to be lower due to less restraint during welding



Transient Analyses for Fatigue Evaluation

- Representative transients selected for analysis
- Thermal transient analysis followed by structural analysis with temps and pressures
- Typical results show:
  - Stress trends consistent throughout model
  - Crack growth rates dominated by PWSCC



Additional Weld Residual Stress Modeling

- Various nozzle repair techniques simulated with stress results used as inputs to fracture mechanics models
  - Nozzle removal repair
  - Embedded flaw repair
- Other penetrations being analyzed
  - Pressurizer side shall penetrations
  - Hot leg nozzle penetrations
  - Pressurizer top and bottom head penetrations

Fracture Mechanics Analyses with Stress Relaxation
Background

- Stress intensity factors are often calculated using superposition method
- For cases with high residual stresses, superposition
  - Conservatively applies residual stresses as primary loads
  - Does not allow for stress relaxation and redistribution with crack growth
- Development work was performed to modify the existing stress analysis model to calculate stress intensities for circumferential flaws above the J-weld including the effects of stress relaxation with crack growth

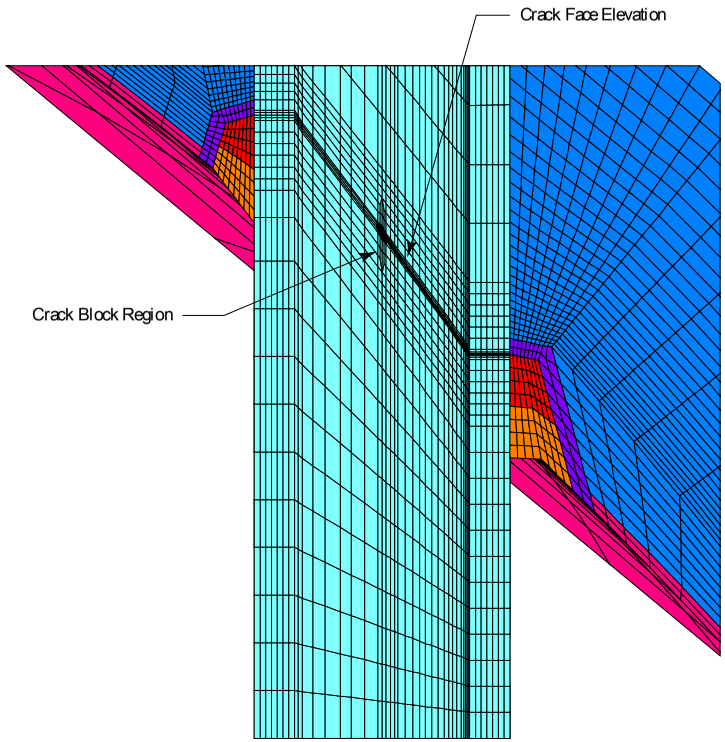
Fracture Mechanics Analyses with Stress Relaxation
Calculation Methodology

- Initial application is for through-wall crack in outer row CRDM nozzle parallel to weld contour with variable distance above top of weld
- Custom fracture mechanics code added to DEI welding residual finite-element stress model for J-groove nozzles
- Stress redistribution from intact to cracked conditions modeled
  - Redistribution modeled as an elastic unloading problem amenable to LEFM
- Equivalent stress intensity factor (K) calculated from J-integral
  - J-integral calculated using numerical volume integration
  - J-integral averaged across nozzle wall
  - J-integral approach captures effect of Mode II and III contributions

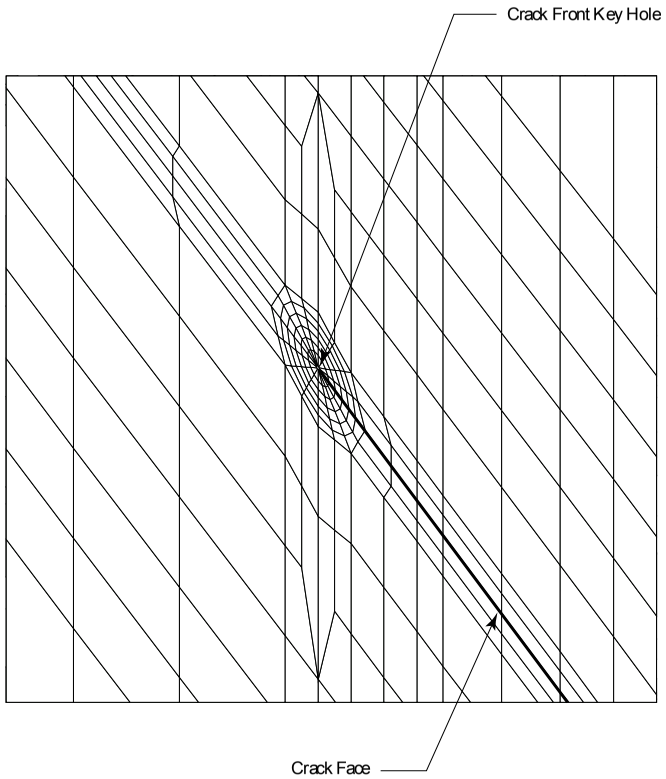
$$K_{eq} = \sqrt{\frac{J_{avg} E}{1-\nu^2}}$$

Fracture Mechanics Analyses with Stress Relaxation

Fracture Mechanics Model



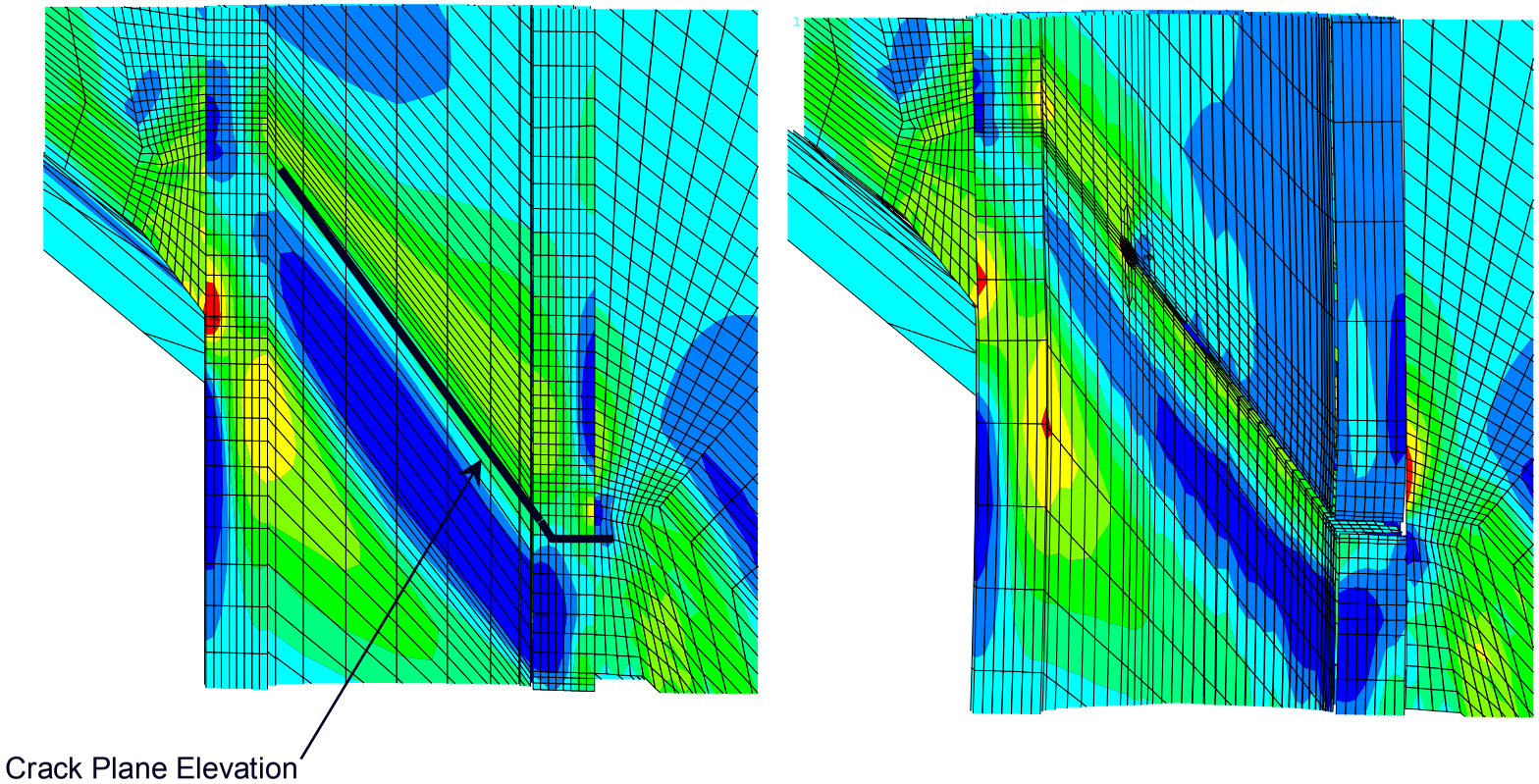
180° Downhill-Centered Crack



Crack Mesh Detail

Fracture Mechanics Analyses with Stress Relaxation

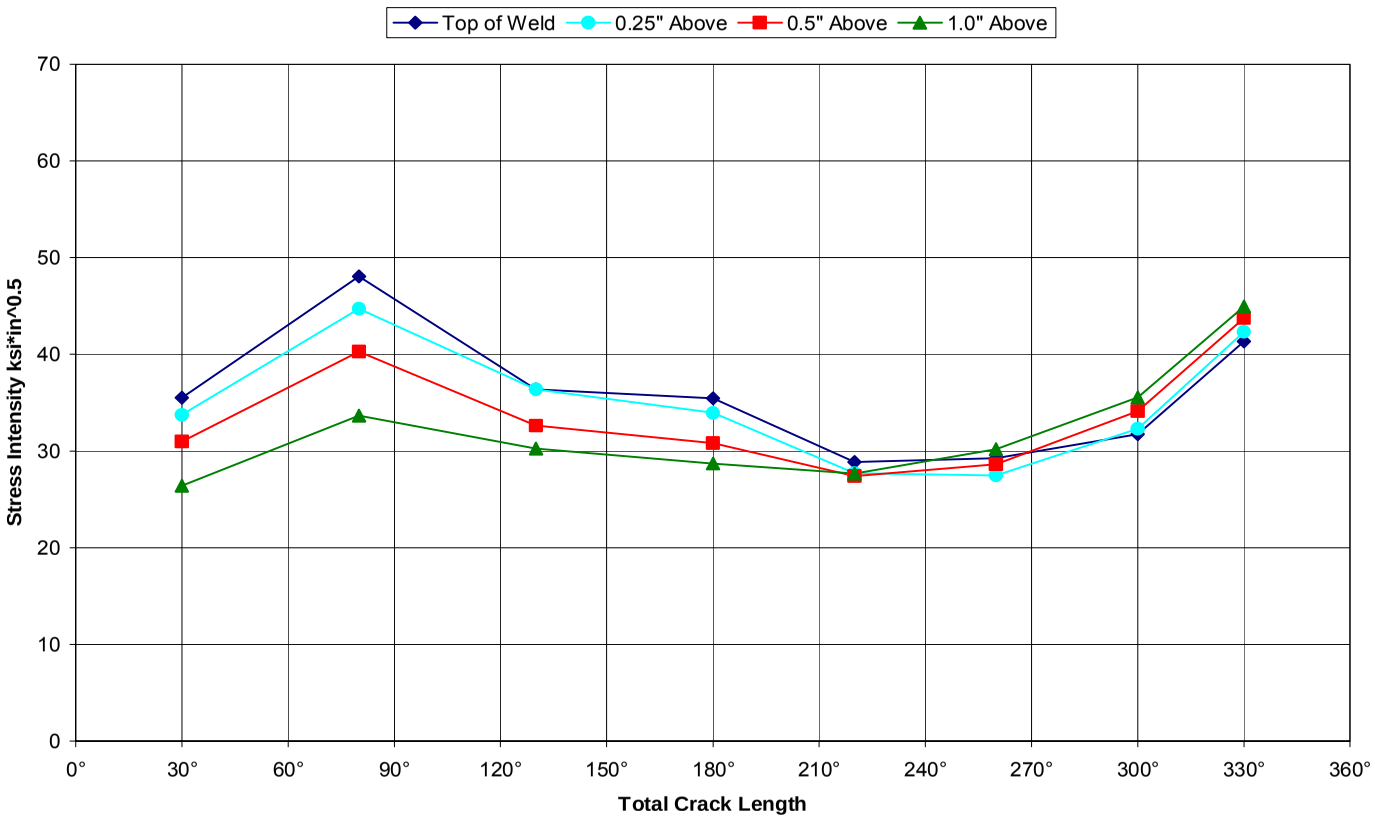
Relief of Axial Stress With Crack Growth



Operating Condition Axial Stress

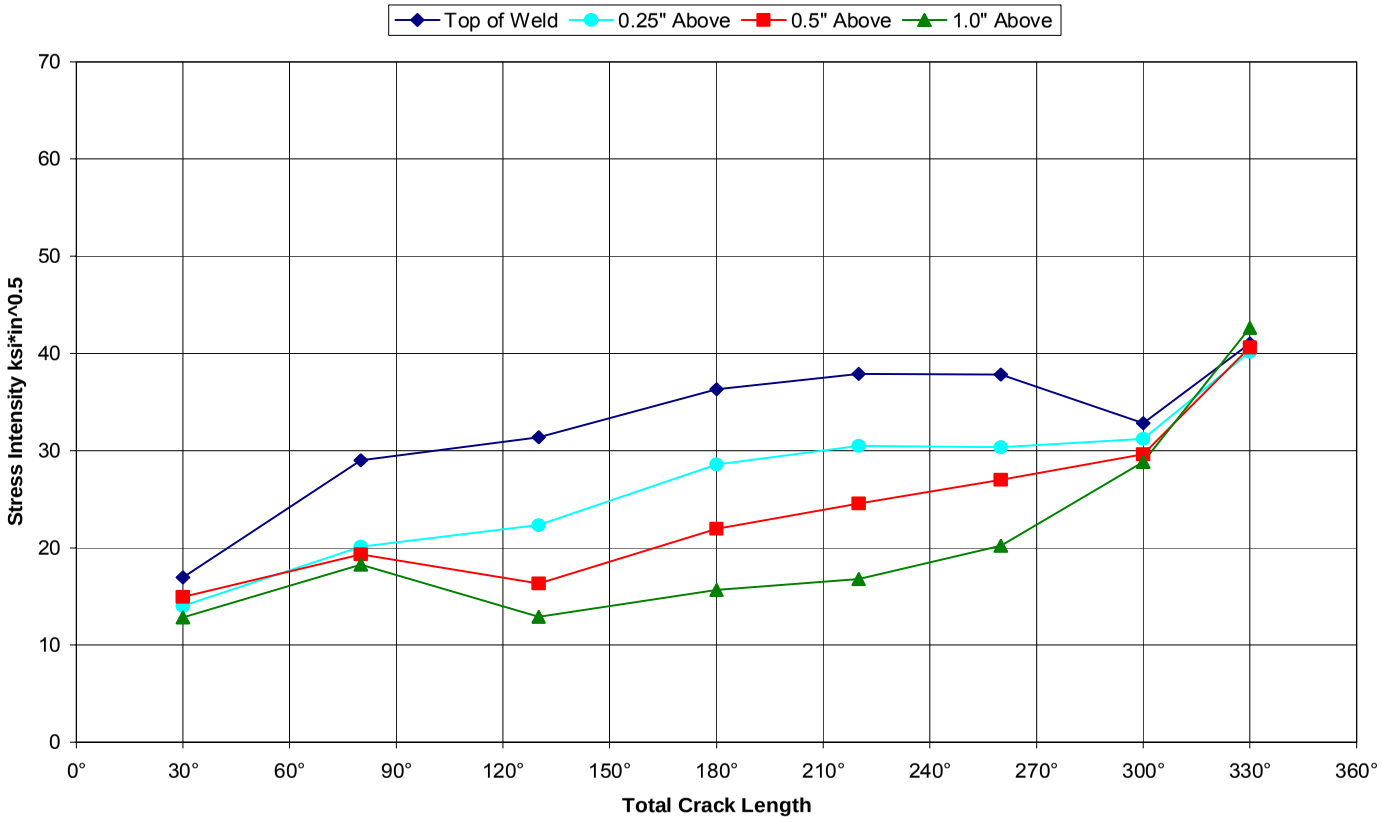
Fracture Mechanics Analyses with Stress Relaxation

Stress Intensity: Downhill-Centered Cracks

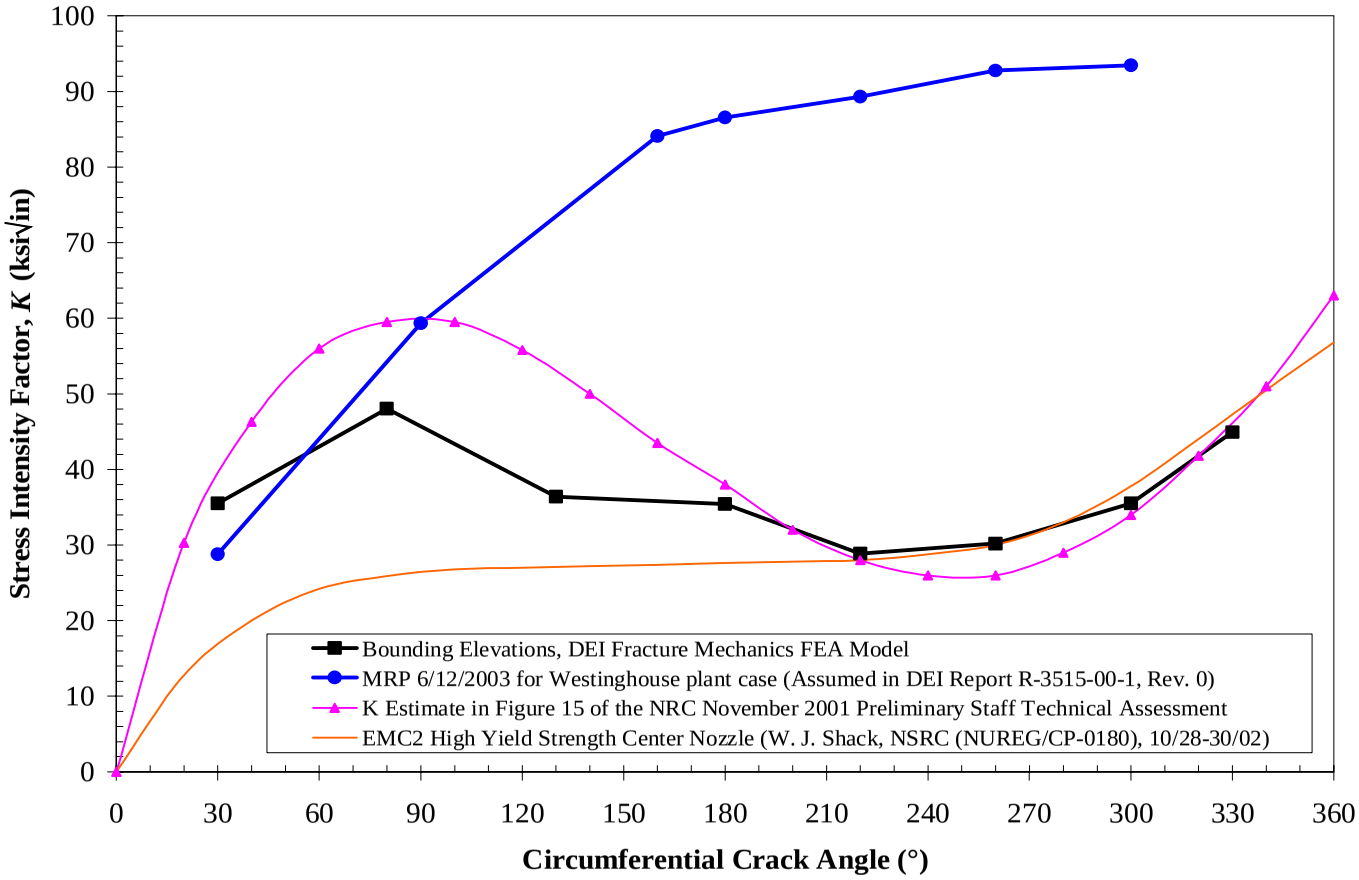


Fracture Mechanics Analyses with Stress Relaxation

Stress Intensity: Uphill-Centered Cracks

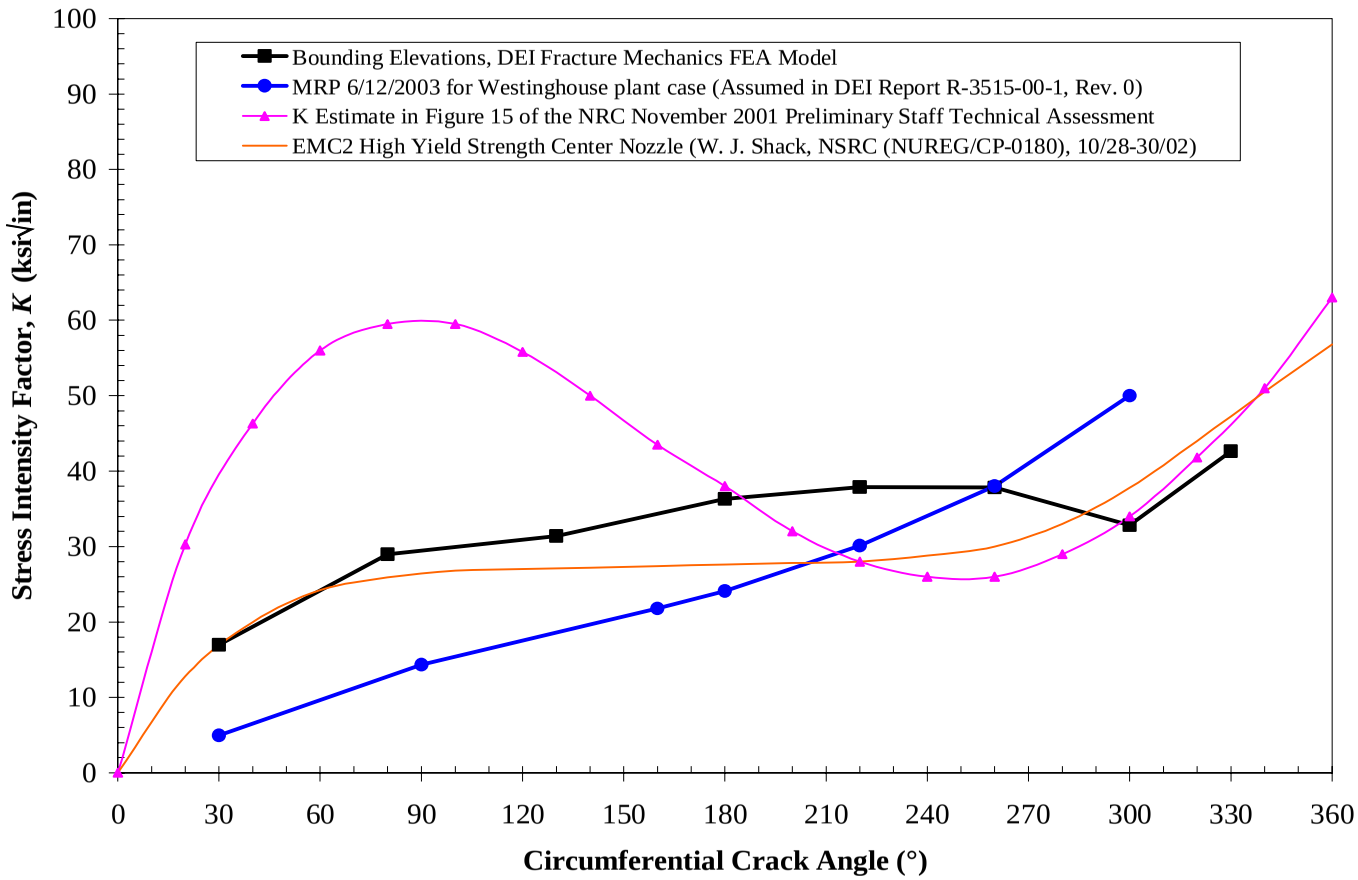


Fracture Mechanics Analyses with Stress Relaxation
Comparison to Other Data: Downhill-Centered Cracks



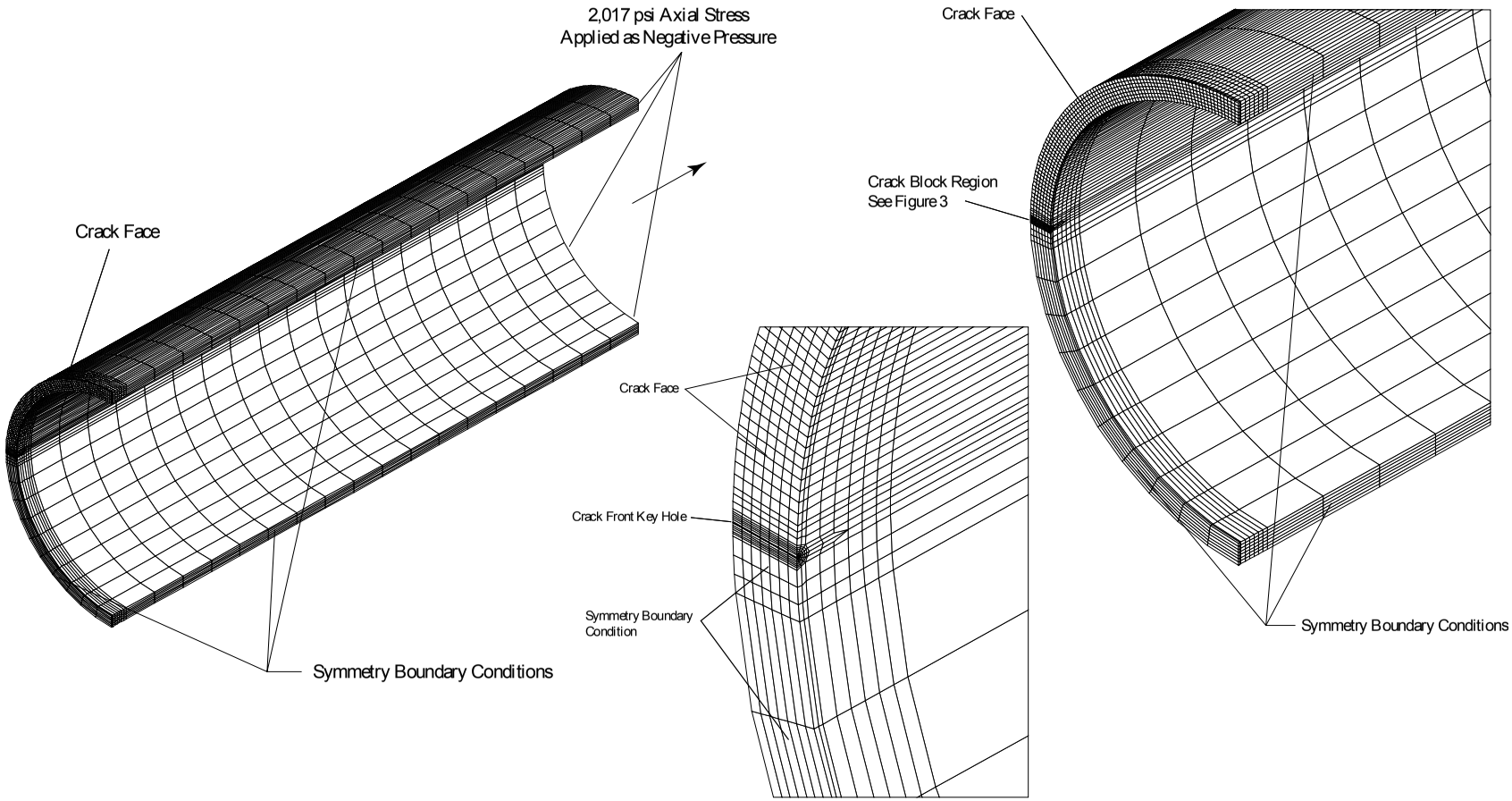
Fracture Mechanics Analyses with Stress Relaxation

Comparison to Other Data: Uphill-Centered Cracks



Fracture Mechanics Analyses with Stress Relaxation

Model Validation Case 1: Pipe with Axial Tension



Fracture Mechanics Analyses with Stress Relaxation
Validation Case 1: Pipe with Axial Tension

- The stress intensity factor calculated for this model was compared to the results published by Zahoor[1] for a mean radius to wall thickness ratio of 10 and a maximum total crack arc of 180°:
  - Results agree within about 10%

Crack Length	K_I Calculated Using Zahoor[1]	K Calculated per FEA Model Test Case
30°	2.9 ksi√in	2.9 ksi√in
80°	6.6 ksi√in	7.1 ksi√in
130°	12.7 ksi√in	13.6 ksi√in
180°	24.0 ksi√in	26.5 ksi√in

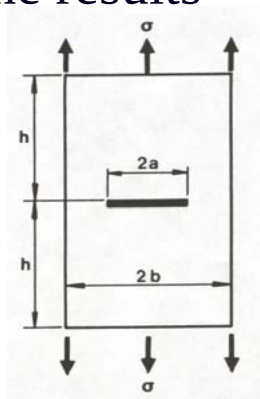
[1]**A. Zahoor, *Ductile Fracture Handbook, Volume 1*, EPRI, Palo Alto, CA: 1989. NP-6301-D.**

Fracture Mechanics Analyses with Stress Relaxation Model
Validation Case 2: Through-Wall Center Crack in Plate

- For large crack sizes, the residual stresses are mostly relieved and the pressure stress determines the stress intensity factor

- A published solution[2] for a through-wall crack in a finite plate for all *a*/*b* and large *h*/*b* was compared to the results for large circumferential cracks
  - The remote axial stress σ was based on the axial pressure loading including pressure on the crack face

$$K_0 = \sigma\sqrt{\pi a}; \qquad \frac{K_I}{K_0} = \frac{1 - 0.5\frac{a}{b} + 0.326\left(\frac{a}{b}\right)^2}{\sqrt{1-\frac{a}{b}}}$$

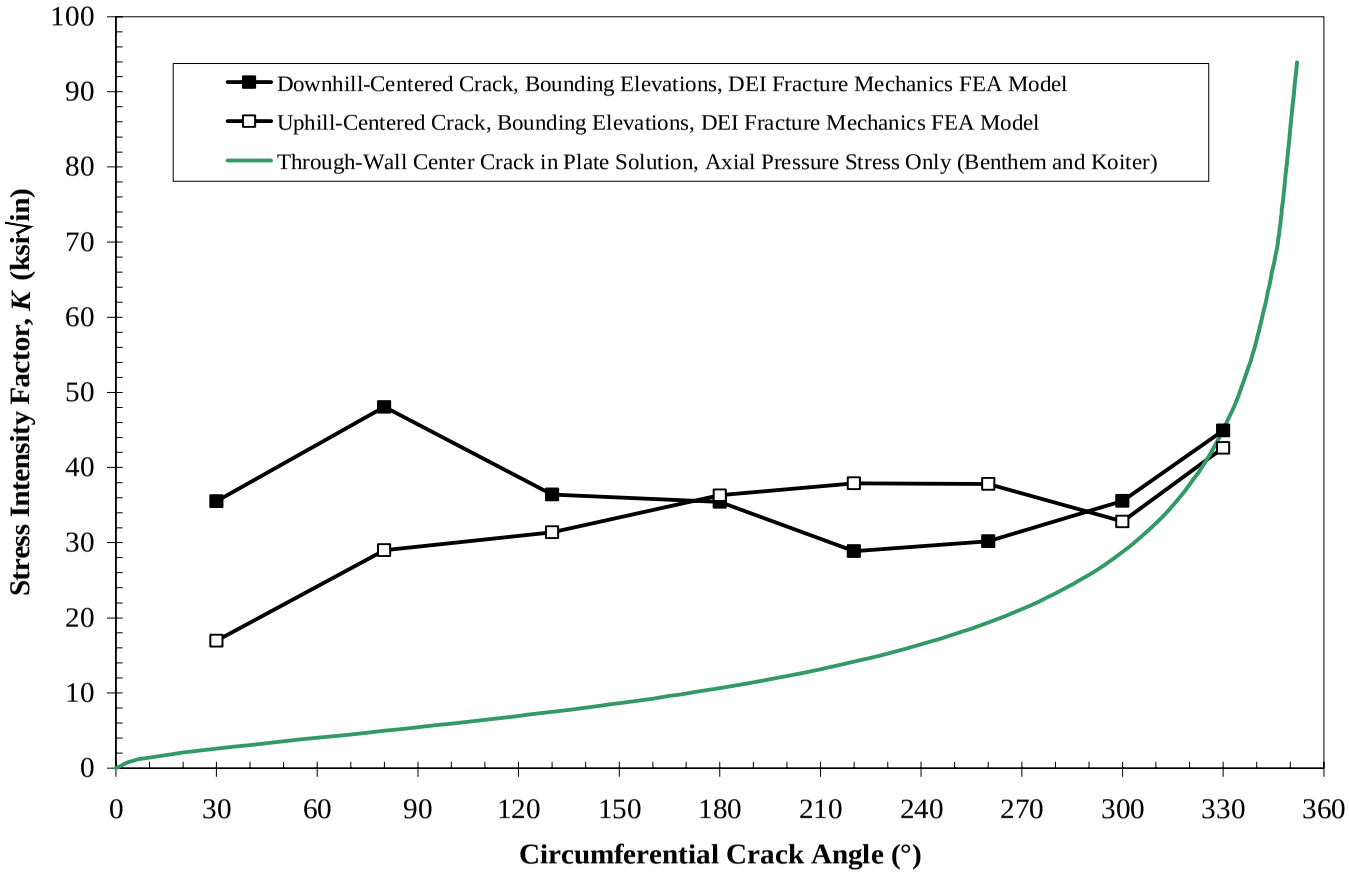


Note: *a* is taken as the projection of the crack midwall half-length on a horizontal plane.

[2]**D. P. Rooke and D. J. Cartwright, *Compendium of Stress Intensity Factors*, Her Majesty's Stationery Office, London, 1976, p. 10.**

Fracture Mechanics Analyses with Stress Relaxation Model

Validation Case 2: Through-Wall Center Crack in Plate



Fracture Mechanics Analyses with Stress Relaxation
Conclusions

- Analysis work shows that stress intensities calculated by superposition without the effect of stress relaxation can be conservative

RPV Penetration Stress Analysis and Fracture Mechanics
Future Efforts

- Continued comparisons of welding residual stress and fracture mechanics model results with others
- New opportunity for comparison between model and as-built results in North Anna RPV head
- Additional fracture mechanics applications:
  - Through-wall axial cracks for wastage analyses
  - J-groove weld cracks for time to grow to leak as well as leak rate calculations

Predicting the First Failure

Roger W. Staehle
Adjunct Professor, University of Minnesota

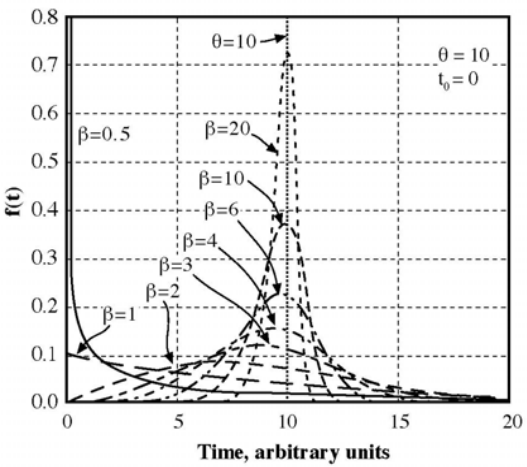
Vessel Penetration Conference
September 29-October 2, 2003
Washington, D. C.

Objectives and Scope

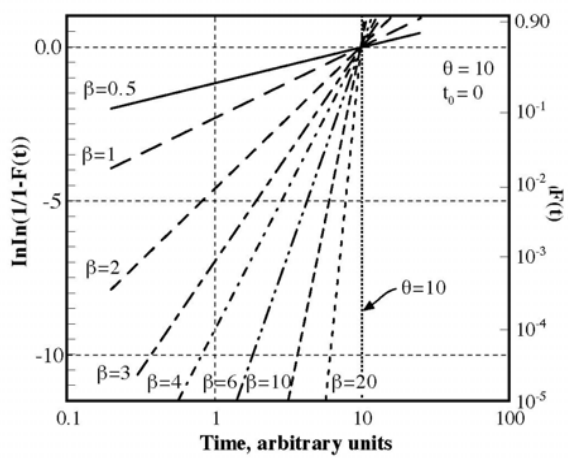
- Predict the first failure as it occurs in a statistical distribution. The first failure is usually the most important and often cannot be readily obtained
- Predict statistical distribution of SCC *a priori* based on physical variables from prior experience.
- Combine statistical distribution with physical variables of pH, potential, species, alloy composition, alloy structure, temperature, stress.
- Integrate multiple environments and submodes using product of reliabilities.
- Can apply to initiation and propagation.
- Evaluate in environments.

Weibull Distribution (Constant θ, Variable β)

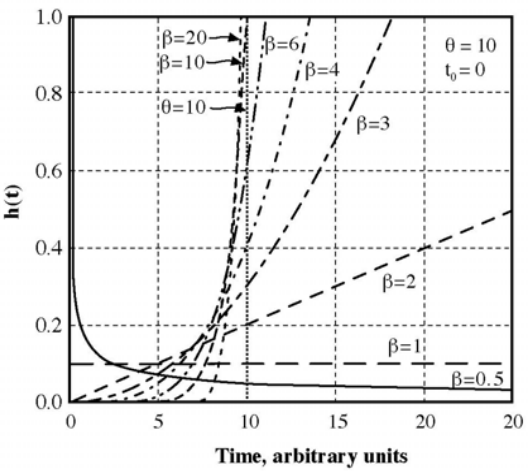
Probability density function (a)



Cumulative distribution function (b)



Hazard function (c)



$$f(t)=\left[\frac{\beta}{(\theta-t_o)^{\beta}}\right](t-t_o)^{\beta-1}\exp\left[-\left(\frac{t-t_o}{\theta-t_o}\right)^{\beta}\right],\ t>t_o \quad (1)$$

$$F(t)=P\{t'\le t\}=\int_0^t f(t)dt \quad (2)$$

$$F(t)=1-\exp\left[-\left(\frac{t-t_o}{\theta-t_o}\right)^{\beta}\right] \quad (3)$$

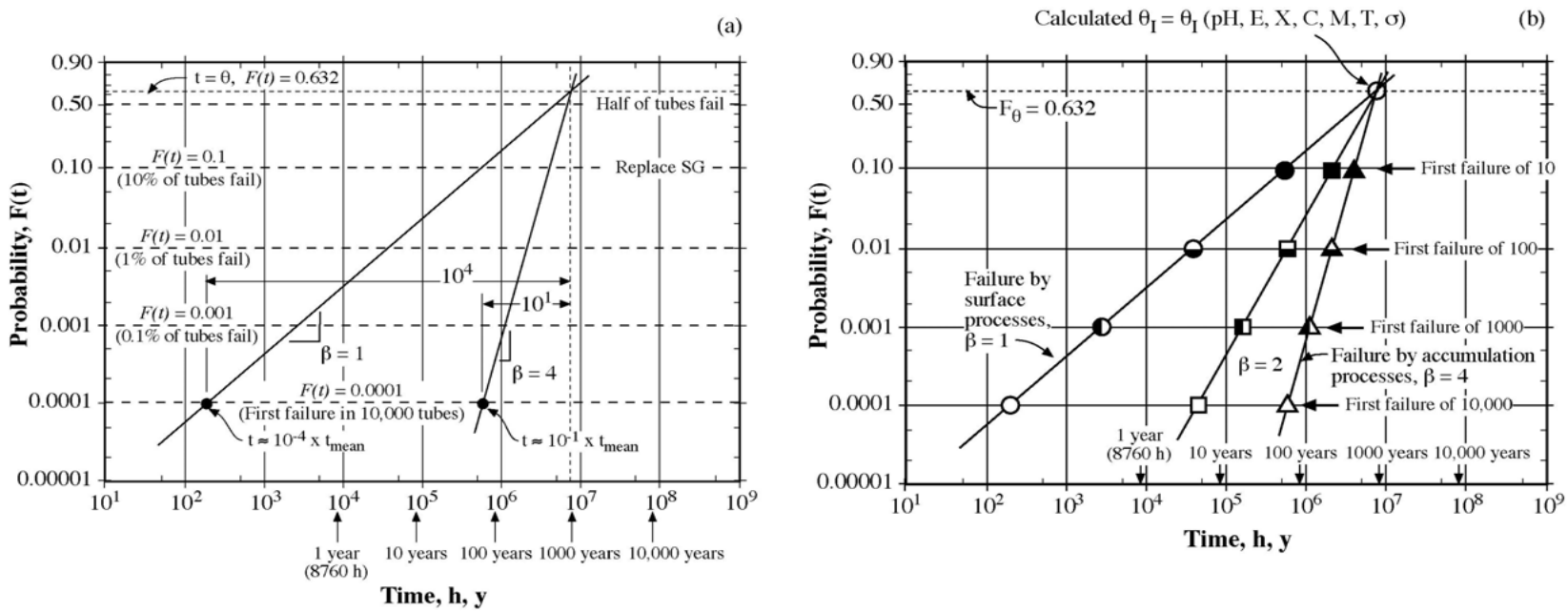
$$\ln\left[\ln\left(\frac{1}{1-F(t)}\right)\right]=\beta\left[\ln(t-t_o)-\ln(\theta-t_o)\right] \quad (4)$$

$$h(t)=\frac{f(t)}{1-F(t)} \quad (5)$$

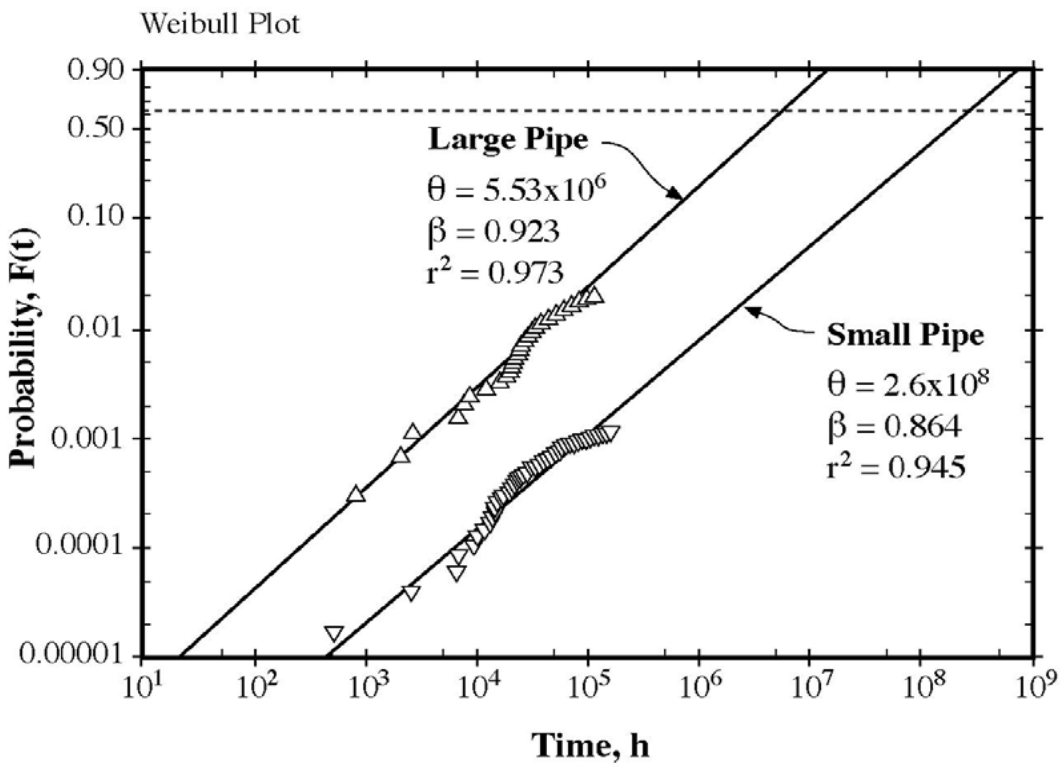
$$h(t)=\left(\frac{\beta}{\theta-t_o}\right)\left(\frac{t-t_o}{\theta-t_o}\right)^{\beta-1}=\frac{\beta}{(\theta-t_o)^{\beta}}(t-t_o)^{\beta-1} \quad (6)$$

θ=Scale parameter
β=Shape parameter
t_o=Location parameter

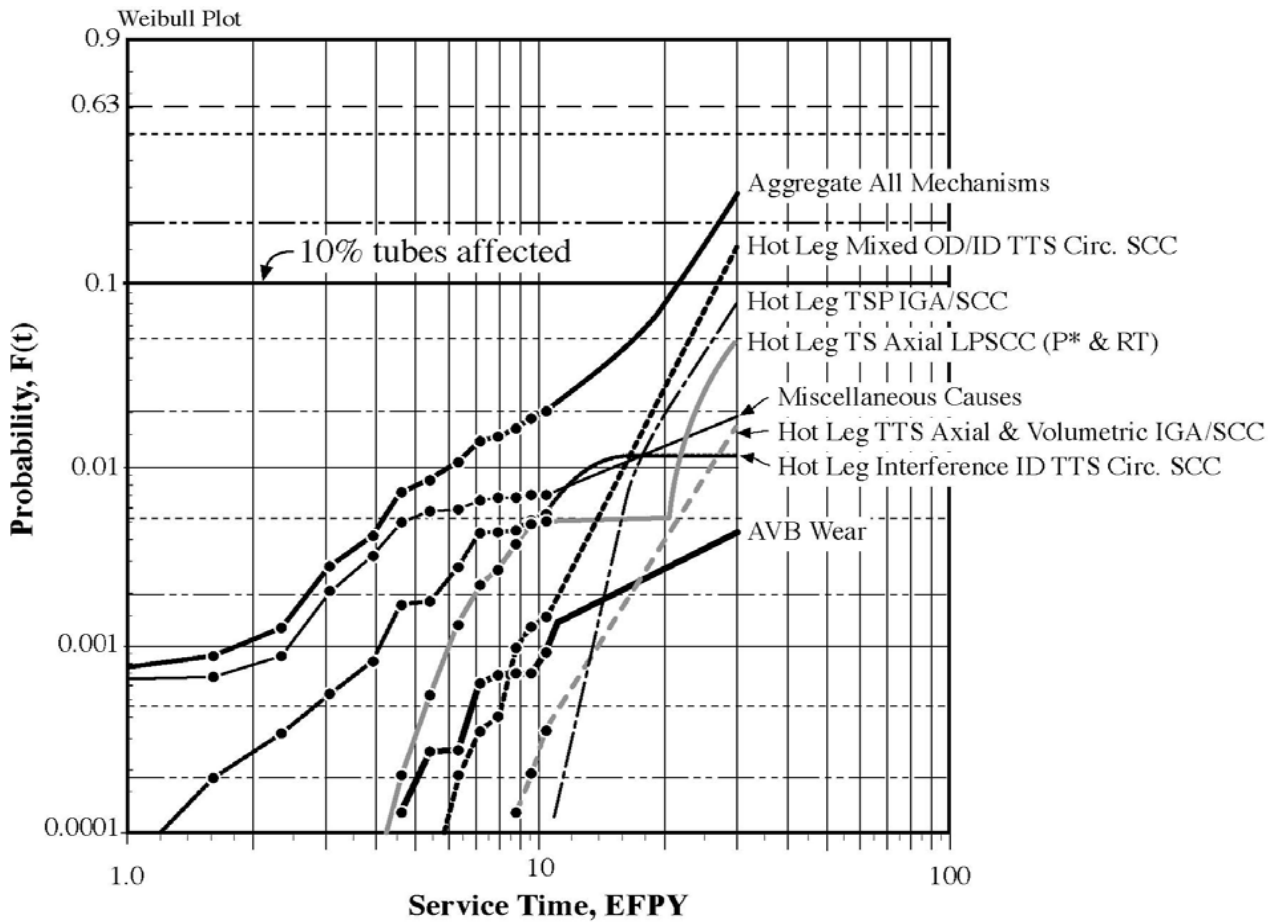
Magnitudes of cdf Depending on Shape Parameter And Number in Sample



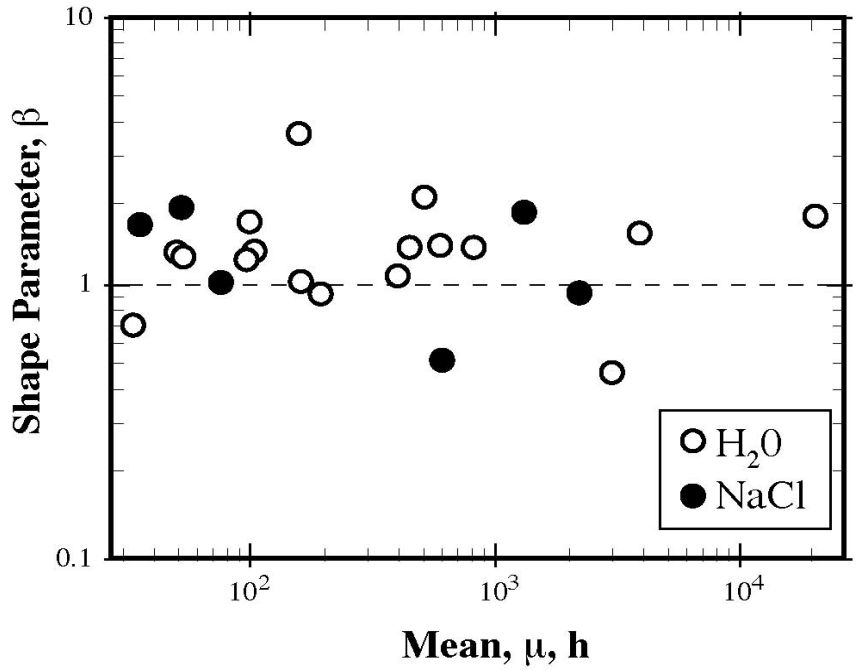
Probability of SCC vs. Time in Large (4 inch diameter) and Small (2 inch diameter) of Welded Stainless Steel Piping in BWR Water (Easton and Shusto)



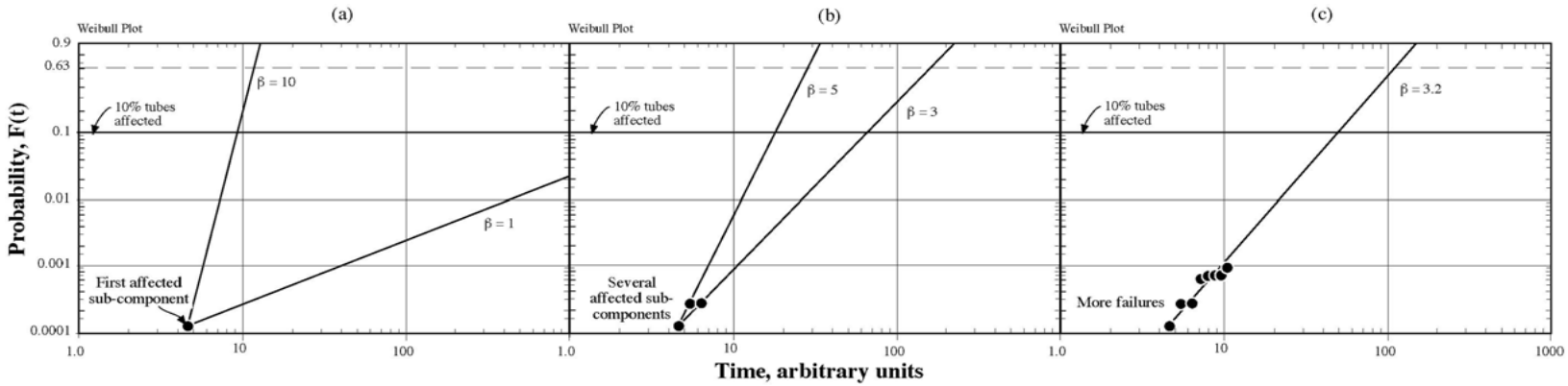
Probability vs. EFPY for Alloy 600 Tubing
in Ringhalls-4 PWR Steam Generator (Gorman and Bjornquist)

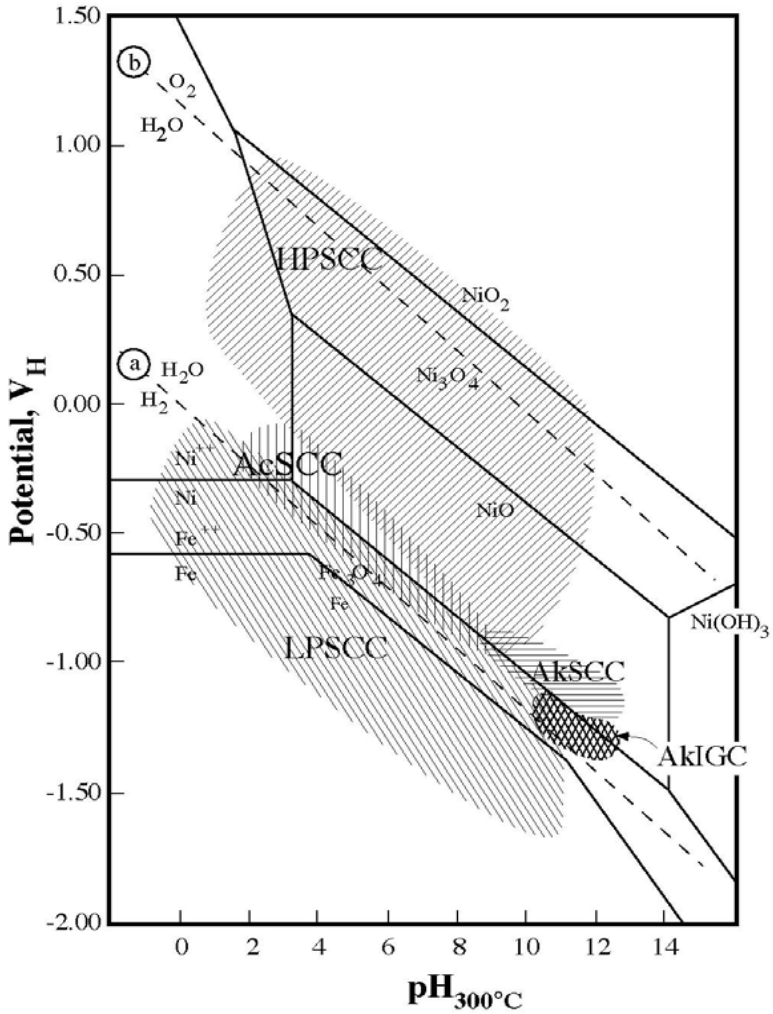


Shape Parameter, β, vs Mean Failure Time in NaCl solutions
Using Sensitized Stainless Steel and No Crevices 30-80°C
(Akashi and Nakayama)

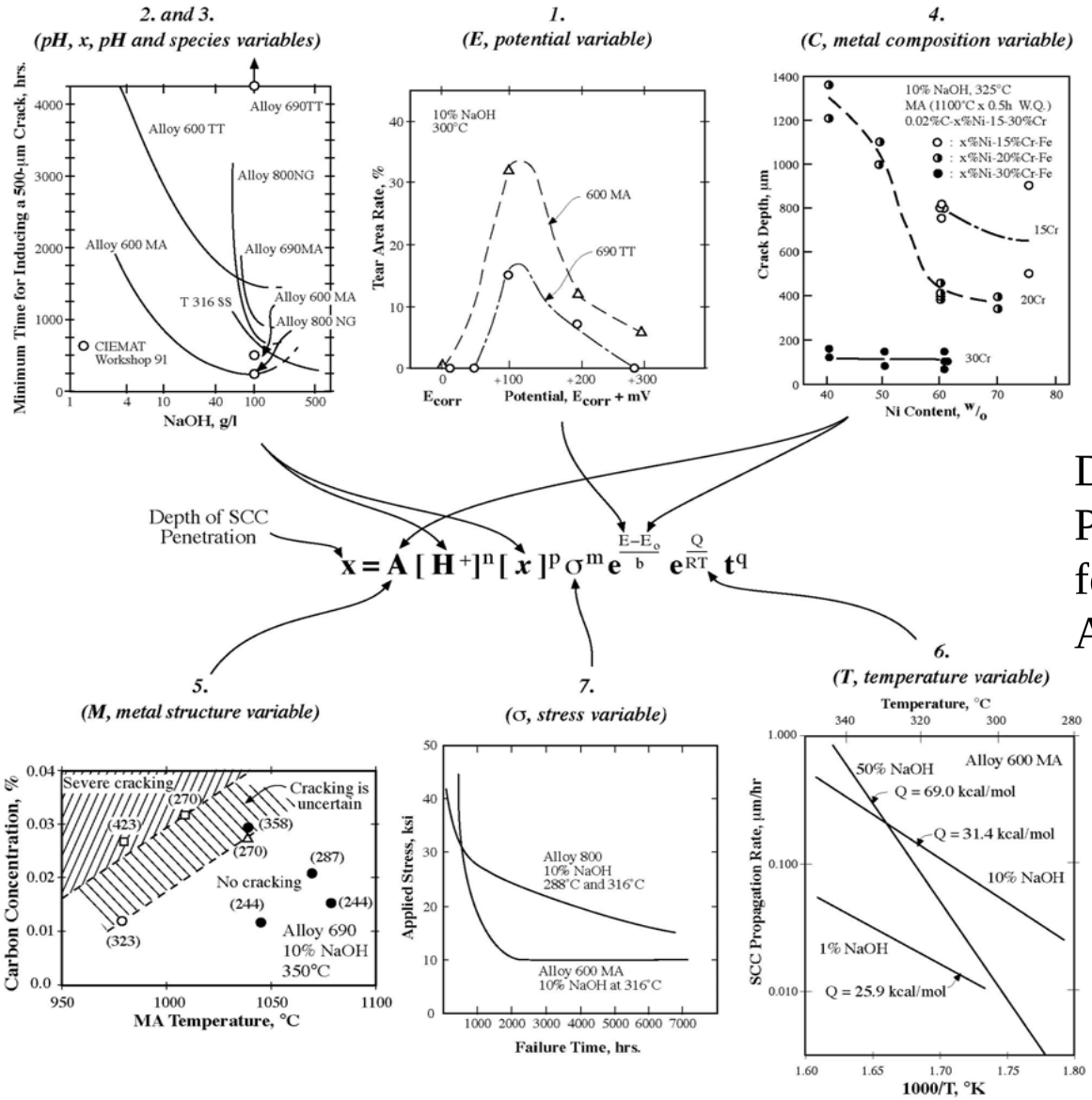


Progressive Development of Prediction from Early Data Using Weibull cdf



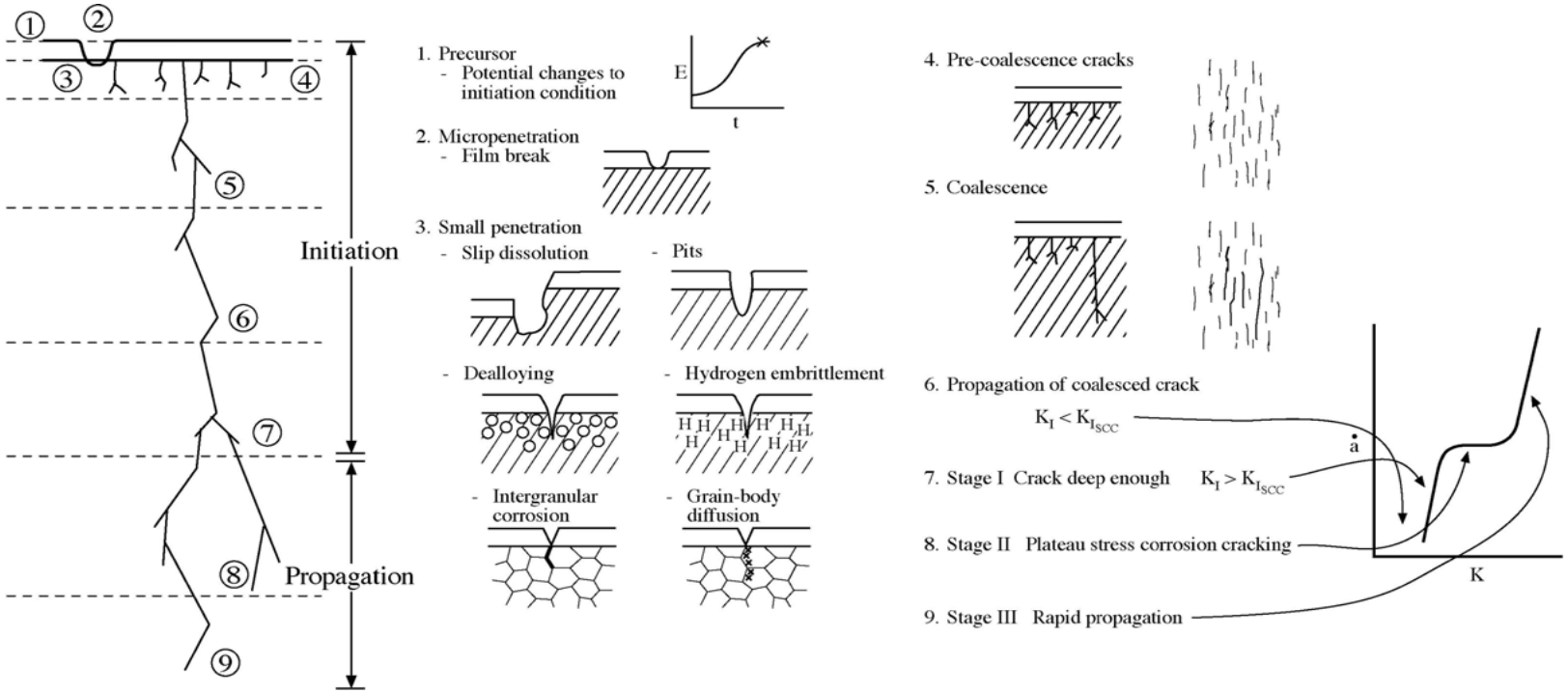


Mode Diagram for SCC of Alloy 600 in 300-350°C Range in Pure Water Applied to PWR Steam Generators

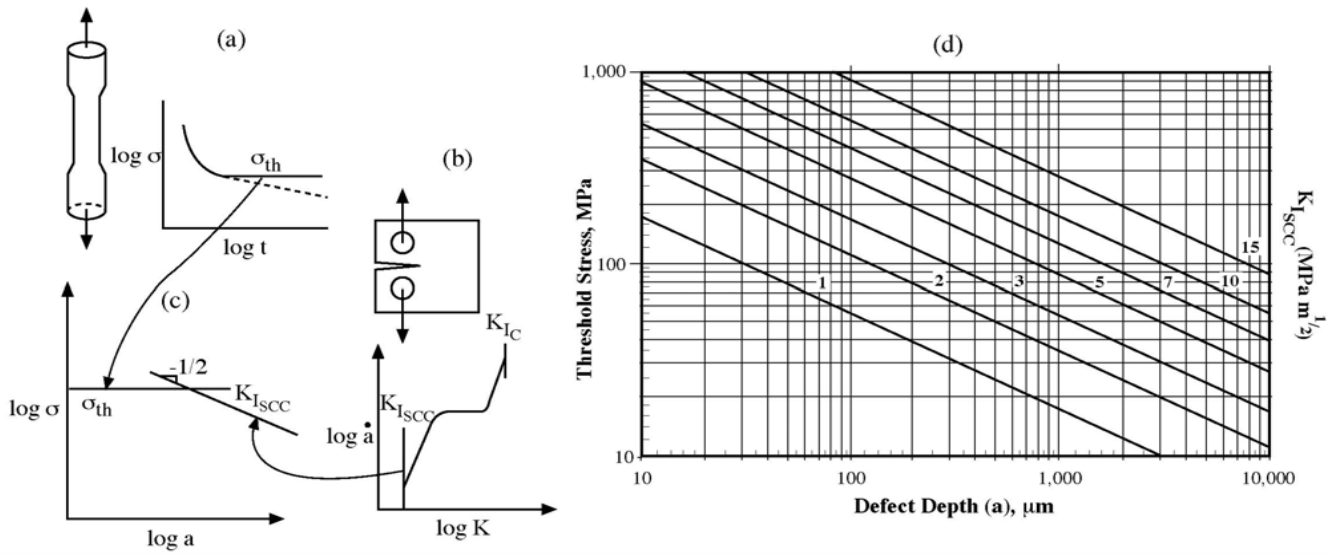


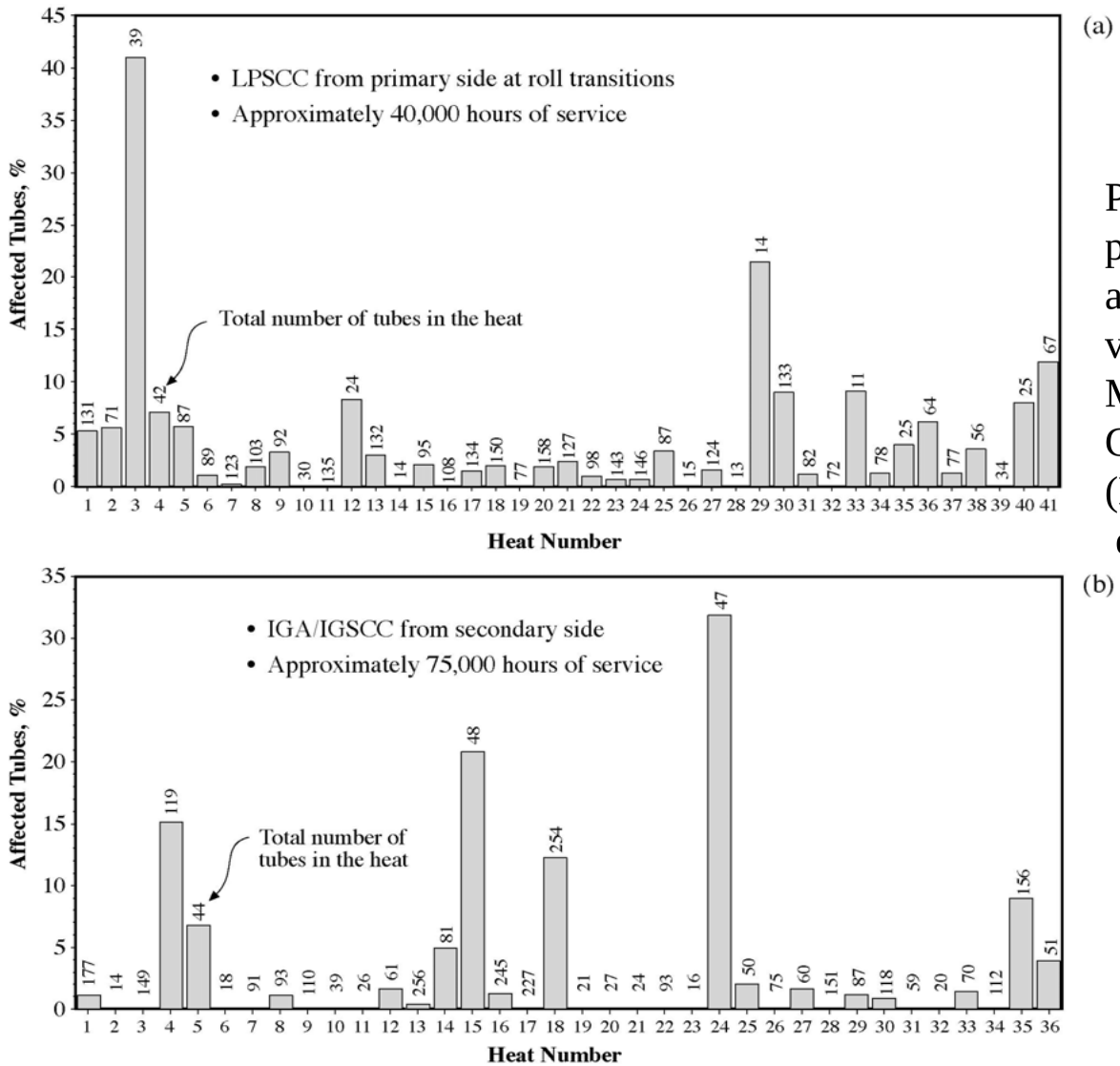
Dependencies of SCC on Primary Variables for Alloy 600 in Alkaline Environments

Nine Stages of SCC



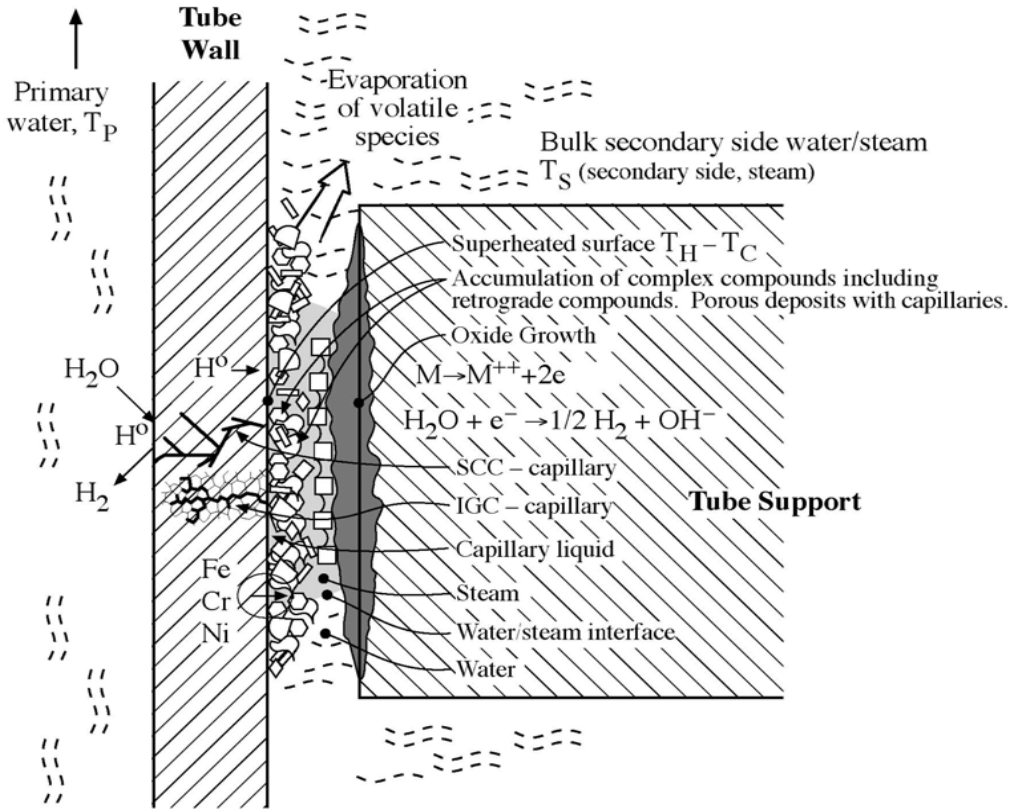
Estimation of Depth of Transition from Initiation to Propagation



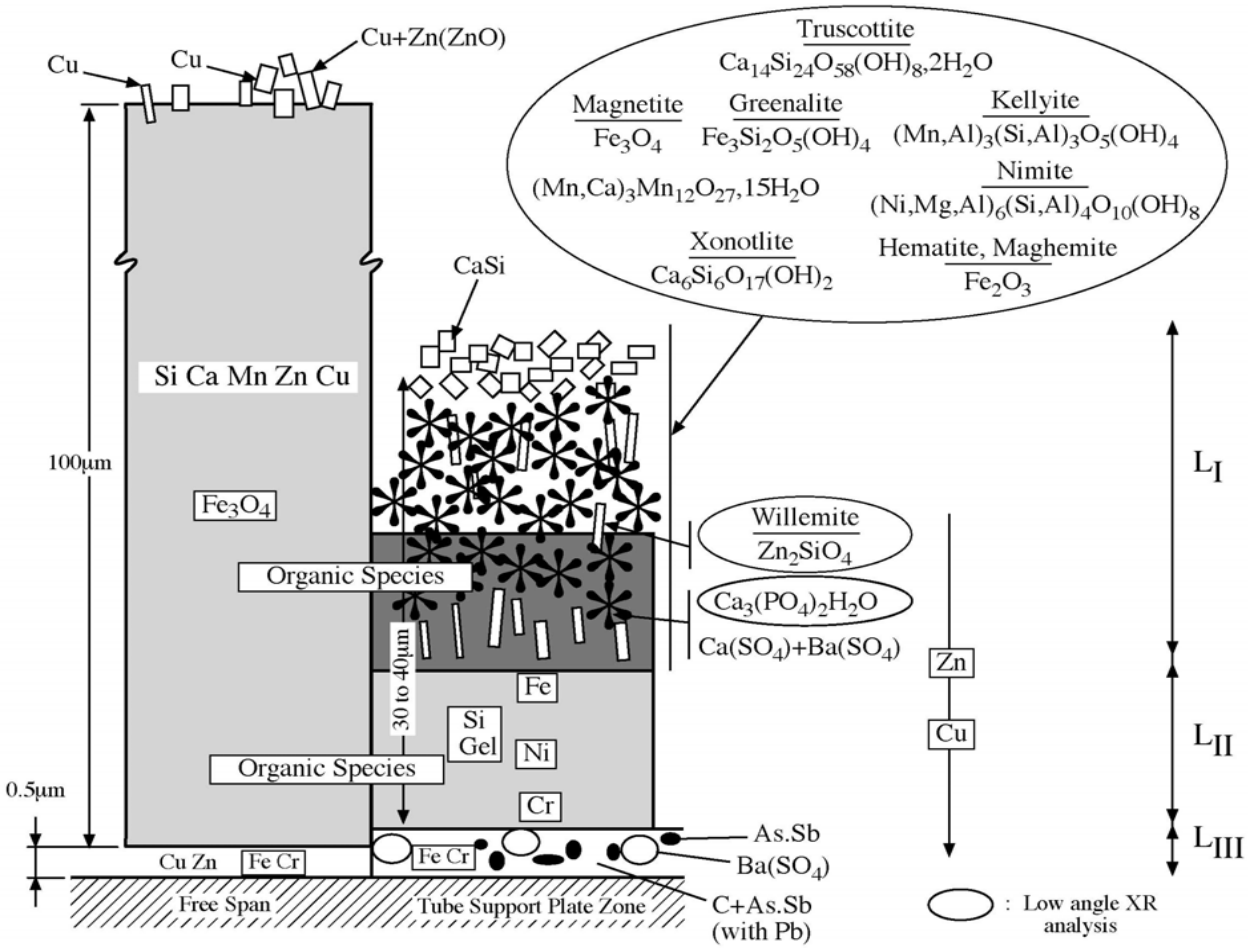


Percent Failure of SG Tubes per Heat for Primary (Upper) and Secondary (Lower) Sides vs.. Heats Produced by Single Manufacturer in Chronological Sequence. (Number of tubes from each heat used shown)

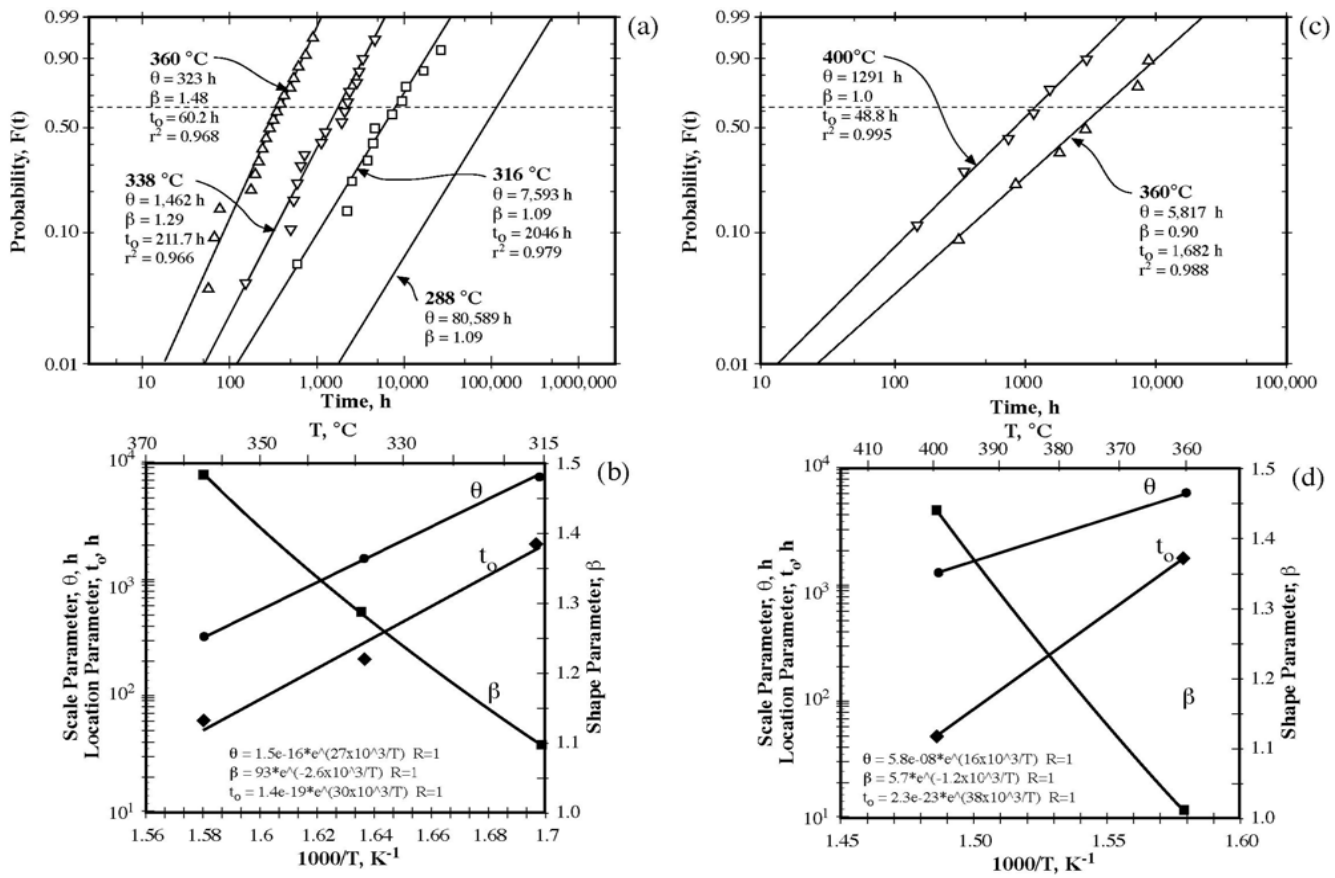
Complexity of Environments in Heat Transfer Crevices



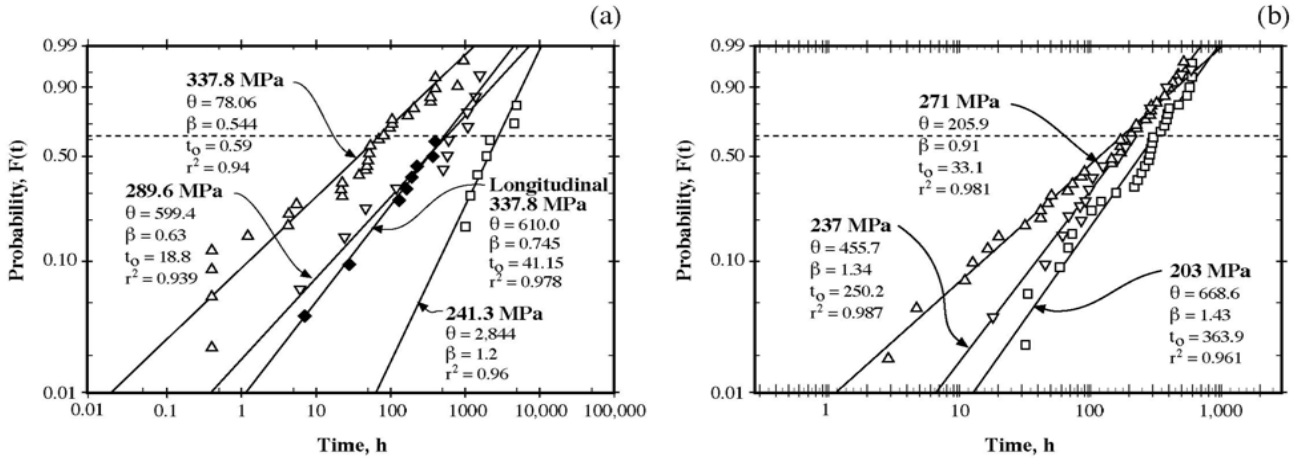
Chemistry, Location, and Depth of Deposits from Heated Crevice from PWR SG (Cattant, Sala)

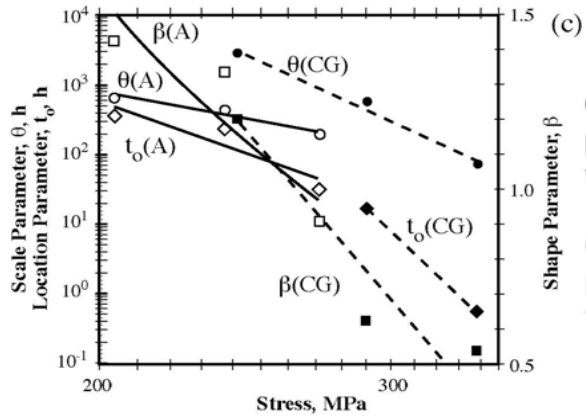


Probability vs. Time for LPSCC of Alloy 600 as a Fuction of Temperature
(Data from Webb, Jacko);
Dependencies of Statistical Parameters on 1/T



Probability vs. Time as a Function of Stress for Sensitized Type 304 Stainless Steel Exposed at 288°C in Pure Oxygenated Water (Clark and Gordon, Akashi and Ohtomo); Dependence of Statistical Parameters on Stress

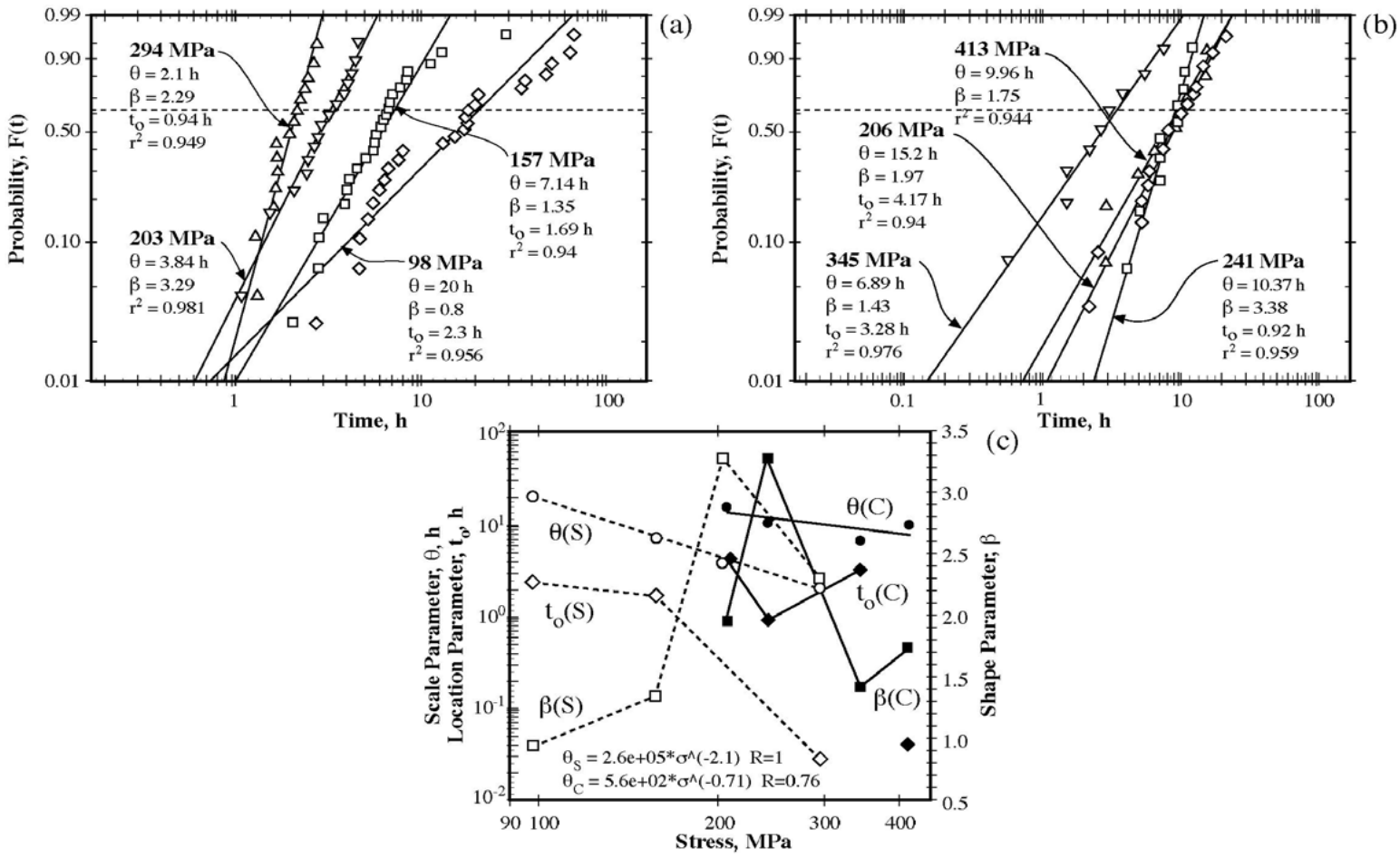




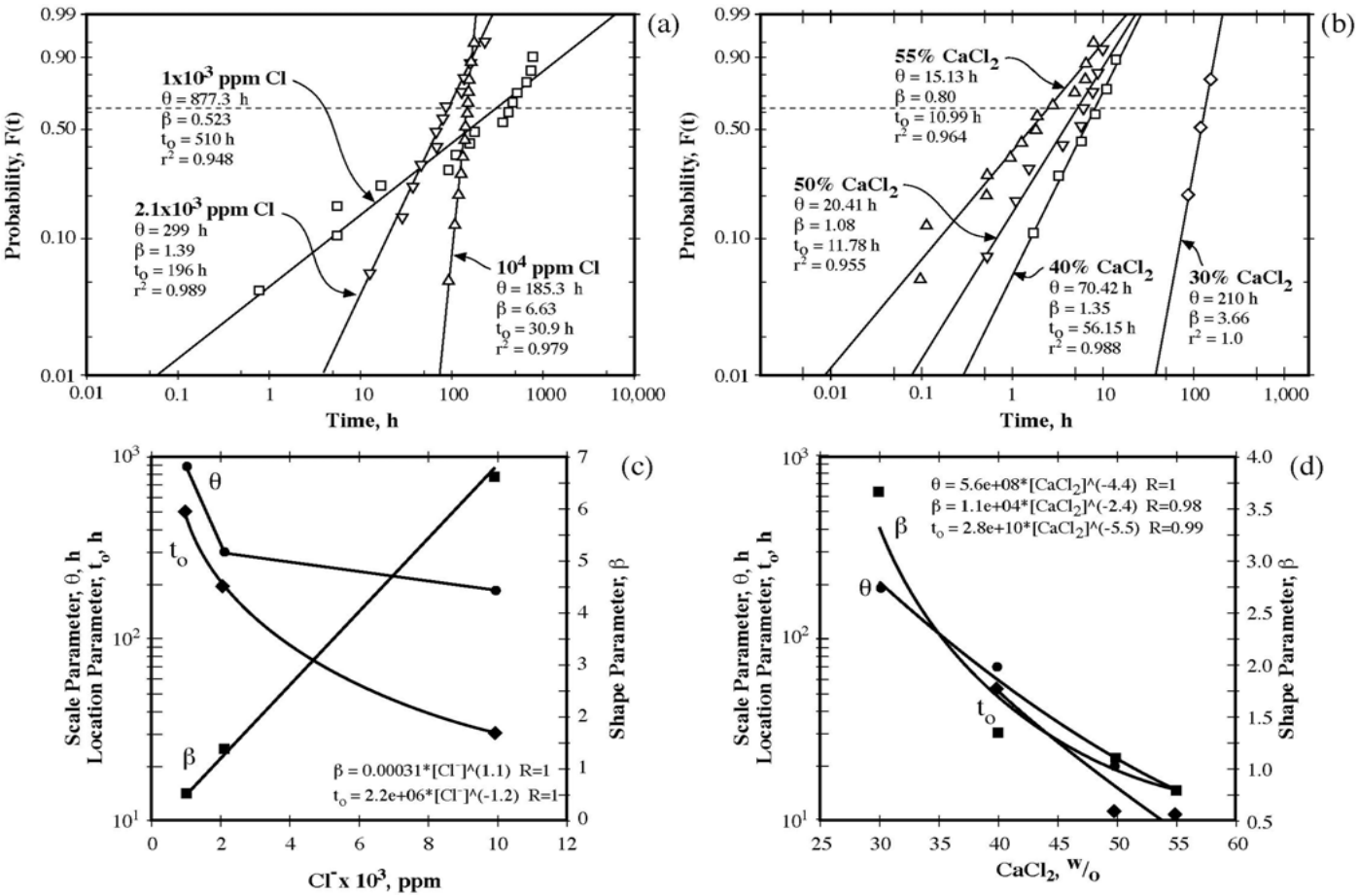
θ_A = 1.5e+12*σ^(-4) R=0.98
β_A = 4.8e+03*σ^(-1.5) R=0.89
t_{oA} = 3.1e+21*σ^(-8.2) R=0.88

θ_{CG} = 6.5e+28*σ^(-11) R=1
β_{CG} = 5.5e+05*σ^(-2.4) R=0.97
t_{oCG} = 4.2e+56*σ^(-22) R=0.1

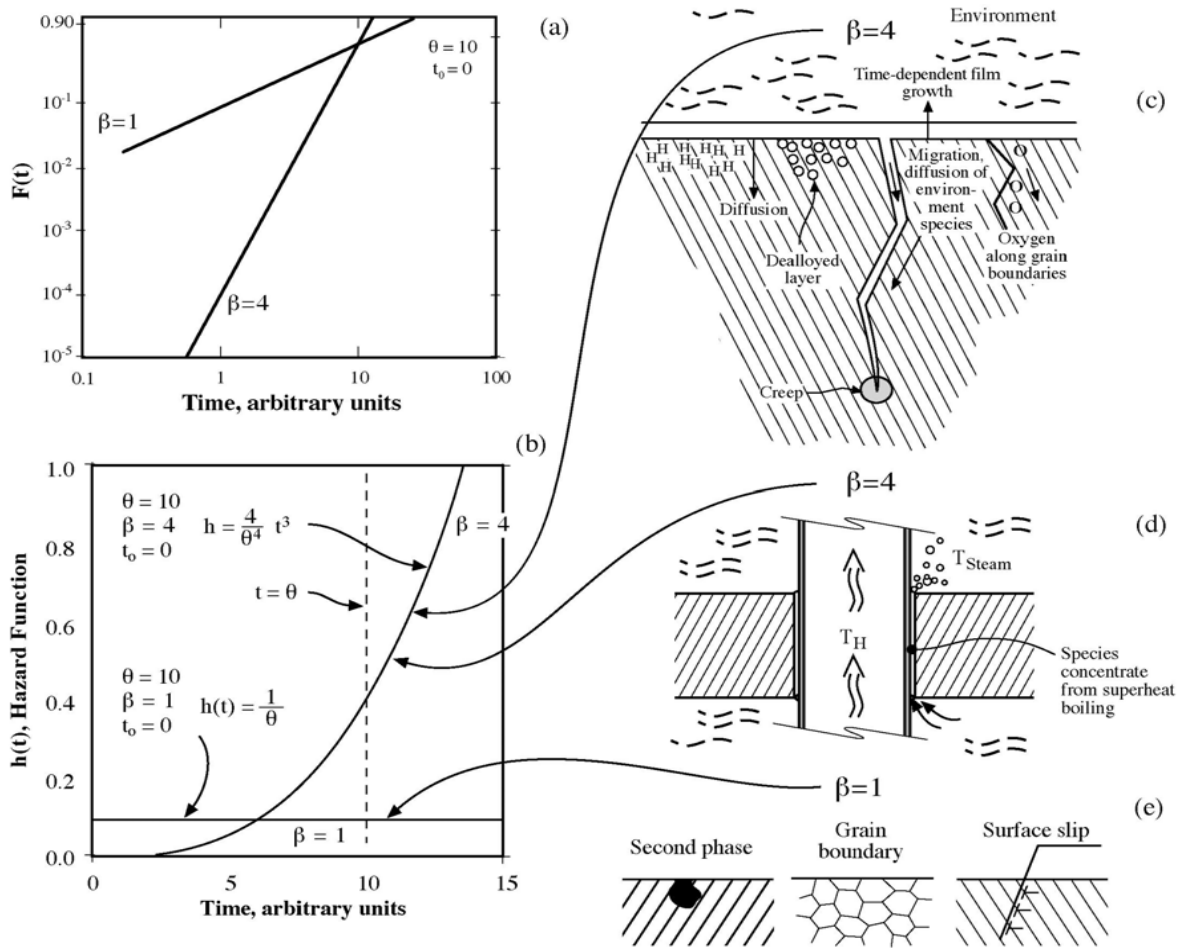
Probability vs. Time for Stainless Steel in Boiling $MgCl_2$ at 154°C
as a Function of Stress (Shibata and Takeyama, Cochran and Staehle);
Dependence of Statistical Parameters on Stress



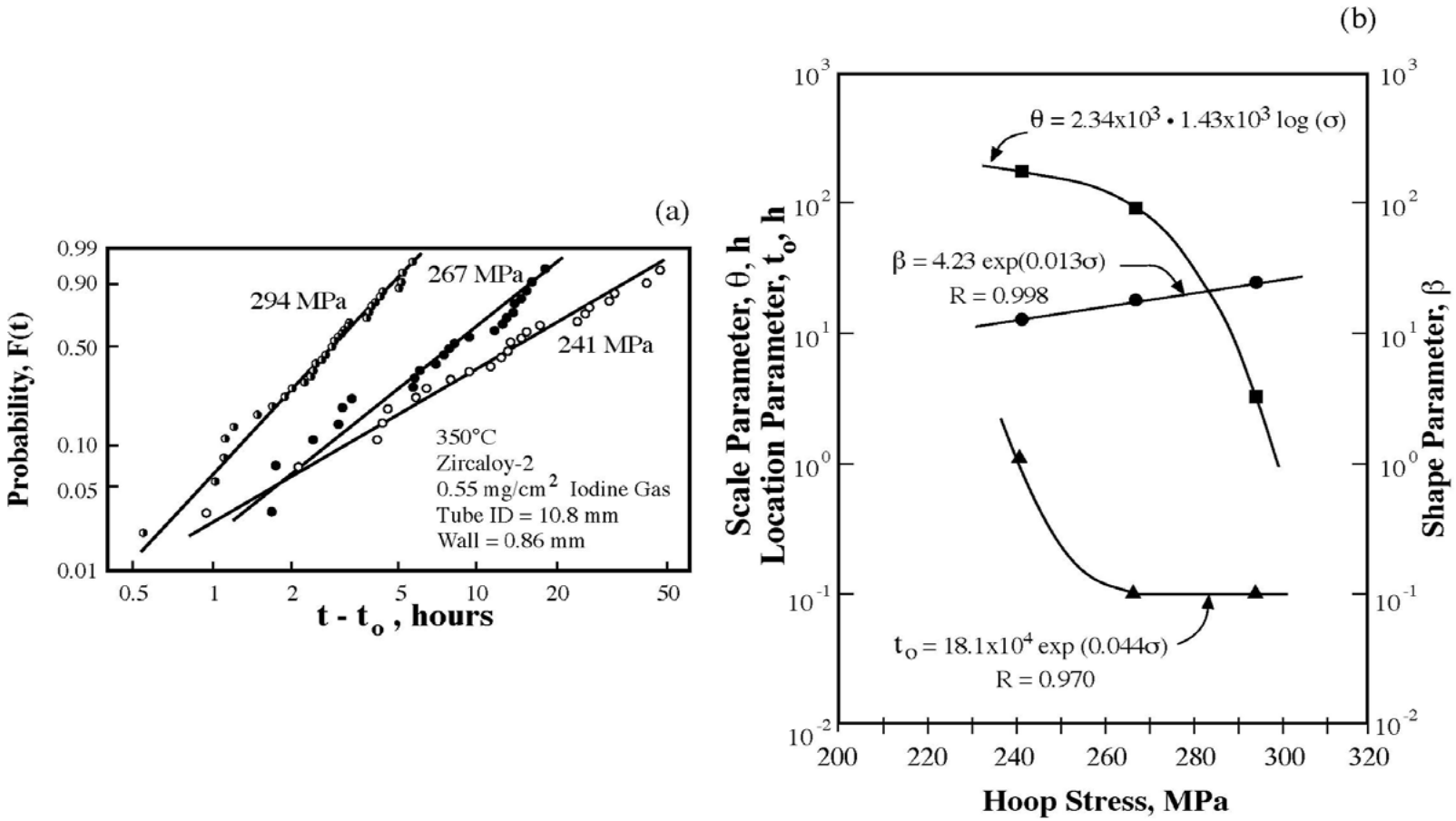
Probability vs. time for SCC ofTtype 304 Exposed to
Dilute and Concentrated Chloride Solutions as a Function of Concentration
(Nakayama et al. 1.75 Sy at 80°C Crevice; Shibata et al. 200MPa at 100°C)
Dependence of Statistical Parameters on Concentration



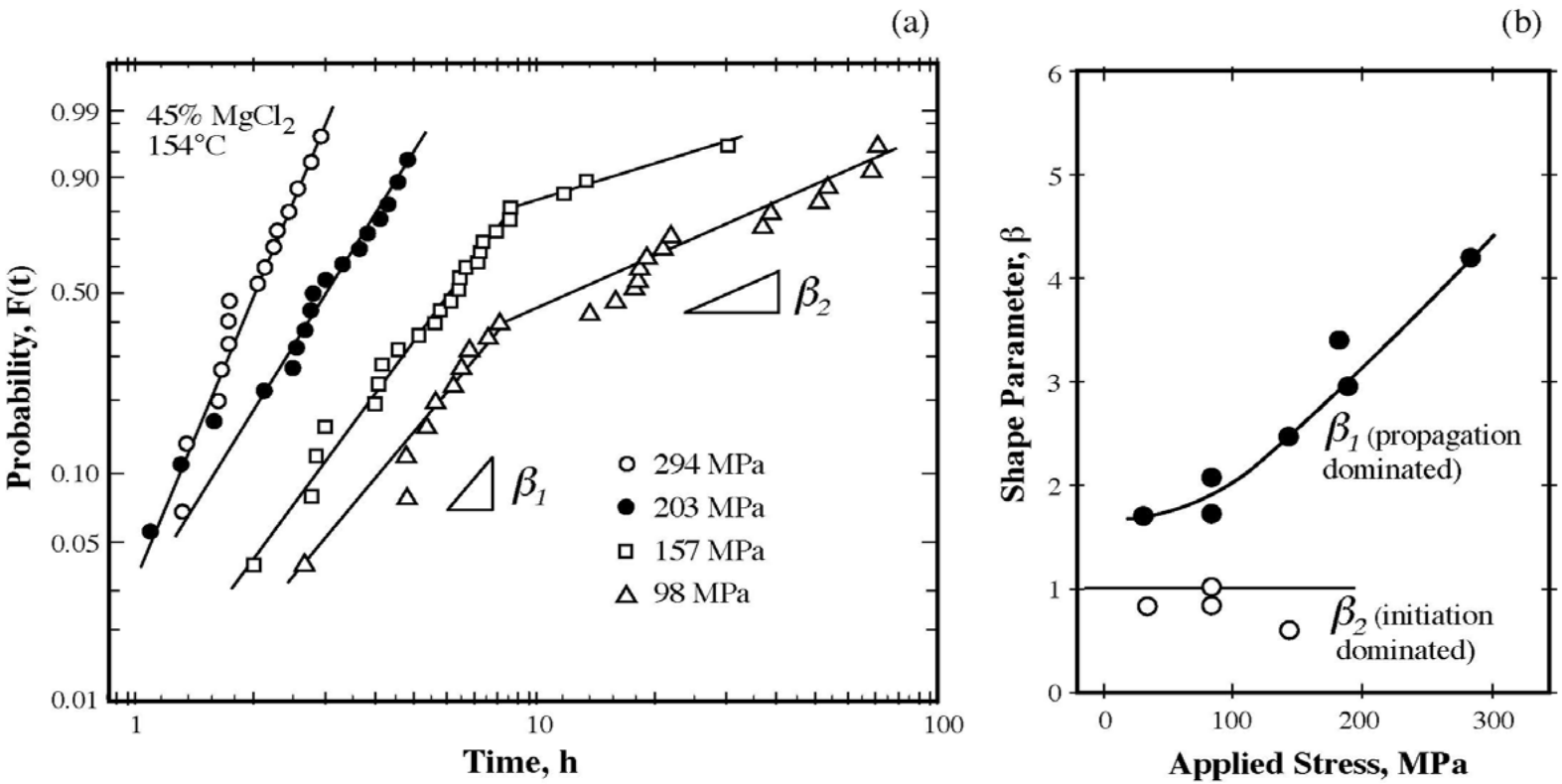
Effects of Physical Conditions on the Shape Parameter;
Comparing Suruface and Time Dependent Processes;
Comparing with Cumulative Distribution and Hazard Function



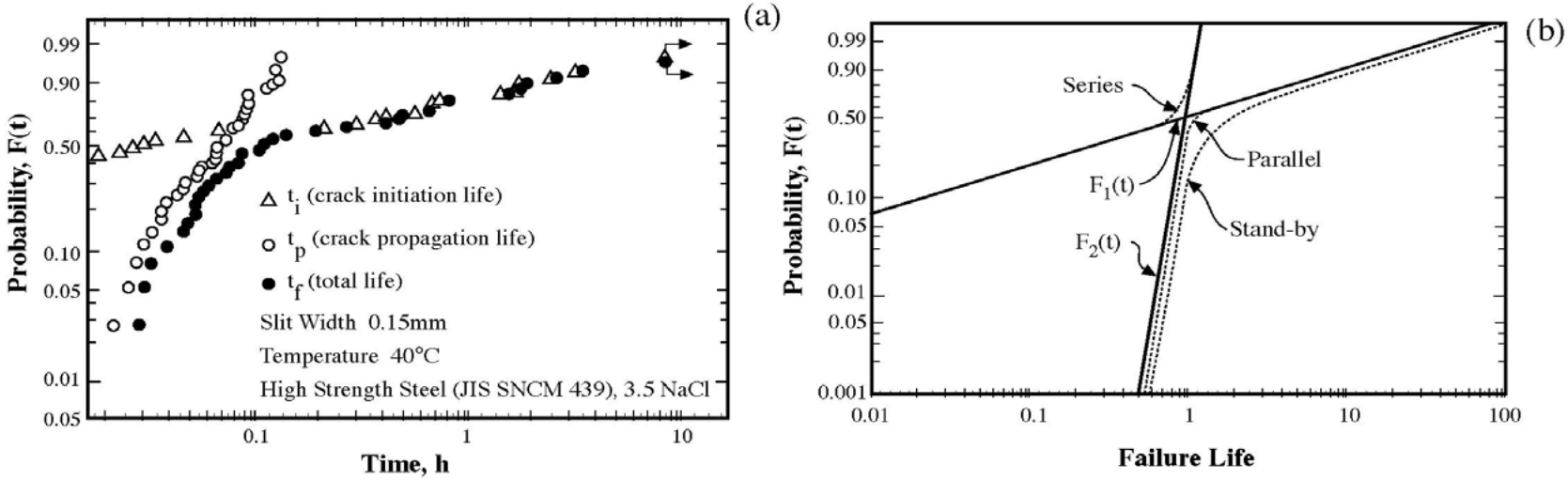
Probability of SCC vs. Time as a Function of Stress for Zircaloy 2 in Iodine Gas at 350°C; Statistical Parameters vs. Hoop Stress (Shimada and Nagai)



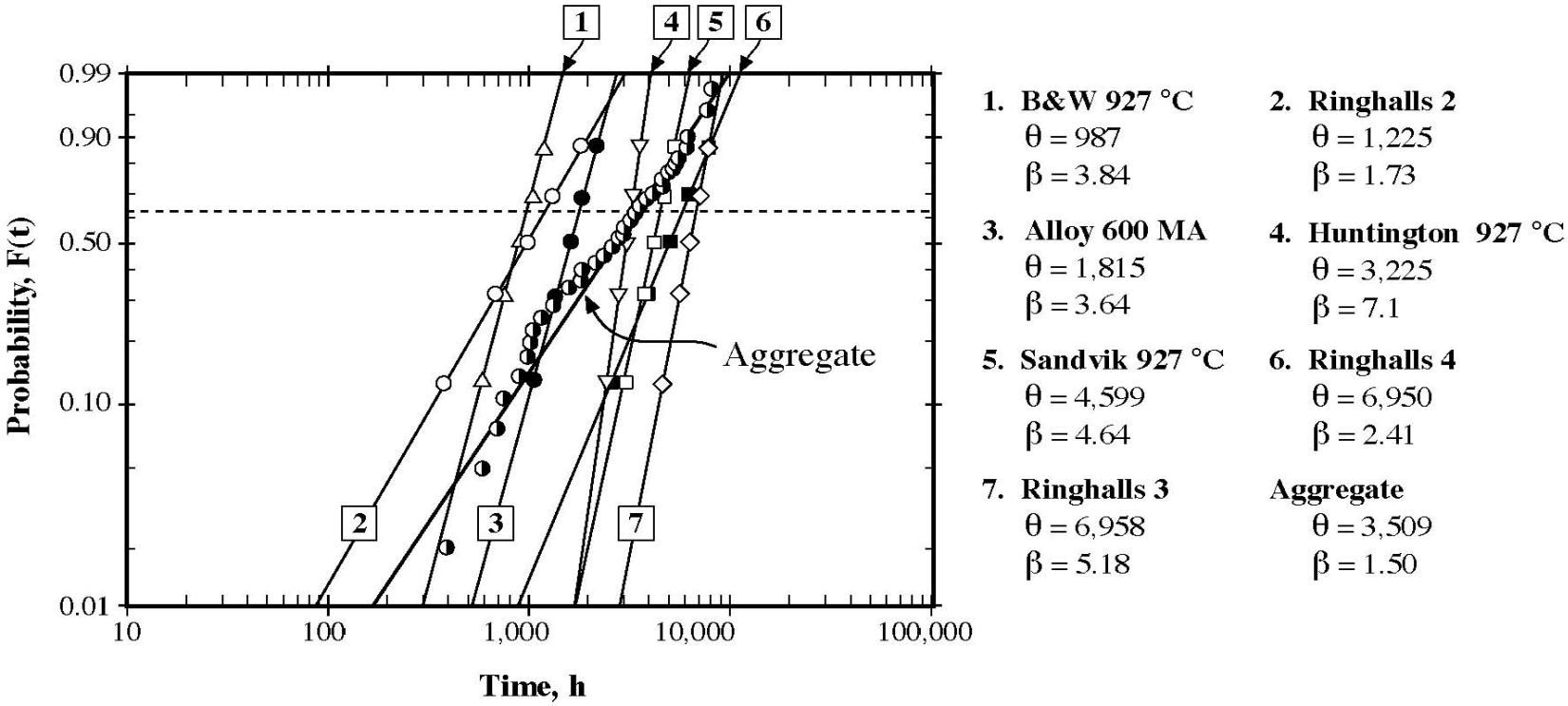
Probability vs. Time for Different Applied Stresses for
Type 304 Stainless Steel Exposed to MgC_{l2} at 154°C;
Shape Parameter vs. Applied Stress (Shibata and Takeyama)



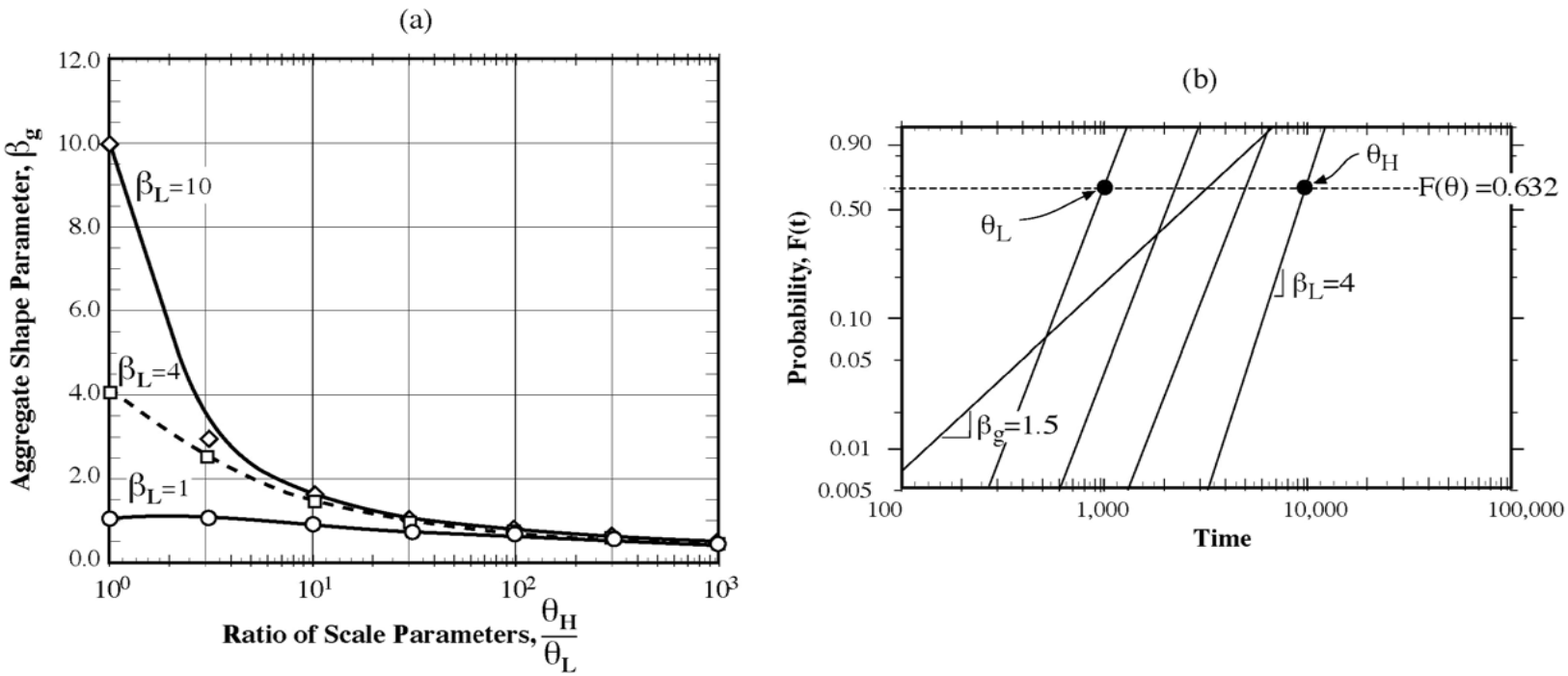
Probability vs. Time for Initiation and Propagation of SCC in a High Strength Steel in 3.5% NaCl at 40°C. (Ichikawa et al.)



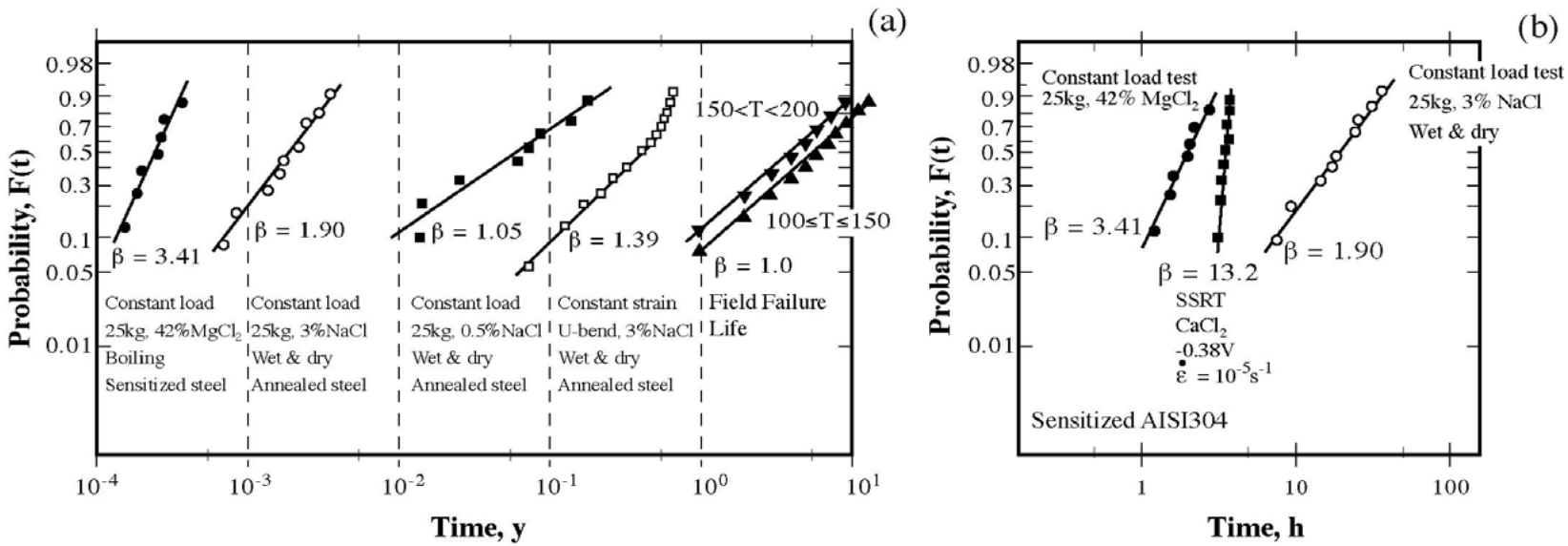
Probability vs. Time for the LPSCC of Alloy 600 in High Purity Water
with Hydrogen Additions Using RUB Specimens at 365°C from Different Heats.
(Estimated Data Points from Norring)
Aggregate of All Specimens



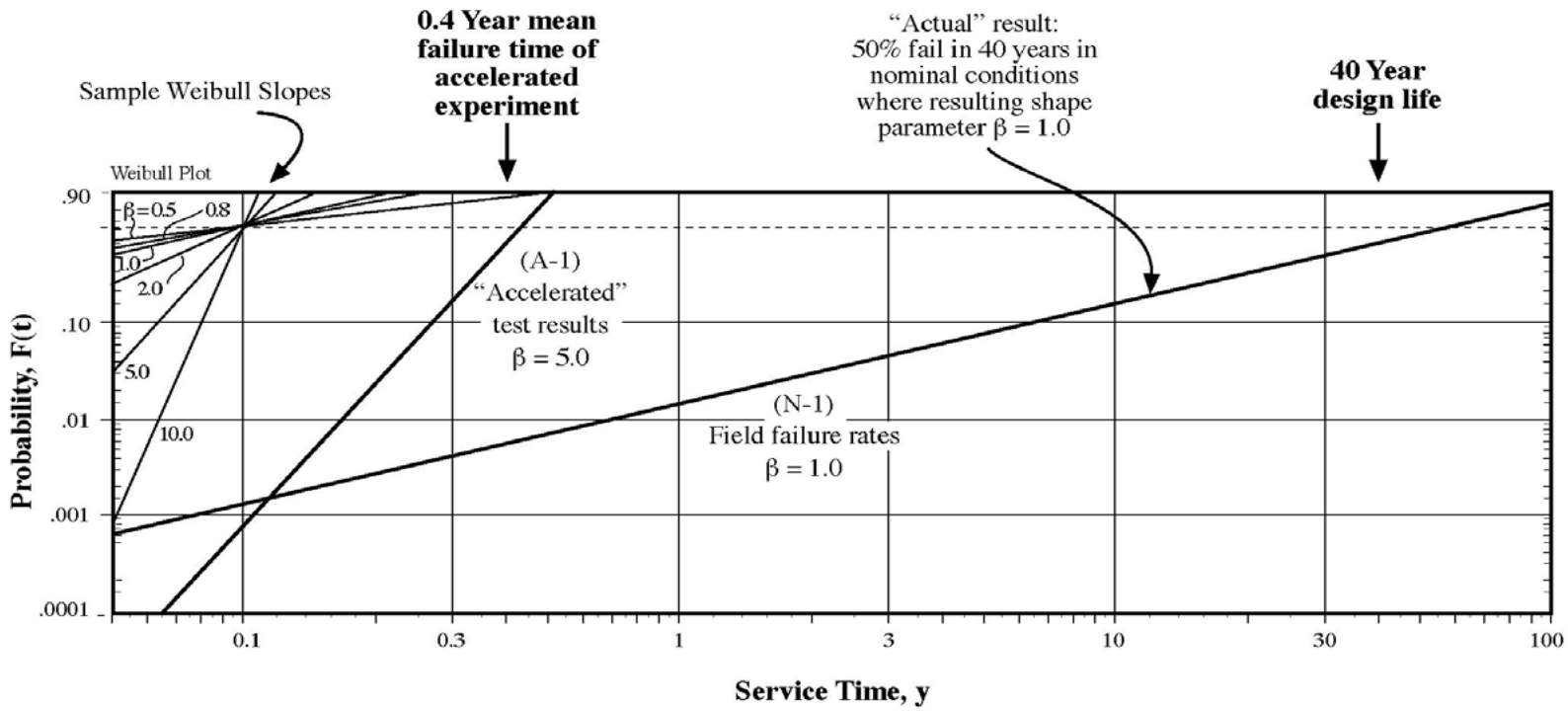
Dependence of Shape Parameter on the Ratio of Scale Parameters for Four Assumed Distributions and Constant Initial Shape Factor



Probability vs. time for SCC of Type 304
Compared with Field Experience for Various Methods of Testing
(Sato et al.)



Probability vs. Service Time for Examples of Accelerated Test and Actual Conditions

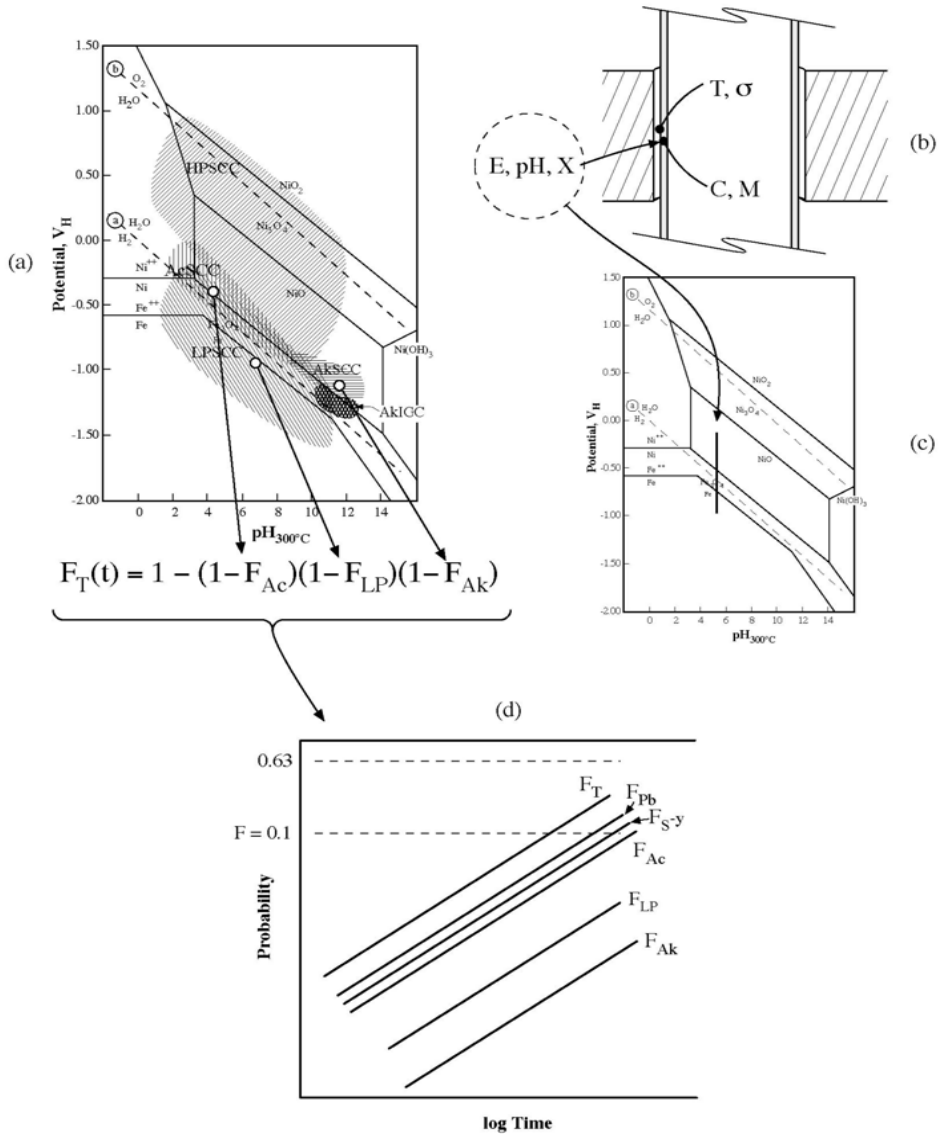


Insert Dependencies on the Seven Primary Variables into Statistical Parameters

pH	pH		
Potential	E		
Identity and concentration of species	X	→	θ
Alloy composition	C		β
Alloy structure	M		t_0
Temperature	T		
Stress	σ		

$$\theta, \beta, t_0 = \theta, \beta, t_0 (E, pH, X, C, M, T, \sigma)$$

$$F(t) = F(\theta, \beta, t_0)$$



- Evaluate Each of the cdfs of the Submodes for the Dependencies on the Seven Primary Variables;
- Develop the Total Probabililty of Failure from Product of Reliabilities, e.g. $R_T = R_{AkSCC} \times R_{LPSCC} \times R_{AcSCC} \times \ldots$
- Evaluate at Selected Environment.

Conclusions

1. It is possible to predict the occurrence of the first failure by using past experience together with a statistical distribution for which the parameters are evaluated with primary variables.

2. This methods enables predicting the occurrence of first failures that do not occur at the same conditions as previous ones.

3. This method enables accounting for the multiple sets of submodes that may occur.

4. There are naturally difficulties of interactions of variables in this approach; however, a first approach is probably much more useful than nothing.

Elevated Temperature Grain Boundary Embrittlement and Ductility-Dip Cracking in Ni-base Weld Metals

John C. Lippold
The Ohio State University

Welding and Joining Metallurgy Group

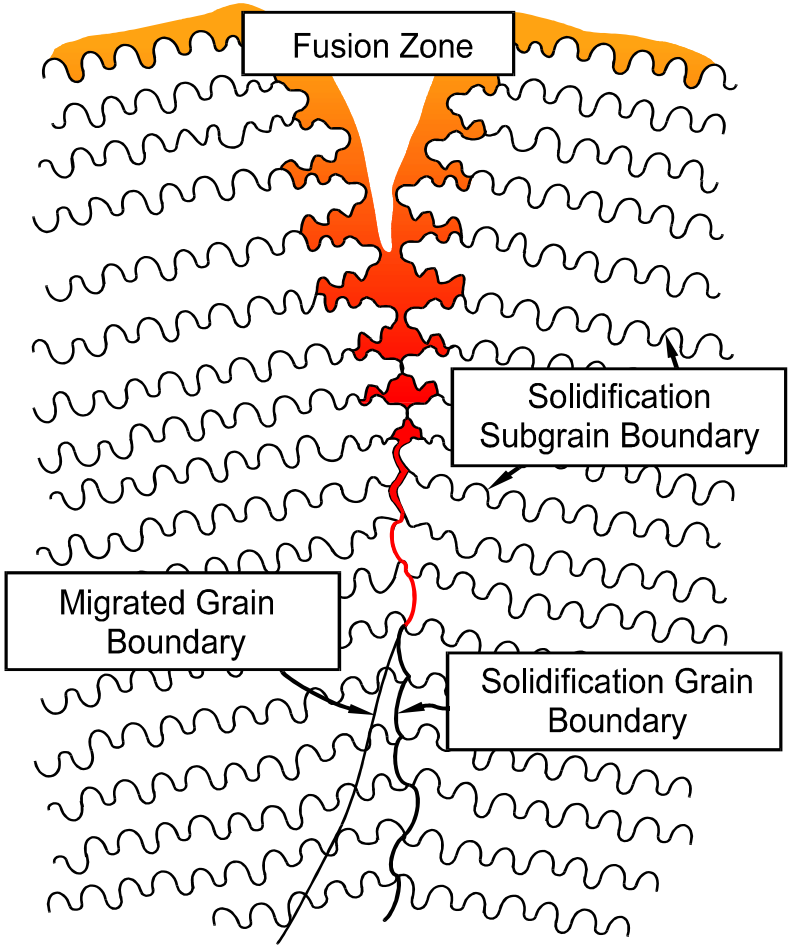
Conference on Vessel Penetration Inspection, Cracking, and Repairs
September 29-October 2, 2003, Gaithersburg, MD

Weldability Issues with Austenitic Materials

Cracking Mechanism	Location	Factors that Promote
Solidification Cracking	Solidification Grain Boundary	Impurity segregation Continuous liquid films
Weld Metal Liquation Cracking	Solidification Grain Boundary Migrated Grain Boundary	Impurity segregation Large grain size High heat input
Ductility-Dip Cracking	Migrated Grain Boundary	Large grain size Grain boundary mobility
Reheat, or Strain-age, Cracking	Migrated Grain Boundary	Relaxation of residual stress Intragranular precipitation Impurity segregation
Copper-Contamination Cracking	Migrated Grain Boundary	Cu abraded on surface Temperature > 1093°C
Hydrogen-Assisted Cracking	Migrated Grain Boundary	Grain boundary precipitation Threshold H concentration

Weld Metal Boundaries

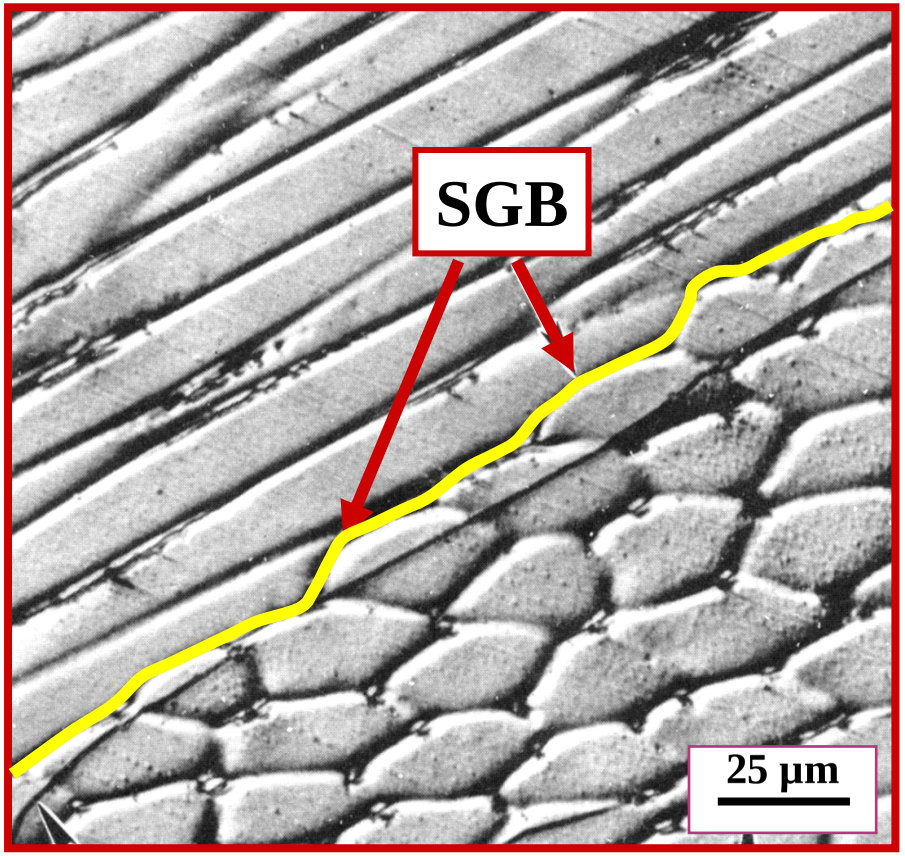
Welding and Joining Metallurgy Group



- **Differentiated by**
  - **Composition**
  - **Structure**
- **Solidification subgrain boundaries (SSGBs)**
  - **Composition (Case 2)**
  - **Low angle misorientation**
- **Solidification grain boundaries (SGBs)**
  - **Composition (Case 3)**
  - **High or low angle misorientation**
- **Migrated grain boundaries (MGBs)**
  - **Local variation in composition**
  - **High angle misorientation**

Solidification Grain Boundary

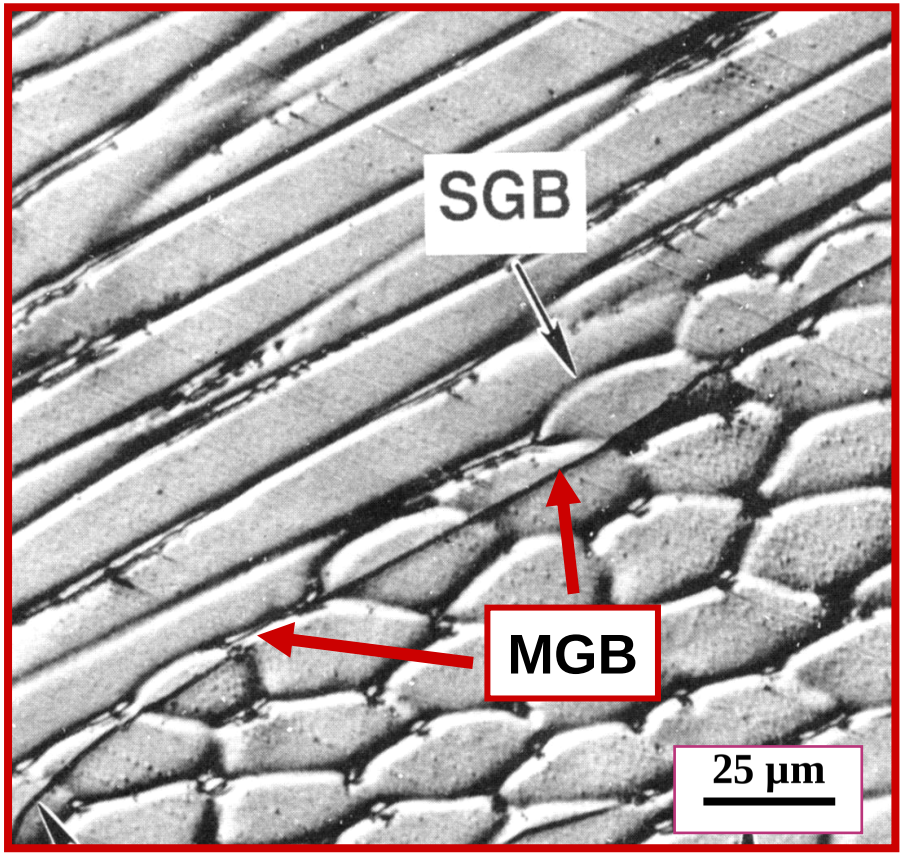
Welding and Joining Metallurgy Group



- Boundary between packets of subgrains
- Results from competitive growth
- Composition dictated by Case 3 solute redistribution
- Large misorientation across boundary at end of solidification - high angle boundary
- Most likely site for solidification cracking

Migrated Grain Boundary

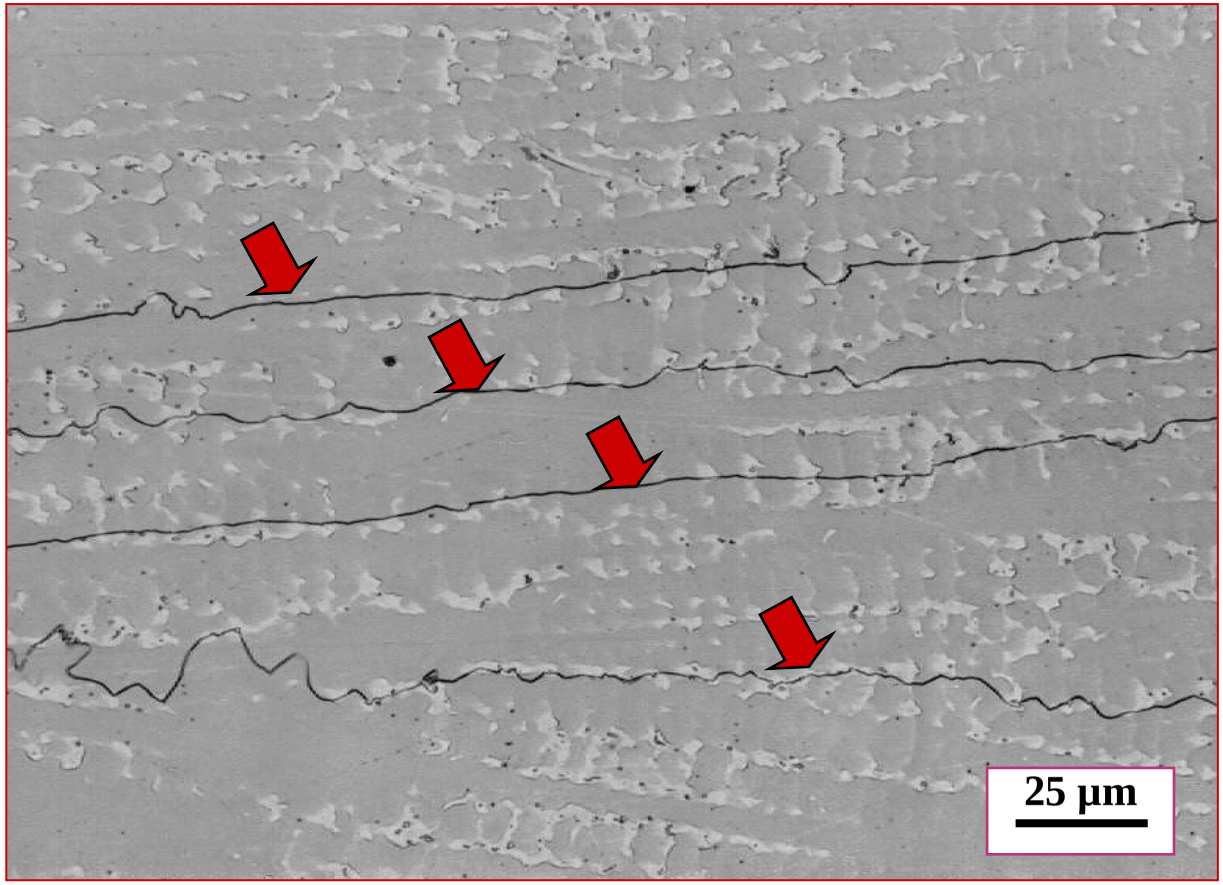
Welding and Joining Metallurgy Group



- Crystallographic component of SGB
- Migrates away from SGB in the solid state following solidification or during reheating
- Large misorientation across boundary - high angle boundary
- Composition varies locally
- Possible boundary "sweeping" and segregation
- Liquation and ductility dip cracking

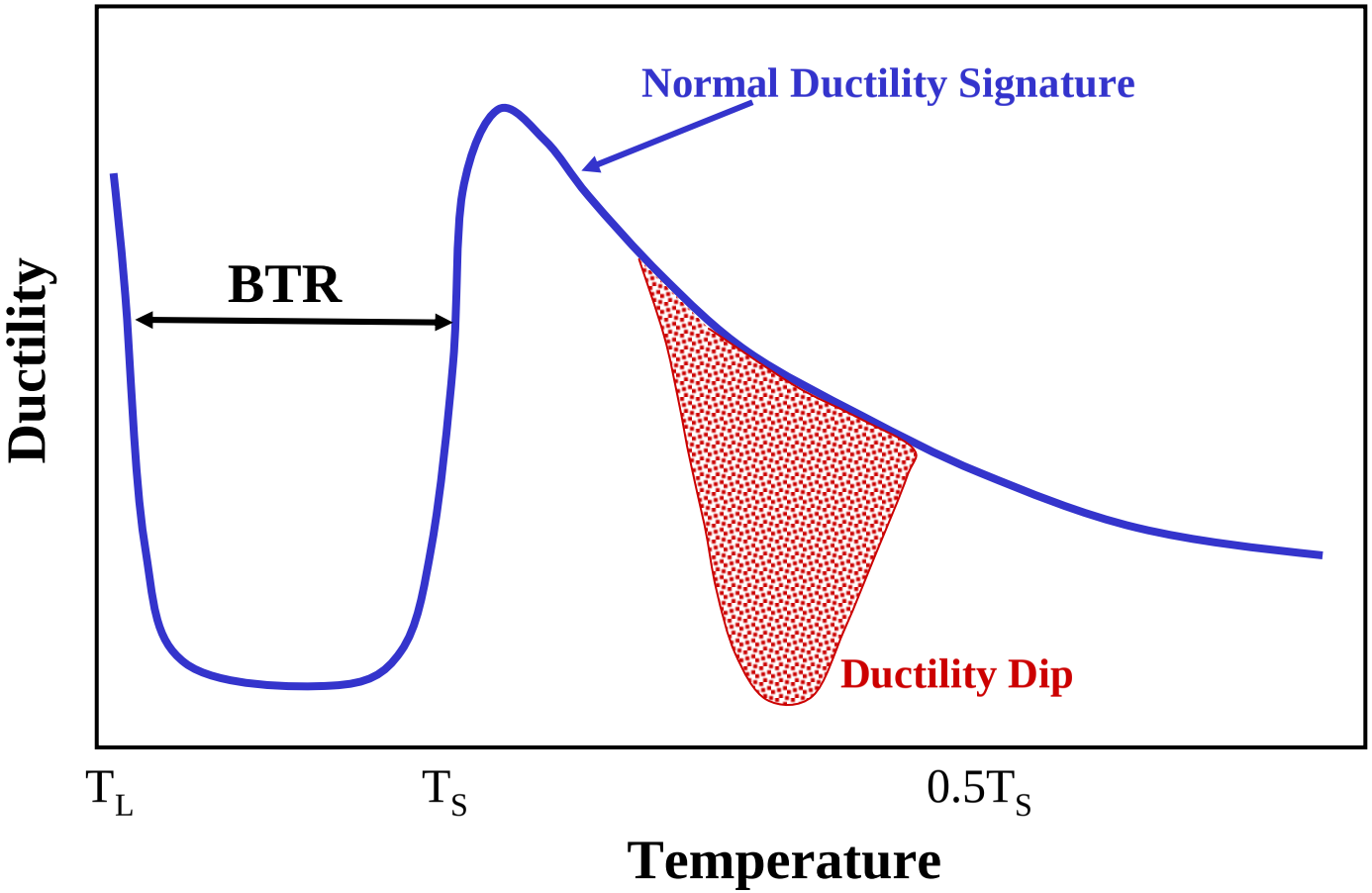
Migrated Grain Boundaries in Filler Metal 82

Welding and Joining Metallurgy Group



Ductility-dip Cracking

Welding and Joining Metallurgy Group

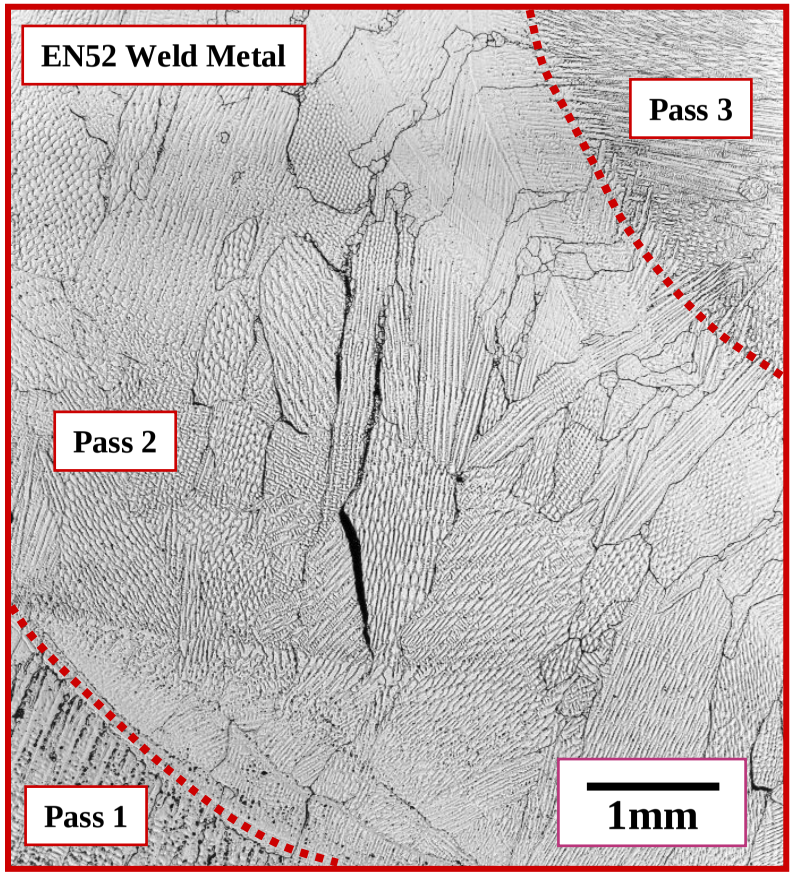


Weld Metal DDC Characteristics

- Sharp drop in elevated temperature ductility
- Solid state cracking
- Austenitic (FCC) Alloys
- Large grain size
- High restraint levels
- Intergranular along migrated grain boundaries

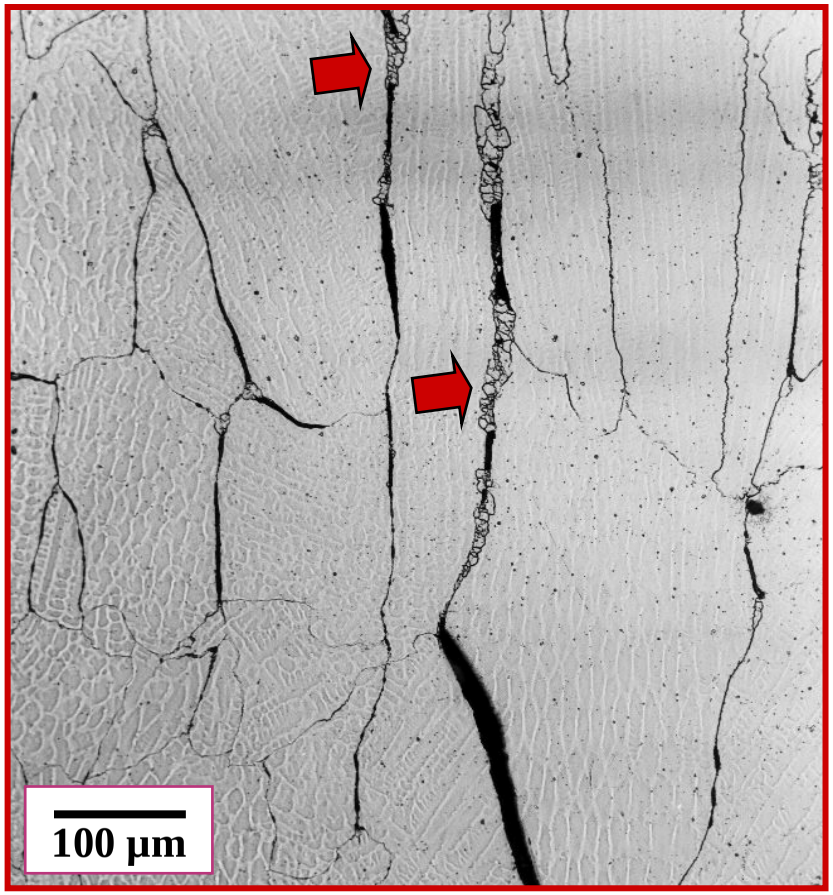
Ductility-dip cracking in Filler Metal 52 multipass weld deposit

Welding and Joining Metallurgy Group



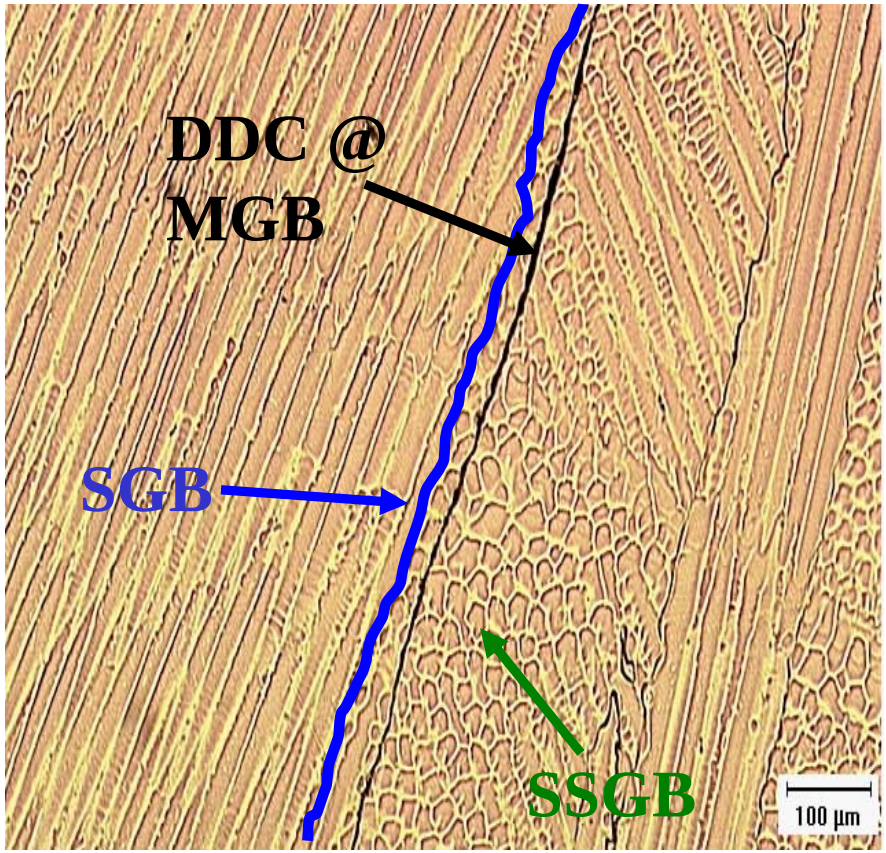
Ductility-dip cracking along migrated grain boundaries in Filler Metal 52 butter layer

- Large grain size
- Ductility "exhaustion" at grain boundaries
- Recrystallization along grain boundaries due to high local strains (arrows)



Migrated grain boundaries in re-heated weld metals

- Crystallographic component of SGB
- High angle boundary
- Migrates on-cooling after solidification and during re-heating (multi-pass welds)
- Large grain size

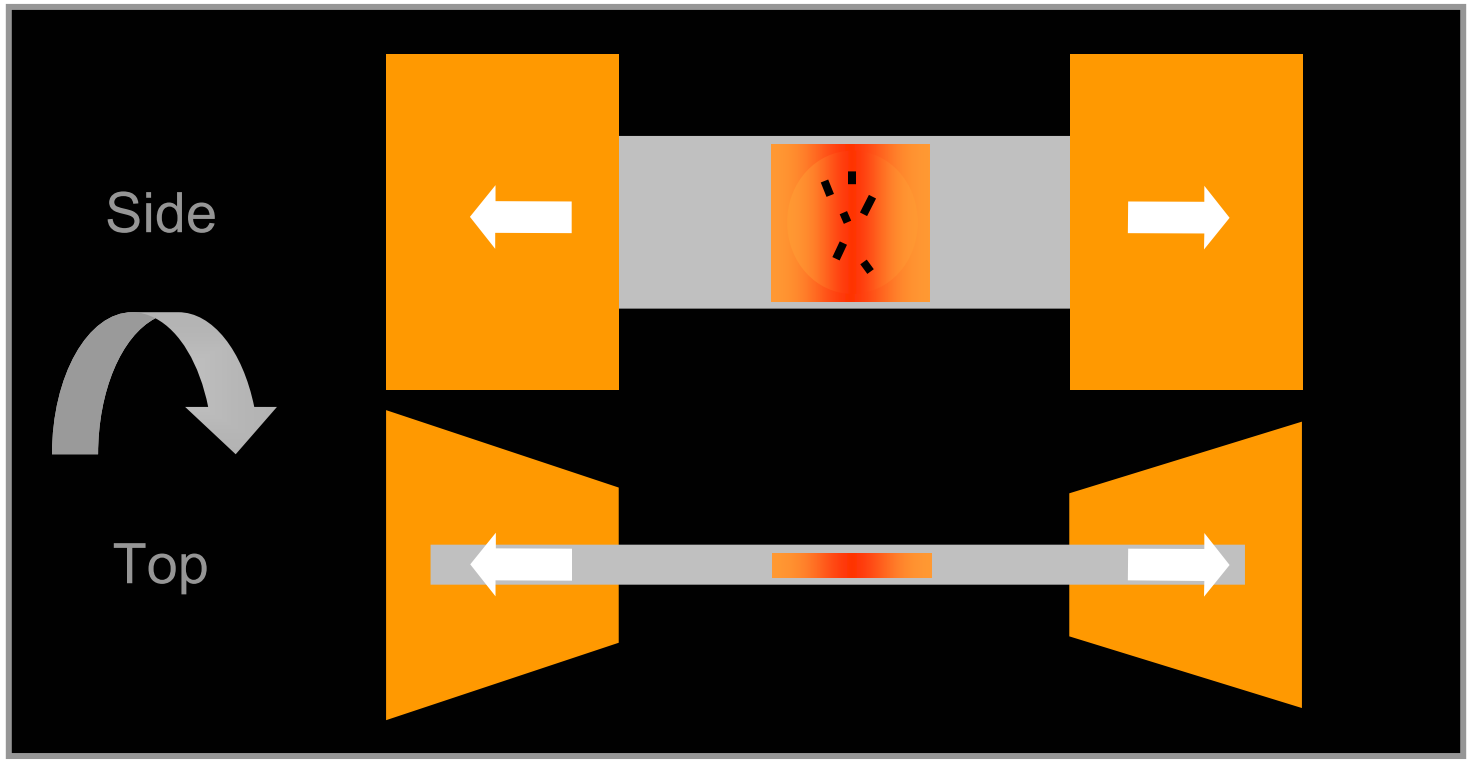


Factors Influencing DDC

- Strain concentration at Grain Boundaries (GB) and Triple Points
- GB orientation relative to the applied strain
- GB tortuosity
- Temperature
  - GB sliding inoperable at low Temperature
  - Recrystallization at high temperature
- Precipitates
- Impurities segregation (Sulfur)
- Hydrogen
  - H induced decohesion
  - H enhanced local plasticity

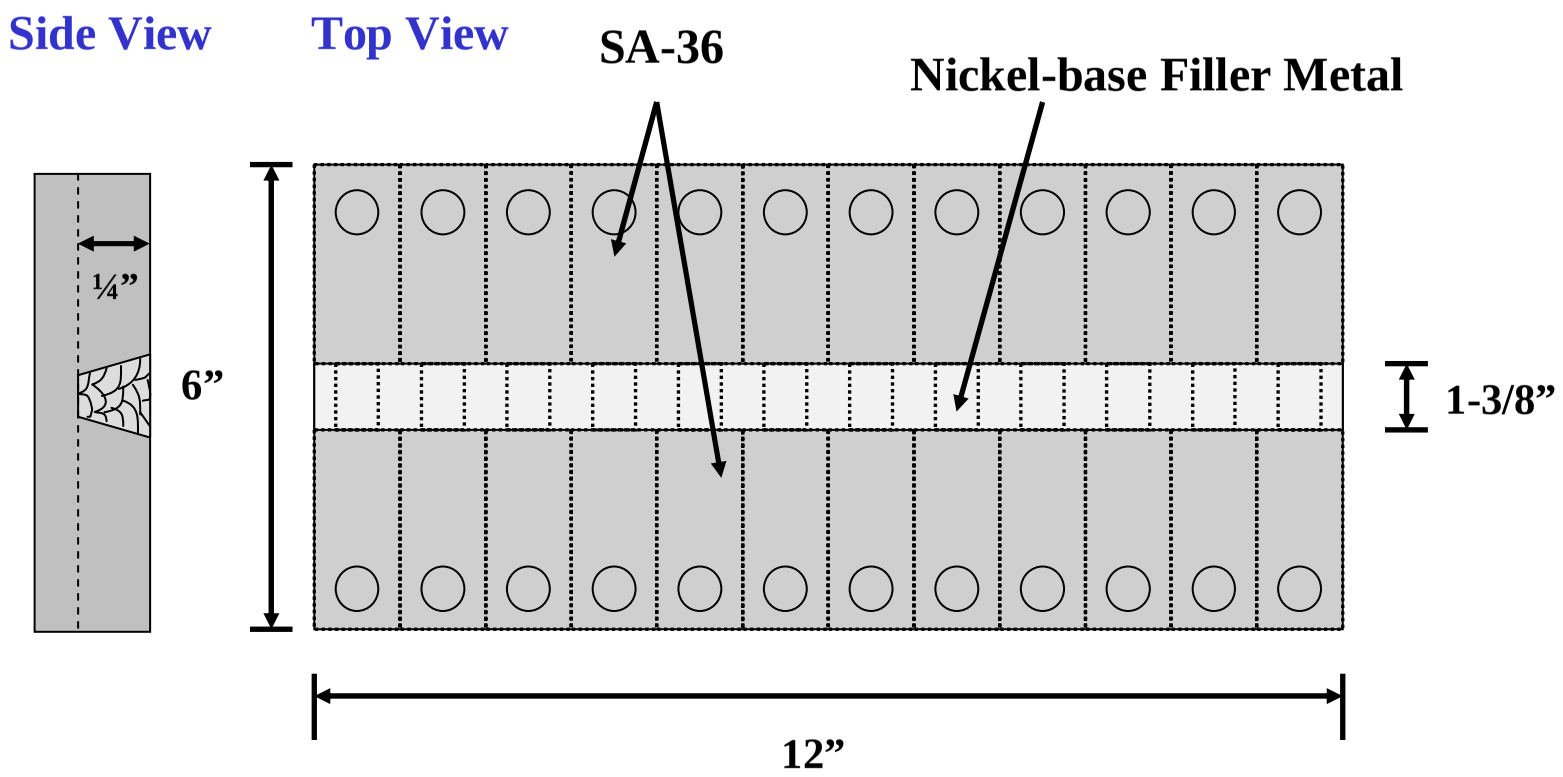
Strain-to-Fracture DDC Test

Welding and Joining Metallurgy Group



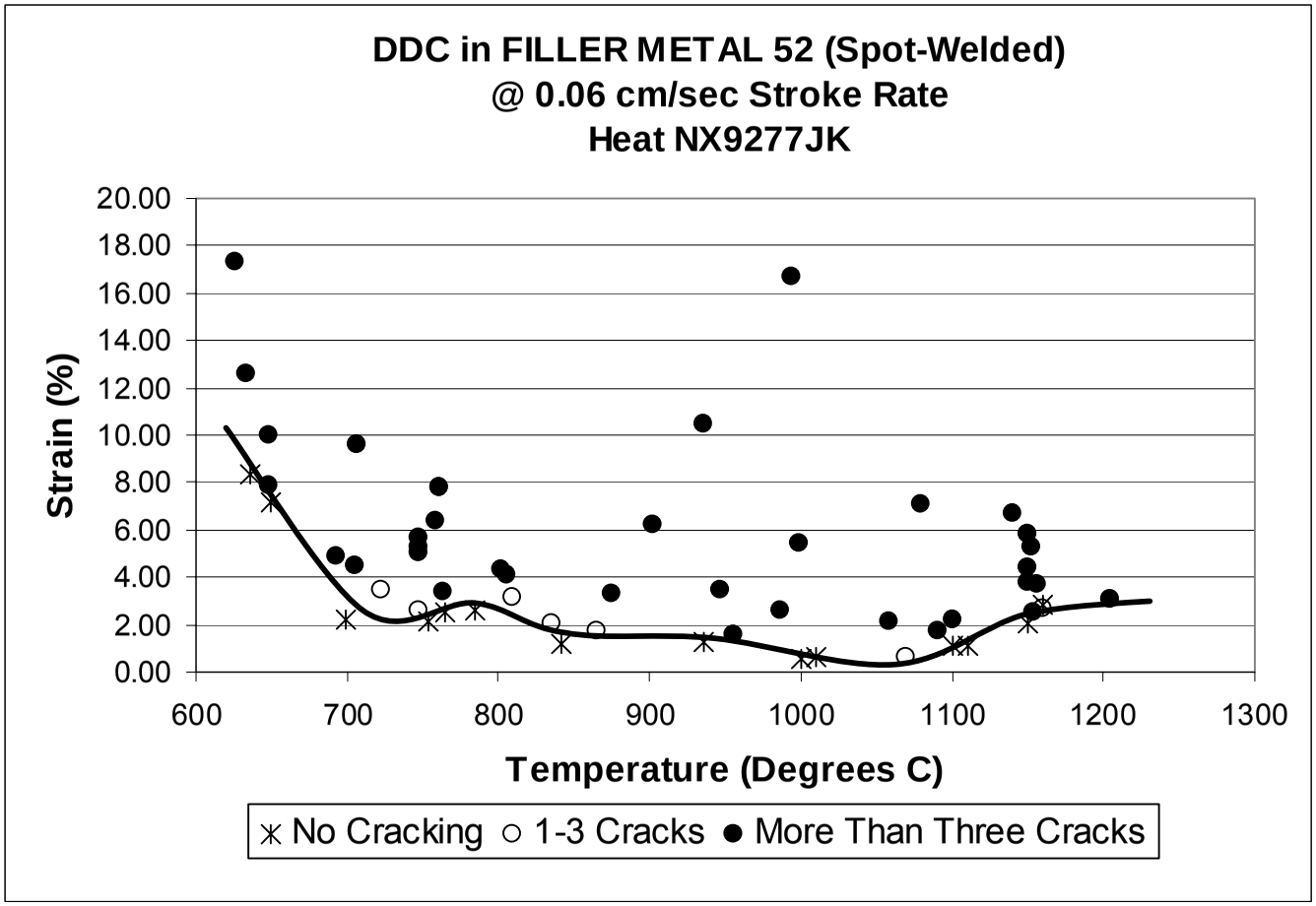
Testing filler metals - sample preparation

Welding and Joining Metallurgy Group



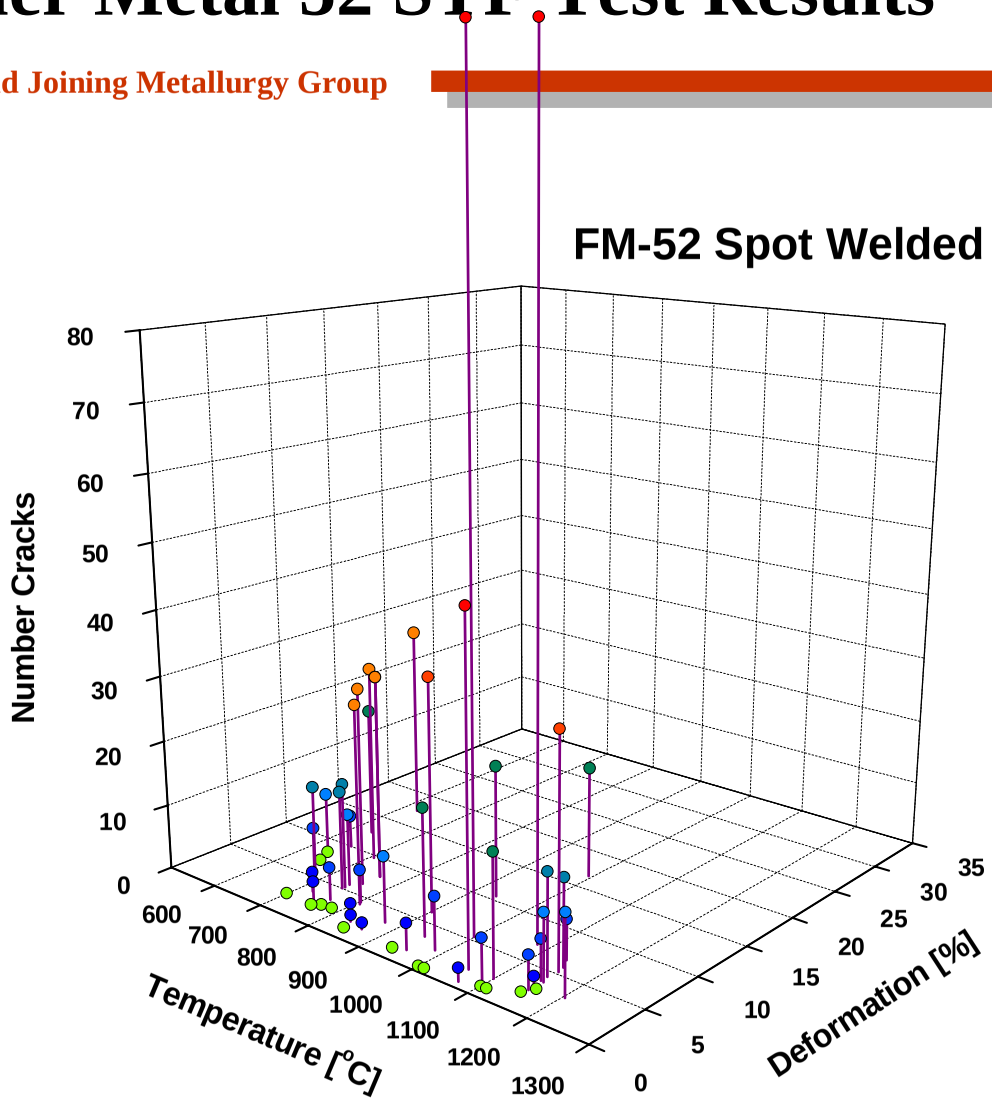
Filler Metal 52 STF Test Results

Welding and Joining Metallurgy Group



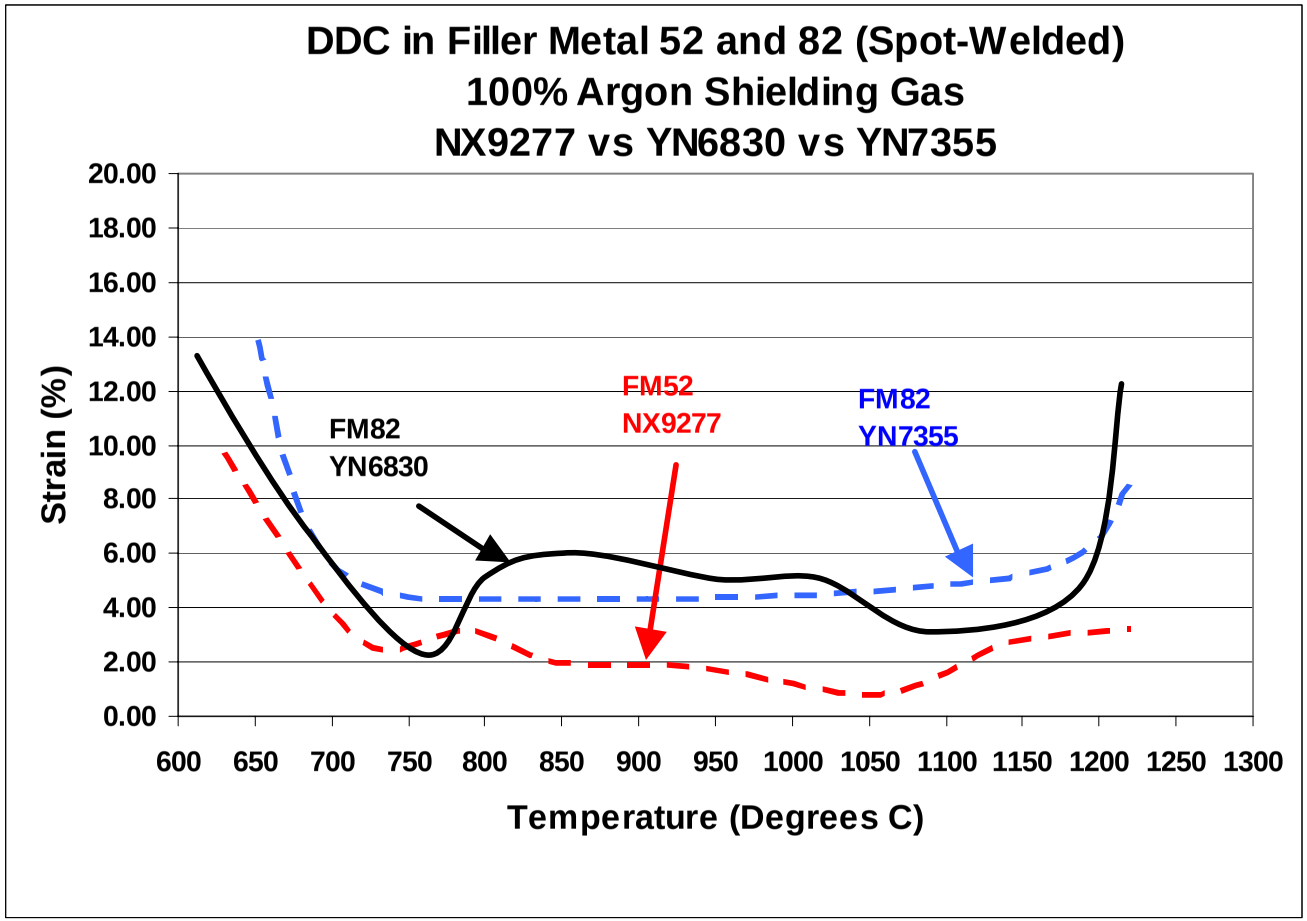
Filler Metal 52 STF Test Results

Welding and Joining Metallurgy Group



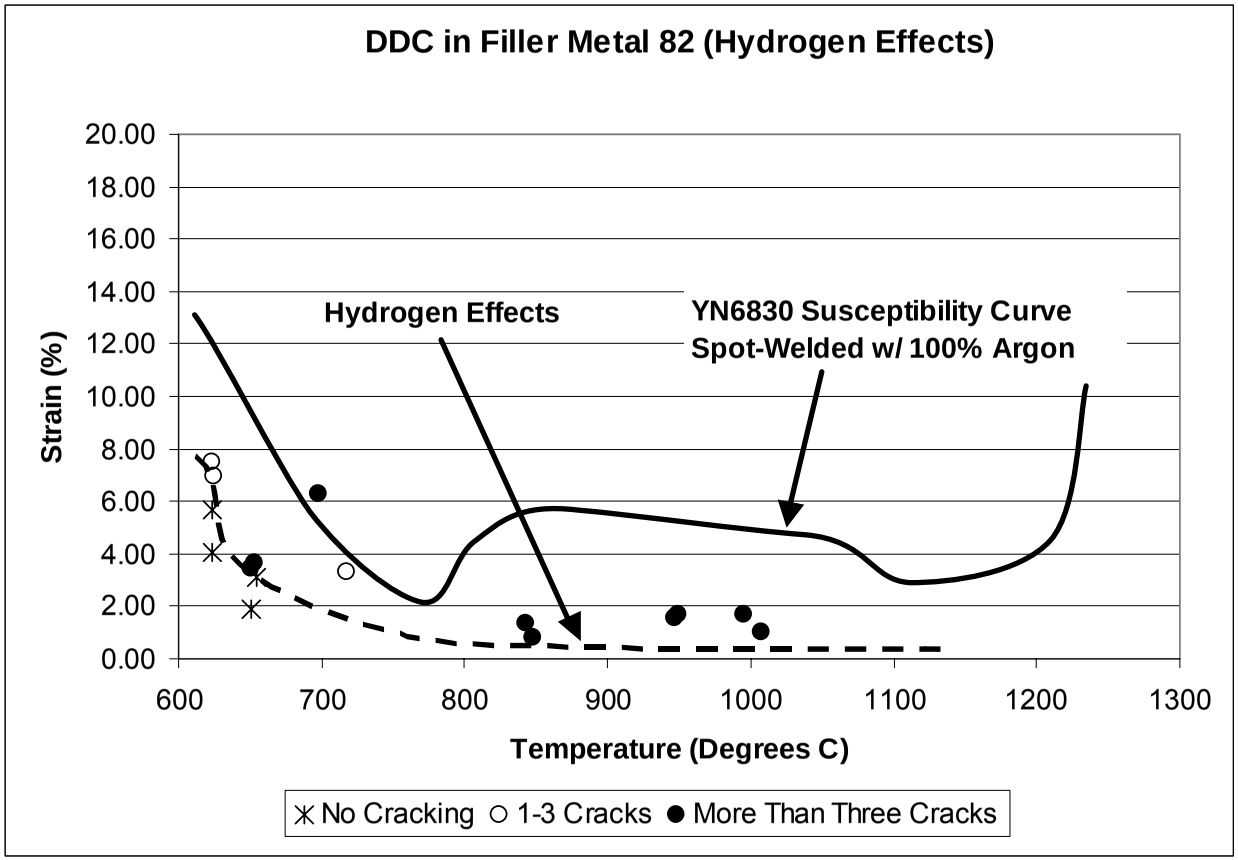
Filler Metal 52 vs. Filler Metal 82

Welding and Joining Metallurgy Group



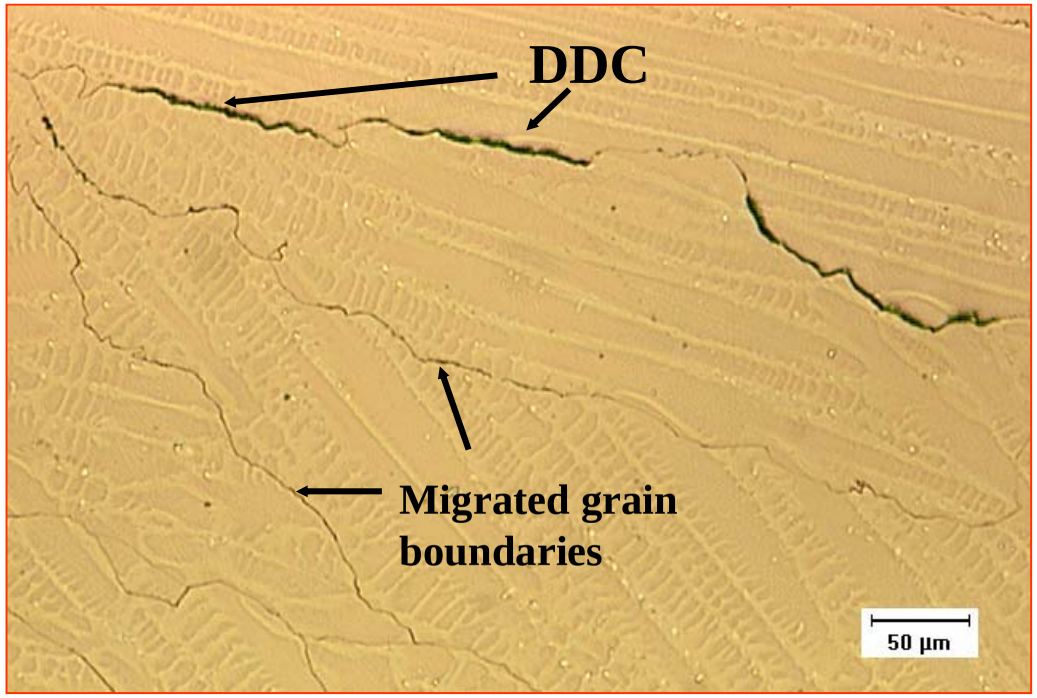
Filler Metal 82 – H_2 additions

Welding and Joining Metallurgy Group



Ductility-dip cracking

Welding and Joining Metallurgy Group



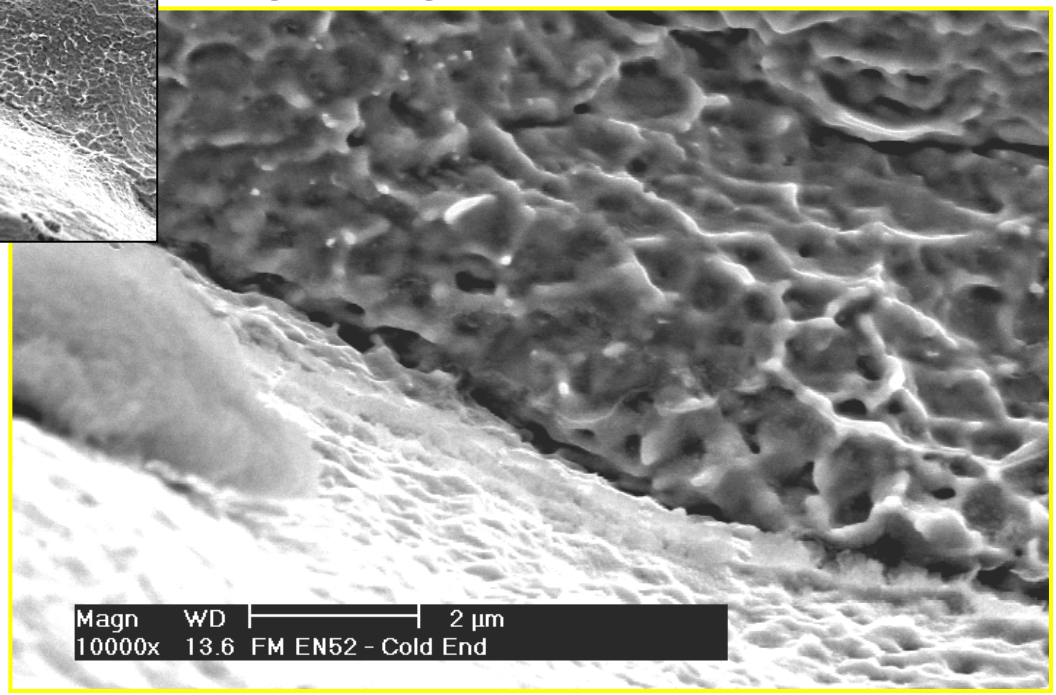
Characteristics

- Fully austenitic
- Large grain size
- Straight, smooth boundaries
- Low impurity content
- High restraint

DDC Fracture Surface in Filler Metal 52

Welding and Joining Metallurgy Group

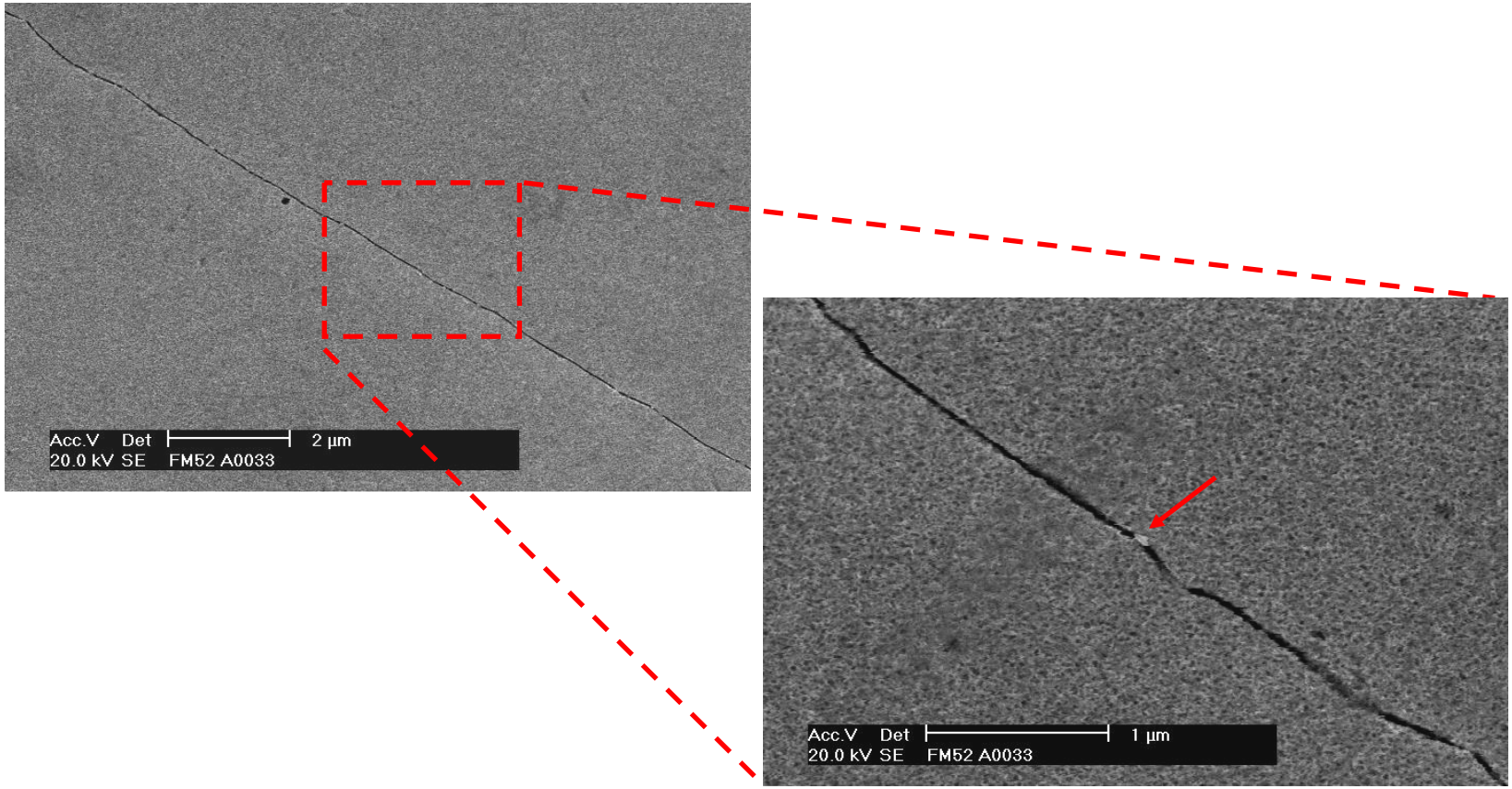
Ductile intergranular fracture along migrated grain boundaries



Grain boundary characteristics – Filler Metal 52

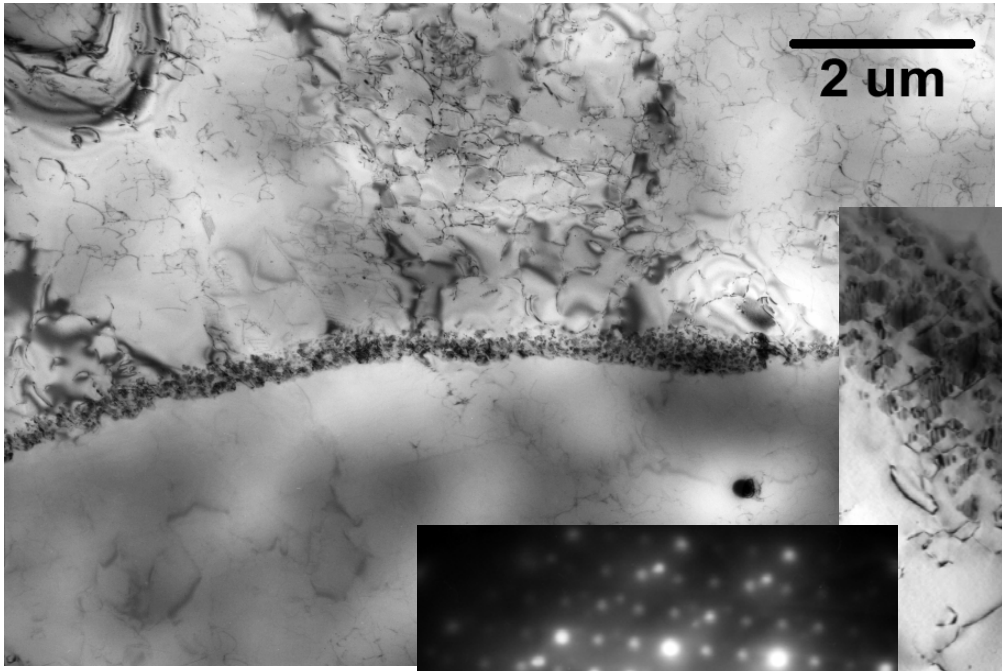
Welding and Joining Metallurgy Group

Long, straight, "clean" MGB in Filler Metal 52 at 986°C

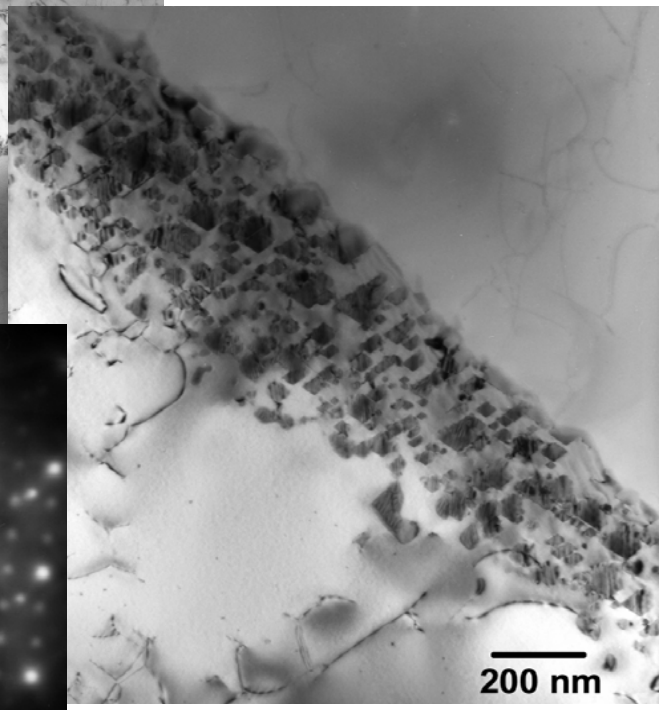


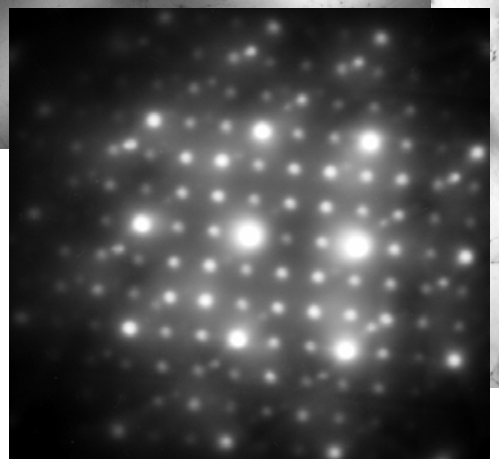
Intergranular Precipitation - FM 52

Welding and Joining Metallurgy Group



990 °C
Strain: 1.6%





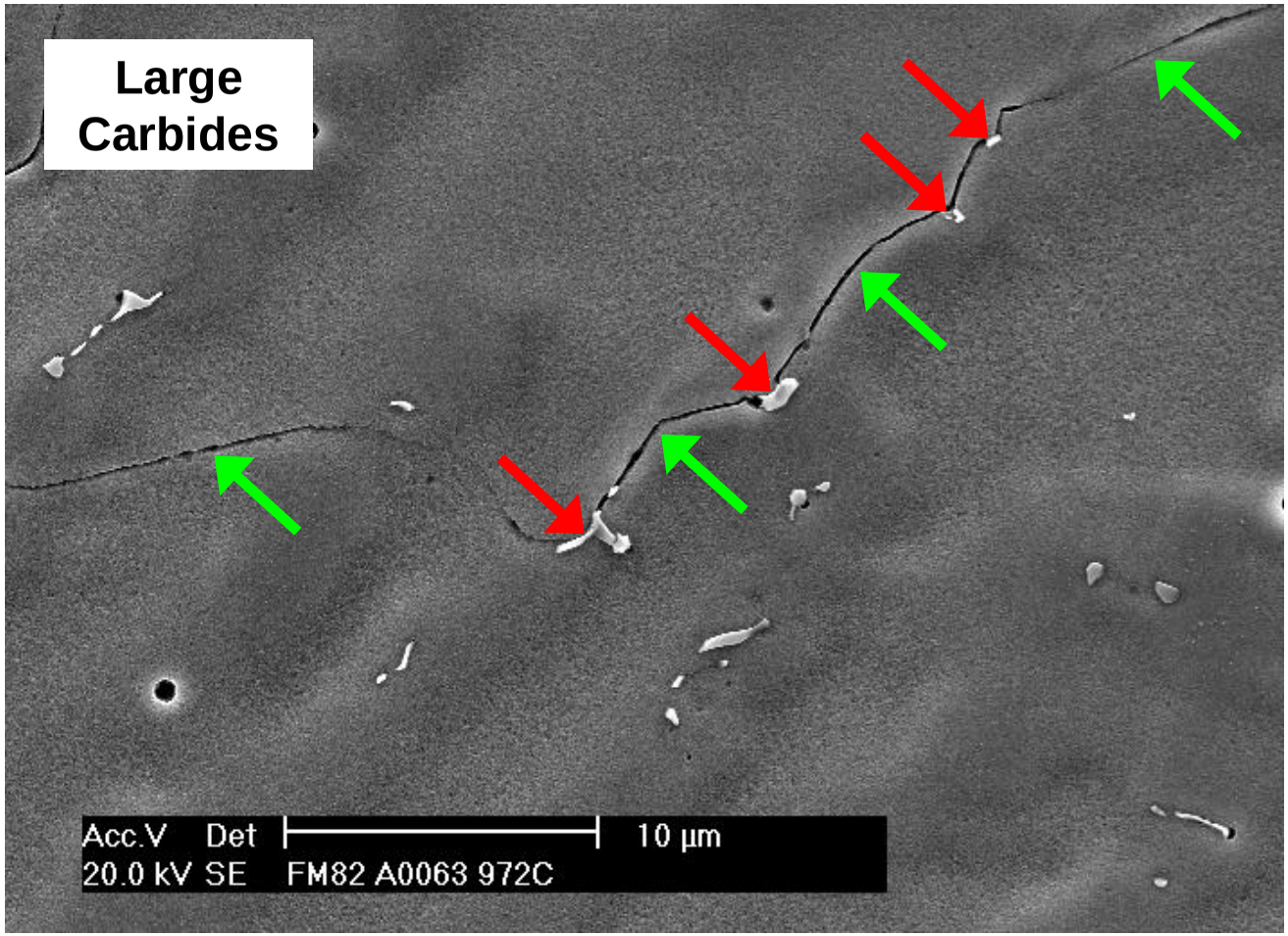
$M_{23}C_6$

10 - 50 nm

Cube-on-Cube
Orientation Relationship

GB Pinning -Filler Metal 82

Welding and Joining Metallurgy Group



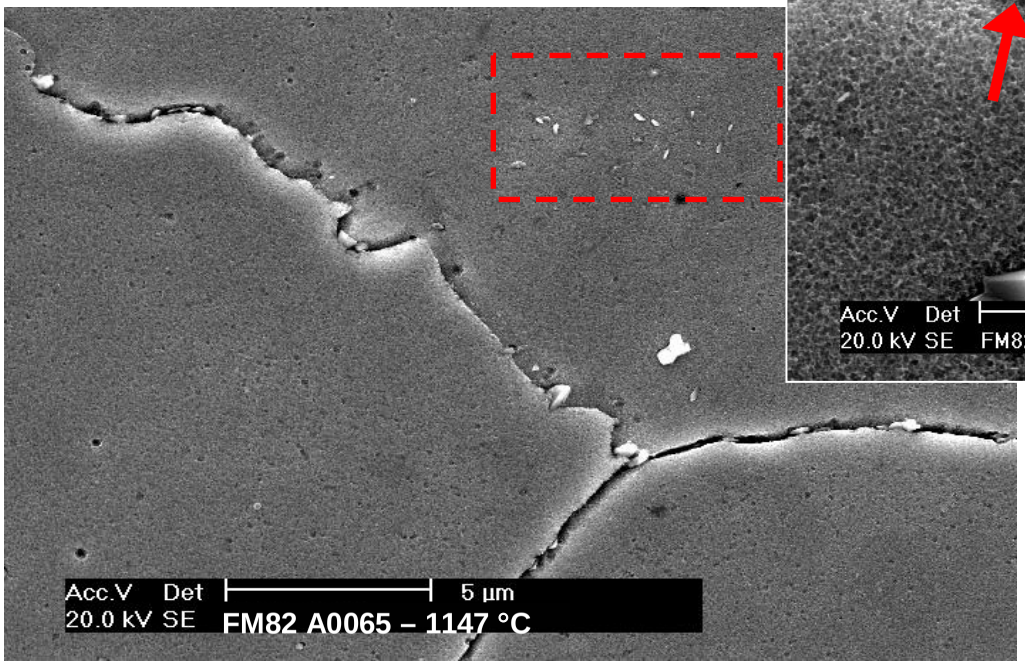
970 °C
Strain: 7.5%

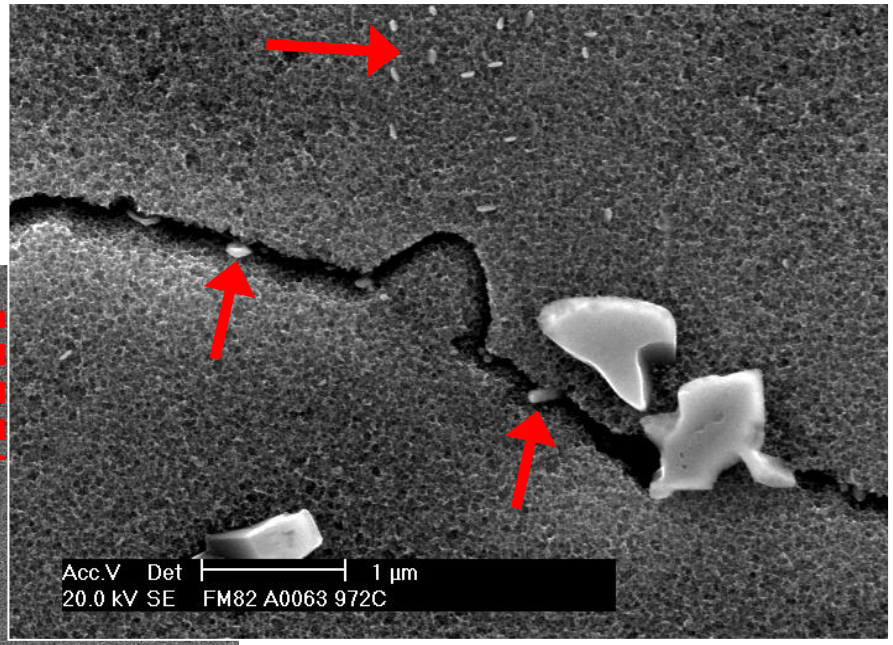
Precipitates in Filler Metal 82

Welding and Joining Metallurgy Group

1150 °C
Strain: 11.3%

Heat – YN6830



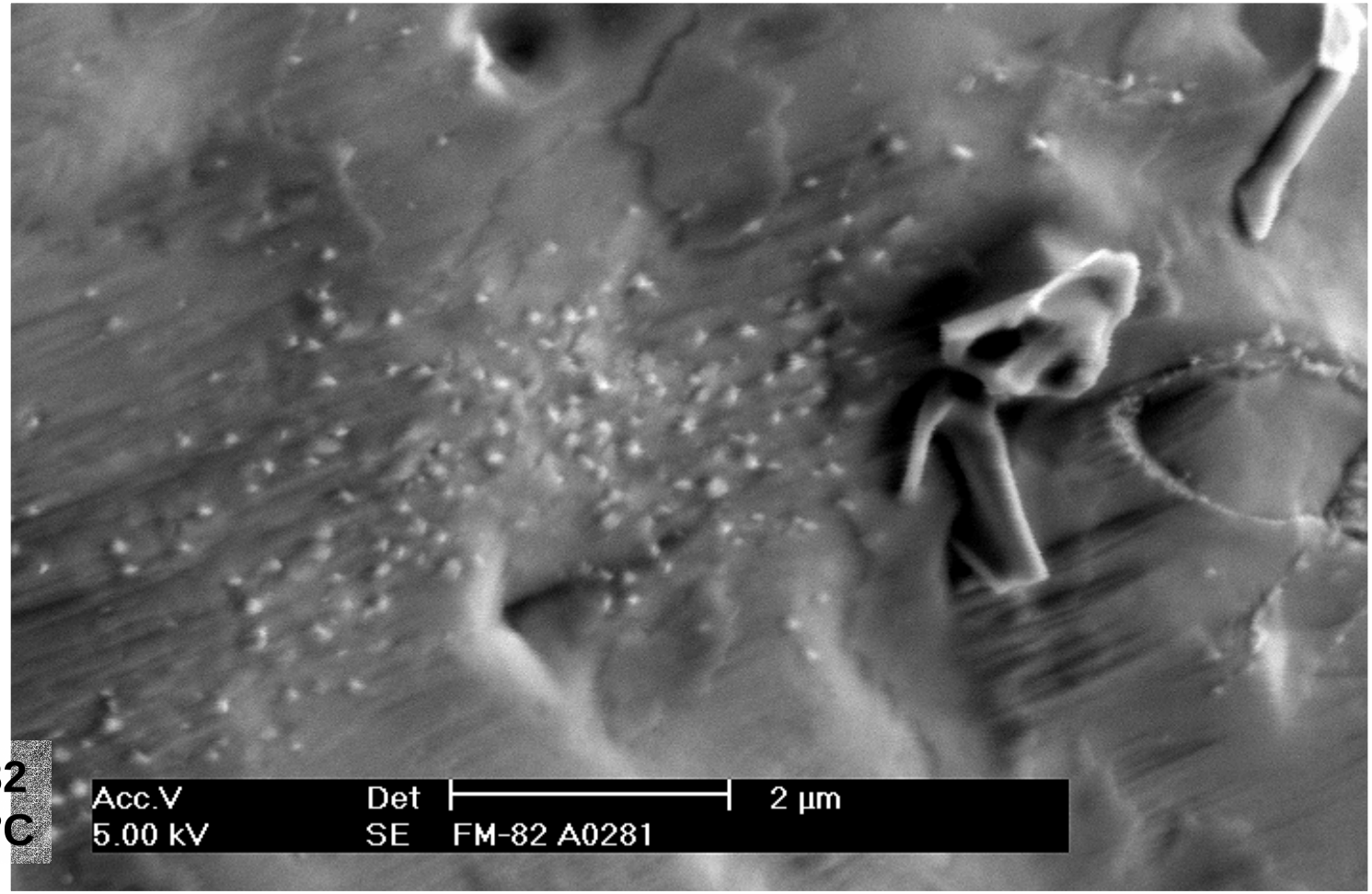


970 °C
Strain: 7.5%

Heat – YN6830

Precipitates on Fracture Surface

Welding and Joining Metallurgy Group



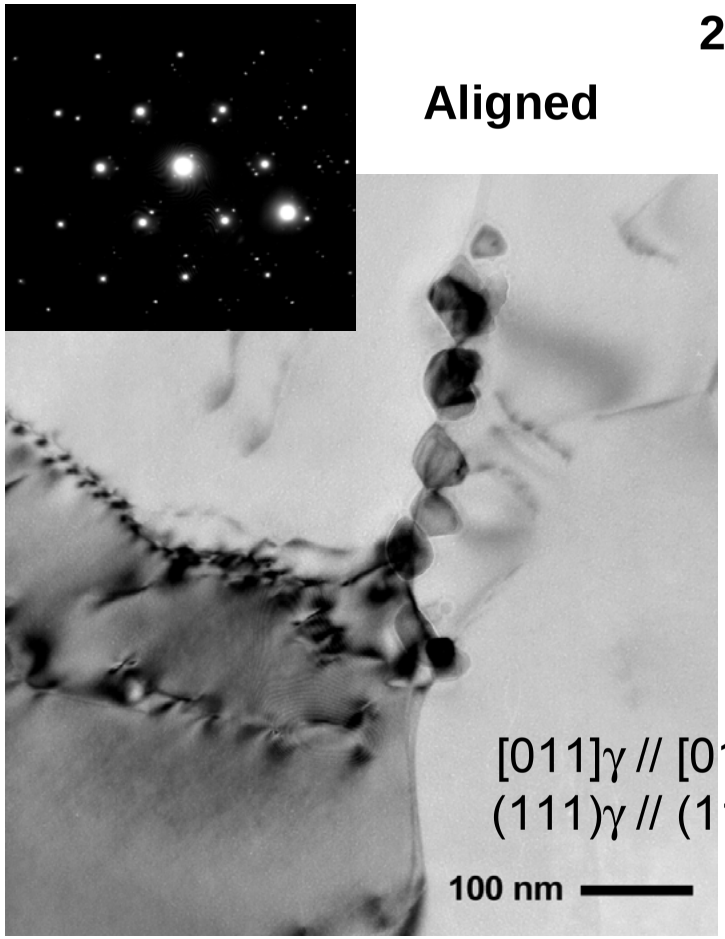
FM-82
950 °C

Medium Size (Nb,Ti)C Precipitates Filler Metal 82

Welding and Joining Metallurgy Group

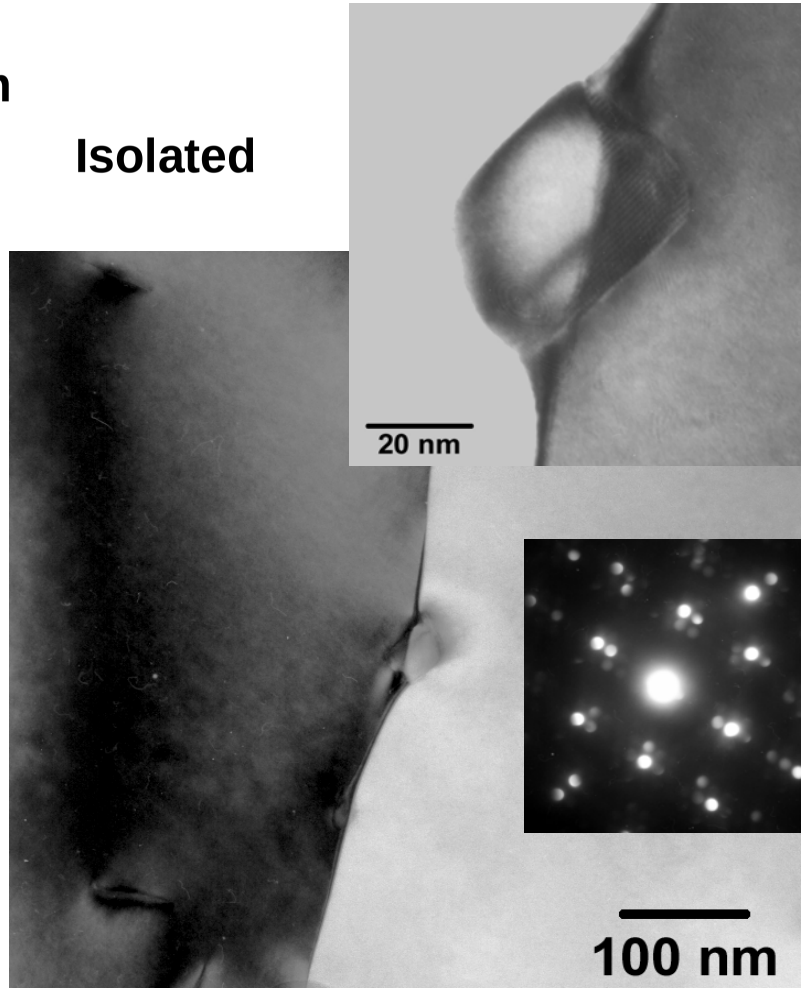
20 – 50 nm

Aligned



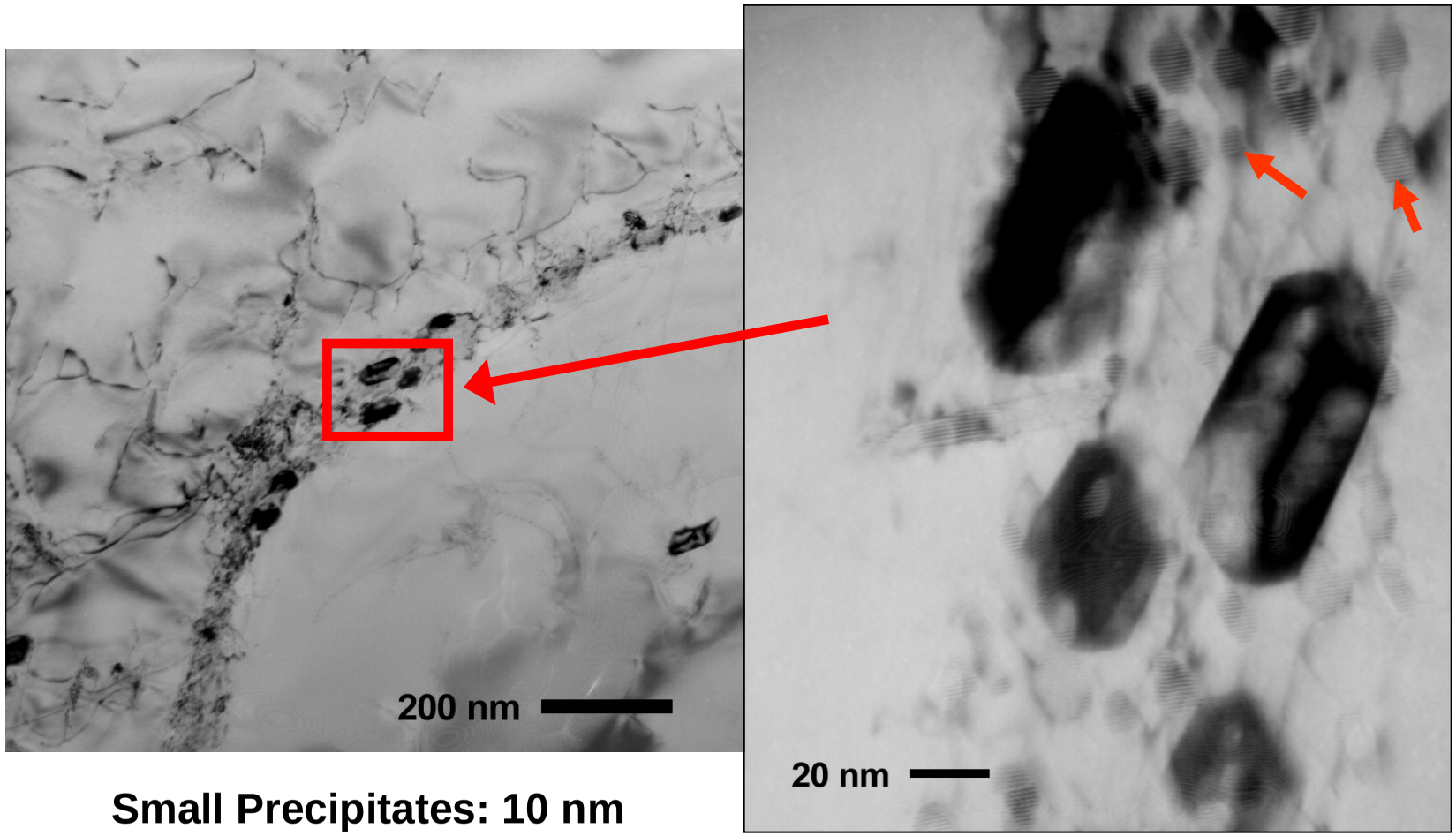
[011]γ // [011]MC
(111)γ // (111)MC

Isolated



Small Precipitates - Filler Metal 82

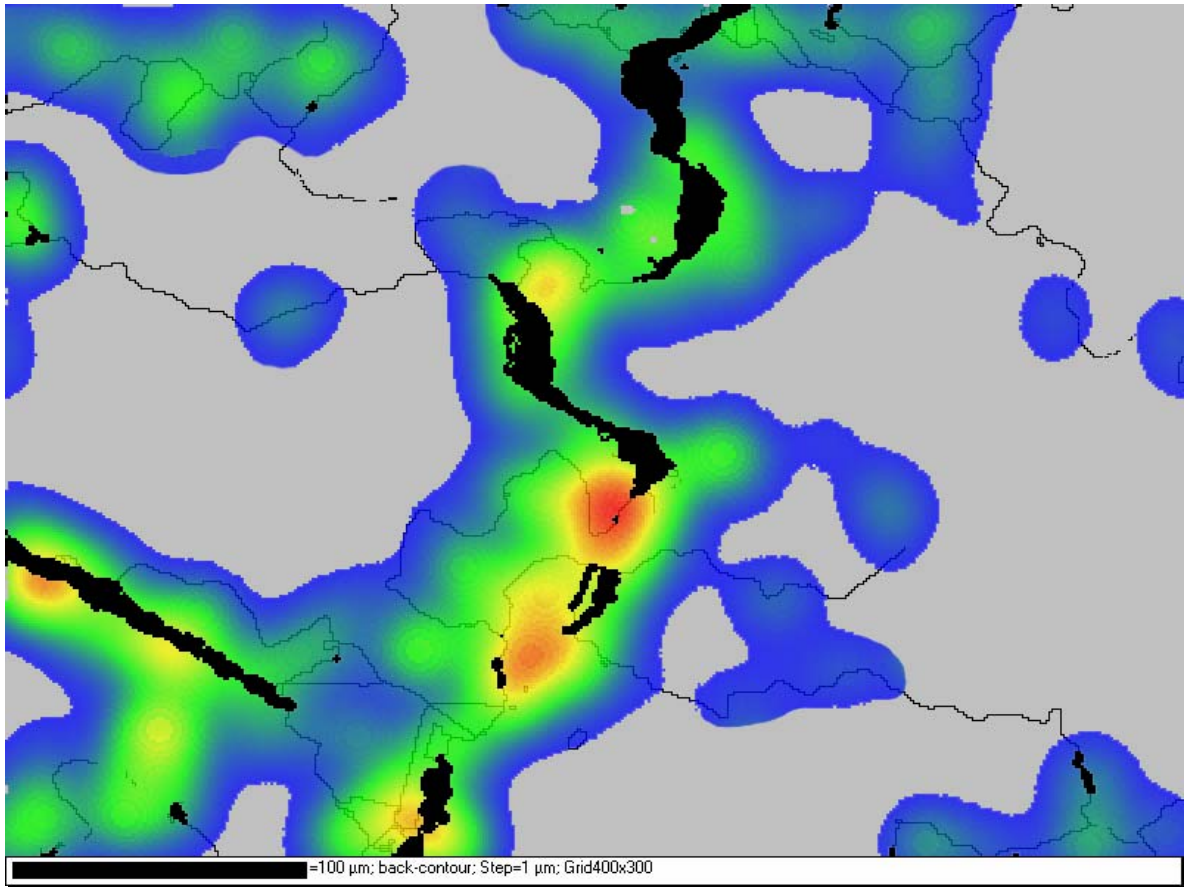
Welding and Joining Metallurgy Group



Small Precipitates: 10 nm

] Strain Distribution

Welding and Joining Metallurgy Group

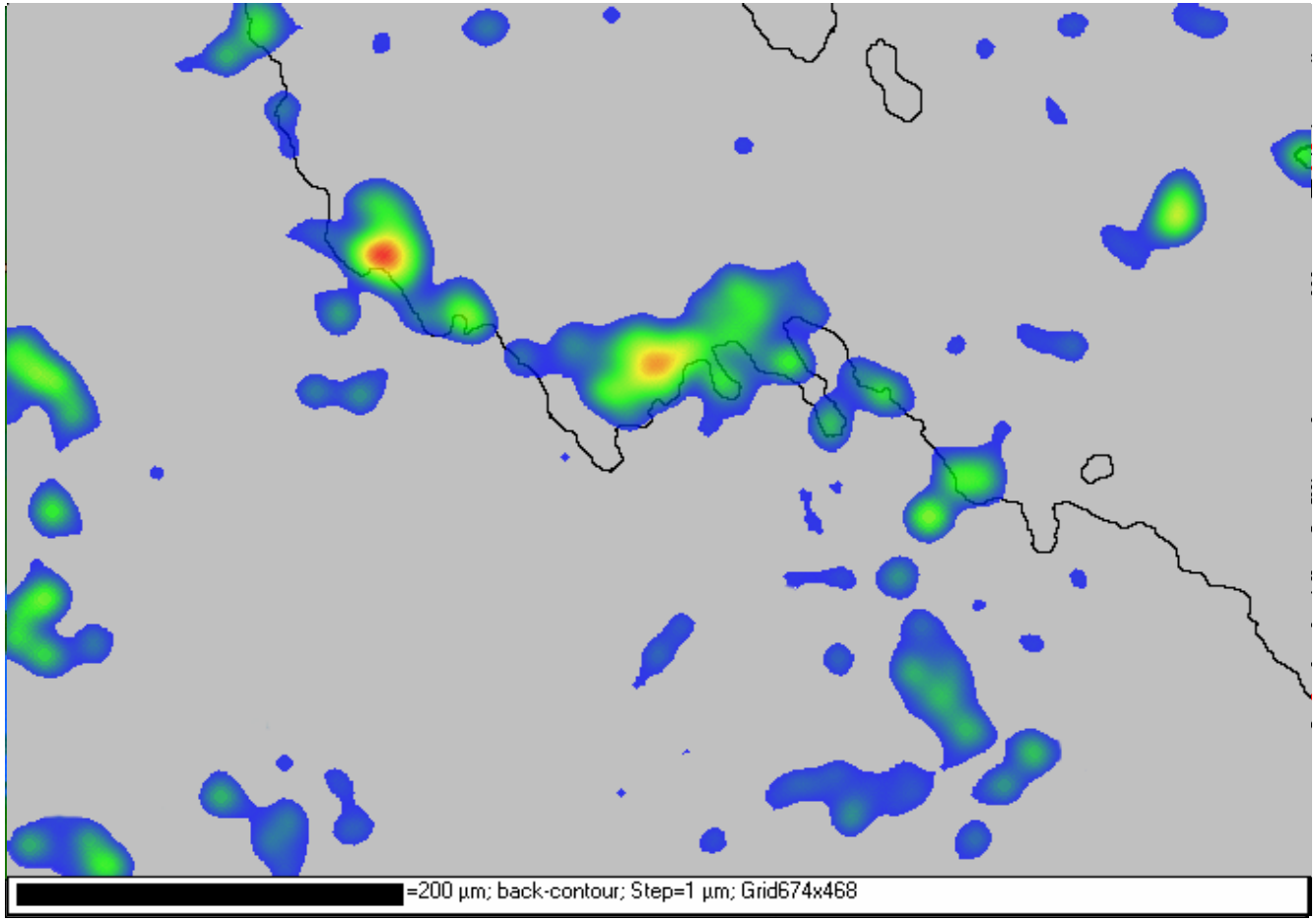


1147 °C
Strain: 11.3%

FM-82
Heat – YN6830

Strain Distribution

Welding and Joining Metallurgy Group



985 °C
Strain: 8.1%

FM-82
Heat – YN6830

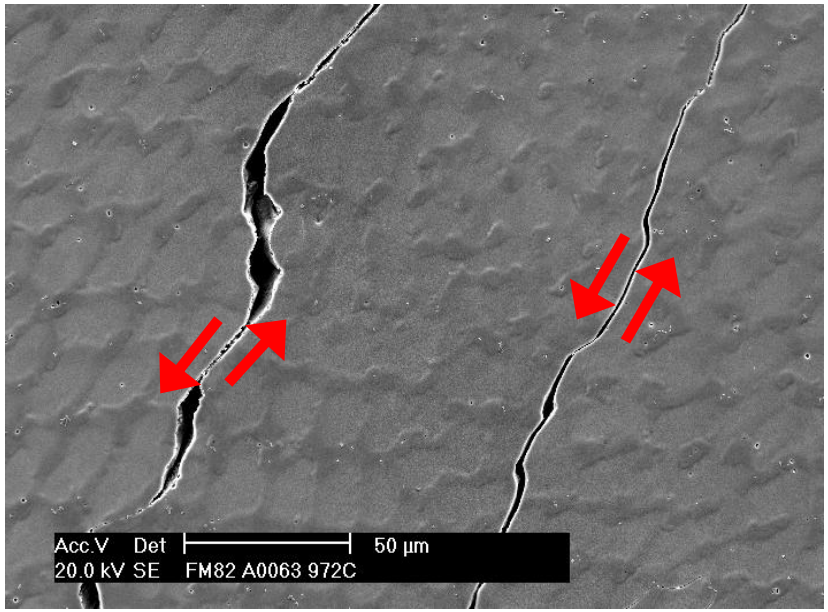
Comparison

- **Filler Metal 52**
  - Long, straight grain boundaries (not tortuous)
  - Sporadic intergranular large carbides and nitrides
  - The nitrides are not enough to avoid grain growth
  - Consistent medium size $M_{23}C_6$ distribution
  - Small amount of intragranular precipitates

- **Filler Metal 82**
  - Very tortuous grain boundaries
  - Consistent inter- and intra-granular eutectic large (Nb,Ti)C distribution (1-3 μm)
  - Sporadic intergranular medium size and small (NbTi)C carbides
  - Small amount of intragranular carbides
  - No $M_{23}C_6$ observed

Insight Into the Mechanism

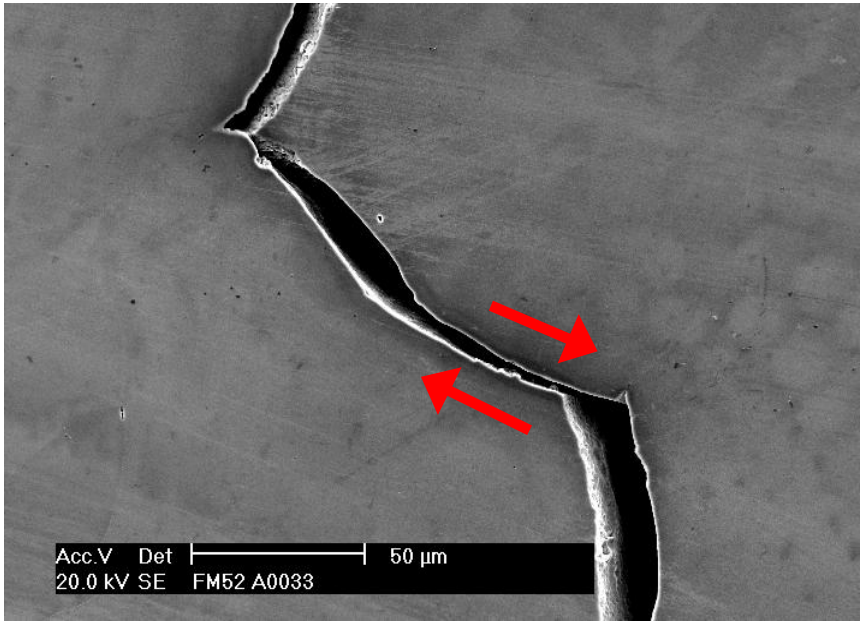
Welding and Joining Metallurgy Group



FM-82
972 °C

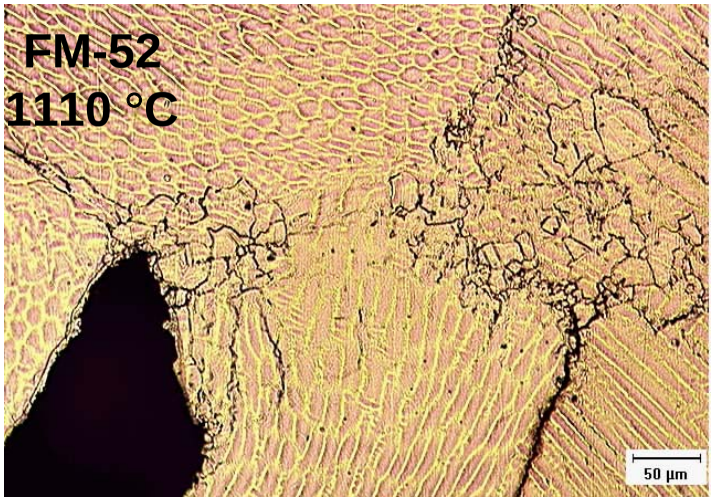
Grain Boundary Sliding

FM-52
986 °C

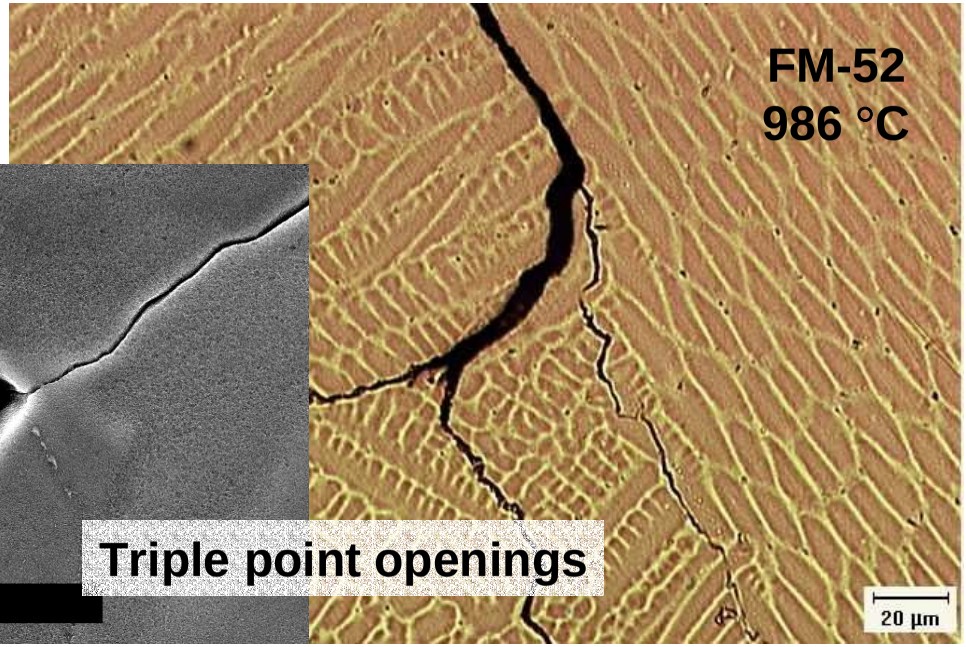


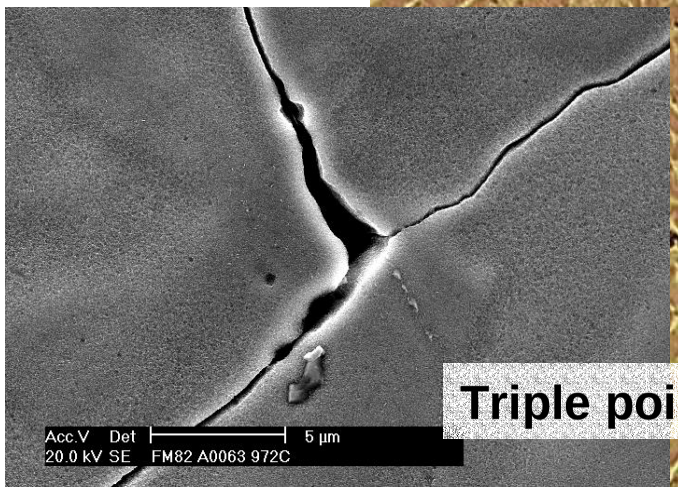
Insight Into the Mechanism

Welding and Joining Metallurgy Group



Dynamic recrystallization at high temperatures





Triple point openings

FM-82
972 °C

DDC Mechanism Insight

- **Effect of grain boundary precipitates**
  - **"Locks" GB and/or "pins" GB migration**
  - **Increases GB tortuosity**
  - **Restricts grain growth**
  - **Reduces GB sliding**
  - **Reduces deformation accumulation at triple points**
  - **May be crack initiators (precipitate itself or interface)**
  - **Interaction with impurities**

  - **Effect depends on**
  - **When and where the precipitate forms**
  - **Precipitate properties (MN - MC - $M_{23}C_6$)**
  - **Interface properties**
  - **Distribution**
  - **Size**

DDC Mechanism Insight

- **Grain boundary tortuosity**
  - **Increases GB area versus straight grain boundaries**
  - **GB "locking" effect**
  - **Reduce deformation accumulation at triple points**
  - **Favors cracks arrest process**

- **Hydrogen Effect**
  - **Increases GB/Interface decohesion**
  - **Interaction with precipitates**
  - **Enhances GB sliding**

Impact of PWSCC and Current Leak Detection on Leak-Before-Break

D. Rudland [(1)], R. Wolterman [(1)], G. Wilkowski [(1)], and R. Tregoning[(2)]

(1) Engineering Mechanics Corporation of Columbus

(2) U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Research

Acknowledgements

- ***Work supported by NRC-RES through subcontract from Battelle to Emc²***

R. Tregoning is NRC project manager

P. Scott is Battelle Project Manager

LB-LOCA Redefinition Program

- ***This effort small part of larger program***
- ***On-going elicitation to assess failure probabilities***
- ***Next generation of probabilistic pipe fracture code under development***
  - ***Discussion with many people during this meeting to get updated subcritical crack initiation and growth models***
  - ***Including many of the piping fracture analysis aspects from NRC's Degraded Piping Program, Short Cracks programs, IPIRG-1 and –2 programs***

Background

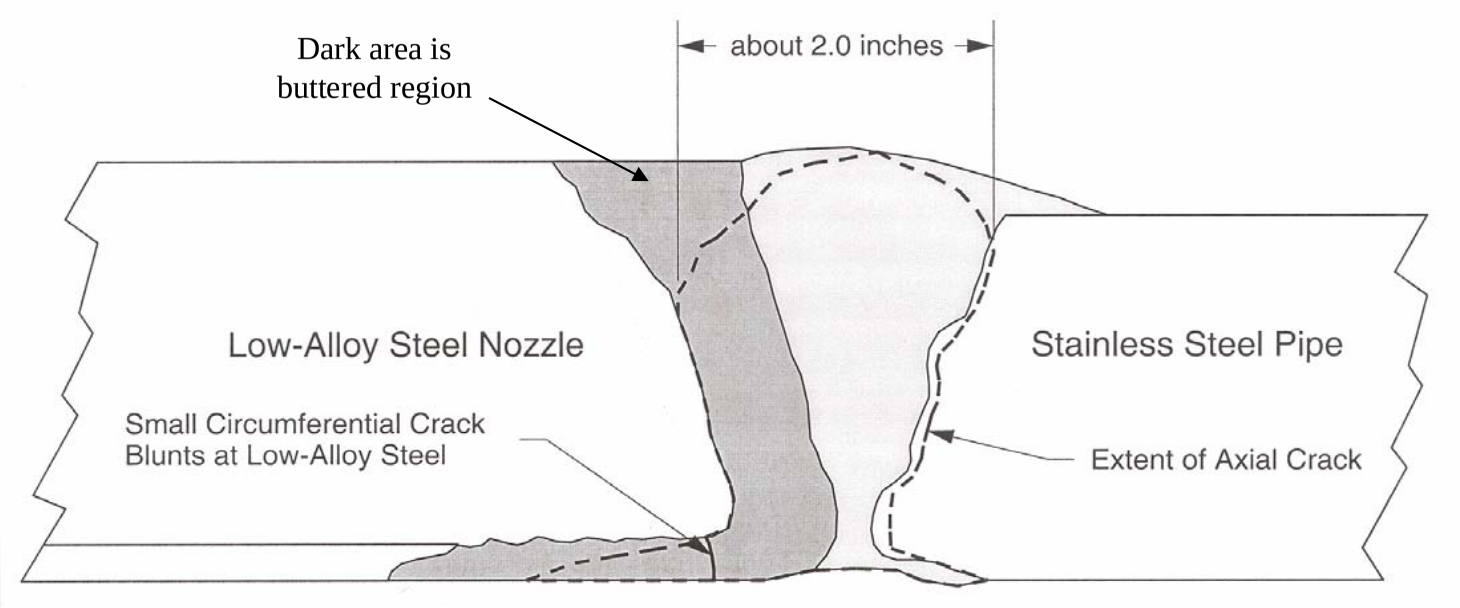
- ***PWSCC in Ringhal and VC Summer hot legs, as well as more recent Belgium and Japanese PWSCC piping experiences raised concern about past LBB approvals for lines that at one time were thought to be free of any cracking mechanism.***

- ***SRP 3.6.3 has a screening criterion to ensure that lines susceptible to potentially large cracks cannot be accepted for LBB relief of dynamic load effects of pipe whip supports and jet impingements shields.***
  - ***"..requirement that corrosion resistance of piping be demonstrated….".***

- ***Fortunately the PWSCC cracks to date have been primarily axial and a few small circumferential cracks; nevertheless, it was desirable to see if LBB could be satisfied if circumferential through-wall cracks occurred.***

Background

- ***V.C. Summer PWSCCs in hot-leg***



Background

- *Inconel 82/182 bimetallic weld locations that might be susceptible to PWSCC*
  - *RPV main coolant nozzles, core flood nozzles*
  - *Pressurizer nozzle, spray nozzles, and surge lines*
  - *Steam generator nozzles and RCP nozzles*
  - *Many branch line connections*
- *Locations vary by NSSS supplier since main coolant piping could be stainless or clad carbon steels*

Revised LBB Analysis

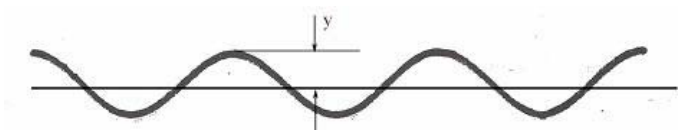
- *As part of the LB-LOCA redefinition program and the technical support for a new LBB Regulatory Guide, many past LBB submittals were reviewed*

- *LBB analysis conducted in this effort using typical LBB loads and recalculating how the leakage size crack may change if it was a PWSCC crack, i.e., PWSCC cracks have a more tortuous flow path than fatigue cracks used in many past LBB submittals.*
  - *Need to define PWSCC crack-morphology parameters (roughness, number of turns, actual flow path-to-thickness ratio) from cracks removed from service.*
  - *Photomicrographs of several PWSCC service-removed cracks were available.*

- *Recalculated leakage cracks for LBB cases and determined margins on leakage crack size versus critical crack size at N+SSE or other critical transient load (i.e., start-up/shut-down thermal loads for a surge line)*

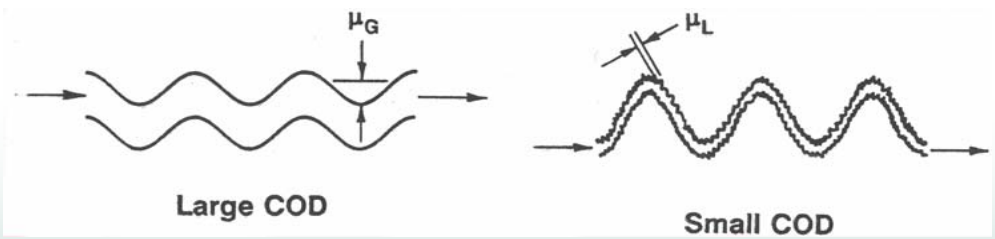
Crack Morphology Parameters

- ***Surface roughness, number of turns, and actual flow path length are key crack morphology parameters.***



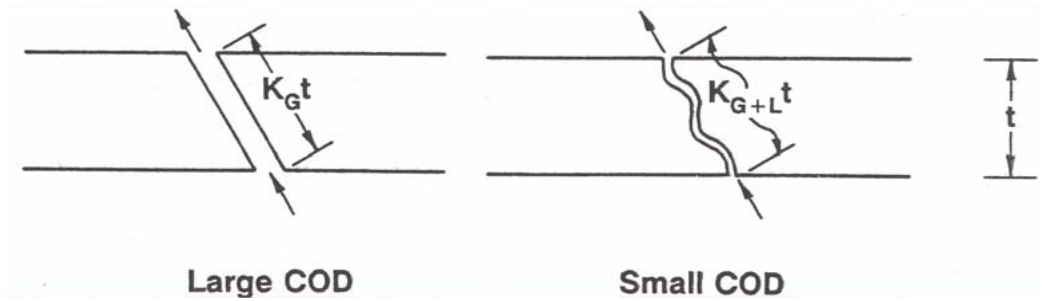
$$R_q = \sqrt{\left(\frac{1}{L}\int_{x=0}^{x=L} y^2 dx\right)}$$

- ***Surface roughness and number of turns can depend on the magnitude of the crack-opening displacement (μ_G = global surface roughness, μ_L = local surface roughness).***



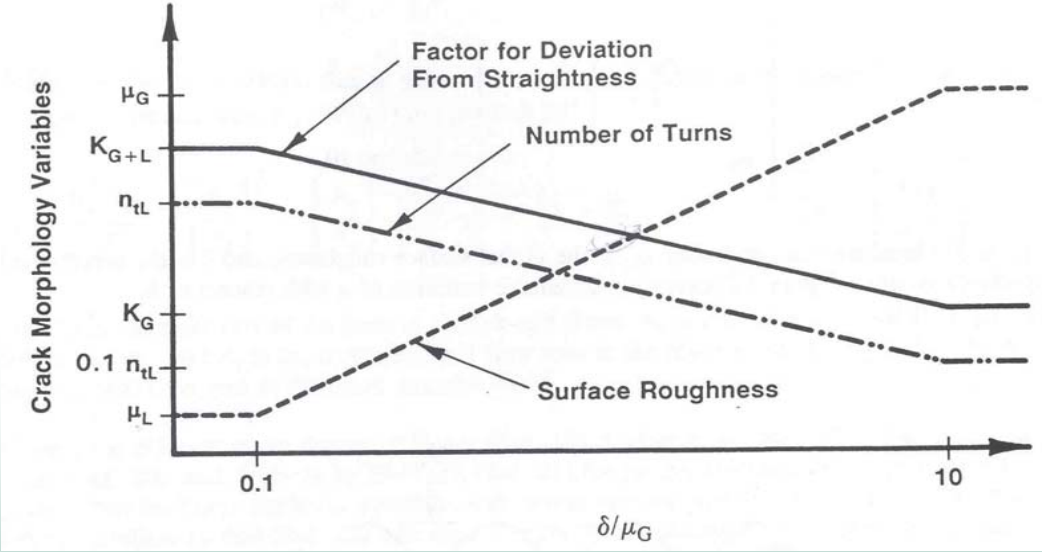
Crack Morphology Parameters

- ***Actual flow path length can depend on number of turns and will be greater than just the thickness of the pipe.***



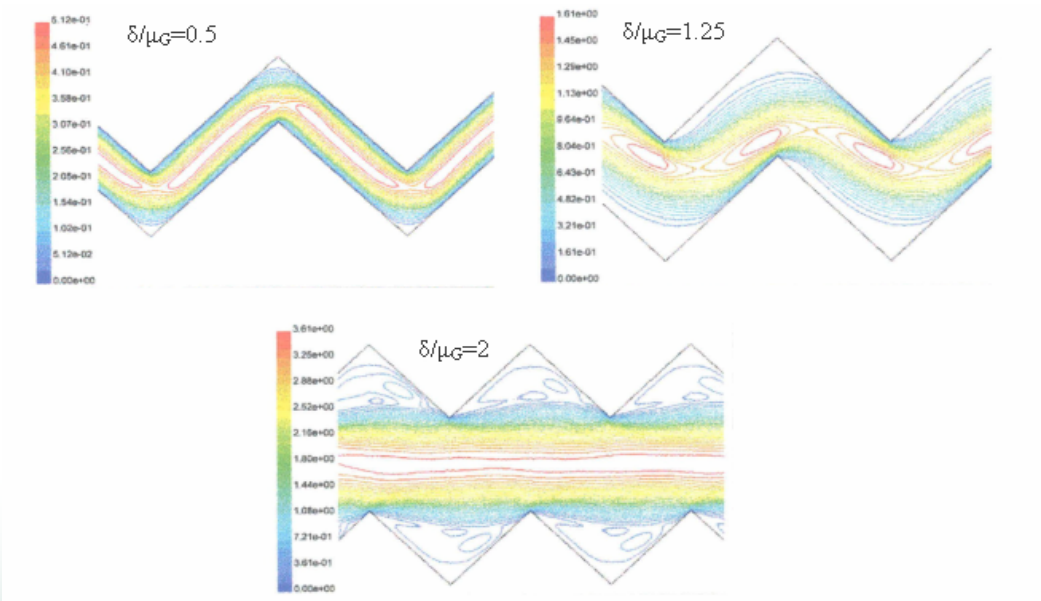
Crack Morphology Parameters

- ***Interpolation procedure used to account for effect of COD on transition from:***
  - ***very tight cracks (lower surface roughness, many turns, longer flow path length) to***
  - ***large COD crack cases (higher roughness, fewer turns, and shorter effective flow length)***



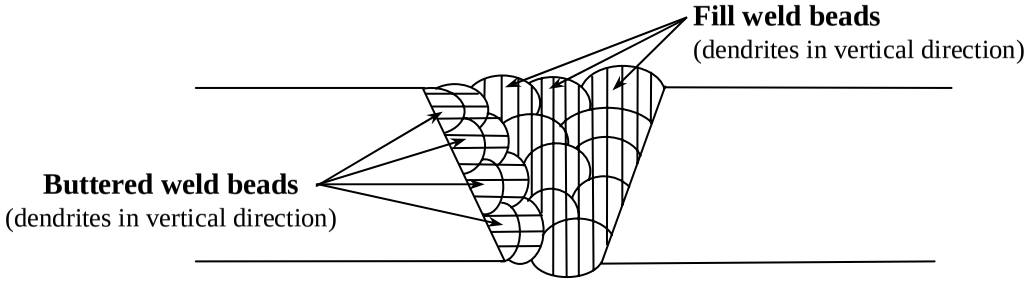
Crack Morphology Parameters

- ***Interpolation procedure is approximate and could be improved with detailed CFM analysis***



Unique aspects of PWSCC in bimetallic welds

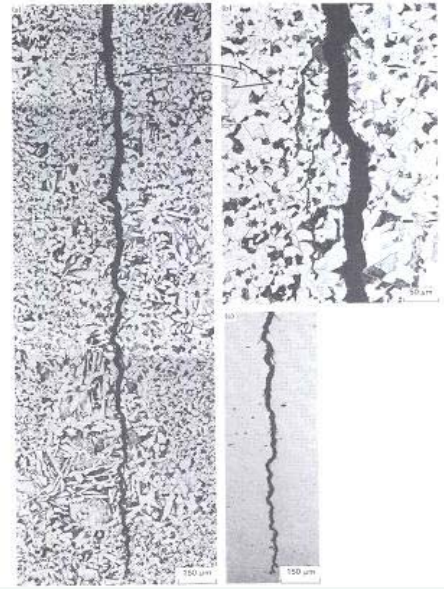
- ***Weld bead orientation may affect crack morphology parameters, i.e., cracks grow parallel to dendritic grains faster***



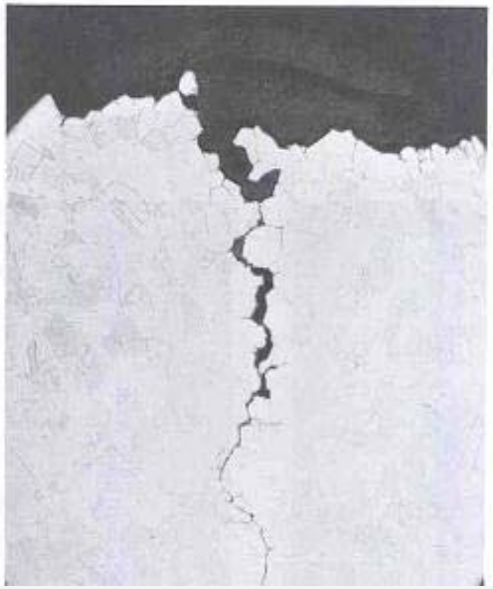
Statistical analysis of crack morphology for different types of cracks

- ***Evaluated service removed cracks in NUREG/CR-6004 "Probabilistic Pipe Fracture Evaluations for Leak-Rate-Detection Applications"***

Air fatigue crack



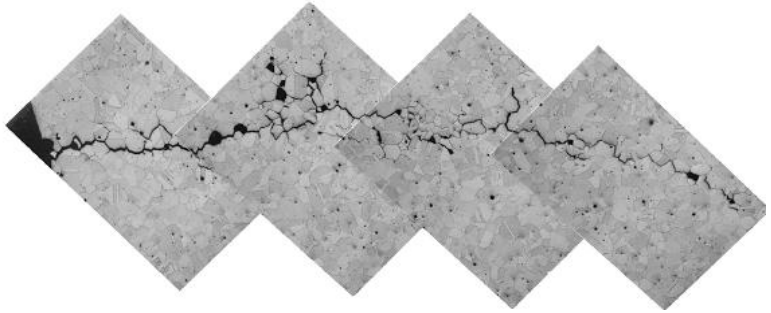
Corrosion fatigue crack



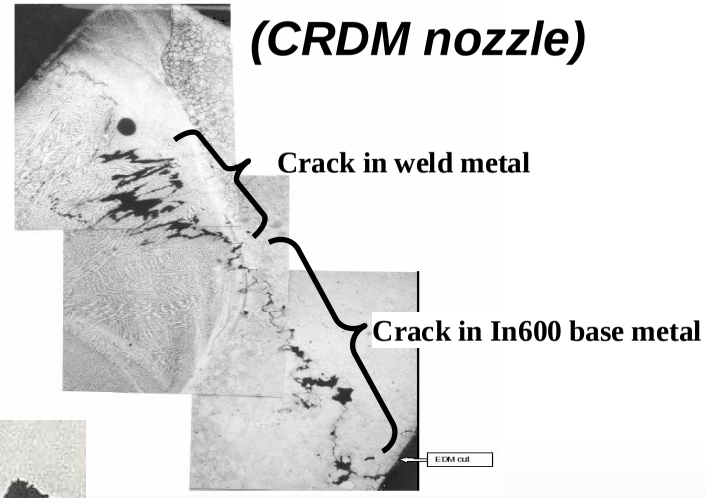
IGSCC crack

PWSCC cracks examined from metallographic sections

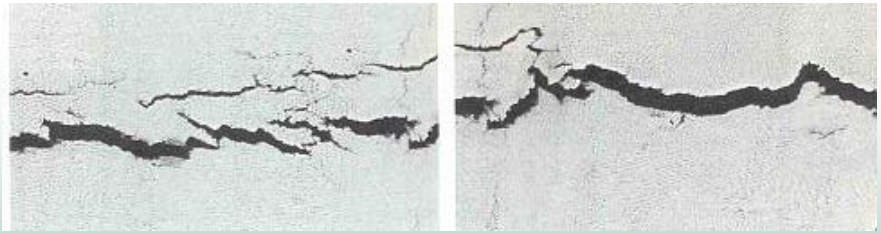
- *Inconel 600 base metal (CRDM nozzle)*



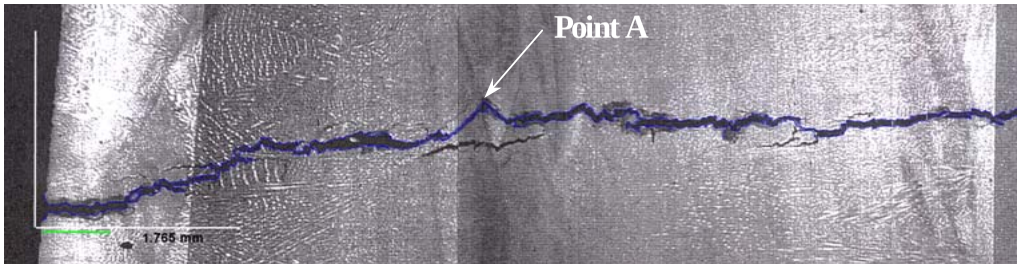
- *Inconel 600 base and weld metal (CRDM nozzle)*

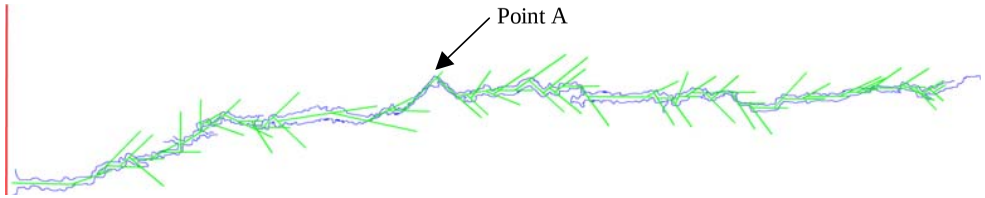


- *In 82/182 weld in pipe*

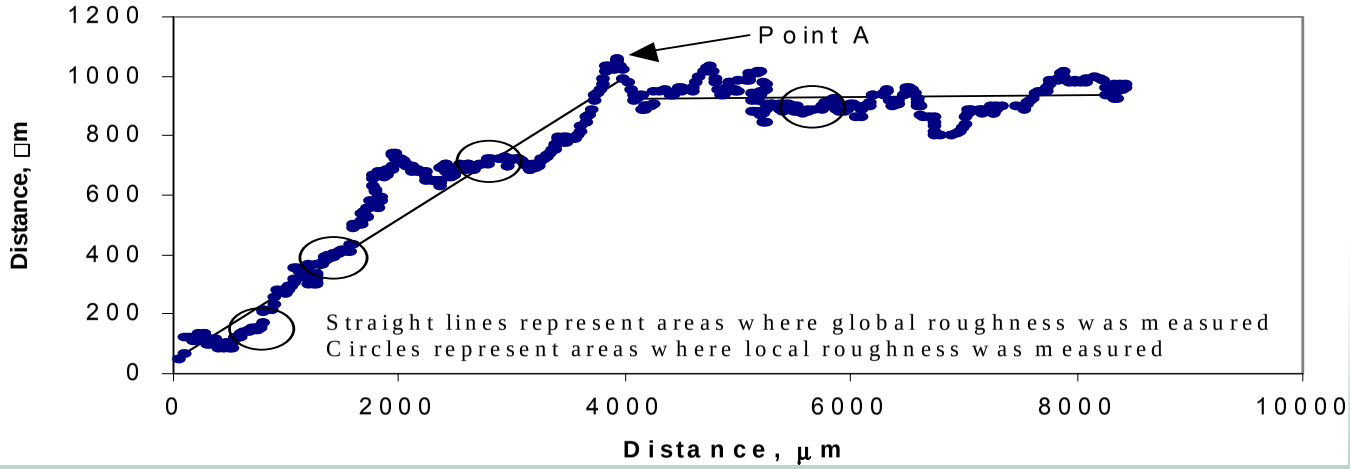


Example of determining crack morphology parameters





# of turns



Roughness

Comparison of Parameters for Various Cracking Mechanisms

- ***PWSCC crack results***

Location	μ_L (μm)	μ_G (μm)	n_{tL} (mm^{-1})	K_G	K_{G+L}
Hot-leg Inconel 82/182 weld Parallel to dendritic grain	7.5	52	3.95	1.022	1.132
	4.75	40	12.4	1.000	1.245
Hot-leg Inconel 82/182 weld Parallel to dendritic grain	21	125.5	5.42	1.015	1.278
	34.2	238	1.97	1.000	1.315
CRDM nozzle Inconel 82/182 weld Transverse to dendritic grains	10.2	282	8.3	1.500	2.487
CRDM tube Inconel 600 base metal	4.3	71	5.72	1.001	1.165
CRDM tube Inconel 600 base metal	22	166	9.56	1.170	1.614
CRDM tube Inconel 600 base metal	5.57	41	8.85	1.010	1.203

Mean and standard deviation of crack morphology parameters

Crack Morphology Variable	Corrosion Fatigue		IGSCC		PWSCC – Base		PWSCC – Weld[a]	
	Mean	Standard Dev	Mean	Standard Dev	Mean	Standard Dev	Mean	Standard Dev
μ_L, μm	8.814	2.972	4.70	3.937	10.62	9.870	16.86	13.57
μ_G, μm	40.51	17.65	80.0	39.01	92.67	65.26	113.9	90.97
n_L, mm^{-1}	6.730	8.070	28.2	18.90	8.043	2.043	5.940	4.540
K_G	1.017	0.0163	1.07	0.100	1.060	0.095	1.009	0.011
K_{G+L}	1.060	0.0300	1.33	0.170	1.327	0.249	1.243	0.079

(a) Crack growth ***parallel*** to long direction of dendritic grains.

Typical LBB Cases Analyzed

Case Number	Piping System	Bimetallic Weld Location	OD, mm (inch)	Wall thickness, mm (inch)
1	Surge line	Surge line to pressurizer	356 (14.0)	35.7 (1.41)
2	Hot leg	Hot-leg safe end to reactor vessel nozzle	879 (34.6)	68.6 (2.70)
3	Hot leg	Hot-leg safe end to reactor vessel nozzle	878 (34.6)	68.3 (2.69)
4	Surge Line	Surge line to hot leg	406 (16.0)	40.4 (1.59)
5	Surge Line	Surge line to pressurizer	356 (14.0)	35.8 (1.41)
6	Surge Line	Surge line to pressurizer	305 (12.0)	33.3 (1.31)

Typical LBB Cases Analyzed

Case Number	Normal Operating Conditions				Faulted Conditions (N+SSE)			
	Pressure, MPa (psi)	Temp., C (F)	F_x w/press, MN (kips)	M_{eff}, kN-m (in-kips)	Pressure, MPa (psi)	Temp., C (F)	F_x w/press, kN (kips)	M_{eff}, kN-m (in-kips)
1	16.0 (2,327)	345 (653)	1.04 (234)	200 (1,770)	16.0 (2,327)	345 (653)	1,078 (242)	241.6 (2,138)
2	15.4 (2,235)	323 (614)	6.61 (1490)	1720 (15,200)	15.4 (2,235)	323 (614)	7,126 (1,602)	1,861 (16,470)
3	15.4 (2,235)	323 (613)	6.19 (1,390)	3,680 (32,600)	15.4 2,235)	322.8 (613)	7,864 (1,768)	4,397 (38,910)
4	14.8 (2,150)	316 (600)	1.29 (290)	209 (1,853)	14.8 (2,150)	316 (600)	NA	NA
5	14.8 (2,150)	316 (600)	0.98 (221)	243 (2,147)	14.8 (2,150)	316 (600)	NA	NA
6	15.5 (2,250)	345 (653)	0.689 (155)	220 (1,950)	15.5 (2,250)	345 (653)	NA	NA

Case Number	Average Properties						Minimum Properties					
	Yield MPa (ksi)	Ultimate MPa (ksi)	E GPa (msi)	ε_0	α	n	Yield MPa (ksi)	Ultimate MPa (ksi)	E GPa (msi)	ε_0	α	n
1[a]	155 (22.4)	474 (68.7)	179.3 (26.0)	0.000863	6.50	3.80	130 (18.8)	454 (65.8)	179.3 (26.0)	0.000723	9.11	3.80
2[b]	146 (21.1)	453 (65.7)	179.3 (26.0)	0.000812	8.10	3.35	142 (20.6)	434 (62.9)	175.8 (25.5)	0.000808	8.04	5.55
3[a]	169 (24.5)	469 (68)	175.8 (25.5)	0.000961	3.75	4.82	163 (23.7)	427 (61.9)	175.8 (25.5)	0.000929	7.30	8.90
4[c]	229 (33.2)	501 (72.7)	172.7 (25.05)	0.001325	12.1	2.83	NA	NA	NA	NA	NA	NA
5[c]	229 (33.2)	501 (72.7)	172.7 (25.05)	0.001325	12.1	2.83	NA	NA	NA	NA	NA	NA
6[b]	146 (21.1)	453 (65.7)	179.3 (26.0)	0.000812	8.10	3.35	142 (20.6)	434 (62.9)	175.8 (25.5)	0.000808	8.04	5.55

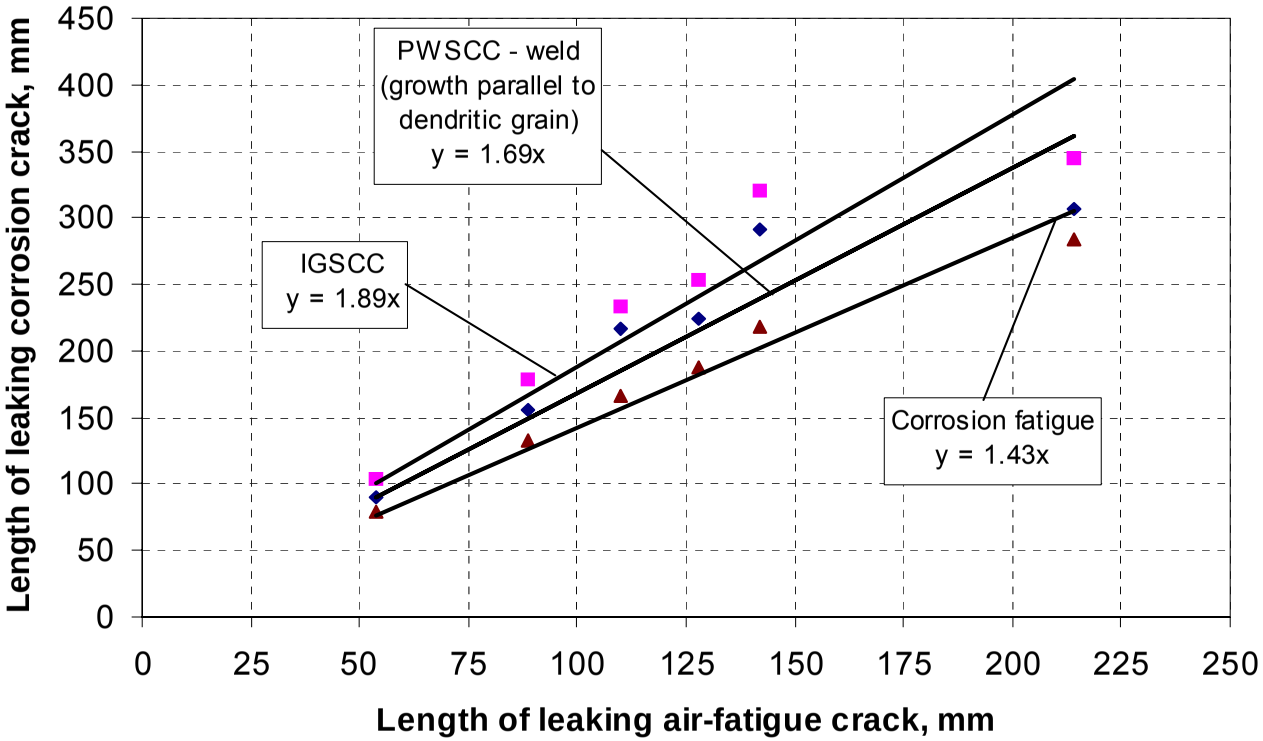
LBB Results – Leakage flaw lengths

- ***PWSCC parallel to dendritic grain – main part of weld***

Case	Applicants'/ Published leakage size flaw, mm (inch)	Leakage crack size, mm (inch) (Using GE/EPRI with original h functions - COD dependence)			
		Air-fatigue crack (300-μinch roughness no turns)	IGSCC	Corrosion-fatigue	PWSCC[(a)]
1[(b)]	71 (2.80)	88.6 (3.49)	178 (6.99)	133 (5.25)	156 (6.13)
2[(c)]	132 (5.20)	142 (5.61)	321 (12.6)	218 (8.52)	291 (11.4)
3[(c)]	85 (3.35)	110 (4.35)	234 (9.23)	166 (6.54)	216 (8.50)
4[(c)]	213 (8.40)	128 (5.03)	253 (9.98)	188 (7.39)	224 (8.81)
5[(c)]	261 (10.26)	214 (8.44)	345 (13.59)	283 (11.13)	306 (12.03)
6[(c)]	76 (3.00)	53.6 (2.11)	104 (4.11)	80.0 (3.15)	90.2 (3.55)

(a) Crack growing ***parallel*** to long direction of dendritic grains in Inconel 82/182 weld.
(b) 5 gpm leak rate – Factor of safety of 10 on 0.5 gpm leakage detection capability.
(c) 10 gpm leak rate – Factor of safety of 10 on 1 gpm leakage detection capability.

Comparison of length of leaking corrosion cracks with the length of air-fatigue cracks



LBB Results – Margins on crack size

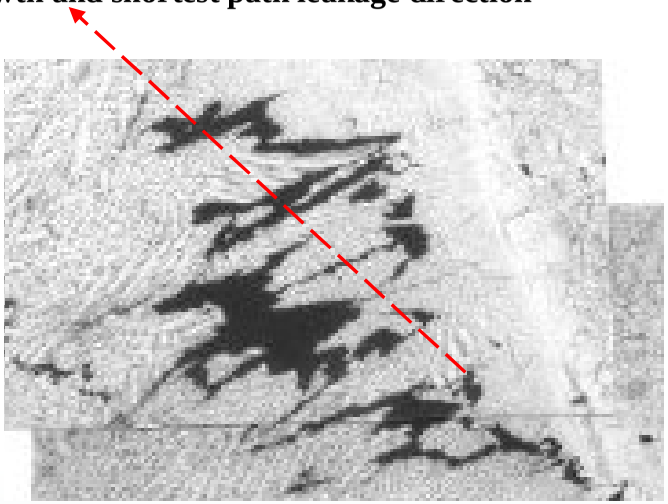
- ***PWSCC parallel to dendritic grain – main part of weld***

Case	Applicant/ Published critical flaw size, mm (inch)	Margin on leakage crack size				
		Applicants'/ Published margin	Calculations from this report			
			Air-fatigue crack (300-μinch roughness no turns)	IGSCC	Corrosion -fatigue	PWSCC[(a)]
1	427 (16.8)	6.0	4.82	2.40	3.21	2.74
2	NA[(b)]	>2	5.51	2.45	3.63	2.70
3	190 (7.5)	2.24	1.72	0.81	1.15	0.88
4	396 (15.6)	1.86	3.10	1.56	2.11	1.77
5	462 (18.2)	1.77	2.16	1.34	1.64	1.51
6	163 (6.4)	2.13	3.03	1.56	2.03	1.80

(a) Crack growing ***parallel*** to long direction of dendritic grains.
(b) Applicant's critical flaw size was not available. Critical flaw size was calculated using NRCPIPE Version 3.0. For this case, the critical flaw size was calculated as 785 mm (30.9 inch).

PWSCC growth across the long direction of the dendritic grains – buttered region

Crack growth and shortest path leakage direction



LBB Results – Leakage flaw lengths

- ***PWSCC perpendicular to dendritic grain – buttered region crack***

Case	Applicants'/ Published Leakage Size Flaw, mm (inch)	Leakage crack size, mm (inch) (Using GE/EPRI with original h functions & SQUIRT with COD dependence)	
		Air-fatigue crack (300-µinch roughness with no turns)	PWSCC[a] (with crack growing *perpendicular* to long direction of dendritic grains)
1[b]	71 (2.80)	88.7(3.49)	187 (7.35)
2[c]	132 (5.20)	142 (5.61)	356 (14.02)
3[c]	85 (3.35)	110 (4.35)	287 (11.28)
4[c]	213 (8.40)	128 (5.03)	271 (10.68)
5[c]	261 (10.26)	214 (8.44)	353 (13.89)
6[c]	76 (3.00)	53.6 (2.11)	120 (4.72)

(a) Crack morphology parameters are derived from only one photomicrograph, Figure 19 of Reference 12.
(b) 5 gpm leak rate – Factor of safety of 10 on 0.5 gpm leakage detection capability.
(c) 10 gpm leak rate – Factor of safety of 10 on 1 gpm leakage detection capability.

LBB Results – Margins on crack size

- ***PWSCC perpendicular to dendritic grain – buttered region crack***

Case	Applicants'/ Published Critical Flaw Size, mm (inch)	Margin on leakage crack size		
		Applicants'/ Published margin	Margins from analysis in this report	
			Air fatigue crack (300-µinch roughness with no turns)	PWSCC[(b)] (with crack growing *perpendicular* to long direction of dendritic grains)
1	427 (16.8)	6.0	4.82	2.28
2	NA[(a)]	>2	5.51	2.21
3	190 (7.5)	2.24	1.72	0.66
4	396 (15.6)	1.86	3.10	1.46
5	462 (18.2)	1.77	2.16	1.31
6	163 (6.4)	2.13	3.03	1.35

(a) Applicant's critical flaw size was not available. Critical flaw size was calculated using NRCPIPE Version 3.0. For this case, the critical flaw size was calculated as 785 mm (30.9 inch).

(b) Crack morphology parameters are derived from only one photomicrograph, Figure 19 of Reference 15.

Conclusions

- ***PSWCC cracks have a more tortuous flow path than air fatigue cracks that were frequently used in past LBB submittals***

- ***PWSCC crack morphology parameters determined from a few limited service cracks***

- ***PWSCC crack morphology slightly less severe than IGSCC if crack grow parallel to dendritic grains, but could be worse if going perpendicular to dendritic grain – buttered region***

Conclusions

- ***An updated LBB analysis was conducted using typical LBB submittals***
  - ***J-R curves for In82/182 in progress***

- ***PWSCC cracks have leakage crack lengths that are longer than air fatigue cracks (used in many LBB submittals) at the same leakrate***
  - ***~70% longer if PWSCC is parallel to dendritic grain – main weldment***
  - ***~110% longer if PWSCC is perpendicular to dendritic grain – buttered region***

Conclusions

- ***Average margin on LBB crack length decreased from 3.39 for air-fatigue crack to***
  - ***1.9 for the PWSCC crack growing parallel to the long direction of the dendritic grains***
  - ***1.55 for the PWSCC crack growing transverse to the long direction of the dendritic grains***

- ***LBB difficult to satisfy for PWSCC crack cases using draft SRP 3.6.3 procedures***

- ***PWSCCs could result in long circumferential surface cracks, which could make breaks more likely to occur than by using the simple circumferential through-wall crack analysis***
  - ***LBB screening criteria not satisfied***

Section 5:
Session 4: Crack Growth Rate Studies for the Disposition of Flaws

US REGULATORY EXPERIENCE AND PROGNOSIS WITH RPV HEAD DEGRADATION AND VHP NOZZLE CRACKING

Presented by

Allen L. Hiser, Jr.
Materials and Chemical Engineering Branch
Office of Nuclear Reactor Regulation

Conference on Vessel Penetration Inspection, Cracking & Repairs

October 1, 2003

OUTLINE

- Background
- Order EA-03-009 (issued February 11, 2003)
  - Inspection requirements
  - Relaxation requests
  - Possible Modifications to Order EA-03-009
- Outlook
- Bulletin 2003-02

BACKGROUND

- Fall 2000
  - Oconee Unit 1 identifies deposits - axial leak

- Spring 2001
  - Oconee Unit 2 and 3 identify circumferential cracks
  - ANO Unit 1 identifies a leaking nozzle

- **NRC issues Bulletin 2001-01 - August 2001**
  - Focus is safety issue (circumferential cracks) for high susceptibility plants
  - Visual examinations considered acceptable

- Fall 2001
  - Circumferential cracks identified - Crystal River 3 and Oconee 3
  - Leaks and repairs at Surry 1, North Anna 2 and TMI

BACKGROUND (cont.)

- Spring 2002
  - Davis-Besse identifies RPV head wastage & circumferential cracking

- **NRC issues Bulletin 2002-01 - March 2002**
  - Focus is safety issue is RPV wastage for all plants

- Spring 2002
  - Millstone identifies part through-wall cracks (moderate plant)

- **NRC issues Bulletin 2002-02 - August 2002**
  - Focus is adequacy of inspection programs - methods (non-visual NDE for high susceptibility) and frequency
  - Licensee responses generally vague on future program, many cite MRP-75 program

BACKGROUND (cont.)

- Fall 2002
  - North Anna 2 identifies
    - ✓ Prevalent weld cracking, & leak from a repaired nozzle
    - ✓ Circumferential cracking at weld root without boron deposits
  - ANO Unit 1 identifies leak from a repaired nozzle
  - Oconee Unit 2 identifies possible through-wall cracking without boron deposits on the RPV head
  - Head corrosion at Sequoyah Unit 2 - above head boron source

- **NRC issues Order EA-03-009 - February 2003**
  - Mandates inspections for all PWRs

- Spring 2003
  - South Texas Project Unit 1 - boron deposits on the lower head

- **NRC issues Bulletin 2003-02 - August 2003**
  - Focus is inspections of bottom head Alloy 600 nozzles of PWRs

- Fall 2003
  - Oconee Unit 1 - Leak from a plugged thermocouple nozzle
  - (Alloy 690 plug and 152 weld)

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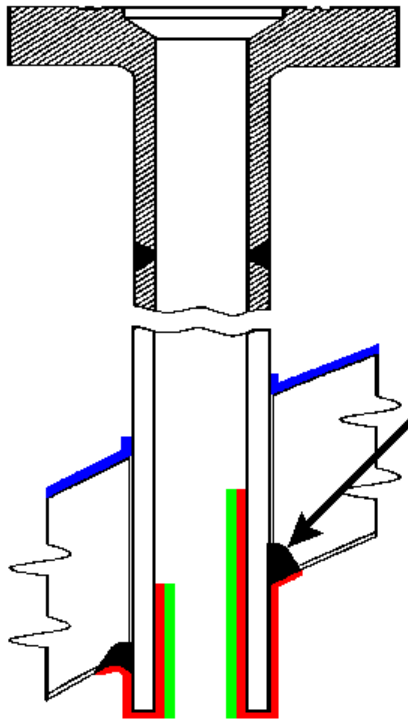
OVERVIEW OF ORDERS

- Issued February 11, 2003
- Issued to all PWRs
- Adequate protection basis
  - ASME Code inspections are inadequate
  - Revisions to inspection requirements are not imminent
  - RPV head degradation and nozzle cracking pose safety risks if not promptly identified and corrected
- Provides a clear regulatory framework pending the incorporation of revised inspection requirements into 10 CFR 50.55a

ORDER REQUIREMENTS

- Evaluate susceptibility - effective degradation years (EDY), based on operating temperature and time
- High plants - bare metal visual AND non-visual NDE at EVERY RFO
- Moderate plants - BMV and non-visual NDE at alternating RFOs
- Low plants - BMV by next 2 RFOs (repeat every 3rd RFO or 5 years), non-visual by 2008 (repeat every 4th RFO or 7 years)
- Non-visual NDE is EITHER:
  - Ultrasonic with evaluation of interference fit leakage, OR
  - Wetted-surface examination

Order EA-03-009
Required Inspection Surfaces



Bare Metal Visual Inspection Area

Ultrasonic Inspection Area

Wetted Surface Inspection Area

ORDER REQUIREMENTS

- Explicit requirements and criteria to inspect repaired nozzles/welds
- Each RFO, must perform visual inspections to identify boric acid leaks from components above the RPV head - follow-up actions include inspections of potentially-affected RPV head areas and nozzles
- Flaw evaluation per NRC guidance (Strosnider letter fall 2001, revised guidance in Barrett letter April 2003)
- Orders also apply to new RPV heads, either Alloy 600 (Davis-Besse) or Alloy 690 (North Anna 2 and many others)
- Post-outage report 60 days after restart

LICENSEE OPTIONS

- Request Director of NRR to relax or rescind requirements of the order based on “good cause”

- Requests for relaxation for specific VHP nozzles will be evaluated using procedures for proposed alternatives to the ASME Code in accordance with 10 CFR 50.55a(a)(3)
  - The proposed alternative will provide an acceptable level of quality and safety
  - Compliance would result in hardship or unusual difficulty without a compensating increase in the level of quality and safety

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NEED FOR ORDERS

- Past process of issuing Bulletins unwieldy, inconsistent, not stable, and has no regulatory weight (licensee commitments only)
- Rulemaking would take at least 1 or 2 years
- Orders can be revised or rescinded as necessary
- Although inspection plans for the next RFOs were generally acceptable, NRC wanted to provide licensees with planning time to meet order requirements
- Concerns that above RPV head leakage could result in undetected RPV head degradation

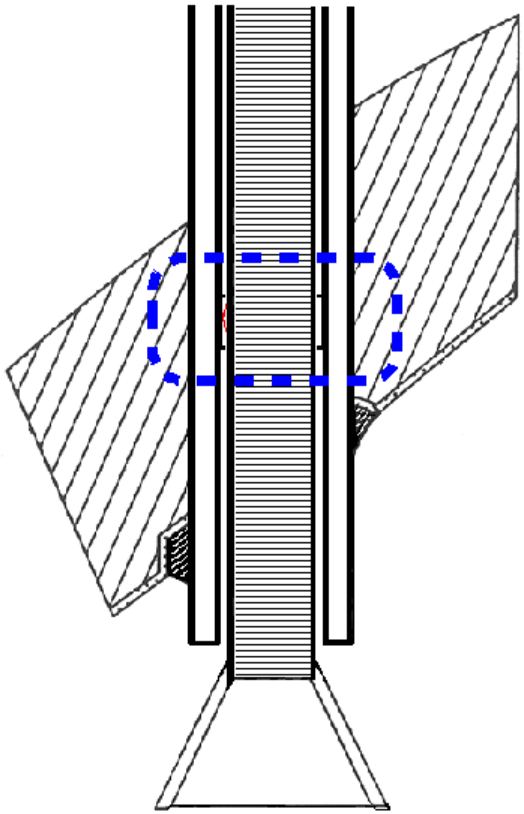
RELAXATION REQUESTS

- Limitations above the J-groove weld
  - Centering tabs & step on nozzle ID
  - Stress in non-inspected area below 28 ksi
  - Hardship - would have required guide sleeve removal and re-welding of a guide funnel onto nozzle

- Limitations below the J-groove weld
  - Guide funnel threads (ID & OD) and tapers on end of nozzles
  - Transducer coupling for time-of-flight-diffraction

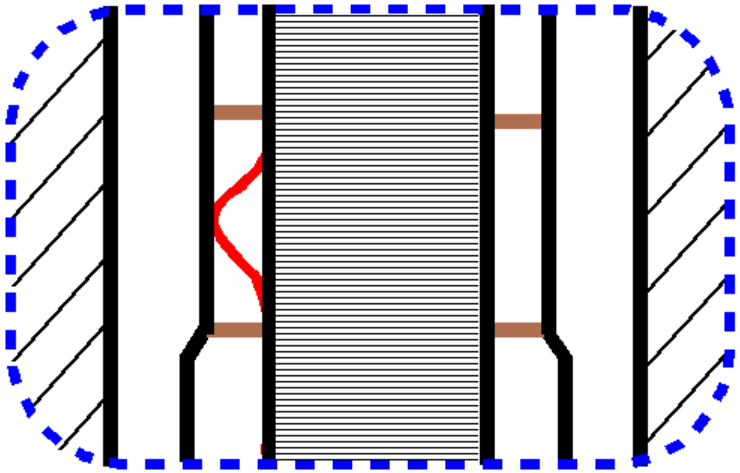
- Bare metal visual examinations
  - Localized insulation and support shroud interferences
  - Insulation prevents total access to RPV head surface
    - ✓ Low frequency eddy current to demonstrate head integrity
    - ✓ Enhanced UT to detect “triple-point” cracking

Calvert Cliffs
Order Inspection Limitations

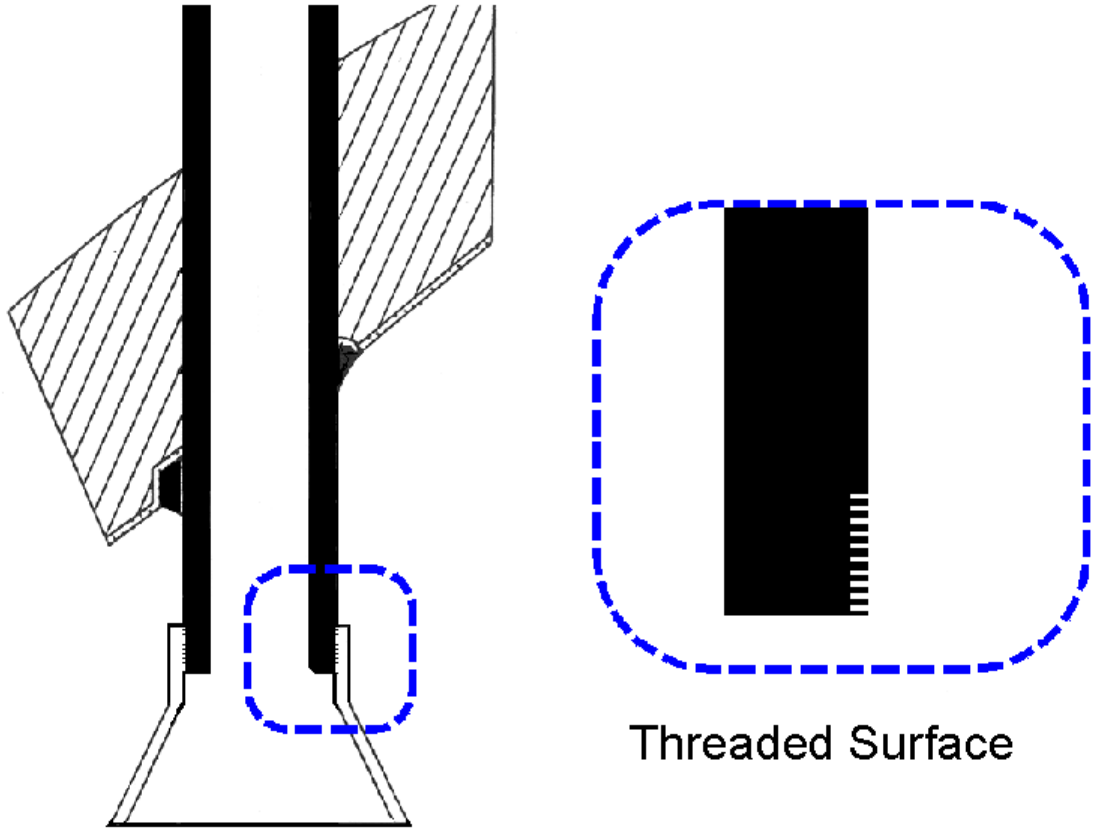


Thermal/Guide Sleeve

Sleeve Expansion Points



Farley Funnel Thread Inspection Limitation



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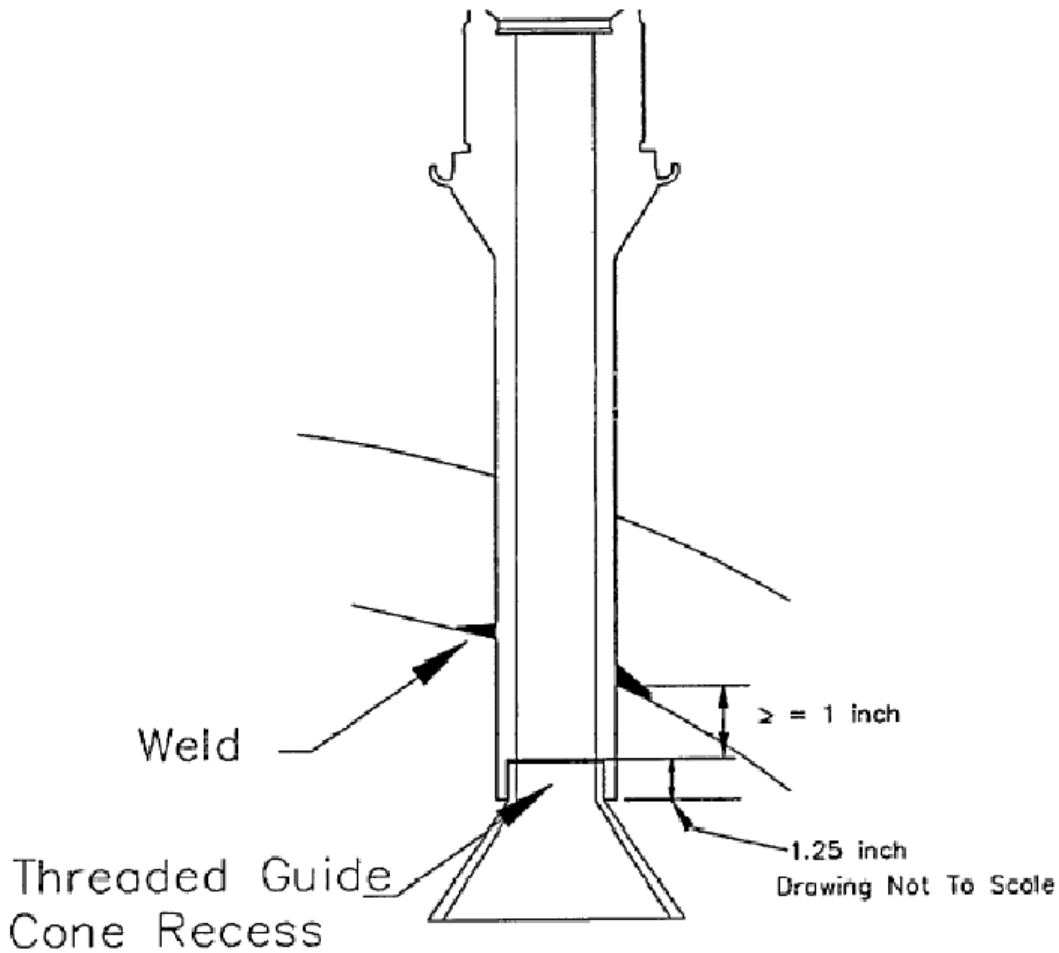
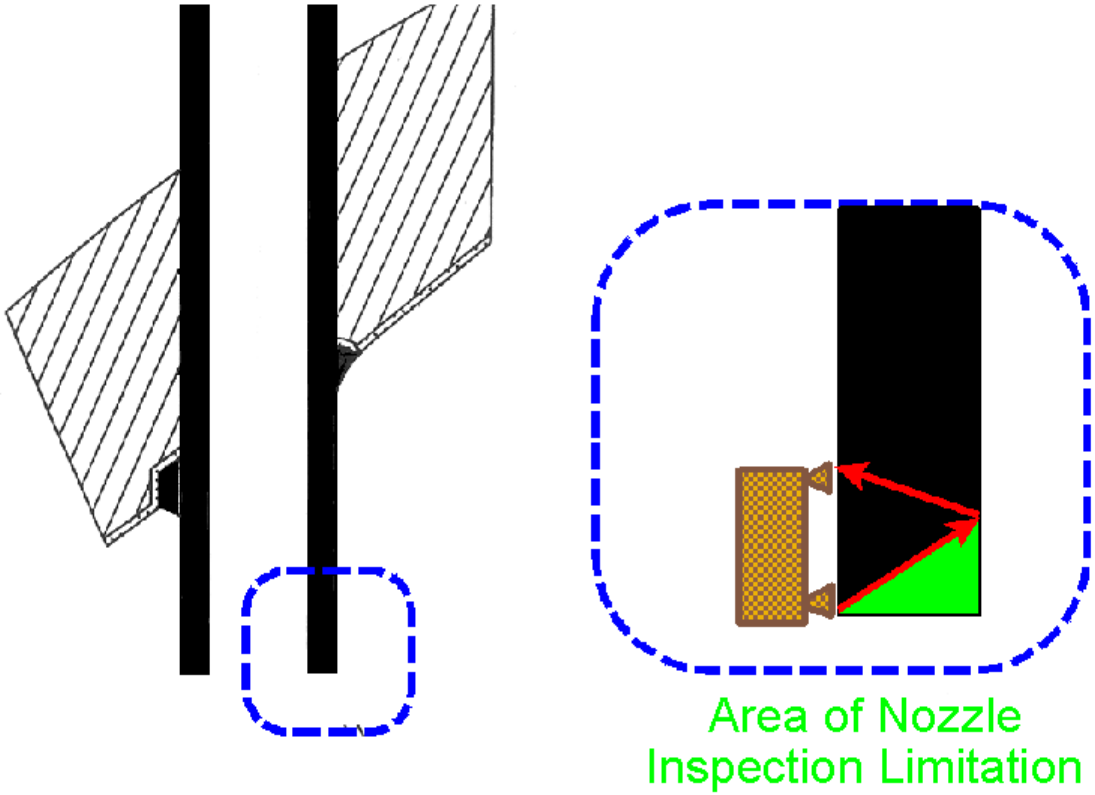
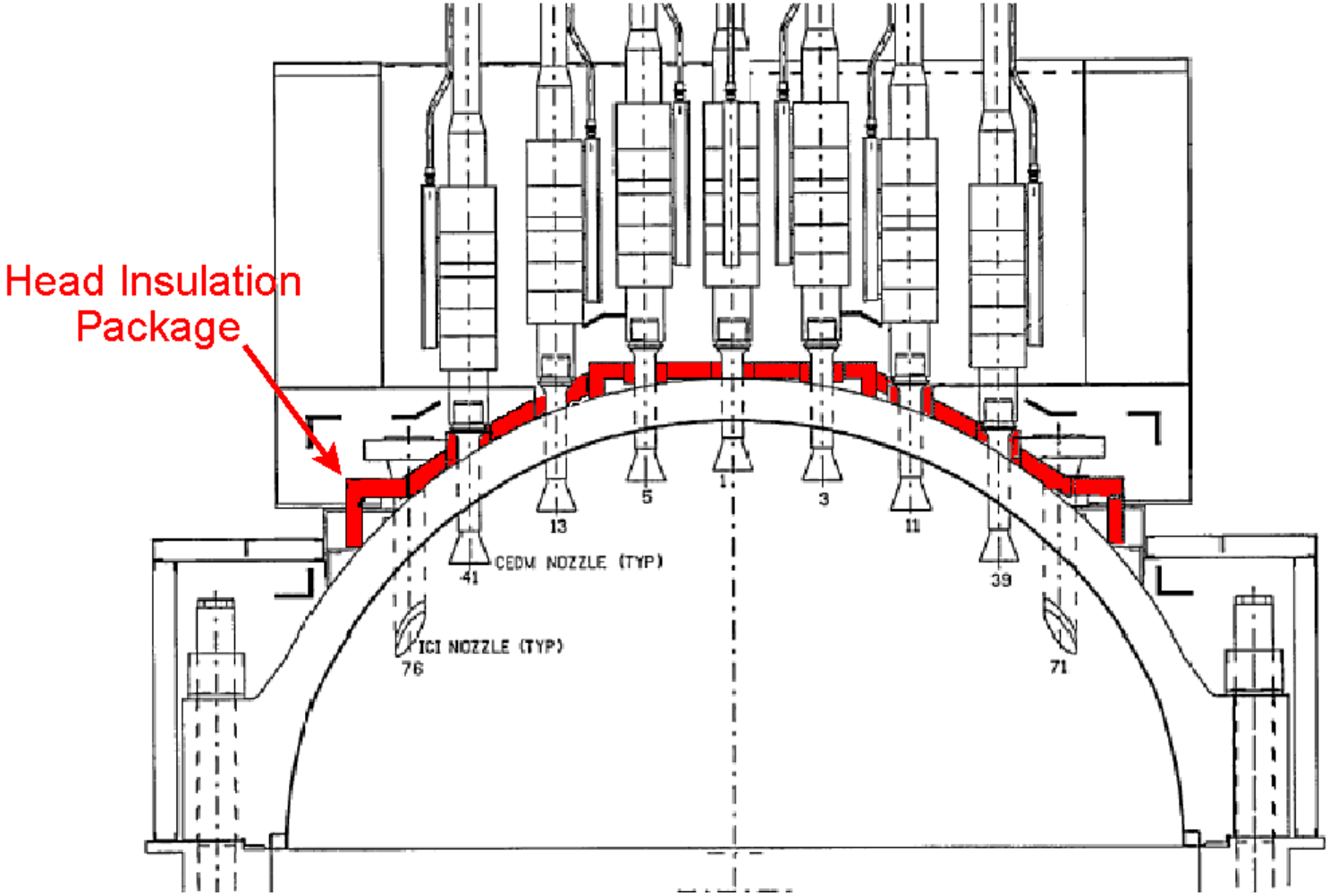
St. Lucie Unit 2
Typical RPV Nozzle With Threaded Guide Funnel



TOFD Transducer Coupling Limitations



Millstone Power Station
Bare Metal Visual Inspection Restraints



OUTLOOK

- Goal is “permanent” requirements for inspections to ensure structural integrity of the RPV head and VHP nozzles

- ASME Code is working to develop inspection requirements
  - Has been based upon industry report (MRP-75)
  - NRC staff has provided comments - report is not acceptable as submitted, acceptability is not certain
  - NRC has suspended review pending revisions by the industry based on fall 2002 findings
  - ASME Code adoption of requirements may not be complete until 2004 or later

- Inspection requirements will be implemented in 10 CFR 50.55a
  - Endorse the new ASME Code requirements (if acceptable) under expedited implementation, OR
  - Codify alternative inspection requirements
  - Will take 1-2 years once acceptable requirements are identified

POSSIBLE MODIFICATIONS TO ORDER EA-03-009

- Initially mentioned with industry on June 12
- Staff highlighted a high volume of similar relaxation requests for non-safety significant portions of the VHP nozzles and a potential for the industry to provide a generic analysis that could provide a technical basis for modifications to the Order - **report received September 26**
- The modification would result in a significant reduction in the burden on both the industry and the staff by reducing the number of repetitive evaluations, without impacting the level of safety provided by the Order

POSSIBLE MODIFICATIONS TO ORDER EA-03-009

- Allow combinations of non-visual NDE (UT and surface examinations) to be used on a RPV head to obtain full coverage for the head
  - Order currently specifies UT **<u>or</u>** surface examinations of **"each"** VHP nozzle or weld
- Modify scope of bare metal visual examination for support structure interferences (outside of VHP nozzle area) - examine above and below support structure
- Refine scope of coverage for each VHP nozzle to some elevation above the bottom of the nozzle, or some established stress level
  - Limitations due to internal or external threads (for guide cones or funnels) and bottom end chamfers restrict access and usefulness of examination data - this was not anticipated prior to Order issuance
  - Possible modification would eliminate need to examine areas with low stress and limited crack growth potential

RECENT INDUSTRY PROPOSAL

- Reduce frequency of UT or eddy current examinations for high susceptibility plants with a prior CLEAN examination (no leaks or cracks)
  - Proposed during teleconference July 8 - licensee submittal August 17
  - Small number of affected plants (4-5?), beginning this fall
  - Basis would be deterministic and/or probabilistic
  - May be a generic approach or plant-specific
- Considerations
  - A high threshold for the acceptability of prior inspections - must be consistent with the inspection criteria of the Order with current state-of-the-art techniques
  - Are two clean Order inspections necessary?

OTHER CONSIDERATIONS

- Use of Bulletins and early inspections for emergent issues intended to establish prevalence of issue - avoid significant events
  - Role of continuing “permanent” ISI activities is to re-establish defense-in-depth considerations
  - Tech. Spec requirements for no pressure boundary leakage
  - GDC 14 - “extremely low probability of abnormal leakage”

- Cause for leakage from plugged thermocouple nozzle (Alloy 690 plug and 152 weld) at Oconee Unit 1

BULLETIN 2003-02: INFORMATION REQUEST

- RPV lower head penetration inspections performed to date and findings
- Description of inspection program during next and **SUBSEQUENT** refueling outages
- If unable to perform BMV inspection of each penetration during next refueling outage, describe inspections able to perform and actions to be taken to permit inspection of each penetration during subsequent refueling outages
- If do not intend to perform either BMV or volumetric exam, provide basis for concluding requirements are and will continue to be met

BULLETIN 2003-02 (continued)

- Within 30 days after plant restart following next lower head inspection, summary of the inspections performed, conditions found, and any actions taken

- Provide response within 30 days if entering refueling outage before end of 2003

- All other addressees, provide response within 90 days

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Stress Corrosion Crack Growth Rates (SCCGRs) for Alloy 182 and 82 Welds

Steven A. Attanasio, John V. Mullen, John W. Wuthrich,
Weldon W. Wilkening, and David S. Morton

Lockheed Martin Corporation
Schenectady, NY

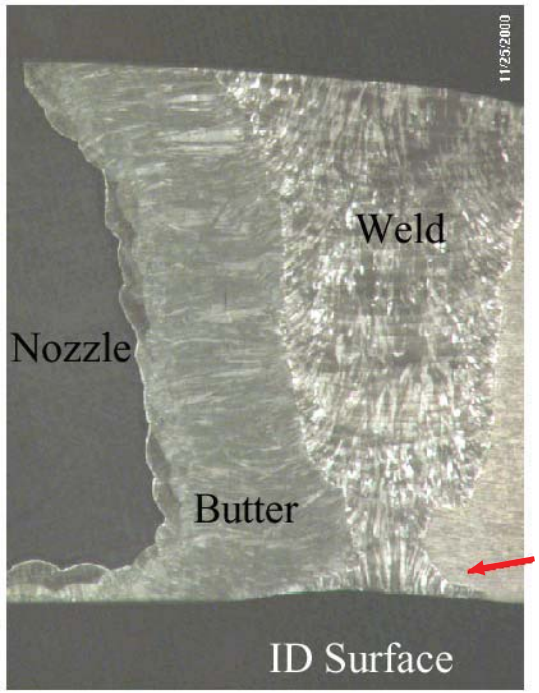
Alloy 600 SCC Workshop
Gaithersburg, MD
September 2003

Outline

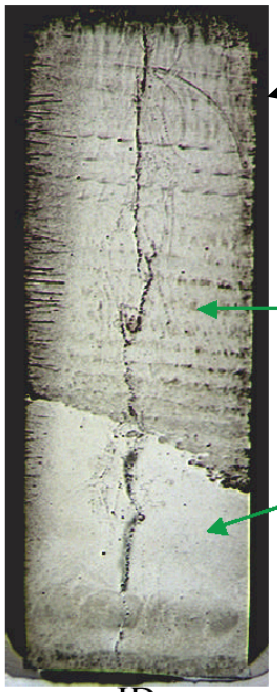
- Background
- Data Overview
- Description of Compliant Self-Loaded Compact Tension Specimens
- Context - EPRI Materials Reliability Program (MRP)
- Use of Average Crack Growth Rate and Maximum-to-Average Ratio
- Alloy 182 and Alloy 82 SCCGR Data
  - Comparison to data from other investigators
  - Comparison of the two alloys
  - Modeling approaches
- Aqueous Hydrogen Effects on SCC of Ni-base alloys, including Alloy 82

Background

- Both Alloys 182 and 82 are susceptible to primary water SCC
  - VC Summer hot leg (*http://www.nrc.gov/NRC/REACTOR/SUMMER/index.htm)*



Weld repair



Cross-Section of Weld

Main Crack

Alloy 82

Alloy 182 butter

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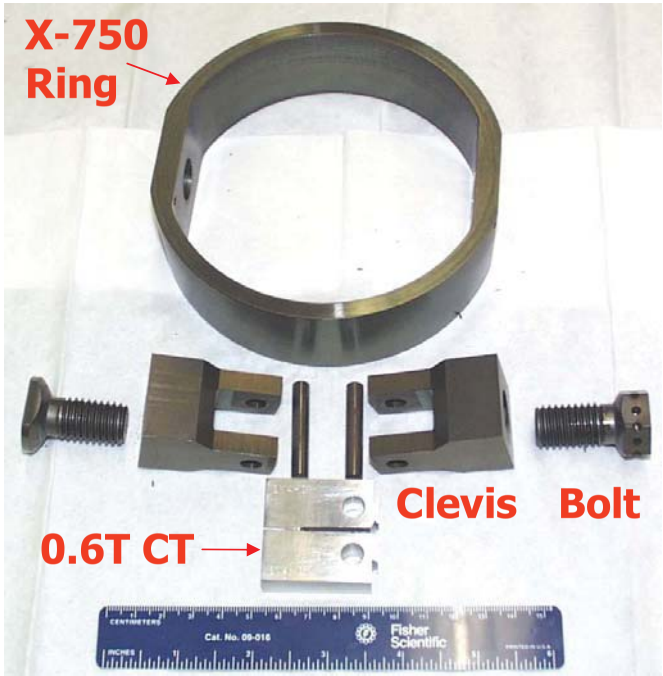
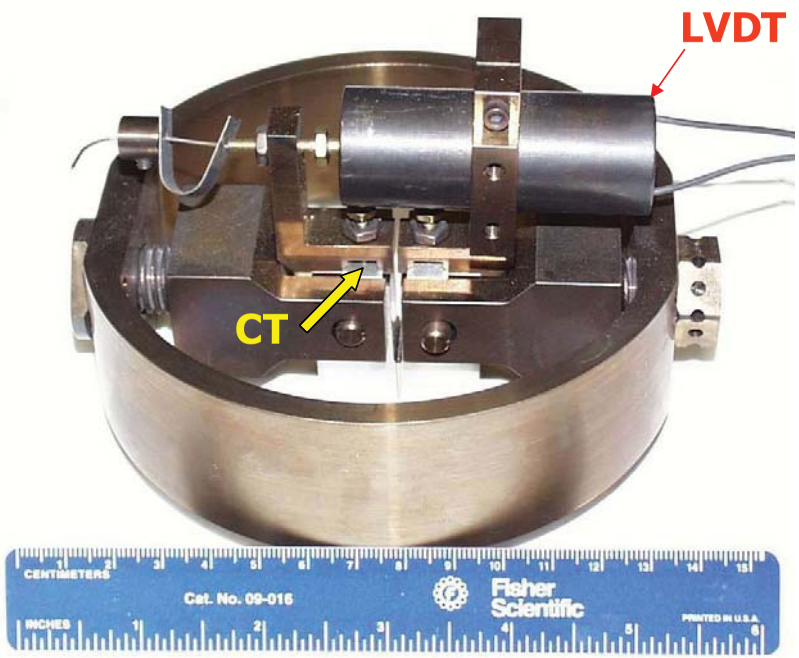
Data Overview

- SCCGR data - compact tension (CT) specimens (most side-grooved)
  - Active load, bolt load, compliant self-loaded (CSLCTs) - precracked
- Alloy 182 and 82 welds
  - Yield strengths of 454 to 530 (182) and 439 to 465 (82)
  - Carbon levels ~ 0.02 and 0.03 wt% (182) and ~ 0.045 wt% (82)
- High temperature hydrogenated water (pH_T ~ 6.6)
  - Single hydrogen concentration in each test (20, 30, 35, or 40 scc/kg)
- Single temperature tests - 316 to 360°C
- Average K_I of 33 to 46 MPa√m (182) and 23 to 55 MPa√m (82)
- All T-S Orientation (growth from root to crown; parallel to dendrites)
- 11 Alloy 182 data points - 2 heats
- 20 Alloy 82 data points - 3 heats
  - Subjected to screening criteria similar to that used by EPRI-MRP group

Compliant Self-Loaded Compact Tension Specimens

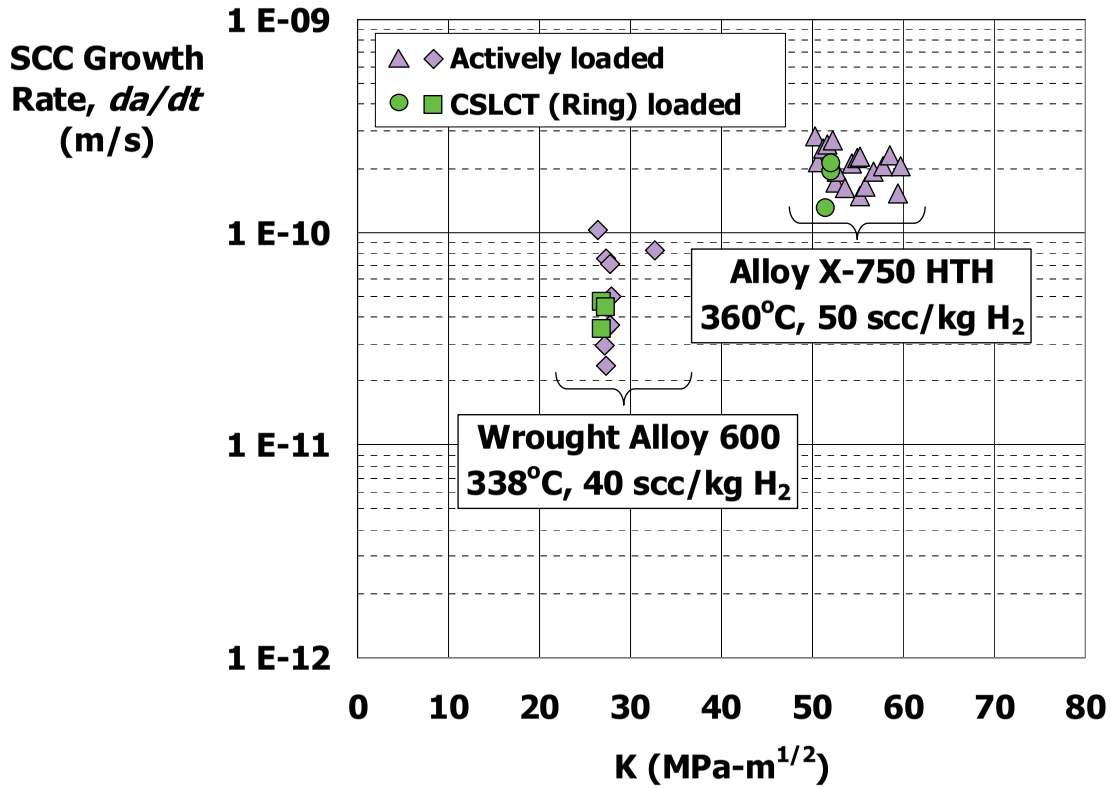




Loading Method:

- Compress ring using Instron machine, rotate bolt to apply 'setup' load to CT specimen
- Release Instron load slowly - CT specimen is loaded as ring expands
- Exact load is determined *via* measurement of ring spring constant and ring displacement
- Account for modulus changes due to heatup by increasing room temperature load

CSLCT Specimen Qualification



- Due to the compliance of the ring, load relaxation is minimal - even as SCC crack grows
- Can test up to 10 CSLCTs in a single 60 liter flowing autoclave (with LVDTs) - efficient

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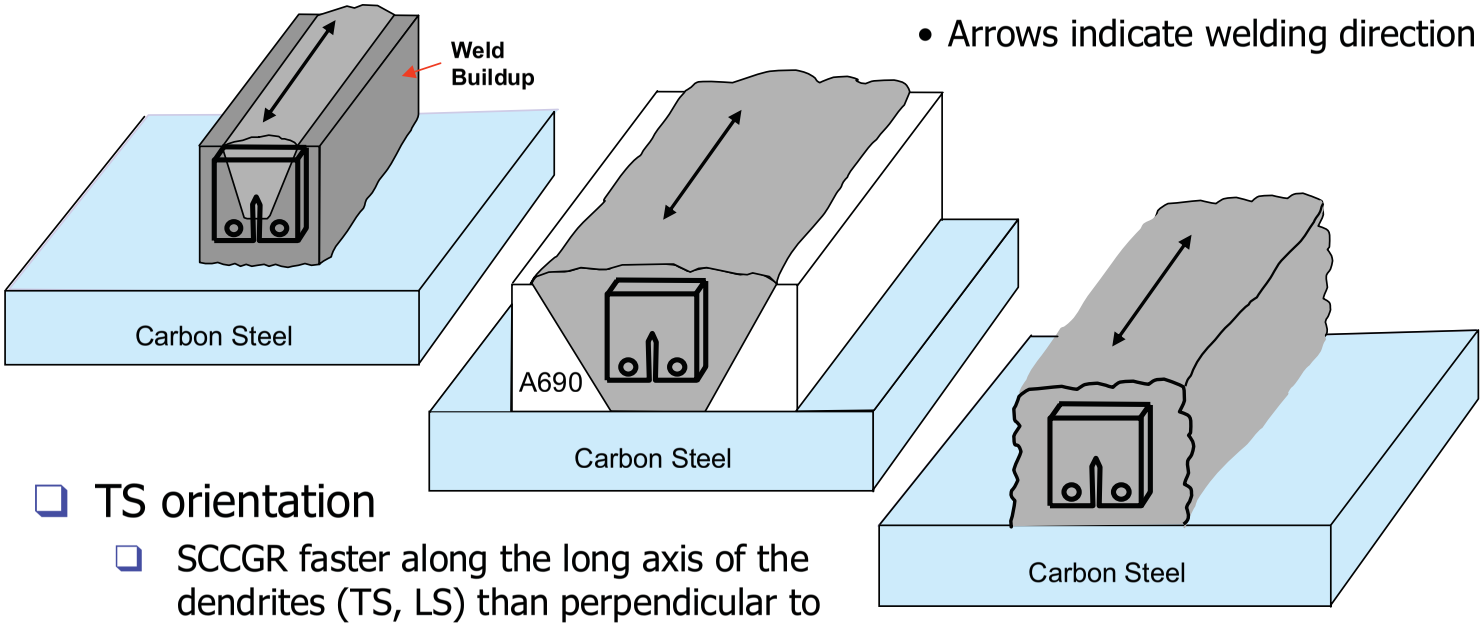
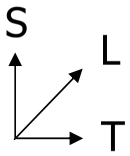
Specimen Fabrication



- Arrows indicate welding direction

- TS orientation
  - SCCGR faster along the long axis of the dendrites (TS, LS) than perpendicular to dendrites (e.g., TL)
    - Proven by Bamford *et al.* and others
- Weld process:
  - 182: Manual shielded metal arc welding
  - 82: Automatic gas tungsten arc welding



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EPRI Materials Reliability Program (MRP) Work

- MRP: Develop a SCCGR Model for Alloy 182 and 82 Weld Metals
  - Similar to the work performed for Wrought Alloy 600
- EPRI MRP-55 - Wrought Alloy 600 SCCGR Model (2002)
  - View/analyze present weld data *in part* using methods from MRP-55
  - Scott model - uses threshold K_I of 9 MPa√m
  - Thermal activation energy (Q_{SCCGR}) = 130 kJ/mole (31 kcal/mole)

$$\frac{da}{dt} = \alpha \cdot (K_I - 9)^{1.16} \cdot exp\left[-\frac{130{,}000}{8.314}\left(\frac{1}{T} - \frac{1}{598.15}\right)\right]$$

(*da/dt* in m/s, K_I in MPa√m, *T* in Kelvin)

  - Each heat described by its value of α
  - Data from different temperatures normalized to 325°C
    - Le Hong *et al.* - Alloy 182 Q_{SCCGR} is ~ 130 kJ/mole (EDF, ETH, CEA data)
    - Mills and Brown - Alloy 82 Q_{SCCGR} = 130 to 150 kJ/mole (31-35 kcal/mole)
      - In the present work, Alloy 82 and 182 data normalized using 130 kJ/mole

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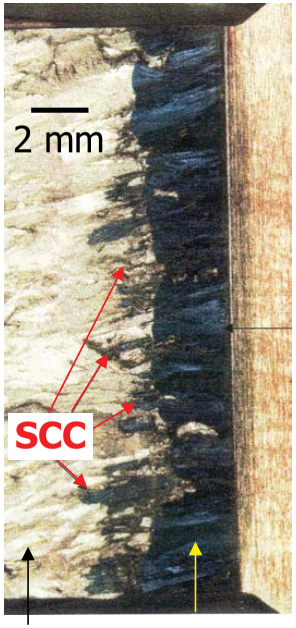
Data Screening Criteria

- Single condition test
- ASTM E647 Size Criteria (flow strength at temperature)
- Minimum average crack extension = 0.2 mm
- Data based on post-test destructive examination (DE)
- Periodic unload-reload only if hold time > 60 minutes
- Careful autoclave chemistry control (including H_2)
- Minimum 'engagement' of fatigue precrack = 50%
  - Quantifies the percentage of precrack length with SCC
- All Lockheed Martin (LM) SCCGR data herein pass these screening criteria



- LM Data reported as $SCCGR_{ave}$, rather than as $SCCGR_{max}$
  - Also report maximum-to-average SCC extension ratio (RATIO)
  - RATIO used by Lockheed Martin (LM) and by Mills (Bechtel)

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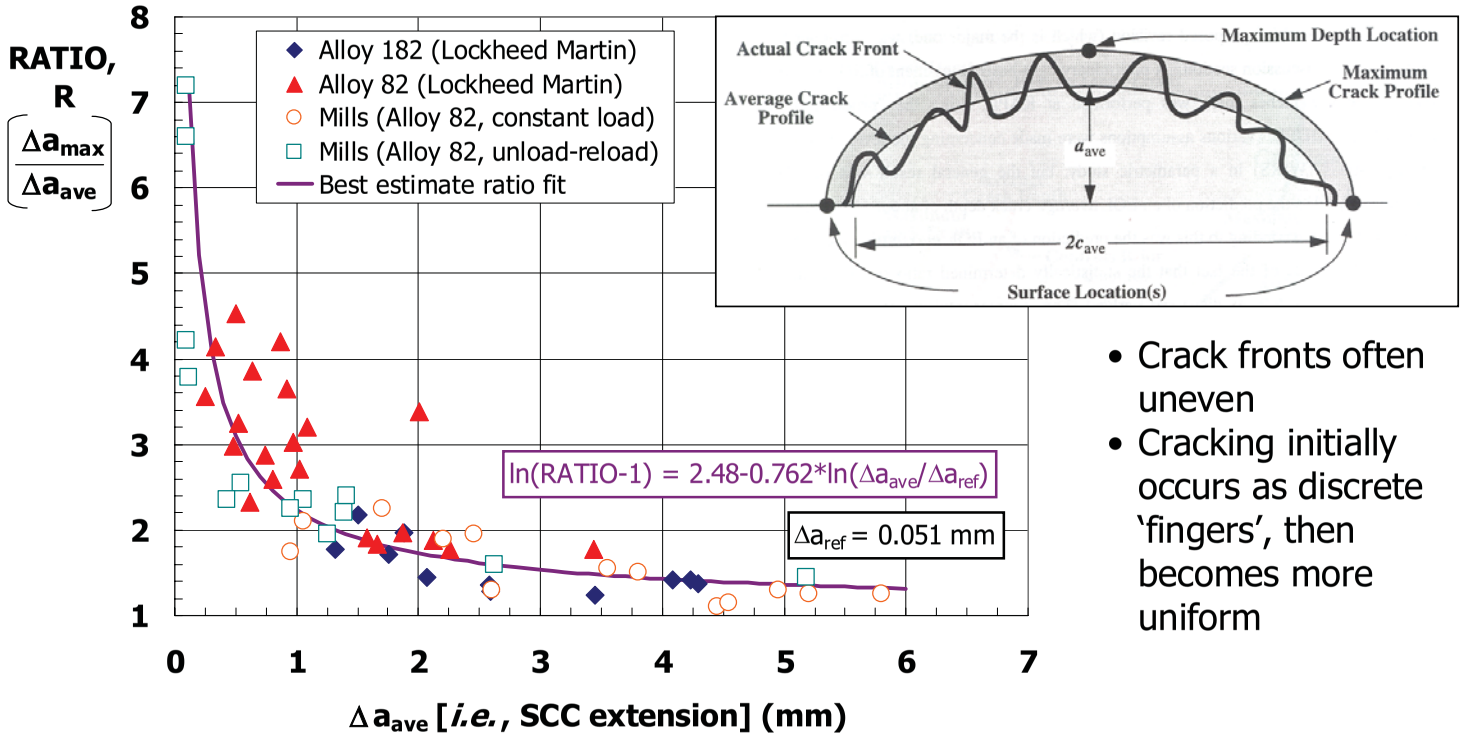
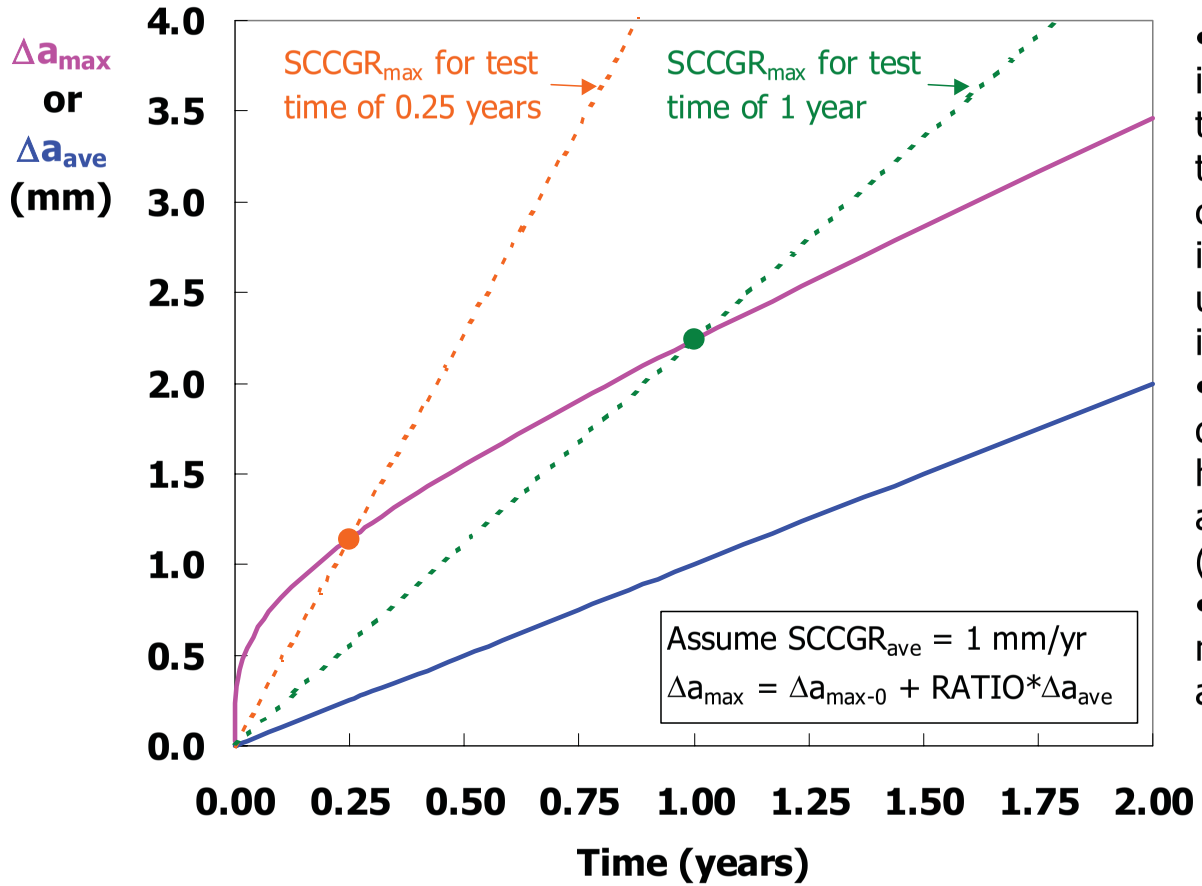
Max./Ave. Ratio Decreases as the Crack Grows



- Crack fronts often uneven
- Cracking initially occurs as discrete 'fingers', then becomes more uniform

- To broaden the ratio data set, some data were used that do not pass the screening criteria
- LM: Δa_{max} is maximum SCC depth at any location along the crack front
- Mills: Δa_{max} is maximum SCC depth at the DE measurement locations (ASTM E813)

Maximum SCCGR Depends on Test Duration



- Assumes no incubation time, or that the data are corrected for incubation time using *in-situ* instrumentation
- All SCCGR data reported herein are average rates ($SCCGR_{ave}$)
- Also report the maximum-to-average ratio

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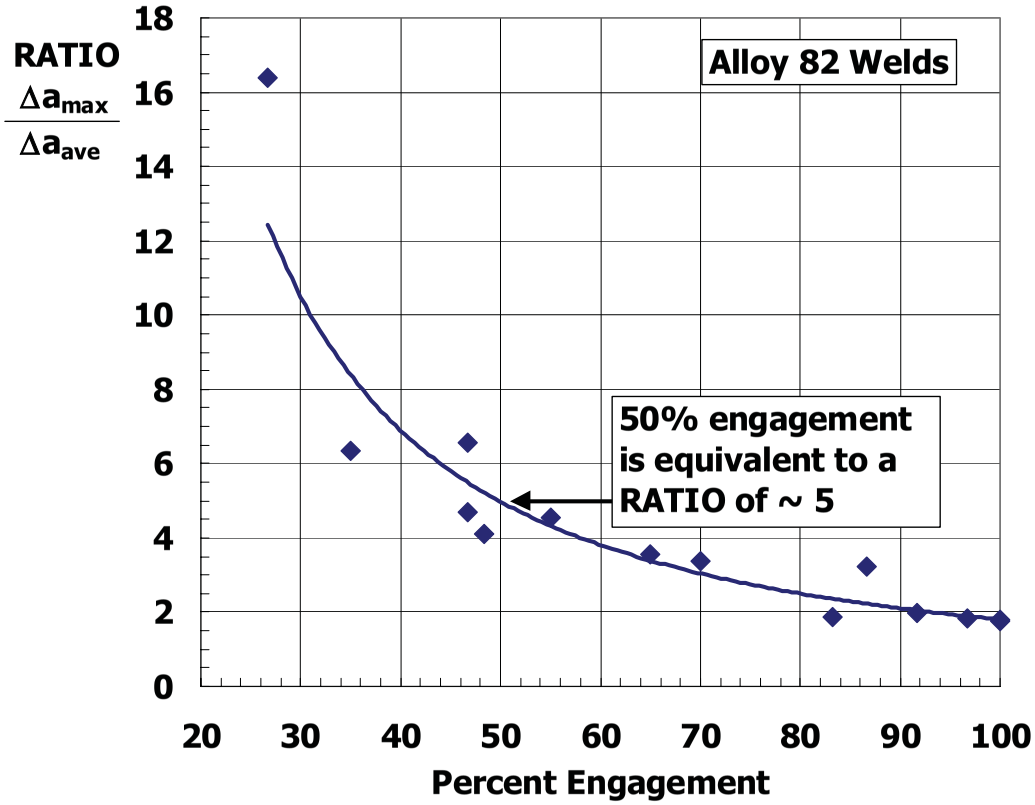
Use RATIO to Infer % Engagement



- Some of the data shown in this plot did not meet the screening criteria

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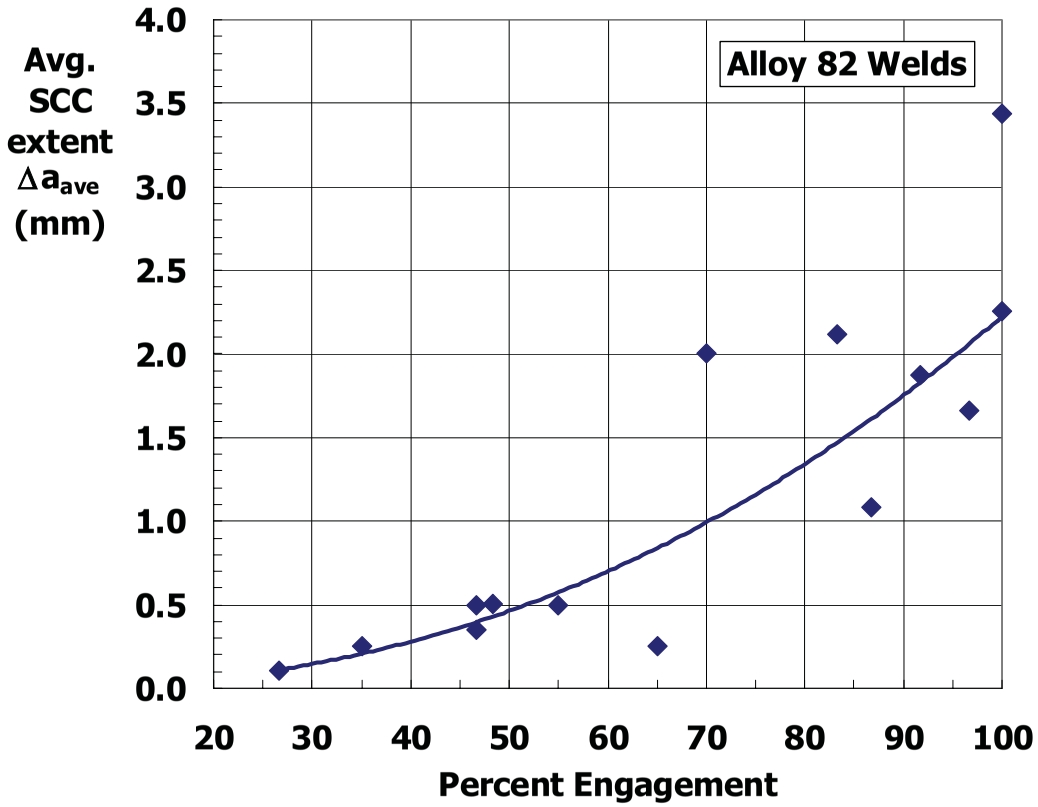
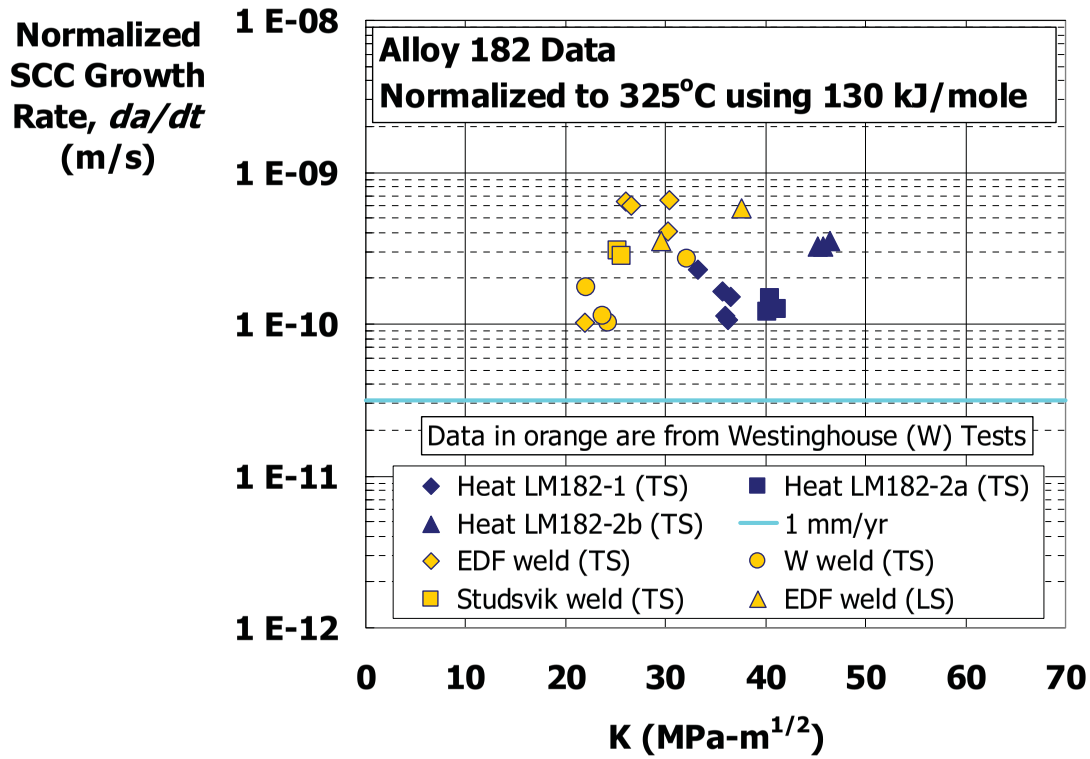
Use SCC Extent to Infer % Engagement



- Some of the data shown in this plot did not meet the screening criteria

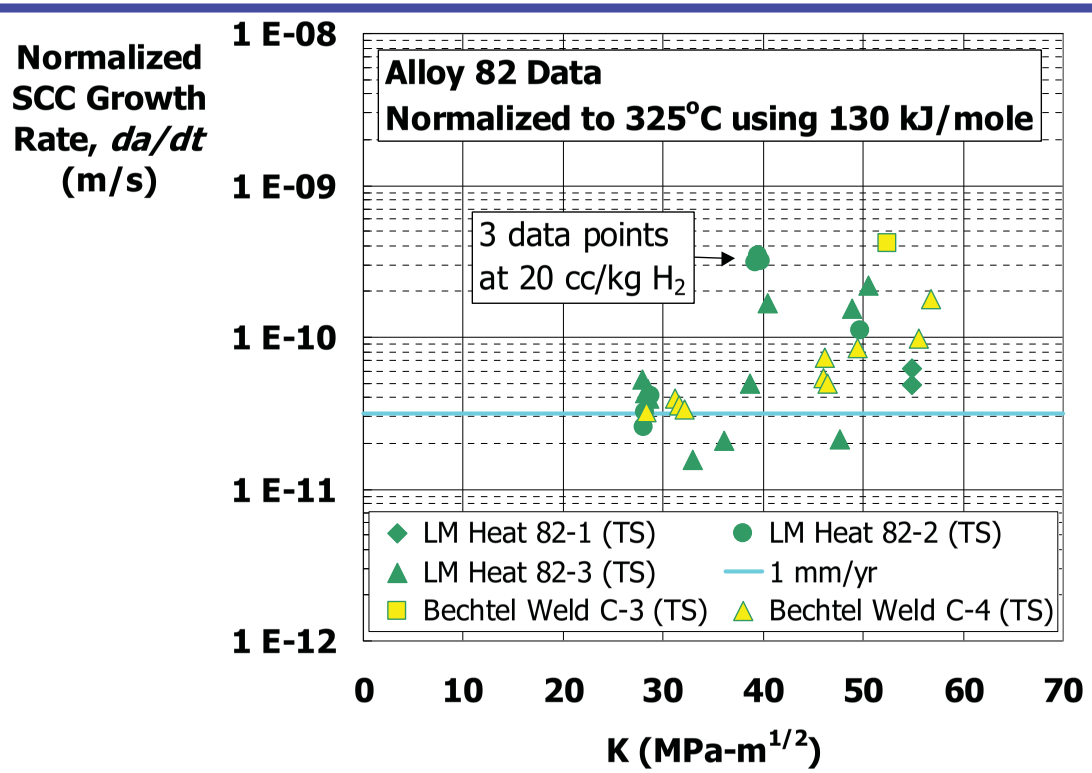
Alloy 182 SCCGRs and Comparison to Other Data



- 3 Westinghouse data points screened due to $\Delta a_{ave} < 0.2$ mm
- LM refers to Lockheed Martin

- Compare to published data where *average* SCCGR was reported (fairest comparison)
- Westinghouse data - 3 welds (W, EDF, Studsvik); carbon 0.025 to 0.053 wt%
- All root-to-crown growth; LM - 35 or 40 scc/kg H_2, Westinghouse (W) - 25 scc/kg H_2

Alloy 82 SCCGRs and Comparison to Other Data



- Compare to published data where *average* SCCGR was reported (fairest comparison)
- All root-to-crown growth; LM data 20 or 40 scc/kg H_2; Bechtel data 40 to 60 scc/kg H_2
- Some of the variability in heat LM82-2 caused by H_2 (highest SCCGRs at 20 scc/kg H_2)

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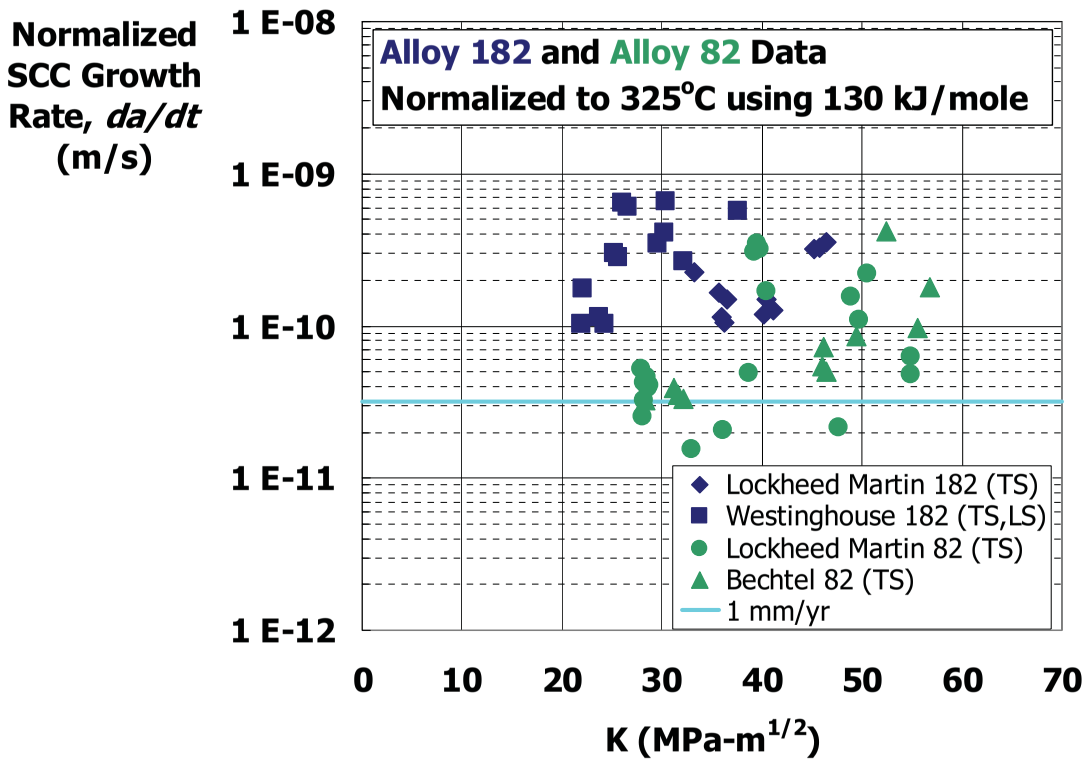
Comparison of Alloy 182 and Alloy 82 - SCCGRs



- Alloy 182 SCCGRs are faster on average (~15 *vs*. 20 %Cr, weld process, carbon levels)
  - May be appropriate to model 182 and 82 using an offset
- Insufficient data to identify and/or quantify an SCCGR threshold

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Empirical Modeling - Evaluate Three Model Forms

- All three forms are exponential in temperature, power law in K_I
- Use data from both 182 and 82 to determine K_I, 1/T dependencies
  - Not enough data to determine independently (most of 182 data at ~ 325°C)
  - Treat with an offset since the two weld metals appear to have different rates
- General model form:

$$\frac{da}{dt} = A \cdot B_{material} \cdot \left(\frac{K_I - K_{th}}{K_o} \right)^{\beta} \cdot exp\left[-\frac{Q}{R \cdot T} \right]$$

- Model 1: $K_{th} = 0$
- Model 2: $K_{th} = 9$
- Model 3: $K_{th} = 9$, β fixed at 1.16 (Scott form)
  - K_o is a normalizing value (1 MPa√m)

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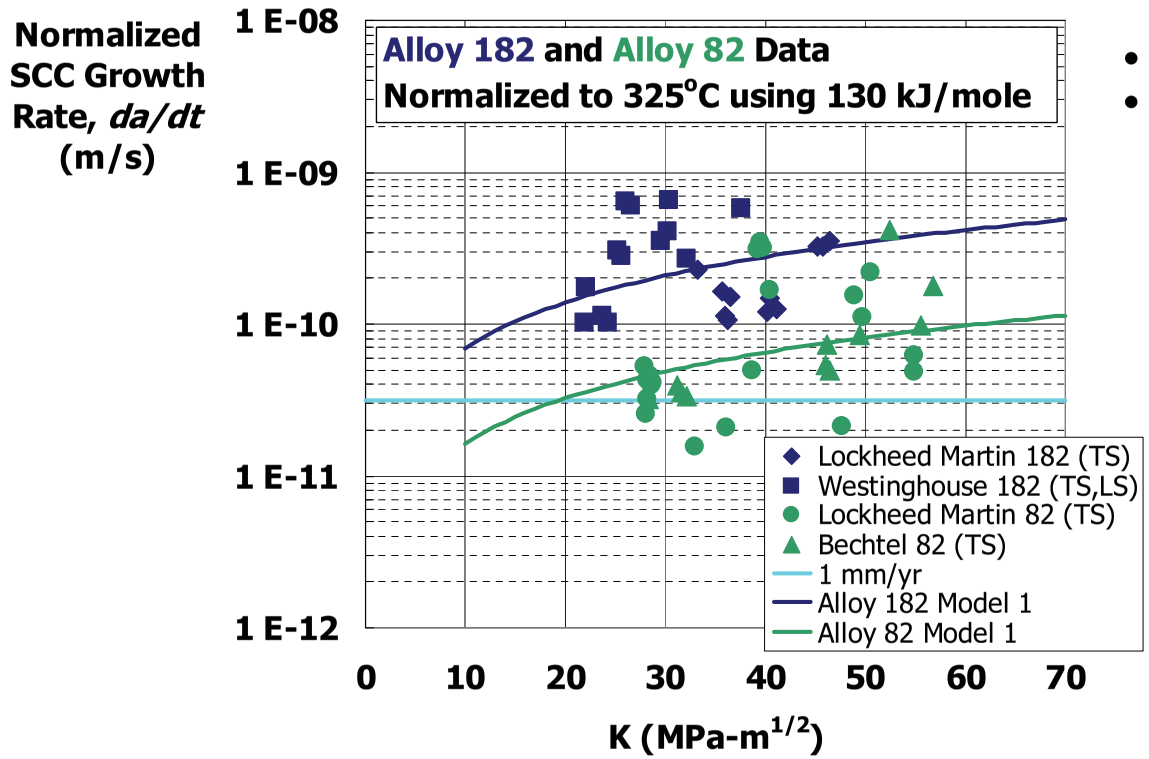
Model 1: No Threshold, K Dependence not Fixed



- $R^2 = 0.550$
- Std. Dev. = 0.760

$$\frac{da}{dt} = 14.76 \cdot \left\langle \begin{matrix} 4.272 \\ 1.000 \end{matrix} \middle| \begin{matrix} 182 \\ 82 \end{matrix} \right\rangle \cdot \left(\frac{K_I}{1} \right)^{0.999} \cdot exp\left[-\frac{148{,}300}{8.314 \cdot T} \right]$$

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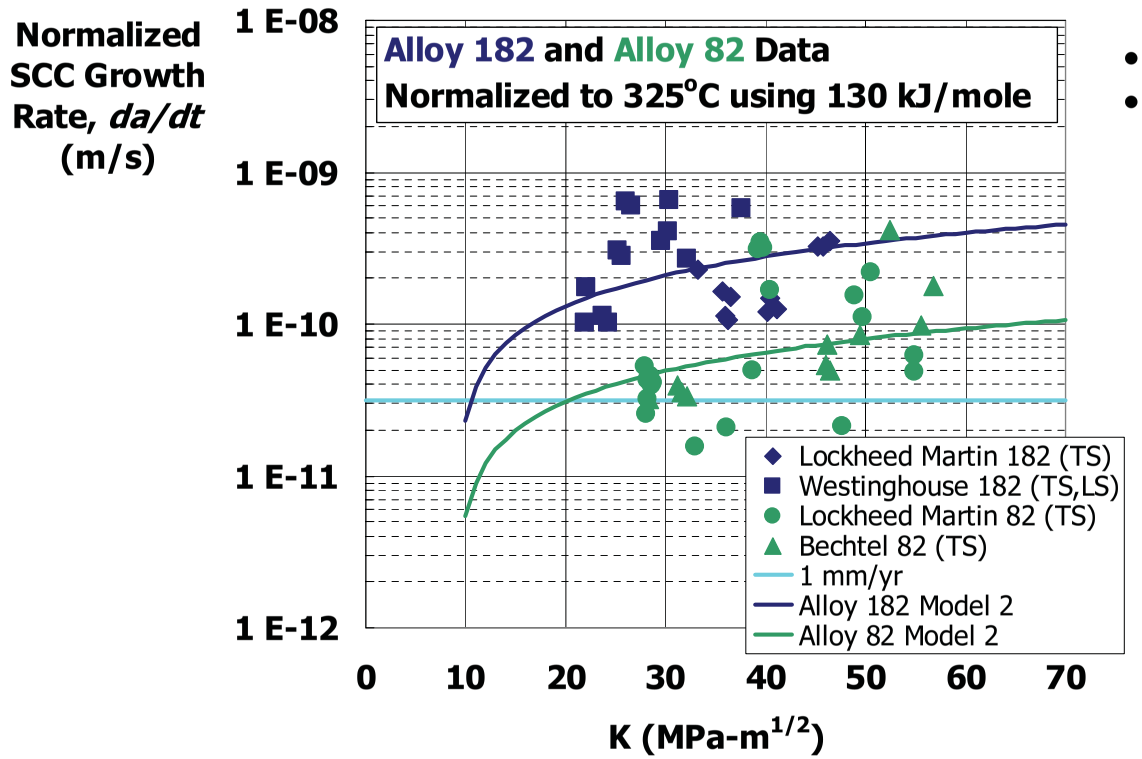
Model 2: Threshold (K_{th} = 9), K Dependence not Fixed



- R^2 = 0.549
- Std. Dev. = 0.760

$$\frac{da}{dt} = 71.24 \cdot \left\langle \begin{matrix} 4.267 \\ 1.000 \end{matrix} \middle| \begin{matrix} 182 \\ 82 \end{matrix} \right\rangle \cdot \left(\frac{K_I - 9}{1} \right)^{0.723} \cdot exp\left[-\frac{150{,}200}{8.314 \cdot T} \right]$$

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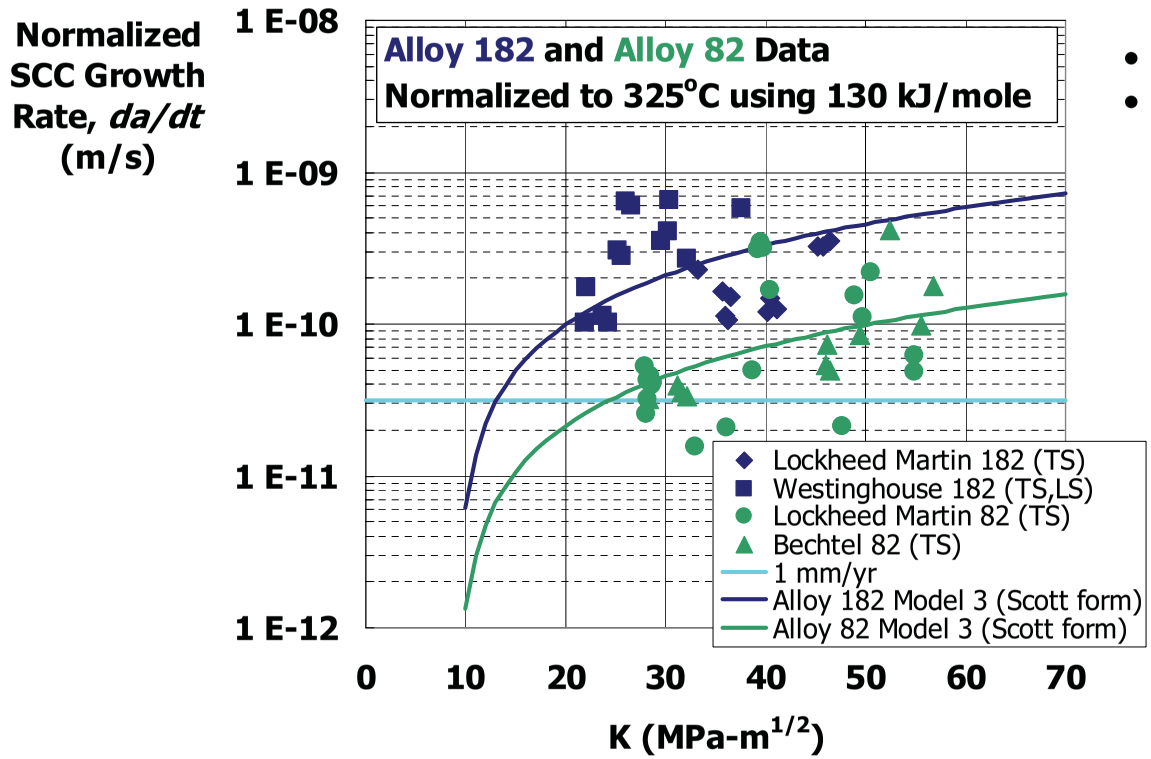
Model 3: Threshold (K_{th} = 9), K Dependence = 1.16



- R^2 = 0.520
- Std. Dev. = 0.764

$$\frac{da}{dt} = 5.028 \cdot \left\langle \begin{matrix} 4.618 \\ 1.000 \end{matrix} \middle| \begin{matrix} 182 \\ 82 \end{matrix} \right\rangle \cdot \left(\frac{K_I - 9}{1} \right)^{1.16} \cdot exp\left[-\frac{127{,}900}{8.314 \cdot T} \right]$$

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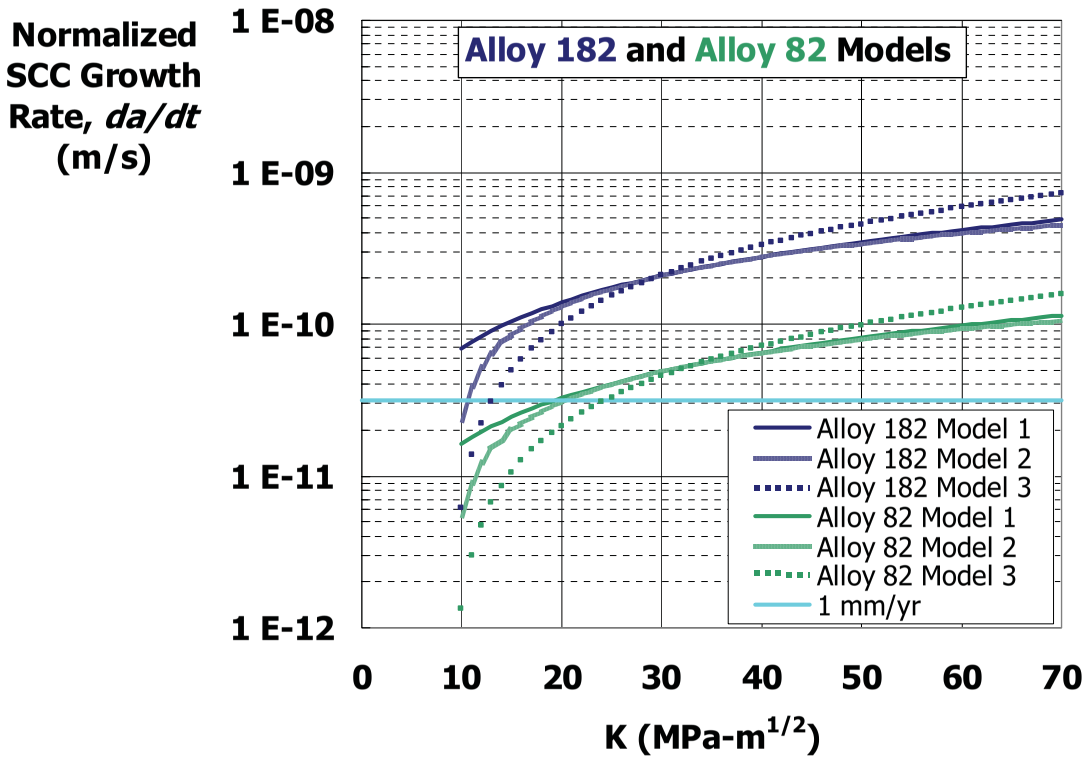
Comparison of Models 1, 2, and 3



- Models 1 & 2 very similar for $K_I \geq 20$ MPa√m (important region for flaw disposition)
- Model 3 (Scott form) within ≤ 1.5X of other models for 20 MPa√m ≤ K_I ≤ 70 MPa√m

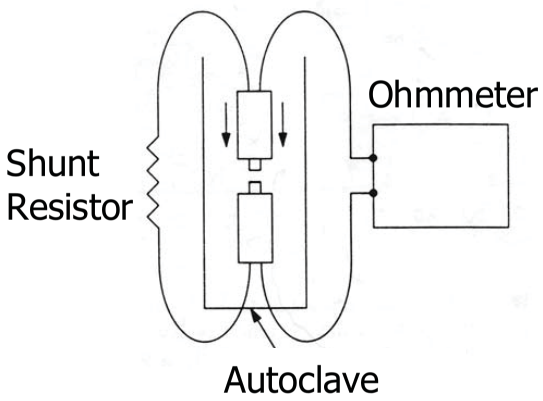
Model Summary

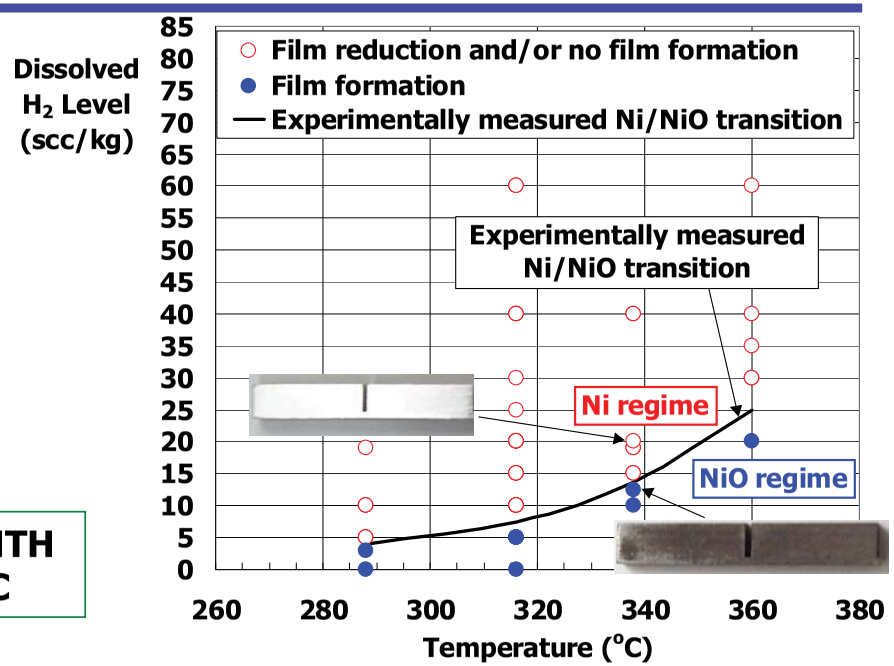
- Models 1 and 2 provide a viable approach for correlating the data
  - Model 3 is also reasonable
- Q_{SCCGR} values are 128 to 150 kJ/mol
- K dependencies are ~ 0.7 to 1.0 (when not forced to 1.16)
  - Somewhat lower than Scott model, but not very different than 1.16
  - K dependence of Alloy 182 may be lower than that of Alloy 82
    - EDF/ETH/CEA $SCCGR_{max}$ data for Alloy 182 suggest a low K-dependence ($K^{0.1}$)
- Weld variability is an issue for all three models (R^2 values ~ 0.55)
  - Attempted to collapse the data using a K-1/T interaction:

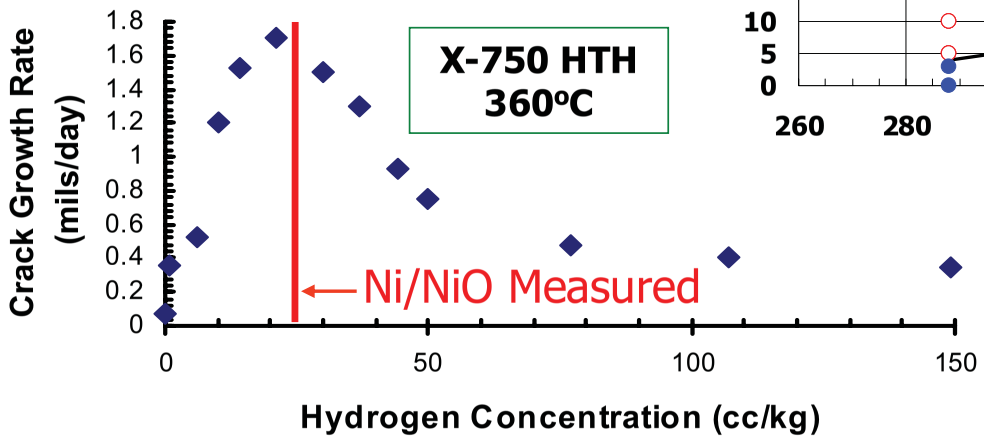
$$\frac{da}{dt} = A \cdot B_{material} \cdot \left(\frac{K_I - K_{th}}{K_o} \right)^{\beta} \cdot exp\left[-\frac{Q}{R \cdot T} \right] \cdot exp\left[\frac{C \cdot \left(\left(K - K_{th} \right) / K_o \right)}{R \cdot T} \right]$$

    - No measureable improvement in either R^2 or standard deviation
    - Not the only possible equation form to describe K-1/T interactions
  - Normalizing the data for aqueous hydrogen may help reduce scatter

Effect of Aqueous H_2 Concentration - Prior Work



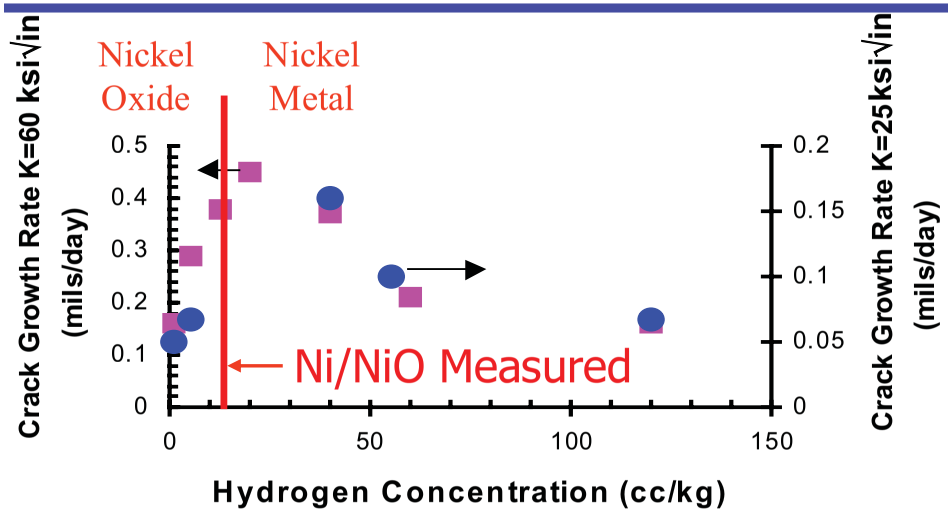




- Similar behavior noted for A600, X-750 AH (Morton, Attanasio)
- Also studied by Scott, Cassagne, Economy, Totsuka, Andresen, *etc.*

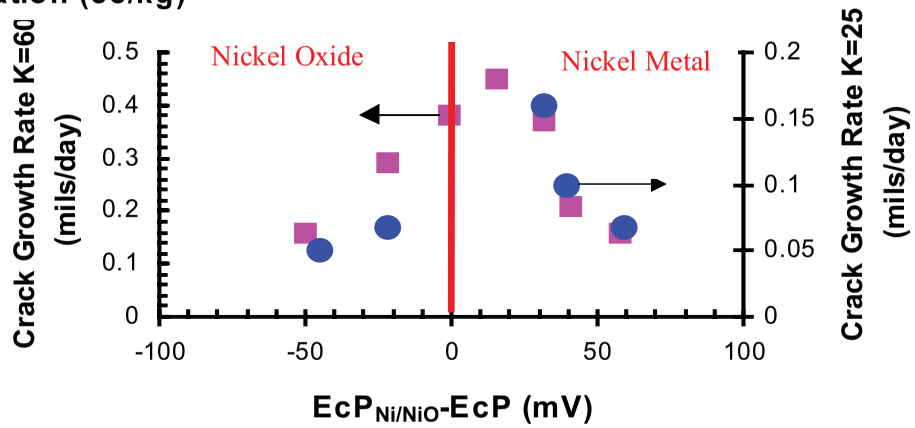
LOCKHEED MARTIN

Effect of Aqueous H_2 Concentration - Prior Work



Wrought Alloy 600
K=66 & 27 MPa√m
(K=60 & 25 ksi√in)
338°C

- Correlations for H_2 effects on SCCGR have been presented for A600, X-750 AH, X-750 AH (Morton)
  - Use EcP *vs.* $EcP_{Ni/NiO}$ as correlating parameter
  - Measure EcP via Pt or YSZ/Fe-Fe_3O_4 electrode



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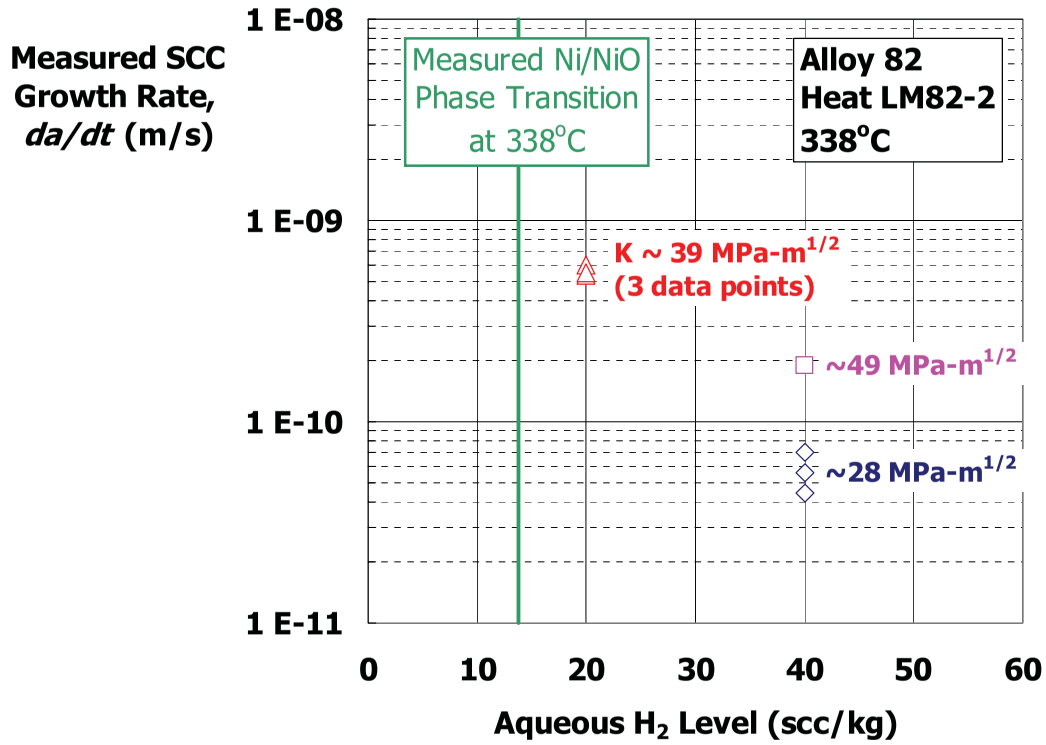
Effect of Aqueous H_2 Concentration - Alloy 82



- SCCGRs increase as measured Ni/NiO phase transition is approached
- 20 cc/kg H_2 specimens are bolt loaded - H_2 effect confirmed using active load specimens
- Developing a weld metal correlation so that data can be normalized for H_2 effects

Conclusions

- Ring-loaded specimens can generate efficient, viable SCCGR data
- Crack shape evolution well-described by the maximum/average ratio
- SCCGR data can be reasonably reported using $SCCGR_{ave}$ + RATIO
- LM data are consistent with $SCCGR_{ave}$ data from other researchers
- Three empirical model forms were evaluated - all seem reasonable
  - Data scatter leads to an appreciable standard deviation in all 3 cases
- Aqueous H_2 level influences SCCGR - more quantification is desirable

Acknowledgements

- Maureen Schurman, Brian Gain, John Schisano
- Norm Perazzo Kerry Cotterell, Bruce Furbeck (CSLCT specimens)
- Bill Mills (Bechtel)
- Glenn White (DEI) and John Hickling (EPRI)

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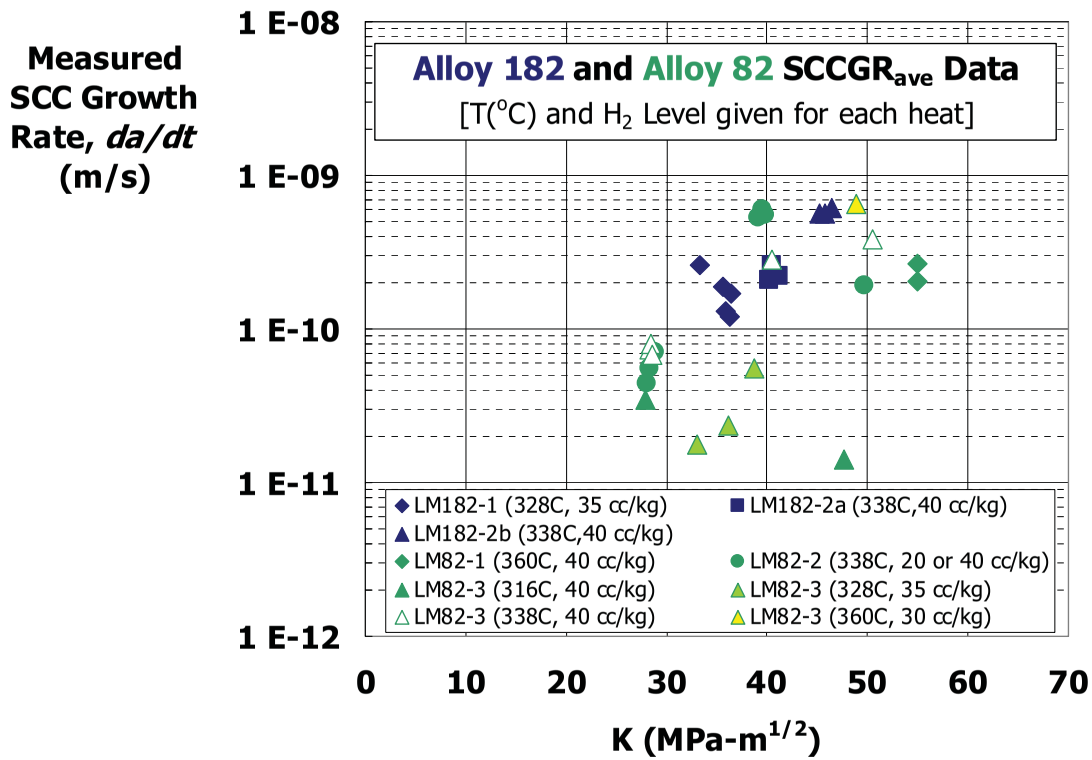
- N Totsuka, S Sakai, N Nakajima and J Mitsuda, CORROSION/2000.
- PM Scott, Research Topical Symposium at CORROSION/96, 1996.
- DS Morton, SA Attanasio and MA Ando, 10th Environmental Degradation Conference, August 2001.
- WJ Mills and CM Brown, Bechtel report B-T-3435, March 2002.
- S Le Hong, JM Boursier, C Amzallag and J Daret, 10th Environmental Degradation Conference, August 2001.
- G Economy, RJ Jacko and FW Pement, *Corrosion*, 43, 1987.
- T Cassagne, B Fleury, F Vaillant, O de Bouvier & P Combrade, 8th Environmental Degradation Conference, August 1997.
- W Bamford and J Foster, EPRI Report MRP-21, June 2000.
- SA Attanasio, DS Morton, MA Ando, NF Panayotou & CD Thompson, 10th Environmental Degradation Conference, August 2001.

Appendix - Measured SCCGR Data (Not Normalized)



- TS orientation (all data)
- K is reported as the average K value during a test
- No unload-reload cycles
- LM (Lockheed Martin) heats 182-2a and -2b have a different yield strength (YS)
  - 454 and 530 MPa, respectively - due to differences in processing
- Room temperature YS for other heats:
  - 182-1: 503 MPa
  - 82-1: 439 MPa
  - 82-2: 465 MPa
  - 82-3: 460 MPa

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Appendix - Compare LM Data to Screening Criteria

- All data conform to the following:
  - Single condition tests
  - Data based on post-test destructive examination
  - Careful autoclave chemistry control
  - No periodic unload-reload
- ASTM E647 Specimen Size Criteria
  - 4 data points rejected
- Reject if percent engagement is <50% or if SCC extent < 0.2 mm
  - 14 data points rejected
- Focus on the data that pass the screening criteria

Appendix - Material Composition

Heat	Ni	Cr	Fe	C	Mn	Cu	Si	Co	S	P	Ti	Nb +Ta
LM182-1	Bal	15.0	7.2	0.03	5.9	0.00	0.7	0.03	0.005	N/A	0.5	2.0
LM182-2	68.7	15.1	7.0	0.02	6.0	0.00	0.8	0.03	0.005	0.01	0.5	1.9
LM82-1	73.4	17.5	1.7	0.047	3.14	0.05	0.26	0.04	0.005	N/A	0.17	3.64
LM82-2	73.5	19.0	1.46	0.045	2.80	0.05	0.12	0.04	0.001	0.013	0.30	2.32
LM82-3	71.5	20.6	1.27	0.045	2.81	0.31	0.14	0.04	0.002	0.012	0.35	2.44

Influence of temperature on Primary Water Stress Corrosion Cracking of Alloy 600 Weld Metals

Yoshito Nishikawa, Nobuo Totsuka and Koji Arioka

Institute of Nuclear Safety System, Inc.

Background

- PWSCC were found in Alloy 182 in PWR nuclear power plants.

- There are some studies on Alloys 82 and 182. But a few studies about influence of temperature and susceptibility of heat affected zone (HAZ).

Purpose

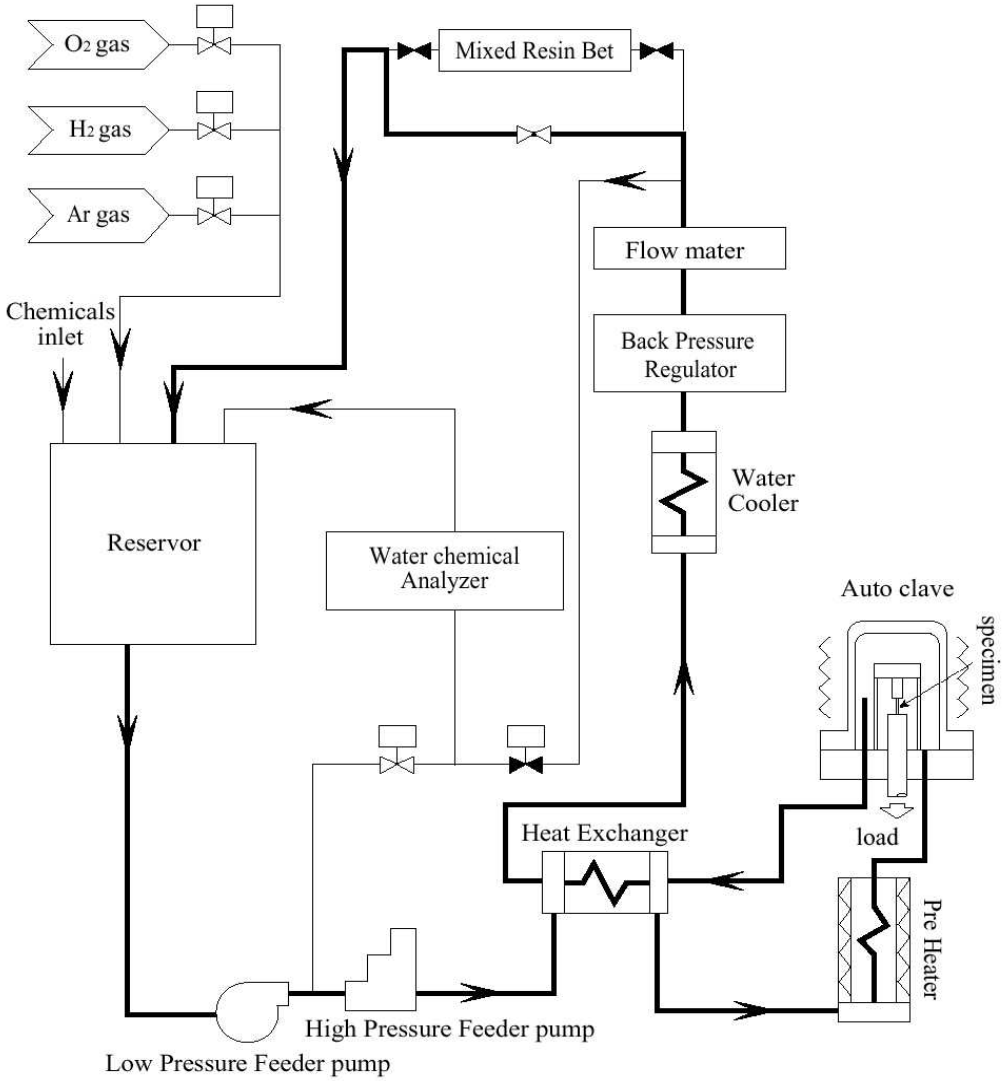
- To clarify the difference of the susceptibility on PWSCC between Alloys 82 and 132 (modified metal of 182).

- To clarify the difference of the susceptibility on PWSCC between weld metal and HAZ.

Chemical Compositions and Mechanical Properties of Weld Metals and Base Metal

Composition (wt%)	C	Si	Mn	P	S	Ni	Cr	Fe	Cu	Nb
82	0.017	0.26	2.54	0.006	0.001	72.9	17.95	3.72	0.01	1.93
132	0.030	0.30	2.10	0.009	0.002	71.5	15.40	8.50	0.01	1.88
600 (Base Metal)	0.030	0.27	0.29	0.010	0.001	72.9	16.20	-	0.05	-
182	≤ 0.10	≤ 1.0	5.0~ 9.5	≤ 0.03	≤ 0.015	≥ 59.0	13.0~ 17.0	≤ 10.0	≤ 0.50	1.0~ 2.5

Mechanical Properties	0.2% YS (N/mm^2)	TS (N/mm^2)	Elongation Rate (%)	Contraction of Area (%)
82	306	625	26.6	20.2
132	291	625	27.3	26.6
600	287	675	43.3	31.8

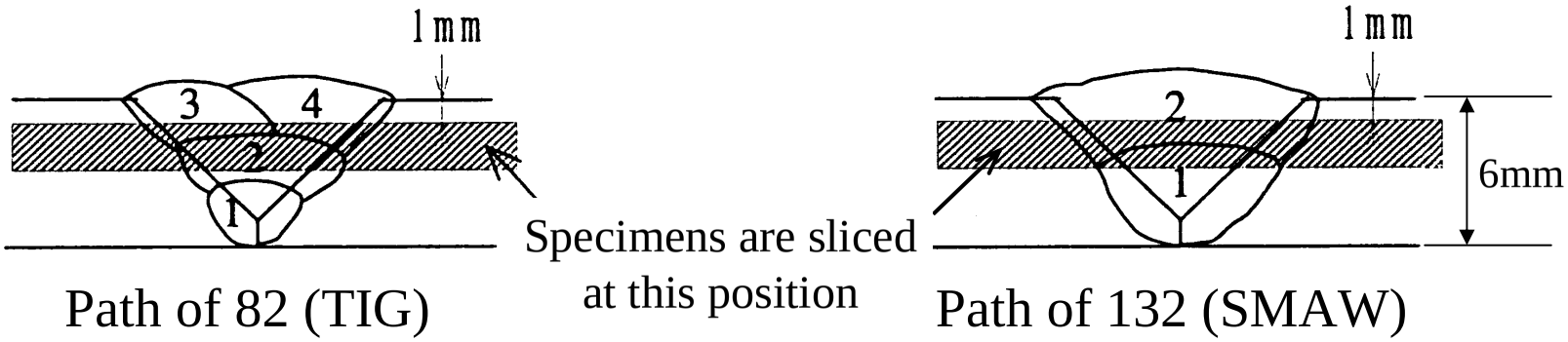


Solution
500 ppm B
2 ppm Li
2.75 ppm H_2

Temperature
360 ~ 330 °C

Strain Rate
5×10^{-7} /s
as 20 mm gauge length

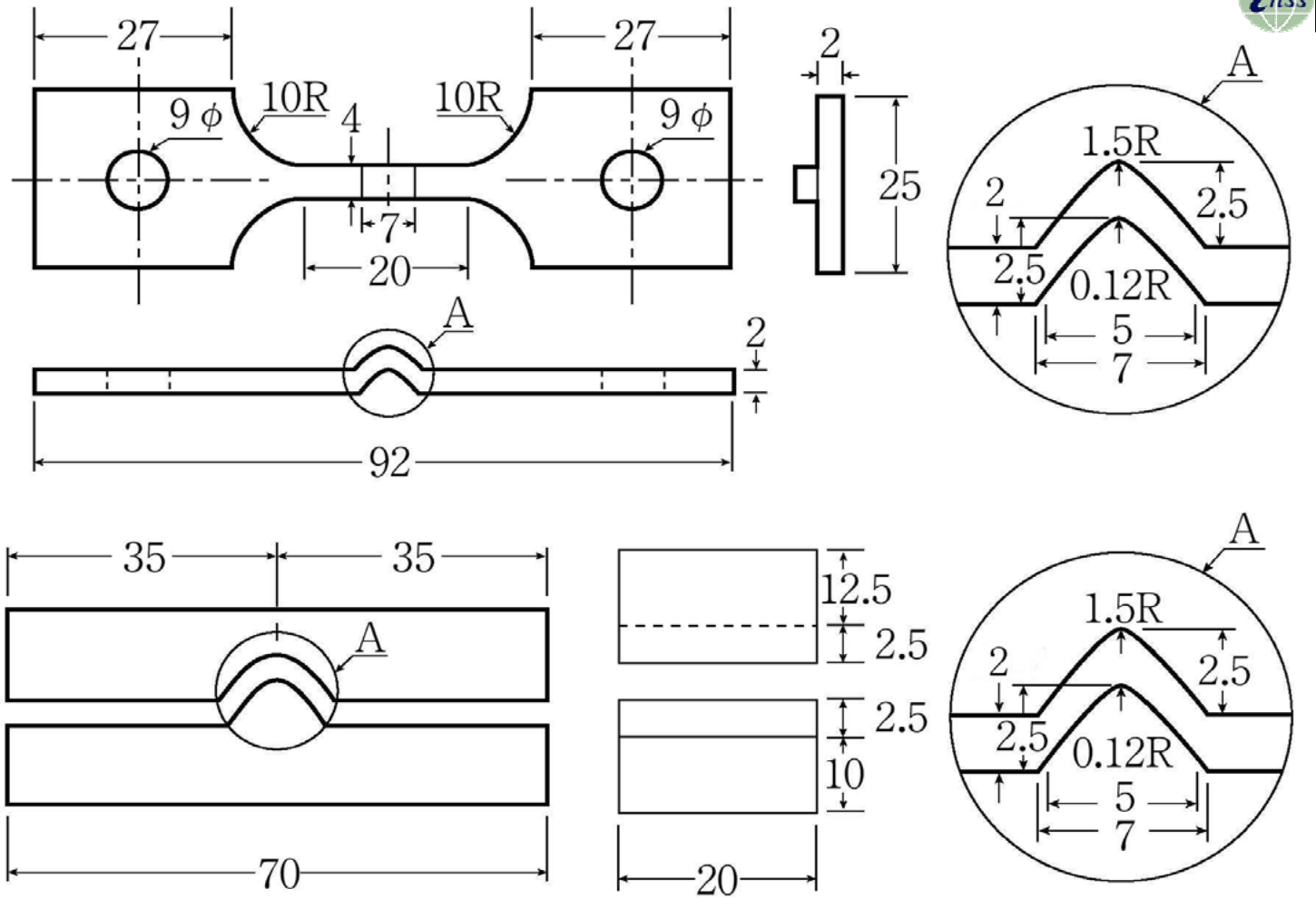
Test System and Environment



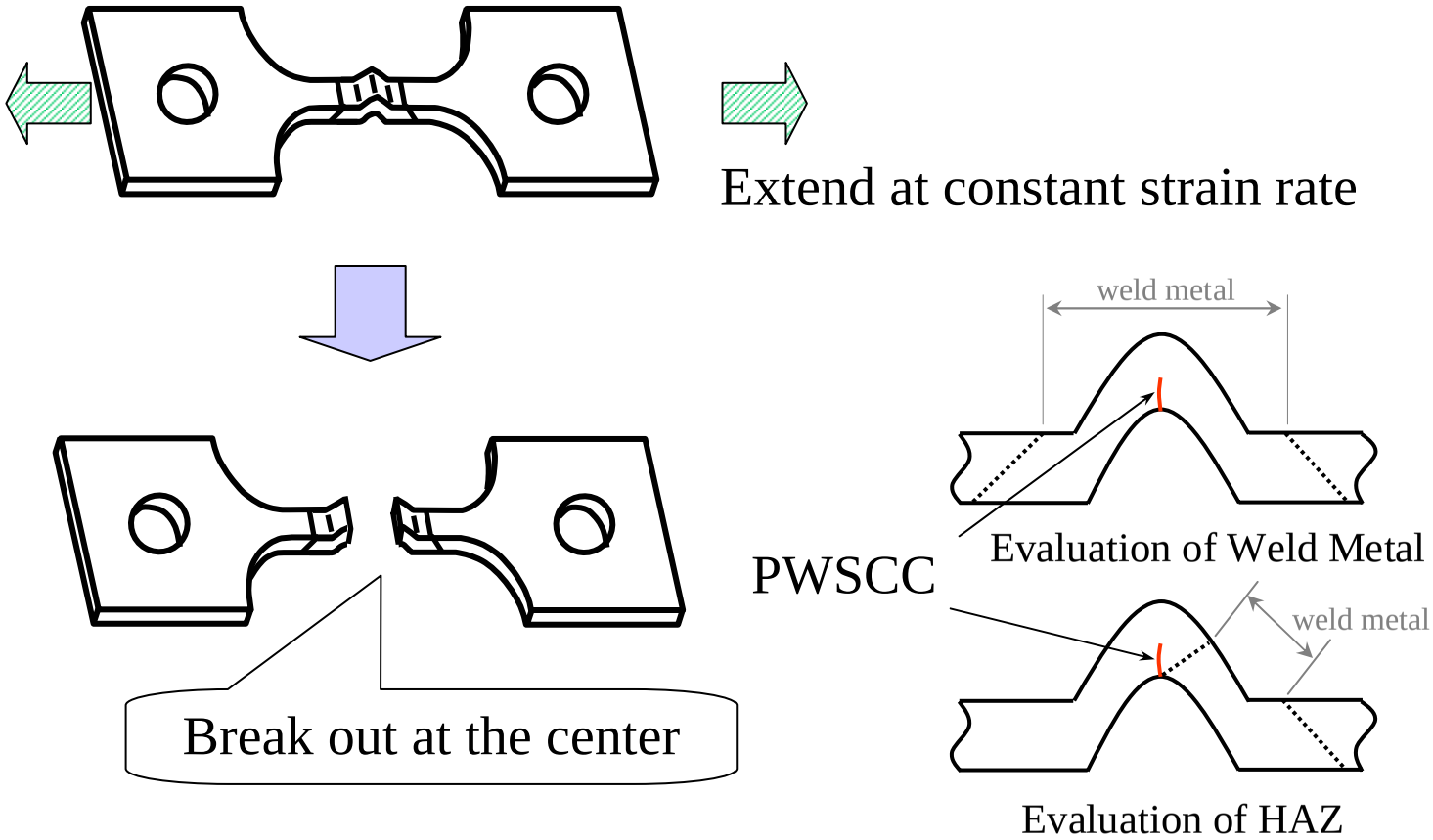
Welding heat

about 10 kJ/cm (both TIG and SMAW)

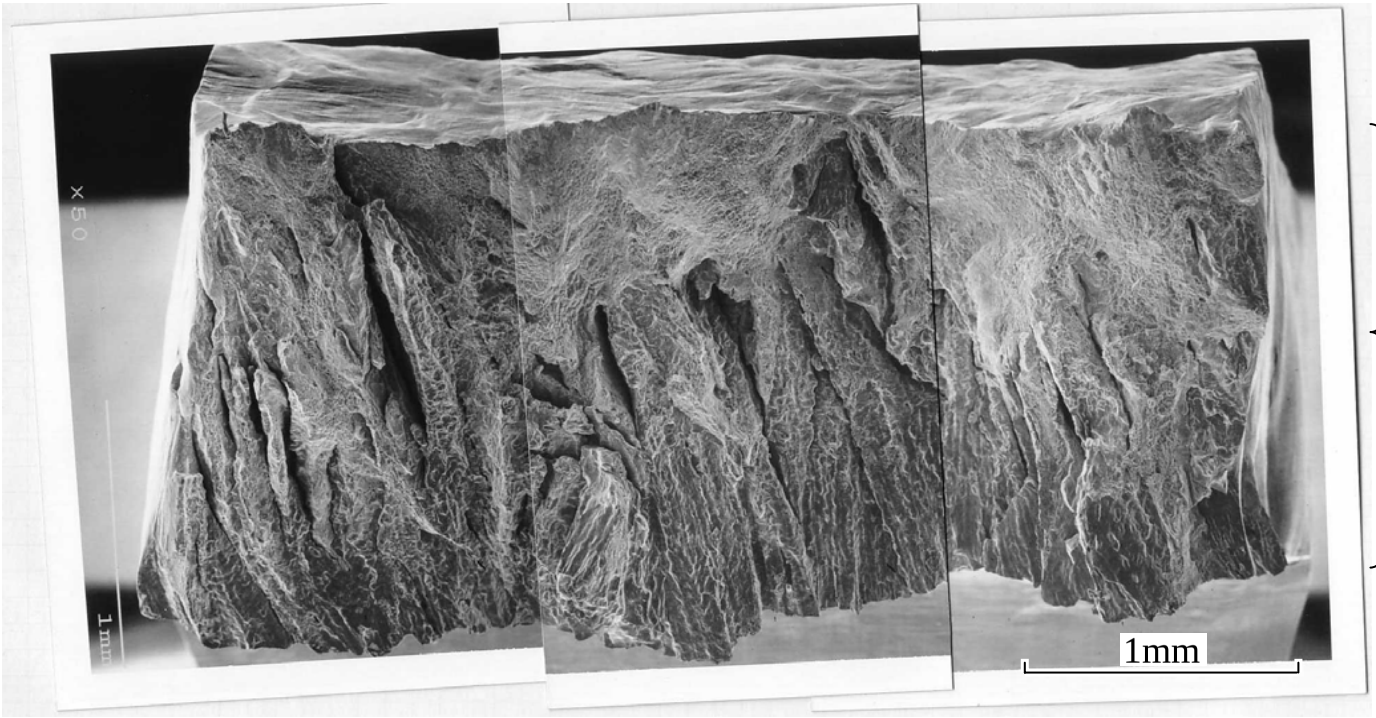
Welding conditions



Specimens Used in the Accelerated SSRT Method



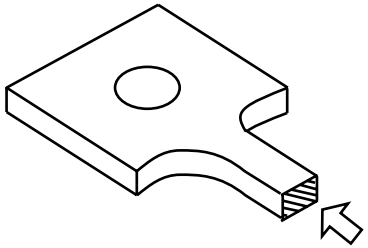
Specimen with hump



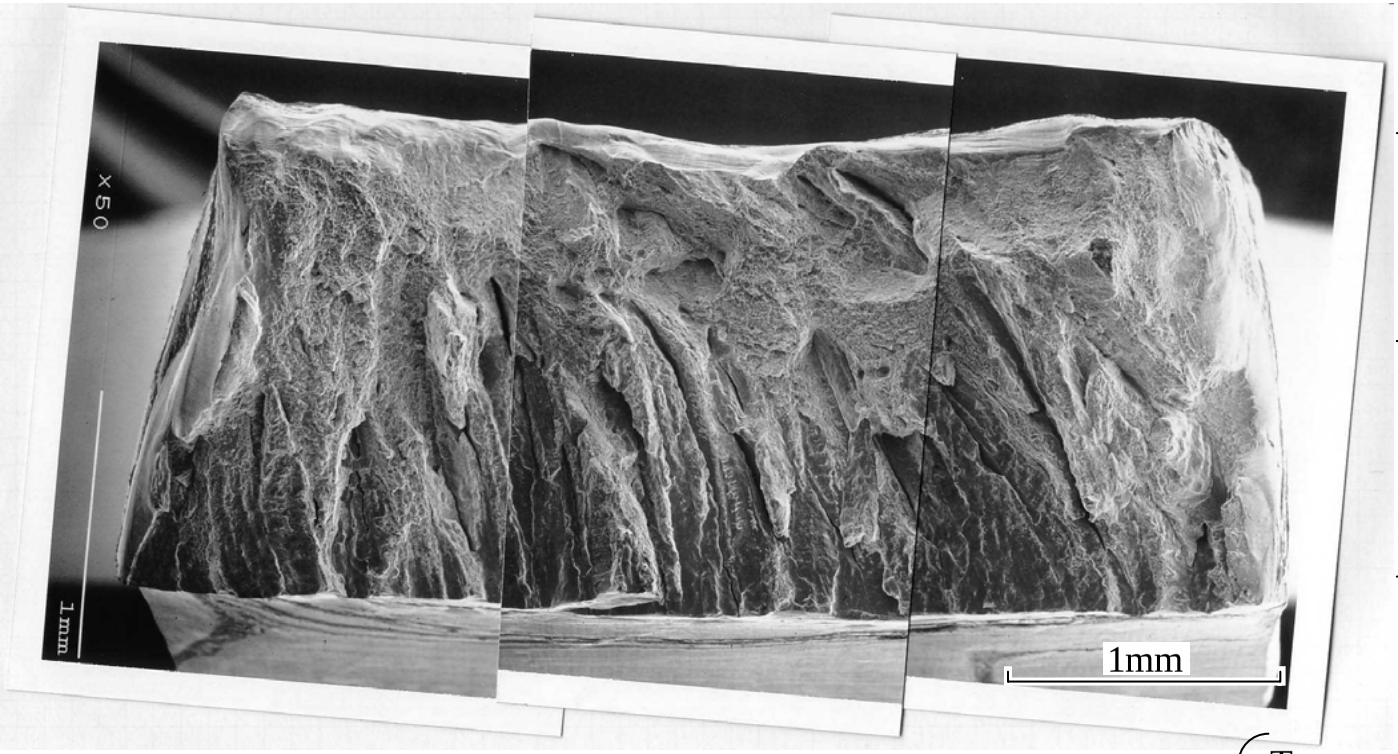
Ductile

Dendritic

Temperature : 360 °C
Strain Rate : $5\times10^{-7}s^{-1}$
Time to Failure: 67.4 hr
SCC% : 52.6 %



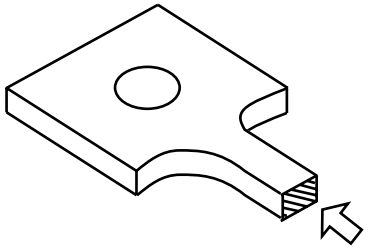
SEM photo of alloy 82



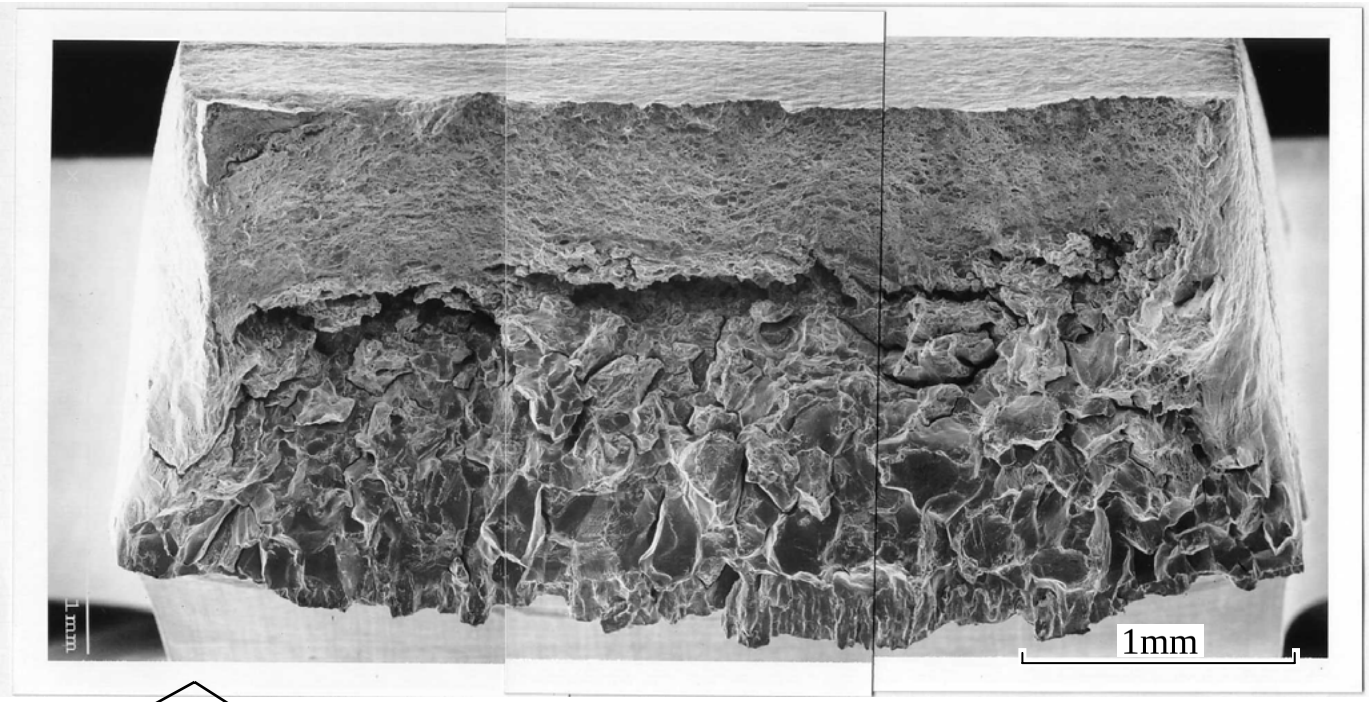
Ductile

Dendritic

Temperature : 360 °C
Strain Rate : $5\times10^{-7}s^{-1}$
Time to Failure: 73.6 hr
SCC% : 33.0 %



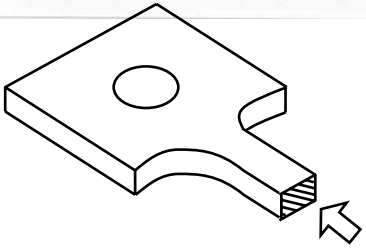
SEM photo of alloy 132



Ductile

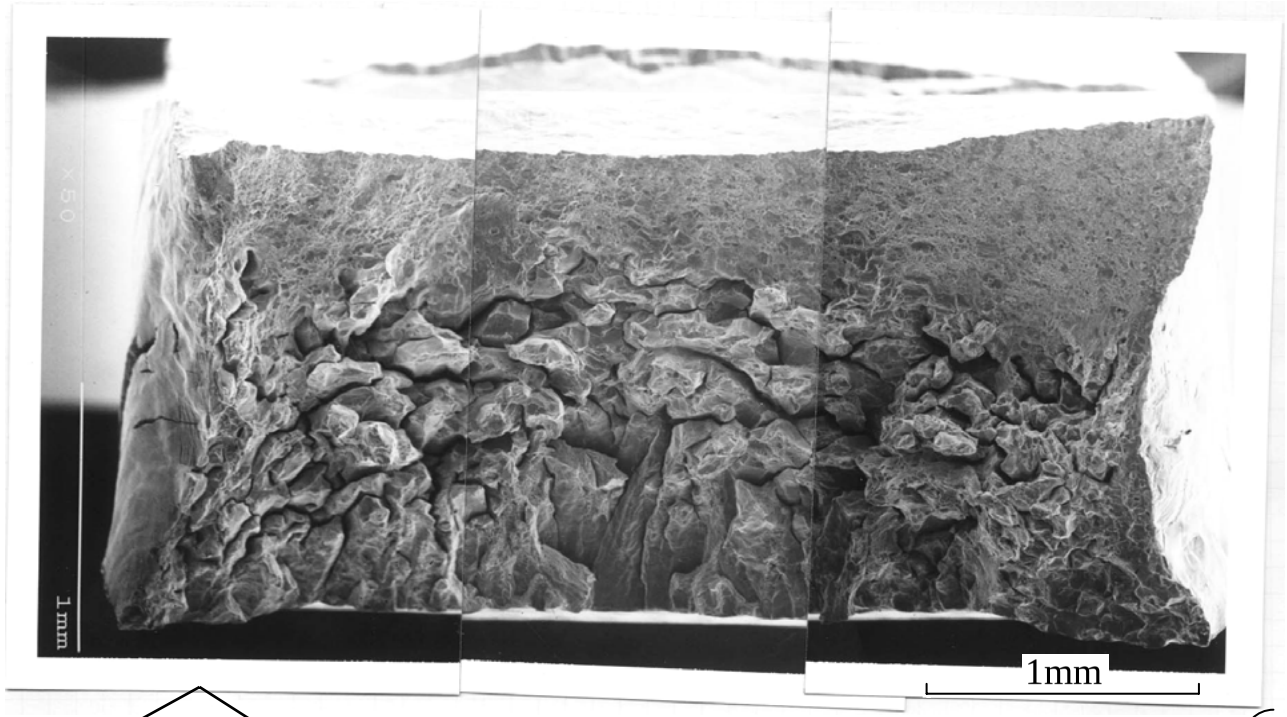
Intergranular Cracking

Dendritic



Temperature : 360 °C
Strain Rate : $5\times10^{-7}s^{-1}$
Time to Failure: 64.3 hr
SCC% : 55.9 %

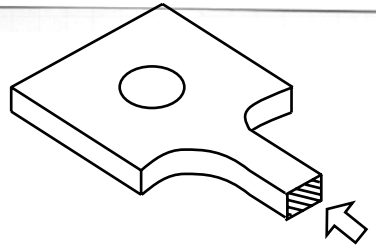
SEM photo of HAZ welded by alloy 82



Ductile

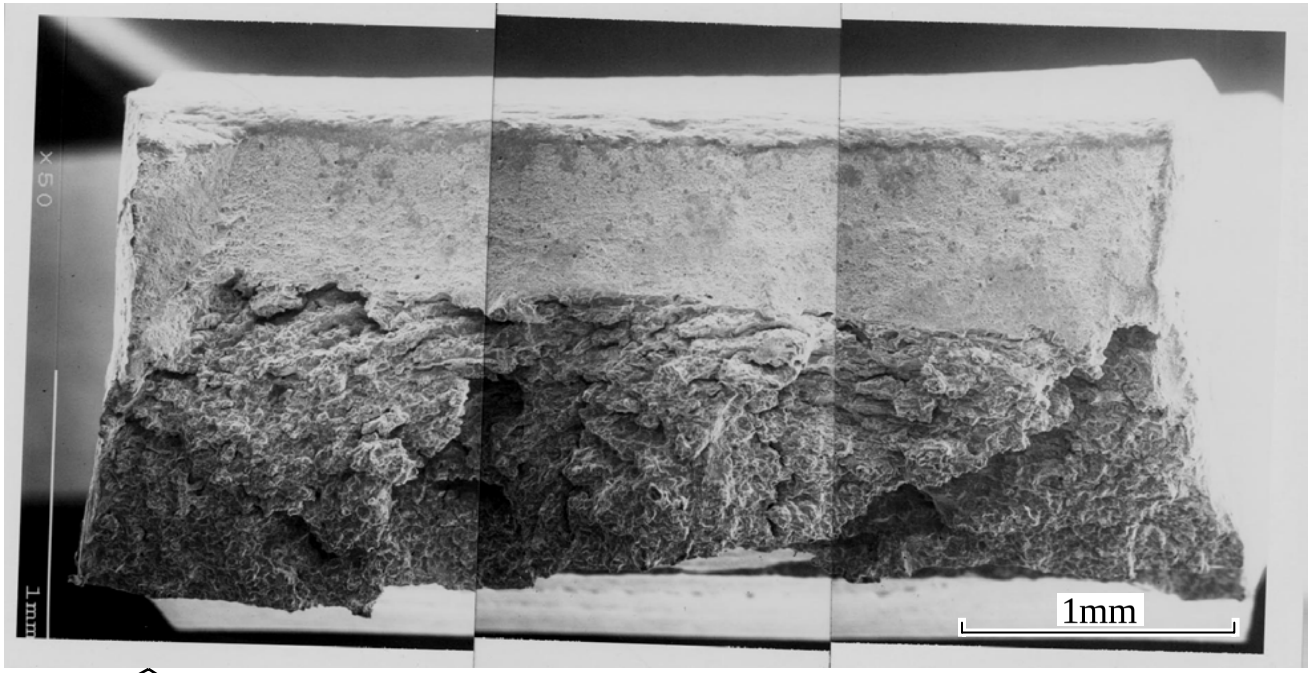
Intergranular Cracking

Dendritic



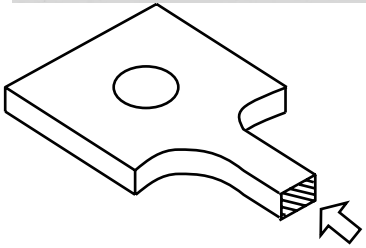
Temperature : 360 °C
Strain Rate : $5\times10^{-7}s^{-1}$
Time to Failure: 82.3 hr
SCC% : 61.8 %

SEM photo of HAZ welded by alloy 132



Ductile

Intergranular Cracking



Temperature : 360 °C
Strain Rate : $5\times10^{-7}s^{-1}$
Time to Failure: 101.9 hr
SCC% : 60.8 %

SEM photo of alloy 600 base metal

Crack Growth Rate (v)
= Plate Thickness × SCC % / Time to failure

$$\mathbf{Ea = - R \ln(v_1 / v_0) / (1/T_1 - 1/T_0)}$$

where

Ea : Apparent activation energy

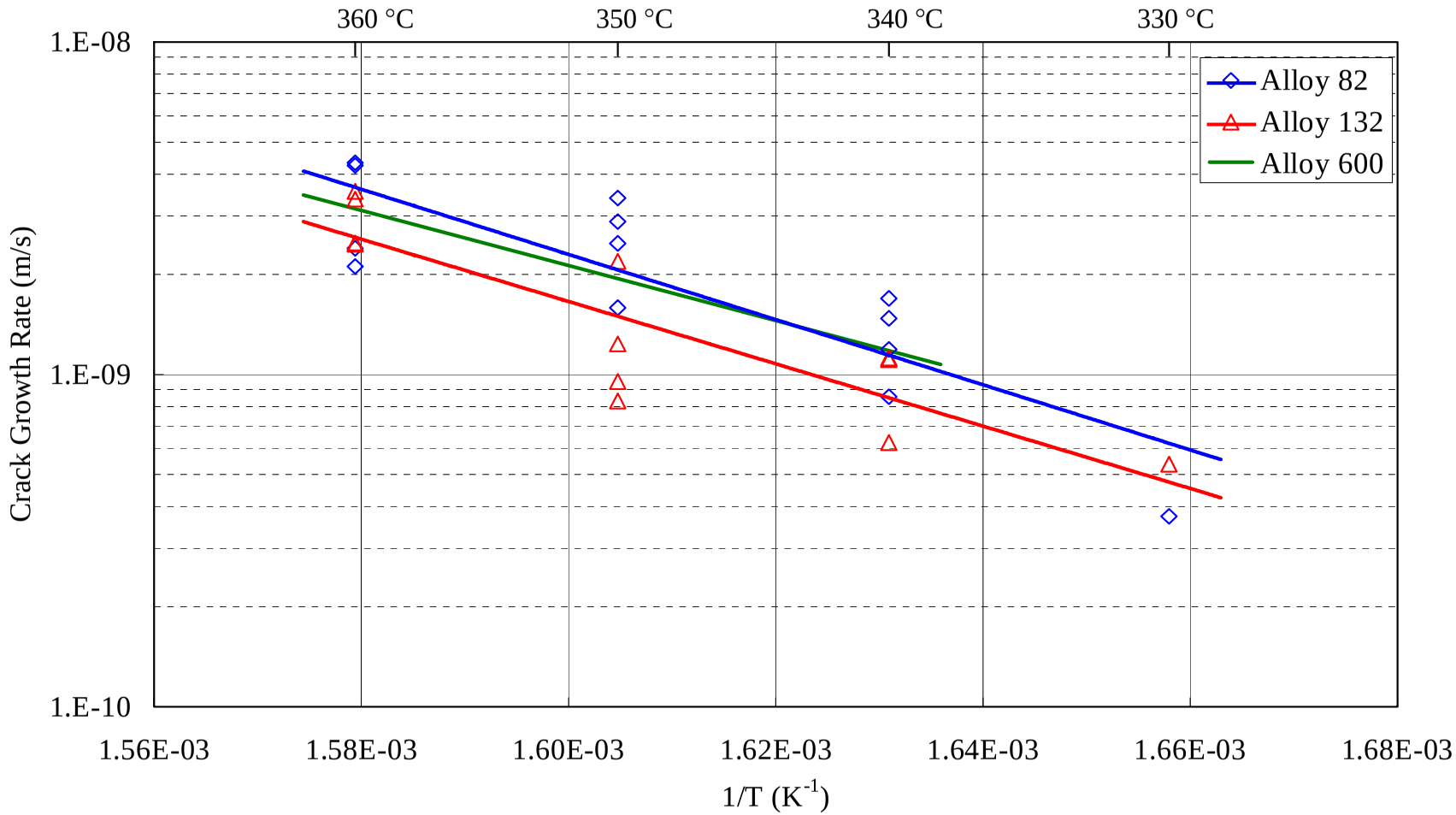
R : Gas constant = 8.3145×10^{-3} kJ/(mol·K)
= 1.9862×10^{-3} kcal/(mol·K)

T_0 , T_1 : Absolute temperature

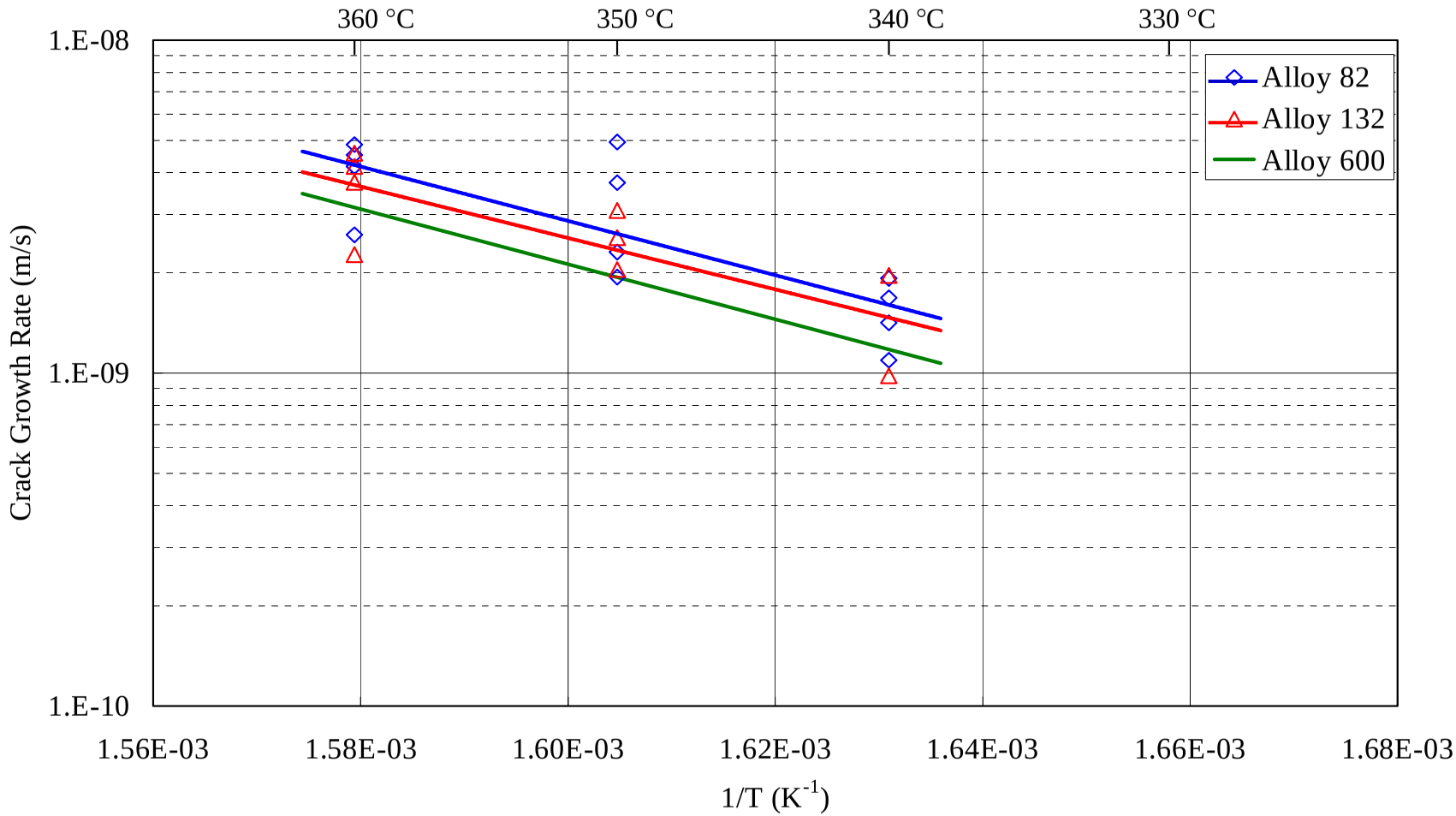
v_0 : Rate at temperature T_0

v_1 : Rate at temperature T_1

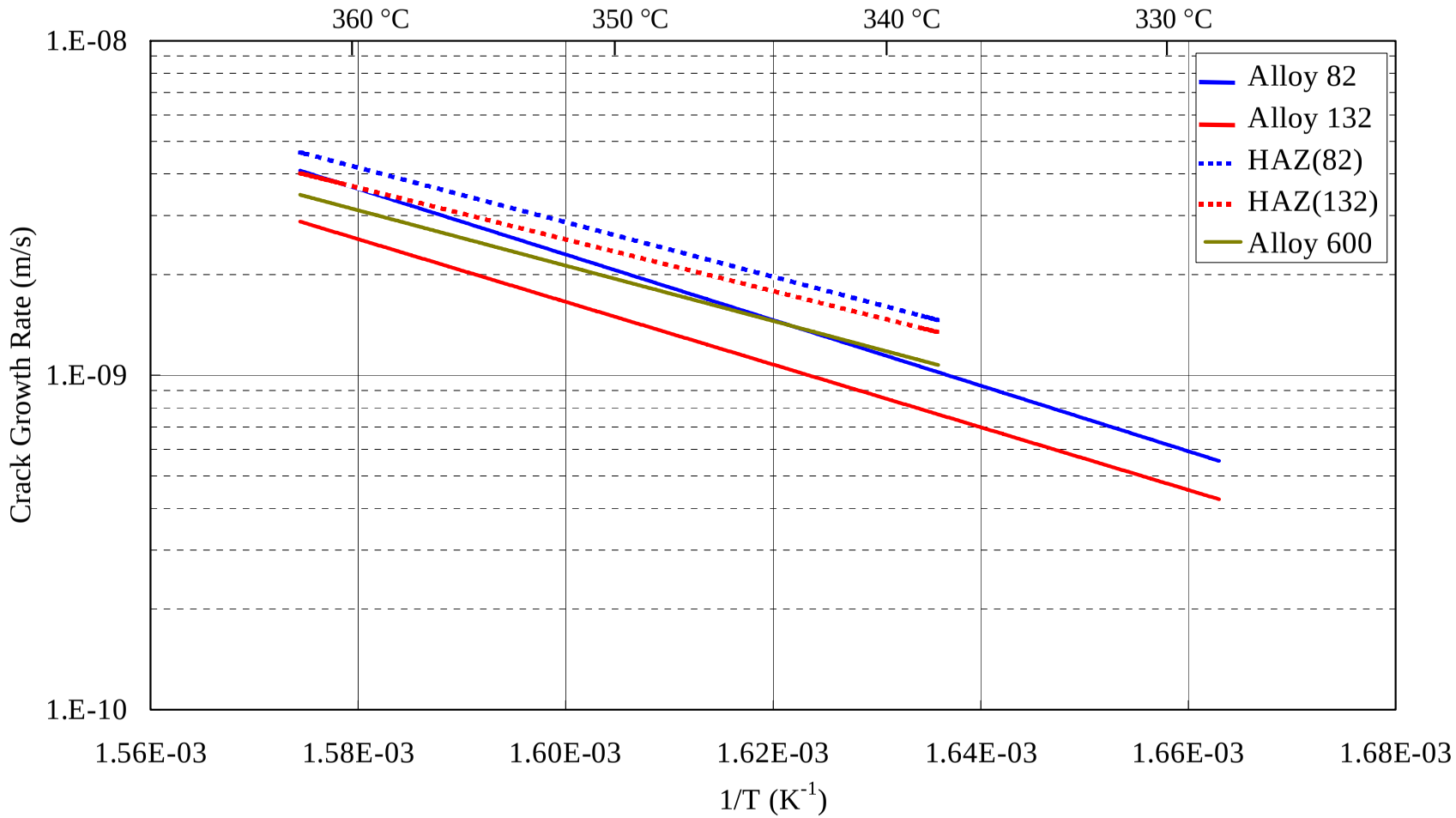
Calculation of Apparent Activation Energy by Arrhenius' Equation



Relationship between Temperature and Crack Growth Rate of Weld Metal in SSRT



Relationship between Temperature and Crack Growth Rate of HAZ in SSRT



Relationship between Weld Metal, HAZ and Base Metal in SSRT

Results

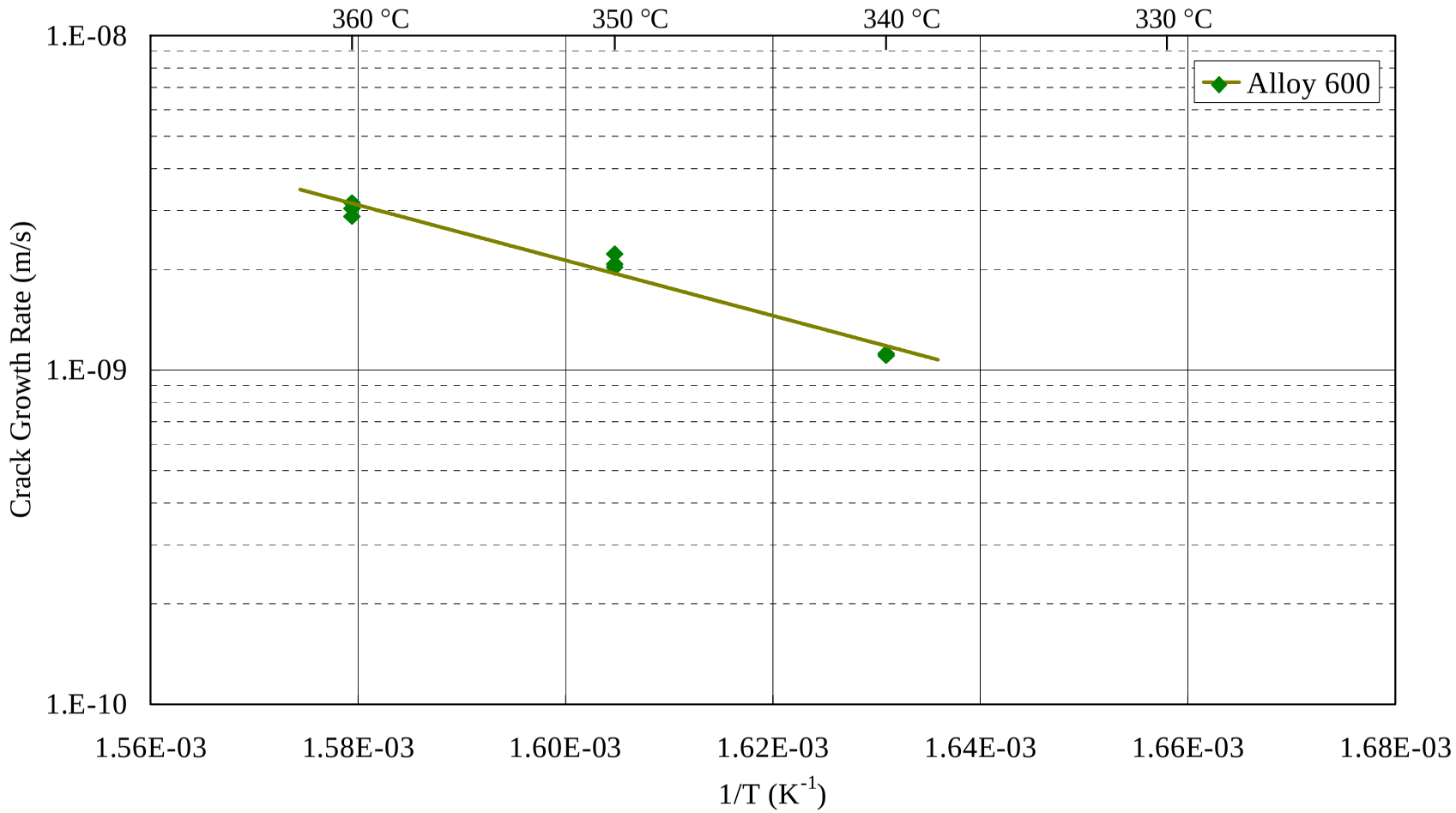
Alloy	Weld Metal or HAZ	Apparent Activation Energy
82	Weld Metal	188 kJ/mol (45 kcal/mol)
132		179 kJ/mol (43 kcal/mol)
82	Heat Affected Zone	156 kJ/mol (37 kcal/mol)
132		148 kJ/mol (35 kcal/mol)

Alloy 600 Base Metal	167kJ/mol (40 kcal/mol)

Conclusions

- The effects of temperature on PWSCC are similar between Alloys 82 and 132.

- The apparent activation energy of weld metal is a little higher than that of heat affected zone (HAZ). It seems that PWSCC on weld metal is more rarely than on heat affected zone at lower temperature.



Crack Growth Rate and its approximately curve of Alloy 600 base metal

Evaluation of Scattering

Alloy	Weld Metal or HAZ	Deviations*	total
82	Weld Metal	1.43	1.44
132		1.38	
82	Heat Affected Zone	1.37	
132		1.33	
600	Base Metal	1.20	

* Deviations: Index numbers of standard deviations of logarithms of deviance of each crack growth rate from the approximated curve

Experimental and Numerical Approaches for Characterizing the Crack Growth Behavior of Alloy 600 in PWR Primary Water, and Lifetime Predictions for Welded Structures

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Tohoku University
Sendai 980-8579, JAPAN

Outline (1)

- Introduction
- Literature Survey

  -Existing Crack Growth Data and Significant Parameters
- FRI Generalized Crack Growth Rate Formulation
- Numerical Analysis
  - K dependence
  - Effects of yield strength
  - Effects of dK/dt

Outline (2)

- Prediction of Crack Growth Behavior in Weld Residual Stress Field
  - -Core Shroud Cracking
  - -VHP behavior
- Disposition of Flaws
- Conclusions
- Acknowledgements

Introduction (1)

- More concerns on PWSCC of alloy 600 and weld metals such as 182 in PWR Vessel Penetrations.

- Need Quantitative Evaluation of the remaining lifetime of the vessel penetration (VP) in PWR

- Need fully understanding of the crack growth behavior of Ni-based alloys from a view point of Disposition of Flaw.

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Introduction (2)

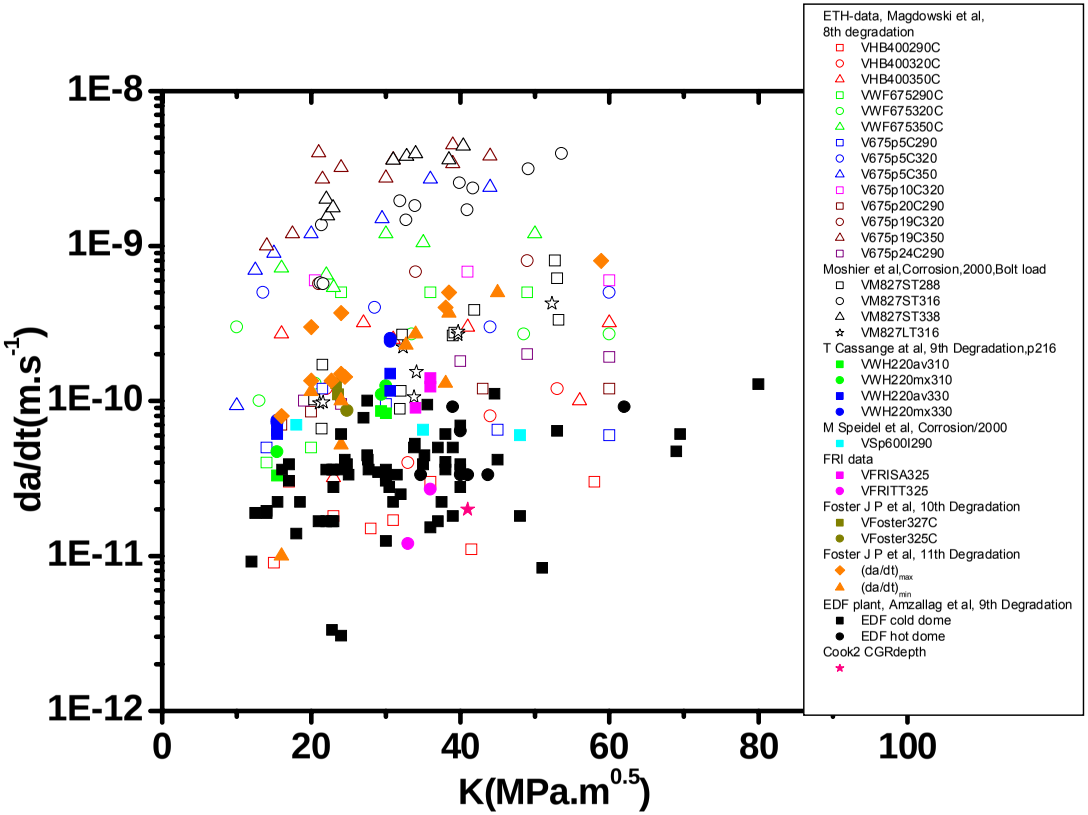
- Special emphasis should placed on the K dependence of crack growth rate as a function of metallurgical variables, mechanical properties, temperature and dK/dt.

- Therefore, multiple factors, such as material, environmental, and mechanical are involved in EAC processes and their synergy effects are complex.

- Prediction of nickel base alloy components in real PWR plants based on PWSCC mechanism and CGR modeling is highly demanded

Literature Survey(1)

-Existing CGR Data-Laboratories & Plants



CGRs of Alloy 600 in PWR environments

- Lab. data:

-thick plate material

-fracture mechanics specimen

- Plant data:

EDF & Cook 2

>Huge scatter of the data in da/dt vs K

Literature Survey(2)

-Significant Parameters for CGR

- Material Chemistry and Microstructure

  -Carbide content and distribution
  (Grain boundary carbides improve SCC resistance)
  -Fraction of Coincidence Site Lattice Boundaries (CSLB)
  (High CSLBs-low IGSCC susceptibility)

- Temperature effects

  CGR increase follows Arrhenius law
  ~180kJ/mol for component failure time(including initiation)
  ~130kJ/mol for crack growth rate

- DH effects

  ~da/dt(max) near the Ni/NiO equilibrium potential line

Literature Survey(3)

-Significant Parameters for CGR

- K effects

  -CGR plateau region at high K level(ETH data, EDF data, et c.)

  -CGR monotonically increase-(Westinghouse data, EDF data, etc.)

Most CGR models are based on K effect

- YS effects

  High YS from material chemistry or cold/warm rolling

  -significantly raise CGR

In empirical equations, a coefficient is used to introduce CW effect

- Loading and dK/dt effects

  -Loading mode effect

  -dK/dt effect for weldments with residual stress/strain

etc.,

FRI Generalized CGR formulation (5)

-CTSR formulation - Gao & Hwang's equation

- Gao and Hwang's definition of work hardening exponent, n,

$$\varepsilon = \begin{cases} (\frac{\sigma}{E}) & for \quad \sigma \le \sigma_y \\ (\frac{\sigma}{E}) + c \cdot (\sigma - \sigma_y)^n & for \quad \sigma > \sigma_y \end{cases}$$

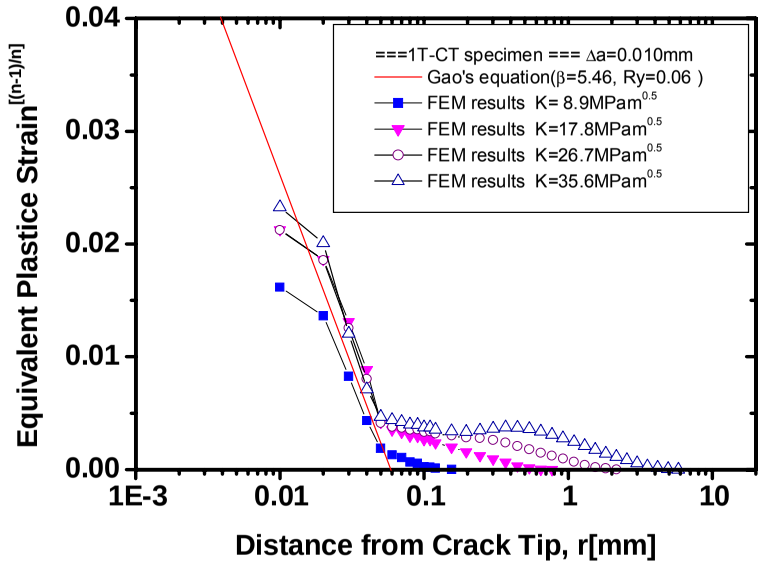
- Gao & Huang's equation for the crack tip strain of a growing crack for constant K and da/dt.

$$\varepsilon_{ct} = \beta(\frac{\sigma_y}{E})[\ln(\frac{A}{r})]^{\frac{n}{n-1}} \qquad \varepsilon_{ct} = \beta(\frac{\sigma_y}{E})\left\{\ln[(\frac{\lambda}{r})(\frac{K}{\sigma_y})^2]\right\}^{\frac{n}{n-1}}$$

Derived under the condition of plain strain and small scale yield

FRI Generalized CGR formulation (6)

-CTSR formulation - Validity Confirmed by 3D-FEM



Equivalent plastic strain distribution at crack tip under constant load conditions, n (Gao's definition) is 10.

- 3D-FEM results match well with the theoretical calculation at different values of stress intensity factor, K.
- Although Gao's equation was derived for a steady growing crack under quasi-static loading (constant K), the 3D-FEM analyses indicate that Gao's equation may still be applicable even under the loading conditions without constant crack growth and/or constant K.

FRI Generalized CGR formulation (9)

-Shoji's model based on Slip/Oxidation mechanism

- FRI theoretical CGR formulation, based on the crack tip reaction kinetics and the theoretical CTSR formulation

$$\frac{da}{dt} = \left[\frac{M \cdot i_0}{z \cdot \rho \cdot F \cdot (1-m)}\right]\left(\frac{t_0}{\varepsilon_f}\right)^m \left\{ \beta \cdot \left(\frac{\sigma_y}{E}\right) \cdot \left(\frac{n}{n-1}\right) \cdot \left[2 \cdot \frac{\dot{K}}{K} + \frac{\dot{a}}{r}\right] \cdot \left\{ \ln\left[\lambda \cdot \frac{\left(\frac{K}{\sigma_y}\right)^2}{r}\right] \right\}^{\frac{1}{n-1}} \right\}^m$$

- *A unique expression for CGR as a function of K- combining a mechanism of crack growth with the mechanics of a crack tip stress/strain field.*
- *Synergistic terms among the material parameters, mechanical properties, electrochemical properties and crack tip mechanics in terms of K and dK/dt*

FRI Generalized CGR Formulation (10)

-CGR equation

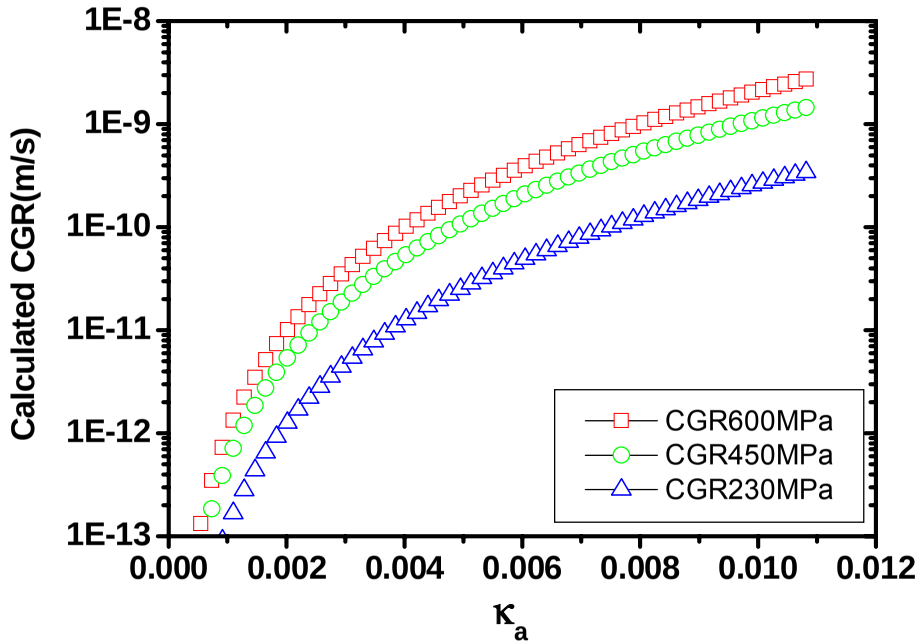
A generalized CGR formulation can be obtained by combining the general oxidation mechanism and the theoretical CTSR equation,

$$\frac{da}{dt} = \kappa_a \cdot \left\{ \beta \cdot \left(\frac{\sigma_y}{E}\right) \cdot \left(\frac{n}{n-1}\right) \cdot \left[2 \cdot \frac{\dot{K}}{K} + \frac{\dot{a}}{r}\right] \cdot \left\{ \ln\left[\lambda \cdot \frac{\left(\frac{K}{\sigma_y}\right)^2}{r}\right] \right\}^{\frac{1}{n-1}} \right\}^m$$

where κ_a is a crack tip oxidation rate constant, which is a function of local material chemistry, local environmental chemistry, transient interfacial rate kinetic law, and the stress/strain state.

FRI Generalized CGR Formulation (12)

-Possible Accelerated CGR testing based on mechanism (1) YS& κ_a effect

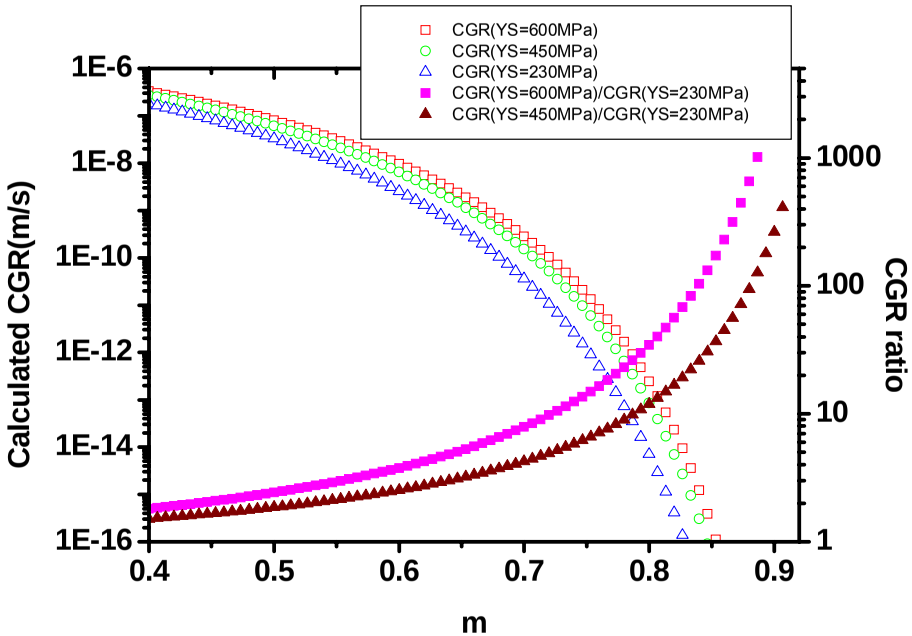


Sensitivity analysis of YS effect at different κ_a levels (m= constant)

- **At each YS level, CGR increases with increasing of κ_a value**
- **A non-linear relationship between CGR and κ_a**
- **CGR increases with YS**

FRI Generalized CGR Formulation (13)

-Possible Accelerated CGR testing based on mechanism (2) YS & m effect



Sensitivity analysis of the effect of YS on CGR for different values of m (κ_a =constant)

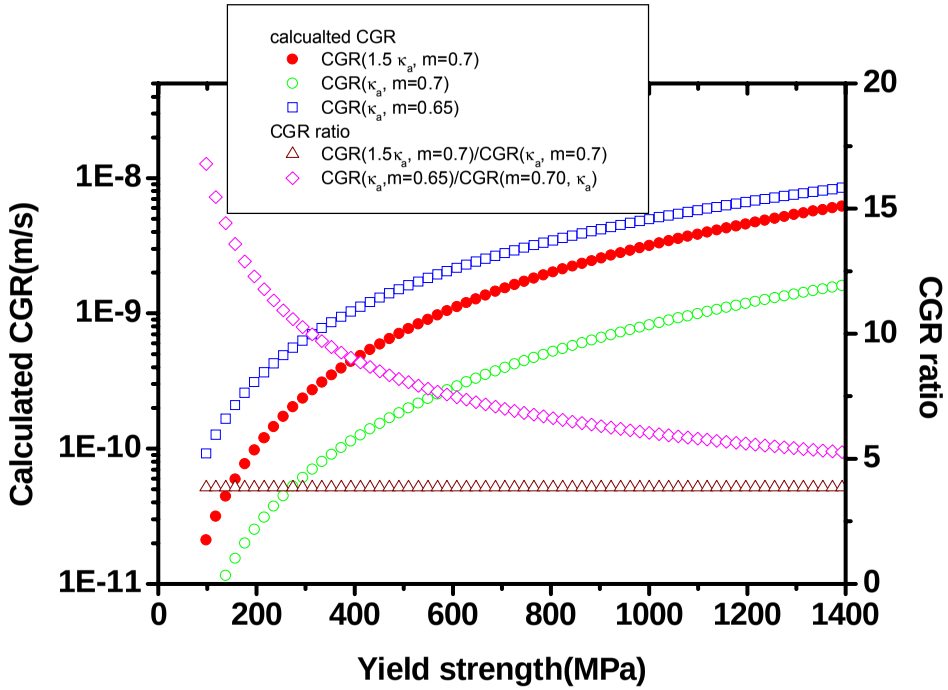
CGR ratio= CGR(YS)/CGR(230MPa)

- CGR decreases with an increase of m
- Effect of YS increases with an increasing m,

-implying that the effect of YS is more significant for materials with a faster repassivation (or fast film recovery) process

FRI Generalized CGR Formulation (14)

- Possible Accelerated CGR testing (3)YS & κ_a & m effect

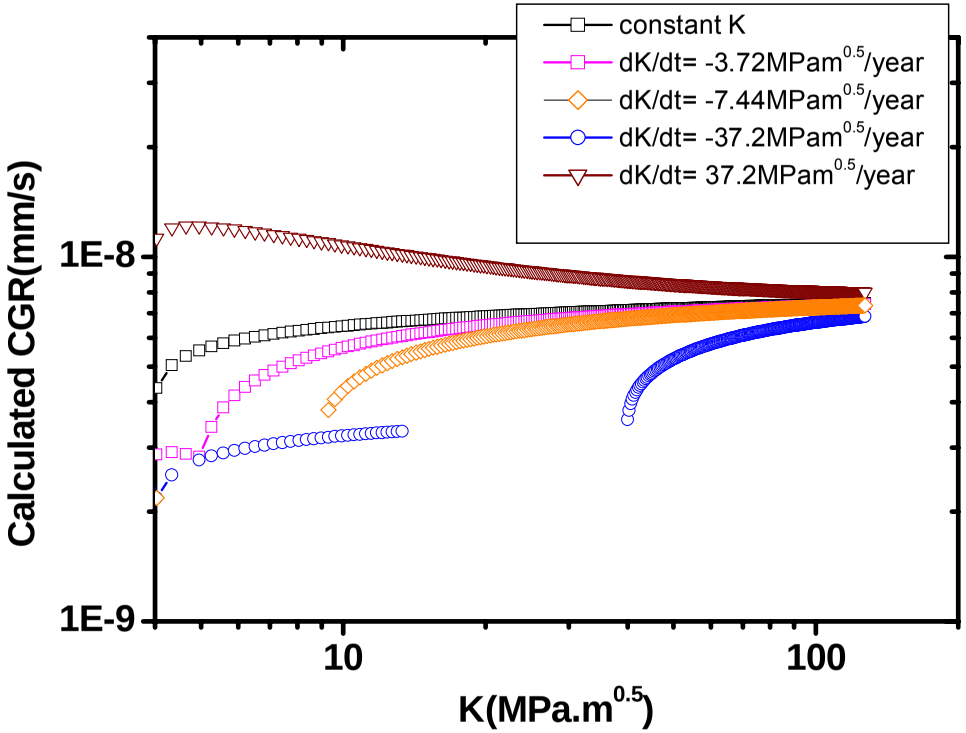


- The enhancement factor by decreasing m is less with an increase of YS.

-CGR enhancement by decreasing *m* (slower film recovery process) could be more significant for materials of lower YSs

FRI Generalized CGR Formulation (16)

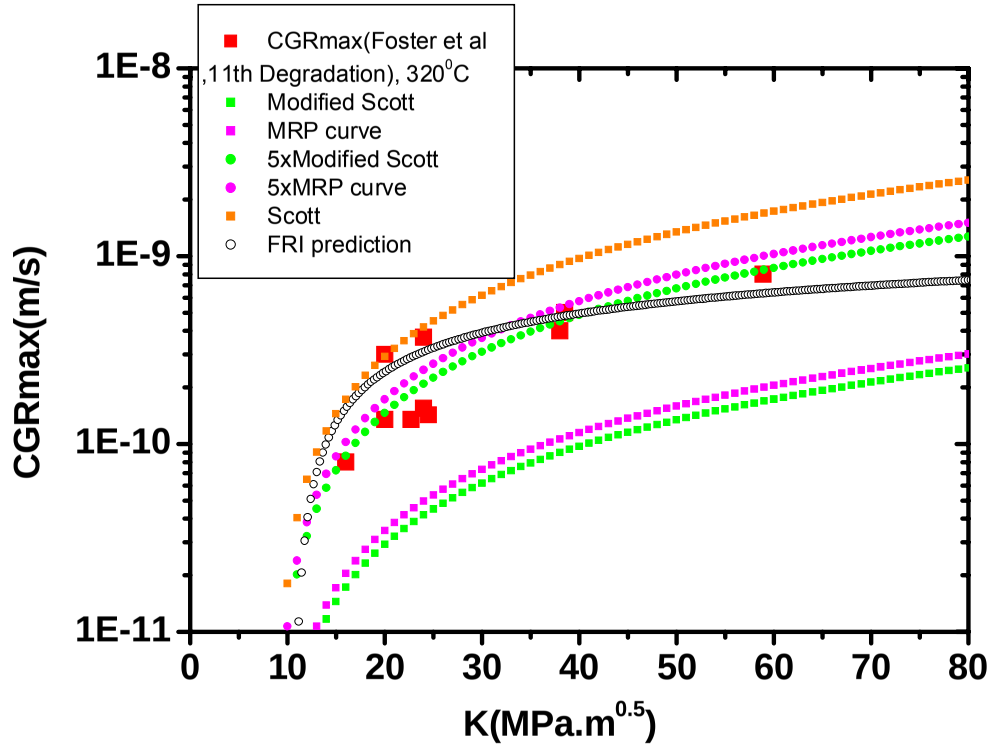
- Possible Accelerated CGR testing based on mechanism (5) K&dK/dt effect



n=9
m=0.5
YS=200MPa
Different dK/dt

- Significant effect of dK/dt on CGR
- Negative dK/dt results in lower CGR and higher threshold
- CGR testing at higher dK/dt accelerates CGR-specimen design

Numerical Analysis of experimental CGR(1)
-K dependence - Moderate K effect

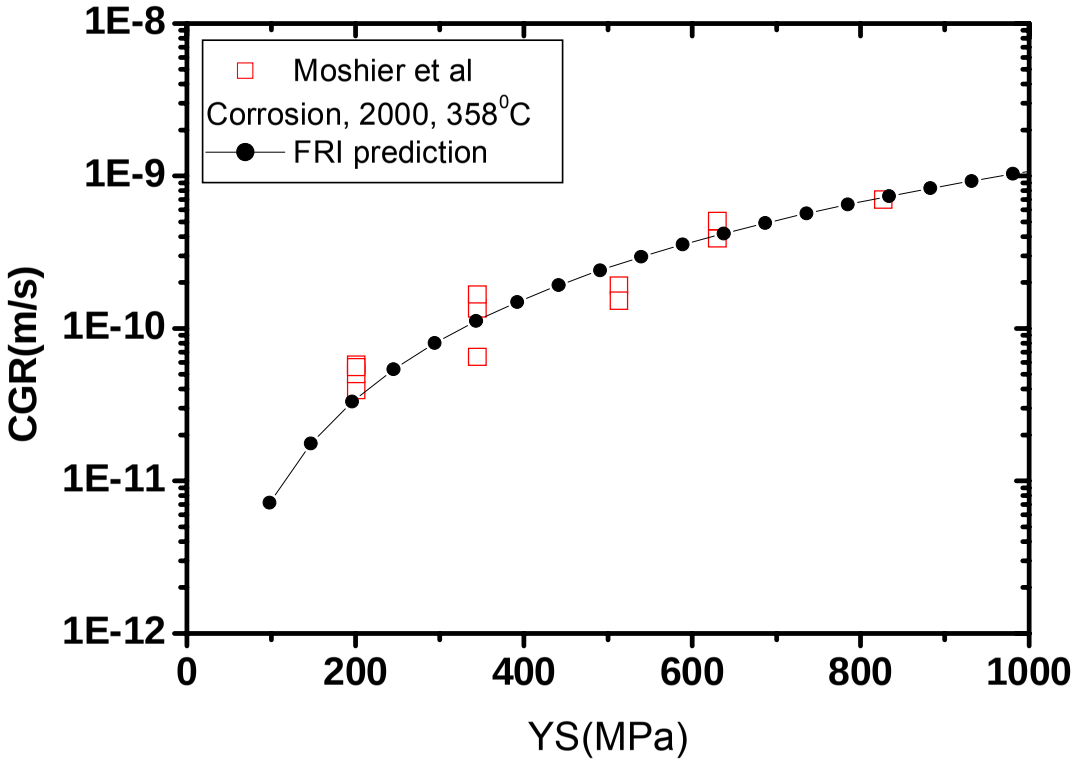


Alloy 600, heat 69
Material of low YS,
YS=274MPa
n=3

Parameter used in the model:
m=0.77

- FRI prediction on the material with YS=274MPa
- Comparison with modified Scott model & MRP model.

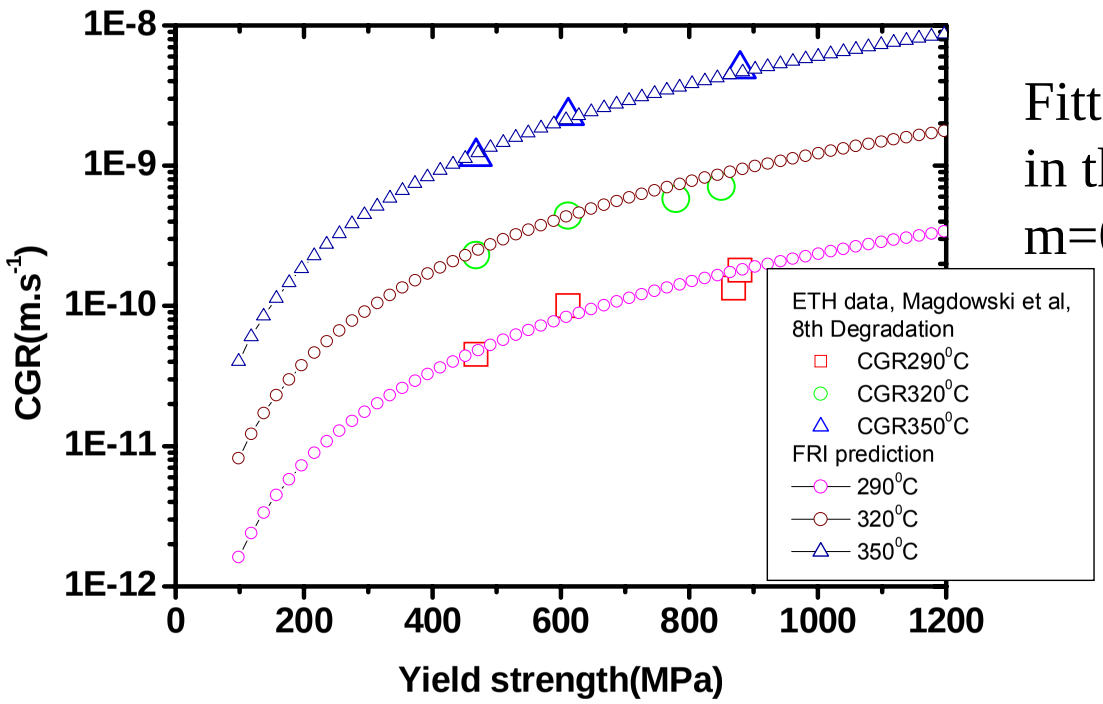
Numerical Analysis of experimental CGR(4)
-YS effect (1)



Parameters used in the model: m=0.70 and n=6

The effect of YS on CGR can be predicted by FRI generalized model

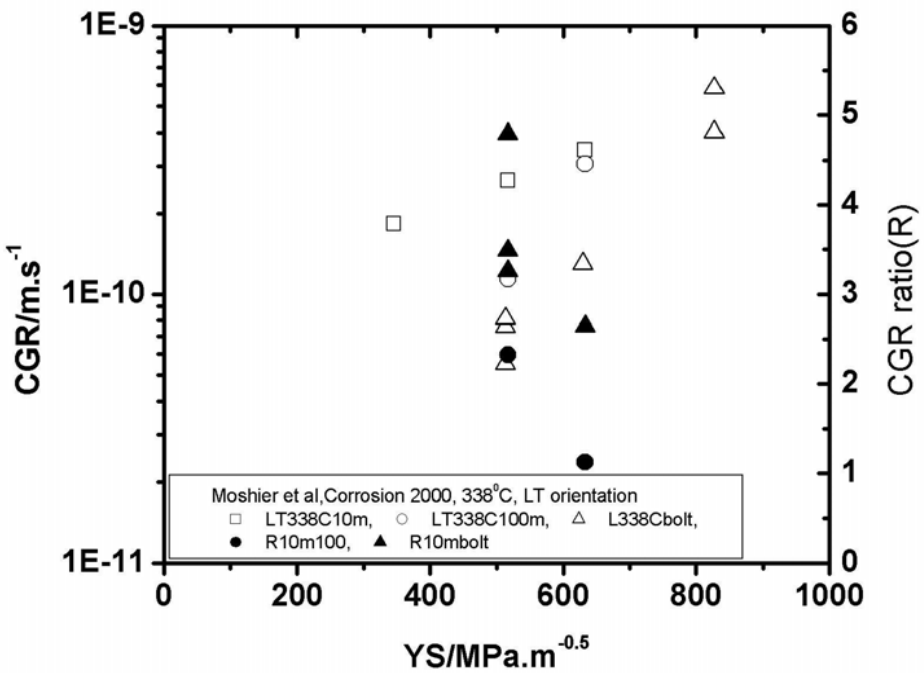
Numerical Analysis of experimental CGR(5)
-YS effect (2) YS & T effect



Fitting parameters in the model: m=0.70 and n=6

- Again, effect of YS can be formulated with the FRI generalized model
- CGRs at different can be calculated by only changing values of κ_a

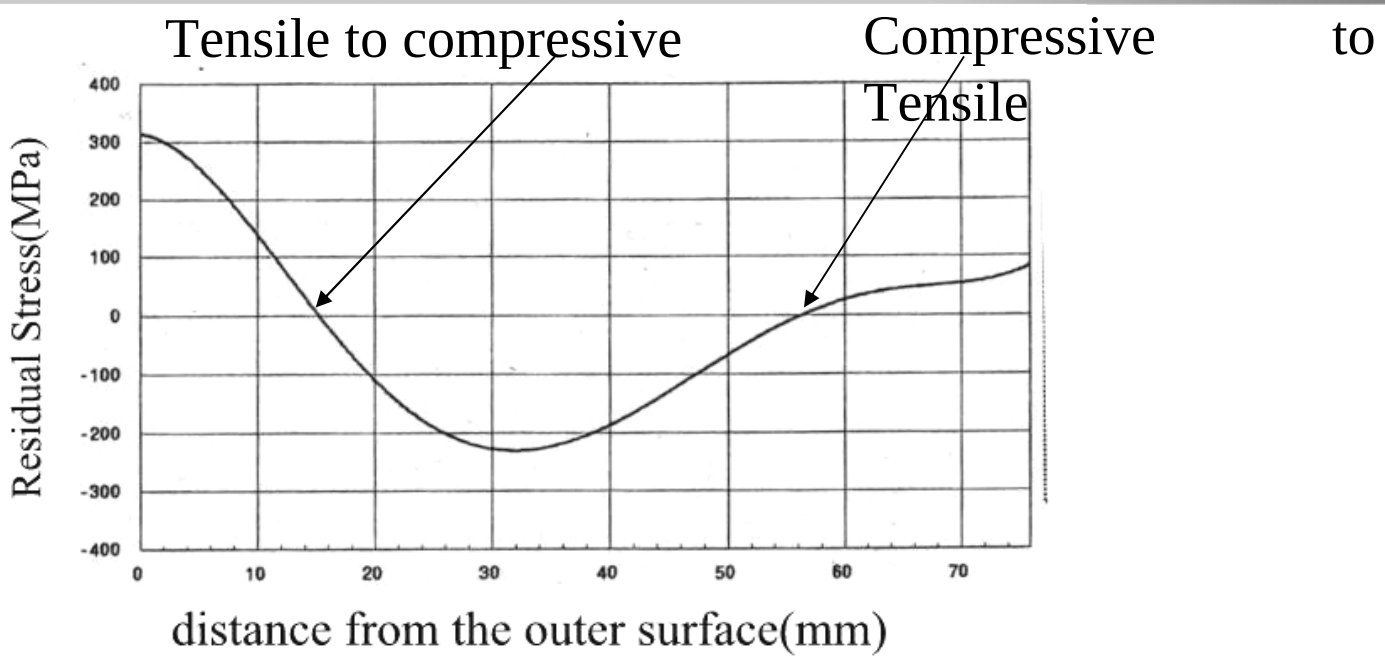
Numerical Analysis of experimental CGR(7)
-dK/dt effect



- CGR(bolt)<CGR(active load) in this data set, can be explained by the sensitivity analysis of dK/dt effect by FRI mode

Prediction of CGR in Weld Residual Stress Field(1)

-Core Shroud Cracking(1)Residual Stress distribution

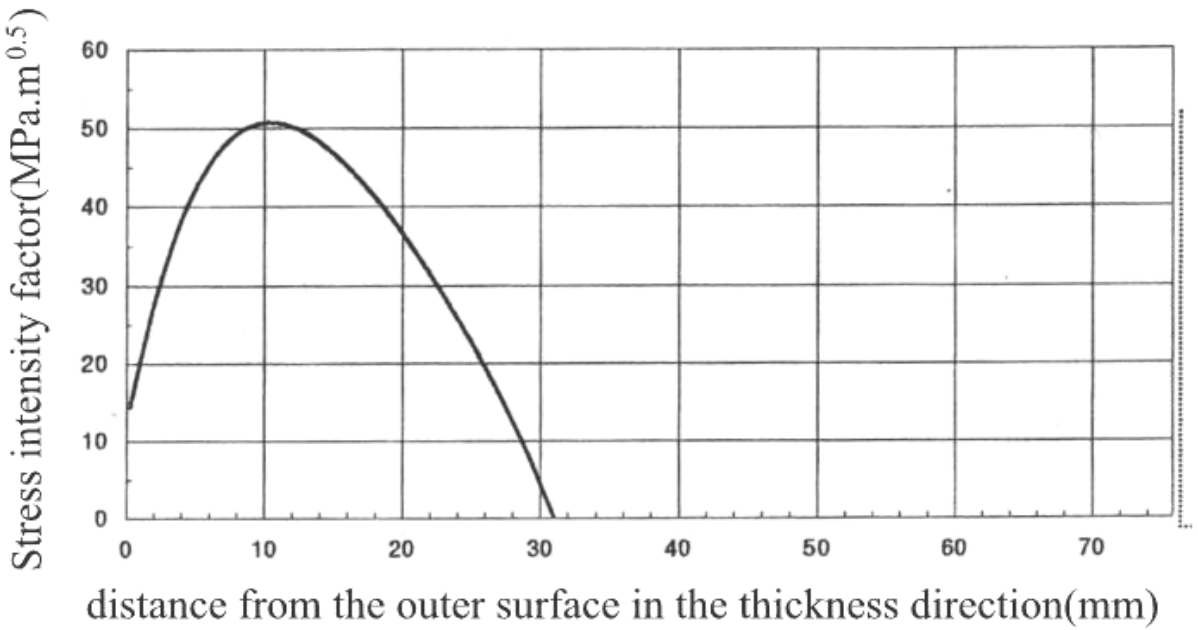


Distribution of the axial residual stress in H6a in a BWR core Shroud

- The residual stress changes from tensile to compressive or vise versa at certain depths of the weldment

Prediction of CGR in Weld Residual Stress Field(2)

-Core Shroud Cracking(2) K distribution

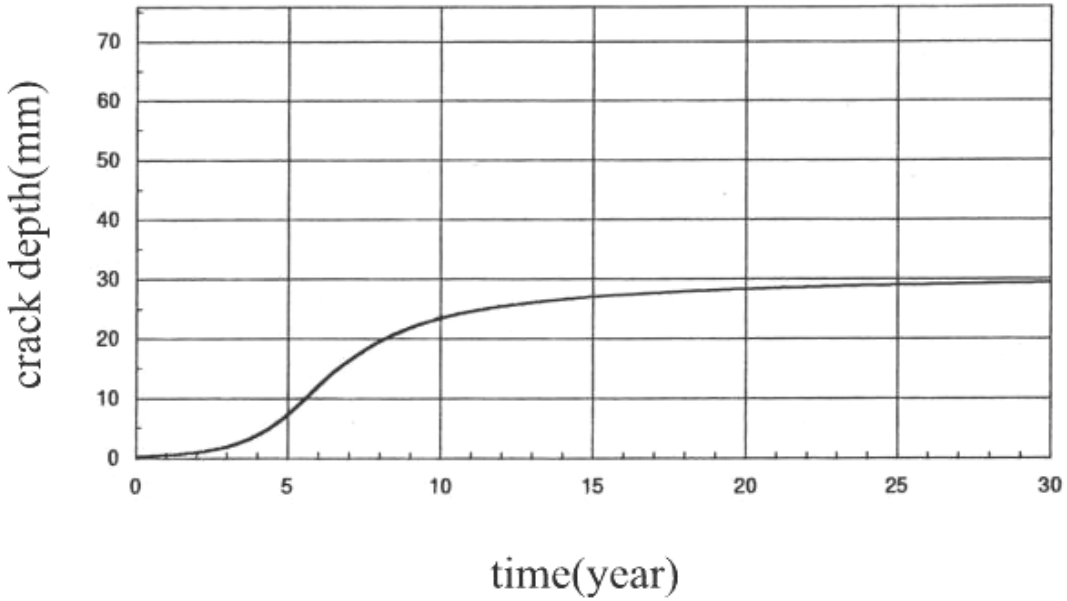


Estimated distribution of K in H6a in a BWR Core Shroud

- K increases to a maximum value and then decreases in the through-thickness direction of the weldment.

Prediction of CGR in Weld Residual Stress Field(4)

-Core Shroud Cracking (4) Crack depth prediction

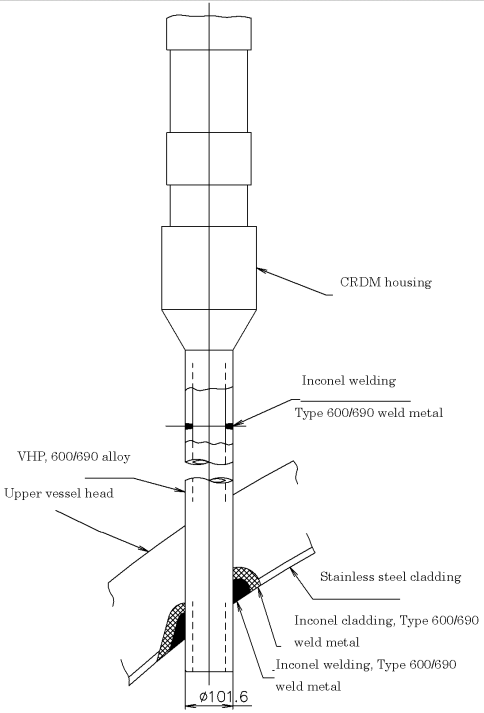


Relationship between the crack depth and time

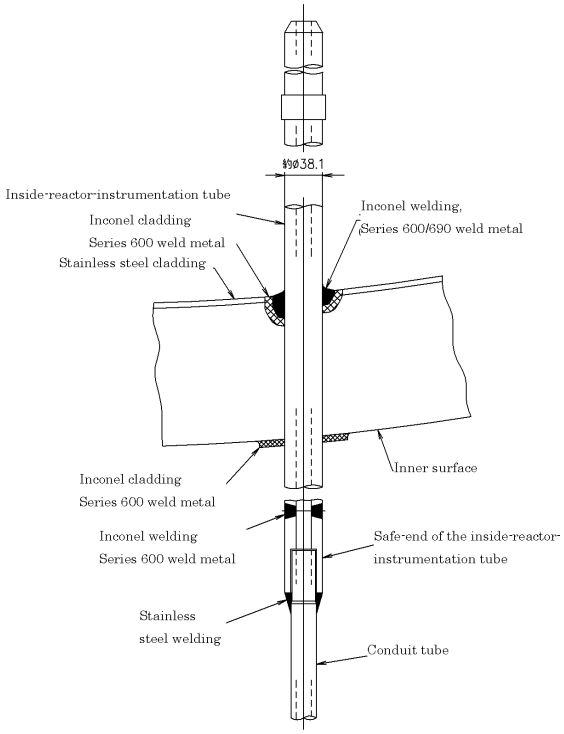
- High crack growth rate is expected for the period of 4-9years
- After ca. 9 years, CGR decreases with time

Prediction of CGR in Weld Residual Stress Field (6)

-Details of a PWR VHP & an Inside-reactor Instrument tube



Structure of the VHP

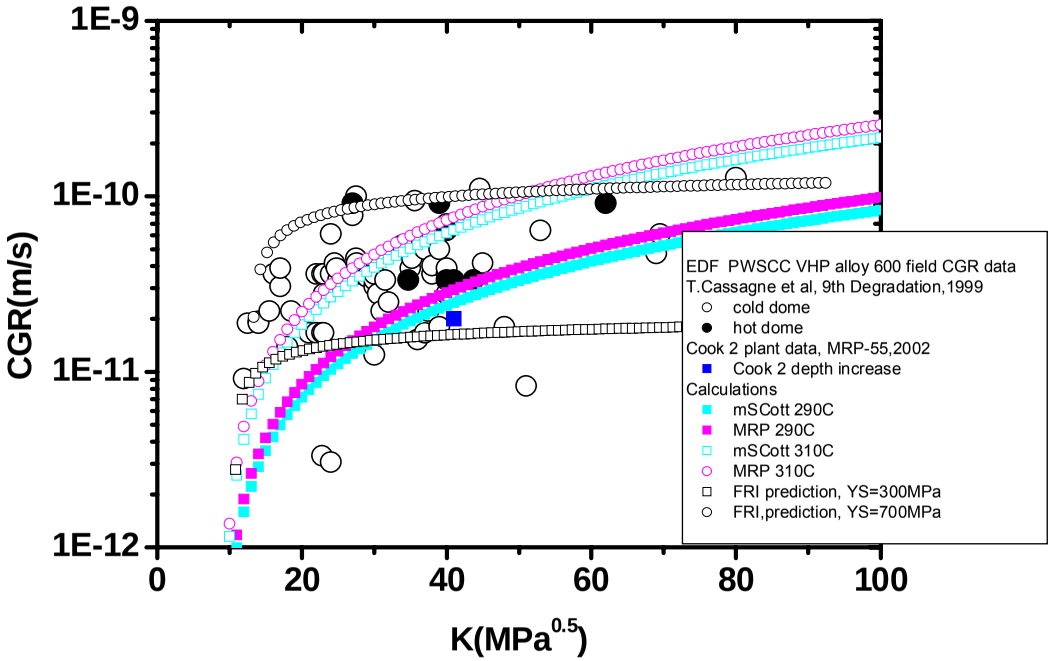


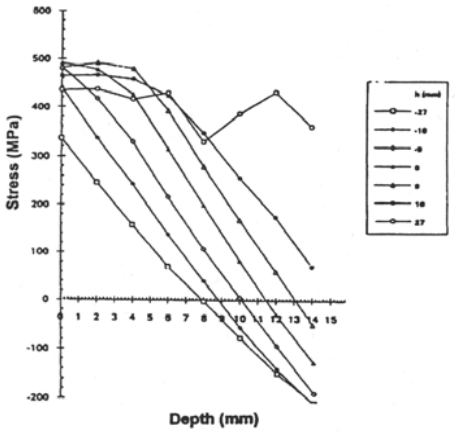
Structure of the inside-reactor-instrumentation tube

Illustration of a PWR VHP(left) and an inside-reactor instrument tube(right)

Prediction of CGR in Weld Residual Stress Field (7)

-PWR VHP(3) Crack growth behavior of PWR VHPs





Weld Residual stress analysis of a PWR VHP (EDF data)

CGR prediction of Plant CGRs(from EDF & MRP) due to variations of YS may partly explain the scattered CGR data in the CGR-K diagram

Disposition of flaws (6)

- PWR environments (5) FRI generalized CGR model

-CGR is very sensitive to YS and this effect could be one of the factor of the scattered CGR in the data base.

-The shape of the CGR-K curve is important for developing the disposition line. **Variability in strain hardening ability may contribute to different types of CGR-K relationship**.

-**Time variation of K(dK/dt) with crack growth can significantly affect the CGR** of structural materials either in BWR or in PWR

Disposition of flaws (7)

- PWR environments (6) FRI generalized CGR model

-**This dK/dt variation** with crack growth can be more important in crack growth under the real plant condition where crack grows **in welded component**.

-**Loading condition and residual stress/stain analysis** is necessary for the crack growth rate formulation and for lifetime prediction of NPP components, especially for weldments.

FRI Generalized CGR Formulation

A generalized CGR formulation can be obtained by combining the general oxidation mechanism and the theoretical CTSR equation,

$$\frac{da}{dt} = \kappa_a \cdot \left\{ \beta \cdot \left(\frac{\sigma_y}{E}\right) \cdot \left(\frac{n}{n-1}\right) \cdot \left[2 \cdot \frac{\dot{K}}{K} + \frac{\dot{a}}{r}\right] \cdot \left\{ \ln\left[\lambda \cdot \frac{\left(\frac{K}{\sigma_y}\right)^2}{r}\right] \right\}^{\frac{1}{n-1}} \right\}^m$$

where κ_a is a crack tip oxidation rate constant, which is a function of local material chemistry, local environmental chemistry, transient interfacial rate kinetic law, and the stress/strain state.

Conclusions (1)

- FRI Model and CGR formulation can predict experimental and field CGR data with a good agreement, taking into account the effects of K, yield strength, strain hardening, temperature and dK/dt on CGRs

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- Based upon the FRI model, CGR should have K dependence in the form of $\underline{\{\ln K\}^{m/n-1}}$ in principle where m is oxidation kinetic parameter and n strain hardening coefficient.

Conclusions (2)

- The significance of K, yield strength and strain hardening coefficient on CGR was demonstrated by numerical analysis.

- Particularly, numerical calculation showed that CGR under negative dK/dt condition can be much lower than those obtained under constant K or positive dK/dt condition.

Conclusions (3)

- The effect of dK/dt on CGR can be critical in lifetime prediction of NPP welded components such as VHPs and BMIs in PWR

- Experimental verification of the crack growth behavior under the condition of positive and negative dK/dt would be highly recommended for better lifetime prediction of NPP welded components. Disposition line for flaw evaluation may take into account of these effects on CGR

Hydrogen Assisted Fracture Model Predictions for Alloy 600 PWSCC

Sensitivities of Crack Growth Rate to Applied Stress Intensity Factor, Temperature, Carbon Concentration, Yield Stress and Crack Growth Orientation and coolant-borne hydrogen

M. M. Hall, Jr., W. C. Moshier and D. J. Paraventi

Conference on Vessel Head Penetration
Inspection, Cracking, Repairs

Sponsored by the US NRC and ANL
September 29 – October 2, 2003
Gaithersburg, MD, USA

OUTLINE

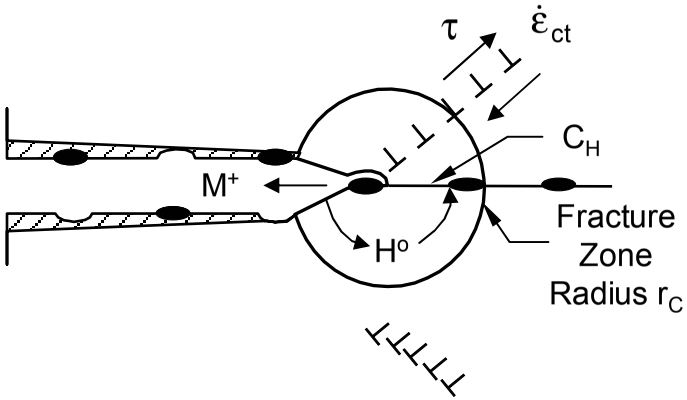
- SCC Variables
- HAF Model Concepts and Equation Development
- Experimental
- SCC Data
- Comparisons to Model

Variables Potentially Affecting NiCrFe Alloy PWSCC CGR*

- Alloy and Corrosion Film Composition and Structure
  - chromium and carbon concentrations, carbide morphology and distribution, grain size (Alloy X-750)
  - cold work (yield stress, strain hardening, strain rate sensitivity)
  - crack growth orientation for cold worked material
- Crack Tip Environment
  - $[H^+] = 10^{-pH}$
  - hydrogen over potential $\eta = E - E_r$ where E_r is the reversible H_2 / H^+ potential determined by coolant-borne hydrogen, DH_2
  - temperature
  - other ionic species
- Stress Intensity Factor

* Variables in red are currently included in HAF Model

Hydrogen Assisted Fracture (HAF) Model*
- Concepts -



$$\dot{a} = \frac{r_c\,\dot{\varepsilon}_{ct}}{\varepsilon_f} = \frac{r_c\,\dot{\varepsilon}_{ct}}{\varepsilon_{fo}}\left(\frac{c_{gb}}{c_o}\right)^{\frac{1}{2}}$$

- Hydrogen evolves at crack tip due to cathodic reduction of water
- Hydrogen absorbs, permeates, diffusively segregates and is trapped at grain boundaries
- Cracks advance due to hydrogen-assisted-creep fracture of hydrogen embrittled grain boundaries
- Rate limiting step potentially may be any of the hydrogen and crack tip strain rate processes

*M. M. Hall, Jr. and D. M. Symons, "Hydrogen Assisted Creep Fracture Model for Low Potential Stress Corrosion Cracking of Ni-Cr-Fe Alloys", Chemistry and Electrochemistry of Stress Corrosion Cracking: A Symposium Honoring the Contributions of R. W. Staehle, R. H. Jones, Ed. TMS, 2001, 447 - 466.

HAF Model Equations

Alloy Composition and Structure

HER/HAR Rate Constant

Coolant Borne H Fugacity

Sievert's Law Constant

H Over Potential, η

~ pH

Strain Hardening $F(\sigma_Y, \text{w/o C})$

Activation Enthalpy for dislocation glide F(C, orientation)

$$\dot{a} = \frac{r_c \dot{\varepsilon}_{ct}}{\varepsilon_f} = \frac{r_c \dot{\varepsilon}_o}{\varepsilon_{fo}} \left(\frac{c_{gb}}{c_o}\right)^{\frac{1}{2}} \left(\frac{K - K_{th}}{K_{IC} - K_{th}}\right)^{\frac{2N}{N+1}\frac{\Delta H}{RT}}$$

H Heat of Solution

Stress Effect on H Solubility

Reversible H_2 Potential $F(DH_2)$

$$\frac{c_{gb}}{c_o} = \frac{S}{c_o}\left[f_{DH_2} + \kappa[H^+]^2 \exp\left(-\frac{\alpha(E - E_r)F}{RT}\right)\right]^{\frac{1}{2}} \exp\left(\frac{-\Delta H_s + 2\sigma_y \bar{V}_H + \Delta H_b}{RT}\right) \operatorname{erfc}\left(\sqrt{\frac{r_c \dot{a}}{4D_H}}\right)$$

Corrosion Generated Hydrogen Fugacity

gb Trapping Energy

H Diffusivity

For $T > 250°C$ $\quad f_{DH_2} << f_{CorH_2}$, $\quad \frac{4D_H}{r_c} >> \dot{a} \Rightarrow \operatorname{erfc}\left(\sqrt{\frac{r_c \dot{a}}{4D_H}}\right) \approx 1$

Q_{cor} $\quad Q_{mech}$

$$\dot{a}_{\dot{\varepsilon}} = \frac{r_c \dot{\varepsilon}_o}{\varepsilon_{fo}} \gamma e^{-\frac{\Delta \tilde{H}}{RT}} \left(\frac{K - K_{th}}{K_{IC} - K_{th}}\right)^{\frac{2N}{N+1}\frac{\Delta H}{RT}} = \dot{a}_o \exp\left\{-\frac{\Delta \tilde{H}}{RT} - \frac{2N}{N+1}\frac{\Delta H}{RT} \ln\left(\frac{K_{IC} - K_{th}}{K - K_{th}}\right)\right\}$$

Modeling Dynamic Strain Aging Effects* on Alloy 600 Crack Growth Rate

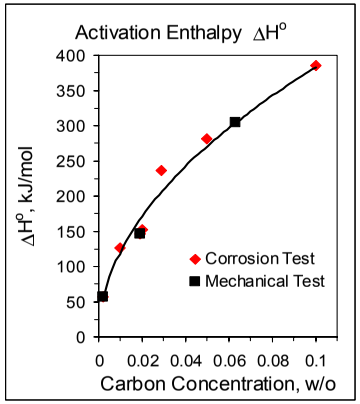
$$\dot{a}_{\dot{\varepsilon}} = \dot{a}_o e^{-\frac{\Delta\tilde{H}}{RT}} \left(\frac{K - K_{th}}{K_{IC} - K_{th}} \right)^{\frac{2N}{N+1}\frac{\Delta H}{RT}}$$

Activation Enthalpy for dislocation glide F(C, orientation)

Mobile ⊥ x o Interaction Energy

Drag-free Activation Energy

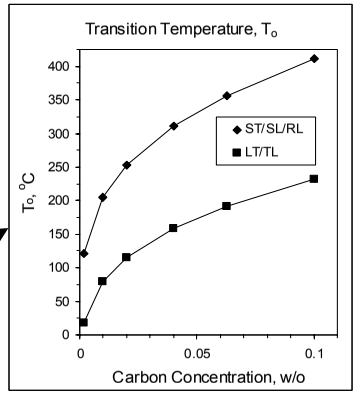
$$\Delta H = \Delta H^o(C) + U(\bar{n}) = \Delta H^o \left\{ 1 - \alpha \exp\left[-\beta \left(\ln\left(\frac{T}{T_o} \right) \right)^2 \right] \right\} \cong \Delta H^o \left| 1 - \frac{T}{T_o} \right|$$



Interaction Strength Factor $F(\sigma_Y, C) \cong 1$ for σ_Y = 826 MPa and 0.063 w/o C

Temperature @ Which Dislocation Wait Time = Solute Diffusion Time

$$T_o \approx \frac{U(\bar{n})/R}{\ln(1/C)}$$



*M. M. Hall and D. M. Symons, "Constitutive Deformation Model for Analysis of Stress Corrosion Crack Tip Strain-Rates in Ni-Cr-Fe Alloy 600", International Conference on Hydrogen Effects on Material Behavior and Corrosion Deformation Interactions, R. Jones, N. Moody, A. Thompson, T. Magnin, R. Ricker and G. Was, Ed., TMS, 2002

Linearized HAF Model Equations

Better Suited for Data Analysis

$$\ln \dot{a} = A_o - A_1 \frac{T_o}{T} \pm A_2 \frac{T_o}{T} \ln K_R \mp A_2 \ln K_R; \quad \pm \Rightarrow \text{orientation}$$

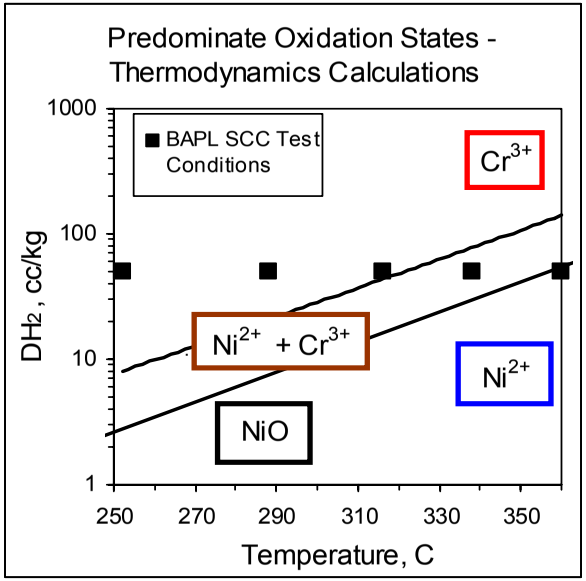
$$A_o = \ln \dot{a}_o \quad A_1 = \frac{\Delta \tilde{H}}{RT_o} \quad A_2 = \frac{2N}{N+1} \frac{\Delta H^o}{RT_o} \quad K_R = \frac{K - K_{th}}{K_{IC} - K_{th}}$$

Experimental

Bettis Data

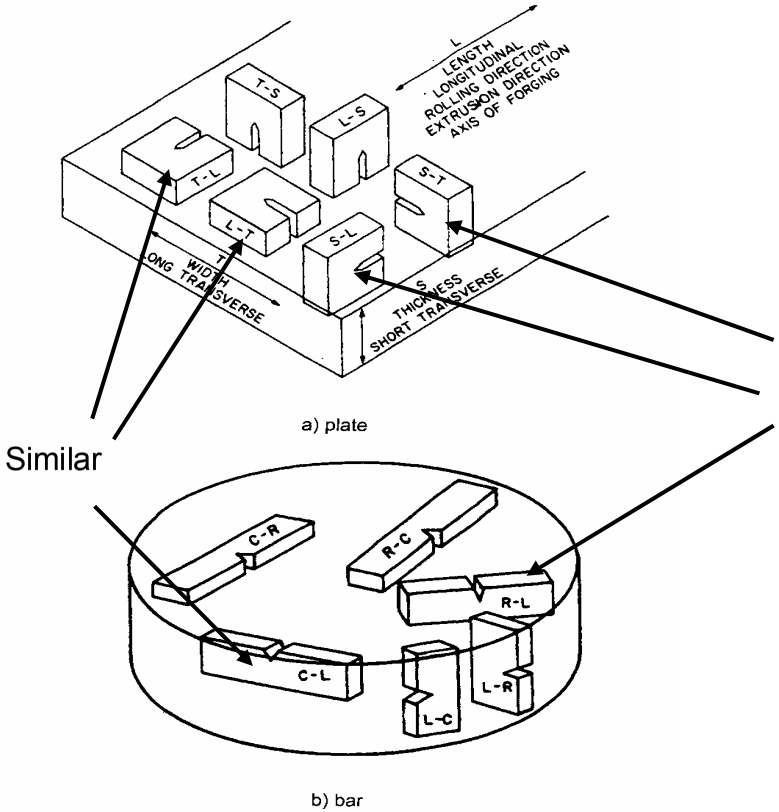
- Alloy 600 plate given HTA – 1100°C/3600s/FC
- 0.063 w/o Carbon
- Extensive gb decoration with carbides
- 0% – 28% CW (YS 187 MPa – 826 MPa)
- 50 cc/kg dissolved hydrogen
- Conventional FM specimens and test methods
- LT and ST crack growth orientations

SCC Test Conditions



- SCC tests conducted at 252° C to 360° C at or on the Ni side of the Ni - NiO phase field boundary

Crack Growth Orientations for Plate and Bar



LT / TL / CL Similar Orientations

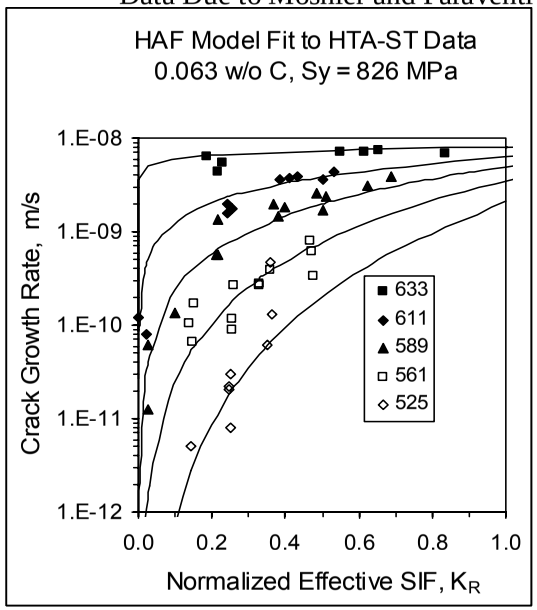
ST / SL / RL Similar Orientations

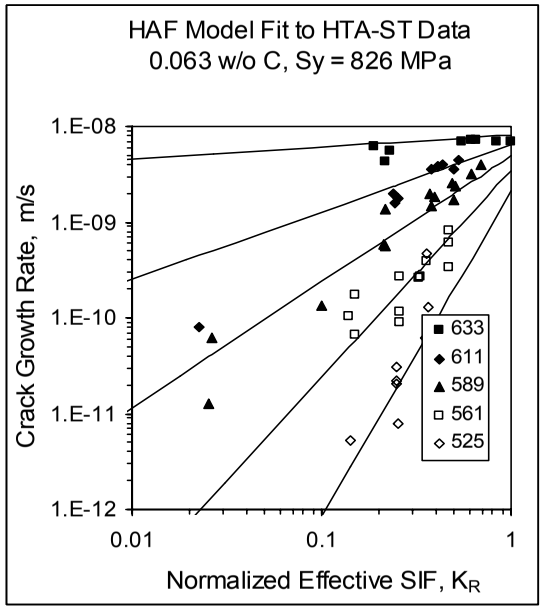
ST / LT orientation CGR data – single heat of Alloy 600

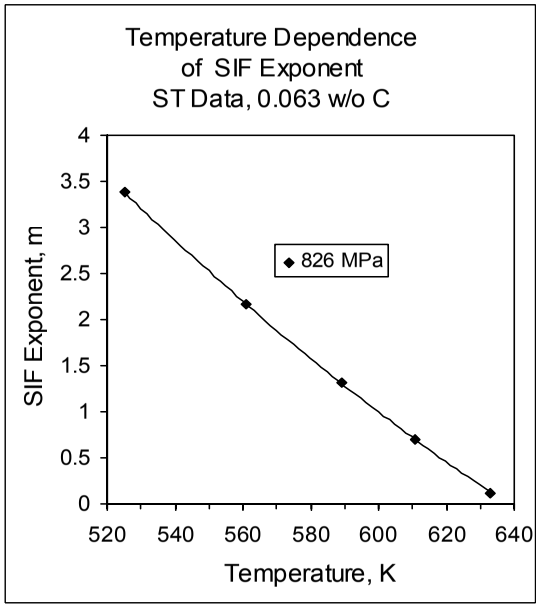
RL / CL orientation CGR data – different heats of Alloy 600

Stress Intensity Factor Exponent m Depends on Temperature and RT Yield Stress

Data Due to Moshier and Paraventi





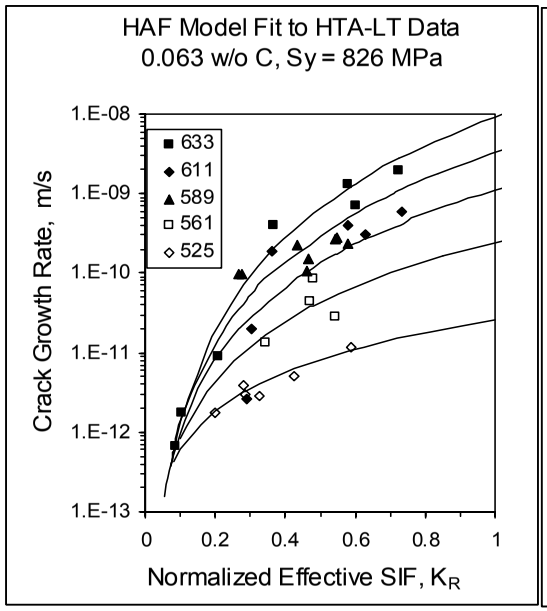


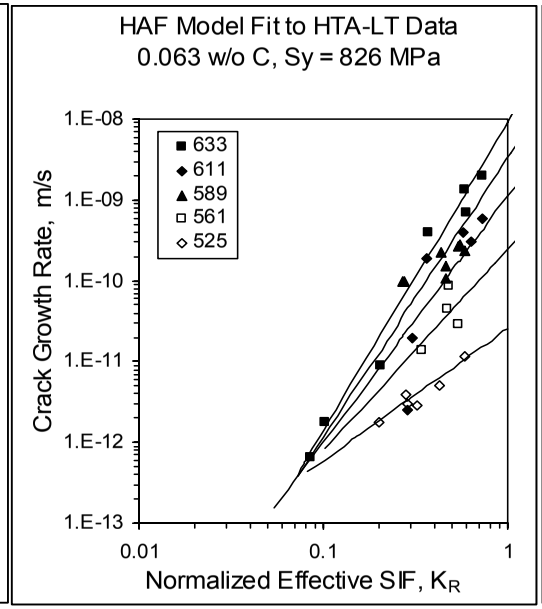
$$K_R \equiv \frac{K - K_{th}}{K_c - K_{th}} \qquad m \equiv \left.\frac{\partial \ln \dot{a}}{\partial \ln K_R}\right|_{T,\eta} \cong \frac{2N}{N+1}\frac{\Delta H^o}{RT}\left(1 - \frac{T}{T_o}\right); \quad T < T_o$$

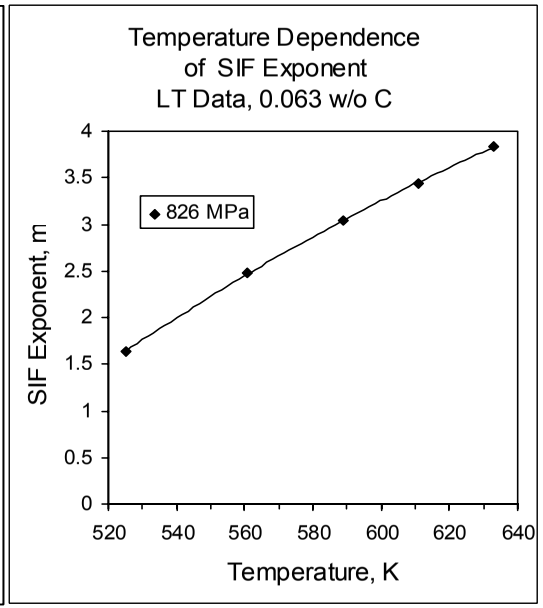
ST orientation m value decreases with increasing temperature

LT Crack Growth Orientation Unlike ST

Data Due to Moshier and







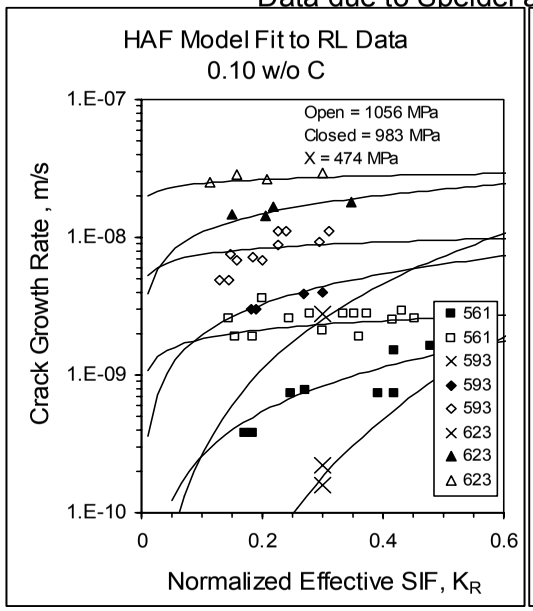
$$K_R \equiv \frac{K - K_{th}}{K_c - K_{th}}$$

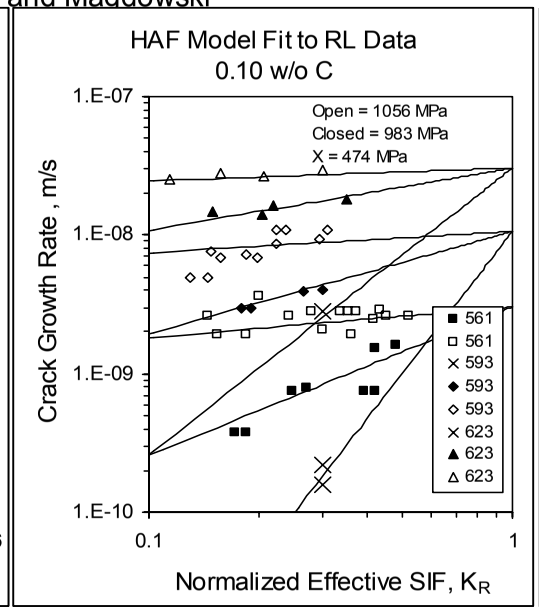
$$m \equiv \left.\frac{\partial \ln \dot{a}}{\partial \ln K_R}\right|_{T,\eta} = \frac{2N}{N+1}\frac{\Delta H^o}{RT}\left(\frac{T}{T_o} - 1\right); \quad T > T_o$$

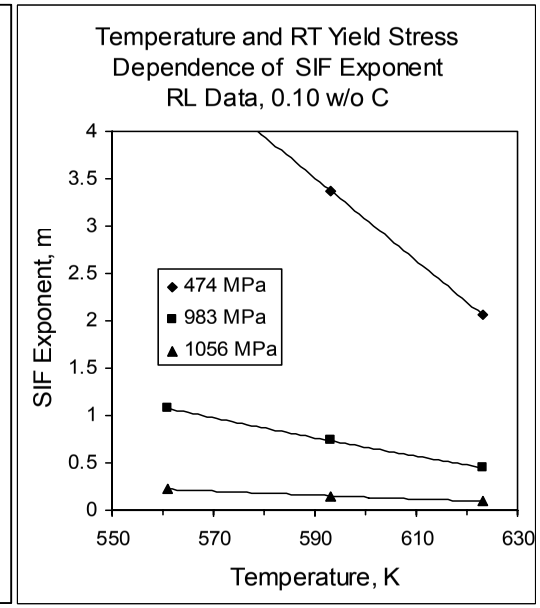
LT orientation m *increases* with increasing temperature

RL Crack Growth Orientation Similar to ST

Data due to Speidel and Magdowski





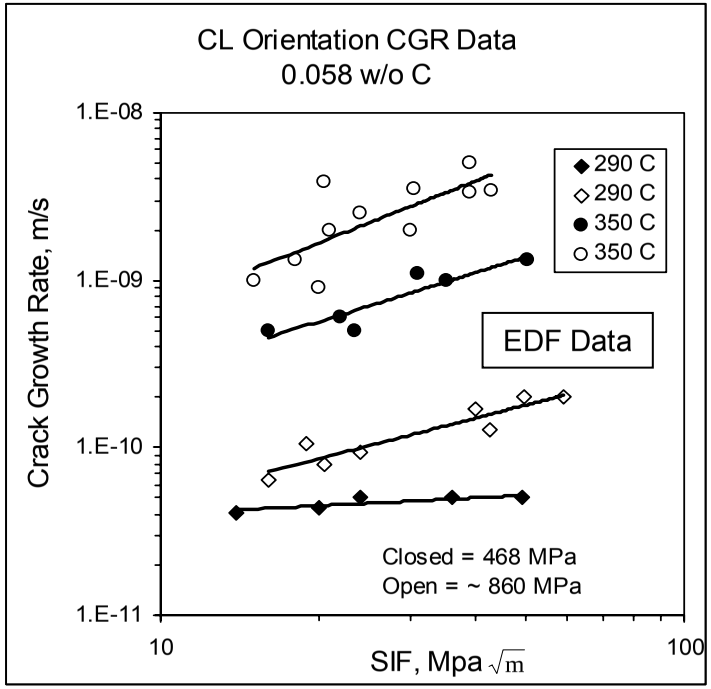


$$K_R \equiv \frac{K - K_{th}}{K_c - K_{th}}$$

$$m \equiv \left.\frac{\partial \ln \dot{a}}{\partial \ln K_R}\right|_{T,\eta} \cong \frac{2N}{N+1}\frac{\Delta H^o}{RT}\left(1 - \frac{T}{T_o}\right); \quad T < T_o$$

RL orientation m decreases with increasing temperature and RT yield stress (pre-strain or CW)

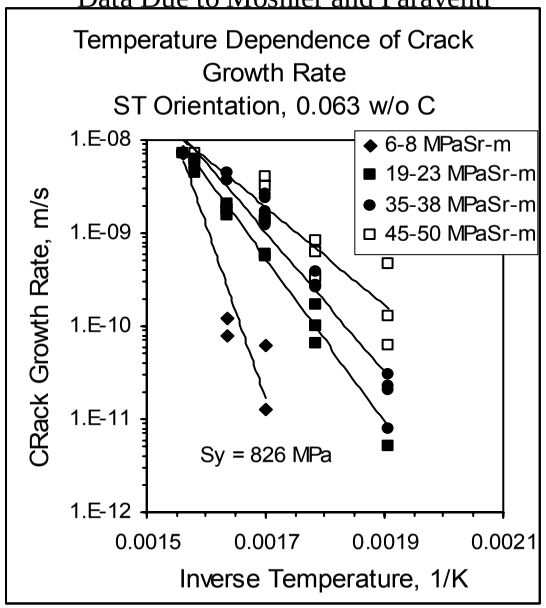
CL Crack Growth Orientation Similar to LT

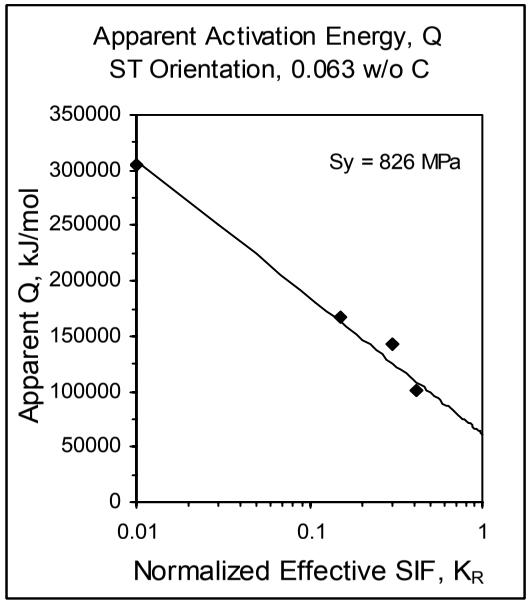


CL orientation m increases with increasing temperature and RT yield stress (pre-strain or CW)

ST Orientation Apparent Activation Energy Q is Decreasing Function of Stress Intensity Factor

Data Due to Moshier and Paraventi



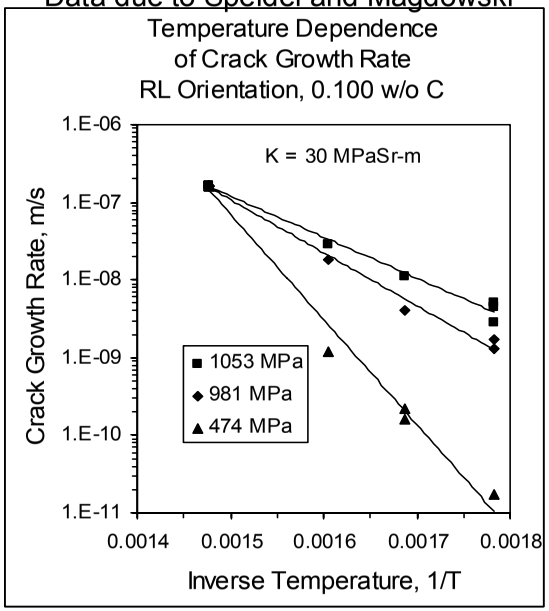


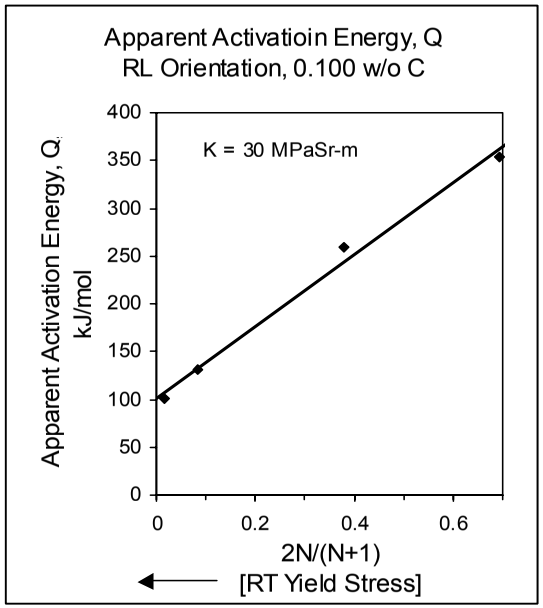
$$Q \equiv -R \left.\frac{\partial \ln \dot{a}}{\partial (1/T)}\right|_{K_R,\eta} = \Delta\tilde{H} - \frac{2N}{N+1}\Delta H^o \ln\left(\frac{K - K_{th}}{K_c - K_{th}}\right)$$

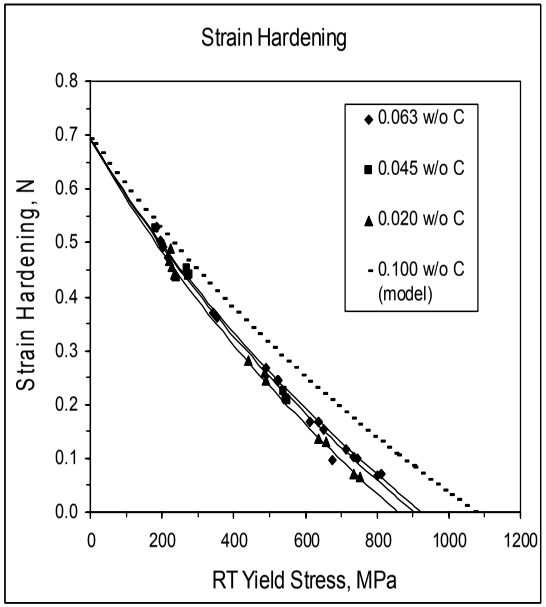
Apparent activation energy Q decreases with increasing Applied Stress Intensity Factor, K

RL Orientation Apparent Activation Energy Q is Decreasing Function of RT Yield Stress

Data due to Speidel and Magdowski



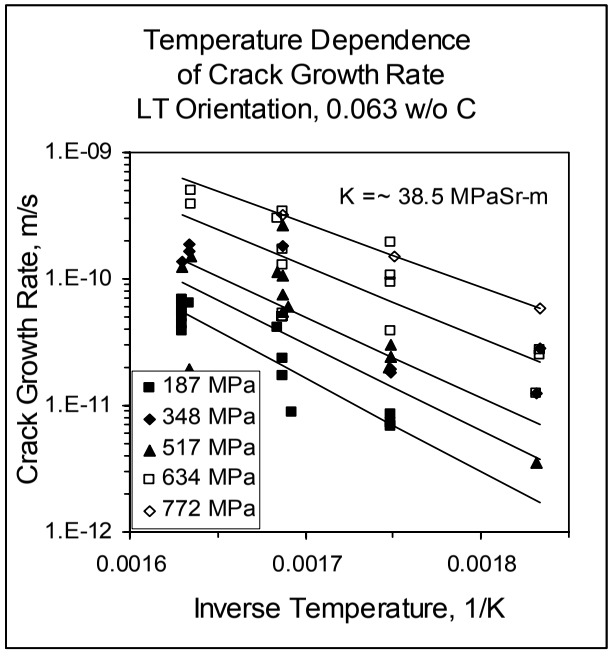


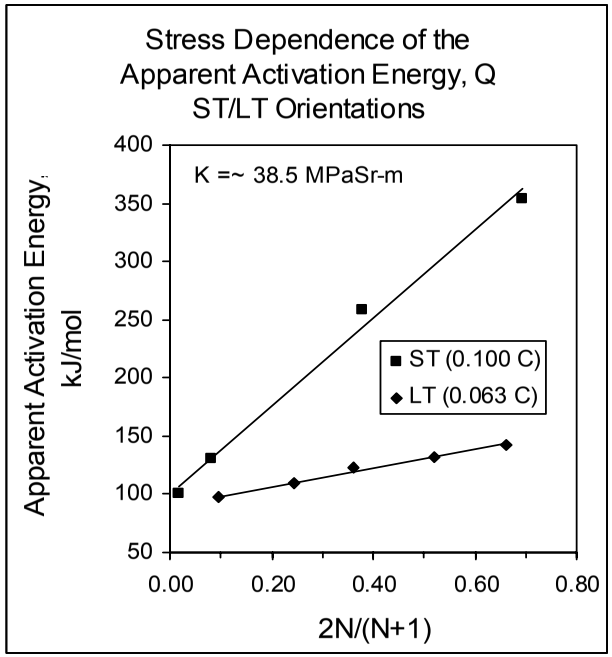


$$Q \equiv -R \left.\frac{\partial \ln \dot{a}}{\partial (1/T)}\right|_{K_R,\eta} = \Delta\tilde{H} - \frac{2N}{N+1}\Delta H^o \ln\left(\frac{K - K_{th}}{K_c - K_{th}}\right) \qquad N = \ln\left(\frac{2}{1 - \sigma_y/\sigma_s}\right)$$

Apparent activation energy Q decreases with increasing RT yield stress (decreasing strain hardening)

LT Orientation Apparent Activation Energy Q Also is Decreasing Function of RT Yield Stress

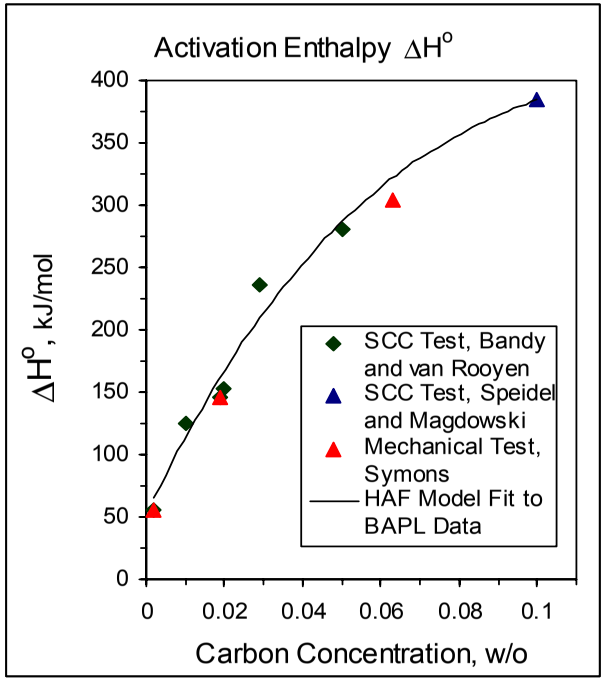




$$Q \equiv -R \left.\frac{\partial \ln \dot{a}}{\partial (1/T)}\right|_{K_R,\eta} = \Delta\tilde{H} - \frac{2N}{N+1}\Delta H^{o} \ln\left(\frac{K - K_{th}}{K_c - K_{th}}\right)$$

LT orientation Q decreases with increasing RT YS (decreasing N) but at a lesser rate than for ST orientation

Reality Checks

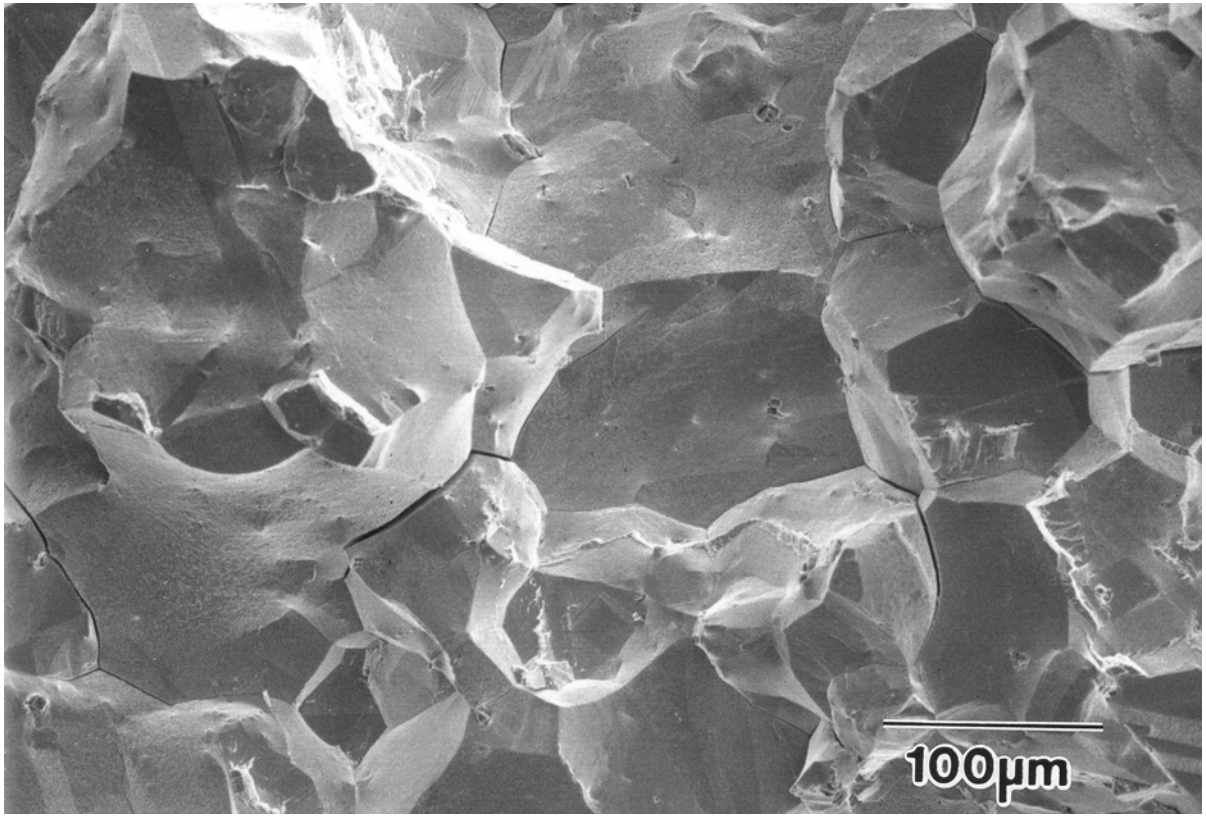


- Model fitting parameters must fall within physical bounds
- Parameter values, e.g, ΔH^o, obtained by fitting models to SCC data should be consistent with data obtained by separate effects tests

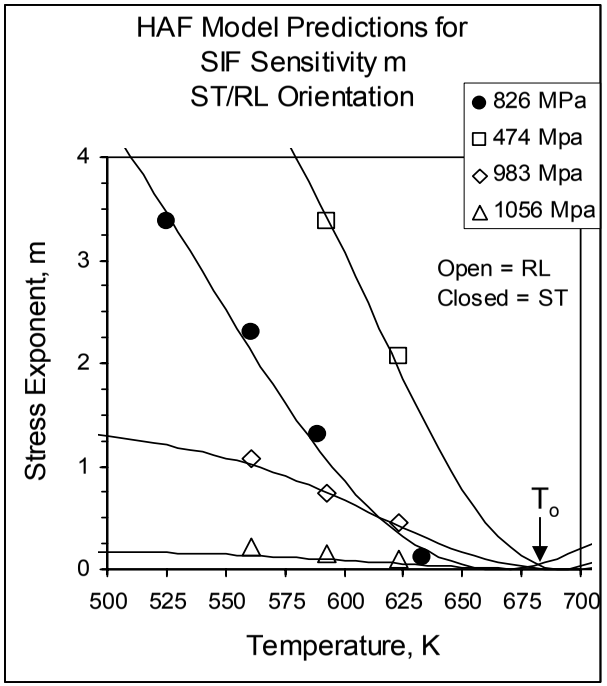
Conclusions

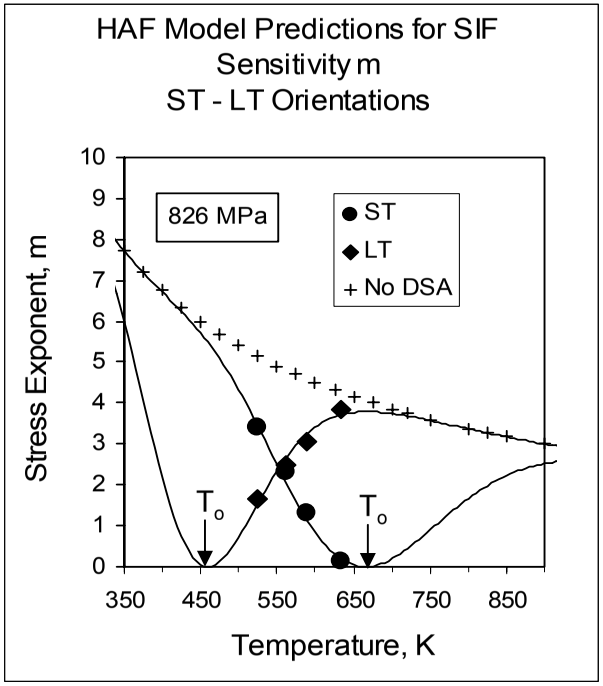
- A600 PWSCC is a complex function of the SCC variables
- To capture this complexity requires comprehensive data sets obtained on single heats of Alloy 600
- Physical models help in sorting out complex behaviors and provide higher confidence disposition curves

QUESTIONS?



Orientation Dependence of CGR Established by Transition Temperature T_o





$$m = \frac{2N}{N+1}\frac{\Delta H^o(C) + U(\bar{n})}{RT} = \frac{2N}{N+1}\frac{\Delta H^o}{RT}\left\{1 - \alpha \exp\left[-\beta\left(\ln\left(\frac{T}{T_o}\right)\right)^2\right]\right\}$$

Modeling Coolant Borne Hydrogen Effects on Alloy 600 Crack Growth Rate

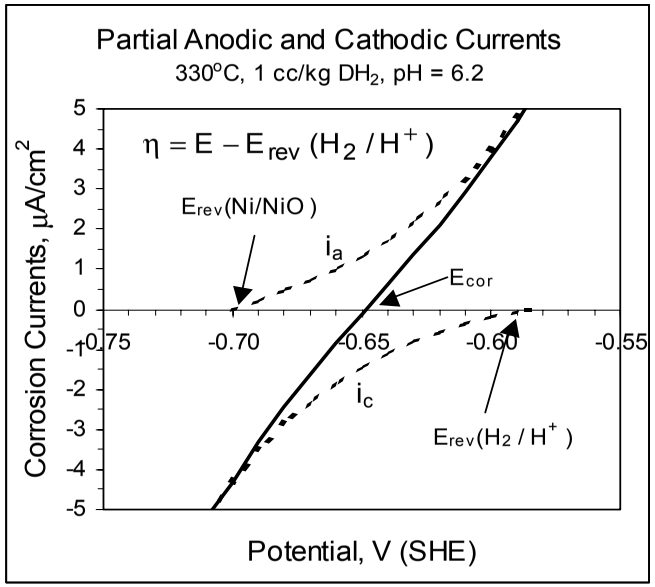
DH_2 establishes E_{rev} (H_2 / H^+)

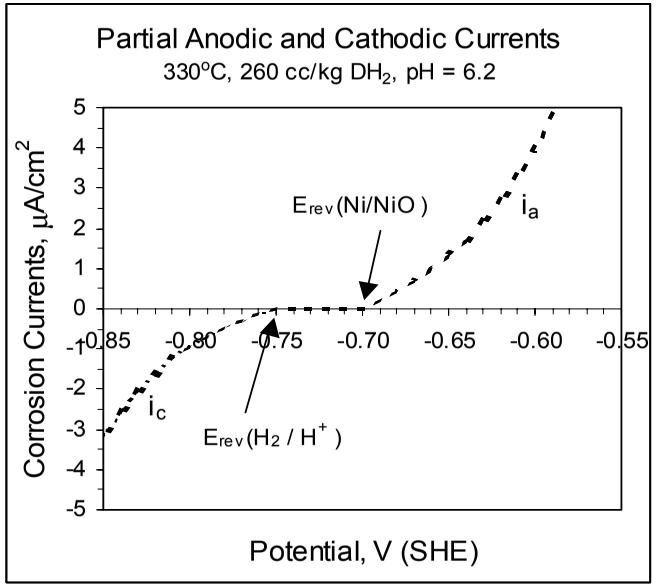
Large DH_2 results in no Ni corrosion and no H_2(cor)

Anode : $Ni + H2O = NiO + 2H^+ + 2e^-$

Cathode : $H^+ + e^- = H^o$; $2H^o \Leftrightarrow H_2(cor)$

$$f_{H_2(cor)} = \kappa [H^+]^2 \exp\left(-\frac{\alpha \eta F}{RT}\right) \propto i_c$$





SCC Growth Rate of Nickel Based Alloy 132 Weld Metal

September 29- October 2, 2003
US NRC Conference on
Vessel Penetration Inspection, Cracking and Repairs

T.Yonezawa*, K.Tsutsumi, H.Kanasaki*, K.Yoshimoto*, Y.Nomura*, S.Asada****

***Takasago R & D Center, Mitsubishi Heavy Industries, LTD.**
****Kobe Shipyard & Machinery Works,**
Mitsubishi Heavy Industries, LTD.

MITSUBISHI HEAVY INDUSTRIES, LTD.
TAKASAGO R&D CENTER

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2. EXPERIMENTAL PROCEDURES
3. RESULTS
4. DISCUSSIONS
5. SUMMARY

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INTRODUCTION

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- **In Japan, maintenance guide rule as ASME Sec.XI for allowable SCC flaw size is not established except austenitic stainless steels for BWRs.**
- **In order to complete data base for the maintenance guide rule for allowable SCC flaw size, the Japanese national project on SCCGR measurement test program on the Alloy 600 and its weld metals of Ni based alloys for PWRs and BWRs has been started from April 2000.**
- **Before starting this project, MHI has checked the propriety and applicability of periodic unloading method for PWSCC GR measurement test.**

INTRODUCTION (Contd.)

MITSUBISHI HEAVY INDUSTRIES, LTD. TAKASAGO R&D CENTER

- **In western PWR plants, Alloy 182 is used for SMAW to Alloy 600. In Japanese PWR plants, Alloy 132 was used for different welding method (:alternating current as welding electric current) as the SMAW and consideration of resistance of hot cracking.**

INTRODUCTION (Contd.)

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Japanese Status on Welding Materials for RV Nozzles

Table Difference of Welding Materials between Japan & Western Countries

	Japanese PWRs	Western PWRs
Welding Materials	Alloys 132 and 82	Alloys 182 and 82
Yield Strength of Base Metal (MPa)	200～350	300～500
Surface Finishing	Polished by Buff	Grinded

Alloy 132 : 70Ni-15Cr-9Fe-1Mn-2.5Nb
182 : 67Ni-15Cr-8Fe-7Mn-1.8Nb-0.5Ti
82 : 71Ni-20Cr-2Fe-3Mn-2.5Nb-0.5Ti

PWSCC CGR is affected by the material properties

INTRODUCTION (Contd.)

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The effect of Cr content on PWSCC susceptibility of Alloy 600.

- The PWSCC susceptibility of Alloy 600 decreases with increasing of Cr content.
- Alloy 132, 182 ; 15Cr
  82 ; 20Cr

⬇

- The stress corrosion cracking resistance of Alloy 82 may be higher than that of Alloy 132 and 182.

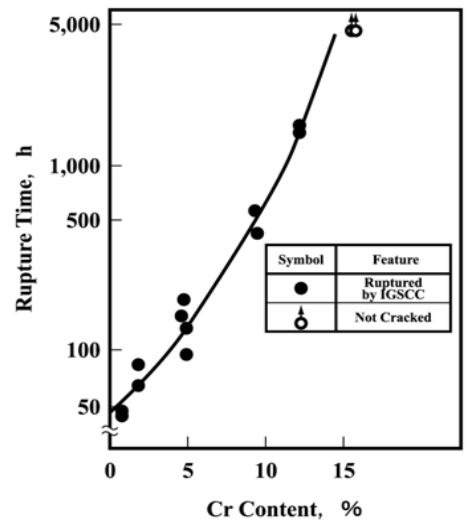

Fig 6. Effect of Cr content on the stress corrosion cracking resistance of solution annealed Ni base-Cr-Fe alloys in 360℃ high temperature water using by constant load stress corrosion cracking test (applied stress is 2.4 × 0.2% Proof stress)

INTRODUCTION (Contd.)

MITSUBISHI HEAVY INDUSTRIES, LTD. TAKASAGO R&D CENTER

The effect of Nb content on PWSCC susceptibility of Alloy 600.

- Nb and Ti addition increase PWSCC susceptibility of Alloy600, due to suppressing of IG carbides precipitation.

- Alloy 132 ; 2.5Nb
  182 ; 1.8Nb-0.5Ti
  82 ; 2.5Nb-0.5Ti

- The susceptibility of Alloy 132 may be same as that of Alloy 182.

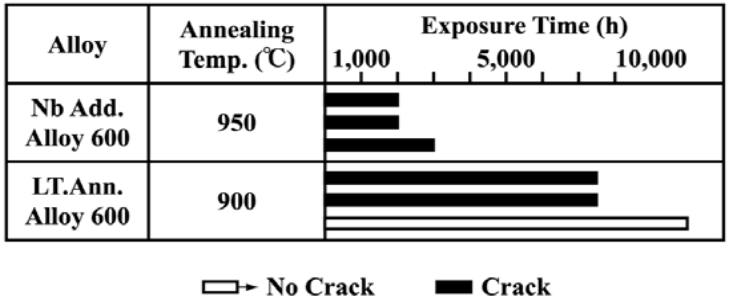

Fig7. Effect of Nb addition on the sress corrosion cracking resistance of annealed Alloy 600 in 360℃ high temperature water, using by prestrained U bent specimen.

INTRODUCTION (Contd.)

MITSUBISHI HEAVY INDUSTRIES, LTD.
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- **In western PWR plants, Alloy 182 is used for SMAW to Alloy 600. In Japanese PWR plants, Alloy 132 was used for different welding method (:alternating current as welding electric current) as the SMAW and consideration of resistance of hot cracking.**

⇩

- **In this study, we tested the PWSCC growth rate of Alloys 132 and 82 welded.**

OBJECTIVES

MITSUBISHI HEAVY INDUSTRIES, LTD.
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- **To compared the PWSCC growth rates of Alloys 132 and 82 with literature data on Alloy 182.**

- **To recommend PWSCC GR measurement test techniques. (The propriety and applicability of periodic unloading method for PWSCC GR measurement test.)**

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EXPERIMENTAL PROCEDURES

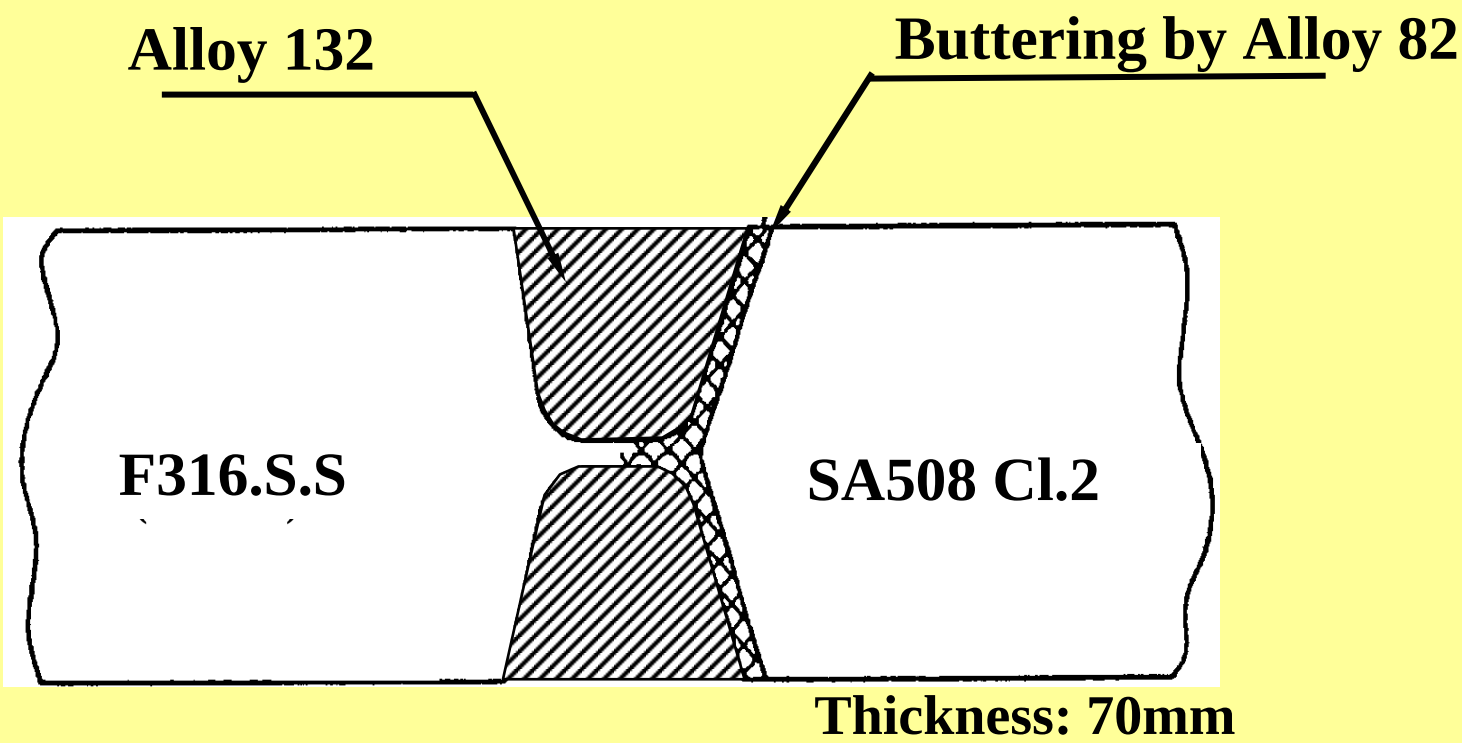
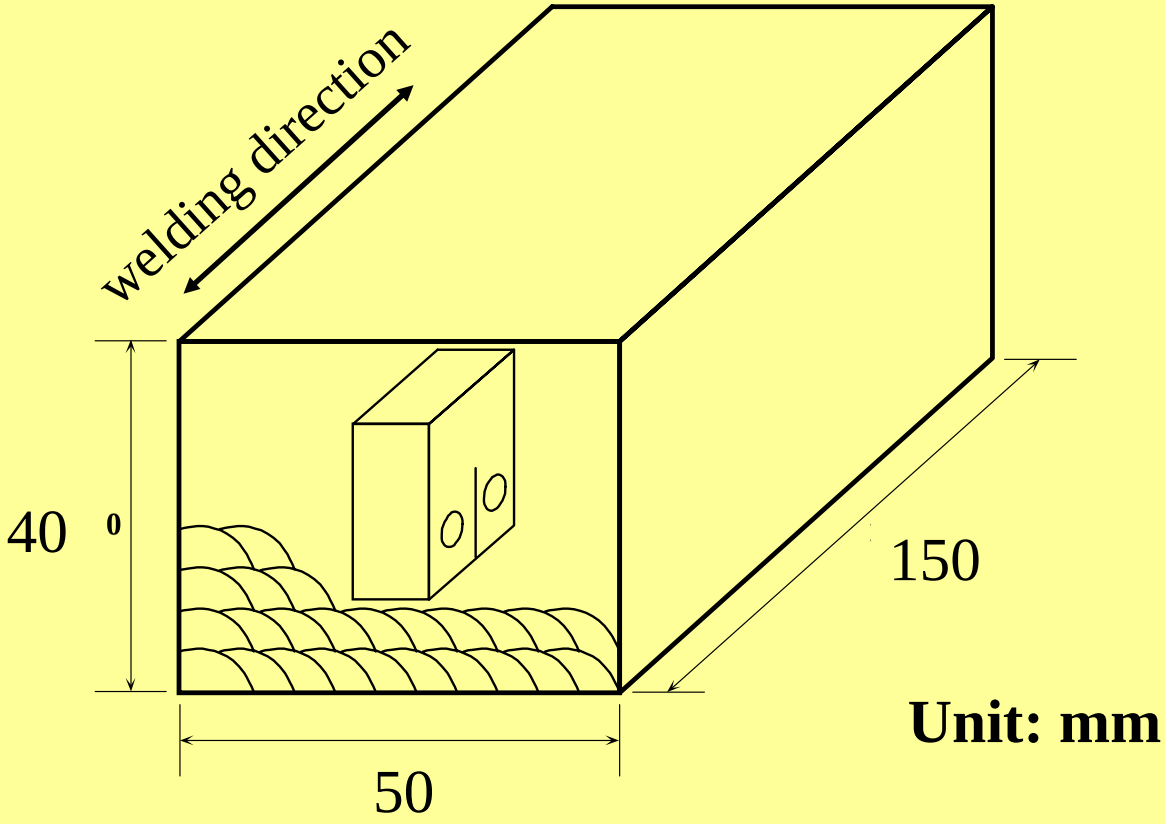


Figure Welding joint configuration of dissimilar metal arc welding model by Alloy 132

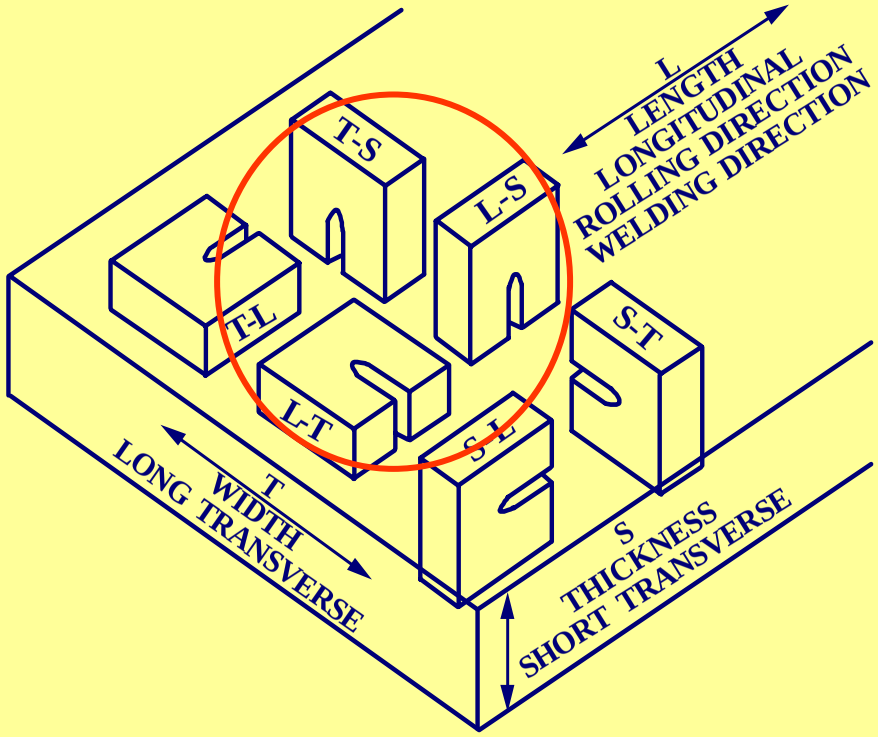
EXPERIMENTAL PROCEDURES



Unit: mm

Figure Machining orientation of CT specimens from deposited metal model of TIG welding by Alloy 82

EXPERIMENTAL PROCEDURES



Test Specimens

- **1/2T CT**
- **Specimen Orientation**
  TS, LS, LT
- **The pre-crack length about 1mm**
- **K_I values**
  20, 35, 60 MPa √ m

Figure Terminology used for orientation of cracks in the test specimens with respect to the weld

EXPERIMENTAL PROCEDURES

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Testing Environment

Temperature	**; 325°C**
H_3BO_3	**; 1800 ppm as Boron**
LiOH	**; 3.5 ppm as Lithium**
DH_2	**; 30cc/kg STP H_2O**
DO_2	**; <5ppb**
Autoclave	**; refreshed type**

EXPERIMENTAL PROCEDURES

The periodic unloading conditions for Alloys 132 and 82, to evaluate the effect of the periodic unloading condition on the CGRs of weld metals.

(1) Trapezoidal wave 1 : R = 0.7, holding time : 360 seconds (0.1 hours)
(2) Trapezoidal wave 2 : R = 0.7, holding time : 1,080 seconds (0.3 hours)
(3) Trapezoidal wave 3 : R = 0.7, holding time : 9,000 seconds (2.5 hours)
(4) Constant loading

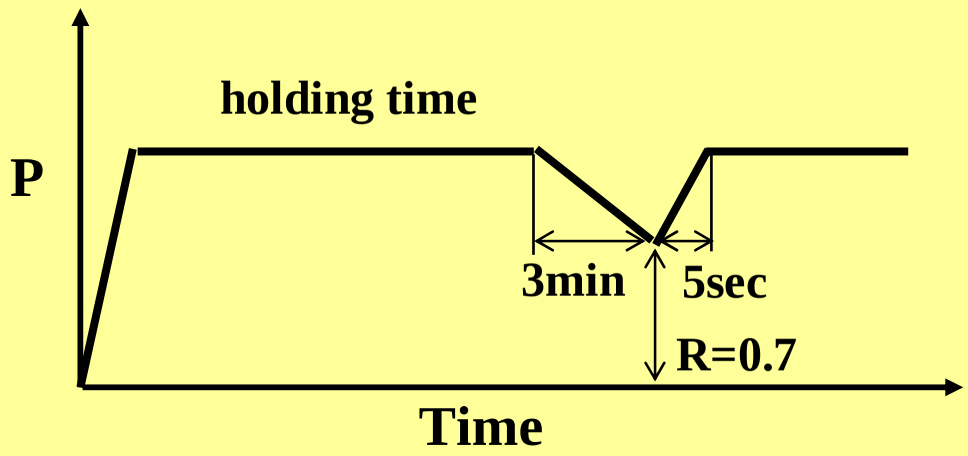

Figure Trapezoidal Wave form

EXPERIMENTAL PROCEDURES

MITSUBISHI HEAVY INDUSTRIES, LTD.
TAKASAGO R&D CENTER

PDM signal → Measuring of SCC Length → CGR data

V_1/V_0 v.s. t ➡ a_{pdm} v.s. t ⇨ Measuring average Crack length Δa ⇨ CGR data

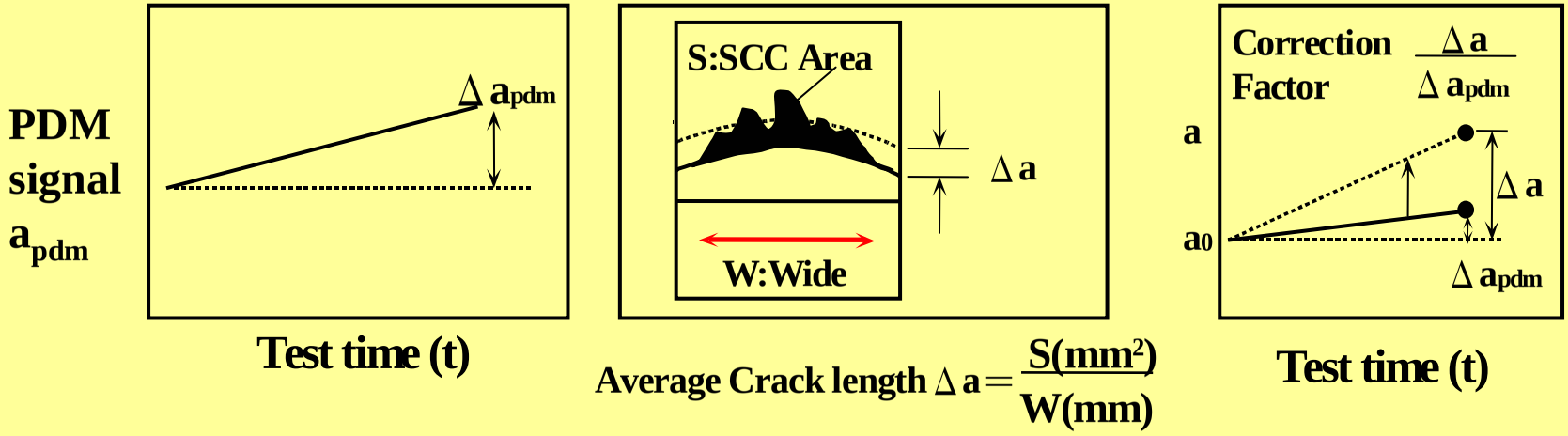

Figure CGR evaluation method

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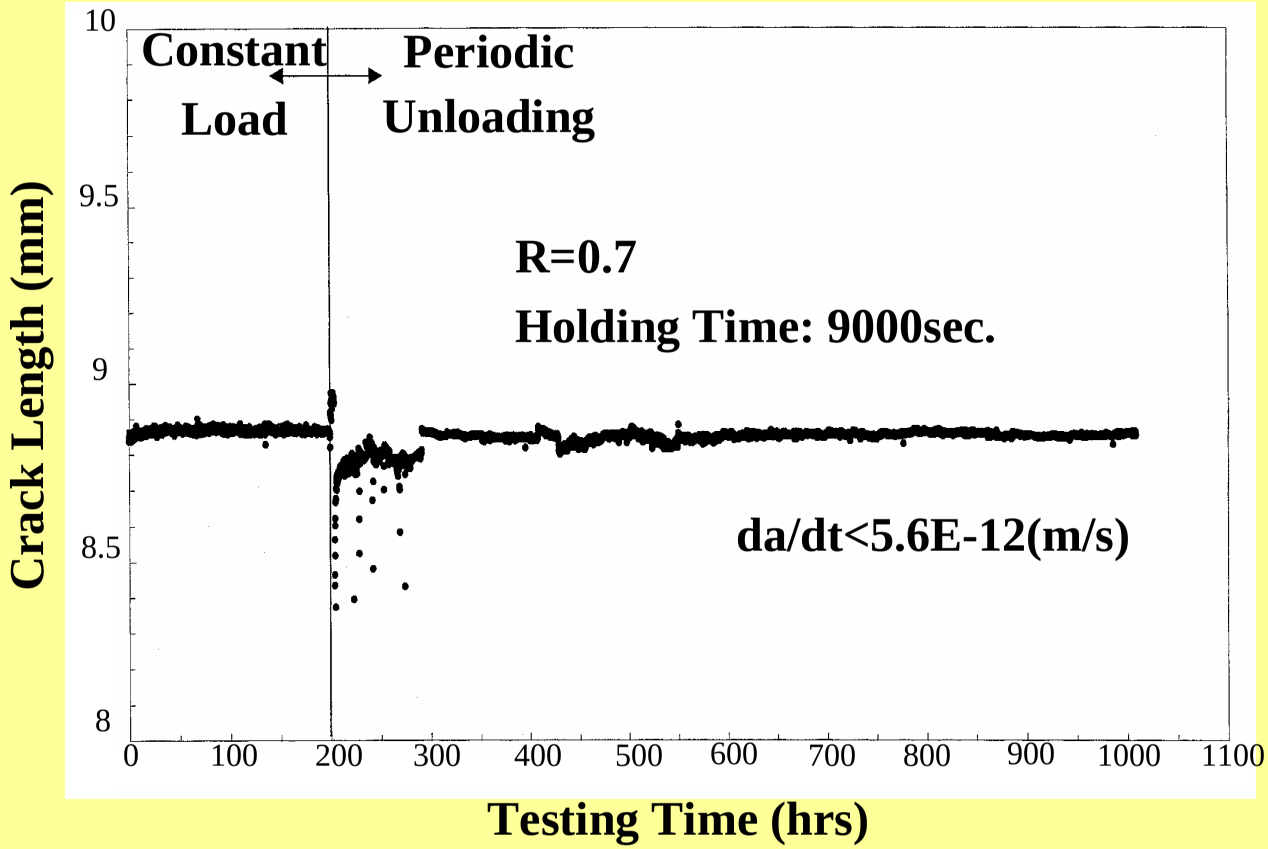
1. INTRODUCTION
2. EXPERIMENTAL PROCEDURES
3. RESULTS
   1) Effect of K value on the PWSCC
   2) Fractography in respect of dendrite orientations
   3) CGR of Alloys 132,82 and 182
4. DISCUSSIONS
5. SUMMARY

RESULTS (Effect of K value)



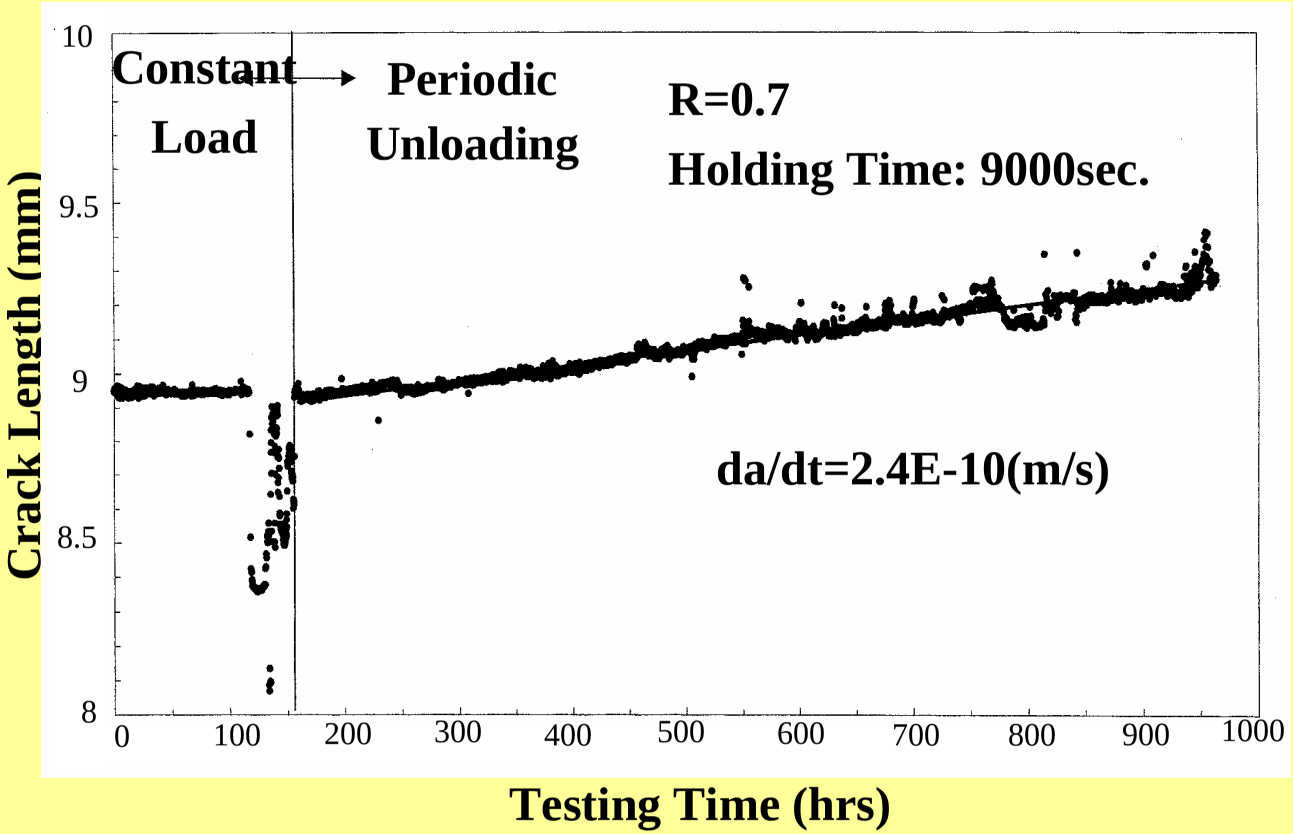
Alloy 132,

K_I values :20 MPa√m,

TS orientation

Figure CGR on-line monitoring results

RESULTS (Effect of K value)



Alloy 132,

K_I values :35MPa√m,

TS orientation

Figure CGR on-line monitoring results

RESULTS (Fractography)

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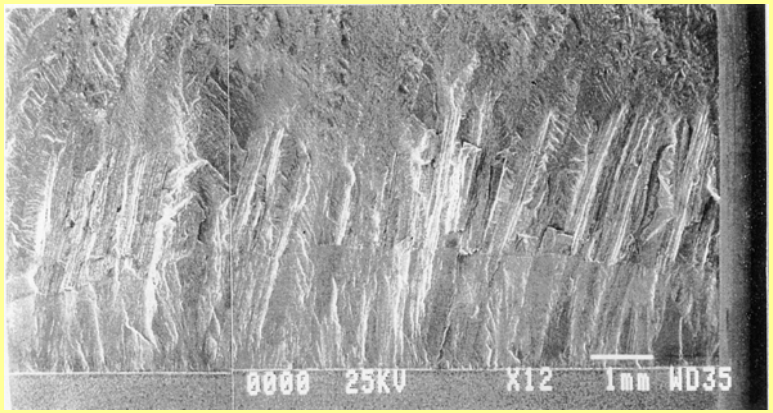
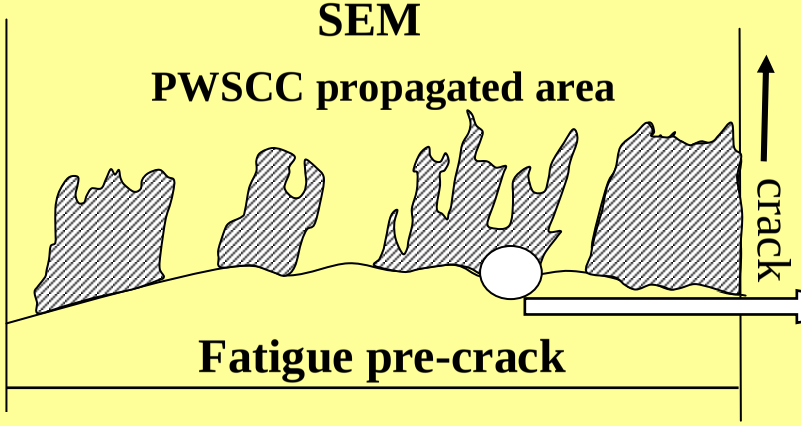


SEM

- The crack front of these inter-dendritic PWSCC was not uniform and the area of no ID PWSCC initiation zone was also observed at the fatigue pre-crack tip.
- The crack propagation path was inter-dentrite and parallel direction for dendrite.



dendrite direction

pre-crack

Inter-dentrite

Figure Fractography of TS specimen after SCC test

RESULTS (Fractography)

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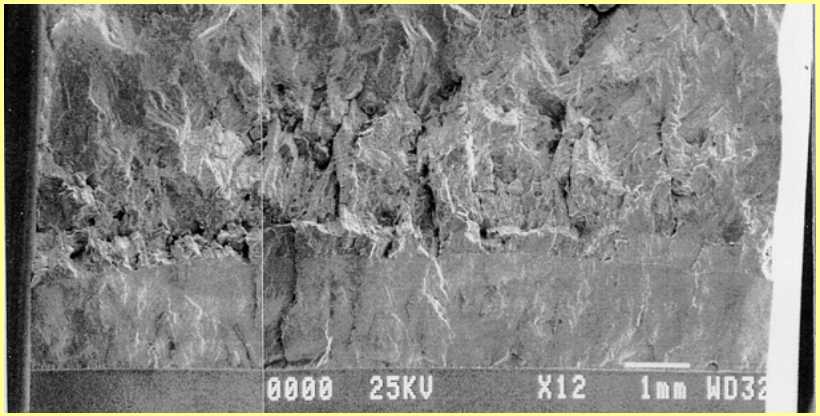
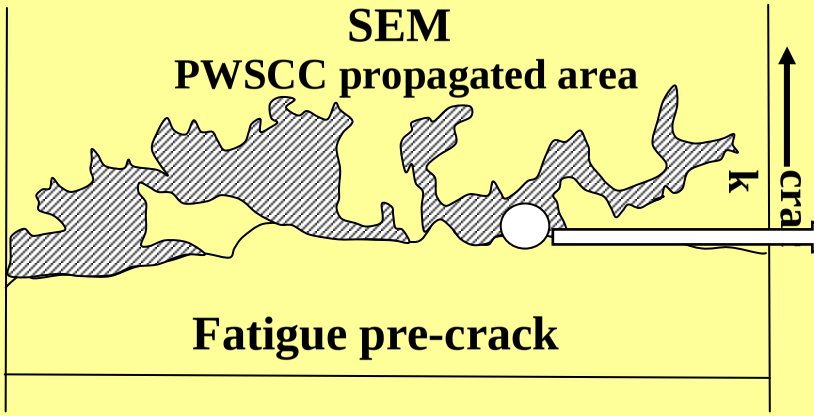
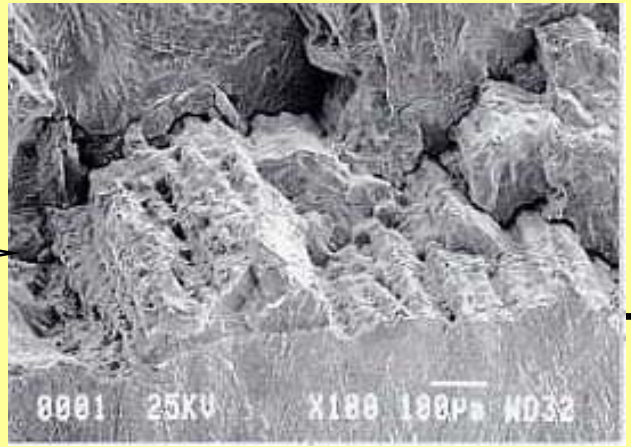


- The crack front of these inter-dendritic PWSCC was complicated and not uniform.
- The crack propagation path was inter-dentrite and perpendicular direction for dendrite.





dendrite direction

pre-crack

Inter-dentrite

Figure Fractography of LT specimen after SCC test

RESULTS (CGR of Alloys 132, 82 and 182)

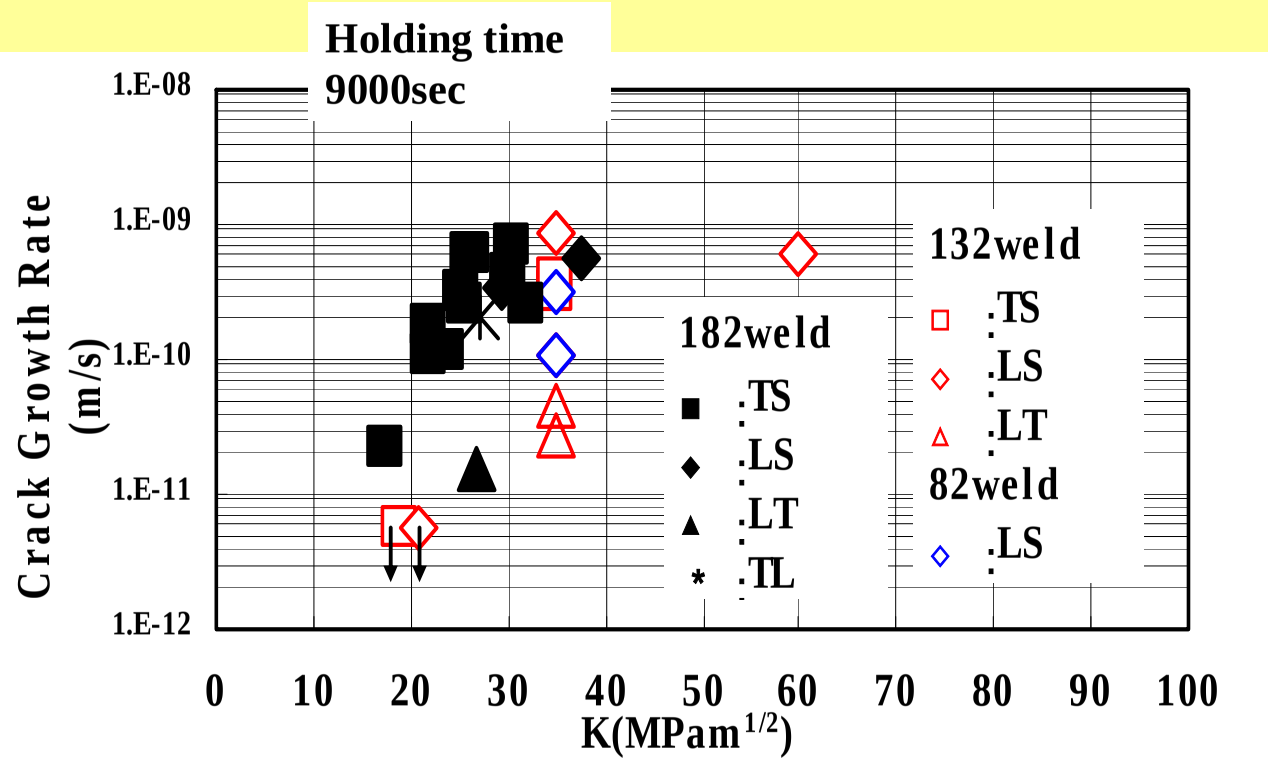
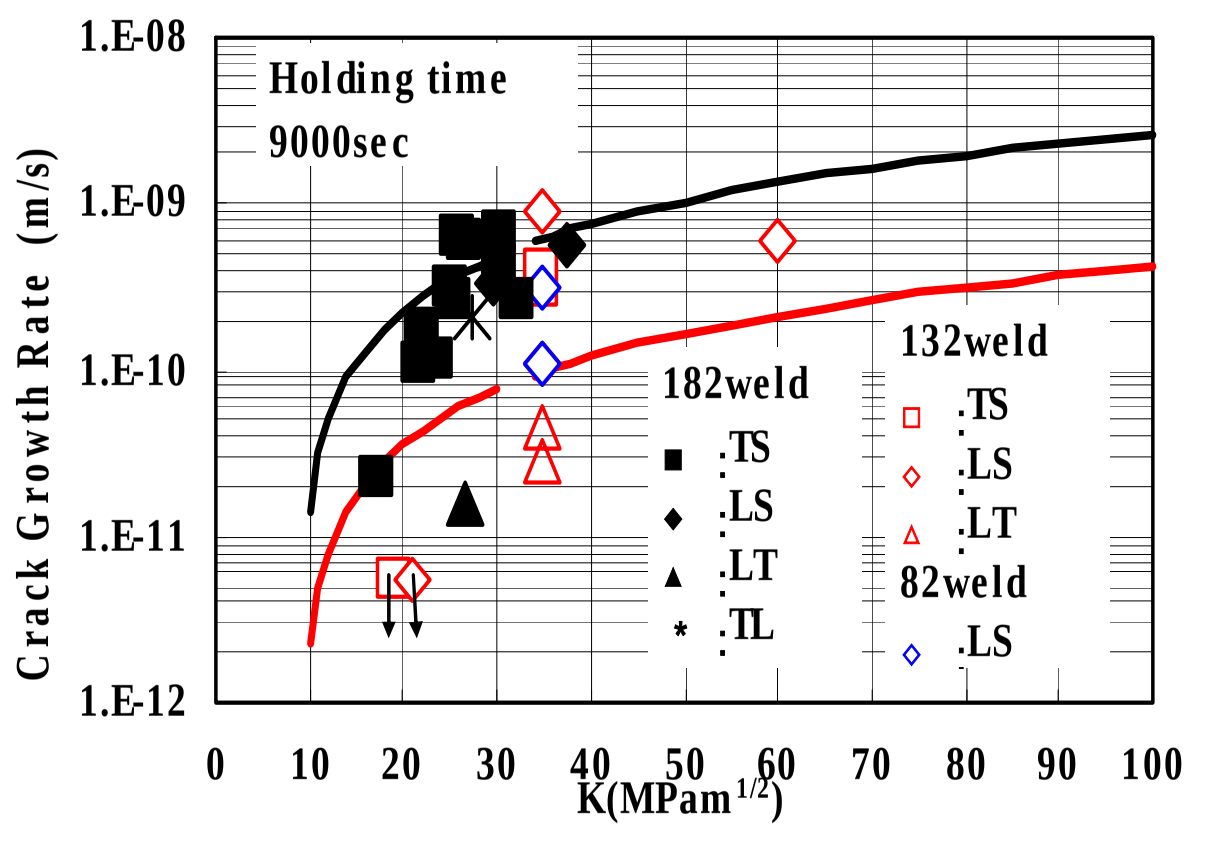


Figure Comparison between CGR of Alloys 132, 82 and 182 weld metal

PWSCC CGRs

1) Alloy 132 ≥ Alloy 82
2) LS, TS > LT
3) LS nearly equal to TS

RESULTS (CGR of Alloys 132,82 and 182)



182 weld(325°C)
W.Banford

Alloy 600 (325°C)
P.Scott

<u>PWSCC GRs</u>

Alloy 182

≒ Alloy132

> Alloy600

Figure Comparison between CGR of Alloys 132, 82 and 182 weld metal

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“the effect of periodic unloading on the CGR”.

(1) Maintaining of the straight crack front

(2) The effect of the holding time on acceleration of the SCC GR

(3) Reducing SCC incubation time

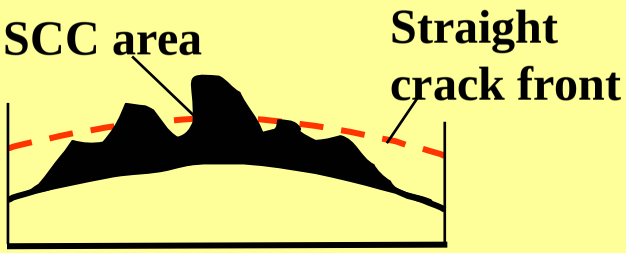
5. SUMMARY

DISCUSSIONS

MITSUBISHI HEAVY INDUSTRIES, LTD. TAKASAGO R&D CENTER

1. Maintaining of the straight crack front

The straight crack front was not gained for the specimens of the Alloy 132 under constant loading in spite of periodic unloading.

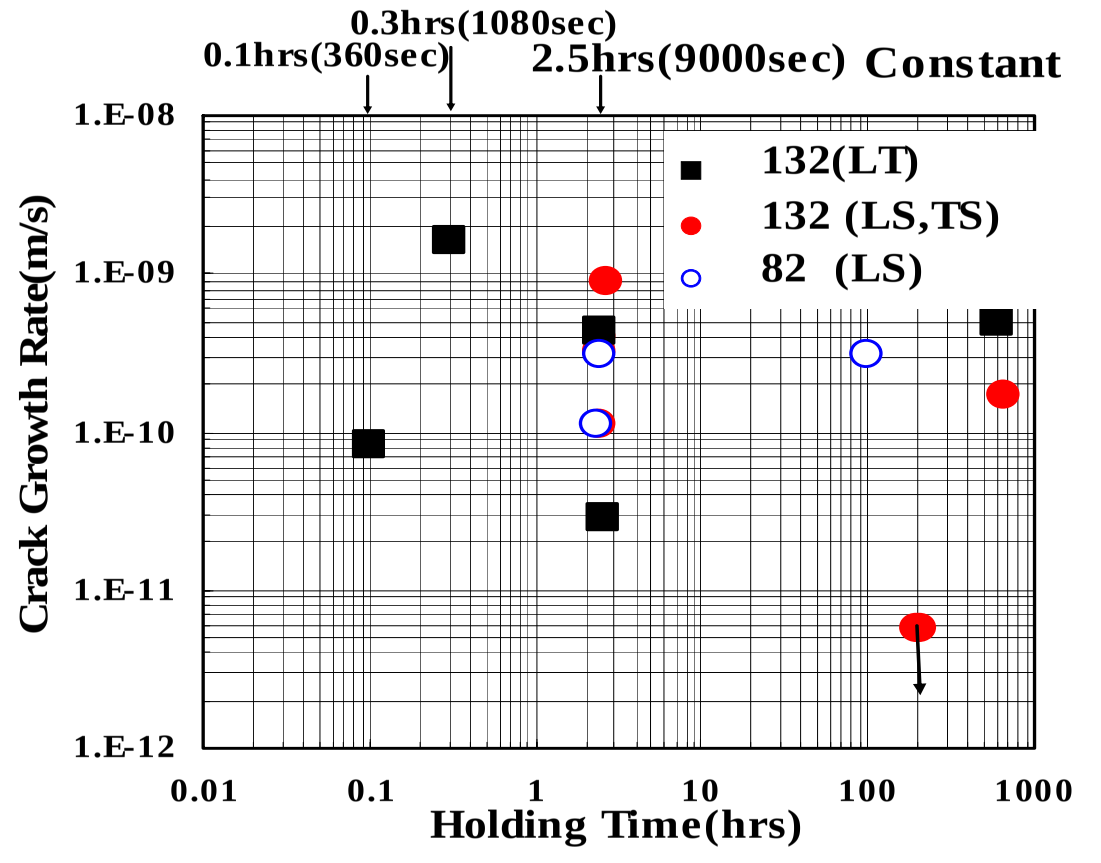


The PWSCC susceptibility is affected by the Metal. Condi. of the G.B. And the Metal. Condi. of G.B. for W.M. is very complicated.

The periodic unloading method has not to be applicable for the ID PWSCC GR measurement of Ni based W. M., to maintain the straight crack front.

DISCUSSIONS

2. The effect of holding time on acceleration of the SCC GR



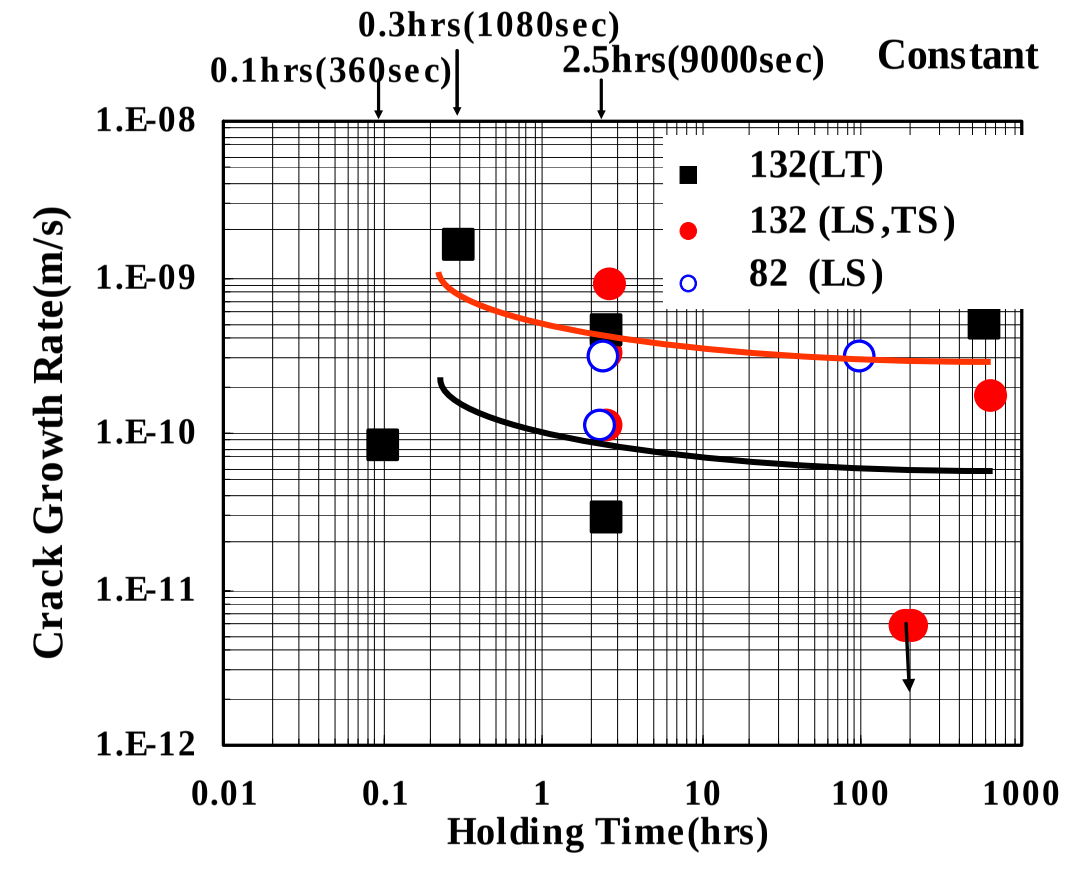
K=35MPa√m
325°C
B/Li:1800/3.5ppm
DO<0.005ppm
DH=30cc/kg H_2O

Figure The effect of holding time for cyclic loading on CGRs

DISCUSSIONS

MITSUBISHI HEAVY INDUSTRIES, LTD. TAKASAGO R&D CENTER

2. The effect of holding time on acceleration of the SCC GR

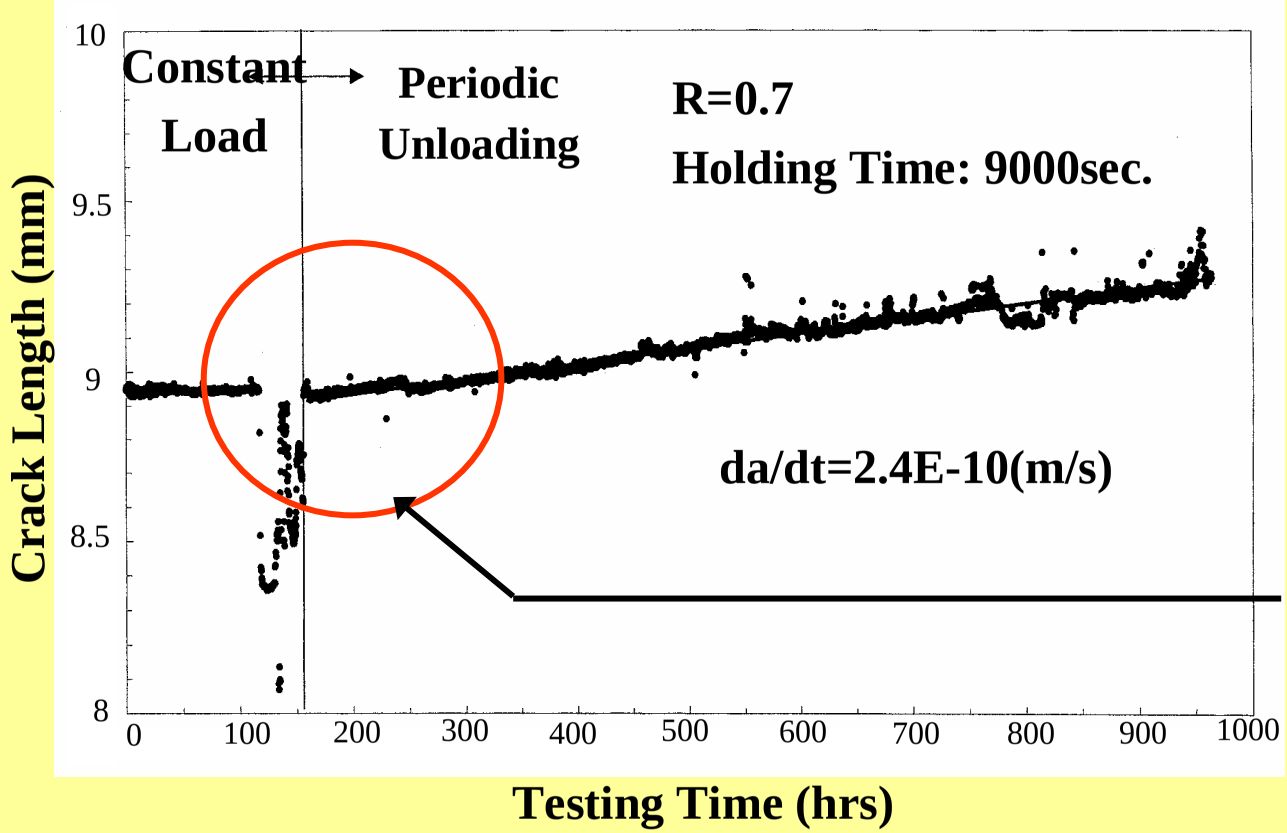


K=35MPa√m
325°C
B/Li:1800/3.5ppm
DO<0.005ppm
DH=30cc/kg H_2O

Figure The effect of holding time for cyclic loading on CGRs

DISCUSSIONS

3. Reducing SCC incubation time



Remarkably changed

The recommended holding times will vary for different materials and specimen orientations.

DISCUSSIONS

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3. Reducing SCC incubation time

•Periodic unloading is recommended for producing the ID pre-crack for the PWSCC GR measurement test. But, the effect of periodic unloading on the real PWSCC GR is not always well known.

•The ID PWSCC GR measurement test should be conducted under constant loading or trapezoidal wave with a sufficiently long holding time to eliminate the influence of fatigue.

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SUMMARY

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(1) The PWSCC GR of Alloy 132 in this study was not larger than that of Alloy 182 reported in the literature.

(1) The PWSCC was propagated along the dendrite, CGRs of the TS and LS specimens were about 3 to 10 times larger than that of the LT specimen.

(1) The crack front of PWSCC on the fracture surface of specimens was not uniform, even under P.U.

(1) P.U. is recommended for producing the ID pre-crack for the PWSCC GR measurement test. The ID PWSCC GR measurement test should be conducted under C.L. or trapezoidal wave with sufficiently long holding time to eliminate the effect of fatigue.

LOCKHEED MARTIN

The Stress Corrosion Crack Growth Rate of Alloy 600 Heat Affected Zones Exposed to High Purity Water

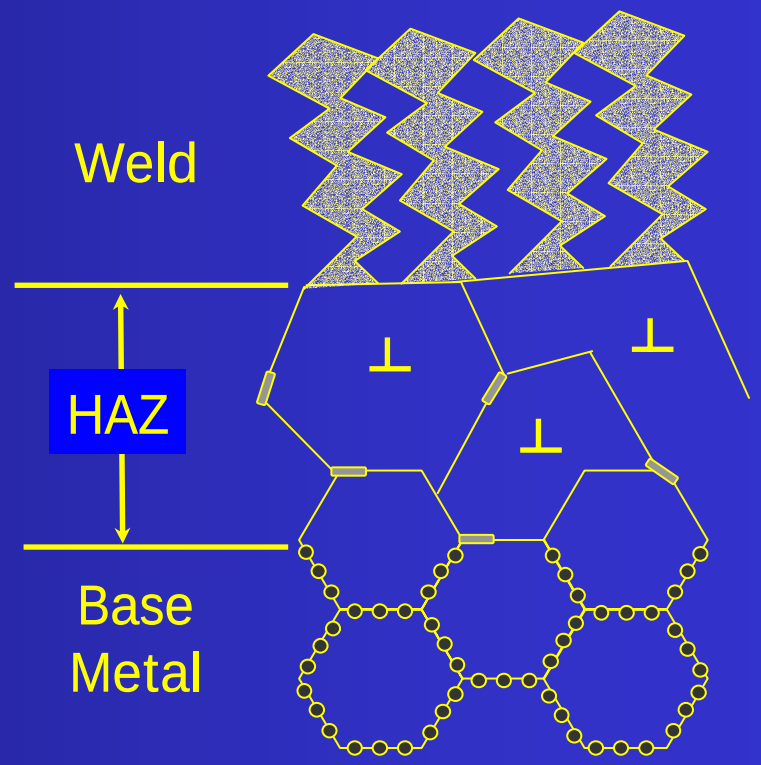
George A. Young, Nathan Lewis, and David S. Morton

Lockheed Martin Corporation
P.O. Box 1072
Schenectady, NY 12301-1072

LOCKHEED MARTIN

Main Points

- Need to consider SCCGR of HAZ independently of base metal (and weld metal)
- Data presented here likely not worst case
- Other nickel-base alloys (*e.g.* A690) likely show increased susceptibility to PWSCC in the HAZ



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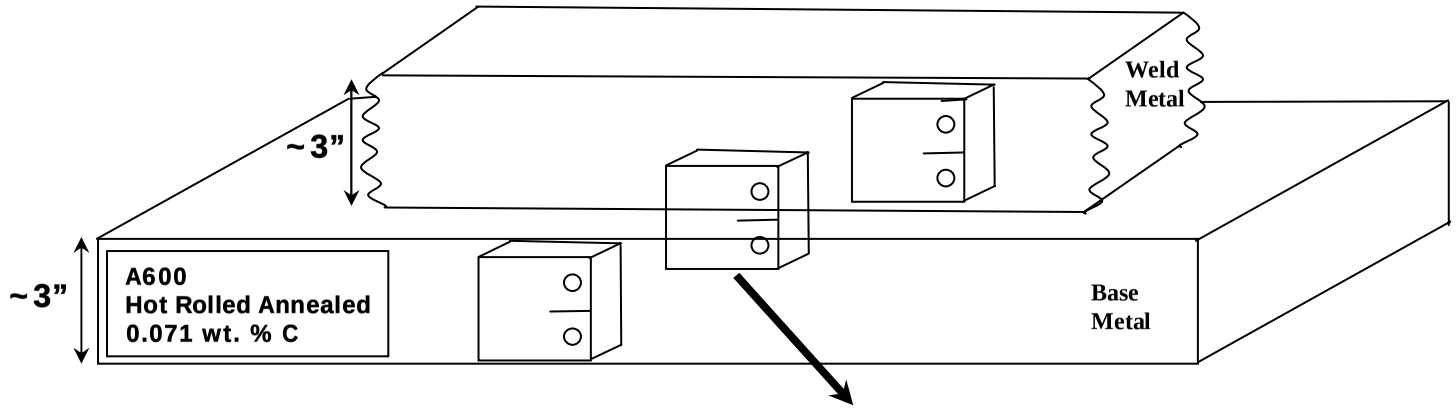
Background

- **Vessel head penetration SCC in three locations**
  - From A600 penetration ID to OD
  - In E-182 weld metal
  - Near the interface of the A600 penetration and the J-groove weld - ***is this SCC in the HAZ?***

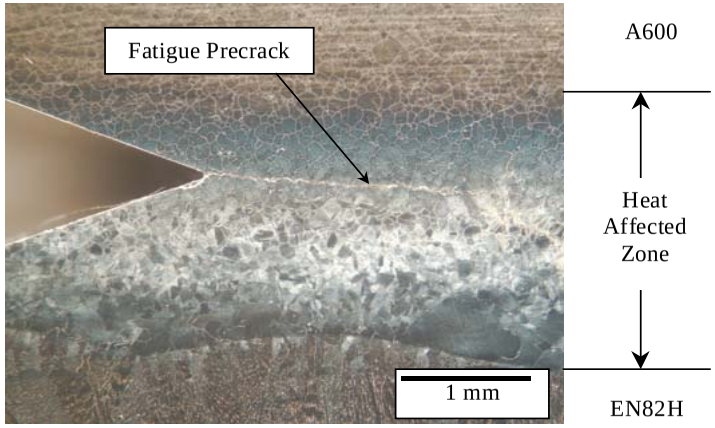
- **Primary water stress corrosion crack growth rate of A600 and its weld metals are well studied - what about the A600 heat affected zone (HAZ)?**

Machine 1.0 CT Specimens from EN82H/A600 HAZ, no PWHT

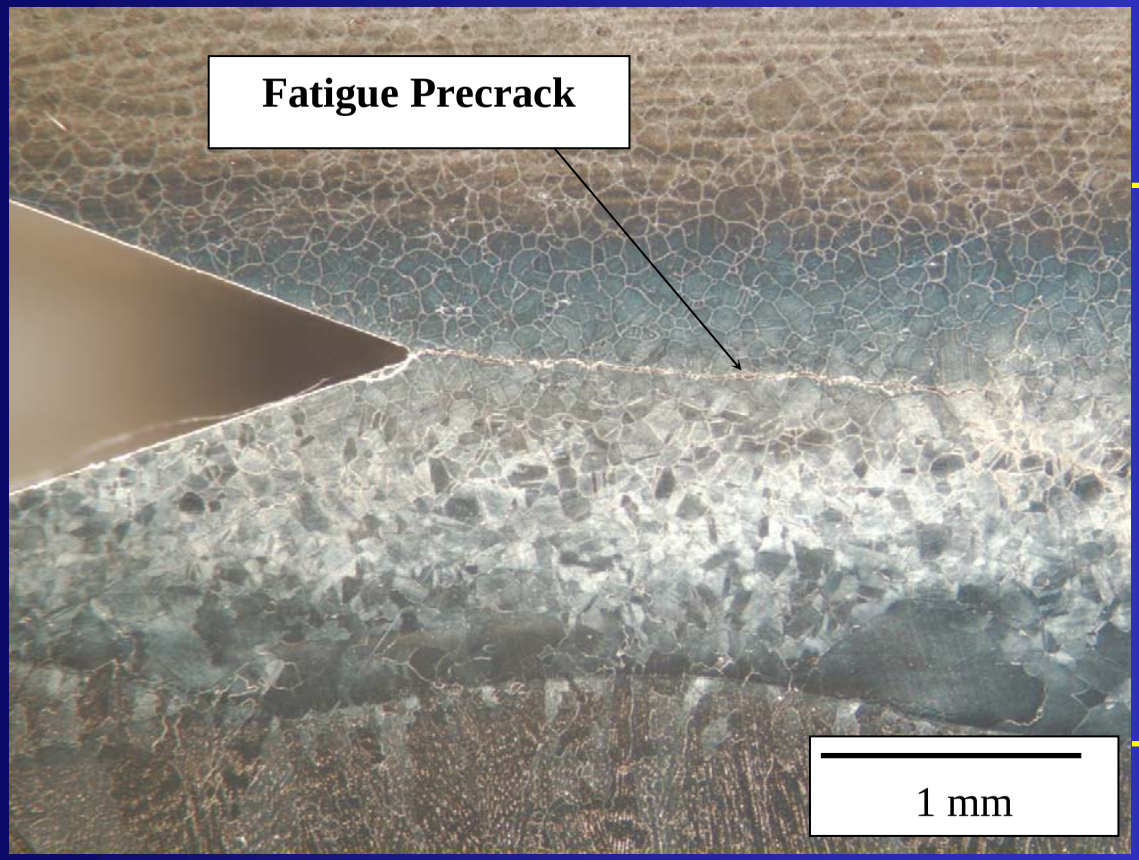


GTAW weld buildup of EN82H

Mill Annealed A600 plate



Notch and precrack entirely in the HAZ



A600

Heat Affected Zone

EN82H

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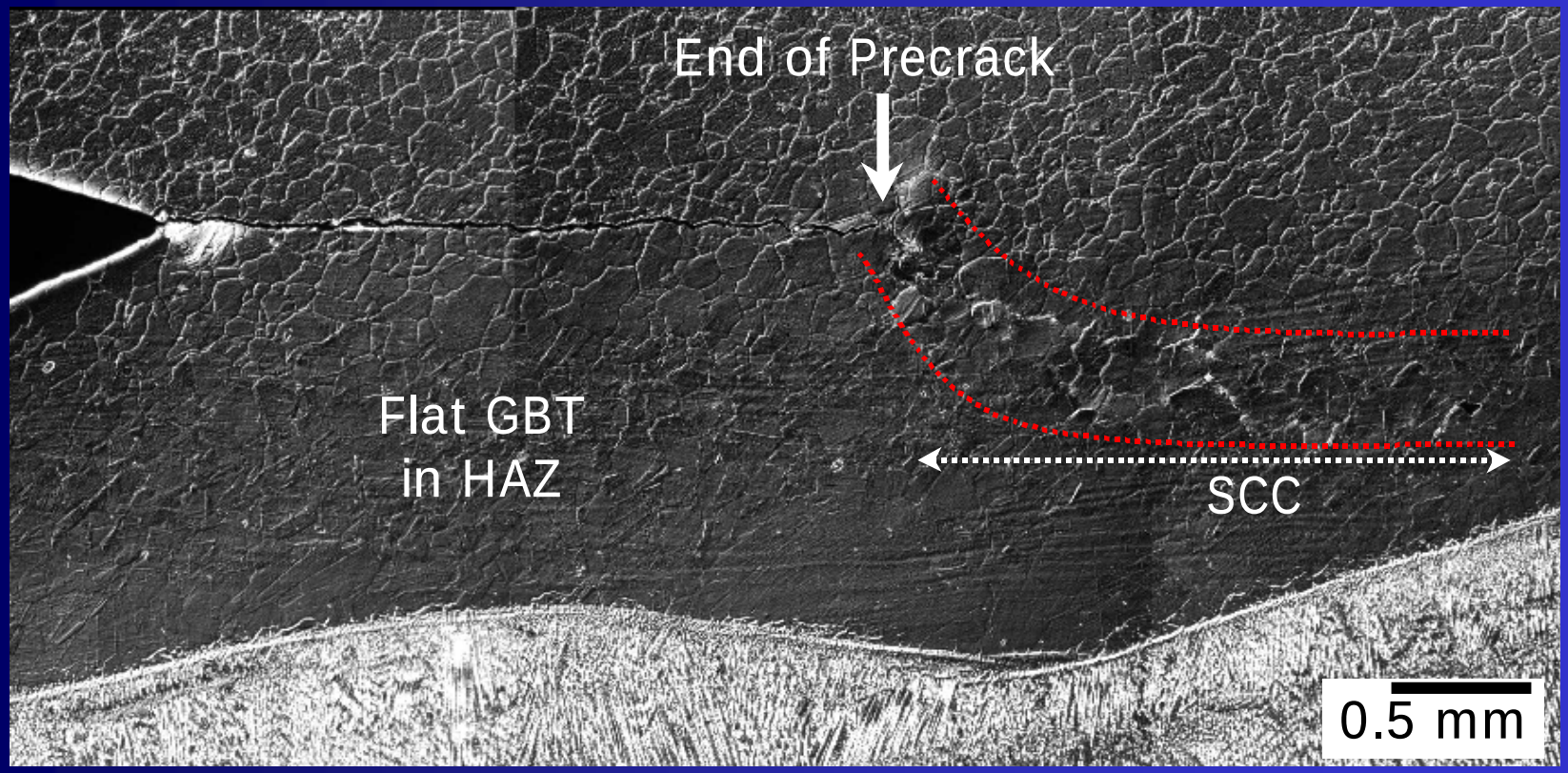
Testing Goals and Conditions

- **Determine temperature dependence (Q_{SCCGR})**
  - Constant electrochemical potential
- **Determine effect of coolant H_2 around Ni/NiO**
- **"Constant" *K* (constant load)**
- **Each sample destructively examined post test**

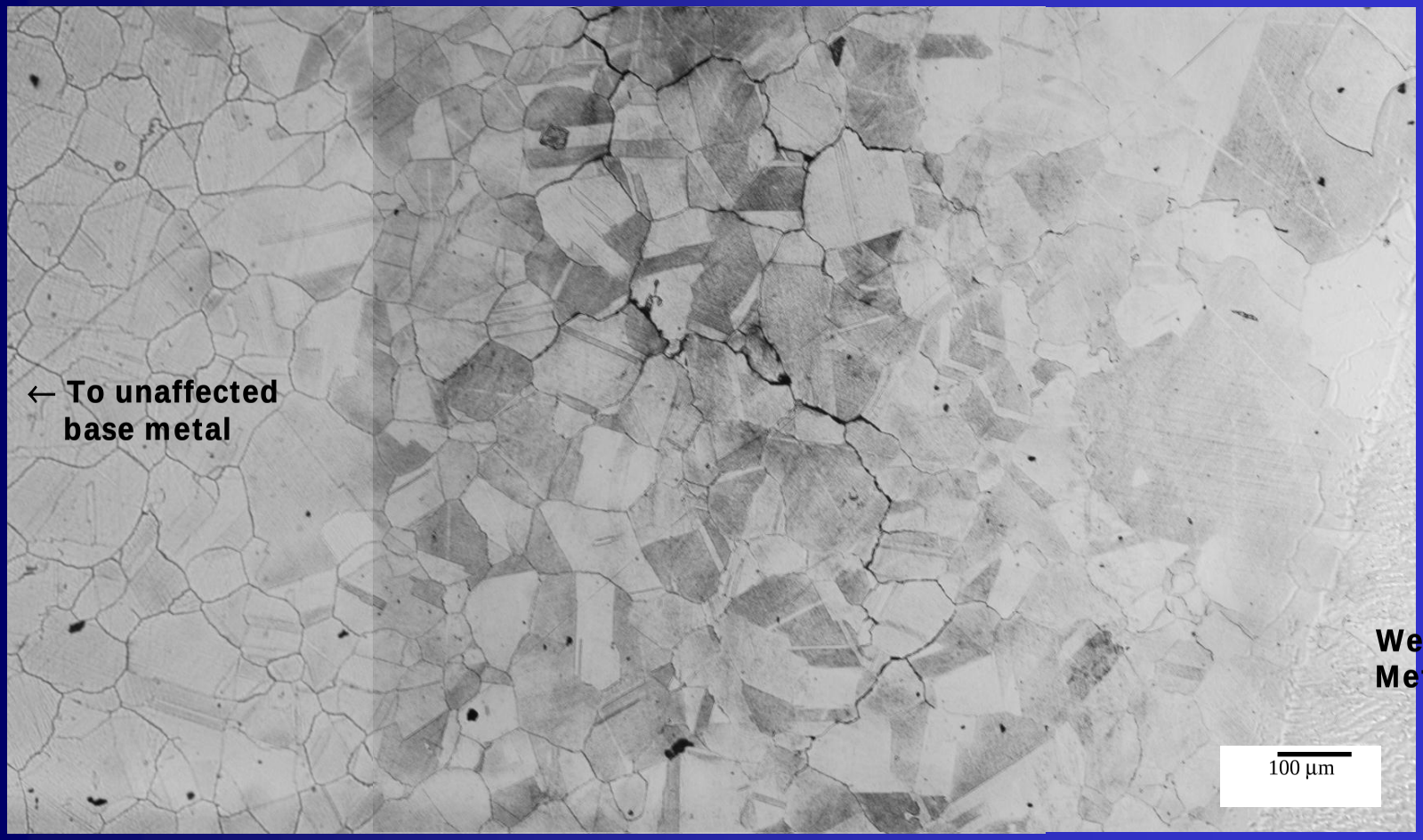
Temperature (^oF / ^oC)	Hydrogen (scc/kg)	Approximate ΔECP from Ni/NiO (mV)	Initial Stress Intensity Factor (ksi$\sqrt{in}$)
600 / 316	9	+2	40
640 / 338	1	-41	40
	18	+6	40
	120	+56	40
680 / 360	30	+6	40

Results

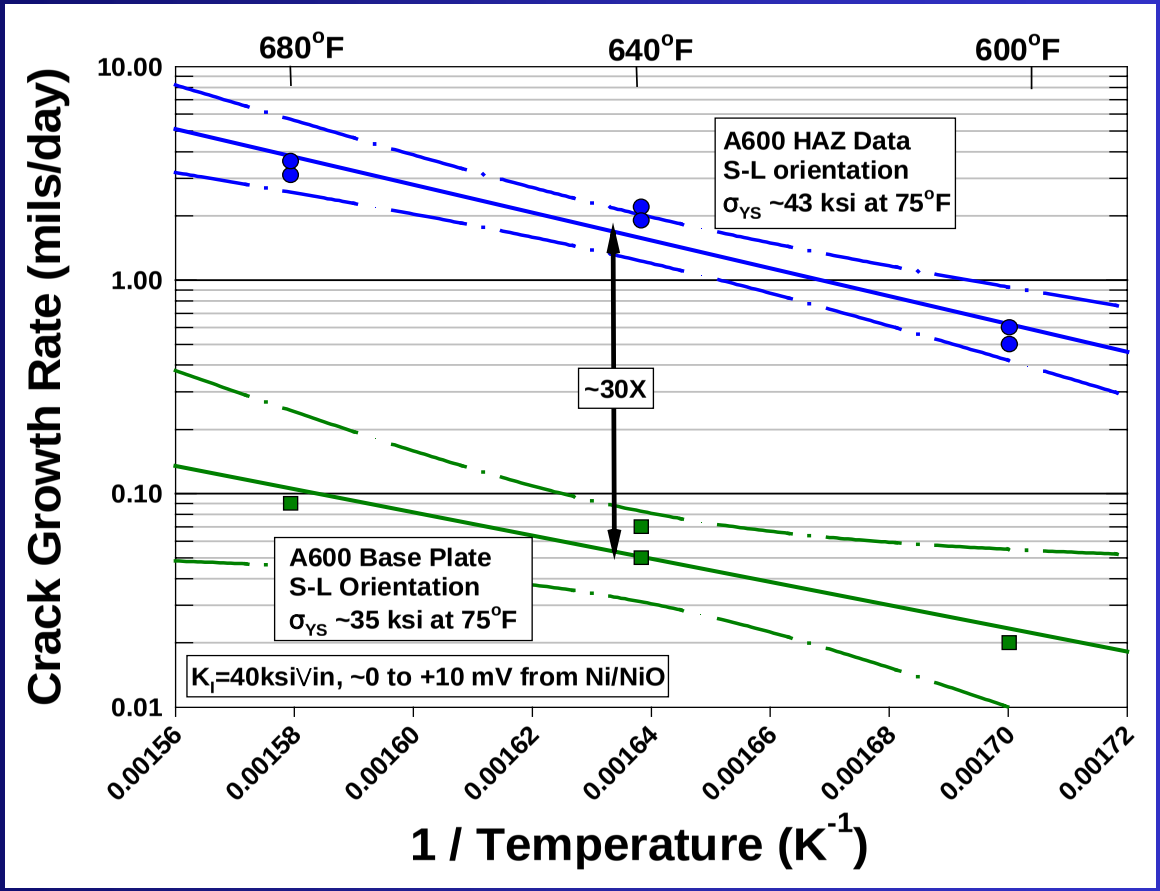
- **SCC occurred entirely in the A600 HAZ**



Branched IGSCC in the A600 HAZ

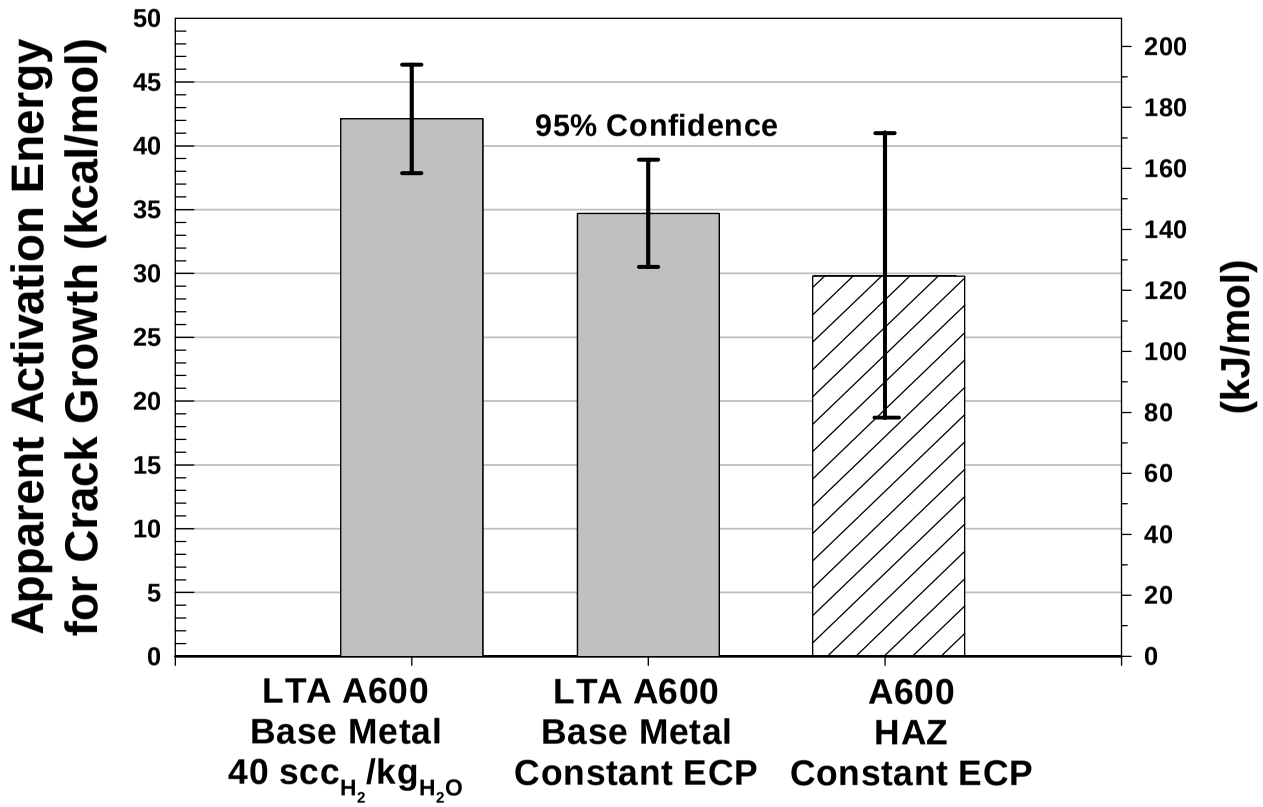


The A600 HAZ displayed ~30X faster crack growth rates than the base metal

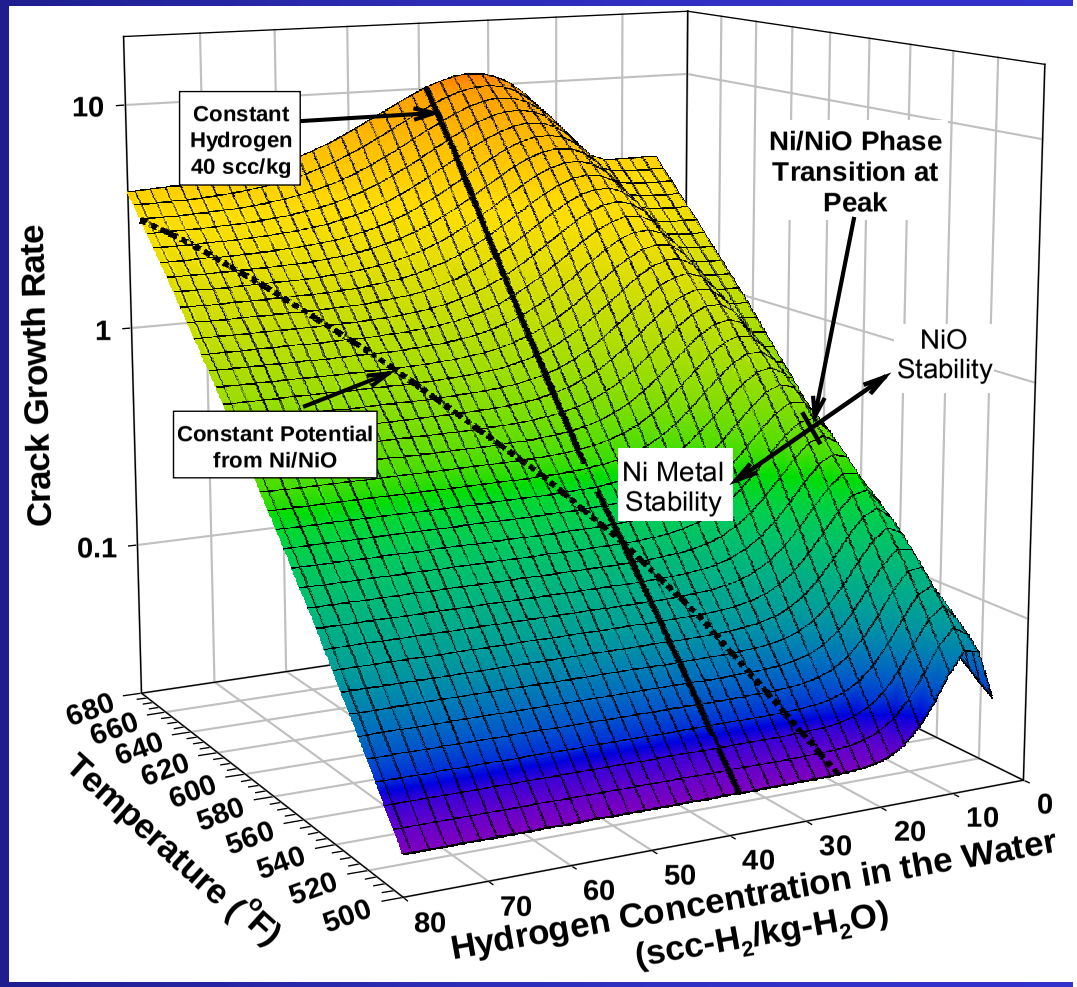


The *Q* for the HAZ is ~ 125kJ/mol

within experimental error of unaffected base metal

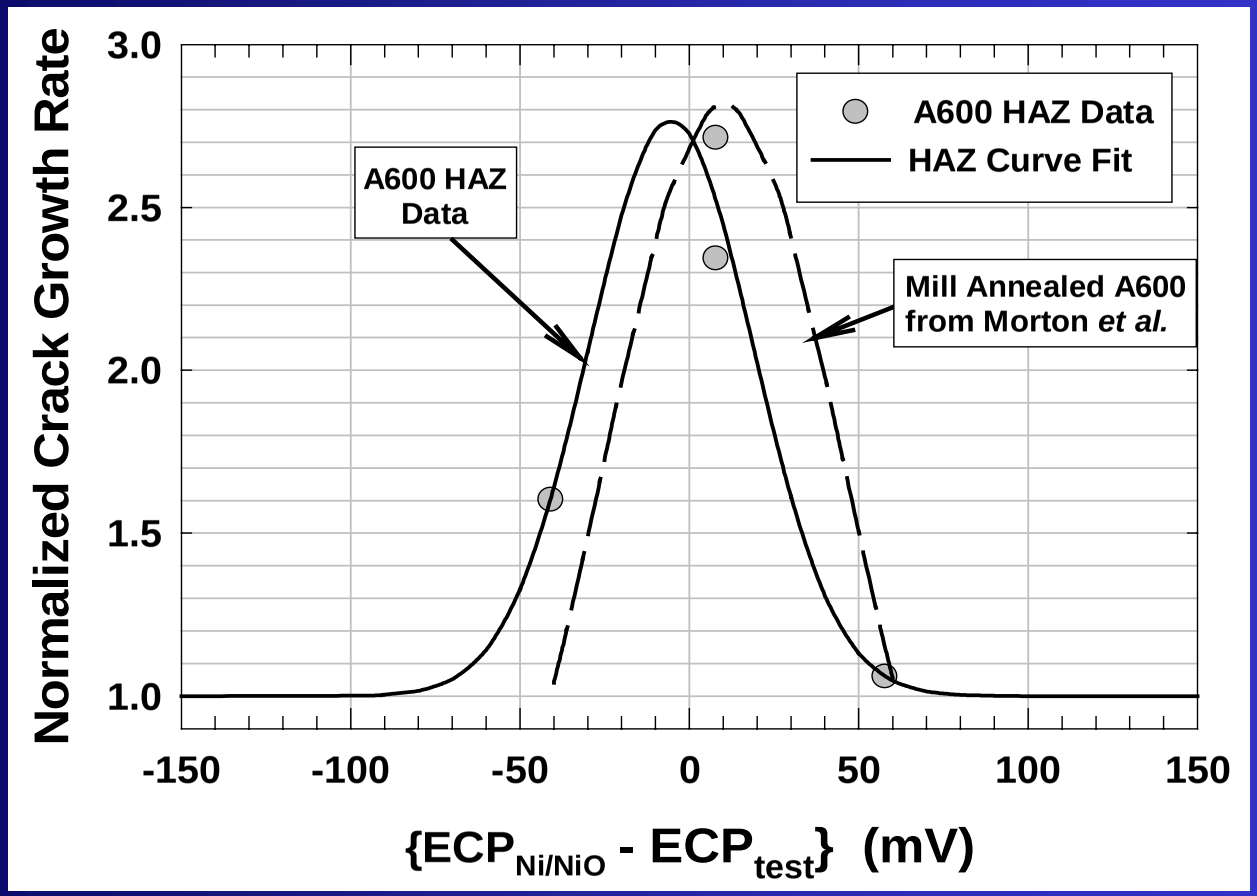


- Need to consider ΔECP when determining the apparent activation energy, *Q*, for crack growth
- Conduct tests at constant ΔECP or well into Ni metal stability for 'true' *Q*



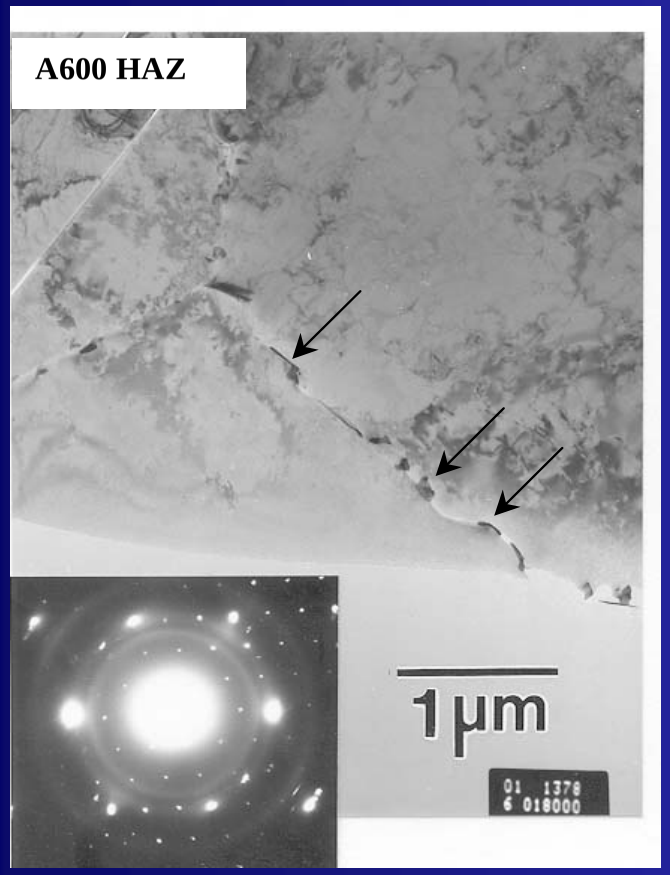
See Morton *et al.*, in 10th Env. Deg. Conf. NACE 2001

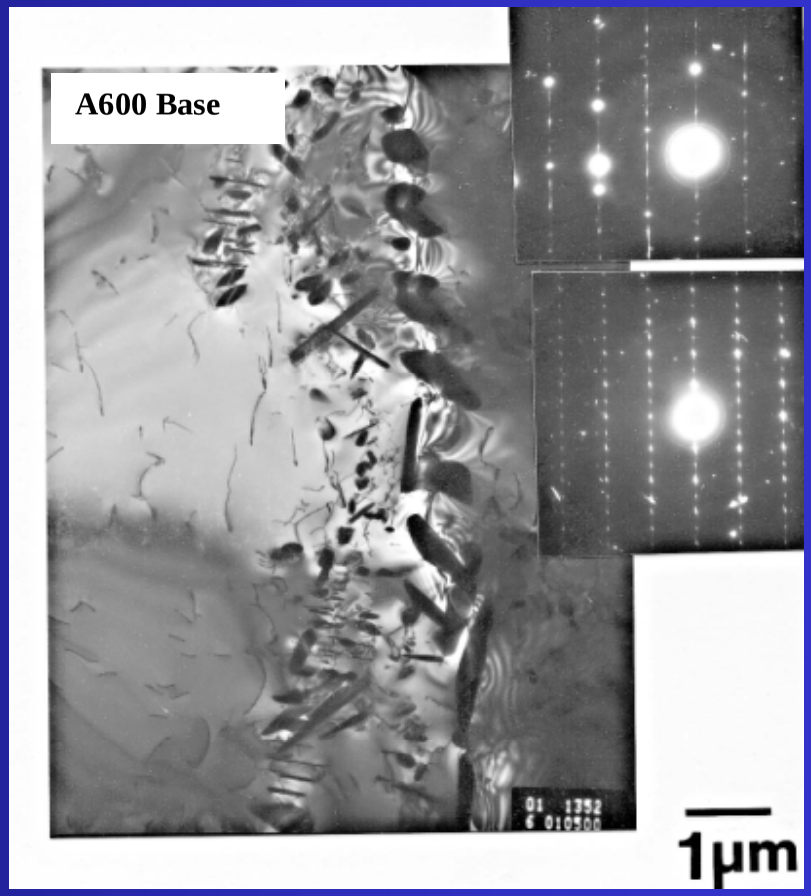
The 'coolant hydrogen effect' for the HAZ is nearly identical the base metal (~2.8X)



Why does the A600 HAZ SCC at fast rates?

→ Fewer grain boundary Cr-rich carbides





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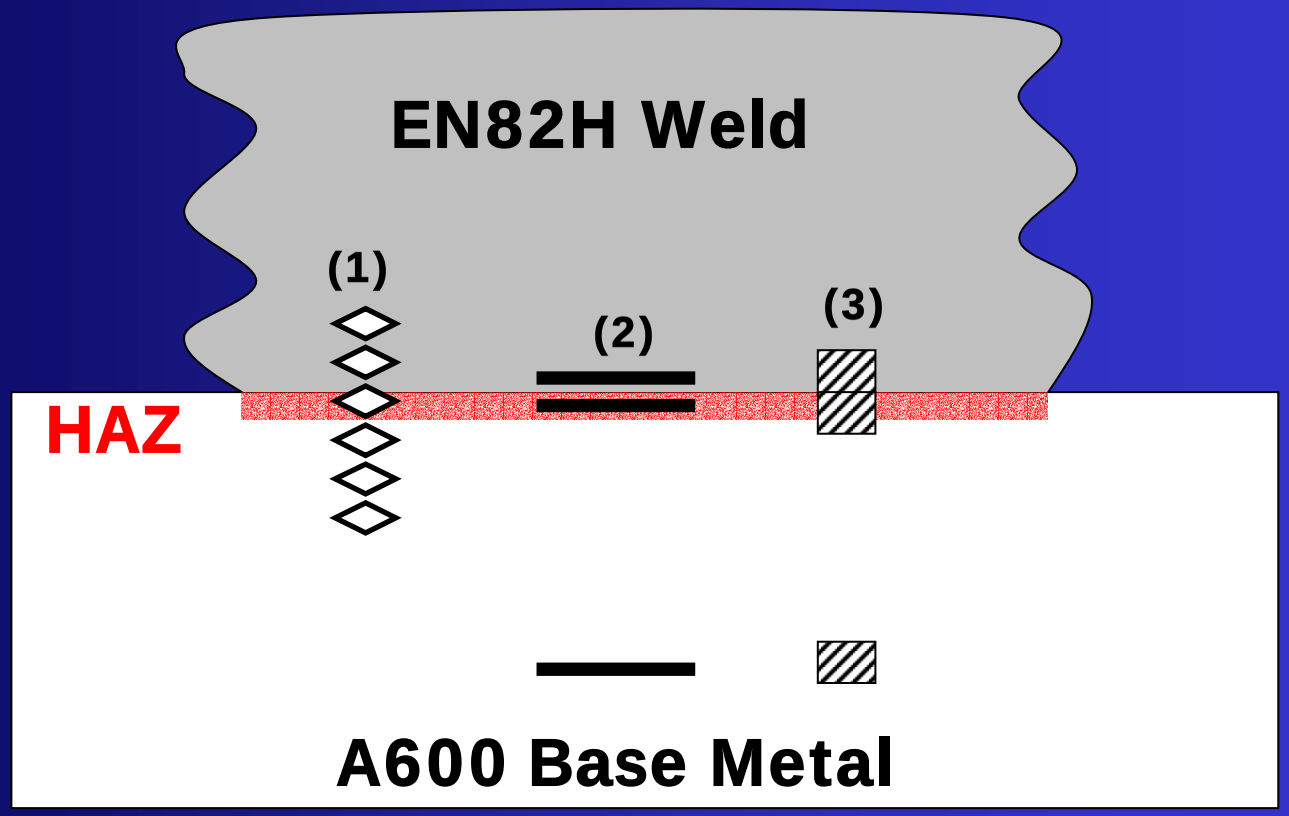
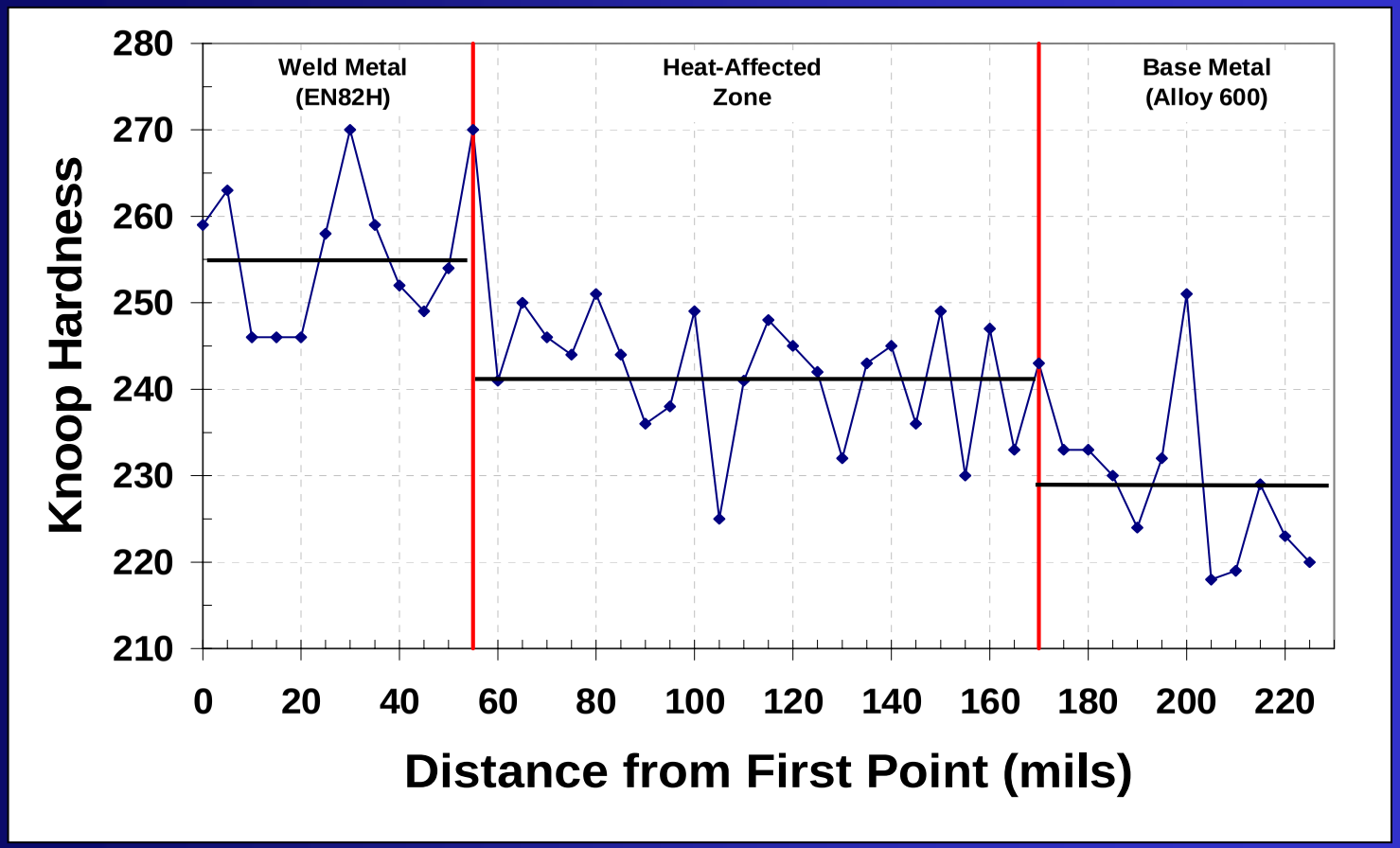
(1) Microhardness
(2) Strain Quantification via EBSD
(3) Strain Mapping via EBSD



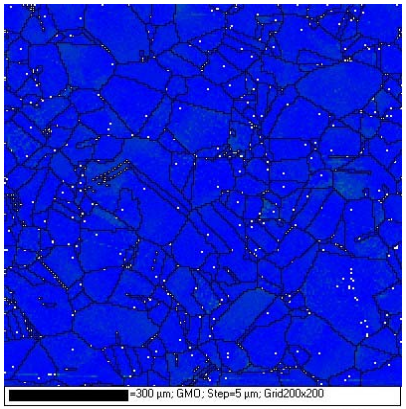
The HAZ shows increased hardness relative to the unaffected base metal

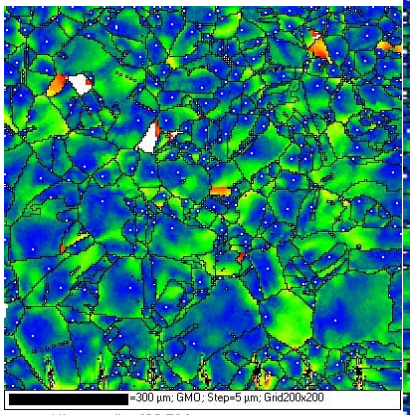


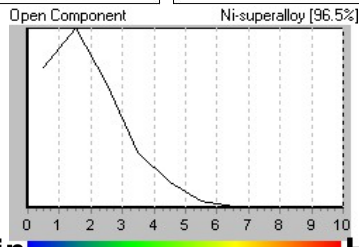
Why does the A600 HAZ SCC at fast rates?

→ increased plastic strain (~6%) in the HAZ

Far from Weld ← A600 HAZ → EN82H GTA Weld

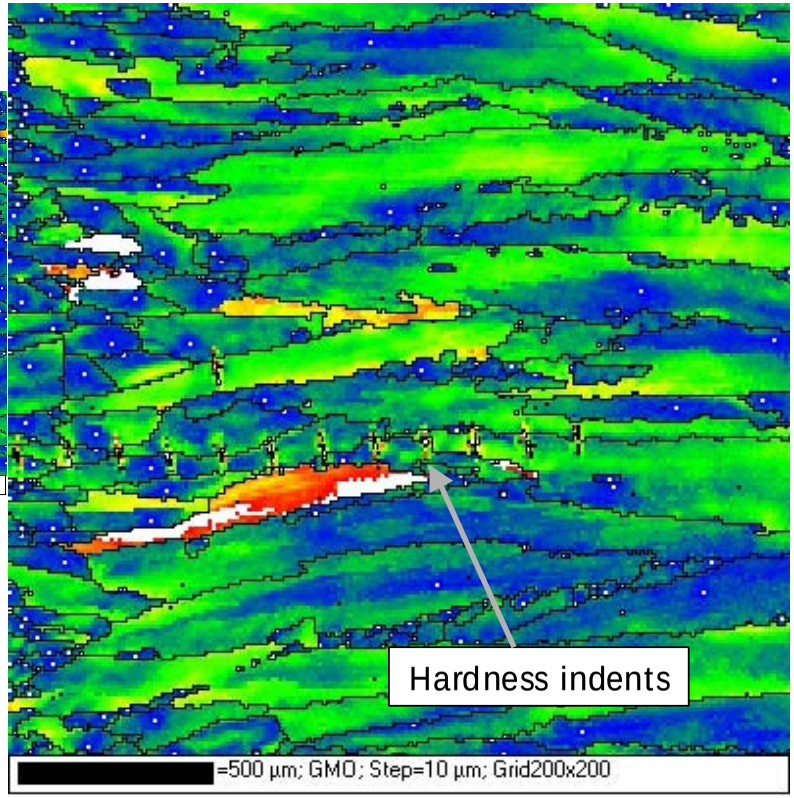






Low strain **High strain**

Misorientation (°)



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Discussion

- **The HAZ tested was from a very PWSCC resistant base plate (well annealed, good microstructure). Other heats may show significantly different crack growth rates.**

- **The HAZ tested was low constraint (~6% ε). Higher constraint welds may contain higher plastic strains (~15% ε ?) and exhibit faster crack growth rates.**

  See Young *et al.* in 6th International Conference on Trends in Welding Research, ASM, 15 April 2002, pp. 912-917.

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Discussion

- **Other nickel-base alloys which rely on grain boundary Cr-rich precipitates for PWSCC resistance (*e.g.* A690) may show increased susceptibility to PWSCC in the HAZ.**

- **Post weld heat treatment / bead tempering may help recover PWSCC resistance but ...**
  - plastic strain may promote intra vs. intergranular carbide precipitation
  - may need significantly longer PWHT times (or higher T) than are typical

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Conclusions

- **Need to consider PWSCC of the HAZ separately from the base metal and weld metal.**
- **The susceptibility of the HAZ is due to:**
  - Loss of grain boundary Cr_7C_3 carbides
  - (Less grain boundary Cr depletion)
  - Residual plastic strain from welding
- **The temperature dependence of the A600 HAZ SCC is very similar to unaffected base metal**

A600 HAZ	125 kJ/mol ± 47 kJ/mol $\vert_{95\%}$
'Typical' A600 base metal	145 kJ/mol ± 18 kJ/mol $\vert_{95\%}$

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Conclusions

- The 'coolant hydrogen effect' in the A600 HAZ is ~2.8X, similar to the unaffected base metal
- The A600 HAZ studied is likely not the worst case HAZ
- Other nickel-base alloys which rely on grain boundary Cr-rich precipitates for PWSCC resistance (*e.g.* A690) may show increased susceptibility to PWSCC in the HAZ.

In-situ Raman Spectroscopic Study on Alloy 600 CRDM Nozzle Material and Its Implications

Ji Hyun Kim, Il Soon Hwang
Department of Nuclear Engineering, Seoul National University
and
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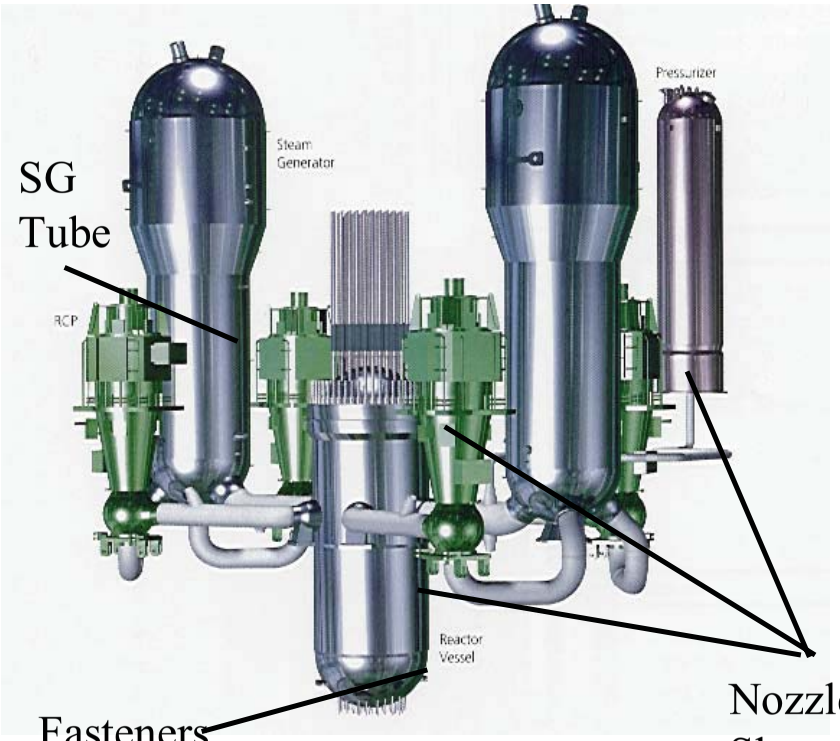
Republic of Korea

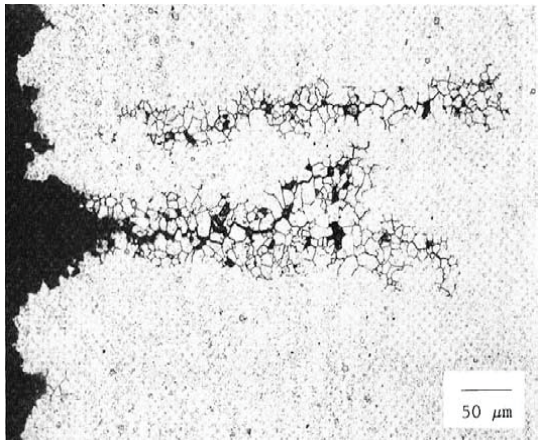
Conference on Vessel Penetration Inspection, Cracking and Repairs
2003. 9. 29 ~ 10. 2
Gaithersburg. MD, U.S.A.

Outlines

- 1. Introduction
- 2. Rationale and Approach
- 3. In-situ Raman Spectroscopy
- 4. Results
- 5. Ni/NiO Equilibrium & Implication to PWSCC
- 6. Conclusions

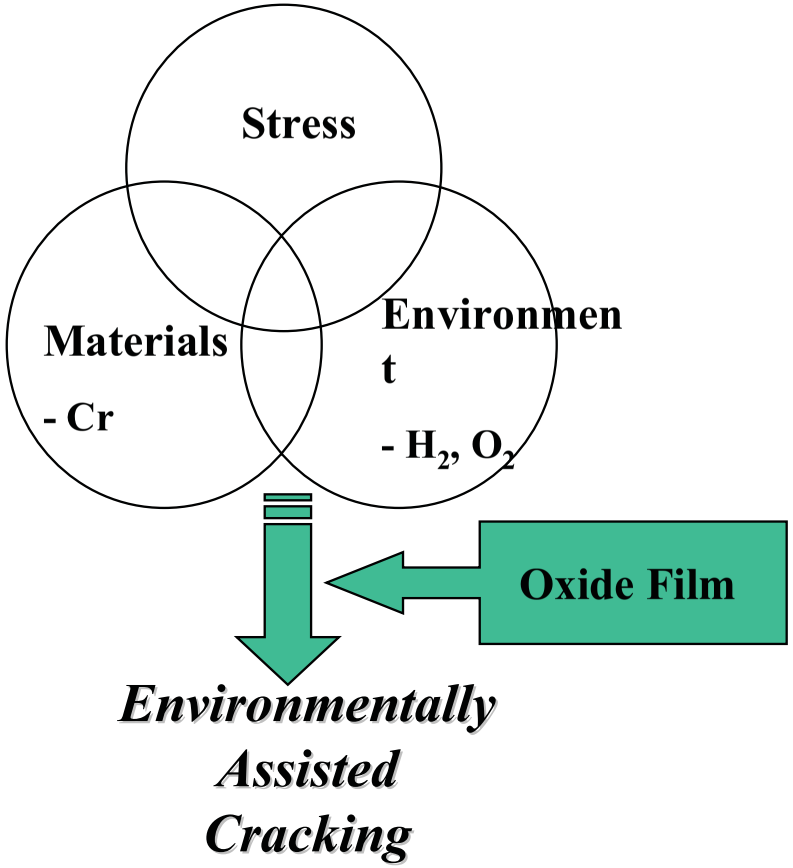
1. Introduction: PWSCC





1. Introduction: PWSCC

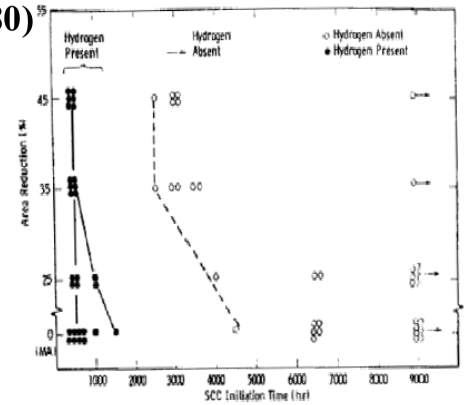
- No general agreement on the mechanism of PWSCC
- It is conceivable that the damage to the alloy substrate is related with the integrity of surface oxide film



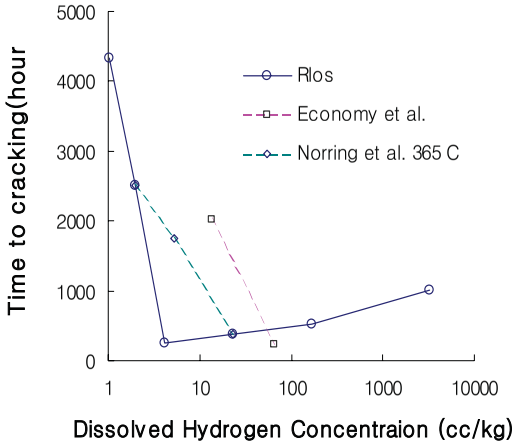
1. Introduction: PWSCC

Influence of [H_2] on PWSCC initiation

(G. Airey. '80)



(T. Cassagne et al. '93)



Influence of [H_2] on PWSCC

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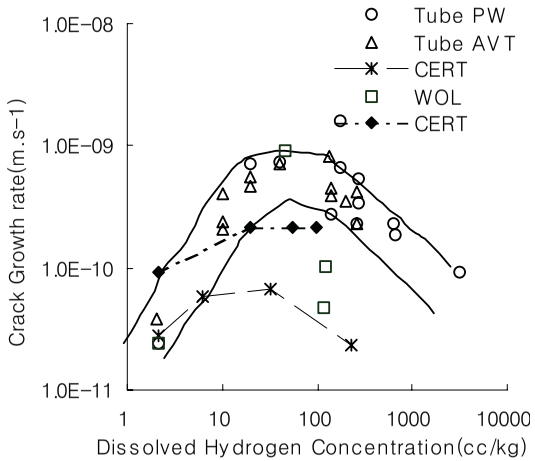
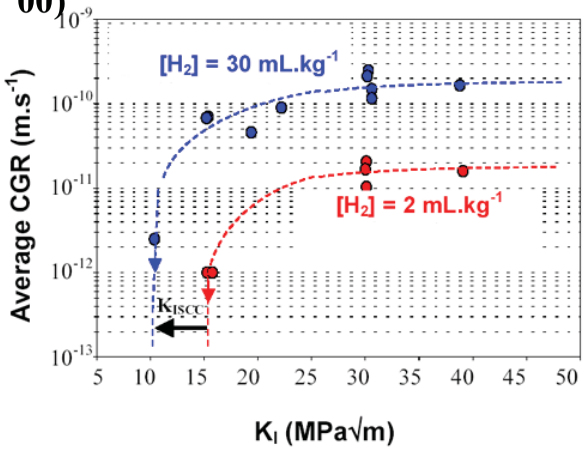


(D. Caron '06)



1. Introduction: PWSCC

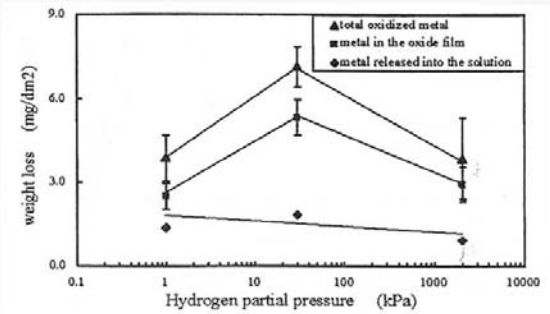


Figure 7: Weight measurements of oxidized metal on alloy 600

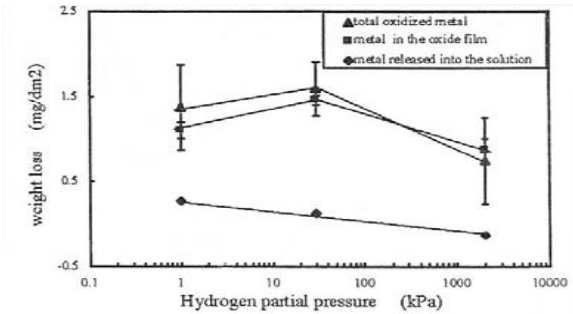


Figure 8: Weight measurements of oxidized metal on alloy 690

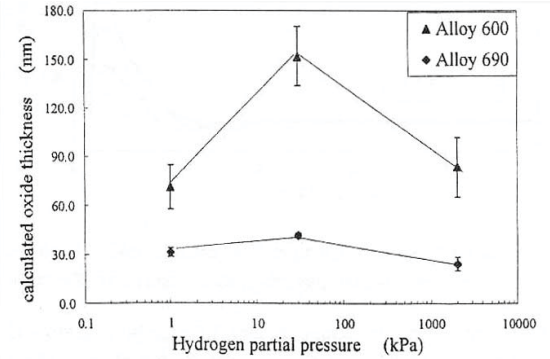


Figure 9: thickness of the oxide layers calculated from the weight measurements (assuming an oxide density of 5)

H_2 overpressure (kPa)	<1	30	2000
Alloy 600 -Weight measurement -X-ray diffraction	60nm 80nm	150nm 175nm	90nm 60nm
Alloy 690 - Weight measurement	30nm	40nm	25nm

(C. Soustelle et al. '99)

- Total amount of oxidized metal(oxide+dissolved cations) as well as oxide thickness are maximum at the intermediate hydrogen overpressure.

2. Rationale and approach

- **The characterization of the oxide film of alloy 600 under PWR primary water conditions**
  - **one of key elements for understanding how the oxide film behaves in the cracking process.**
- **In-situ study can give potentially a clearer picture of the corrosion mechanism**
  - **Removal of the material from the corrosion environment can result in modification of the oxide film structure and chemistry.**
- **In-situ oxide study in high temperature water**
  - **for pure metals and alloys in <u>air-saturated</u> or <u>BWR</u> water**
  - **by T. Devine et al. and J. Maslar et al.**

⇨ ***Need in-situ information on oxide film of alloy 600 in <u>PWR</u> environment***

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2. Rationale and approach

- **Characterization of oxide structure and chemistry under various PWR environments by in-situ experimental method**
  - **Ex-situ reference oxide powder experiment**
  - **In-situ experiment at various PWR conditions**

  - **Ni/NiO domain on ECP-T coordinate**
  - **Comparison with thermochemical calculations on Ni/NiO**

  - **Oxide structure examination**
  - **Comparison of oxide chemistry with earlier ex-situ results**

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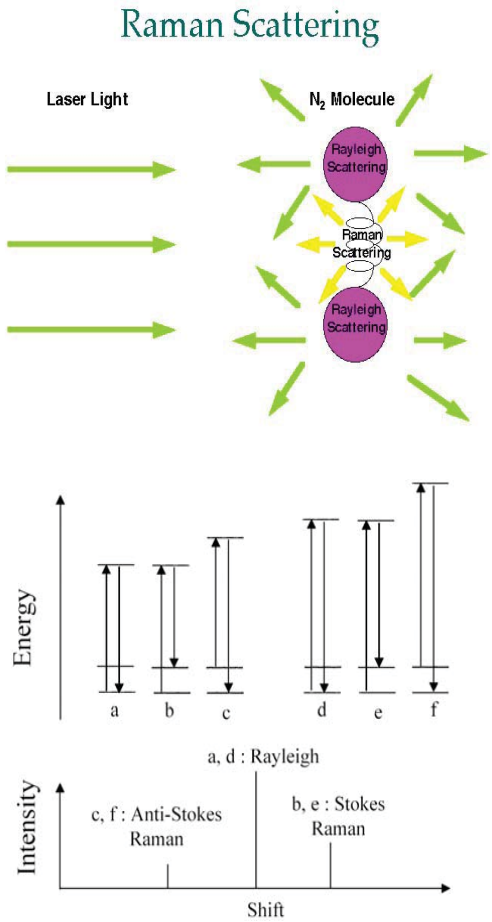
3. In-situ Raman Spectroscopy

- **Raman spectroscopy**
  - **the measurement of the wavelength and intensity of inelastically scattered light from molecules by irradiating a sample with the monochromatic radiation from a laser.**
  - **Performed by collecting the light that is inelastically scattered by the sample.**



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3. In-situ Raman Spectroscopy

Material

- **Alloy 600 : hot forged, SA at 1050°C for 2hrs and water cooled**

Elem.	C	Mn	Fe	S	Si	Cu	Ni	Cr	Al	Ti	Nb	P	B	N
Comp.	0.06	0.26	8.31	0.001	0.3	0.12	75.12	15.25	0.16	0.36	0.04	0.009	0.002	0.001

Water environment

- **PWR primary water chemistry**
  - ✓ **Deionized and deaerated water : DO_2 < 10 ppb (inlet)**
  - ✓ **Boron: 1,000 ppm, Lithium : 2 ppm**
- **Hydrogen gas injection**
  - ✓ **Pure hydrogen gas of 0.7 atm overpressure : ~ 30 cm^3(STP)/kg**
  - ✓ **5% hydrogen & 95 % He of 0.6 atm overpressure : ~ 1 cm^3(STP)/kg**
- **Temperature : 250 ~ 350 ℃**
- **Pressure : 180 atm**

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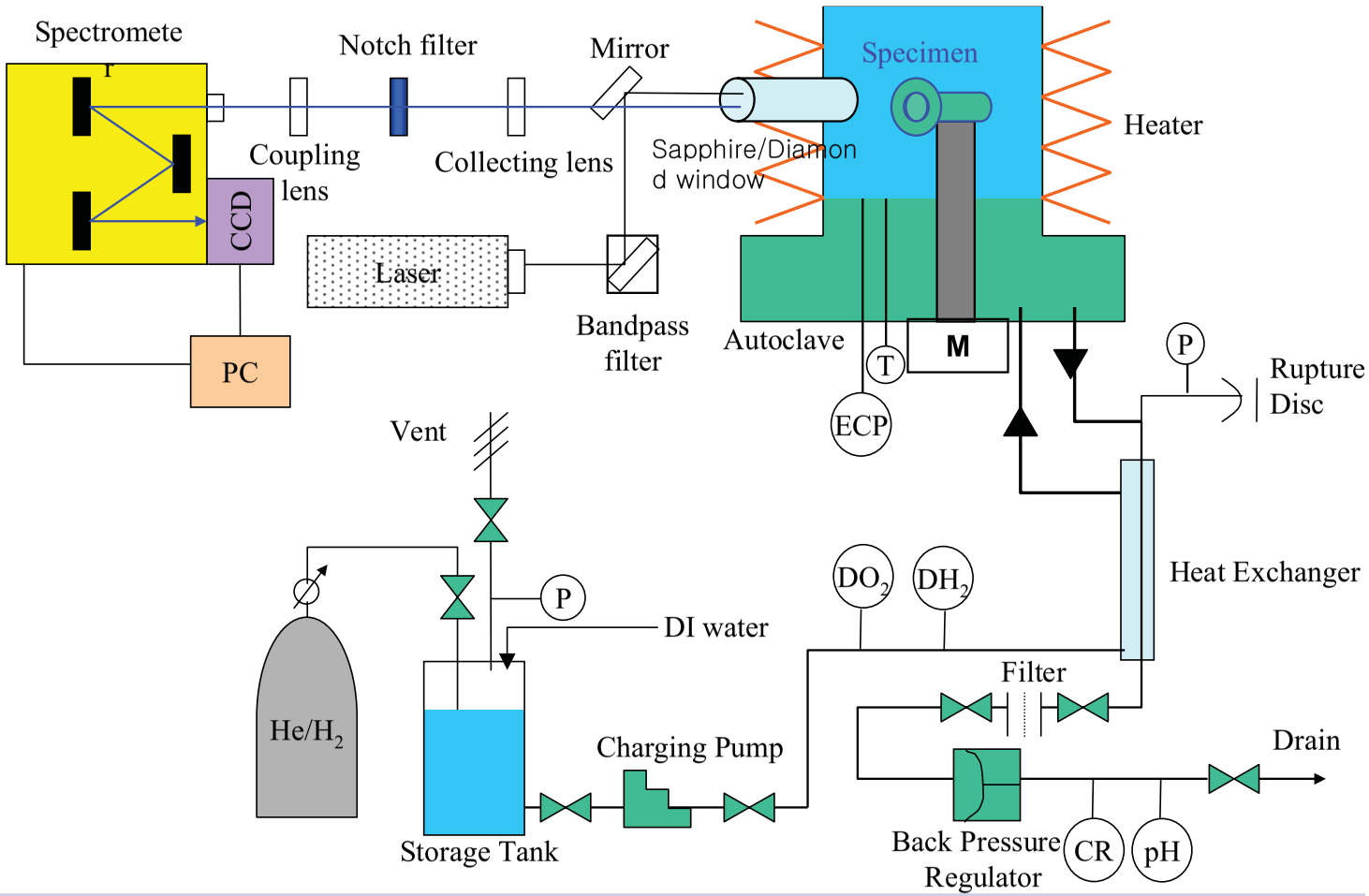
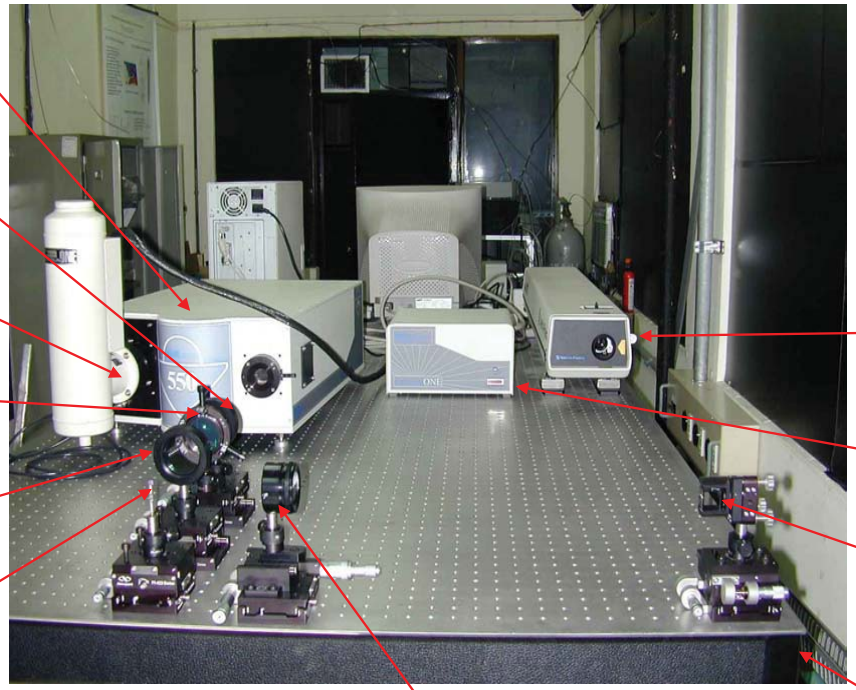
3. In-situ Raman Spectroscopy

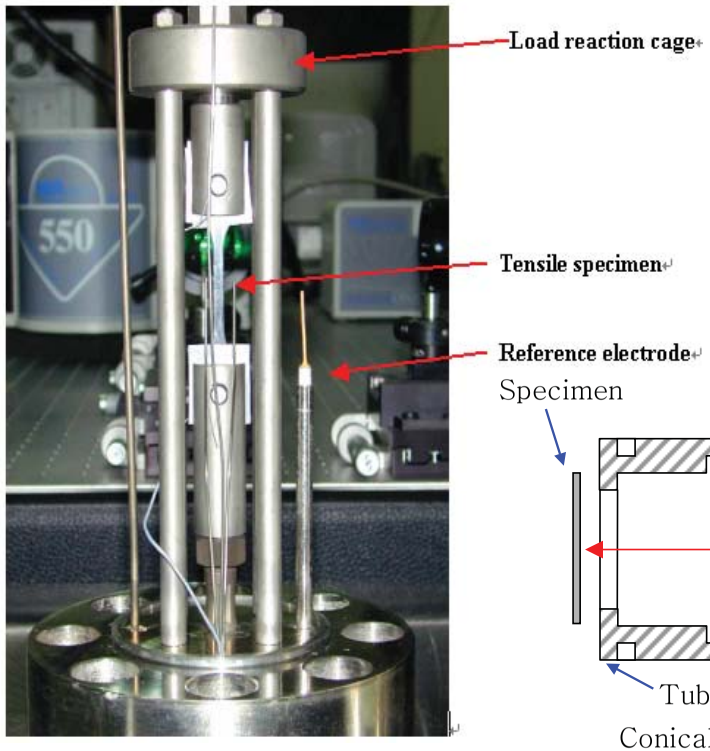


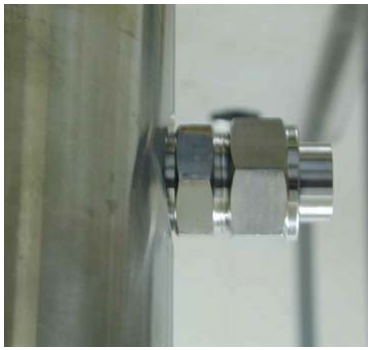
3. In-situ Raman Spectroscopy

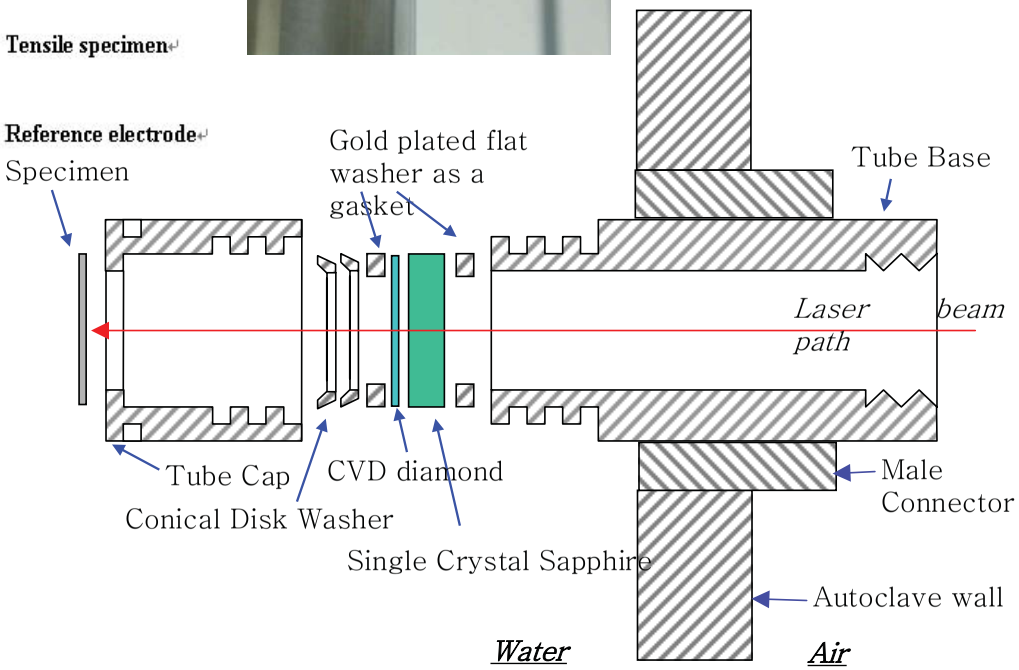
➢ Bird's-eye view of Raman system



3. In-situ Raman Spectroscopy







3. In-situ Raman Spectroscopy

- **Reference Raman spectra measurement in air**
  - **NiO**
  - **$NiFe_2O_4$**
  - **Cr_2O_3**
  - **$NiCr_2O_4$**

- **In-situ Raman spectra measurement**
  - **Dissolved hydrogen concentration variation**
  - **Temperature variation**

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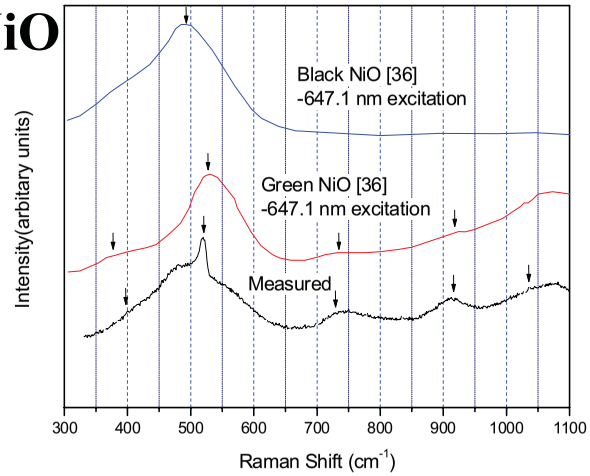
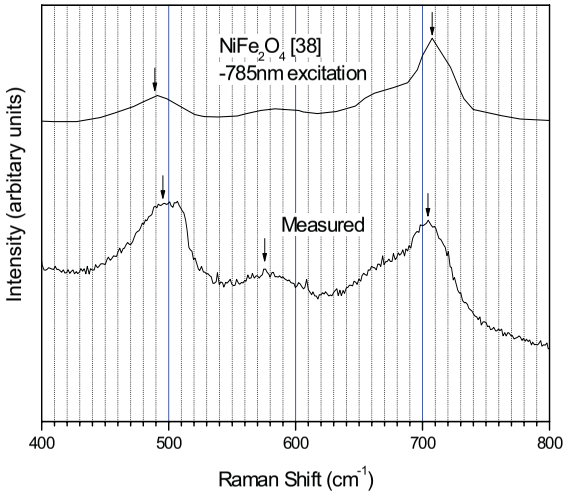
4. Results : Reference Powder in Air at RT

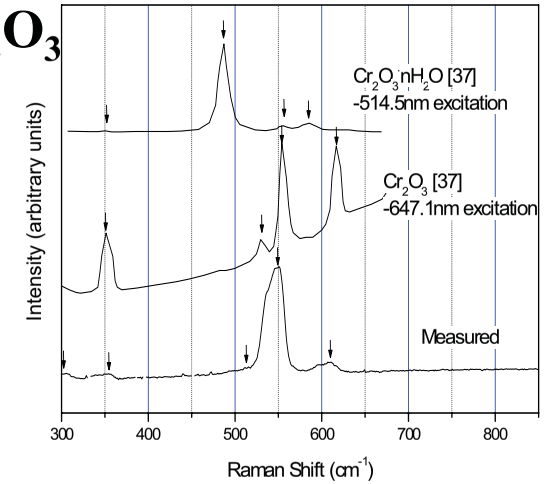
- **NiO**



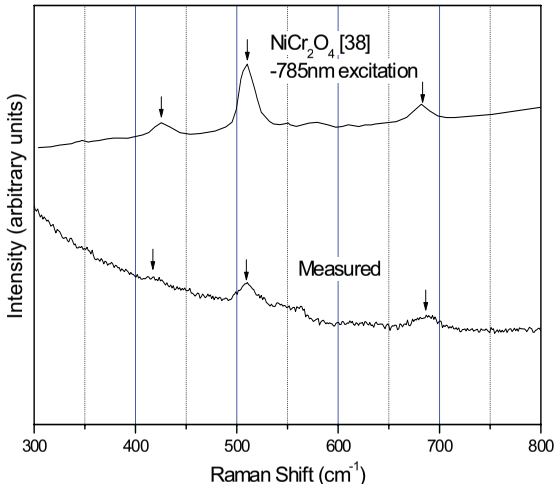
- **$NiFe_2O_4$**



- **Cr_2O_3**



- **$NiCr_2O_4$**



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4. Results in PWR conditions

- **Temperature and alloy 600 exposure time prior to in-situ Raman spectra measurements**

Temperature (℃)	Total exposure time prior to first measurement at temperature (h)	Hold time at each temperature prior to first measurement (h)
250	28	2
290	33.5	3
320	42	7
350-I	47.5	3.5
350-II	69.5	20.5

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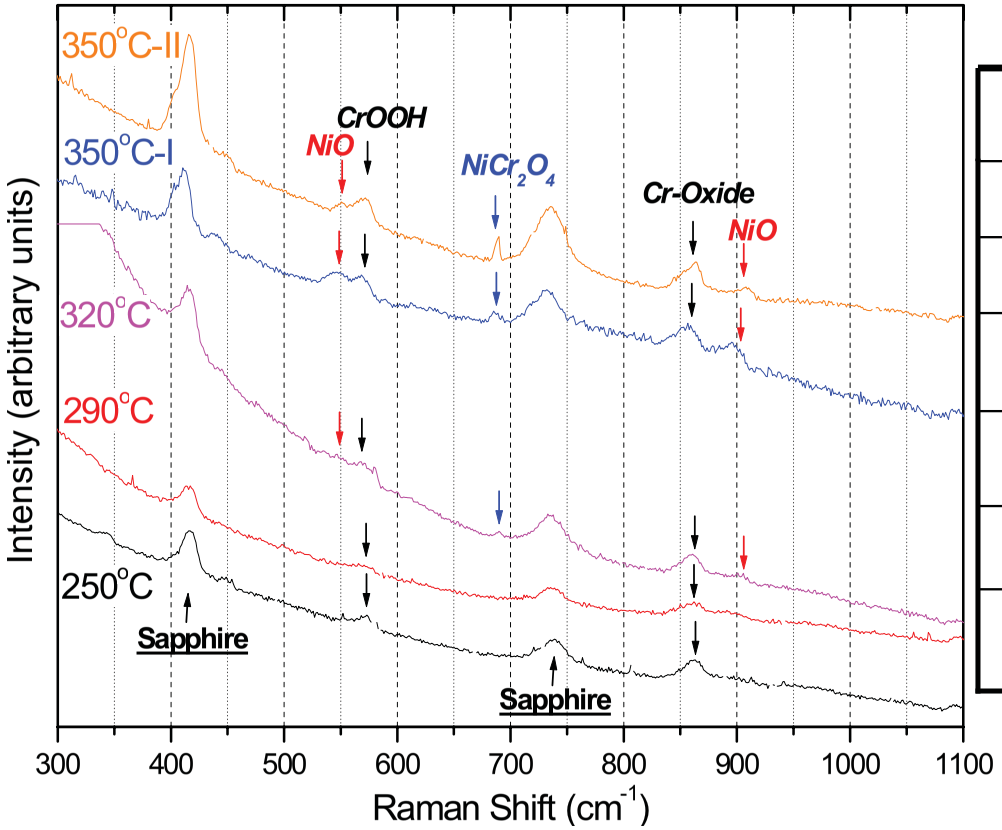
4. Results in PWR conditions

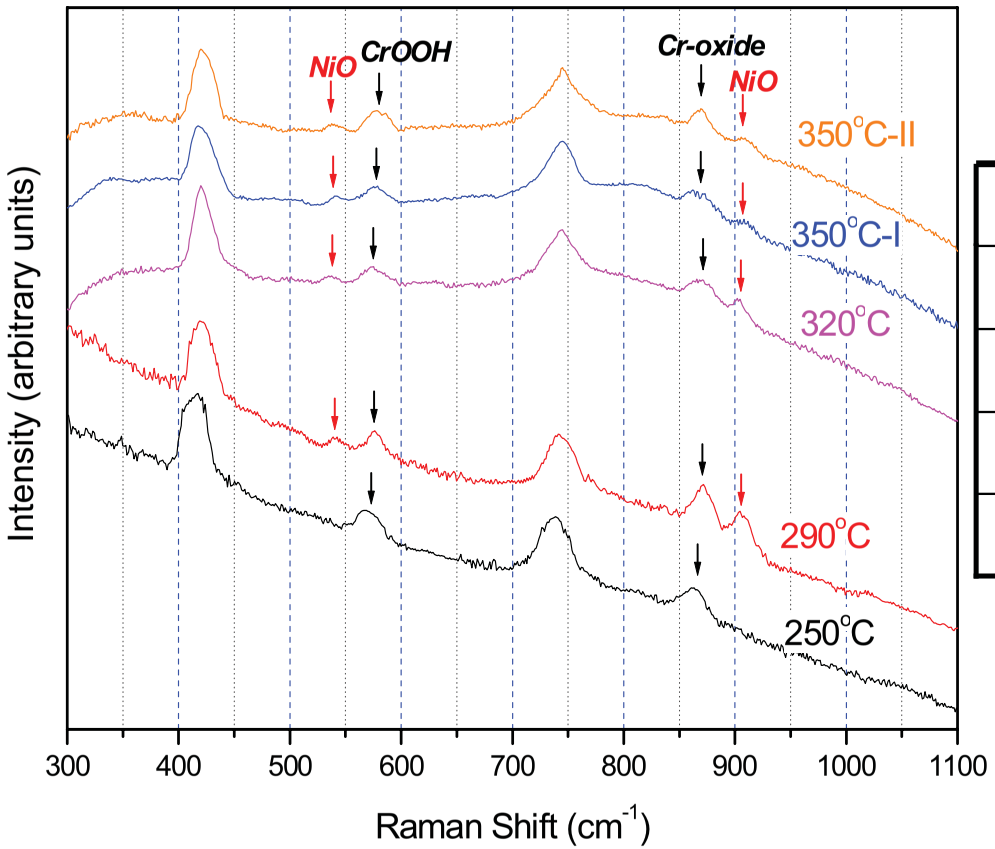
➢ In-situ Raman Spectra with DH_2=30cc/kg



Species	Peaks
$NiCr_2O_4$	430 510 682
CrOOH	ca. 546-587
Cr^{III}/Cr^{VI} oxide	340-350 840-880
$NiFe_2O_4$	570 704
NiO	550 910
Sapphire	417 751

4. Results in PWR conditions

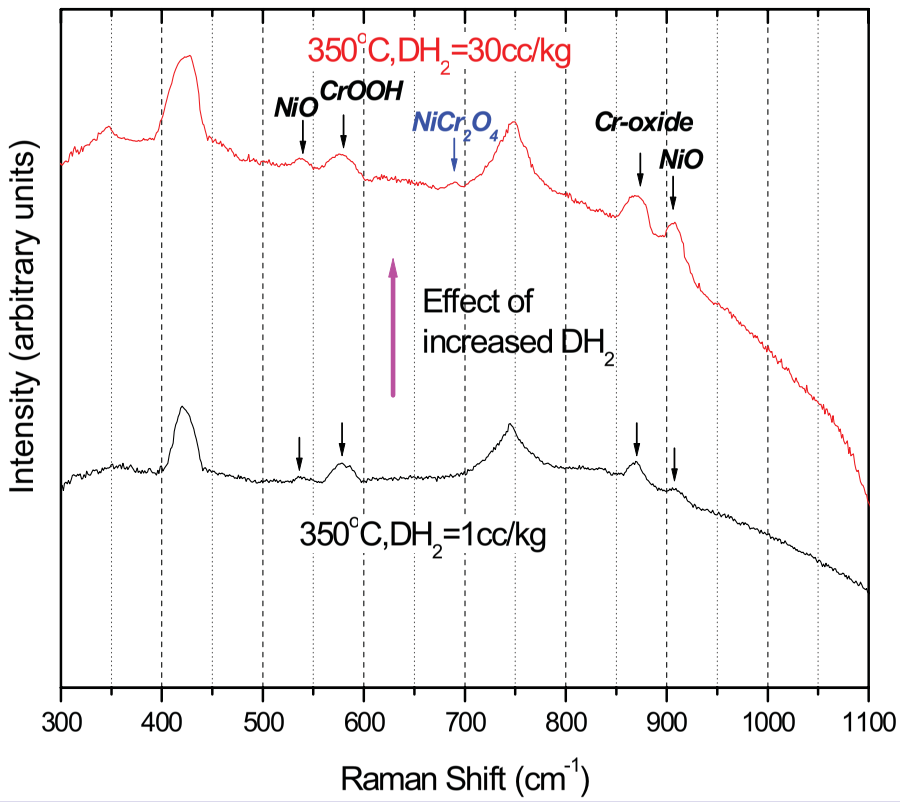
➢ In-situ Raman Spectra with DH_2=1cc/kg

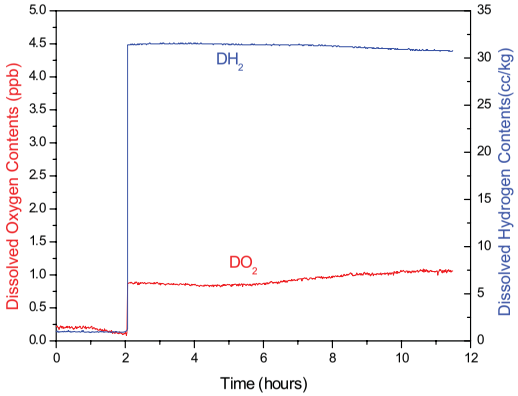


Species	Peaks
CrOOH	ca. 546-587
Cr^{III}/Cr^{VI} oxide	340-350 840-880
NiO	550 910
$NiCr_2O_4$	430 510 682

4. Results in PWR conditions

- **Change of dissolved hydrogen concentration**
  - **1cc/kg -> 30cc/kg**

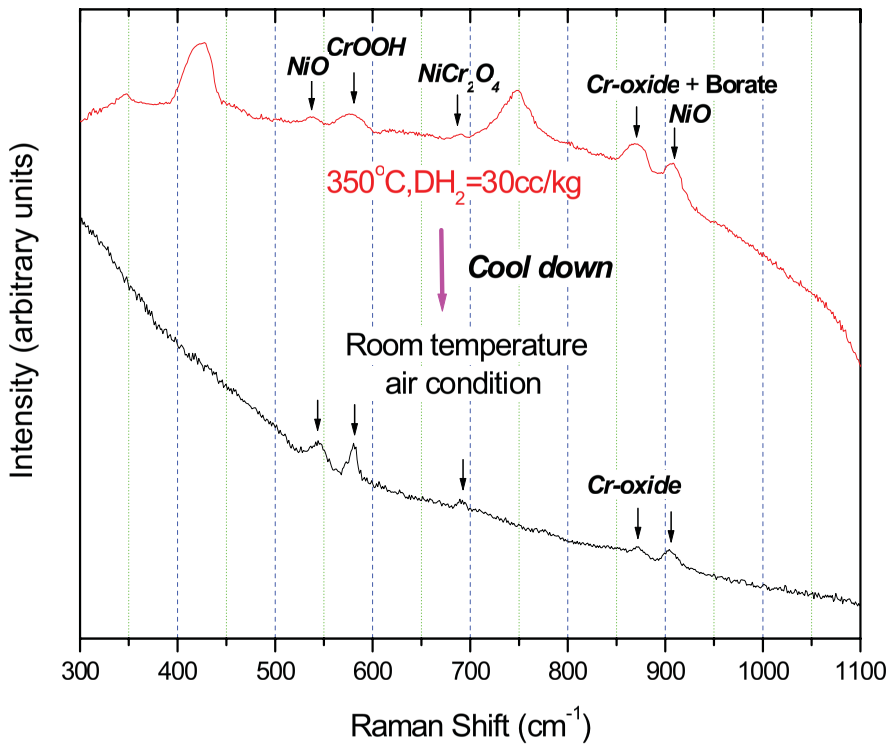




Species	Peaks
CrOOH	ca. 546-587
Cr^{III}/Cr^{VI} oxide	340-350 840-880
NiO	550 910
$NiCr_2O_4$	510 682

4. Results: in-situ vs. ex-situ

- **After cool-down to room temp. and exposure to air**
  - **No remarkable change in Raman spectrum**
  - **lower of Cr-oxide peak(~870cm^{-1}) : absence of borate**



4. Results: in-situ vs. ex-situ

➢ Comparison with past work

	In-situ (This work)	Soustelle et al.	Caron	Nakagawa et al.
Method	In-situ Raman	GDOS+EDS	XPS	Synchrotron XRD + TEM
T (°C)	350	360	330	320
Exposure time (hrs)	71	300	1869	1000
Oxide(s) at high DH_2	CrOOH, Cr-Oxide, NiO +$NiCr_2O_4$	Compact layer ($NiCr_2O_4$) + Precipitates ($NiFe_2O_4$)	$NiCr_2O_4$	(Ni+Cr-rich) oxide + Ppt. ($NiFe_2O_4$)
Oxide(s) at low DH_2	CrOOH, Cr-Oxide, NiO	Compact layer ($NiCr_2O_4$)	NiO	NiO

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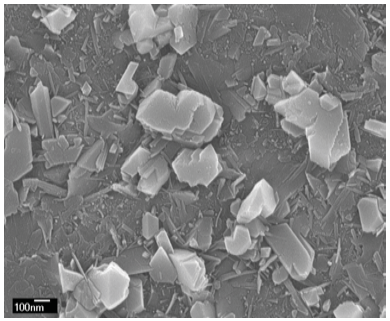
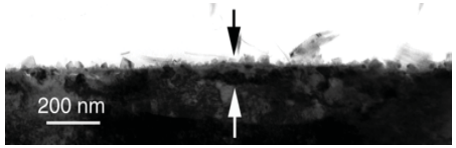
4. Results: in-situ vs. ex-situ

- $NiFe_2O_4$ detected at high DH_2 condition in ex-situ studies could not be observed in-situ at above 290℃. Suppression of precipitate layers in this work is attributed as the cause for the difference. But FE-SEM post-examination of oxide showed scarcity of precipitates on film.
- CrOOH that was not detected in the past was observed by Raman.
- NiO, Cr_2O_3, $NiCr_2O_4$ were observed in agreement with results of earlier ex-situ studies.



FE-SEM micrograph



TEM micrograph

5. Ni/NiO equilibrium: measured & predicted

- **Regular solution theory**
  - **Enthalpy of mixing**
    - ✓ Hertzman & Sundman (1985)
    - ✓ Use binary interaction coefficients to describe the enthalpy of mixing and extrapolation of high temperature (> 1100 K) thermodynamic data
  - **Standard Gibbs energy of formation of austenitic Ni-Cr-Fe solid solution**

$$\Delta_f G_T^o(alloy) = \sum_i^3 x_i \Delta_f G_T^o(i, fcc) + RT \sum_i^3 x_i \ln x_i + {}^E G_T^o + {}^{mag} G_T^o$$

where $\Delta_f G_T^o(alloy)$ = standard Gibbs energy of formation of the alloy

$\Delta_f G_T^o(i, fcc)$ = standard Gibbs energy of formation of component i in the fcc structure of alloy

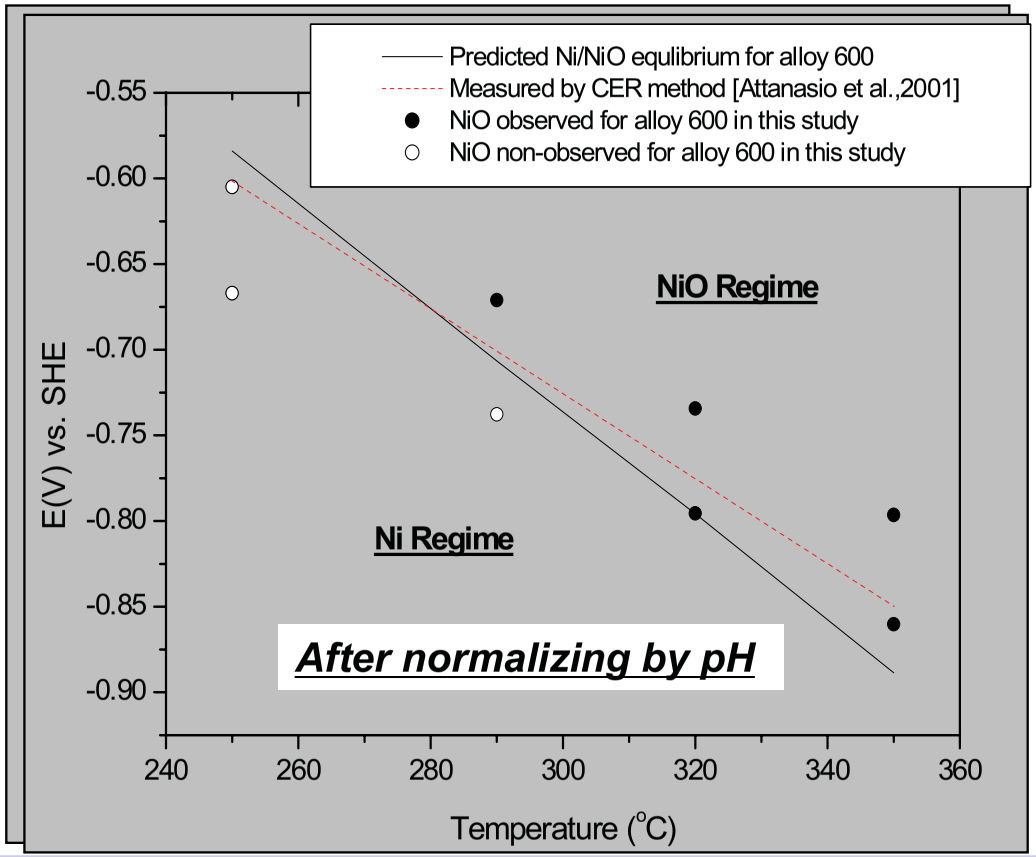
${}^E G_T^o$ = excess Gibbs energy

${}^{mag} G_T^o$ = standard Gibbs energy due to magnetic ordering

- **Chemical thermodynamic data**
  - Room temperature data: standard literature source and HSC database
  - HT data by Criss-Cobble, HKF relation and extrapolation procedure
  - Data for chromium hydrolysis species : Ziemniak (1998)
  - Data for nickel and iron hydrolysis species : Tremaine et al. (1980)

5. Ni/NiO equilibrium: measured & predicted

- **DH2 vs. T and Comaprision with Earlier Work**



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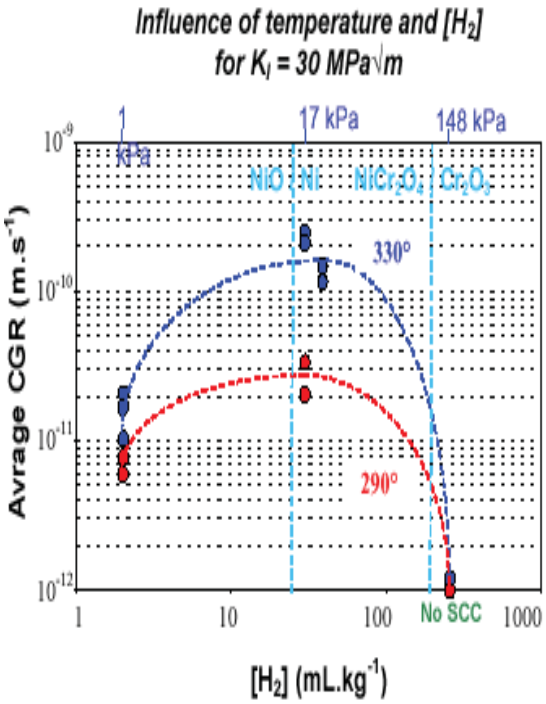
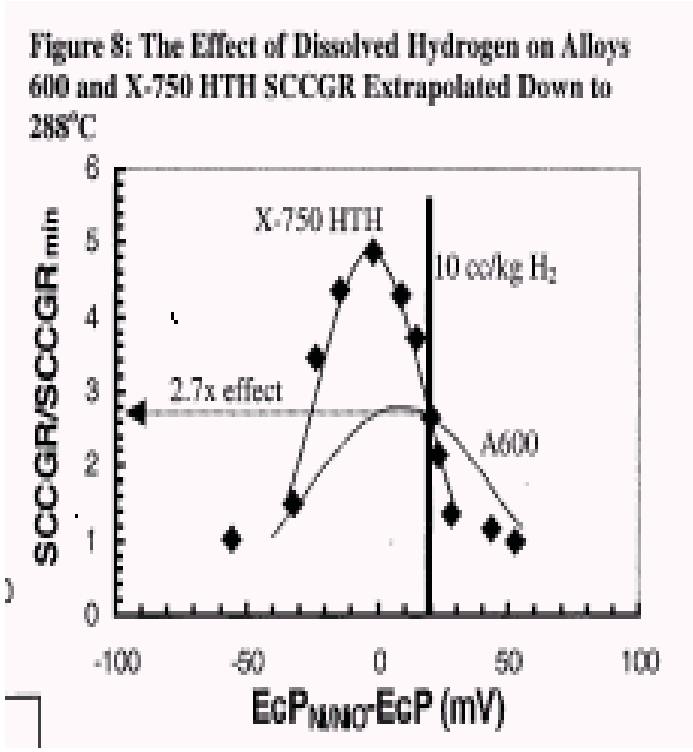
5. Ni/NiO equilibrium: Implication to PWSCC





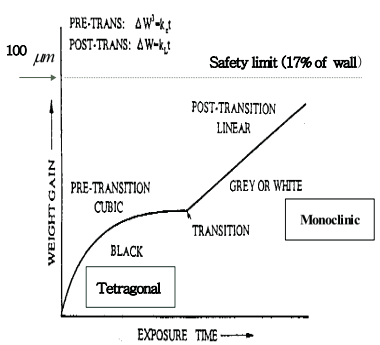
(T. Cassagne et al. '97 @ 330C)

(S. Attanasio et al., '01 @ 288C)

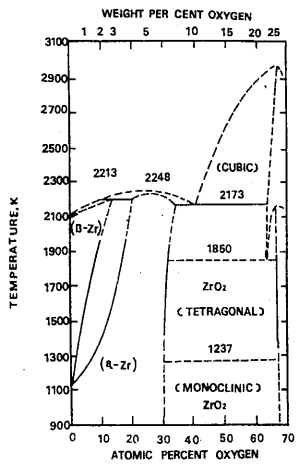
5. Ni/NiO equilibrium: Implication to PWSCC

Accelerated corrosion due to Tetragonal/Monoclinic phase transition of ZrO2

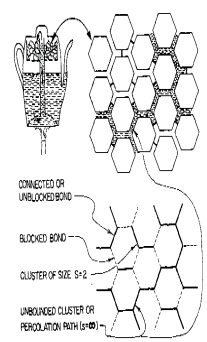
New Hypothesis on PWSCC
Redox alteration of Ni/NiO may enhance film-percolation and PWSCC



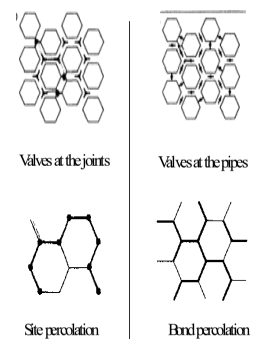
Oxidation behavior of zirconium alloys in nuclear power plants [Edward Hillner, 1977]



Phase diagram of Zirconium oxide [F. Garzarolli,1991]



Percolation model of a flow through a porous medium that is modeled as a network of interconnected channels..



Plumbing analogy for the distinction Between site percolation and bond percolation

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5. Ni/NiO equilibrium: Implication to PWSCC

Implication to Mitigation Effort

- Tighter DH2 Control at PWR
  - DH2 controlled by cover gas pressure in CVCS
  - H2 pressure may vary with time(0~50 cc/kg?)

- Systematic investigation on DH2 effect
  - Initiation and crack growth rate study as function of DH2, temperature and stress
  - Explore alternate DH2 levels;
    - either lower or higher than now (30 cc/kg H2O)

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6. Conclusions

- **In-situ Raman spectroscopy system was developed to obtain needed information on oxide films on Alloy 600 in in PWR water conditions .**
- **Some unique observations were made, compared with earlier ex-situ results;**
  - **CrOOH phase, undetected by ex-situ methods, was observed under most conditions.**
  - **$NiFe_2O_4$ usually found in precipitate layer was not observed, conceivably due to the suppression of precipitate layers in this work.**
- **NiO, Cr_2O_3 and $NiCr_2O_4$ phases were observed, in reasonable agreement with ex-situ results.**

6. Conclusions

- **Ni/NiO equilibrium was determined as function of dissolved hydrogen concentration and temperature.**
  - **Comparison of observed results with thermodynamic predictions showed a good agreement on Ni/NiO equilibrium at the temperature range from 250 to 350 degree C.**
  - **A good agreement was found between in-situ Raman results and those from contact electrical resistance (CER) measurements on Ni/NiO equilibrium.**

- **Fluctuation in DH2 in PWR may cause Ni/NiO alternation and accelerate PWSCC**
  - **Stable DH2 control at PWR is suggested**
  - **Systematic study is needed for lower/higher DH2 control for mitigation.**

Analysis of Alloy 600 Stress Corrosion Cracking with an Artificial Neural Network.

M.J. Pattison, S. Belsito, S. Banerjee

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Contents

1. Available models
2. Approach taken – why neural networks?
3. ANN model developed
4. Results and comparison with data
5. Relative importance of variables

Existing Models

Scott (1991) model:

$$CGR = 2.8 \times 10^{-11} (K - 9)^{1.16}$$

Ford (1987), Ford et al. (1997)

$$CGR = 7.8 \times 10^{-3} n^{3.6} \left(4.1 \times 10^{-14} K^{4}\right)^{n}$$

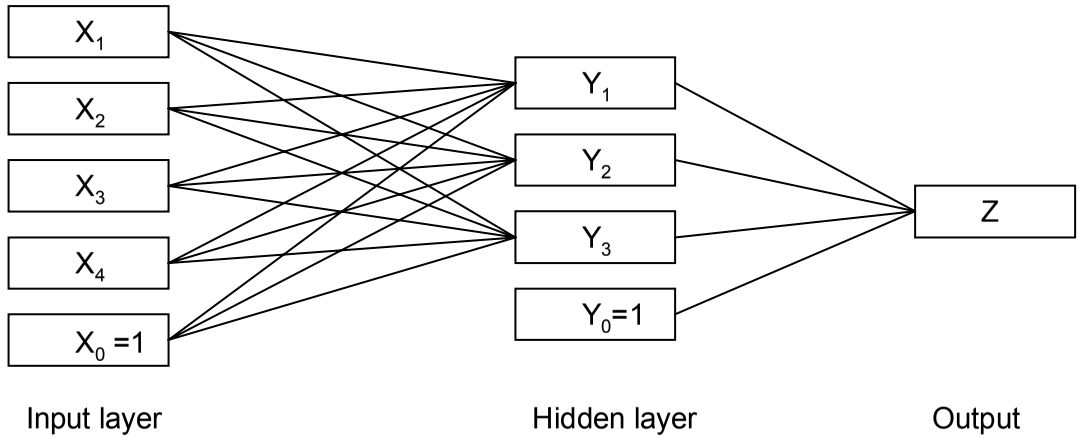
Model temperature dependence as:

$$CGR \sim \exp\left(-E / kT\right)$$

Principal Variables

- Applied stress
- Temperature
- Solution chemistry
  - Impurities and additives, e.g. lithium, boron, sulphates
  - pH
  - Dissolved gases: hydrogen, oxygen
- Alloy properties
  - Composition
  - Grain size
  - Cold/hot work - affects structure and yield strength
  - Grain carbide coverage
  - Carbides present

Diagram of Neural Network



$$Y_j = f\left(w_{0j} + \sum_{i=1}^{i=m} w_{ij} X_i \right)$$

$$f(x) = \tanh(x)$$

$$Z = f\left(w_0^h + \sum_{i=1}^{j=n} w_j^h Y_i \right)$$

Training of Neural Network

Objective: Calculate weights, **w**, so as to minimise the energy function:

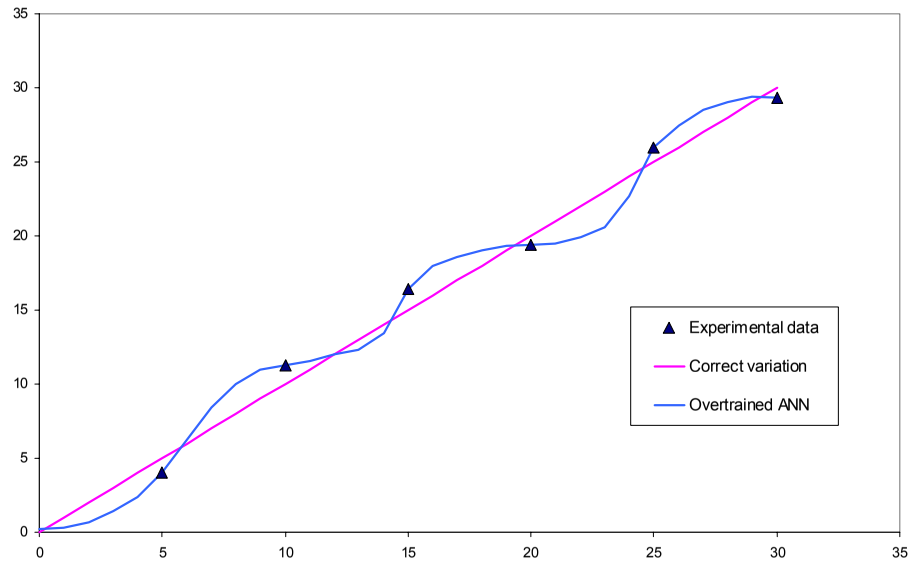
$$e(\mathbf{w}, \mathbf{x}, m) = \sum_{k=1}^{n} \left(z - z_p \right)^2$$

The MetaSolve algorithm uses a novel, computationally efficient, iterative approach using ODEs to determine the weights

Verification of Solution

- Danger of overtraining – with sufficient hidden nodes, the neural net can fit the data to any degree of accuracy
- With an overtrained net, data used for training can be reproduced well, but poor performance will be obtained for other data
- Usual to split the database into two parts – one for training and one for testing

Validation of Model

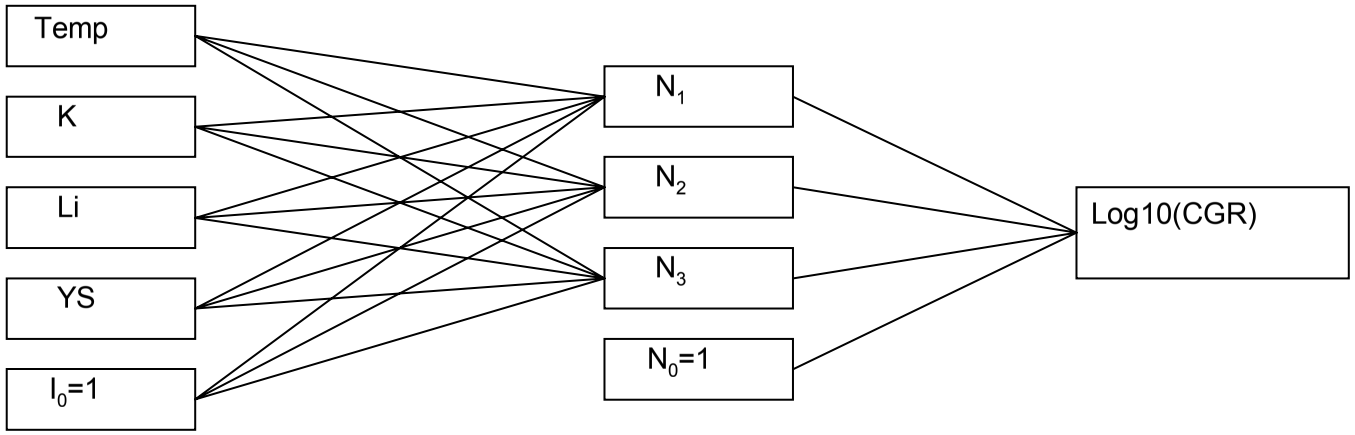


- Overtraining can happen if too many nodes used for number of data
- Split database to check for this:
  - 75% for training, 25% for testing

Database Available

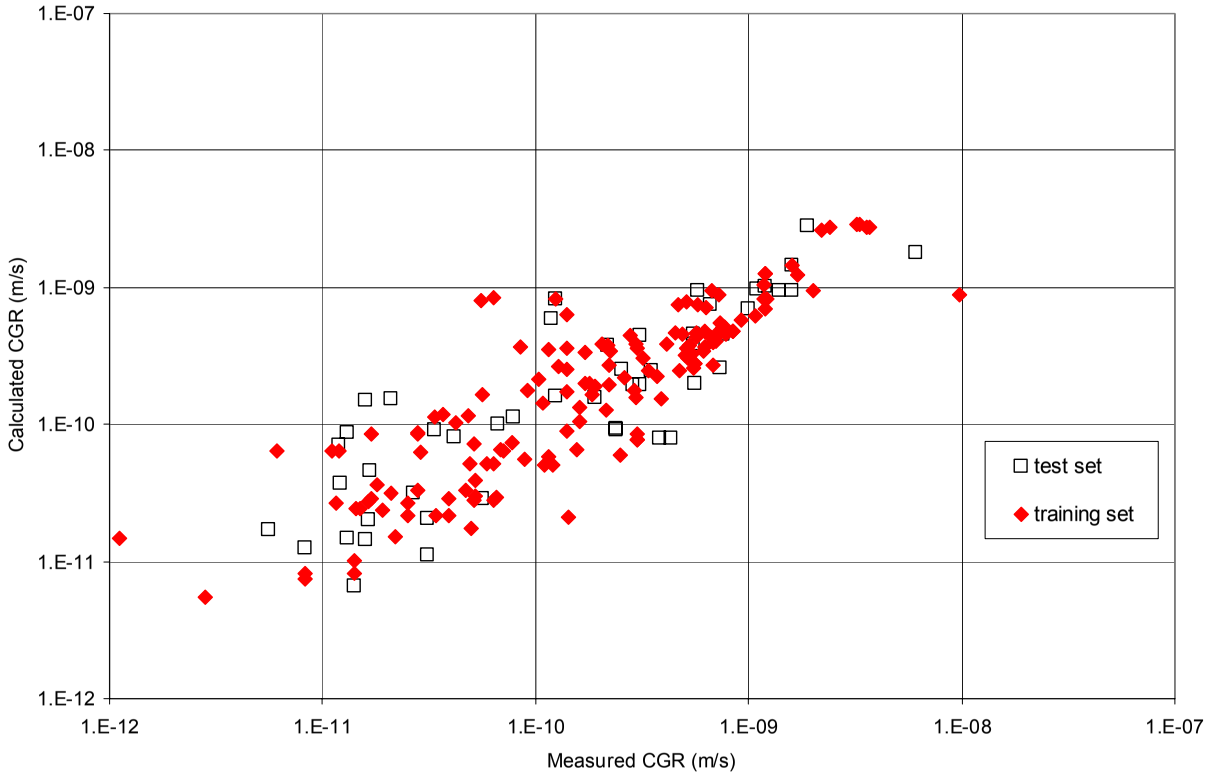
- ~200 experimental measurements of crack growth rates (CGRs)
- Data cover a wide range of applied stress, temperature, and water chemistries
- Number of different specimens used
- Conditions similar to those in a PWR
- Split database 75% for training, 25 for testing

Network Derived

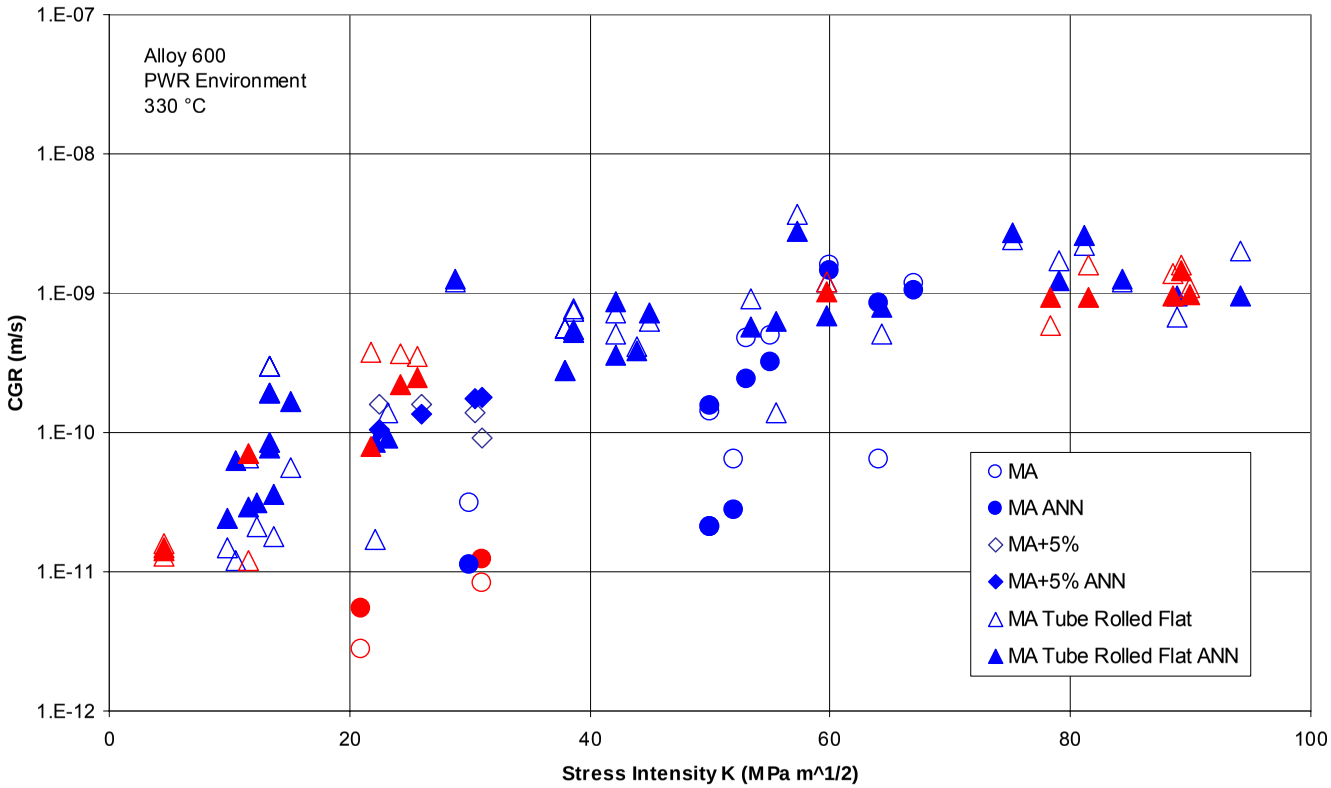


	Node 0	Node 1	Node 2	Node 3
Temperature		-0.19699	-0.27891	-0.2595
Stress		-0.26174	-1.948	-0.39729
Li conc.		-0.07173	2.20143	-0.07249
Yield strength		0.91762	-2.62216	1.57788
I0		-1.34723	-1.59432	-1.38374
Log10(CGR)	-11.364	-0.83189	5.31381	-5.89371

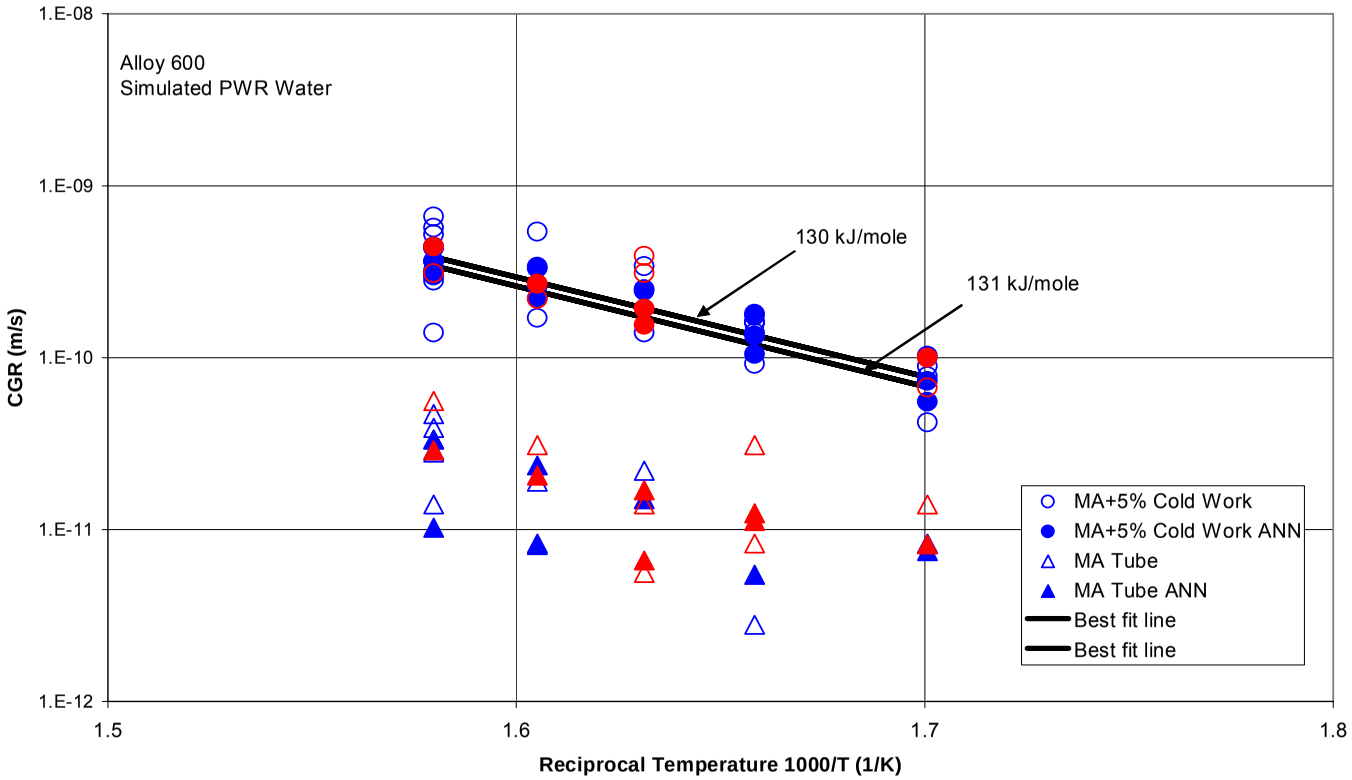
Comparison of Measured and Predicted Data



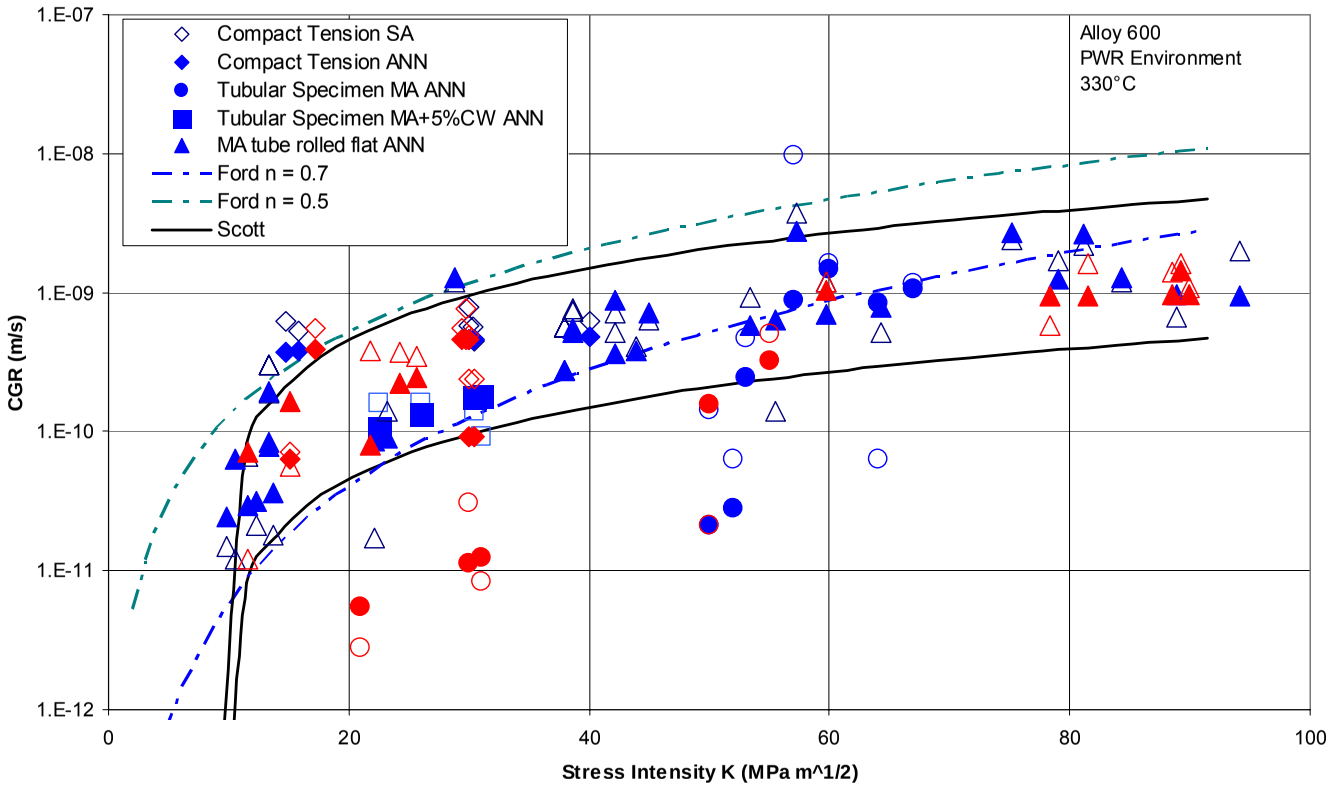
CGR vs. Applied Stress



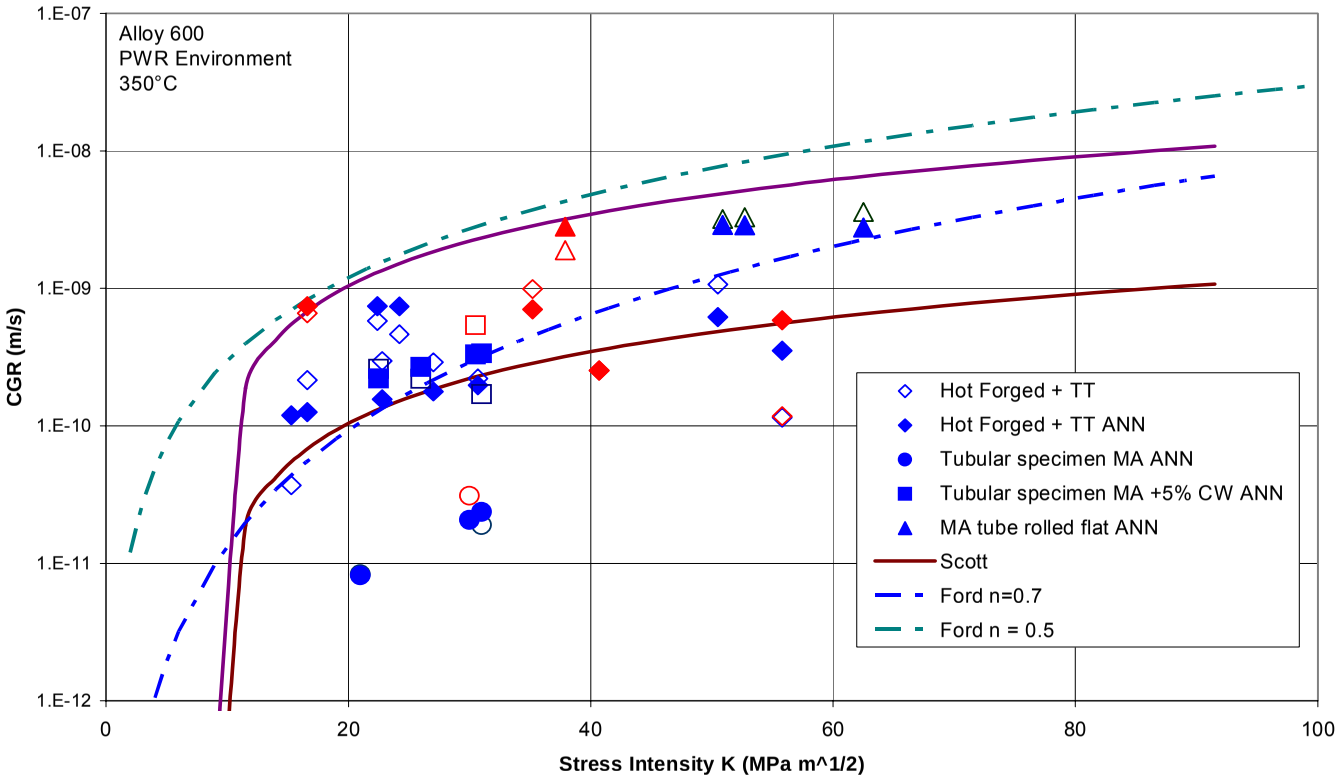
CGR vs. Temperature



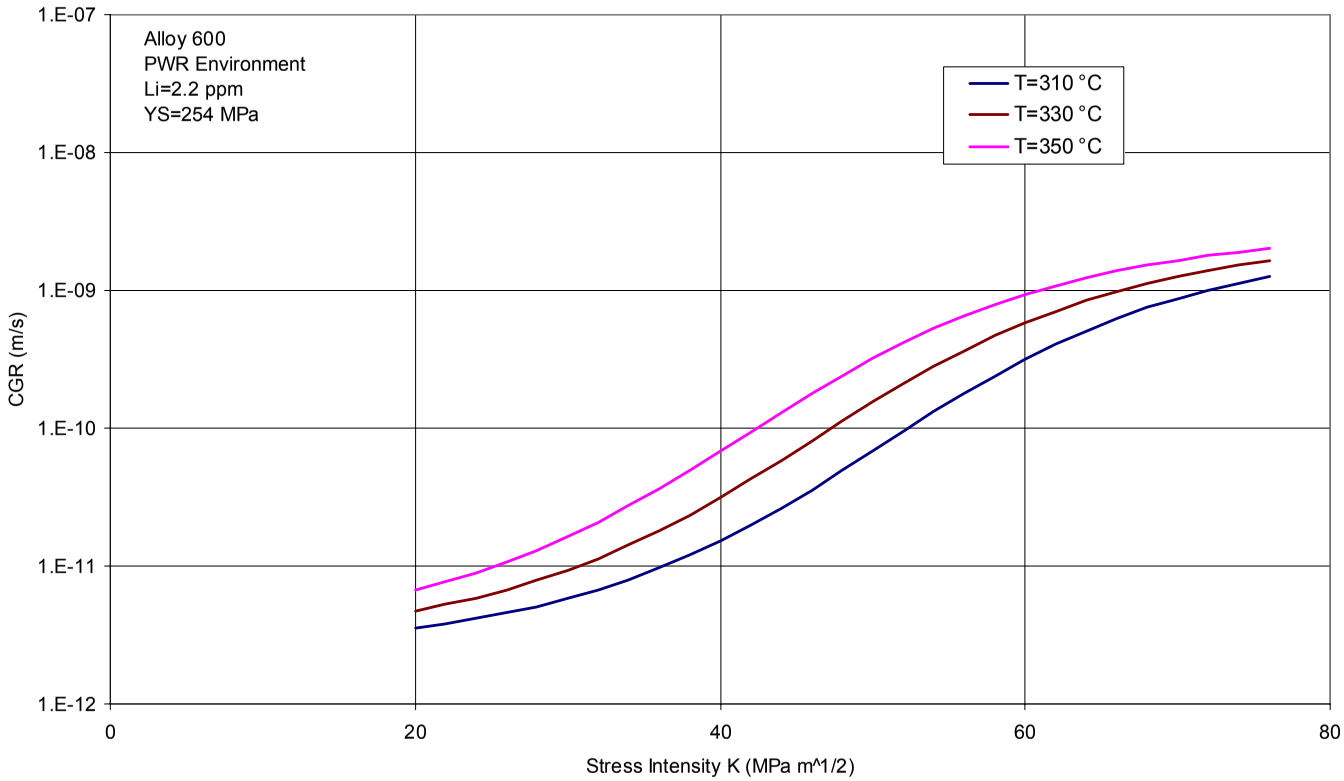
Comparison with Correlations - 330°C



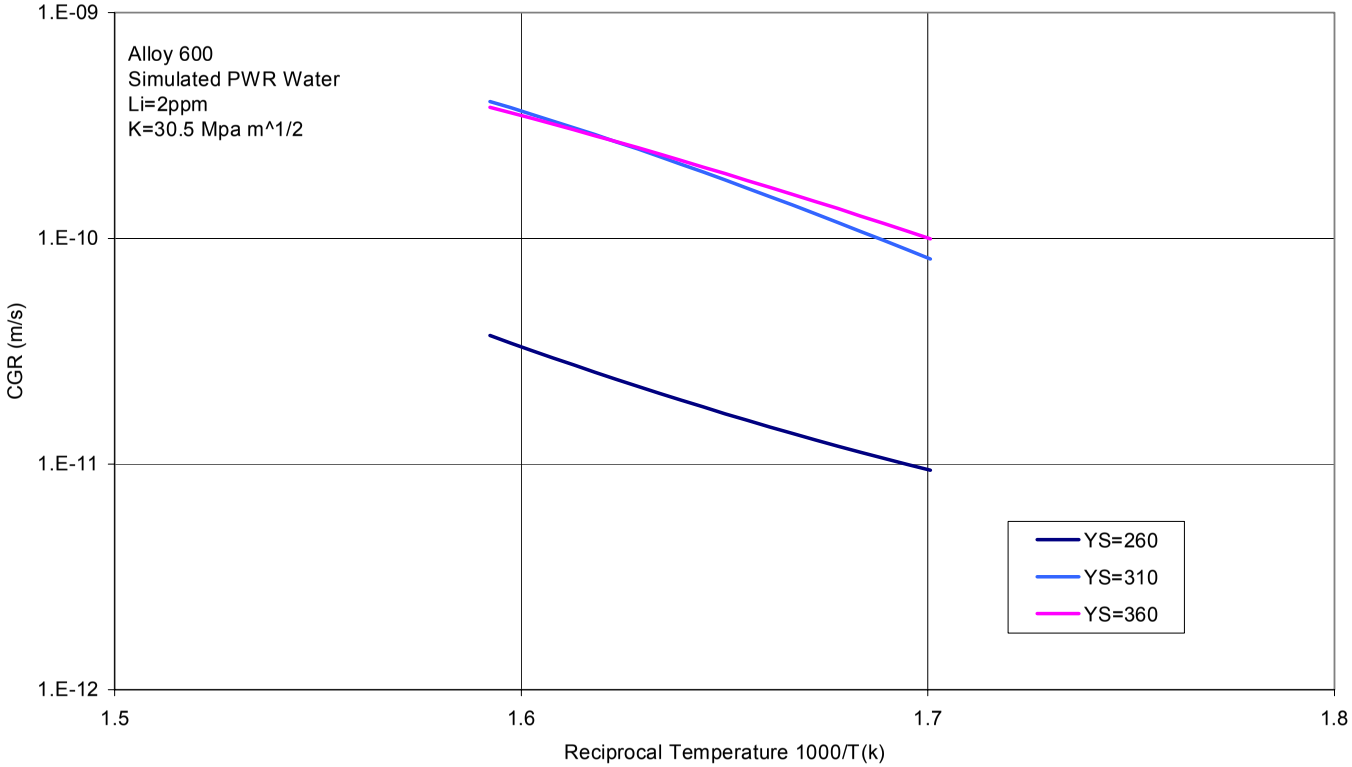
Comparison with Correlations - 350°C



Variation of CGR with Stress for Different Temperatures



Variation of CGR with Temperature for Different Yield Strengths



Relative Effect of Variables

Parameter	Variation [decades]	Range	Direction	Notes
Temperature	0.5 (factor of 3)	310 – 350˚C	CGR decreases with temperature	Few data were available for lower temperatures. An activation energy of 130kJ/mol predicts a variation of about 0.75 decades over this range.
Lithium concn.	1 (factor of 10)	0-10 ppm	CGR increases with Li concn.	Most records in database had a conc. of ~2ppm. Comprehensive data for a range of concns. were only available for specimens with a yield strength of ~500 MPa
Applied stress	1 to 2.5 (factor of 10 to 300)	20–60MPam^{½}	CGR increases with applied stress	The CGR was much more sensitive to this parameter for specimens with a low yield strength
Yield strength	1.5 (factor of 30)	200-500MPa	CGR increases with yield strength	Yield strength correlates strongly with amount of cold work

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CONFERENCE ON VESSEL HEAD PENETRATION INSPECTION, CRACKING AND REPAIRS
Gaithersburg, MD – Sept. 29-Oct. 2, 2003

Results of Accelerated SCC Testing of Alloy 82, Alloy 182 and Alloy 52M Weld Metals

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Presentation Content

- Background
- Experimental Program and Approach
  - Materials
  - Test Environments
- Results of Corrosion Testing
- Conclusions

Background

- Increased incidences of environmental degradation (PWSCC) of Alloy 600 and the corresponding weld metals have emphasized the need for expanding the corrosion test database.
- The research reported here was conducted to examine:
  - Crack initiation in Alloy 52M (and controls of Alloy 182 and Alloy 600), used for recent weld metal repairs at Ringhals 3 and 4,
  - Crack initiation in Alloy 82 and Alloy 182 weld metal specimens removed from the V.C. Summer RV nozzle safe-end that cracked in service in 2000, and
  - Crack growth rates in the V.C. Summer Alloy 82 and Alloy 182 safe-end weld metals.

Overall Test Matrix

MATERIAL	CRACK INITIATION 400°C	CRACK INITIATION 360°C	CGR TESTS 0.5T-CT 325°C
Alloy 82	--	X	X
Alloy 182	X	X	X
Alloy 52M	X	--	--
Alloy 600	X	--	--
Approx. Stress	500 MPa (73 ksi)	500 MPa (73 ksi)	--
Levels	360 MPa (52 ksi)	400 MPa (58 ksi)--	--
Stress Intensity	--	--	20, 35 MPavm

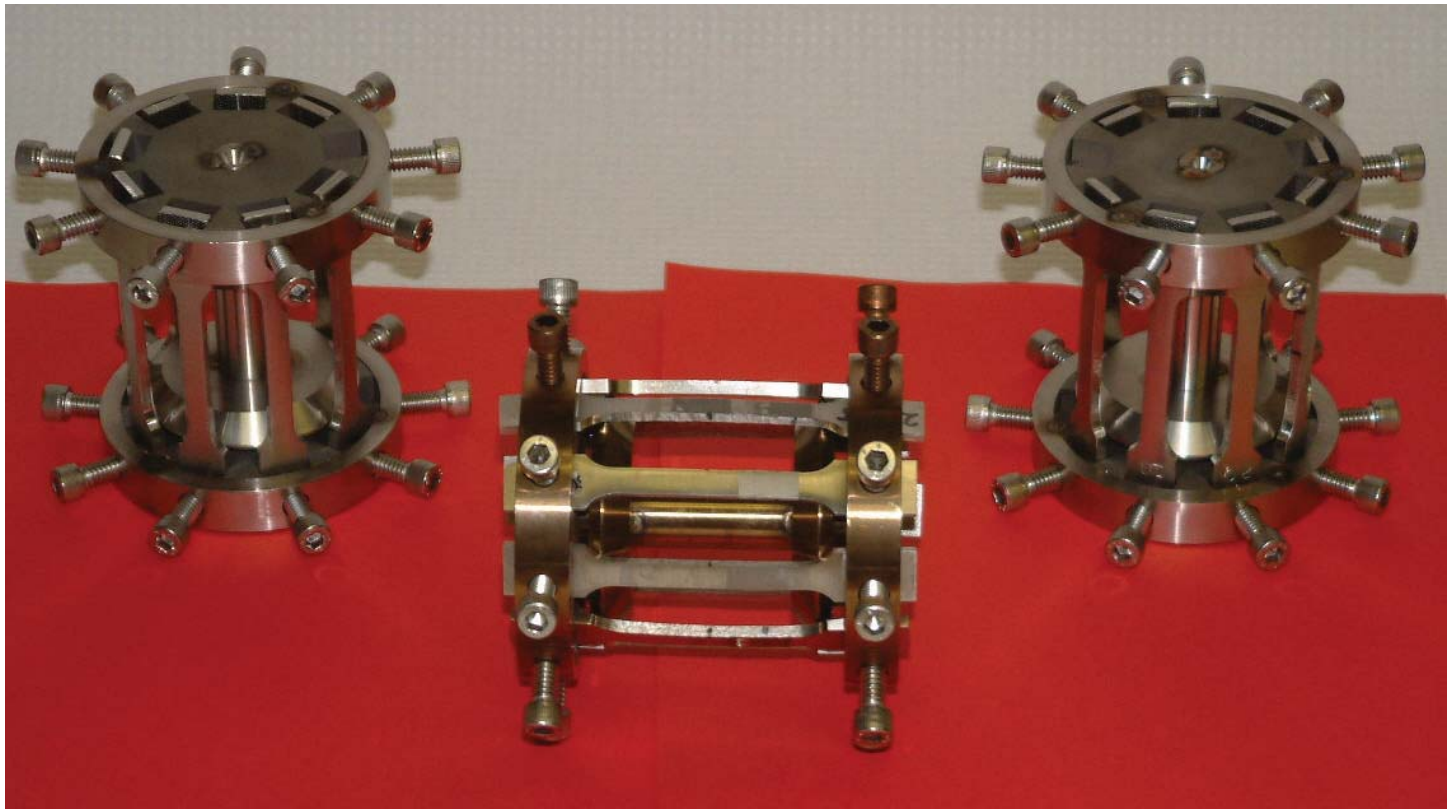
Experimental Program – Crack Initiation Tests

- Four-point bent-beam specimens of Alloy 52M and Alloy 182 weld metal were tested at strains of 0.35 and 1.0 % in a 400°C doped steam environment for periods equivalent to more than forty years at normal operating temperatures.
  - Alloy 600 specimens from archived sections of a CRDM nozzle were included as controls.
- Four-point bent-beam specimens of the V.C. Summer Alloys 82 and 182 weld metals were exposed for 3522 hours in a 360°C (680°F) simulated primary water environment with applied loads equivalent to surface stresses of 400 and 500 MPa.

Test Configuration – 400°C Steam Tests
Alloy 52M / Alloy 182 welds – 4 point Bending

Welds for Ringhals 3 and 4 tests are 9 mm thick,
Specimens machined from pre-repair qualification welds

Photos of Alloy 82/182 VC Summer Weld Specimens Accelerated testing in 360°C Primary Water



Experimental Program – Crack Growth Rate Tests

- Crack growth rate tests were performed on 0.5T-compact tension specimens of the V.C. Summer Alloy 82 and Alloy 182 weld metals.
- Testing was performed in 325°C (617°F) simulated primary water; 3.5 ppm Li, 1800 ppm B, 32 cm^3 (STP)H_2/kg H_2O.
- Specimens were actively loaded to nominal stress intensities of 20 and 35 MPa√m.
- Specimens were periodically unloaded to 0.7 initial load
  - Unloading period 1000 s / 9000 s / or constant load
- Crack growth was monitored using reverse DC potential

Crack Initiation Test Results – Alloy 52M, Alloy 182 and Alloy 600 in 400°C Doped Steam

- Alloy 52M is a modified version of Alloy 52 and is used for GTA welding of Alloy 690 [30% Cr compared to 14-16% Cr typical for Alloy 600 and Alloy 182].
- The doped steam-plus-hydrogen environment, containing
  - 30 ppm of F^-, Cl^-, and $SO_4^=$ and
  - 75 kPa of hydrogen in 20 MPa steam,
  - provides an acceleration factor estimated as 195 relative to corrosion at the 322.8°C Ringhals 3 & 4 RV outlet temperature.
- Weld specimen test articles were 180 mm x 40 mm x 9 mm Alloy 600 specimens were 102 mm x 19 mm x 3.8 mm.

Crack Initiation Test Results – Alloy 52M, Alloy 182 and Alloy 600 in 400°C Doped Steam (cont'd.)

- The 4-point bent-beam specimens were loaded to either
  - 0.35% strain or
  - 1.0% tensile surface strains;
  - the strains were monitored by strain gages.
- The stresses were "stabilized" by 16 to 19-hour exposures at 400°C, after which the specimens were unloaded and reloaded
- These strains corresponded to residual stresses in the range
  - 320 to 400 MPa [46.4 to 58.0 ksi] for 0.35% strain and
  - 440 to 560 MPa [63.8 to 81.2 ksi] for 1.0% strain.

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Crack Initiation Test Results – Alloy 52M, Alloy 182 and Alloy 600 in 400°C Doped Steam (cont'd.)

- Interim inspections were performed at intervals varying from 120 hours (early) to 450 hours; at 418 hours, the strains were "verified" by unload-reload.
- After 2051 hours (equiv. to 45.7 efpy), crack initiation was not observed in the Alloy 52M specimens.
- For Alloy 182, cracking occurred in the high-stress specimens after 214 hours [4.8 equiv. efpy], and in the low-stress specimens after 450 hours [10 equiv. efpy].
- Alloy 600 controls cracked only at the high-stress condition in times from 450 to 598 hours [10 to 13.3 equiv. efpy]. This heat of Alloy 600 exhibits generally good resistance to PWSCC.

Crack Initiation Test Results – V.C. Summer Alloy 82 and Alloy 182 in 360°C Primary Water

- Specimens were pre-strained to permit testing at 400 and 500 MPa [58.0 and 72.5 ksi] as four-point bent-beams.
- The test environment was 2.0 ppm Li, 500 ppm B and 25-35 cm^3 (STP) H_2/kg water at 360°C (680°F).
- After a total exposure time of 3522 hours, crack initiation was not observed in careful post-test examinations.
- Time equivalent to 5.9 efpy in VC Summer Nozzle
  - Cracking detected at VC Summer after 13.1 efpy in 2000

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Crack Growth Rate Test Results – V.C. Summer Alloy 82 and Alloy 182 in 325°C Primary Water

- 0.5T-compact tension specimens of the V.C. Summer weld metals were tested at stress intensities of 20 and 35 MPa√m.
- The test environment consisted of 3.5 ppm Li, 1800 ppm B and 30-35 cm^3 (STP) H_2/kg water at 325°C (617°F).
- Specimens were fatigue pre-cracked in air at a stress intensity less than 15 MPa√m.
- Specimens were periodically unloaded to 0.7 initial load.
- Reverse DC potential drop was used to monitor crack growth

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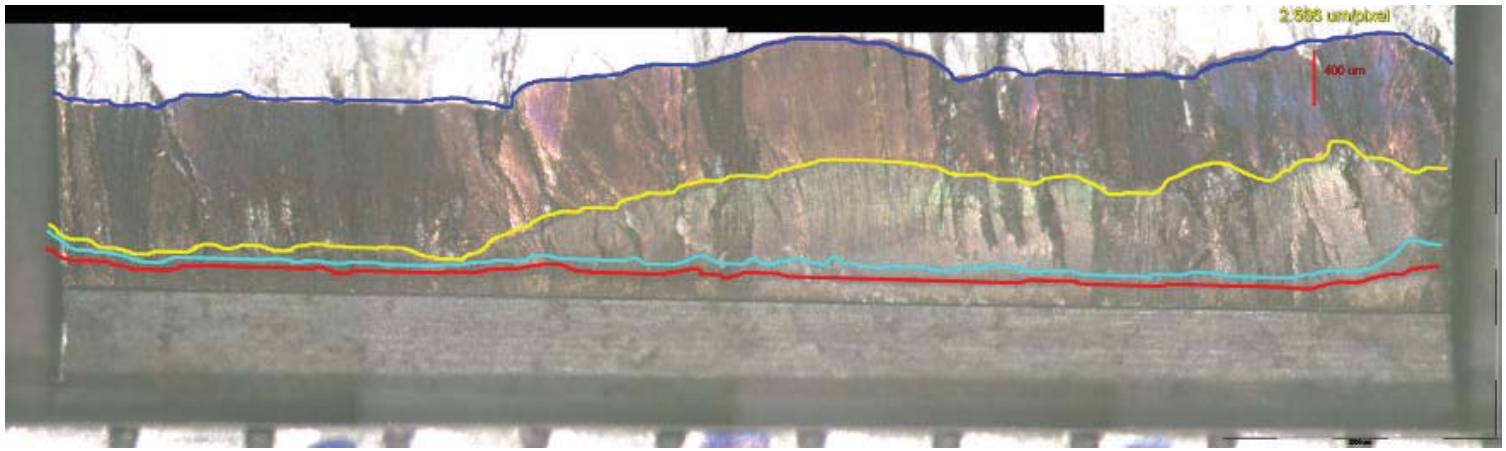
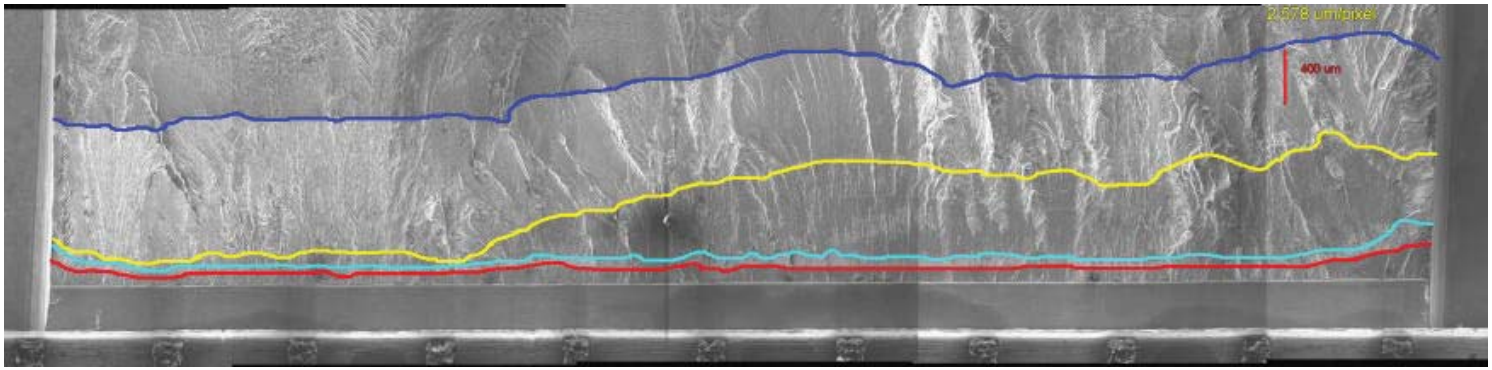
Crack Growth Rate Test Results – V.C. Summer Alloy 82 & Alloy 182 in 325°C Primary Water (cont'd.)

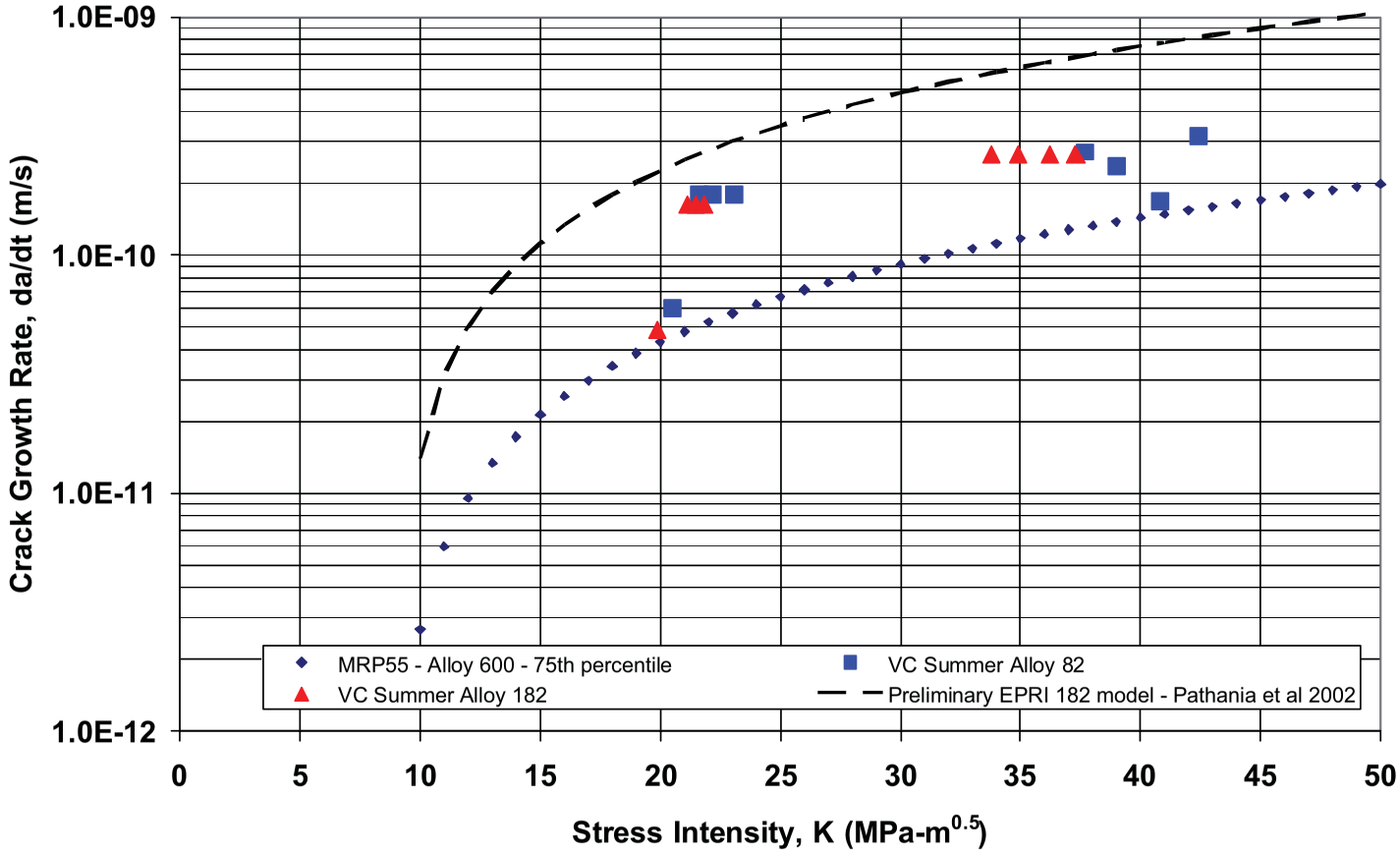
- Only relatively small differences were observed in the crack growth rates in the Alloy 82 and Alloy 182 specimens.
- The crack growth rates were measured to be between the 75th percentile curve for Alloy 600 (EPRI-MRP) and the curve presently proposed in a preliminary EPRI model for Alloy 182 (PWR MRP-21; TR-1000037).

Fractographs – Optical and SEM of 182





Comparison of VC Summer Alloys 82 and 182 Results with EPRI Models



Summary - 400°C Doped Steam Crack Initiation Tests for Ringhals 3 and 4

- Alloy 52M exhibited complete resistance to crack initiation under conditions of high stress (strain)
  - for exposures equivalent to more than 45 years of [322.8°C] operating experience.
- Crack initiation occurred in Alloy 182 and Alloy 600 specimens in shorter periods
  - Alloy 182 equivalent to 5 – 10 efpy
  - Alloy 600 equivalent to 6 – 13 efpy in service.

Summary - 360°C Primary Water Initiation Tests VC Summer Weld Material

- V.C. Summer Alloy 82 and Alloy 182 nozzle safe-end weld metal specimens, strain-hardened and stressed to 400 and 500 MPa, resisted crack initiation for 3522 hour exposures in primary water
- Equivalent to > 5 efpy at 320°C (608°F) approximate nozzle outlet temperature].

Summary - 325°C Primary Water Growth Rate Tests VC Summer Material

- Crack growth rates measured for Alloy 82 and Alloy 182 RV nozzle safe-end weld metals at stress intensities of 20 and 35 MPa√m were similar
- Growth rates obtained were between the 75th percentile curve for Alloy 600 and a preliminary Alloy 182 curve proposed by EPRI.

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Conclusions

- Cracking did not initiate in Alloy 52M under extremely aggressive and accelerated test conditions
- Under similar conditions, crack initiation occurred in Alloy 182 weld metal and Alloy 600 CRDM nozzle material
- The V.C. Summer Alloy 82 and Alloy 182 weld metals exhibited fairly good resistance to crack initiation; measured crack growth rates were consistent with the general industry database.

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CONFERENCE ON VESSEL HEAD PENETRATION INSPECTION, CRACKING AND REPAIRS
Gaithersburg, MD – Sept. 29-Oct. 2, 2003

Metallurgical Investigation and Root Cause Assessment of the Reactor Vessel Head Penetration Alloy 182/82 J-Groove Weld Cracking in Two Rotterdam Vessels

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[1]Westinghouse Electric Company, Pittsburgh, PA;
[2]Dominion Generation; [3]Vattenfall AB

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Objective

- To establish the Mechanism and Root Cause of the CRDM Alloy 182/82 J-Weld Cracking in Rotterdam Vessels

Investigation Centered on J-Groove Weld Indications

- Ringhals 2 CRDM Penetration 62
- North Anna 2 CRDM Penetration 62

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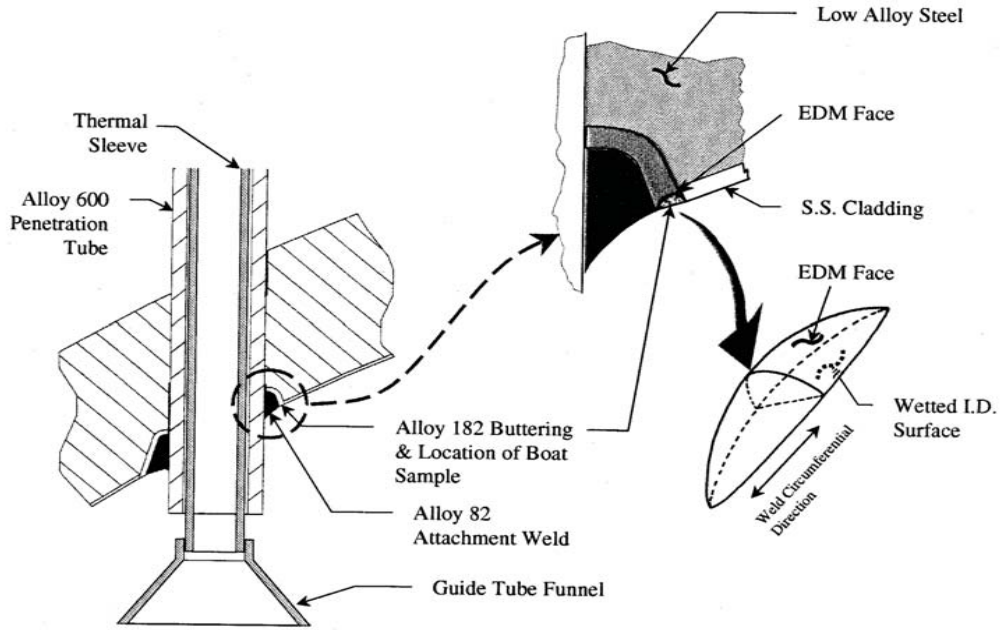
Summary of Hot Cell Investigations

- Surface Examinations
- Metallographic Examination of the boat Sections
- Fractographic Examination of the freshly opened cracks
- Chemistry Assessment of the weld metal regions and fracture surface by:
  - Energy Dispersive X-Ray Analysis
  - Microprobe Analysis
  - X-Ray Diffraction Analyses Techniques
- Review of the original Fabrication Records
- Mechanistic and Root Cause Assessments

NORTH ANNA 2 - BACKGROUND

- Fall 2001 Outer Surface Inspections of the RV Head revealed Boric Acid Crystals encircling three (Nos. 51, 62 and 63) of the 69 Penetrations
- Subsequent inspection of the Bottom ID Surface of the Vessel Head revealed crack-like indications in the vicinity of the J-Groove weld/butter region of the three penetrations
- An 0.5 inches wide, 2 inch long boat sample, circumferentially positioned in the butter region of the weld and containing the affected region, was removed for investigation
- Hot Cell investigation was conducted at Westinghouse Pittsburgh Laboratories

NORTH ANNA BOAT SAMPLE



Schematic Representation of the Boat Sample Location in North Anna 2 Reactor Vessel Head Penetration J-Groove Weld

SUMMARY OF NORTH ANNA 2 BOAT SAMPLE

- Examinations confirmed extensive hot cracking in the buttering adjacent to the low alloy steel and stainless steel interfaces
- Few of the hot cracks extended to the wetted ID surface of the buttering
- The propensity of hot cracking in the buttering decreased as we moved away from low alloy steel interface

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NORTH ANNA 2 BOAT SAMPLE

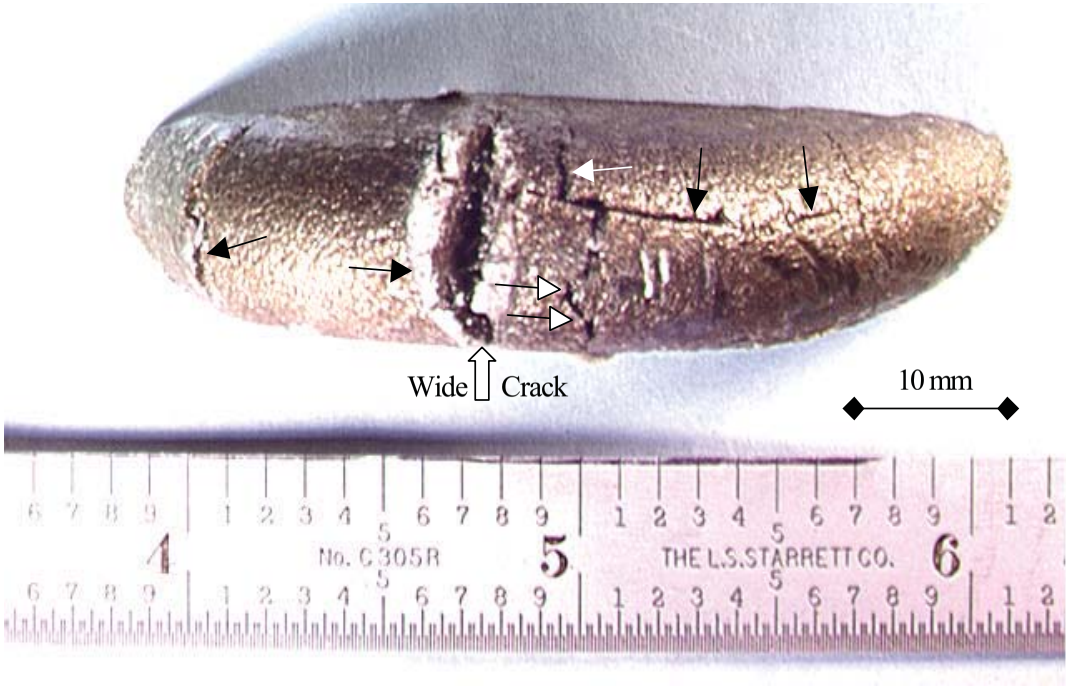
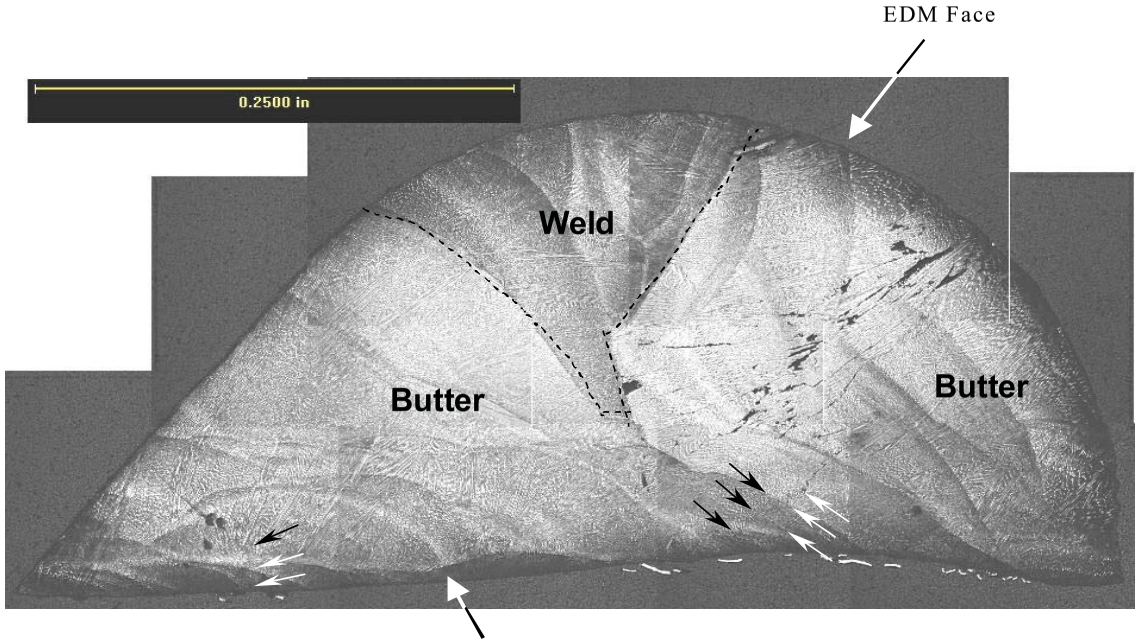


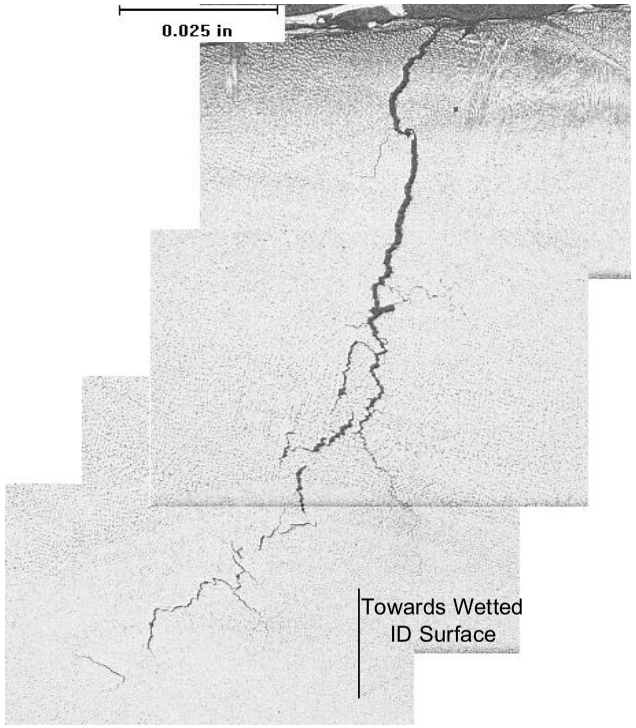
Illustration of the EDM Cut Face
North Anna 2 Boat

NORTH ANNA 2 BOAT SAMPLE



Metallography with Identified Butter and Weld Regions By EDAX Analysis, North Anna 2 Boat

NORTH ANNA 2 BOAT SAMPLE



Axial Section of North Anna 2 Boat, Showing PWSCC Crack Progressing from EDM Cut Fact to the Wetted ID Face of RVH

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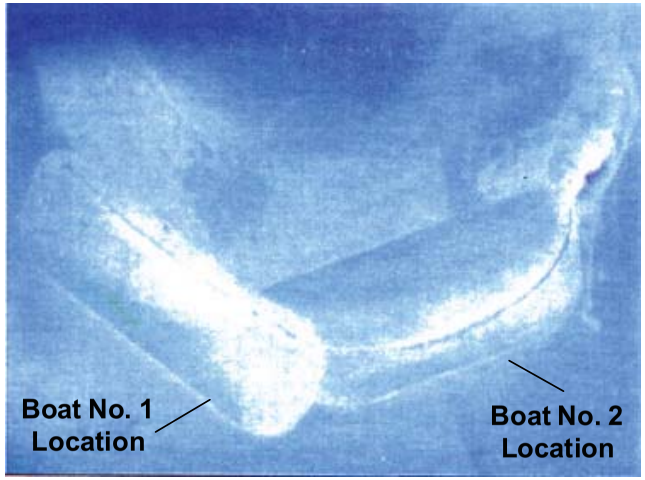
RINGHALS 2 - BACKGROUND

- 1993 outage inspections revealed a 7-inch (18 cm) long circumferentially-oriented surface indication in the J-weld of Penetration No. 62
- Investigations centered on:
  - Two small boats – 1 inch diameter and 0.1 inch thick
  - Two large boats – 2.75 inches long, 0.8 inch deep
- Hot Cell investigations were conducted at:
  - Studsvik Laboratory in Sweden
  - Westinghouse Laboratories in Pittsburgh, USA

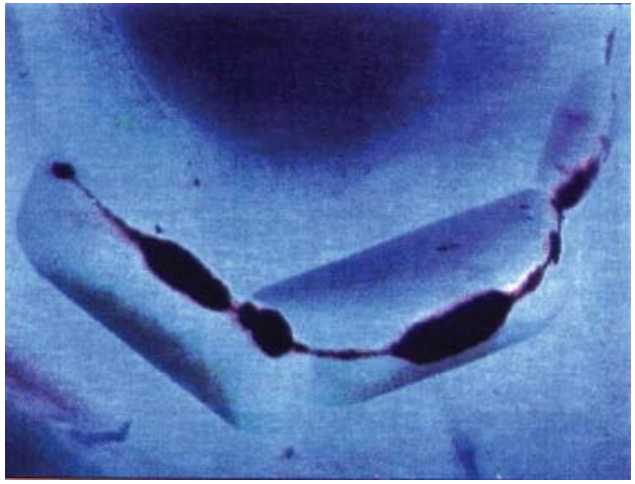
SUMMARY OF RINGHALS 2 BOAT SAMPLES

- Evidence of 0.02 inch-wide crack between low alloy steel and Alloy 182 buttering running along the entire boat length
- The crack was arrested and blunted as it extended into the Type 309 stainless steel cladding
- The crack appeared wider at the EDM cut face and it narrowed down as it approached cladding
- Incomplete wetting (fusion) of the first layer of buttering resulting in “lack of fusion” defects at the interface
- Significant carbide precipitation in the fusion zone
- The interconnected microfissures provided access of primary water to the weld interface and contributed to:
  - Microscopic wastage of low alloy steel interface
  - Secondary crack extension of the weld defects by PWSCC

RINGHALS 2 BOAT SAMPLE



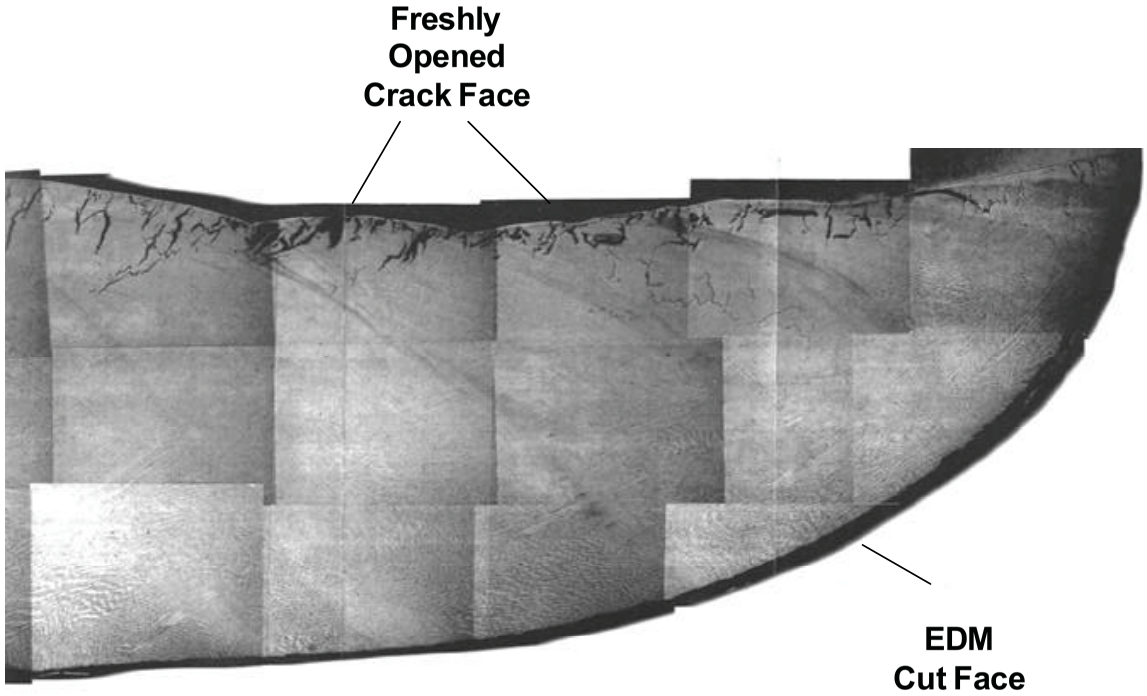
Before PT



PT Results

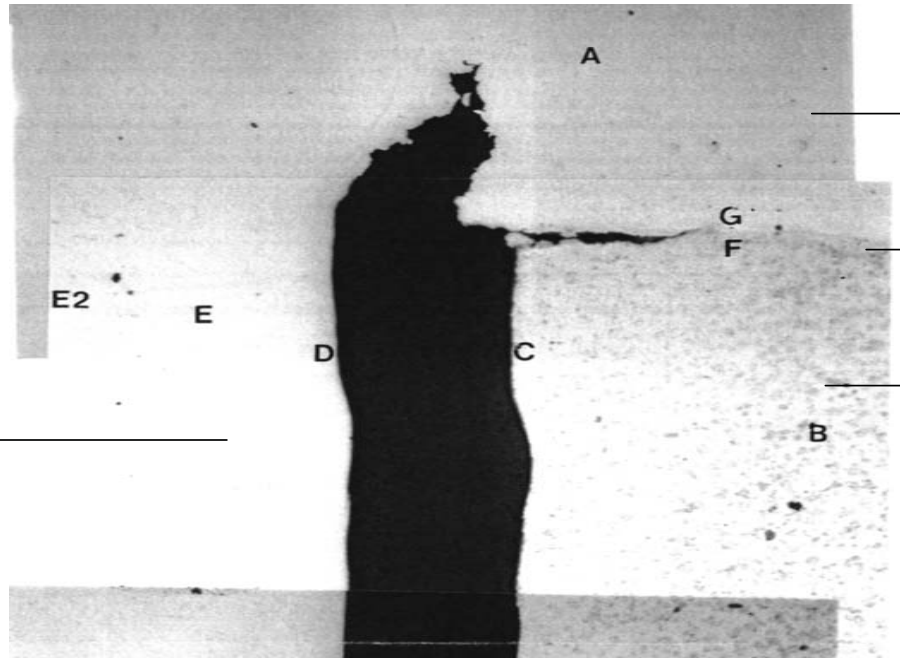
Appearance of Crack at the Bottom of Divots
(Ringhals 2 Penetration 62)

RINGHALS 2 BOAT SAMPLE



Cracking Morphology in the Butter at the Nozzle Interface (Large Boat 1)

RINGHALS 2 BOAT SAMPLE



Type 309 Stainless Steel Cladding

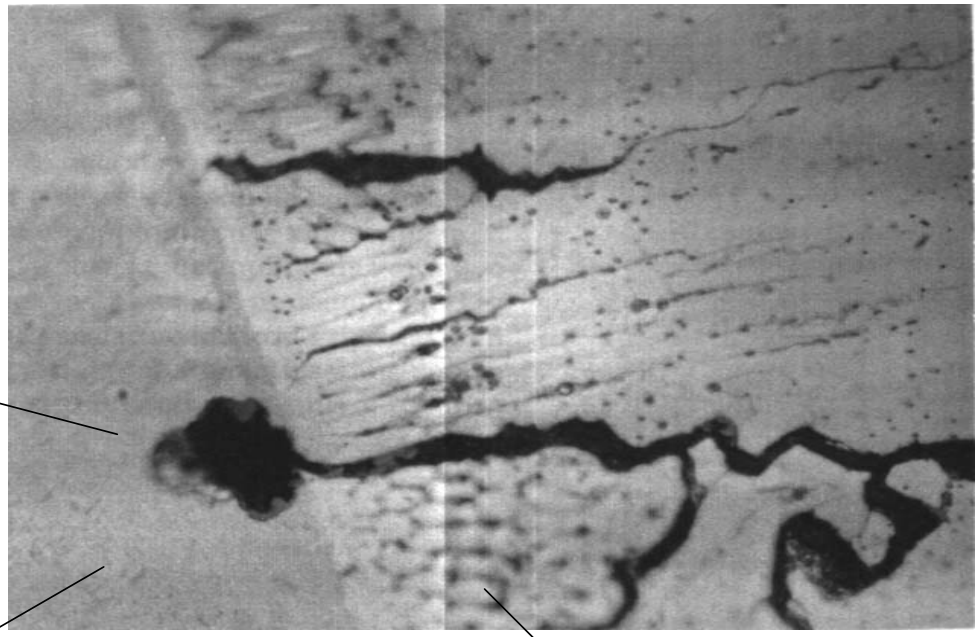
Interface

Low Alloy Steel Nozzle

Alloy 182 Butter

Crack Termination at the Cladding

RINGHALS 2 BOAT SAMPLE



Evidence of Carbon Steel Wastage at the Butter Interface

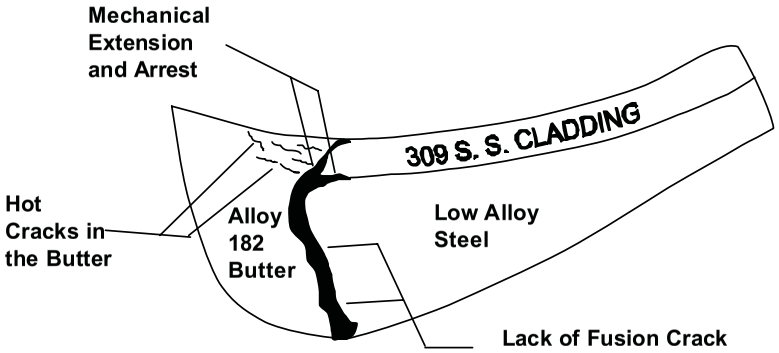
ROOT CAUSE CONSIDERATIONS AND POSTULATED MECHANISM

- The J-Weld preparation by Air Arc Gouging Technique left an oxide layer and carbon residue on the low alloy steel surface
- Inadequate cleaning prior to welding left oxide, carbon and moisture on the surface
- The surface condition contributed to a non-wetting and lack of fusion bonding during the deposition of the first layer of buttering at the low alloy steel interface

ROOT CAUSE CONSIDERATIONS AND POSTULATED MECHANISM (continued)

- Attempt to repair this during subsequent depositions was unsuccessful, leaving presence of heavy carbides, slag inclusions and poor bonding at the interface
- A thin initial layer of buttering and non-uniform temperatures may have led to the de-bonding of the weld interface under the influence of thermal stresses even while the top (ID surface) layers of the weld metal were being deposited
- The movement of the crack faces and the crevice condition of the crack created a strain field at the crack tip during the fusion of the top layers of the weld inducing microfissures due to hot cracking of the weld metal

RINGHALS 2 BOAT SAMPLE



Ringhals 2 Boat Sample (Transverse Section)

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CONCLUSIONS

- North Anna and Ringhals Boat Samples showed similar characteristics
- The investigation results of the CRDM Penetration cracking at Ringhals 2 and North Anna 2 units supports that the observed cracking originated from the original fabrication of the J-Weld buttering
- The microfissuring of the final layers of weld metal buttering occurred by a “hot cracking” mechanism. Excessive strains caused by the occurrence of a sub-surface larger lack-of-fusion crack at the weld metal to low alloy steel interface most likely contributed to the cracking in the Ringhals weld.

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CONCLUSIONS (continued)

- The occurrence of the main crack at the weld interface and the microfissuring of the weld metal are both caused by the inadequate surface preparation of the J-Groove prior to the welding and/or weld repair
- The root cause of the cracking in the Ringhals and North Anna vessels examined here is believed to be lack of fusion at the Low Alloy Steel Interface
- Primary water accessed to the area of lack of fusion through exposed hot cracks at the wetted surface provided potential for additional cracking by PWSCC

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French Regulatory Experience and Views on Nickel-Base Alloys PWSCC Prevention & Treatment

by

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French Nuclear Safety Bodies Presentation Outline

- Context & objectives of a presentation by French Nuclear Safety Bodies
- Specific features of French nuclear organizations and practices
- An all PWR fleet prone to « generic effects » illustrated by the Inconel Zones

- Features , Principles and Evolution of French Regulatory Rules
- Specific Features of Alloy 600 PWSCC
- « Inconel Zones Review », A Proactive Approach to maintenance vs PWSCC
  - background
  - objectives
- Treatment of Inconel Zones
- Use of PWSCC initiation models (Interest and limitations)
- Involvement of ASN / IRSN in the implementation and follow-up of a comprehensive In Service Inspection (ISI) Program
- Status of Vessel Head Inspection and Replacement
- Status and Prospects for Bottom Vessel Head Penetrations in France

- Future Prospects and Investigation Needs
- French Nuclear Safety Authority (ASN) & IRSN CONCLUSIONS

Context & Purpose of the IRSN/DGSNR Presentation in this Conference

Presentation of the French Nuclear Safety Organizations & their role

EDF the French sole Nuclear Operator in France, in the first place, responsible for the Nuclear Safety of a fleet of 58 PWRs: It has:

- **A large expertise in terms of R/D, failed components investigation capabilities,**
- **International activities and is an active EPRI member,**
- **Structured and comprehensive maintenance programs and central support staffs to anticipate problems and instruct an important experience feedback,**
- **Units and staffs devoted to manage safety, set doctrines & audit their implementation.**
- **been PROACTIVE with regard to the Inconel vessel penetrations since 1991**

The vigilance and positions of the French Safety Bodies may have played a crucial role in the early strategies and steady follow up of the Inconel Saga.

Hence the objectives of the IRSN/DGSNR (ASN) presentations:

- **Recall the main specific aspects of the French situation vs. the Inconel zones,**
- **Recall the main regulatory features and their evolutions in France,**
- **Present the « PROACTIVE Inconel Zones » return of experience », as perceived by the Safety Bodies from the technical and regulatory stand point,**
- **Explain the reasons for the technical and regulatory positions of DGSNR/IRSN on the now 13 years old « Inconel Zones Review » in France,**
- Bring some Testimony in the USA, in the wake of the « Davis Besse Lessons Learned Issue »

Specific features of French Nuclear Organizations & Practices

- One Nuclear Power Operator of a fleet of 58 PWRs — EDF
- One Power Reactor Manufacturer — Framatome-ANP
- One Scientific Organization in charge of Nuclear R&D — CEA
- One Regulatory Body for Nuclear Safety & Rad Protection (ASN) ⇔ DGSNR
  - Central Staff (150 members) + regional offices (100 members) ….
- One Body for Nuclear Safety and Radiological Protection, (staff 1500) — IRSN
  - performing Research mainly in accident studies, radiological protection…
  - & Technical Support to DGSNR, (staff : 350), some specialists following Materials, Components, NDE, R&D issues, with some limited confirmatory or exploratory Research

- **No License Renewal in FRANCE,**
- **Importance of Decennial Complete Visits for: (DCV = 10 yearly outage)**
  - Comprehensive Components Condition Investigations, Repairs , Replacements
  - and for Safety Reassessment, & Implementation of Safety improvements
- **Decennial Complete Visits (DCV)** including regulatory hydro test for primary circuit
  - CP 0 (900 MWe) Second DCV, nearing Third (BUGEY 3 CRDM Leak at 1st DCV)
  - CP1-CP2 (900 MWe) first DCV, some Second DCV
  - P4-P'4 (1300 MWe) first DCV
  - Latest French Design N4 series (4 Units) , commissioned in 1996-99

An All PWR Fleet of 58 Reactors, where Alloys 600/182-82 extensively used

- **An important all PWR fleet (63 GWe- 80 % of French electricity)**
- **Standardized in 4 PWR series constructed and commissioned in a crash program,**
- **Sensitivity to generic effects,**
- **Advantage for the return of experience.**

Some differences with the use of alloys 600, 600 TT, 690 , Stainless Steel within the series

SERIES	Loops/MWe	N° of units	Date of Commission	Main Specific initial features, as commissioned
CPO	3 /900	6	1977-79	Hot Plenum, Bugey 3 (1978)
CP1-CP2	3 /900	28	1981-87	Cold Plenum, Blayais 1, (1981) some SG tubing in 6OO TT
P4 –P'4	4 /1300	20	1984-93	Hot Plenum, Alloy 600 TT for SG Alloy 600 for PZR nozzles, Cat. 2 (1987)
N4	4 /1450	4	1996-99	Alloy 690 for SG, CRDM (4 units) Alloy 690 for BMI (2 units) 3 last Units with Vessel/Primary loop Alloy /82 DMW (600°C stress relieved)

Specific Features of Nickel base Alloys PWSCC

PWSCC may be considered as a major contributor to degradation & aging in PWRs, particularly difficult to assess since:

- **The degradation mechanisms are not yet fully established neither understood,**
- **Characterized by incubation times (crack initiation) which can be very long,** ex: **Fessenheim 2** CRDM first incipient penetration crack detected after some **130 000 h.**, to be compared to some units like **Cattenom (30 000 h.) or Blayais (80 000 h).**
- **Inconel PWSCC crack initiation times t_i are not only governed in a deterministic manner** by various parameters difficult to assess , quantify, and weigh, i. e. :
  - **Actual Wall Temperature and temperature dependence (activation energy)**
  - **Bulk and Surface Residual + Operational Stresses (σ) $\Rightarrow$ 1/ t_i α. σ^n , n= 4±?**
  - **Material composition (C content) & microstructure (grain boundary Chromium Carbide relative coverage) and other metallurgical unknowns,**
- **Inconel PWSCC crack initiation times are also governed by stochastic processes** and characterized by a large scatter (large distribution of time to initiation for identically stressed carefully controlled identical Inconel specimen even in the laboratory tests,
- **Stress Assessment** : actual **residual stress** fields, **bulk**, **surface**, **static** and some **dynamic operation cycling or transients** may strongly govern in a complex manner both Crack Initiation (CI) & Crack Propagation Rates (CGR).

Features, Principles and Evolution of French Regulatory Rules to Ensure Integrity of the Main Primary Circuit *(1/3)*

Evolution of French Regulatory Practices:

- **Ministerial order 1974 :** concerning the Main Primary Circuit **(manufacturing and operation),**
- **Ministerial order 1999 : concerning the surveillance in operation for Main Primary and Secondary Circuits,**
- **RCCM code (last edition June 2000), (Rules for Conception, Construction of PWR Mechanical components): compiled by EDF (utility) and Framatome (designer/manufacturer);**
- **RSEM code (first edition 1997) :**
  - **Rules of Surveillance in Operation for PWR Mechanical components, compiled by EDF**
  - **and accepted by French Safety Authority (ASN)**
- **Regulatory decisions since 2000: ASN may write and publish decisions (web site),**
  - **with requests about important technical problems,**
  - **for example the decision for Inconel Zones (IZ) in March 2001.**

Features, Principles of French Regulatory Rules to Ensure Integrity of the Main Primary Circuit (*continued*, *2/3*)

- **Preclude (avoid and prevent leak) any leak in the main primary circuit**
- **Make sure that no flaws would lead to a leak during operation**
- **Methodology pertaining to the so called « Sensitive Zones »(SZ)**
  - **Search for possible degradations through:**
    - **Design files (Stress analysis reports),**
    - **Fabrication files (repairs, deviation from procedures),**
    - **Complex loads such as mixing fluids, possible synergetic effects of cyclic loads on SCC,**
  - **Sensitivity analysis ⇒ zones ranking regarding their sensitivity to some likely degradation mechanisms (such as corrosion, SCC, Fatigue, Corrosion-fatigue..),**
  - **⇒ Determination of Sensitive Zones (SZ),**
  - **In SZ, knowledge and characterization of the Degradation mechanism(s) anticipated,**
  - **In SZ, determination of flaw critical size (with security margins),**
- **Methodology for In Service Program (ISI)**
  - **Definition of an ISI program as preventive, and capable to detect flaws prior to reaching critical size,**

Features, Principles of French Regulatory Rules to Ensure Integrity of the Main Primary Circuit (*continued 3/3*)

- **Coverage of Inconel Zones Families would be possibly achieved by inspection of several precursor SZ among all the SZs:**
  - **Precursor should be truly representative of SZ (i.e..: same degradation mechanism), provided it is truly demonstrated as a forerunner for initiation, and exhibits a faster degradation propagation rate (CGR),**
  - **⇒ requires the definition of extension rules in ISI program.**
- **Methodology of NDE qualification:**
  - **Ensure flaw detection before reaching critical size,**
  - **⇒ choice of NDE method & performances and a qualification process,**
  - **In SZ ⇒ flaw detection demonstration:**
    - **When flaws have already been detected in components,**
      ⇒ »specific» qualification,
    - **When flaws are « feared » but not yet detected,**
      ⇒ »general» qualification,
  - **In Non SZ ⇒ only a description of methods performances is required,**
  - **For each NDE method, the nature, the objective & NDE intervals should be specified.**

INCONEL ZONE REVIEW for the French FLEET of 58 PWRs
(Background which entailed a Strong PROACTIVE PROJECT)

- **1959, by CORIOU et. al. in CEA/Saclay first Laboratory Discovery of Alloy 600 propensity to crack by SCC in PURE WATER at 350 °C,**
- **1959-1975, confirmation of Alloy 600 SCC in Pure & in nominal Primary Water (hence the acronym PWSCC, PW for Pure or Primary Water), then ⇒**
- **Alloy 600 and Nickel base alloys prone to PWSCC <u>in nominal Primary Water</u>**
  (hydrogenated HT water ⇒ places Ni base alloys in the unfavorable SCC susceptibility range close to Ni/NiO transition).
  ⇒ Generic problem on highly stressed Nickel base alloy components,
  ⇒ Hence a source of primary components failures and primary water leaks for which anticipation methodologies may be limited*.
- **In 1989, in addition to many SG tubing problems, 2 fast PWSCC degradations could occur in France within the first fuel cycle on 1300 MWe units (Nogent 1)**
  - **Circumferential through wall Cracking on new alloy 600TT, SG tubing on top of TS,**
  - **Leaks on PZR instrumentation nozzles of 1300 MWe units (made from alloy 600).**
- **1989, Initiation of the "Inconel Zones Review" by EDF & Framatome, at the "strong request of ASN, i.e. more than 1 year before the Bugey 3 CRDM leak.**

* <u>refer to</u> :« ***status of alloy 600 components degradation by PWSCC in France; incentives & limitations of life predictions as viewed by a Nuclear Safety Body*** » , by G. TURLUER, IPSN/DES/SAMS, Fontenay-aux Roses, France,Proc. of Intern. Symposium on Plant Aging & Life Prediction of Corrodible Structures , May 15-18, 1995, Sapporo, Japan

PROACTIVE « Inconel Zones Review » in France: Objectives and Tasks

- Review for all « Inconel Zones (IZ) Potential PWSCC Occurrence,
- Assess all IZ fitness for service,
- Develop NDE inspections techniques & tooling,
- Implement NDE Program for the most PWSCC prone IZ,
- Justify the IZ Review by a comprehensive R&D Program,
- Refine an empirical PWSCC initiation model for ranking purposes,
- Verify the postulated IZ, time to cracking by a sufficiently large NDE program:
  - Either full scale, (100 %)
  - Or on significant sampling rate,
- Perform a Safety assessment for each IZ, postulating worse consequences:
  - From Leaks, which, in many instances of un-sustained leak, may lead to dry boric acid/salts deposits, with no measurable general corrosion, BUT:
    - small concealed low leak rates may entail penetration OD SCC (Bugey 3, Occonee)
    - to higher leak rates ⇒ corrosion/flow accelerated corrosion to low alloy steel,
  - From a possible Break, including Control rod ejection.
- Prepare for mitigation techniques, including repair or replacement

Use of PWSCC Initiation deterministic (empirical) Models as a Predictive Tool for PWSCC Occurrence in Plants ?

- Crude Temperature/time models(?), ignoring paramount effects of stress, metallurgical factors, & batch to batch variations, are irrelevant, (misleading?)
- More sophisticated models such as those developed in France,
  either expressed in terms of relative sensitivity of Inconel Zones or estimated time to initiation :
  - Need a sufficient validation with NDE findings in the field,
  - Then may be used with caution for ranking purposes (precursor determination),
  - CANNOT be used to predict the time to macroscopic crack initiation (ti) for a given component, since :
    - Intrinsic material sensitivity to PWSCC can only be qualitatively estimated,
    - Effective Stress, including surface CW, residual Surface Stress due to assembly, machining, grinding or final surface finish (Sigma to the power 4 ± x) cannot be estimated everywhere exactly on as fabricated components,
    - Uncertainty brackets cannot easily be estimated (in terms of index or time ti).
- IRSN & DGSNR accepted only the empirical models only for
  - comparing and integrating Inconel zones data,
  - Ranking purposes to set inspections priorities,
- IRSN/DGSNR did not accept any absolute time to initiation prediction of the kind «no cracking anticipated before 30years of operation » for a given zone,
- Hence the request to proceed to NDE at least on a sampling basis

Implementation of a comprehensive In Service Inspection (ISI) Program IRSN & ASN involvements (1/2)

Vessel Head CRDM Penetrations

Needs
- Detect, localize cracks
- Identify & size them

Determine field CGR

→

NDE Development
- NDE qualification:
- Remote Video inspect.
- Dye Penetrant ,
- Eddy Current (EC)
- UT

→

NDE Implementation
- focus on Max, not only on mean crack depth & CGR
- Devise an adapted NDE program as a function of previous NDE (results)
- Plan a timely V.H. replacement Program
- In situ CGR evaluation from O to max CGR

Safety Bodies involvement at all stages to follow up the dossiers and give advice on

- ☞ methods qualifications, performance assessment,
- ☞ NDE program definition and scope,
- ☞ CGR field data (kinetics and crack profile evolutions) assessment
- ☞ NDE results evaluation,
- ☞ Annual validation of the maintenance program (surveillance, RVH replacement)

↓

IRSN recommendations ⇒ to ASN acceptation, requests &, if need be, ASN decisions

Inplementation of a comprehensive In Service Inspection (ISI) Program IRSN & ASN involvments (2/2)

Other Inconel Zones :
R.V. Bottom Mounted Instrument (BMI) Penetrations
Local Vessel under clad defect repairs with Inconel 182

Nuclear Safety Bodies examine

- ☞ **Maintenance & NDE doctrines,** including the analysis of possible «Inconel Zones» degradation, potentially prone to PWSCC or to other types of degradations,
- ☞ NDE objectives definition files (*technical requirements*,..)
- ☞ Methods qualification results (performances,..)
- ☞ Procedures,
- ☞ NDE Results,
- ☞ NDE « maintenance » programs,
- ☞ Miscellaneous : Mitigation and repair files, ..

IRSN specialists issue recommandations to ASN leading either to EDF proposal acceptation or to further requests or possible ASN decisions*. *(*Published on ASN web site)*

Status of Vessel Head Penetration Inspection and Replacement (as of 07/03)

- **After 12 years of Inconel Zone Policy implementation in France:**
  - **42 vessel heads replaced,** out of 54 units initially fitted with alloy 600 CRDM

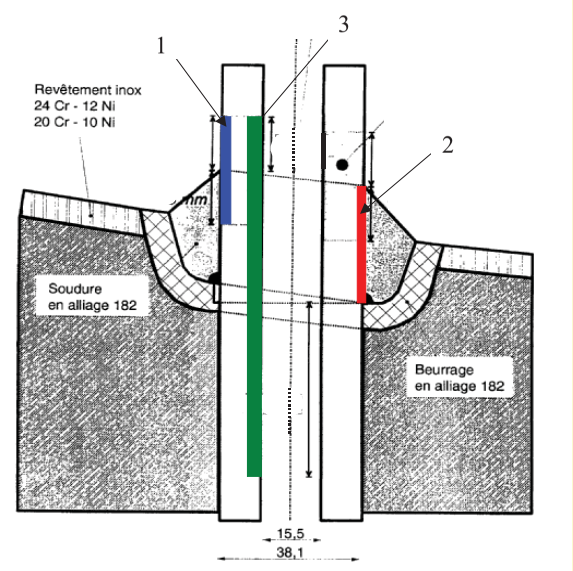
  ⇒ **46 units** in operation **with alloy 690 CRDM & vent penetrations,**
- **On 11 out of 42 retired VH, CRDM J groove welds have been inspected in details, by remote high resolution video inspection**
  - **No PWSCC crack initiations were ever found**
- **3 replacement vessel heads with penetrations in alloy 690 have been successfully inspected after some 10 years of operation,**
- **Vessel head replacement planning for the future would normally depend on regular NDE results, on remaining un-replaced VH,**
- **but in many instances, replacement is made by anticipation,**
- Would the VH replacement planning in France be affected by the sudden surge of urgent vessel replacement needs in the USA ?

Present Status of the Inconel Zone Treatment in France (as of 07/03)

- **Focus on Reactor bottom head penetrations (BMI) assessment and inspection**
  - Normally, BMI are stress relieved with the vessel (600 °C), after welding into the vessel,
  - Some repaired or straightened penetrations after the in shop vessel stress relief,

- So far, 12 units successfully inspected for BMI penetrations integrity, (including Bugey 3 inspected 3 times).

  Schematic representation of BMI zones ⇒ inspected by NDE
  - 1 search zone for OD cracks
  - 2 search of interfacial defects
  - 3 search zone for ID cracks



- **Steam Generator Partition Plate and its welded zones**: (in progress),
- Other zones …(in progress).

Future Prospects and Needs (to better analyze World Wide Experience)

- Focus in the future On Weld Metal Behavior, in the Field & Lab,
- Need to better assess initiation & CGR dependence on Temperature,
- Provide enough accurate data on:
  - Actual IZ wall temperature
  - Account for variations of PWSCC Sensitivity of Inconel components as a function of process, & fabrication variables & metallurgical state,
  - Improve the evaluation of residual AND Operational Stresses,
  - Take into account the final surface state resulting from machining, grinding, or other surface finish,
  - NDE performances and resolution,
- Express and use CGR in terms of maximum rate, or CGR brackets and not only by « mean values »,
- Take into account possible synergistic effects of various forms of mechanical stresses or strains other than residual ones (ex. low f cyclic ripple or load transients),
- Last but not least, review & refine crack initiation anticipation methodology, in order to mitigate early enough leak consequences.

ASN/IRSN French Experience: CONCLUSIONS (1/2)

- **PRECLUDING LEAKAGE: Successful strategy,**

  since Bugey 3, no other CRDM leak

- Importance of regulatory hydro-test at 1.2 times the design pressure

  as an in depth defense measure, with «bare metal Surface access» for leak detection,

  not as an « NDE method of detecting flaws »,

- **Recourse to extensive ISI,**
  - First 100% to assess the whole fleet condition with regard to PWSCC for CRDM penetrations,
  - Then flexible re-inspection schedule for PWSCC affected un-replaced vessel heads,
  - NDE inspection & re-inspection of BMI on an oriented sampling basis, with a priority to units comprising repaired or straightened up BMI after vessel stress relief treatment,
  - ASN allowed maintaining some medium size PWSCC cracks for «in the field CGR» assessment by UT.

ASN/IRSN French Experience: CONCLUSIONS (2/2)

- **Considerable R&D by EDF and Framatome to constitute & improve:**
  - **Crack initiation data base from Lab & Field NDE detection,**
  - **Propagation data bases : Max CGR derived from Lab & Field,**
  - **Comparisons should be made with international data ,**
    ⇒ looking for clear, fair & «CONSERVATIVE SCREENING CRITERIA»
  - **reported regularly to ASN & IRSN,**
- **Timely replacement of the most PWSCC affected vessel heads**
- **Only 3 young units (N4) with stress relieved alloy 82 DMW on Vessel/Primary loops junctions,**
  Now in France, no Inconel parts linked to the Pressurizer,
- **Now, continued focus on BMI & other Inconel Zones,**
- **Interest to follow up closely worldwide experience feedback**
  for weld materials where PWSCC initiation and propagation were observed,
  since weld cracking by PWSCC hardly experienced in France. Why?
- **So far, so good.., in France, but .. let us keep vigilance as plants age!**
  One example of precaution : 3 full NDE inspections of replacement Vessel Heads with Inconel 690 penetrations after some 10 years of operation.

Section 6:
Session 5: Mitigation of Nickel-base Alloy Degradation and Foreign Experience

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Belgian activities on alloys 600 and 182 issues

R.Gerard

Ph.Daoust

NRC-ANL conference, Gaythersburg, MD, Sept.29-Oct-2, 2003

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Belgian Nuclear Units operated by Electrabel

Unit	Capacity MWe,netto	First Operation	NSSS designer
Tihange 1	962	1975	Westinghouse
Tihange 2	1008	1983	Framatome
Tihange 3	1015	1985	Westinghouse
Doel 1	392.5	1974	Westinghouse
Doel 2	392.5	1975	Westinghouse
Doel 3	1006	1982	Framatome
Doel 4	985	1985	Westinghouse

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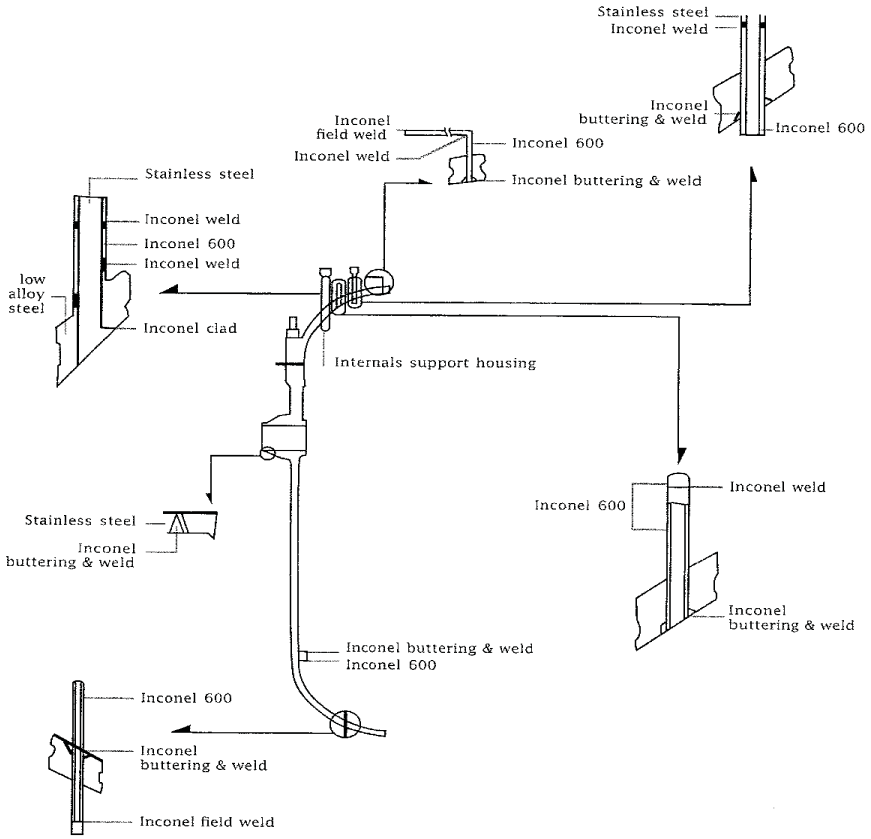
RV Alloy 600 components

figure 1



Alloy 600 – Base material Inspection status in Belgium (2003)

Head Penetrations

Inspection date	Unit	Age*	EFP* (hours)	T° (°C)	Inspector	Inspected penetrations	Inspection method	Results
Oct. 92	Tihange 1	17	123 000	318	ABB-R	65	ET	no crack (1 indication)
March 98	Tihange 1	23	163 000	318	FRA	65 + 1	ET + UT	Several cracks (1 heat)
October 99	Tihange 1	24				RPV head replaced		
Oct. 93	Tihange 2	10	81 000	287	ABB-R	65 + 1	ET	no crack
March 00	Tihange 2	17	131 000	287	ABB-R	65 + 1	ET	**no crack**
March 93	Tihange 3	8	59 000	318	ABB-R	65 + 2 + 3	ET	no crack
Dec. 96	Tihange 3	11	87 000	318	ABB-R	65 + 2 + 3	ET	1 indication
June 98	Tihange 3	13	99 000	318	ABB-R	65 + 2 + 3	ET	1 indication
September 01	Tihange 3	16	124 000	318	W-R(3)	65 + 2 + 3	ET	**1 indication no propagation**

* At the inspection date

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Alloy 600 – Inspection status in Belgium (2003)

Inspection date	Unit	Age*	EFP* (hours)	T° (°C)	Inspector	Inspected penetrations		Results
Head Penetrations								
Sept. 93	Doel 1	19	137 000	307	W	49	ET	no crack (1 indication)
August 98	Doel 1	24	174 000	307	ABB-R	49 + 1	ET + UT	Several indications (small cracks)
August 99	Doel 1	25	182 000	307	ABB-R	11	ET + UT	small cracks
August 01	Doel 1	27	198 000	307	W-R(3)	36	ET + 4UT	small cracks propagation
Sept.03	Doel 1	29	215 000	307	FRA	49	UT+visual (welds)	
May 94	Doel 2	19	125 000	307	W	49	ET + UT	no crack(2)
May 00	Doel 2	25	170 000	307	W-R	49 + 1	ET + UT	small cracks
May 03	Doel 2	28	194 000	307	FRA	49	UT+visual (welds)	small scratches (no longer characterized as cracks)

* At the inspection date
(1) Intercontrôle (IC) and AIB-Vinçotte
(2) Indications of original defects in the weld due to lack of fusion
(3) ex ABB-R

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Alloy 600 – Inspection status in Belgium (2003)

Inspection date	Unit	Age*	EFP* (hours)	T° (°C)	Inspector	Inspected penetrations		Results
Head Penetrations								
June 93	Doel 3	10	82 000	287	ABB-R	65 + 1	ET	no crack
April 00	Doel 3	17	134 000	287	ABB-R	65 + 1	ET	no crack
April 94	Doel 4	9	66 000	314	ABB-R	65 + 2 +3	ET	no crack
June 99	Doel 4	14	100 000	318	ABB-R	65 + 2 + 3	ET	no crack

* At the inspection date
(1) Intercontrôle (IC) and AIB-Vinçotte
(2) Indications of original defects in the weld due to lack of fusion
(3) ex ABB-R

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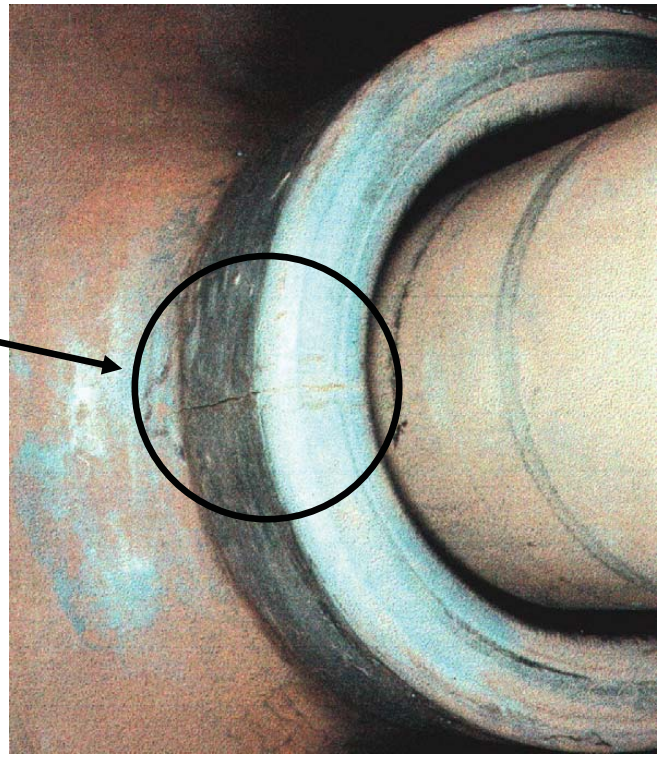
Tihange 1 RPV head – Cracking in 03/1998

Long axial through-wall crack below weld



Operation justified for one additional cycle (17 months) before replacement

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Stress corrosion crack growth

- Different crack growth rates in depth and in length directions often seen in field experience
- MRP law conservative for CGR in depth direction; could underestimates CGR in length (based on simple analysis with constant stress level)
- Difference too big to be explained by non uniform stress distribution (especially since stresses could be expected to decrease away from the weld)
- Power law with 1.16 exponent probably overconservative at high K_I (plateau-like behavior?)

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Equivalent Degradation Years

Unit	Temp (°C)	EDY
Tihange 2 - Doel 3	287	1.9
Doel 1-2	307	12.7 – 11.6
Tihange 3 – Doel 4	318	18.3 – 17.6
Tihange 1 (RPV head replaced 1999)	318	24
Tihange 1 new head	318	4

EDY: equivalent years at the reference temperature of 316°C (Arrhenius law with activation energy 50 kcal/mole)

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Bare metal visual inspections

5 units inspected 2002 (some only partially)

“Clean” heads with locally some rusty streaks and boric acid traces, attributed to canopy seals leaks

No evidence of RPV head corrosion

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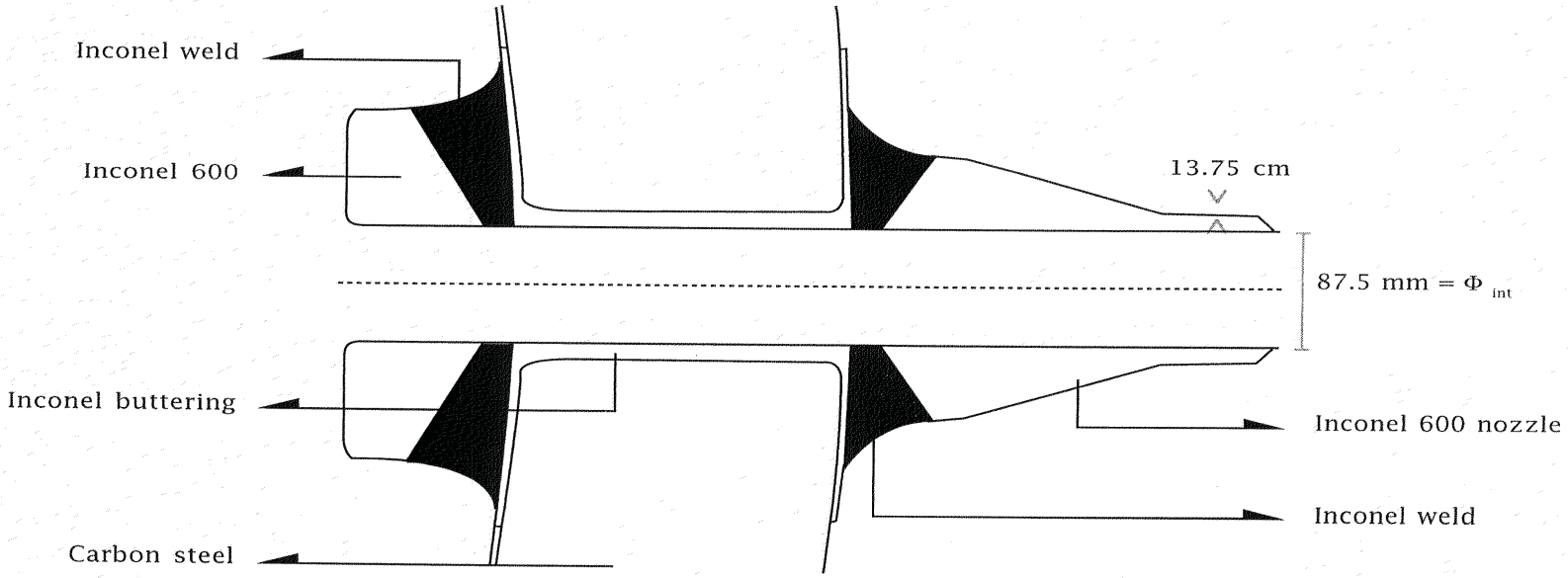
Safety injection nozzles

(Doel 1-2) figure 3



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Alloy 600 – Inspection status in Belgium (end 2002)

Inspection date	Unit	Age*	EFP* (hours)	T° (°C)	Inspector	Inspected penetrations		Results
BMI Penetrations								
May 95	Doel 2	20	132 000	287	TRC	13	ET + UT	no crack(2)
May 00	Doel 2	25	175 000	287	W-TRC	13	ET + UT	no crack(2)
SI Nozzles								
Oct. 95	Doel 1	21	160 000	287	(1)	2	UT	no crack(2)
August 99	Doel 1	25	188 000	287	IC	2	ET + UT	small surface indication + (2)
May 00	Doel 2	25	175 000	287	IC	2	ET + UT	small surface indication + (2)

* At the inspection date
(1) Intercontrôle (IC) and AIB-Vinçotte
(2) Indications of original defects in the weld due to lack of fusion

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Alloy 600/82/182 – Weld and buttering parts

Component	Part	Base material	Weld	Buttering	Cladding	Units
Pressurizer	Safe ends welds		✓	✓		D3/T2/D4/T3
Steam Generator	Partition plate	✓	✓	✓		D1/D2
	Tube	✓	✓			D1/D2
	Tubesheet				✓	D3/D4/T3
	Drain		✓	✓		D4/T3
	Nozzle safe ends welds		✓(82)			T1
Vessel	Safe ends welds		✓	✓		D3/T2/D4/T3
	BMI	✓	✓	✓		ALL
	CSB	✓	✓	✓		ALL
	SIN	✓	✓	✓		D1/D2
Vessel Head	Penetrations	✓	✓	✓		ALL except T1

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Alloy 82/182 – PWSCC Inspection Result

Component	Part	Inspection type	Result (PWSCC)
Pressurizer	Safe ends welds	External UT, PT, VT2	Surface indications (Ti 2)
Vessel	Safe ends welds	Internal UT	Nothing to report (NTR)
		External PT, VT2	
	CSB	Internal VT3	NTR
	BMI	External VT2	NTR
		Internal VT3	NTR
	SIN	Internal UT, ET	Surface indications (*)
		External PT, VT2	
Vessel Head	Penetrations	External PT, VT2	NTR
		Visual internal	NTR

(*) unknown origin

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SAFE ENDS : Alloy 182 status

- Alloy 182 present on Reactor Pressure Vessel and Pressurizer Nozzles (D3/T2/D4/T3).
- Inventory available including fabrication process (material, welding, repair, stress-relieving, surface finish and inspection results).
- Alloy 182 welds on RPV were submitted to the final stress relief heat treatment of the vessel (8h at 610°C), but not the pressurizer welds
- Higher temperature makes pressurizer welds more sensitive

Typical safe-end weld

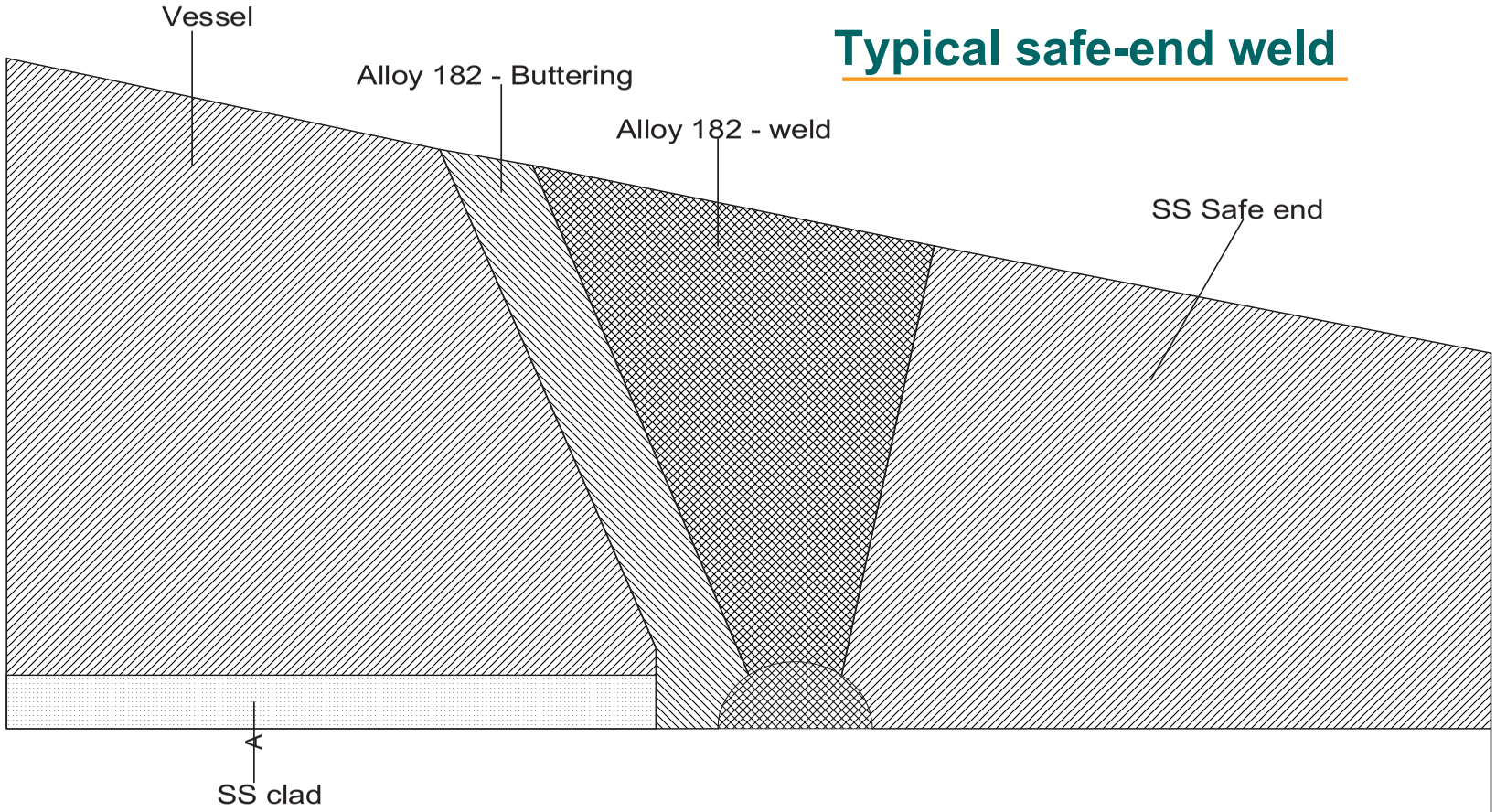

Figure 2 : Tihange 2 - Doel 3 : Vessel Safe End

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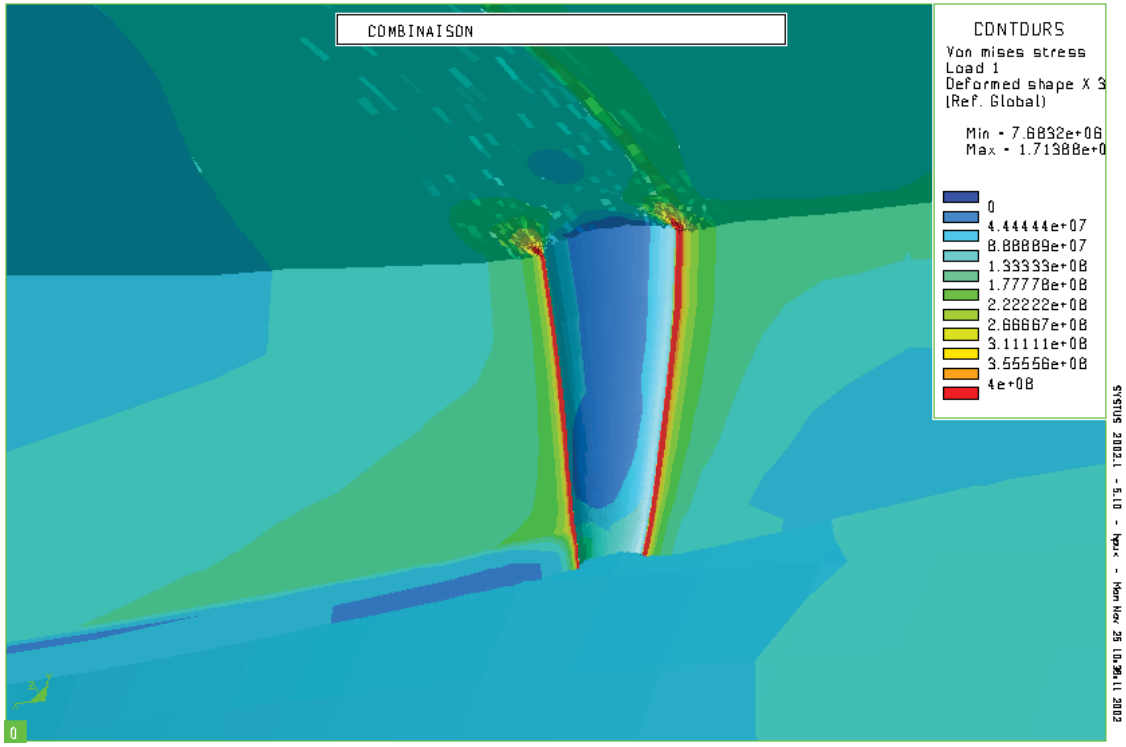
Stress and fracture mechanics analyses – RPV outlet

- Normal operating stresses at RPV outlet nozzle to safe end weld are maximum 220 MPa, well below threshold for initiation (≈ 350 MPa).
- Axial stresses much lower than circumferential stresses ➔ axial crack more likely
- If initial defect is postulated, Defect Tolerance Analysis (Vessel Outlet Nozzles) indicates high crack growth rate. Confirms that axial defect is more critical than circumferential defect.

Through-wall defect analysis in RPV inlet nozzle (weld repaired in fabrication after stress relief in one unit)



Crack stable with margins

Very small leak rate (2 - 5 kg/h)

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Stress and fracture mechanics analyses – Pressurizer surge nozzle to safe-end weld

- Normal operating hoop stresses 300 to 350 MPa at inside surface, close to threshold for initiation (≈ 350 MPa).
- High contribution of postulated residual hoop stresses
- Axial stresses much lower than circumferential stresses ➔ axial crack more likely
- Operating temperature 345°C
- Most critical location based on semi-empirical ranking (based on stress, temperature, PWHT, fabrication repairs, consequences)

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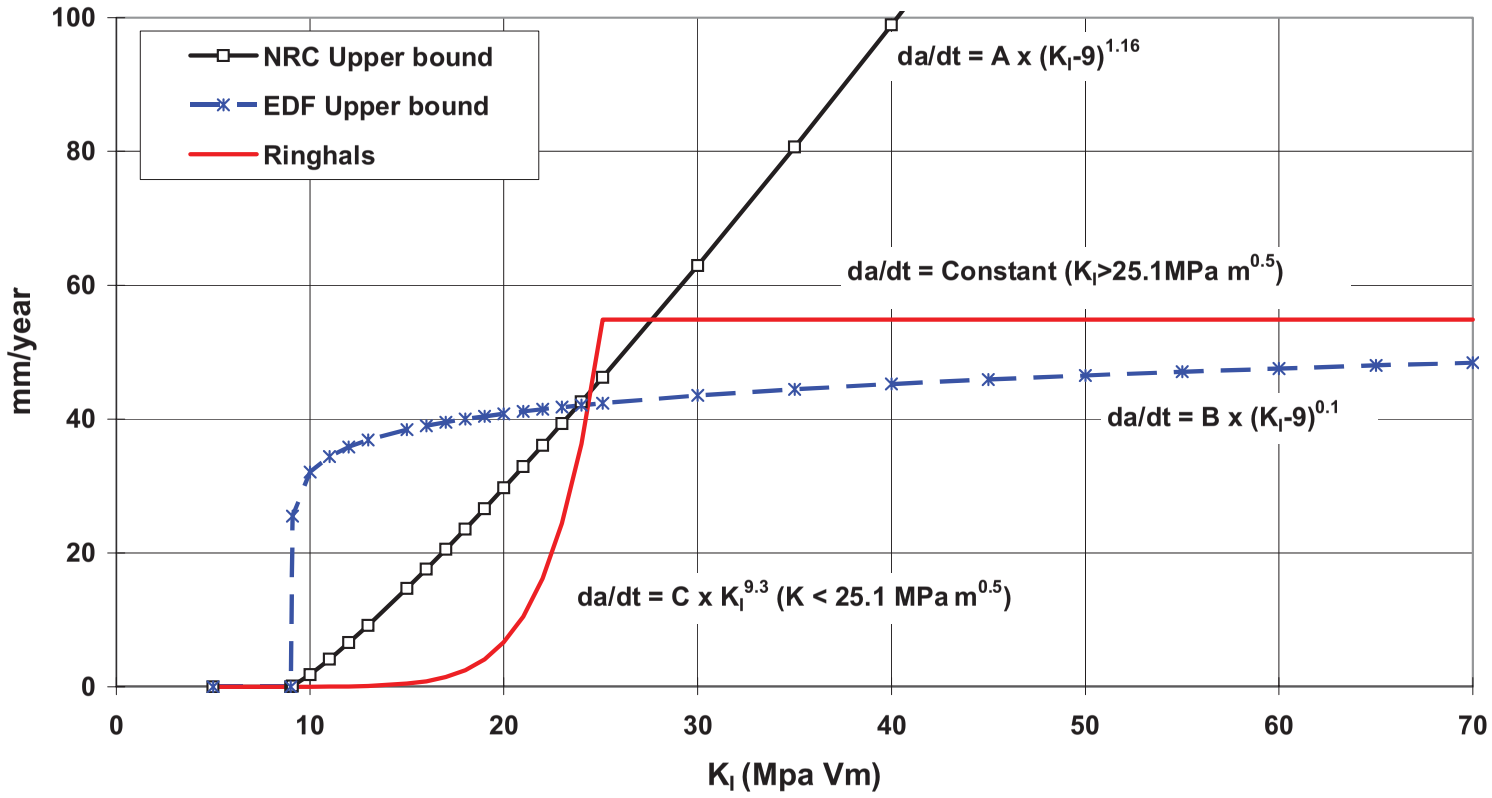
Crack growth rates - Inconel 182 at 345°C (Arrhenius with Q=130 kJ/mole)



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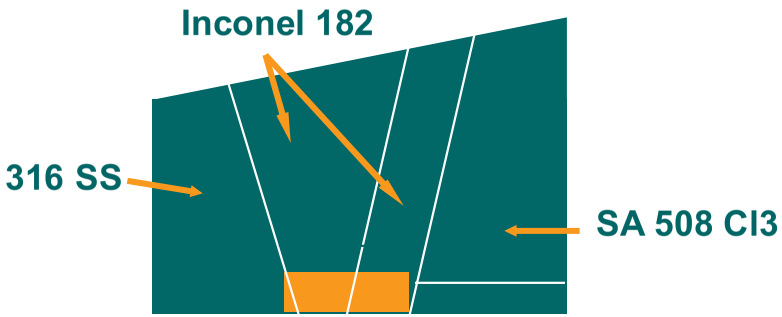
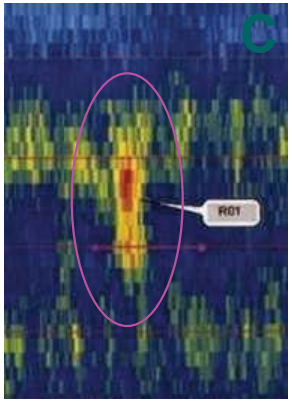
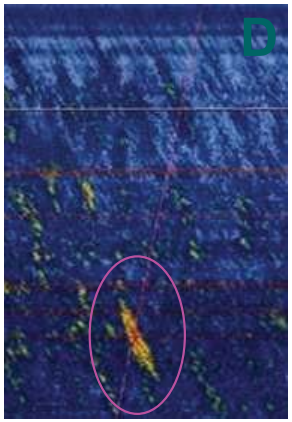
Stress and fracture mechanics analyses – Pressurizer surge nozzle to safe-end weld

- If initial defect is postulated, Defect Tolerance Analysis indicate very high crack growth rate.
- Not possible to base an inspection plan on such crack growth rates (or inspect every 2 months!)
- Lack of data of high K_I, leading to significant differences in extrapolations from existing data
- Increased inspection frequency recommended, using qualified technique

Pressurizer surge nozzle to safe-end weld Tihange 2 – Oct. 2002 inspection







- Axial indication
- Close to fabrication repair
- Could be exposed to primary water
- Flaw dimension ≈ 4 x 26 mm

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Pressurizer surge nozzle to safe-end weld

- Defense in-depth analysis of through-wall axial crack (limited to the weld) shows it should remain stable
- Estimated leak rate at the limit of detectability with existing systems; local systems added (humidity sensor + infrared camera)
- Restart authorized for 6 months
- Validation of MSIP (Mechanical Stress Improvement Process, AEA patent) on surge line geometry (conical safe-end)

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Pressurizer surge nozzle to safe-end weld

- Principle of MSIP:
  - Mechanically contract the pipe on one side of weldment
  - Replace residual tensile stresses with compressive stresses
- MSIP: Specific stress analysis and qualification on mock-up with Tihange 2 exact geometry
- Evaluation of potential repair techniques
- Reinspection in May 2003 – No crack growth
- Next inspection scheduled October 2003

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Alloy 600 / Alloy 182 – Belgian strategy

Alloy 600 Components	Strategy
RVH Penetrations	Follow cracks D1/D2 Crack growth analysis Reinspect other heads Evaluate repair/replacement options
BMI/CSB/SIN	Follow ASME ISI program Reevaluate following STP1 event

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Alloy 600 / Alloy 182 – Belgian strategy

Alloy 182 components	Strategy
RPV / pressurizer safe-ends welds	Perform Defect Tolerance Analysis Anticipate and enhance inspections Residual stress analysis Validate MSIP on surge line nozzle
RVHP welds	Visual inspections (internal + external) Evaluate other surface inspection techniques
Others	Follow ASME ISI program

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Conclusions

- RPV head penetration program in place since 1992
- Significant cracking detected in Tihange 1 in 1998; head replaced in 1999
- Small indications in other units followed by regular inspections; slow propagation
- Program on Inconel 182 safe-end welds started after VC Summer event
- Fracture mechanics analysis + ranking critical locations + increased inspections

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Conclusions (continued)

- Analyses show pressurizer safe end welds most critical location (not stress relieved, high residual stresses, high temperature)
- Increased inspections implemented on these welds
- Small indication in Tihange 2 surge line weld, suspected to be PWSCC, to be followed. Potential solutions: MSIP or repair.
- The proactive inspection and justification strategy followed in Belgium made it possible to detect flaws well before they could cause leaks in the primary pressure boundary.

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FRAMATOME ANP

Conference on Vessel Head Penetration Inspection, Cracking and Repairs

German Experience with RPV Head Penetrations

Klaus Degmayr
Framatome ANP GmbH, Erlangen, Germany
Oct 2nd, 2003

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FRAMATOME ANP

Content (1)

- NPPs with PWR built by Siemens/KWU *)
- The NPP Obrigheim RPV Head Design
  - Operation Data
  - Design of Penetration Nozzles
  - Characteristic Features of the Obrigheim Design
  - KWO Manufacturing Sequence
  - Evaluation of PWHT with Respect to PWSCC
  - Integrity Evaluation of the KWO RPV Head
  - Investigations, Inspections Measurements in KWO
  - Non Destructive Examination
  - Leakage Detection, Global and Local
  - Design of Flange
  - In-Service Experience of NPP KWO

*) name of predecessor company of Framatome ANP GmbH, Germany

Content (2)

> *The current Siemens/KWU Design of RPV Head Nozzles since NPP Stade*

- *Characteristic Features of the Siemens/KWU Design*
- *The Current Siemens/KWU Flange Design*
- *In-Service Experience of All Other German Plants*

> *Summary and Conclusions*

NPPs with PWRs and Year of Start-Ups built by Siemens/KWU

PWR plant	Country	Year of Start up	MWe cross/net
Obrigheim	GER	1968	357 / 340
Stade	GER	1972	672 / 640
Biblis A	GER	1974	1204/ 1146
Biblis B	GER	1976	1300 / 1240
Neckar 1	GER	1976	840 / 785
Unterweser	GER	1978	1300 / 1230
Grafenrheinfeld	GER	1981	1300 / 1235
Grohnde	GER	1984	1395 / 1325
Philippsburg 2	GER	1984	1349 / 1268
Brokdorf	GER	1986	1395 / 1326
Isar 2	GER	1988	1400 / 1320
Emsland	GER	1988	1341 / 1270
Neckar 2	GER	1989	1360 / 1225
Borssele	NL	1973	481 / 449
Atucha 1	ARG	1974	357 / 335
Gösgen	CH	1979	1020 / 970
Trillo	ES	1988	1066 / 1000
Angra 2	BRA	2000	1309 / 1229

KWO Operating Data

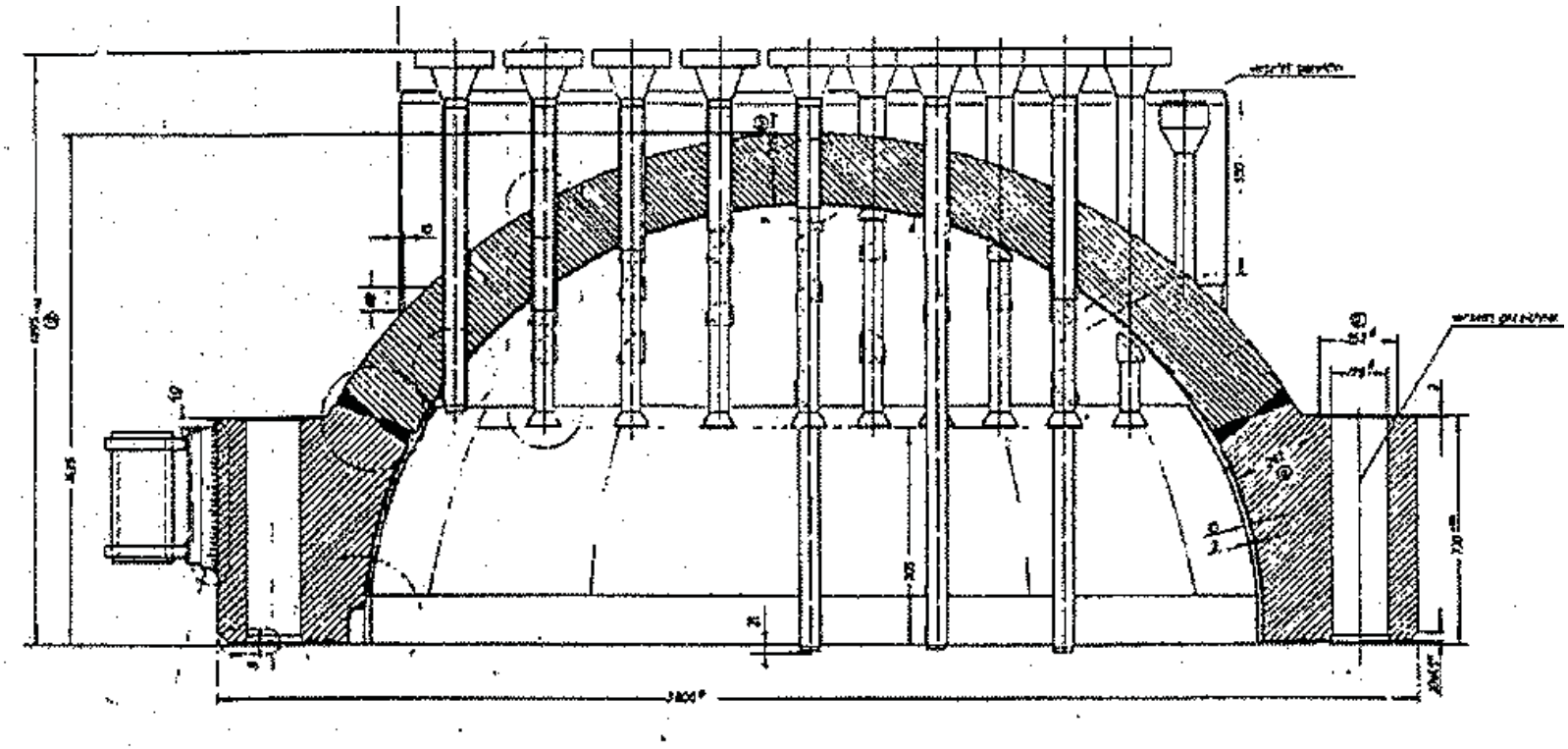
> Operation Time until 2003: approx. 240,000 hours

> Pressure: approx. 145 bar

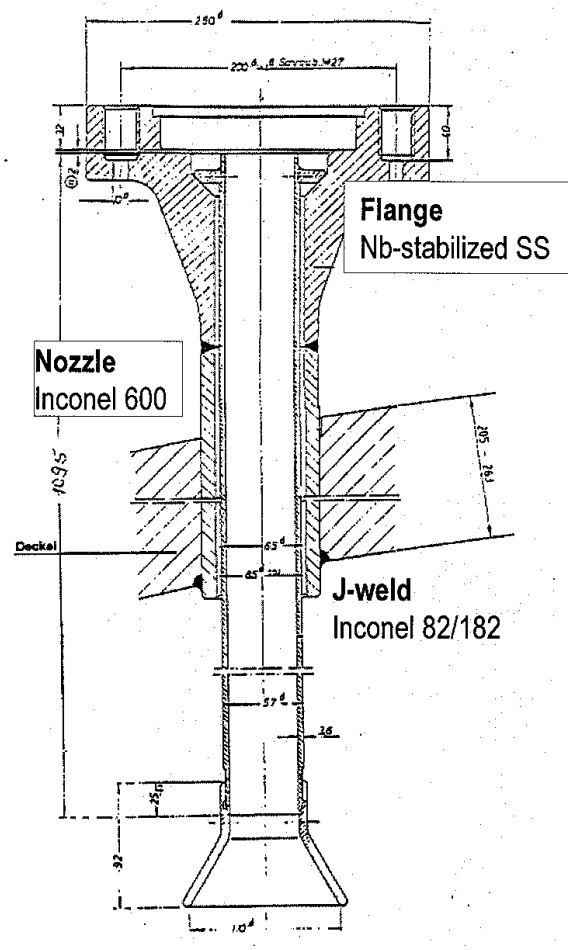
> Operation Temperature

- RPV inlet 279 º C
- RPV outlet 308.5 º C
- upper plenum 306.8 º C
- head outside 282,2 º C
- nozzle weld inside 284 – 295 º C

The NPP Obrigheim RPV Head Design



Design of Penetration Nozzle



> *material*

- *nozzle: Inconel 600*
- *flange: Nb-stabilized SS*
- *J-weld: Inconel 82/182*

> *dimensions*

- *inner diameter: 85 mm*
- *outer diameter: 105 mm*

> *connection*

- *shrink fitted, welded into RPV head*

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Characteristic Features of the Obrigheim Design (1)

> *Material*

- *RPV closure head:* *22 NiMoCr 37*
- *RPV head inner surface:* *Austenitic SS cladding*
- *Head penetration nozzles:* *Inconel 600*

> *Weld*

- *J-groove weld without buttering of the head*
- *weld material:* *Inconel 82/182*

> *Heat treatment (PWHT):*

- *stress relief annealing of entire RPV closure head*
  600 º C ≥ 10 hours

Characteristic Features of the Obrigheim Design (2)

> *Manufacturing*

- *seamless pipe, hot formed*
- *solution annealing:* *1000 – 1050 º C*
- *roughness:* *outside max. 5 µm*
  inside max. 80 µm

> *Chem. composion:* *low C-content*

> *Mech. properties:* *low yield strength (227 – 257 N/mm²)*

KWO Manufacturing Sequence (1)

> *fitting in of tubes into the RPV closure head*

- *cooling down tubes, head at ambient temperature*
- *shrinking of tubes into the head shell*

> *Welding*

- *preheating of the head up to 150 º C for welding*
- *shielded Metal Arc Welding (SMAW)*
- *welding sequence: starting with the center nozzle, followed by nozzles on outer circumference in a circular manner*
- *delayed cooling*

KWO Manufacturing Sequence (2)

> *non destructive examination (NDE)*

- *grinding of each layer*
- *surface of weld layer by Liquid Penetrant Testing*
- *final surface by Liquid Penetrant Testing*

> *Post weld heat treatment (PWHT)*

- *540 º C / 8 hours + 600 º C / 10 hours*

RPV Head KWO
Evaluation of PWHT with Respect to PWSCC

> *Susceptibility of Inconel 600 to PWSCC is reduced by PWHT:*

- *magnitude of residual stresses is reduced down to a level not high enough for initiating PWSCC*
- *due to carbide precipitation during heat treatment the PWSCC resistance is increased (TT condition vs. MA condition)*

> *Effect is confirmed by several extensive investigations on „thermally treated“ Inconel 600 and 690 material*

RPV head KWO Integrity Evaluation

> *Susceptibility of KWO head penetrations to PWSCC is condidered low, since*

- *operational loading (incl. residual stresses) is low;*
  Typical stresses in nozzle end are less than 2/3 of the yield strength at operation temperature.
- *Consequently, secondary effects (like cracking in circumferential direction) can be excluded (confirmed by UT of 4 nozzles without internals)*

> *Safety margin is ensured by*

- *special leakage detection system: sensory (electrical) cable*
- *general leakage detection systems: activity, condensate, environmental temperature, relative humidity, sump water*
- *shut down capability is available in case of nozzle rupture*

Investigations, Inspections, Measurements in KWO

> *Non Destructive Testing of Penetrations and RPV head*

- *ultrasonic testing (UT)*
- *liquid penetrant testing (LPT)*
- *eddy current (EC)*

> *Leakage Detection at KWO*

- *global leakage detection*
- *local leakage detection*

> *Visual Inspection of RPV closure head*

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Non Destructive Examination of Penetrations and RPV Closure Head

Testing Procedure	Extent of Testing	Inspection Year	Intervals
UT	4 penetrations w/o internals, entire length of penetration, longitudinal and circumferential indications	1992 extra inspection	-
LPT	4 pentrations w/o internals, entire length of penetration, including flange weld	1992 extra inspection	-
Eddy Current	24 + 4 outer penetrations, rotating probe, entire length (4), narrow gap probe up to 250 mm (24)	1992 extra inspection	-
Eddy Current	All penetrations over entire length including flange weld, longitudinal and circumferential indications	1994 2000	8 years
Specific visual inspection with cam	Internal head surface including penetration and weld	2000	4 years
UT of closure head ligament	All cosure head ligaments, volume between penetrations, faults originating from bore	1976, 1980, 1983, 1987, 1992, 1996, 2000	4 years

source: KWO

Leakage Detection at KWO

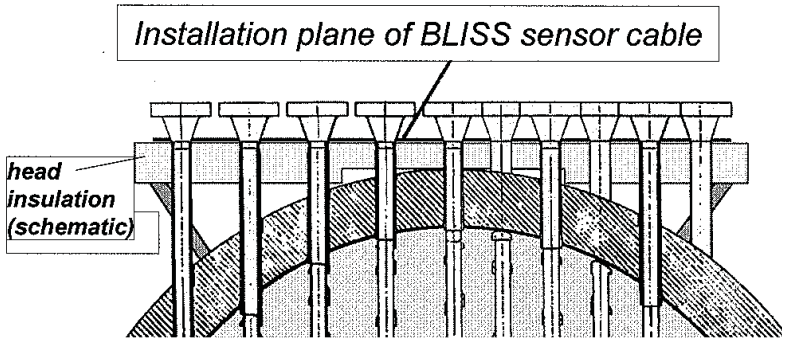
> *Global Leakage Detection (Plant Environment)*

- *inert gas measurement of plant environment* — *from approx. 10 l/h*
- *condesate measurement in air circulation cooler* — *from approx. 10 l/h*
- *termperature in air circulation cooler* — *from approx. 2 – 3 l/h*
- *relative humidity in air circulation cooler* — *from approx. 2 – 3 l/h*
- *sump water collection of building TF 01*
- *sampling exhaust air inner plant environment* — *from approx. 10 – 15 l/day*

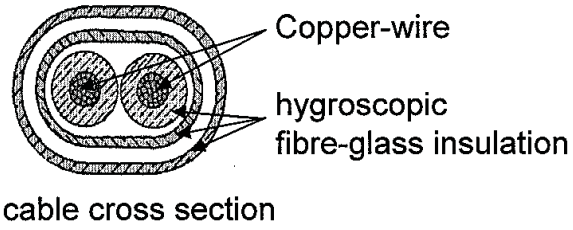
> *Local Leakage Detection (RPV Head)*

- *leakage detection system (BLISS)* — *humidity yes/no*
- *humidity control system (FLÜS)* — *< 1 l/h*

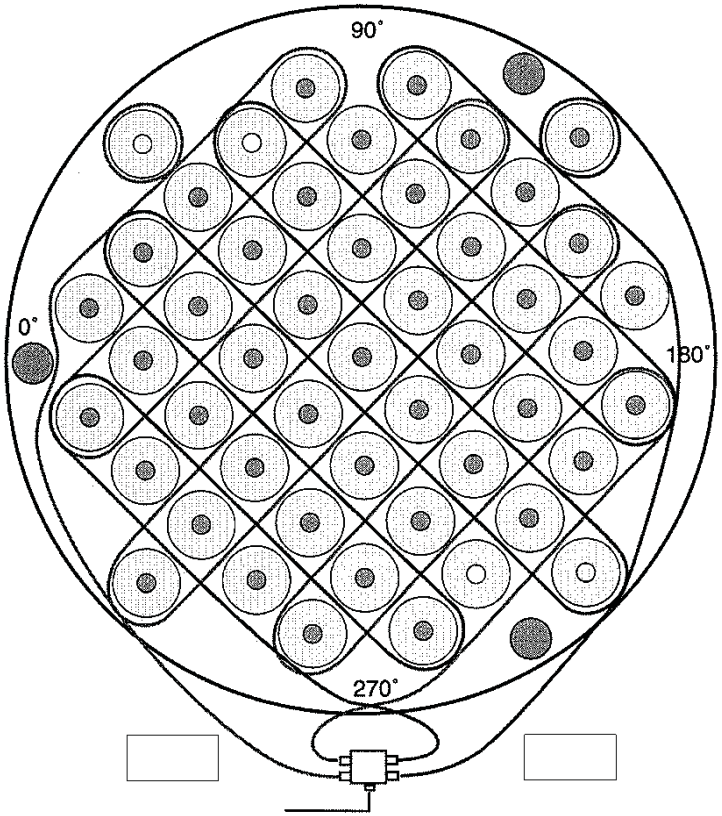
Local Leakage Detection BLISS



Leakage detection system BLISS in area of penetration flange, monitoring of flange connection YA01 M001 (sensor-cable)



Bartec Leakage Indication Sensor System



source: KWO

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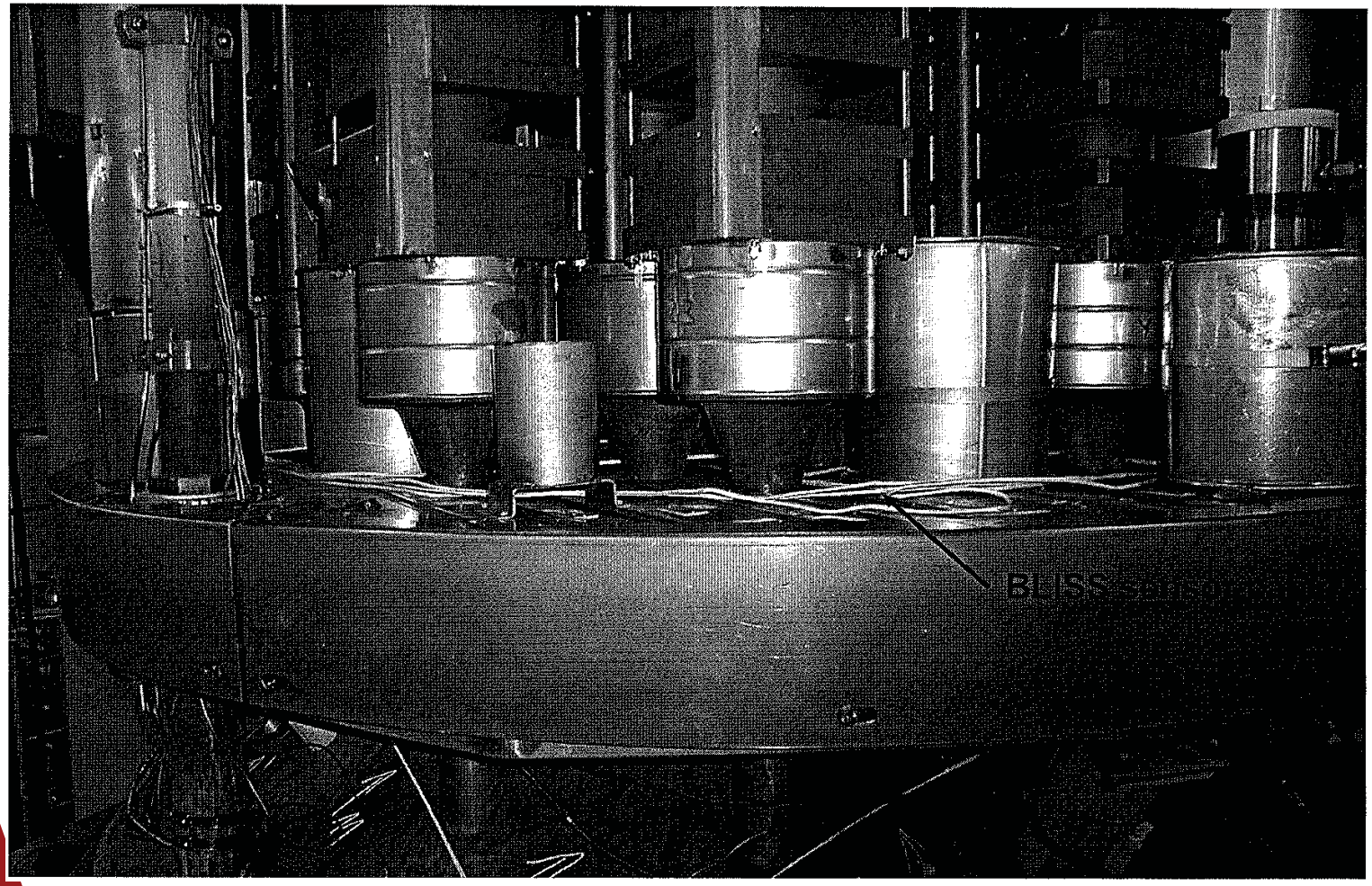
Visual Inspection of RPV Closure Head during Revision in 2002



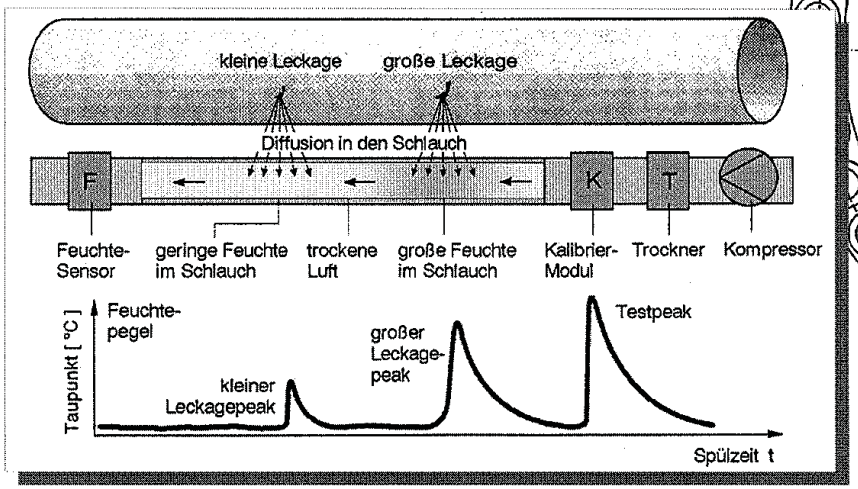
source: KWO

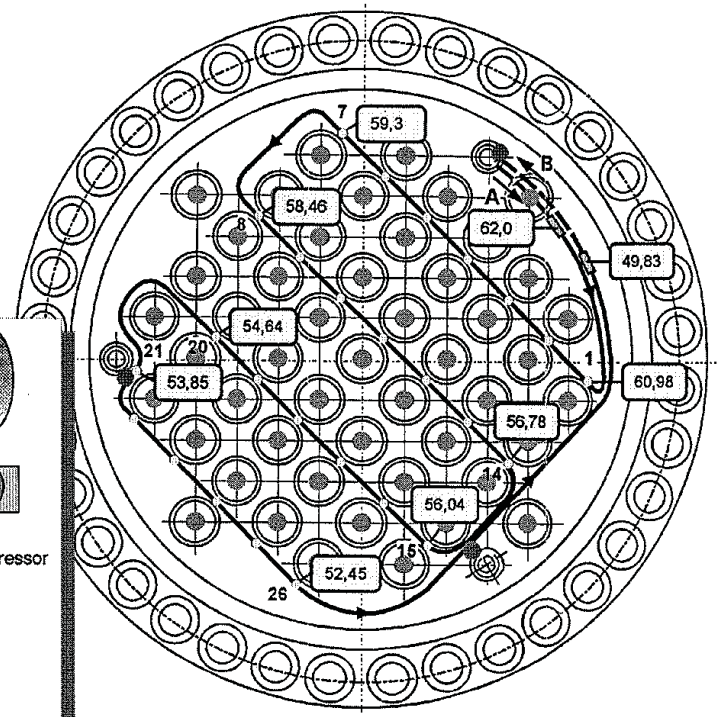
Local Leakage Detection System in RPV Head FLÜS

Humidity control system FLÜS

in area of RPV penetrations

YA01 M010 (sensor-hose)

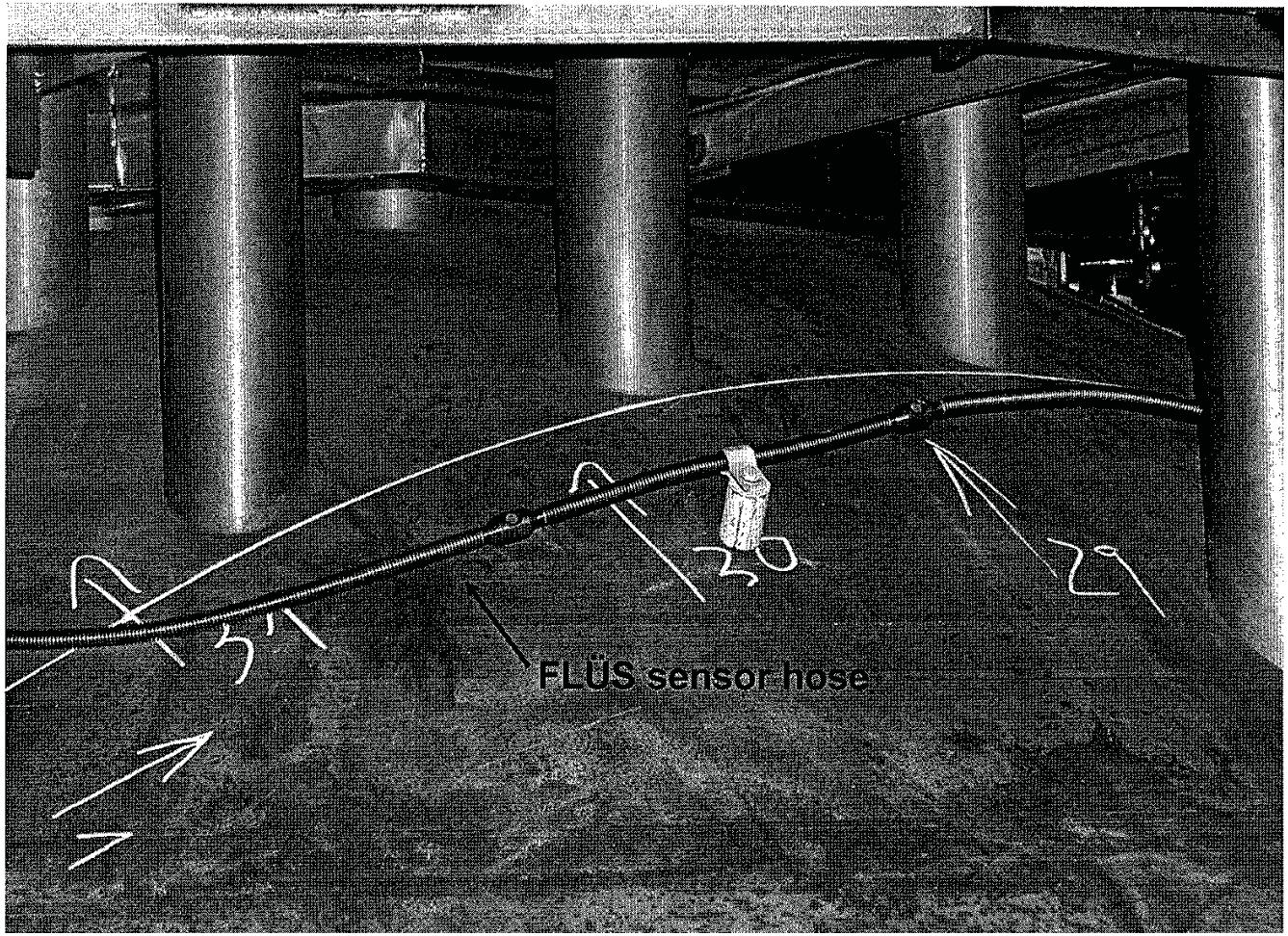




- leakage-simulation point 1/2/3
- Ni-sinter tablet (diffusion point)
- coupling
- distance in m

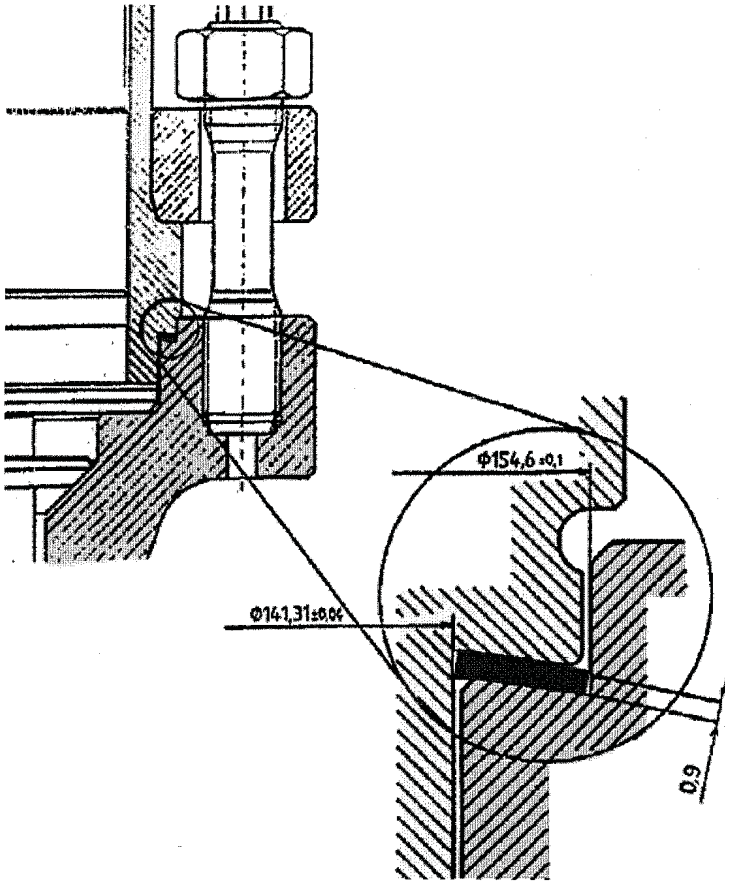
source: KWO

Visual Inspection of RPV Closure Head during Revision in 2002



source: KWO

NPP KWO Flange Design



Gasket: material X10Cr13

In period from 1980 to 1994 4 minor leakage incidents, which were detected immediately

1996 total gasket change, followed by Helium leakage test

source: KWO

In-Service Experience of NPP KWO

> *The structural integrity of head penetrations at the NPP KWO is considered sound due to the following facts:*

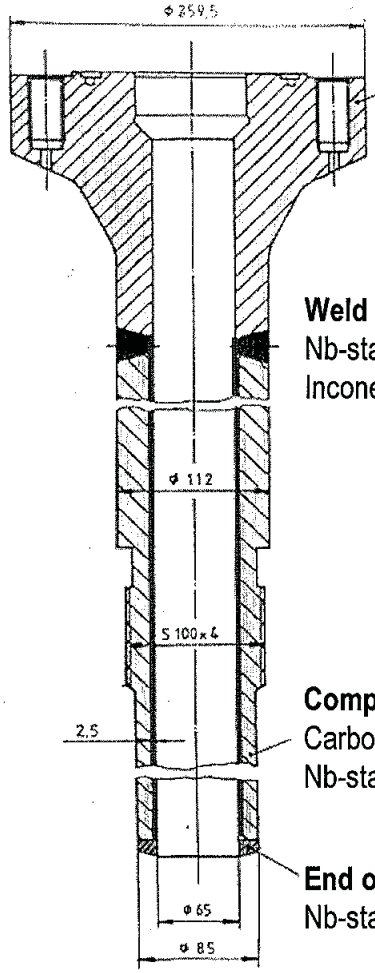
- *heat treatment history of head penetration material included a solution and stress relief annealing resulting in a low level of residual stresses and minor susceptible microstructure*
- *good access allowing regular visual and comprehensive non-destructive inspections*
- *sensitive leakage detection systems on a local and a global scale*

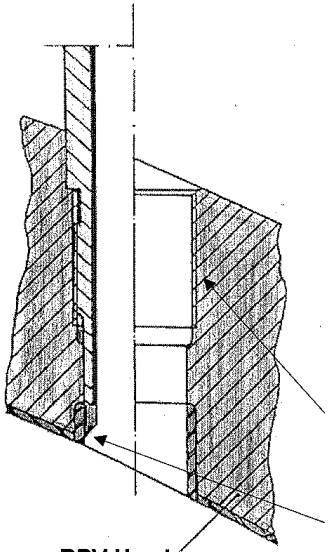
⇨ ***Cracking is not expected***

NPPs with PWRs and Year of Start-Ups Built by Siemens/KWU

PWR plant	Country	Year of Start up	MWe cross/net
Obrigheim	GER	1968	357 / 340
Stade	GER	1972	672 / 640
Biblis A	GER	1974	1204/ 1146
Biblis B	GER	1976	1300 / 1240
Neckar 1	GER	1976	840 / 785
Unterweser	GER	1978	1300 / 1230
Grafenrheinfeld	GER	1981	1300 / 1235
Grohnde	GER	1984	1395 / 1325
Philippsburg 2	GER	1984	1349 / 1268
Brokdorf	GER	1986	1395 / 1326
Isar 2	GER	1988	1400 / 1320
Emsland	GER	1988	1341 / 1270
Neckar 2	GER	1989	1360 / 1225
Borssele	NL	1973	481 / 449
Atucha 1	ARG	1974	357 / 335
Gösgen	CH	1979	1020 / 970
Trillo	ES	1988	1066 / 1000
Angra 2	BRA	2000	1309 / 1229

The Current Siemens/KWU Design of RPV CRDM Nozzles (since Stade)





RPV Head:
22 NiMoCr 37/20MnMoNi55

RPV head inner surface:
Austenitic SS cladding

Head Penetration Nozzles:
Compound tube St 52.4/1.4550
End of nozzle buttered with Nb-stabilized austenitic SS

Separation of tasks:

Main loading:
Trapezoidal screw thread

Sealing:
J-groove weld with Nb-stabilized SS,

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Characteristic Features of the Siemens/KWU Design

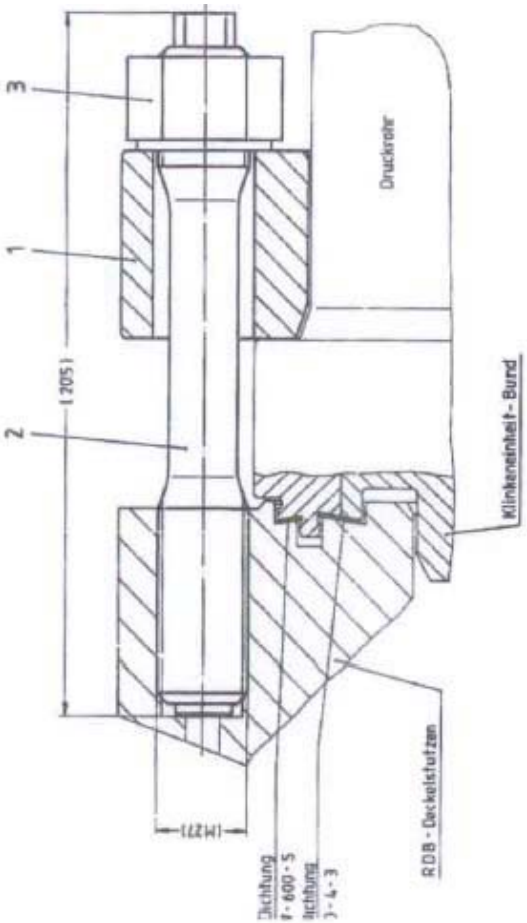
> *material*

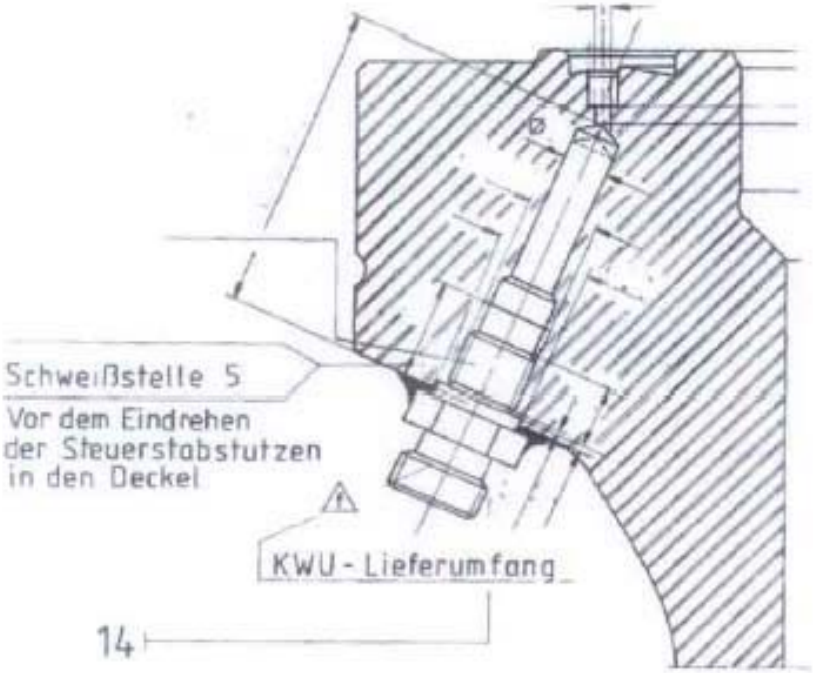
- *RPV head:* *22 NiMoCr 37/ 20 MnMoNi 55*
- *RPV surface cladding:* *Austenitic SS cladding (Nb stabilized)*
- *head penetration nozzles:* *compound tube made of St 52.4/1.4550*
  end of nozzle buttered with
  Austenitic SS cladding (Nb stabilized)
- *CRDM flange* *Nb stabilized SS*

> *design*

- *trapezoidal screw thread for load bearing*
- *J-groove weld with Nb stabilized SS*

The Current Siemens/KWU Flange Design





- *conical gasket: 2 seals*
- *material: 1.4541 (SS 321 typ.)*
- *vacuum testing after installation*
- *test pipe used for leak detection*

RPV Head after Removal from the Vessel

990

Visual Inspection

Easy Access to RPV Head and Penetrations in German PWRs

In-Service Experience of All Other German Plants

- *Different design and materials of head penetrations greatly reduce the risk of cracking.*
- *access and ISI of head penetrations and RPV head enable:*
  - *visual Inspection during every outage*
  - *UT inspection of closure head ligaments (outer and inner surface and volume inspection) every 4 and 5 years resp. to KTA 3201.4*
- *Leak detection system including:*
  - *humidity measurements*
  - *measurement of the condesate rate at the air recirculation system coolers*
  - *measurement of accumulated sump water*

Summary and Conclusions

Two Different Designs Found in German Plants

> *KWO similar to abroad design*

- *special treatment during manufacturing and*
- *very effective in-service control systems*

ensure to have and to get no problems

> *current design (Stade – Neckar 2)*

- *choice and combination of material reliable over years*
- *optimized conditions by separating the function load bearing and sealing*
- *optimized welding design and welding process*

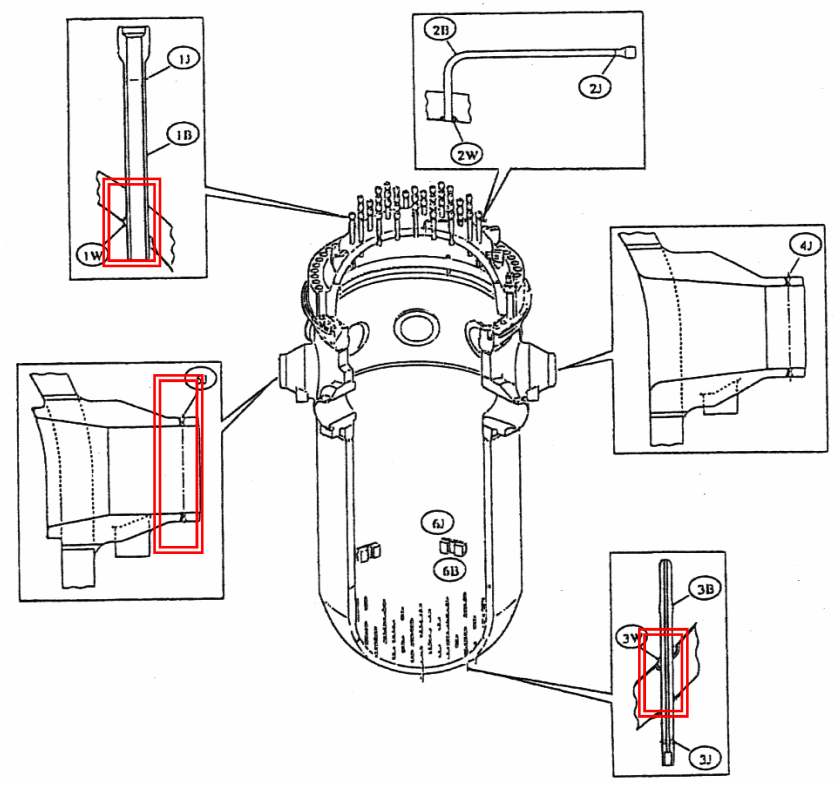
994

eop

Activities on Alloy 600 Cracking of PWRs in Japan

Masahiko Toyoda, Seiji Asada and Nobuyuki Hori
Mitsubishi Heavy Industries, Ltd.
Kobe Shipyard and Machinery Works

Activities on Alloy 600 Cracking of PWRs in Japan



Maintenance Programs on PWSCC of Alloy 600 in Japan are discussed, specially for

- **RVH Penetration Nozzle**
- **BMI Nozzle**
- **Hot Leg Nozzle**

Activities on Alloy 600 Cracking of PWRs in Japan

: Ready for field application : Under development		RVH Penetration Nozzle		BMI Nozzle		Hot Leg Nozzle
		Base metal	J - weld	Base metal	J - weld	
Cracking	Japan	Takahama #2 (<1mm)	No Indication in Inspected	Takahama #1 (≤1mm?)	No Indication in Inspected	No Indication in Inspected
	US & Europe	Many	More than 10 plants	South Texas 1 (under investigation)	No report	V.C.Summer Ringhals
PWSCC Assessment	Stress	Tension (> σ_y)	Tension (> σ_y) (Surface: Compression)	Tension (> σ_y)	Tension (> σ_y) (Surface : Compression)	Nearly equal to σ_y
	Temperature	Converted from T-hot to T-cold		T-cold		T-hot
	Susceptibility	Moderate	Low	Moderate	Low	Moderate
Inspection	Technique	ECT UT	VT ECT	ECT UT	VT ECT	UT ECT
	Application	17 plants	Not yet	6 plants	Not yet	5 plants
Mitigation		Done (T-cold conversion)		WJP (5plants)	WJP	WJP
Counter Measure or Contingency		RVH Replacement (11plants)		Emergency Repair Method BMI Nozzle Replacement		690 Cladding Spool-piece Replacement

RVH Penetration Nozzle

- **RVHs for 11 plants have adopted alloy 690 penetration nozzle (Replaced).**
- **T-cold modification as mitigation measurement has been adopted in 11 relatively new plants leaving alloy 600 nozzles.**
- **NDIs (ECT for nozzles) were carried out for 6 plants in 1993 and 1994, no indications were detected.**

RVH Penetration Nozzle

- **No official request of specific inspection against VHP nozzles has been issued by government.**

- **Some of T-cold modification plants are scheduled to inspect VHP nozzle and J-weld in the future.**

Activities on Alloy 600 Cracking of PWRs in Japan

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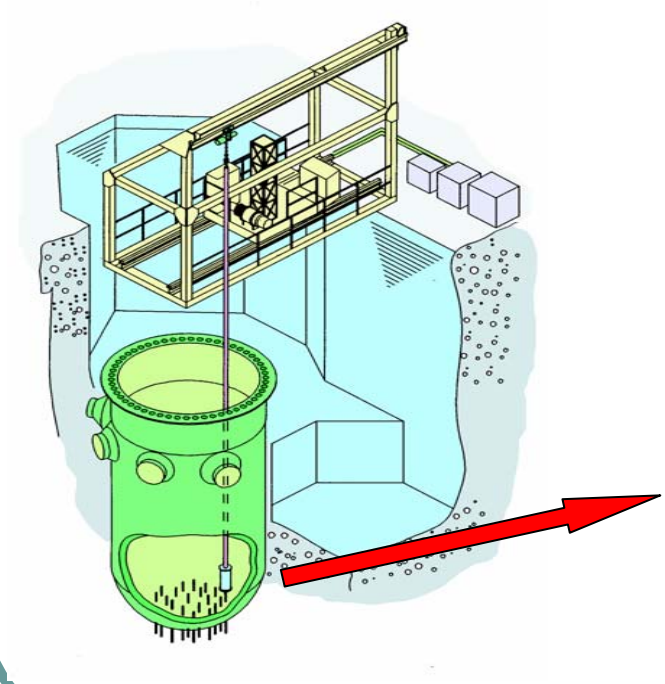
BMI Nozzle

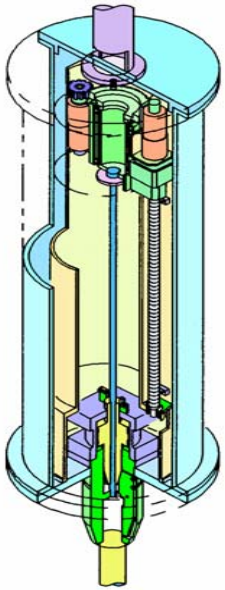
- **Based on recent PWSCC assessment, BMI nozzles are suspected to have cracking and mitigation measurement is recommended.**
- **ECT and water jet peening (WJP) technology for BMI nozzles have been developed by MHI as mitigation measurement in accordance with PWSCC assessment.**

BMI Nozzle

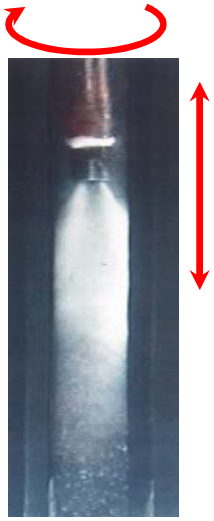
Concept of WJP Technology for Field Application

Field work image





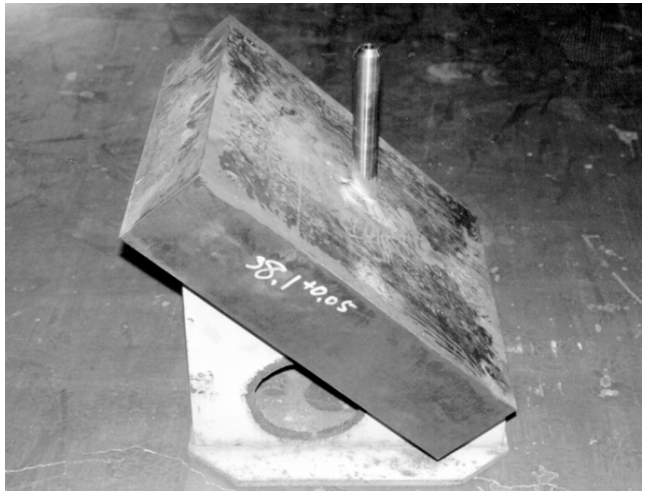
WJP equipment



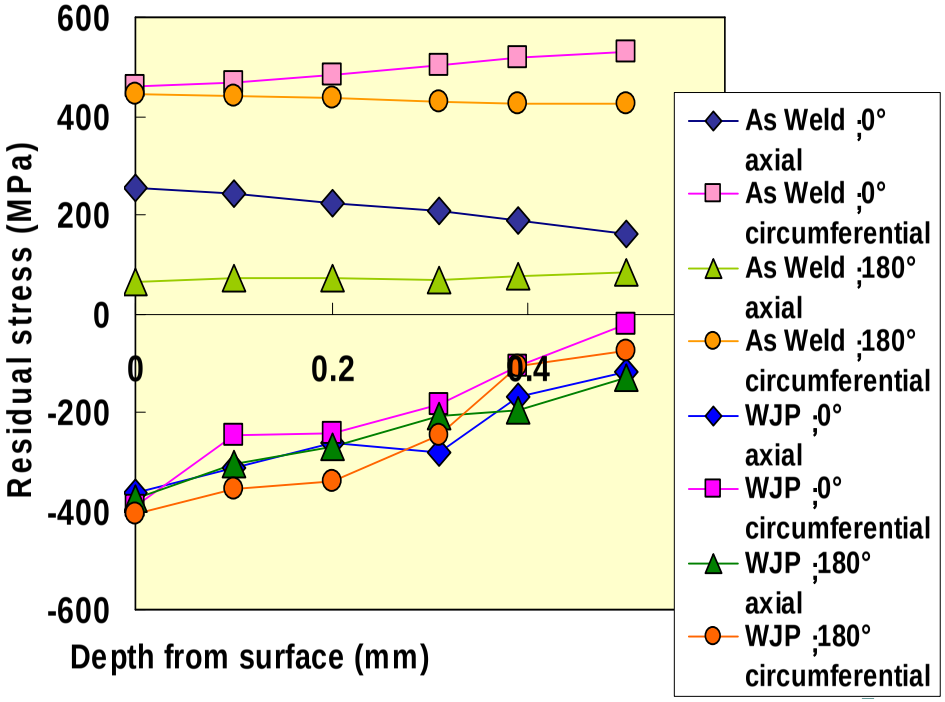
State of WJP in small diameter pipe

BMI Nozzle

Improvement of Residual Stress by WJP Technology



Mock-up of BMI

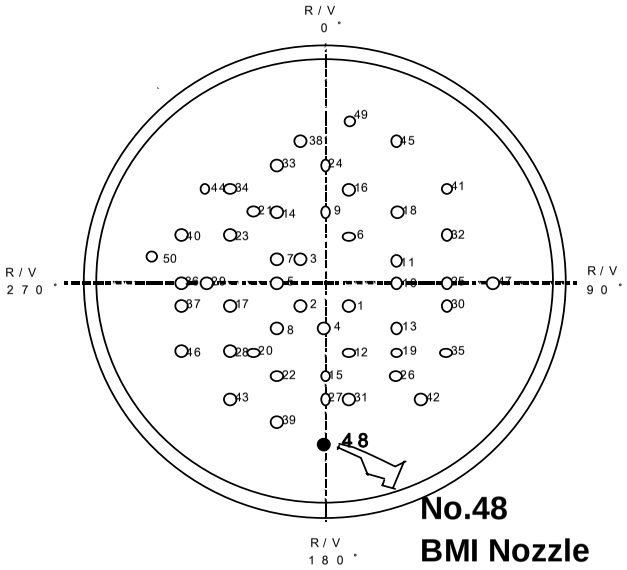


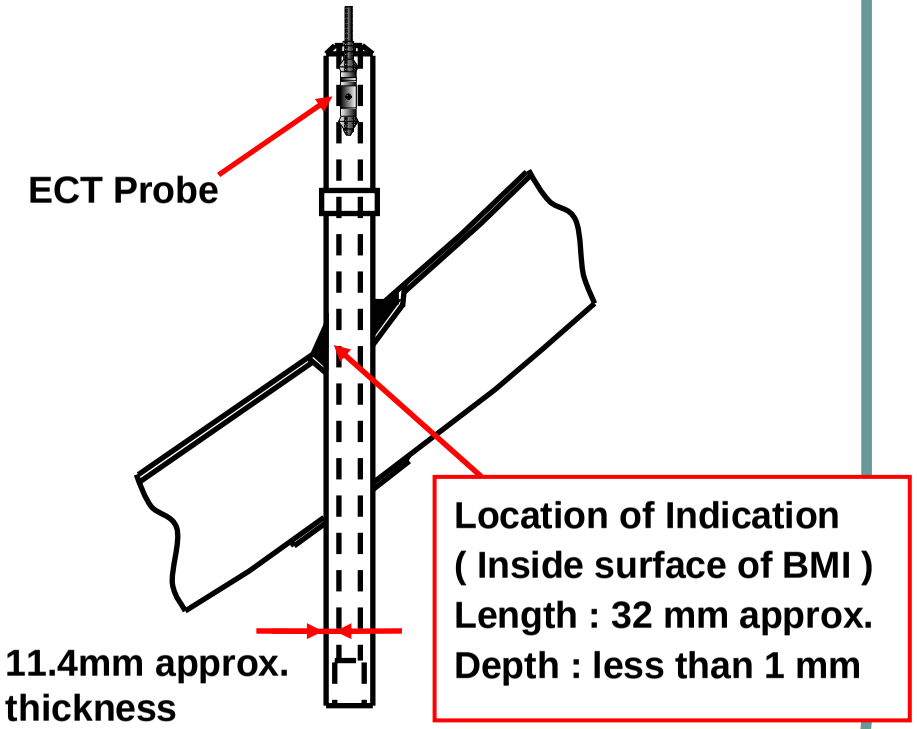
Result of residual stress measurement

BMI Nozzle

- **Kansai Electric Power Co. planned to perform WJP to all (50) BMI nozzles as preventive measure against PWSCC.**
- **Before WJP, ECT was performed on inner surface of the BMIs to conform soundness of the surface.**
- **An indication was found at BMI nozzle in Takahama unit1.**

BMI Nozzle


R / V
0 °
R / V
270 °
R / V
90 °
R / V
180 °
48
No.48
BMI Nozzle


ECT Probe
11.4mm approx.
thickness
Location of Indication
(Inside surface of BMI)
Length : 32 mm approx.
Depth : less than 1 mm

BMI Nozzle

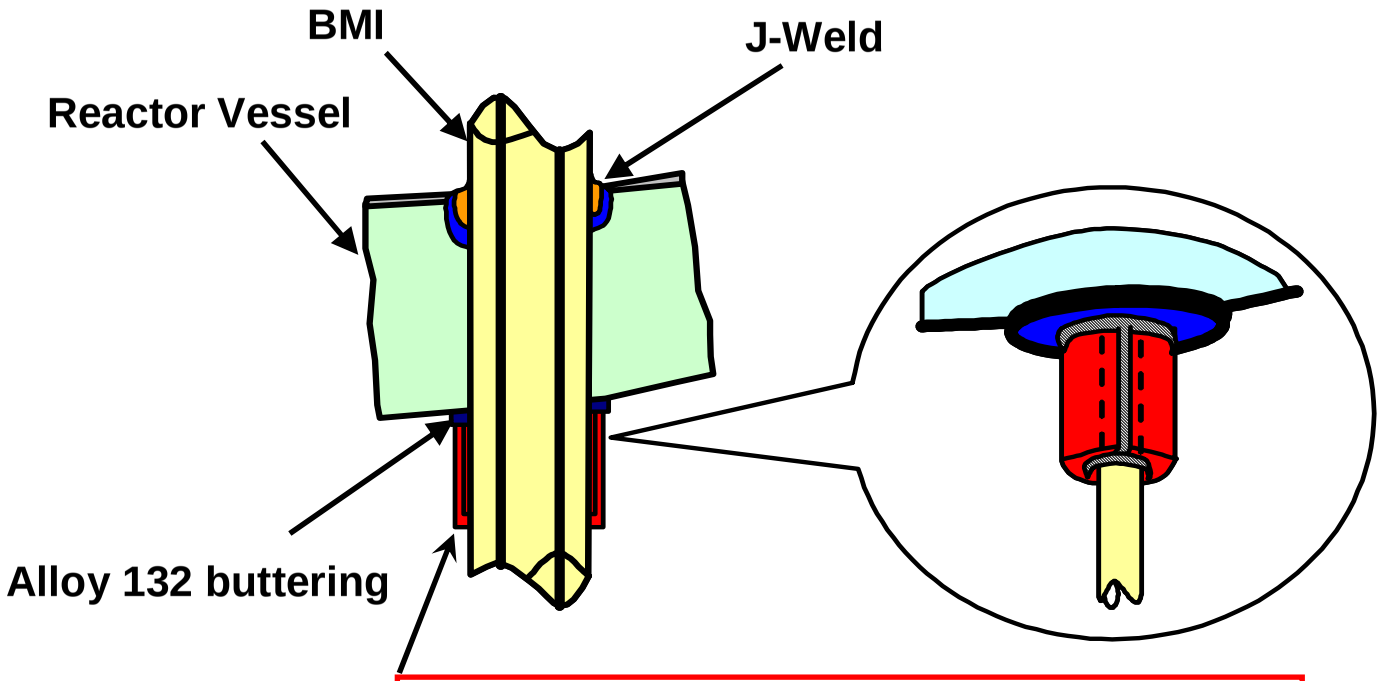
- **The indication is not identified as PWSCC.**
- **The indication will be left as it is.**
- **Additional inspection will be performed after a few cycles.**

BMI Nozzle

- **Inspection and WJP technology for J-Weld is under development.**
- **Emergency repair method and replacement technology have been developed for the case of encountering the leakage from BMI nozzles.**

BMI Nozzle

Concept of Emergency Repair Method



The leakage can be repaired with the cap.

Activities on Alloy 600 Cracking of PWRs in Japan

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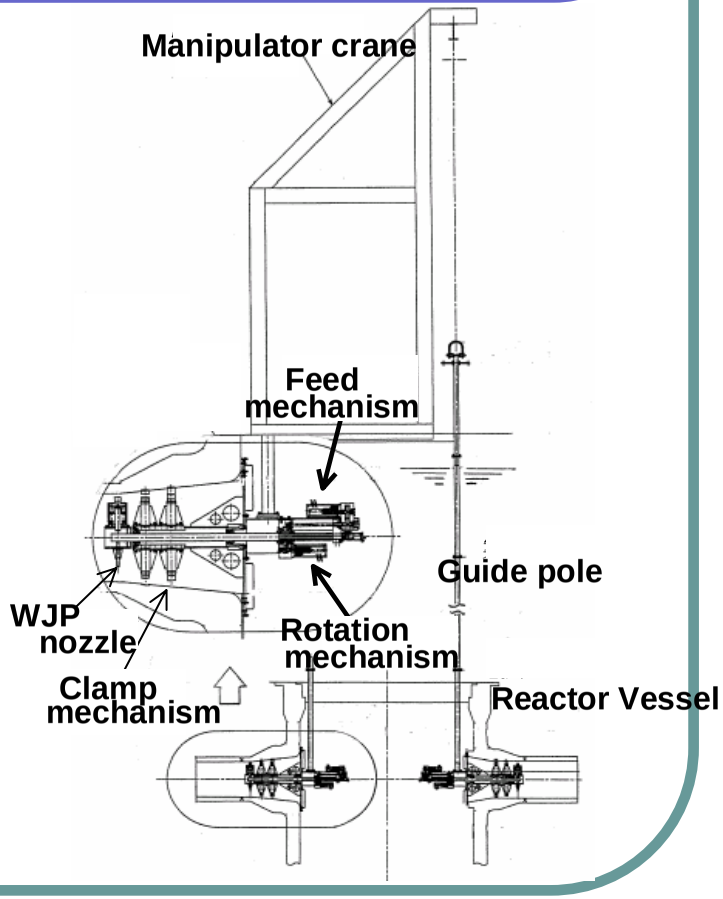
Hot Leg Nozzle

- **UT from inside or outside of hot leg nozzles have been performed and no indications have been reported.**
- **In case of emergency, spool piece replacement technology and equipment have been developed.**
- **WJP technology as mitigation measurement is under development.**

Hot Leg Nozzle

Concept of WJP for Hot Leg Nozzle



Activities on Alloy 600 Cracking of PWRs in Japan

- **PWSCC in alloy 600 is recognized as important common issue for PWR plant operation.**
- **PWSCC assessment and countermeasure for J-Weld and dissimilar weld are important.**
- **In order to maintain plant operation, it is necessary to implement inspection and preventive maintenance in accordance with PWSCC assessment.**

Tsuruga Unit-2 Pressurizer ; Leakage from the Dissimilar Weld (Alloy 600) of the Relief Nozzle

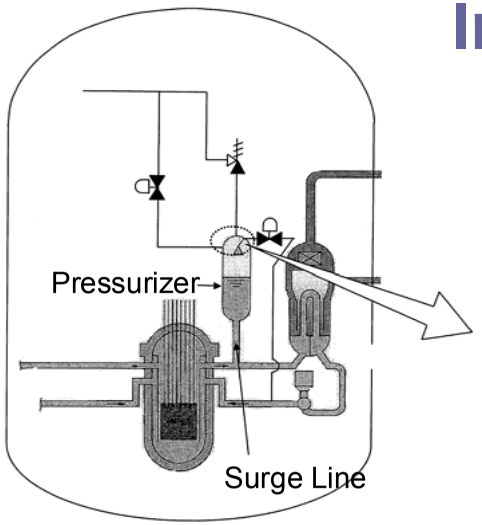
The Japan Atomic Power Company

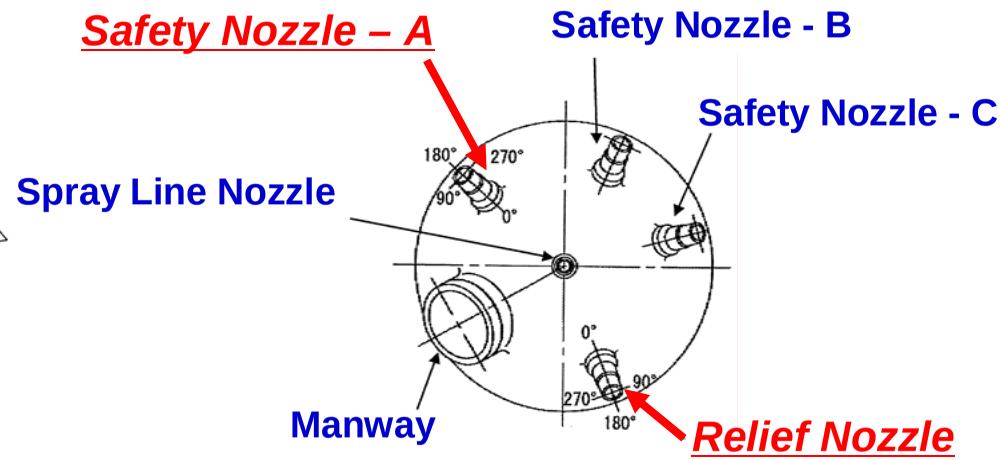
Tsuruga Unit-2

- Start of Operation : February, 1987
- Power : 1,160 MWe
- Type : 4-loop
- Fabricator : Mitsubishi Heavy Industries

- This Outage (found leakage) : #13
- Accumulated operating time: about 120,000 H

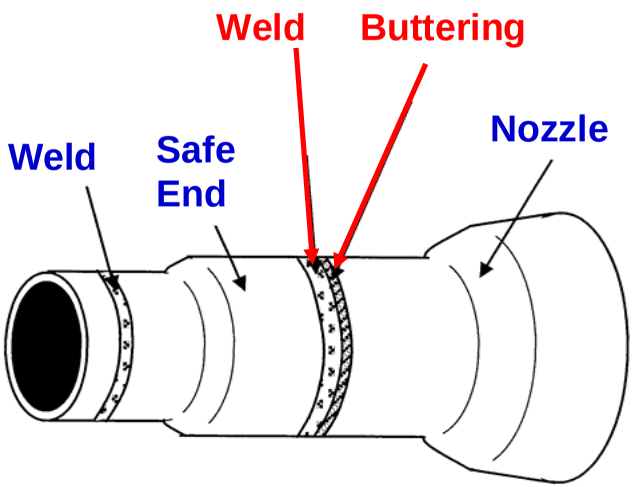
Inspection Results

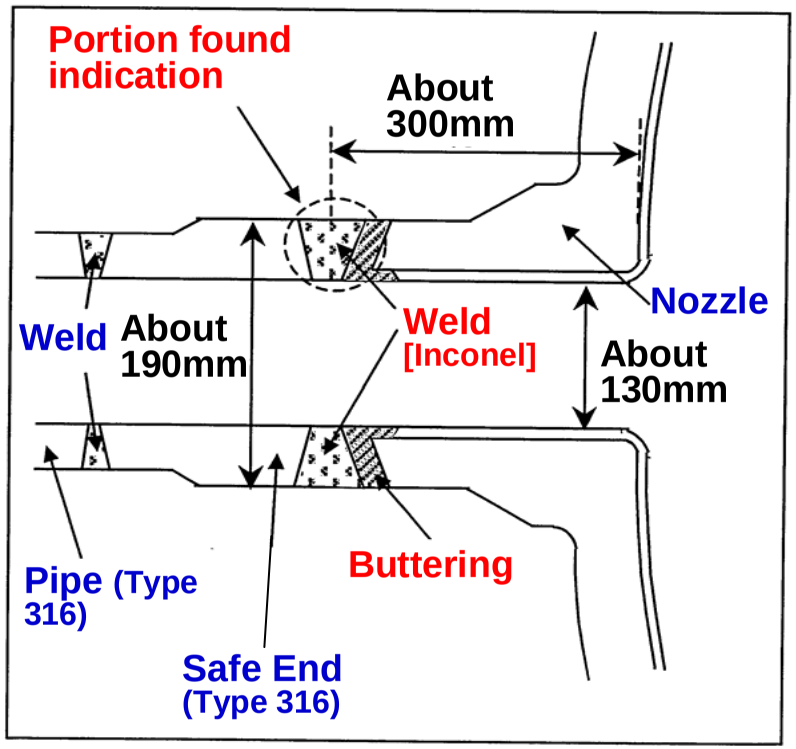




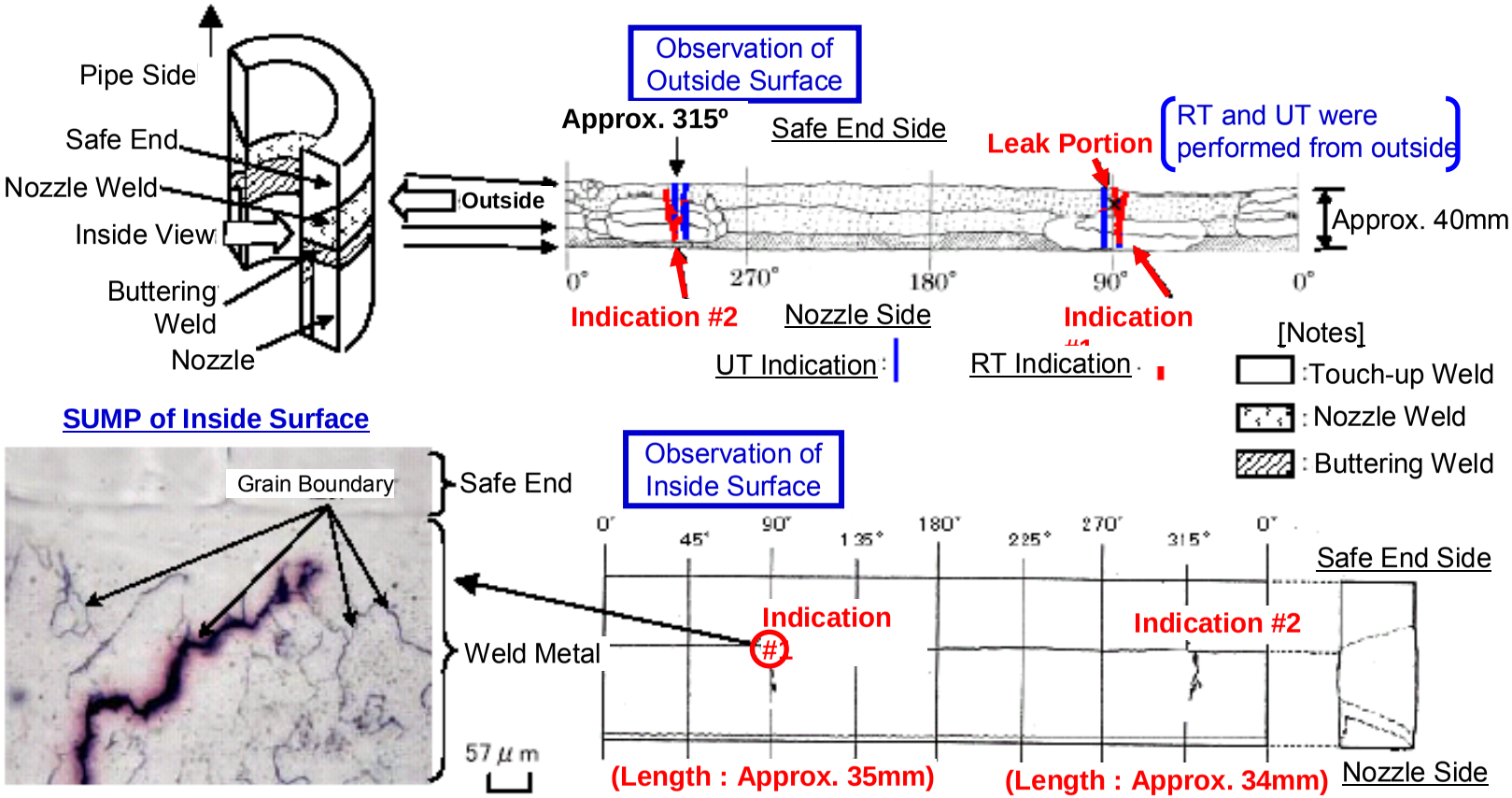
	Indication	Position	Number	Max. Length	Notes
Relief Nozzle	Found	90º	2	About 40mm	- Boric acid deposit - UT, RT
	Found	315º	3	About 40mm	-UT, RT
Safety Nozzle-A	Found	35º	2	About 50mm	-UT, RT
Safety Nozzle-B	No				-UT
Safety Nozzle-C	No				-UT
Spray Line Nozzle	No				-UT

Safety Nozzle & Relief Nozzle (Same Size)





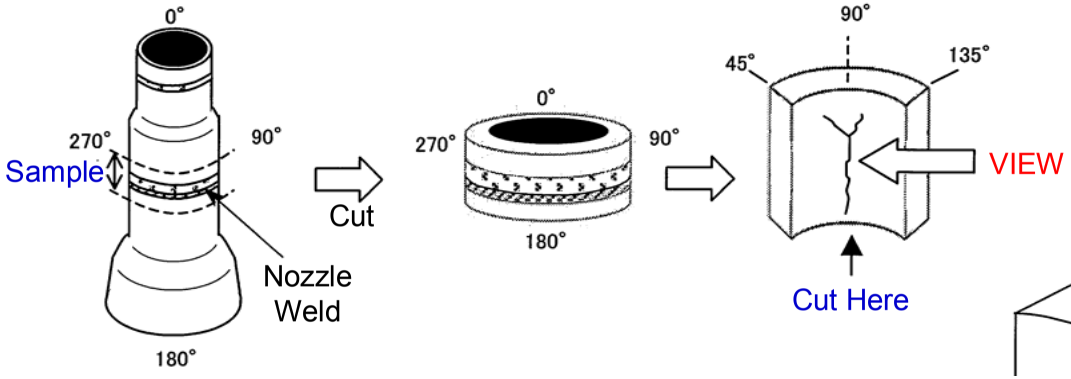
Observation of Inside & Outside Surface

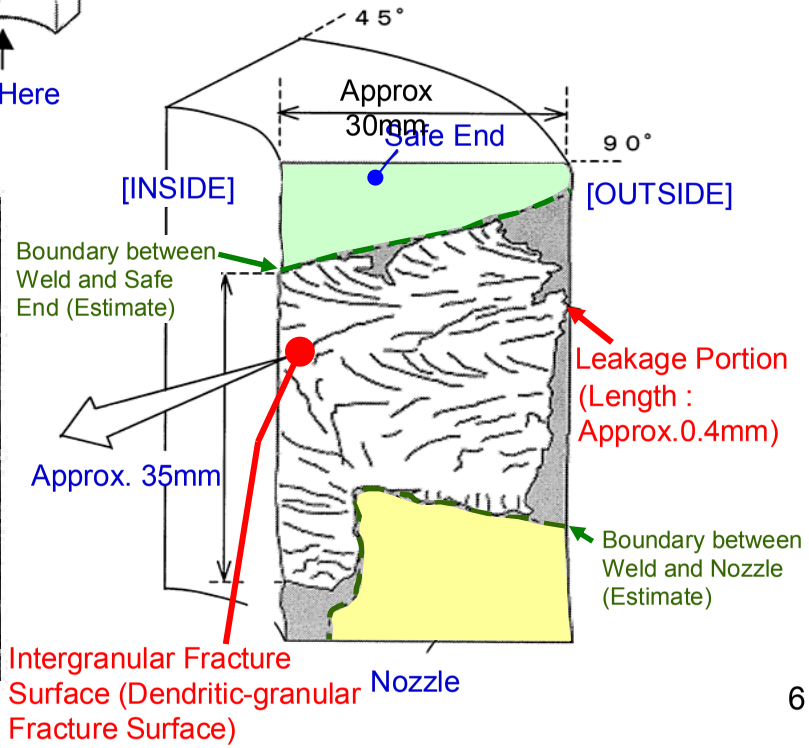


The crack branches off along the grain boundary but does not attach the safe end

Observation of Fracture Surface

- Indication #1 at **90º**





If you want to look at more clear picture, please access to web-site of http://www.japc.co.jp/

If you have more additional questions, please contact to Mr. Hoshio.
His E-Mail Address is
tomohiko-hoshino@japc.co.jp

RPV Heads: Inspection vs. Replacement Strategies for Ringhals-PWR

Pål Efsing - Ringhals AB

Christer Jansson - SwedPower AB

Presentation made at "Vessel Head Penetration"-meeting in Washington DC. September 29 - October 2 2003

Ringhals

Ringhals at a glance

- **PWR:**
  - **3 Westinghouse (US) units**
  - **Ringhals 2 870 MW**
    - » **Comm. 1975**
  - **Ringhals 3 920 MW**
    - » **Comm. 1981**
  - **Ringhals 4 915 MW**
    - » **Comm. 1983**
- **BWR:**
  - **2 Westinghouse Atom units**
  - **Ringhals 1 835 MW**
    - » **Comm. 1976**
  - **Barsebäck 2 615 MW**
    - » **Comm. 1977**

Approximately 1500 employees

20% of the Swedish production capacity

Majority owned by Vattenfall, Minority owner: Sydkraft

Background

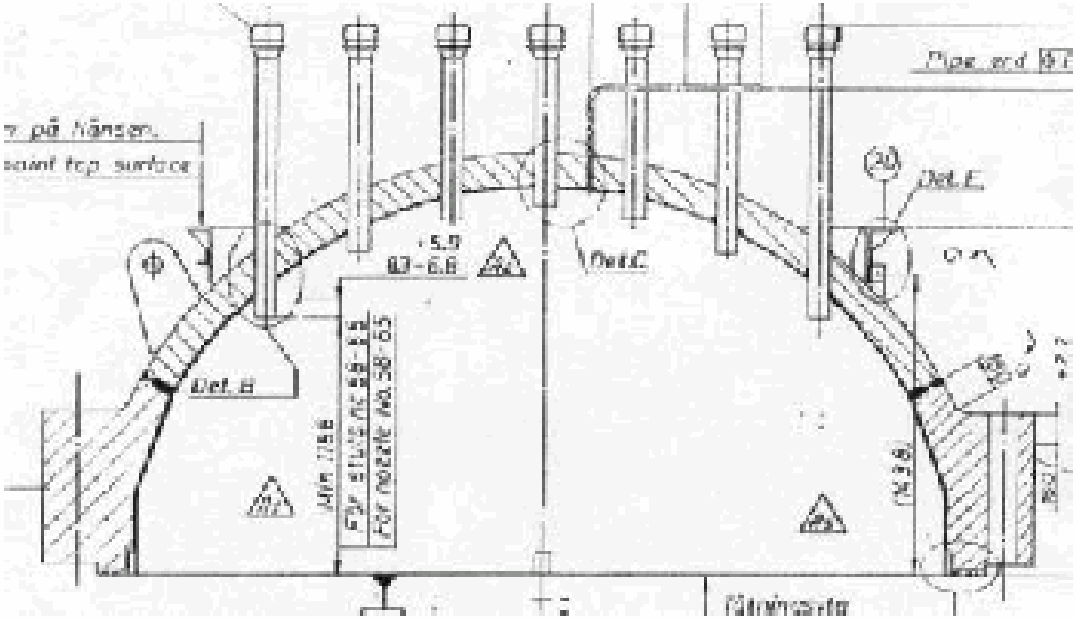
Previous control order

- By “the rule of thumb”/Augmented inspections:
  - *No shorter inspection intervals than 3 years*
- Inspections with “validated inspection system”

Introduction of a more rigid control order with the release of the “new” regulatory guide: SKIFs 1994:1

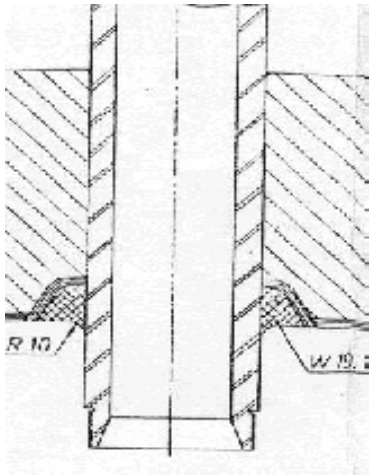
- Qualification of inspection systems
  - *Swedish Qualification body, SQC*
- Introduction of “accredited third party body”
  - *Strengthening of the control program to be reviewed by the 3rd party body*

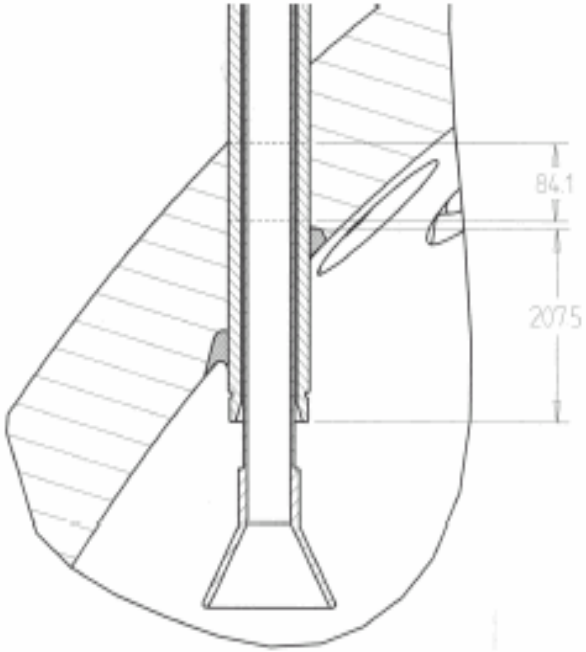
RPV Head Ringhals 3 and 4

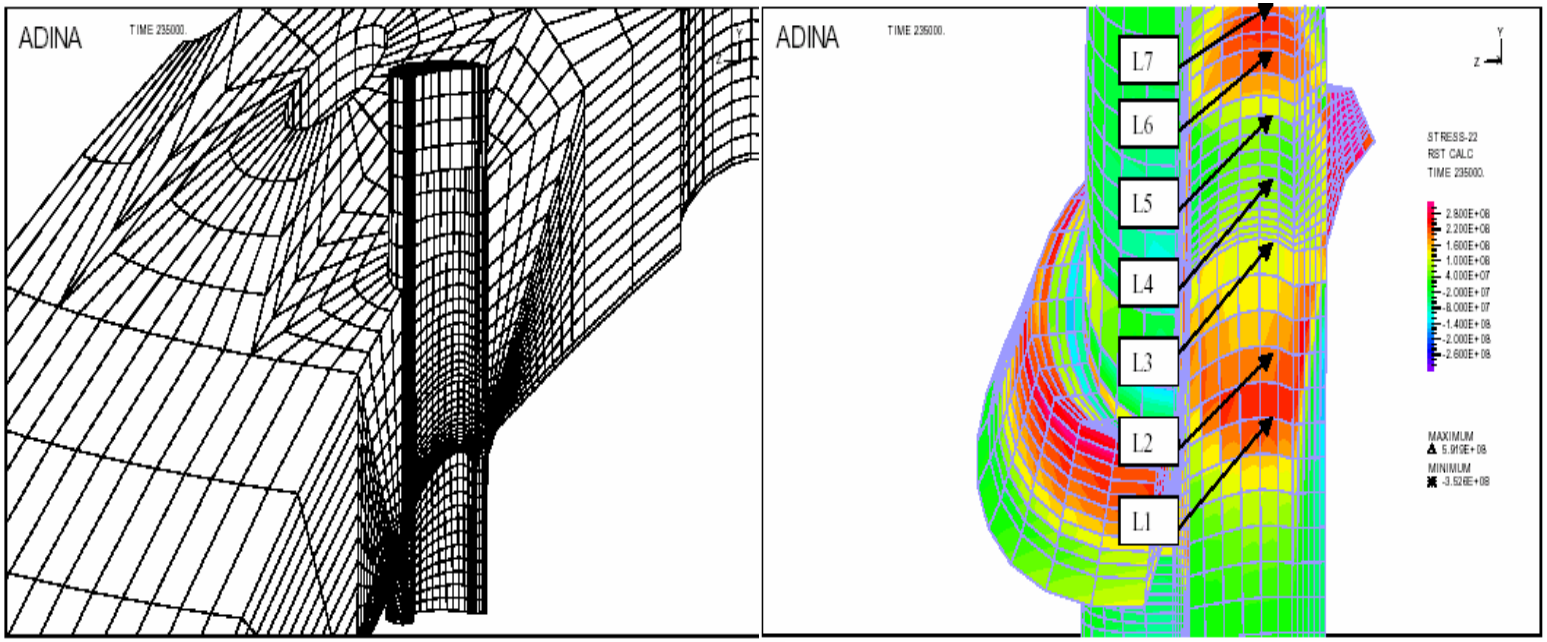


Ringhals

Vessel head penetrations






ADINA
TIME 235000.
ADINA
TIME 235000.
L7
L6
L5
L4
L3
L2
L1
STRESS-22
RST CALC
TIME 235000.
2.800E+08
2.200E+08
1.600E+08
1.000E+08
4.000E+07
-2.000E+07
-8.000E+07
-1.400E+08
-2.000E+08
-2.600E+08
MAXIMUM
5.919E+08
MINIMUM
-3.526E+08

Ringhals

Qualification of an inspection system

DaD - Damage and Defect analysis

- To ensure correct inspection means
- To evaluate residual risks

WCD - MSIT - Worst Case Defect with Minimum Suggested Inspection Technique

- To capture the most intriguing inspection task for the suggested technique

Defect Tolerance analysis

- To give correct inspection interval and detection targets
- To give “risk ranking”

Defect tolerance analysis

Current praxis:

According to ASME XI and/or R6-methodology to assess critical and acceptable defect sizes

To:

Establish a detection target

Establish an inspection interval

How:

"Inverse crack growth calculation"

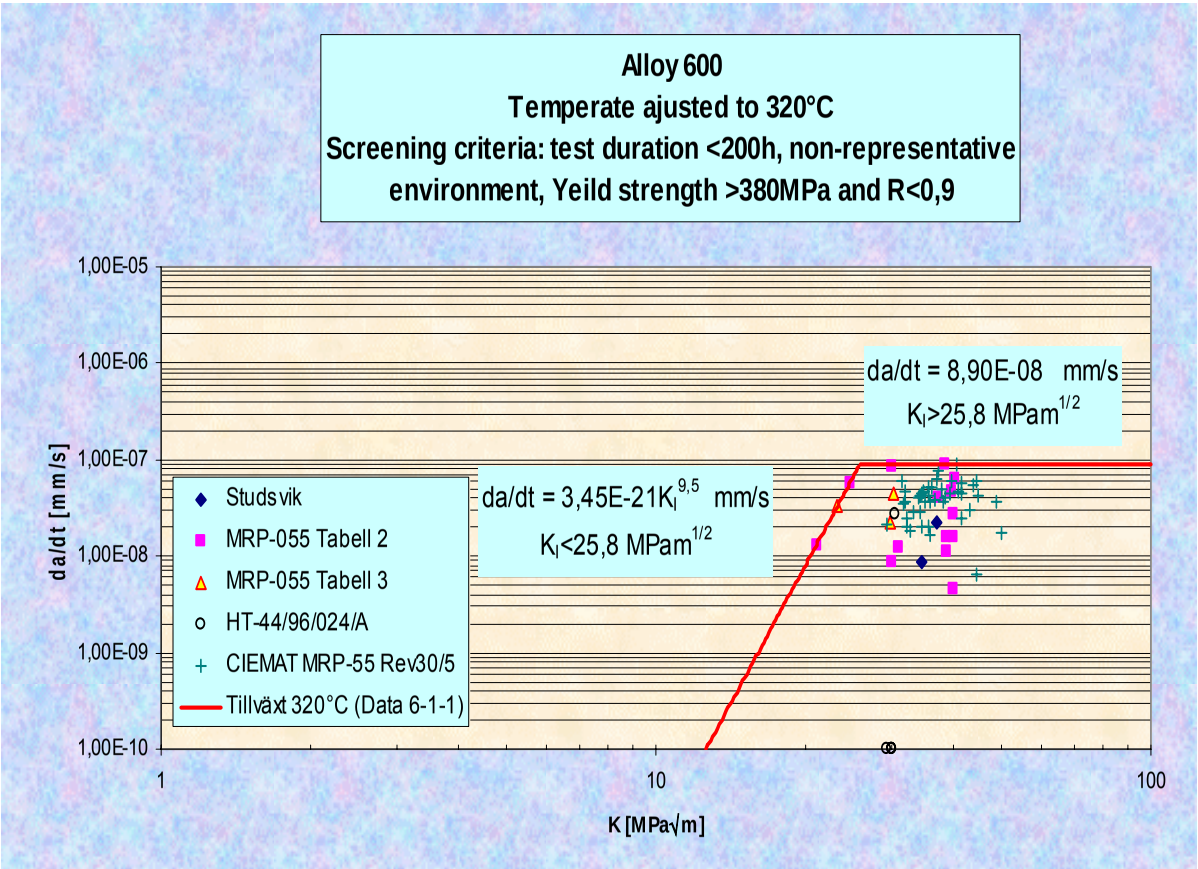
- **Inspection interval and detection target dependent on estimated crack growth:**
  - **Other parameters are code and practice dependent**
  - **Single determining parameter assuming other input are fixed**
  - **Some guidance in regulatory guide**
  - **Some guidance from third party body**
- **Thus: Critical issue to assess crack growth within needs of both reactor safety and reactor economy!**

- **All work in this area review by independent 3rd party body:**
  - **Including assessment of crack growth rates**

Assessment procedure

- **Assuming a reviewed data base with sufficient data**
  - **“Aggressive screening”**
- **Several filters included in the screening procedure:**
  - **Test procedures / Administrative issues**
    - » **Constant load testing!**
    - » **Hold time / cycling of specimen**
  - **Environmental issues**
    - » **Constant monitoring**
  - **Mechanical issues**
    - » **Yield strength / R-value / Pre-fatigue /**
    - » **Temperature dependence**

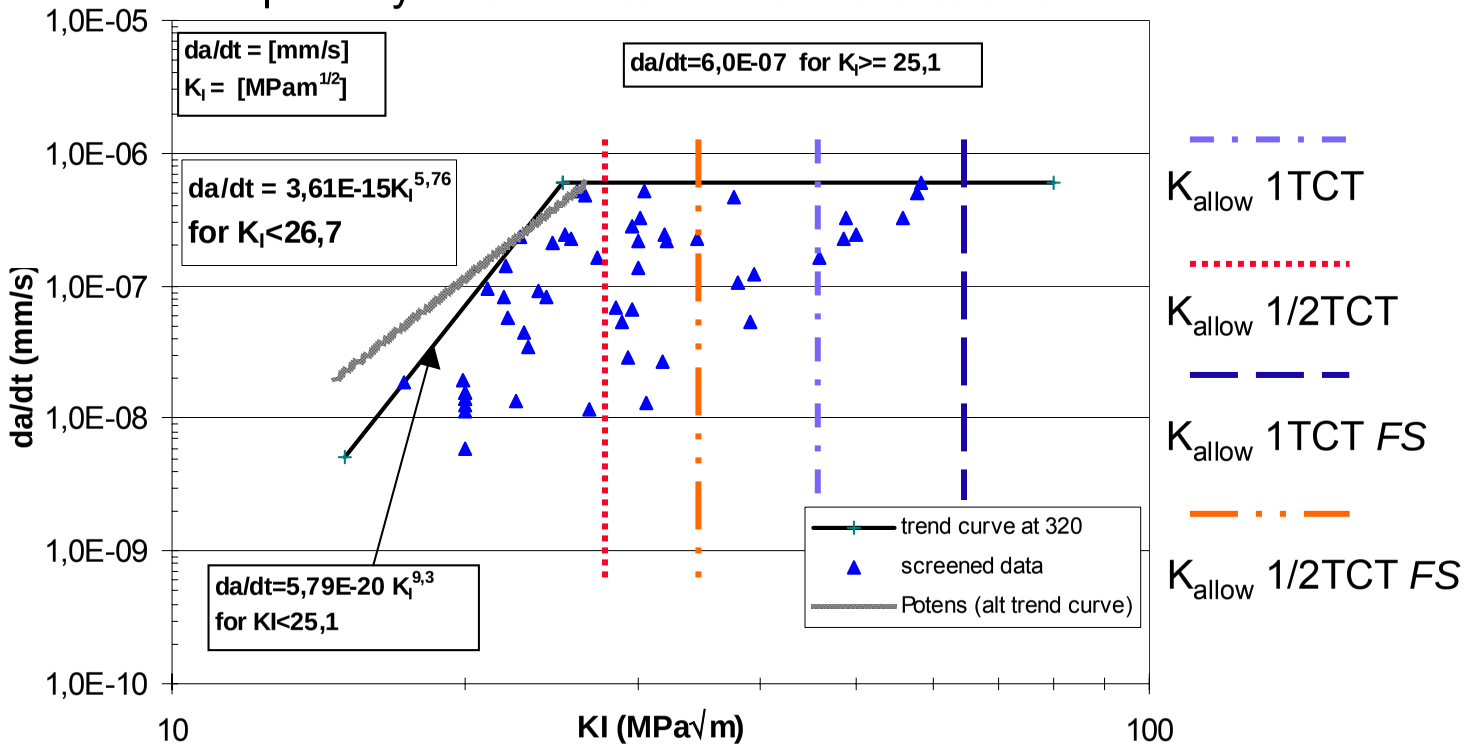
Assessment of crack growth rate



Ringhals

Assessment of crack growth rate

Screened data and bounding curves for Alloy 182 crack growth in PWR primary water. Data recalculated to 320 °C



Ringhals

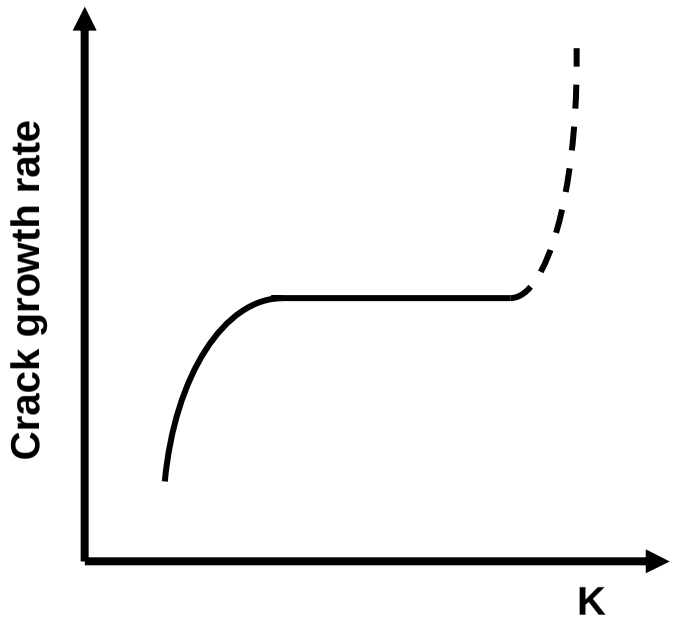
Available data does:

Give sufficient evidence to formulate K-dependent part of CGR-curve for most technically interesting materials

Indicate the need for valid high-K data

- Obvious objective to clearly demonstrate K-independence at higher K-levels
- General trend indicated here found in many systems

Indicate the need to enhance data base to be statistically significant at low to medium high K-levels



Reactions from the reviewer:

3rd Party Body

- Database: Accepted
- Acceptance standards of specimen sizes, geometrical issues, flow stress vs. Yield stress etc
- No acceptance on temperature recalculation using Weibull curve and relating SCC to thermally activated processes
- No acceptance of plateau value from our definition
  - » Wanted to tie the plateau value to a specific K-value rather than the data base

Regulatory Body

- Non-solvable issues with 3rd party body
- Assumed responsibility for theoretical issues outside competence of 3rd party body
- Acceptance of temperature recalculation using Weibull curve and relating SCC to thermally activated processes
- No general acceptance of plateau value but open for discussion on specific issues given sufficient evidence

Inspection results

- **Surface breaking defects found in 26 penetrations between 2000 and 2002**
  - **Depth less than 2 mm (lower bound inspection capability)**
    - » **Measurements on samples: < 1mm!**
  - **lengths varying from less than 4 mm to 18 mm**
  - **Defect clusters found in 16 penetrations, “Crackled surface”**

The situation:

Despite good quality data:

Rapid crack growth - small detection targets - complicated qualification of NDT - short inspection interval

Easy to come to the conclusion that replacement or exchange is the “solver” for most issues

As long as EAC/operationally induced defects are an issue it is “efficient” both with respect to reactor safety issues and plant economics issues, to consider replacement

Demands on Engineering Department at power plants

Defend Cost efficiency and Availability

Current technology vs. Future

- **Produced in:**

– Penetrations in Alloy 600	– Penetrations in Alloy 690
– Welded with Alloy 82/182	– Welded with Alloy 52
– Butt welds in RPV head	– No butt welds in RPV head, single forging possible
– Known situation	– New situation

Decision making

- **Effort to estimate cost for inspections, including qualification costs**
- **Costs of replacement heads fairly well known**
- **Largest estimated individual cost - forced outages to repairs or prolonged outages due or inspections of penetrations**

Thus:

- **Replacement head ordered for delivery in 2004 and 2005**
  - **Single forging**
  - **Penetrations in Alloy 690**
  - **Nozzle welds made in Alloy 52**

- **Foreseen actions to establish a better situation:**
  - **Data collection from other RPVH and focused crack growth experiments**
    - » **10 year inspection interval possible if further evidence is provided that supports the indications from previous experience and initiation studies**

Pros and Cons

- Known fracture toughness of both the weld metal and the base metal
- Good field experience with some replacements
- Documented resistance to crack initiation due to EAC

- Insufficient “good quality data” on crack growth
- Few reactor years in total operated compared to 600/182/82
- Possible that thermal fatigue plays role in initiation portion of the issue
  - Possible that we will be back in same situation again!

Still judged that the new RPVHs are less susceptible to crack initiation and environmental degradation than the current ones - thus it is a correct step to ensure future safe and economical production, for the remainder of the expected technical life

Conclusions

Despite good quality data:

- Rapid crack growth - small detection targets - complicated qualification of NDT - short inspection interval

Easy to come to the conclusion that replacement or exchange is the "solver" for most issues

As long as EAC/operationally induced defects are an issue it is "efficient" both with respect to reactor safety issues and plant economics issues, to consider replacement

Demands on Engineering Department at power plants

Defend Cost efficiency and Availability

Only possible decision : replace RPVH

Alloy 600 PWSCC Mitigation: Past, Present, and Future

S. Fyfitch
Framatome ANP, Inc.

U.S. NRC and ANL Conference
on Vessel Head Penetration Inspection, Cracking, and Repair
Marriott Washingtonian Center, Gaithersburg, MD

Outline

- Main Factors That Cause PWSCC
- Brief History of Alloy 600/182/82 PWSCC
- Previous PWSCC Mitigation Techniques
- Present PWSCC Mitigation Techniques
- Potential Future Mitigation Techniques
- Closing Remarks

Main Factors That Cause PWSCC

- ***PWSCC is cracking of Alloy 600/182/82 material under the combined action of stress and corrosion***
- ***Three main factors necessary to initiate PWSCC***
  - ***Mechanical loading***
  - ***Corrosive environment***
  - ***Susceptible material***

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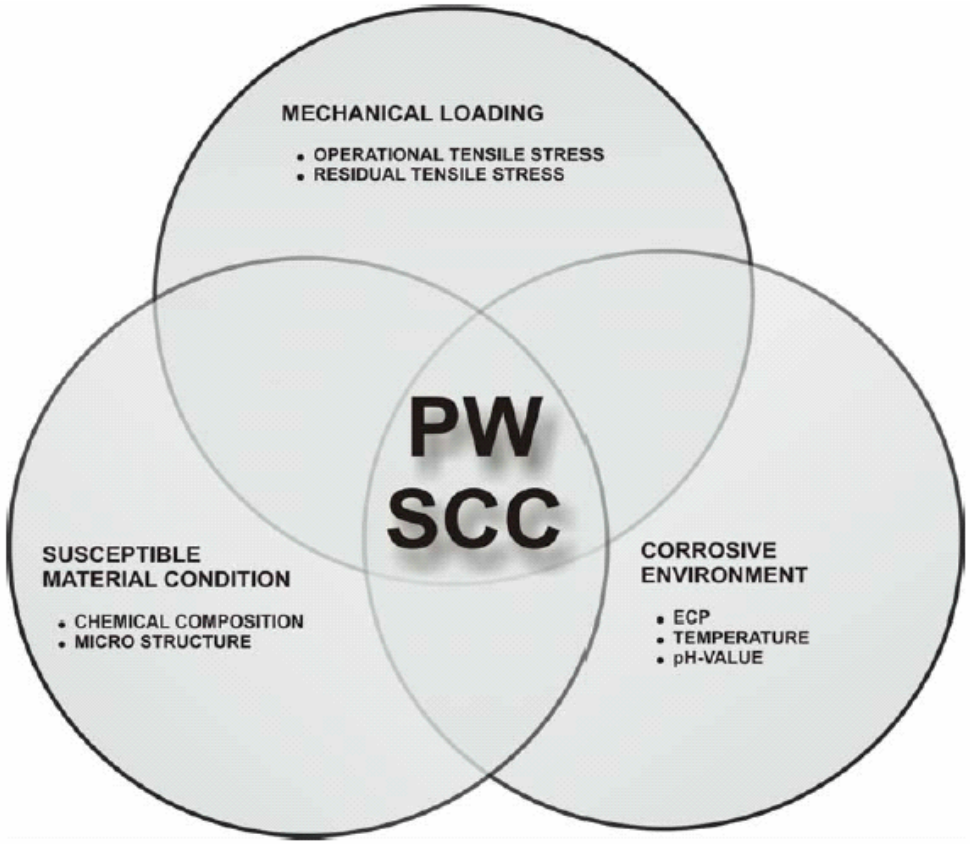
Main Factors That Cause PWSCC



Alloy 600/182/82 PWSCC Experience in Commercial PWRs

Component Item	Date PWSCC Initially Observed	Service Life[a] (Calendar Years)
Steam Generator Hot Leg Tubes and Plugs	~1973	~2
Pressurizer Instrument Nozzles	1986	2
Steam Generator Cold Leg Tubes	1986	18
Pressurizer Heaters and Sleeves	1987	5
Steam Generator Channel Head Drain Pipes	1988	1
Control Rod Drive Mechanism Nozzles	1991	12
Hot Leg Instrument Nozzles	1991	5
Power Operated Relief Valve Safe End	1993	22
Pressurizer Nozzle Welds	1994	1
Cold Leg Piping Instrument Nozzles[b]	1997	13
Reactor Vessel Hot Leg Nozzle Buttering/Piping Welds	2000	17
Control Rod Drive Mechanism Nozzle/RV Head Welds	2000	27
Surge Line Nozzle Welds[c]	2002	21
Reactor Vessel Lower Head In-Core Instrumentation Nozzles/Welds[c]	2003	14

PWSCC Mitigation Techniques

- **Categories of Mitigation Techniques**
  - **Mechanical surface enhancement (MSE)**
    - **Shot peening**
    - **Electropolishing**
  - **Environmental Barriers or Coatings**
    - **Nickel plating**
    - **Weld deposit overlay**
  - **Electrochemical corrosion potential (ECP) control**
    - **Zinc addition**
    - **Modified water chemistry**

Previous PWSCC Mitigation Techniques

MSE Techniques

- ***Shot Peening***
- ***Flapper Wheel Grinding***
- ***Electrical-Discharge Machining***
- ***Stress Relief Heat Treatment***
- ***Electropolishing***

Objectives:

Reduce tensile stress and/or induce compressive residual stress on exposed surface

Extend crack initiation time and reduce crack propagation rate

Previous PWSCC Mitigation Techniques

ECP Technique

> ***Temperature Reduction***

Objective:

Extend crack initiation time and reduce crack propagation rate

Present PWSCC Mitigation Techniques

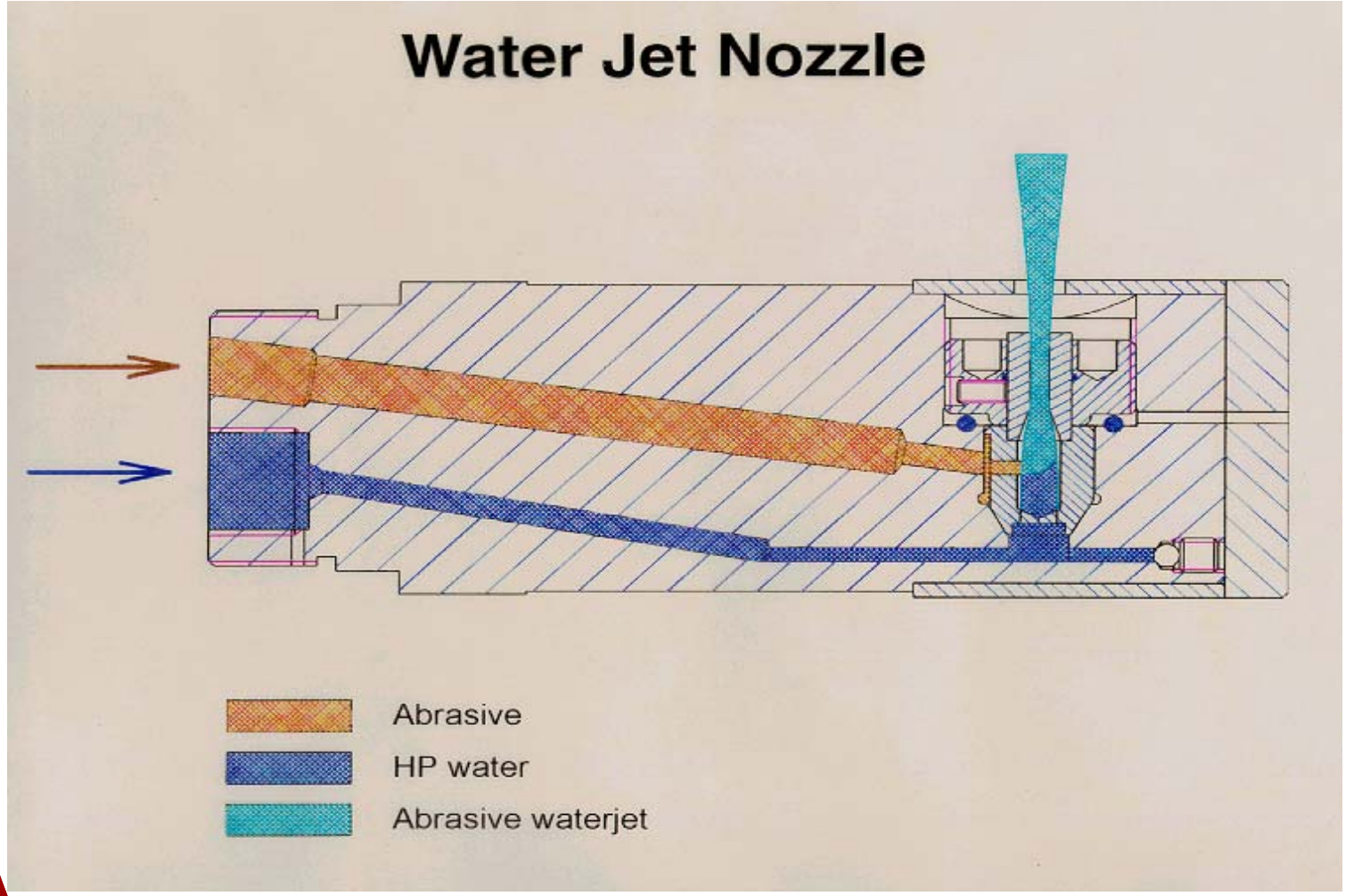
MSE Techniques

- ***Abrasive Water Jet Conditioning***
- ***Mechanical Stress Improvement Process (MSIP)***

Objective:

Reduce tensile stress and/or induce compressive residual stress on exposed surface

Abrasive Water Jet Conditioning



MSIP

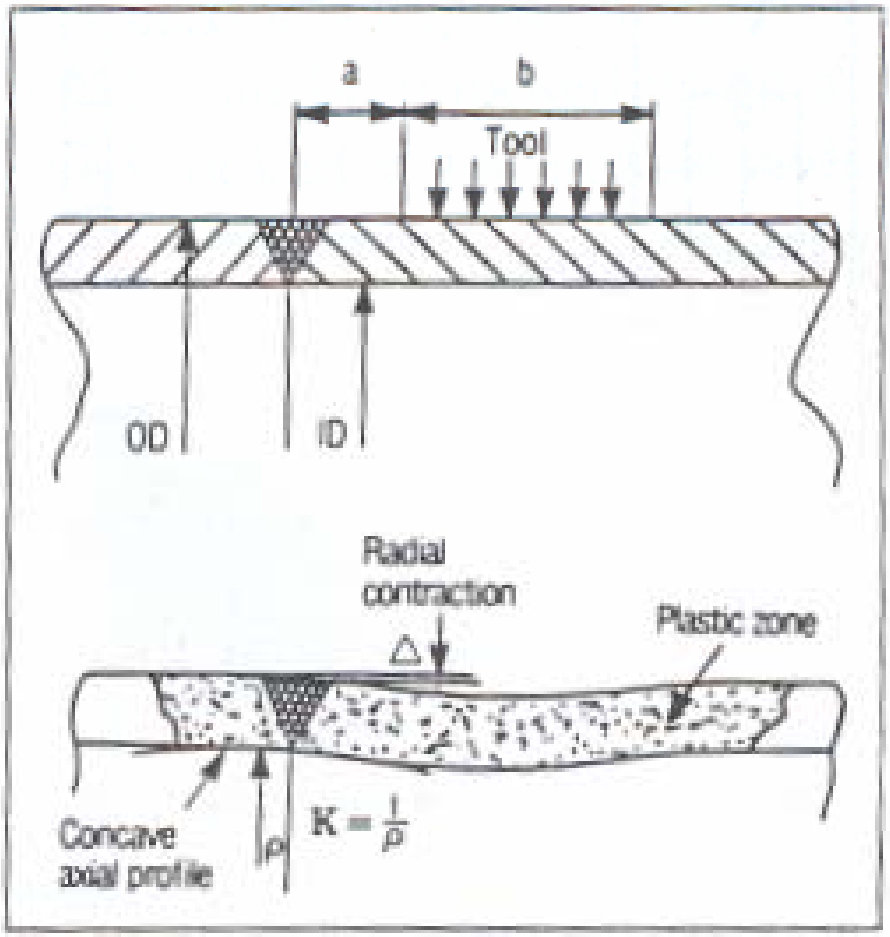


FIGURE 2 TOOL LOCATION AND DEFORMATION CONTOUR AFTER APPLYING MSIP

Present PWSCC Mitigation Techniques

Environmental Barrier or Coating Techniques

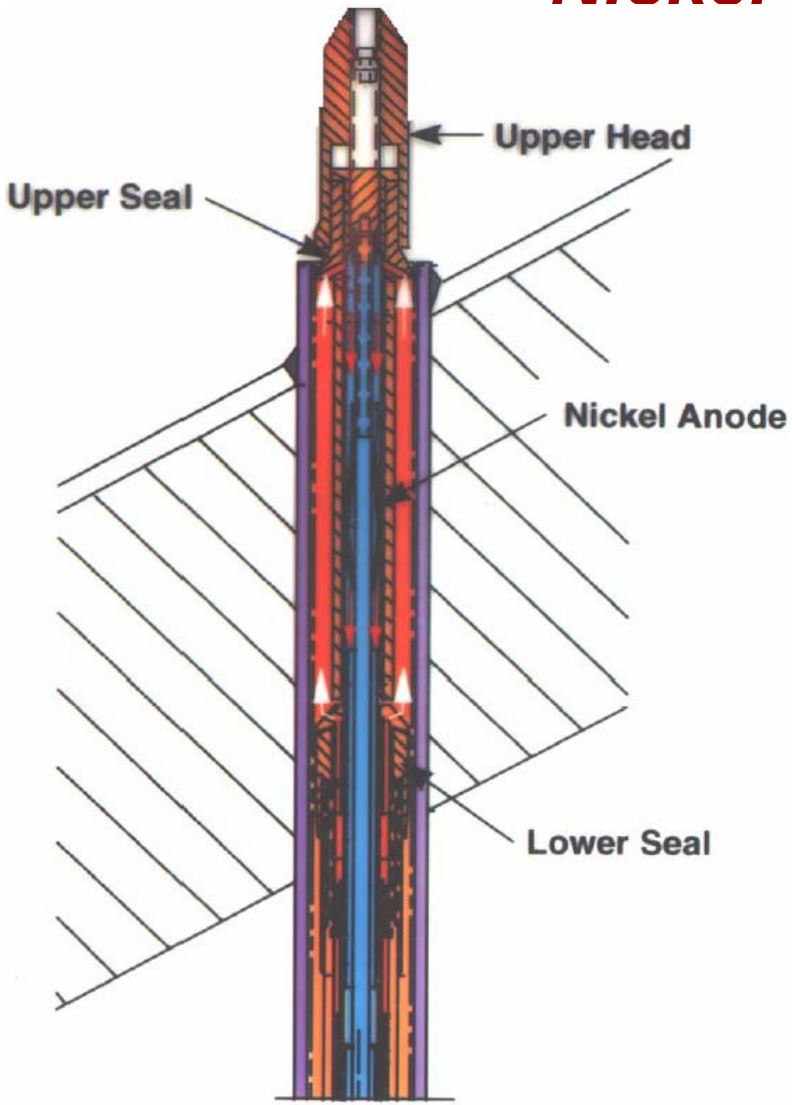
- ***Nickel Plating***
- ***Weld Deposit Overlay***
- ***Electroless Nickel Plating***
- ***Laser Weld Deposit/Cladding***

Objectives:

Eliminates the environment that may cause PWSCC
Stops existing cracks from propagating

Nickel Plating

End Effector



Present PWSCC Mitigation Techniques

ECP Control Technique

> ***Zinc Addition***

Objectives:

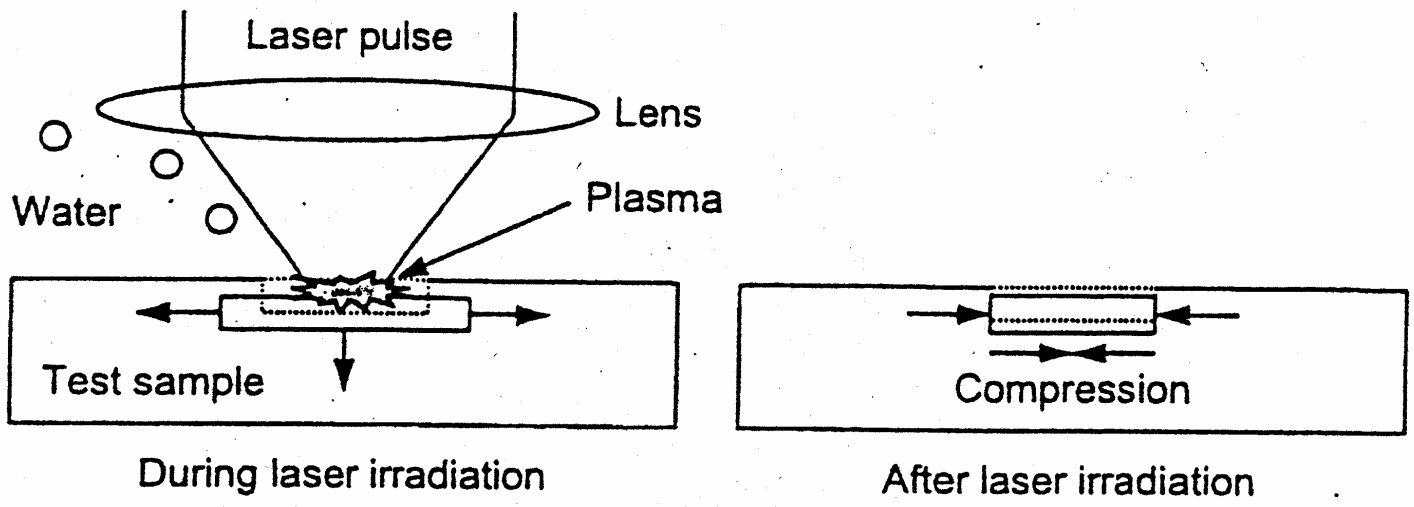
Inhibits PWSCC initiation
Potentially reduces crack propagation

Potential Future Mitigation Techniques

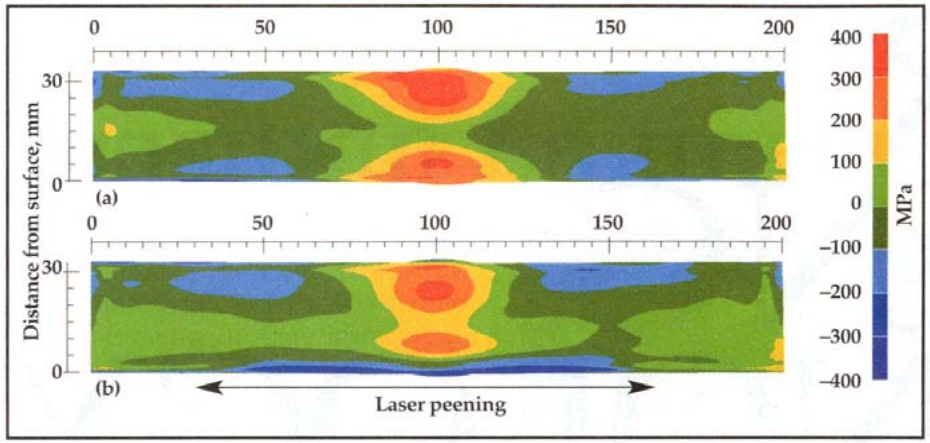
MSE Techniques

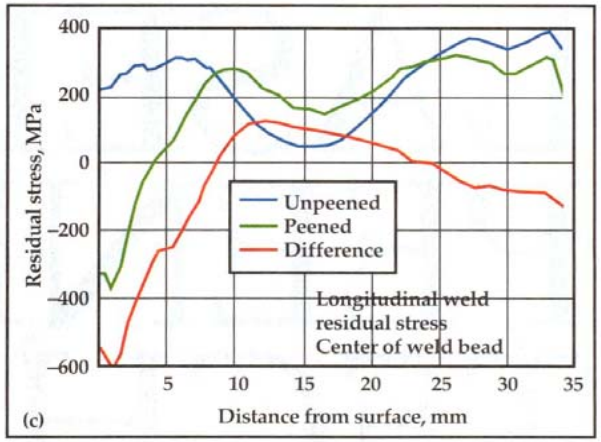
- ***Laser Shock Peening***
- ***Low Plasticity Burnishing***
- ***Heat Sink Welding***
- ***Induction Heating Stress Improvement (IHSI)***

Laser Peening

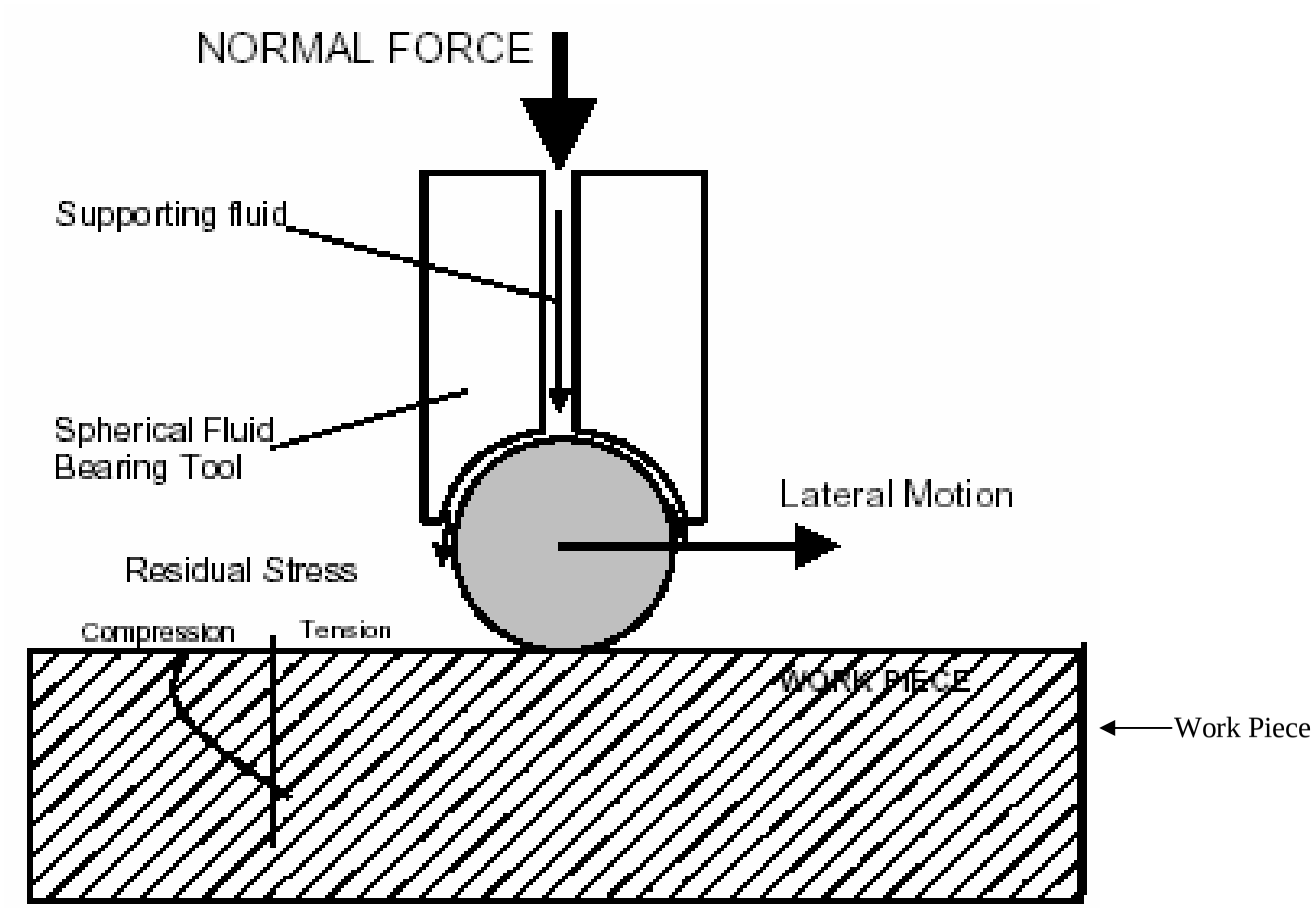


Laser Peening Residual Stresses

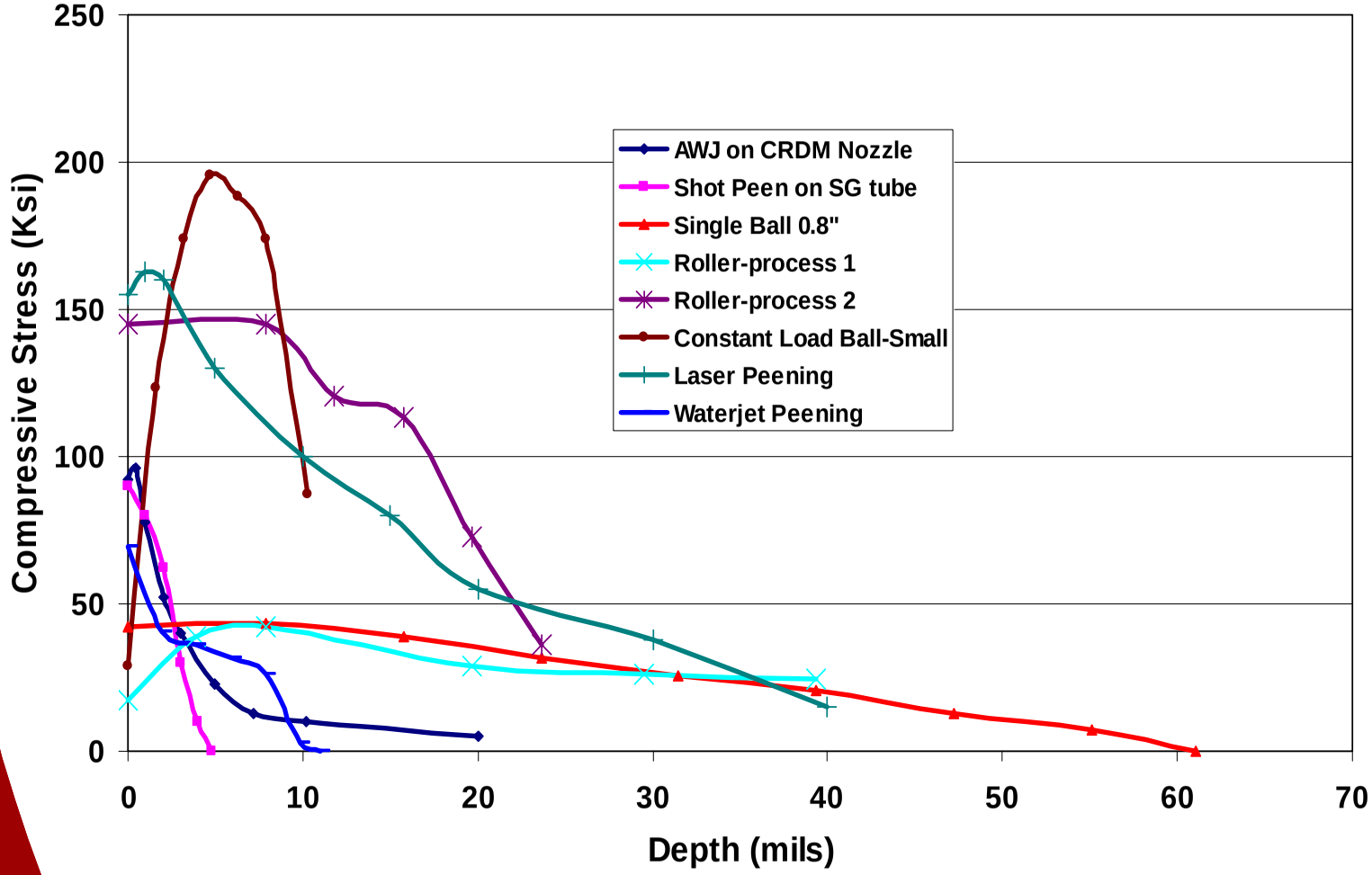




Low Plasticity Burnishing



Comparison of Potential Remediation Techniques



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Potential Future Mitigation Techniques

Environmental Barrier or Coating Techniques

- ***Ion Implantation and Ion Beam Enhanced Coatings***
- ***Thermal Spraying***

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Potential Future Mitigation Techniques

ECP Control Techniques

- ***Modified Primary Water Chemistry Control***
- ***Other Chemical Additions***
- ***Anodic Protection***

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Closing Remarks

- ***PWSCC of Alloy 600/182/82 should be a major concern for most utilities***
- ***Replacement with less susceptible material is the obvious alternative***
  - ***Alloy 690/152/52 materials mostly utilized***
  - ***Not considered remedial***
- ***Mitigative techniques very geometry dependent***
- ***Many techniques not effective if crack already initiated***
- ***Future NDE requirements must be considered***
- ***Most techniques require further developmental efforts***

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Closing Remarks

- ***Utilities need to evaluate a variety of techniques***
  - ***One mitigative technique not applicable to all locations***
- ***Cost-benefit analyses need to be performed***
- ***Utilities should consider developing site-specific Alloy 600 aging management programs***
  - ***For current license attainment***
  - ***For license renewal***

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A Reactor Vessel Upper Head Temperature Reduction Program to Prevent and Mitigate Alloy 600 Cracking

David R. Forsyth, Pat L. Strauch and Paul J. Kreitman

Westinghouse Electric Company LLC

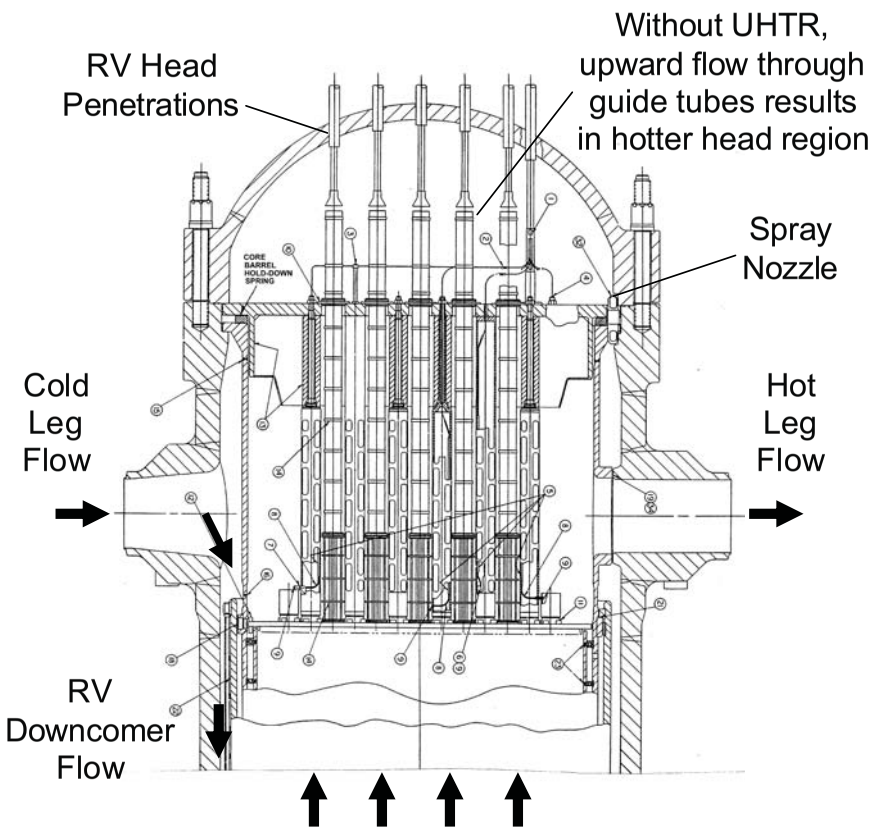
Outline

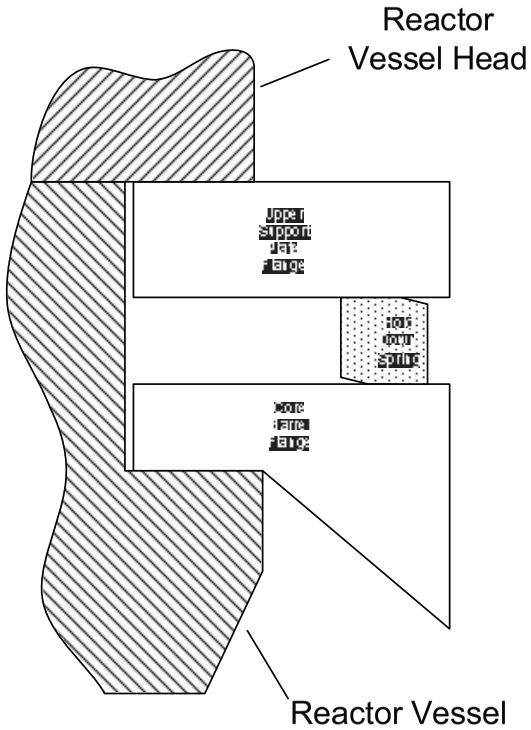
- What is an Upper Head Temperature Reduction (UHTR) Program
- Benefits
- Effects of Temperature on Cracking
- Westinghouse Fleet Experience

Upper Head Temperature Reduction (UHTR) is a Field Modification Performed on the Reactor Vessel (RV) Internals Structures

- Increases the bypass flow from the RV downcomer region (which is at cold leg temperature) into the upper head region
- Lowers the bulk fluid average temperature underneath the closure head to the cold leg temperature
- This lowers the RV head penetration temperatures

Upper Internals Components





Detail of Components where UHTR Modification is Implemented (by providing a flow path to the upper head region)

Benefits of UHTR

- Significant reduction in effective degradation years (EDY) accumulation rate
  - Can lead to reduced number of required inspections of either a new closure head or an existing closure head
- Reduces the risk associated with head penetration cracking
  - significantly increases time for crack initiation
  - significantly reduces rate of crack propagation
- Significantly increases Peak Clad Temperature margin for large break LOCA
  - provides margin to support an increase in power output
- Slightly increases RCS flow
  - increases steam generator tube plugging margin

Effect of Temperature on Cracking

Effective Degradation Years:

$$EDY_{600°F} = \sum_{j=1}^{n} \left\{ \Delta EFPY_j \exp\left[-\frac{Q_i}{R} \left(\frac{1}{T_{head,j}} - \frac{1}{T_{ref}} \right) \right] \right\}$$

where:

EDY_{600F} = total effective degradation years, normalized to a reference temperature of 600F

$\Delta EFPY_j$ = effective full power years accumulated during time period j

n = number of time periods with distinct 100% power head temperatures

Q_i = activation energy for crack initiation (50 kcal/mole)

R = universal gas constant (1.103×10^{-3} kcal/mole-R)

$T_{head,j}$ = 100% power head temperature during time period j (R = F + 459.67)

T_{ref} = reference temperature (600F = 1059.67R)

Effect of Temperature on Cracking

Crack Growth:

$$\dot{a} = \exp\left[-\frac{Q_g}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]\alpha\left(K - K_{th}\right)^{\beta}$$

where:

$\dot{a}$ = crack growth rate at temperature T (inches/year)

Q_g = activation energy for crack growth (31 kcal/mole)

R = universal gas constant (1.103×10^{-3} kcal/mole-R)

T = absolute operating temp. at location of crack (R)

T_{ref} = absolute reference temperature to normalize data

α = crack growth amplitude (3.69×10^{-3})

K = crack tip stress intensity factor (ksi vinch)

K_{th} = stress intensity factor threshold (8.19 ksi vinch)

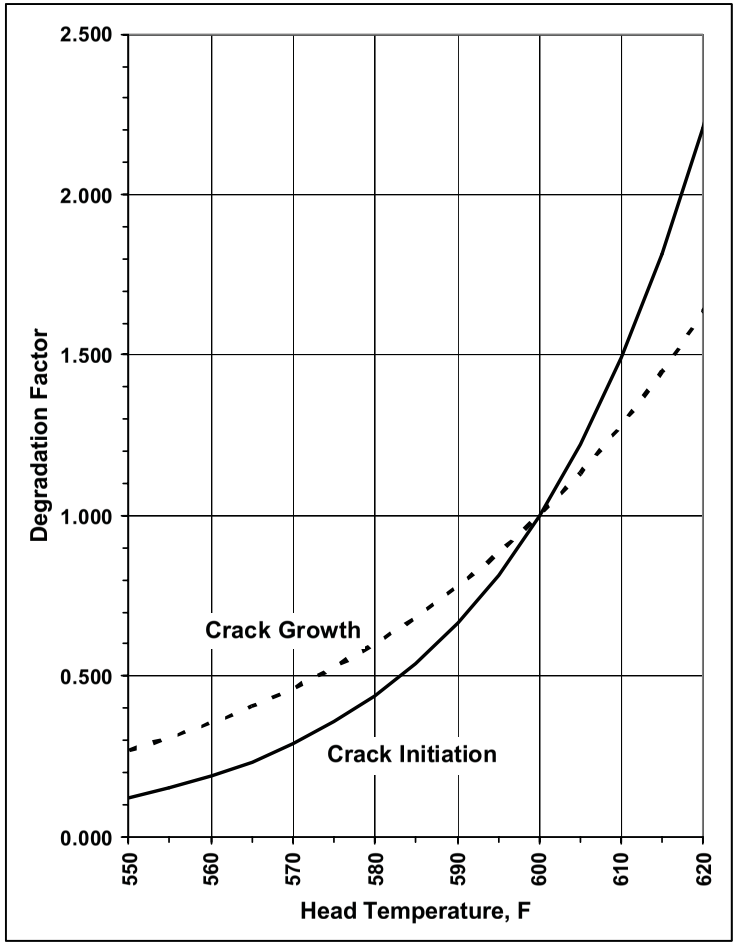
β = exponent (1.16)

Effect of Temperature on Cracking

	Degradation Factors*	
Temp	Initiation	Growth
600F	1.00	1.00
550F	0.12	0.27

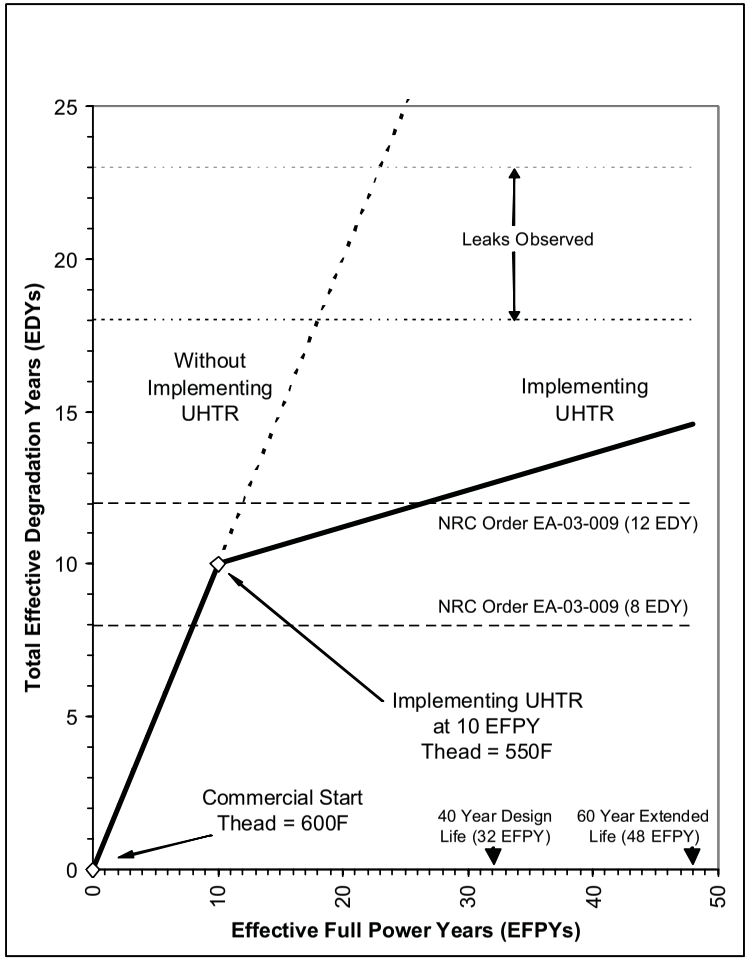
i.e., crack initiation and growth rates at 550F are 12% and 27%, respectively, of their rates at 600F

*Exponential terms in Equations on previous two pages



Example of UHTR Effectiveness for a Unit Approaching the 8 EDY Limit, with Respect to NRC Order

- Early UHTR implementation results in most favorable results
- May extend life into license renewal period



Domestic Plant Ranking vs. EDY

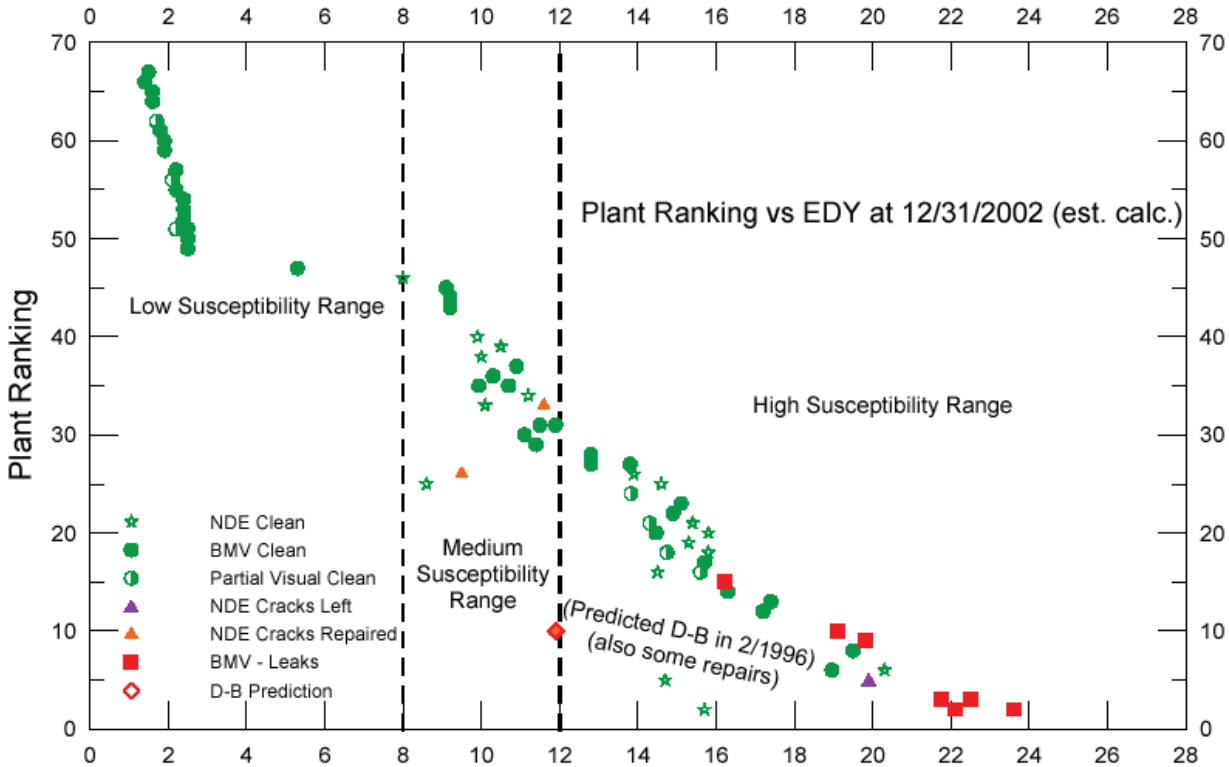


Figure 1. Ranking of domestic plants according to the EDY formula, showing results of inspections, evidence of leakage, and repairs. Many plants are shown with multiple symbols, indicating a "clean" inspection at inspection opportunity, followed by a different finding at a subsequent inspection (e.g., Oconee 2: clean NDE @ EDY=15.7, leaks and circ. flaws @ 22.1)

Westinghouse Fleet Status

- Approximately Half (30) of the Westinghouse Units were Designed and are Operated with Upper Head Fluid at Cold Leg Temperature

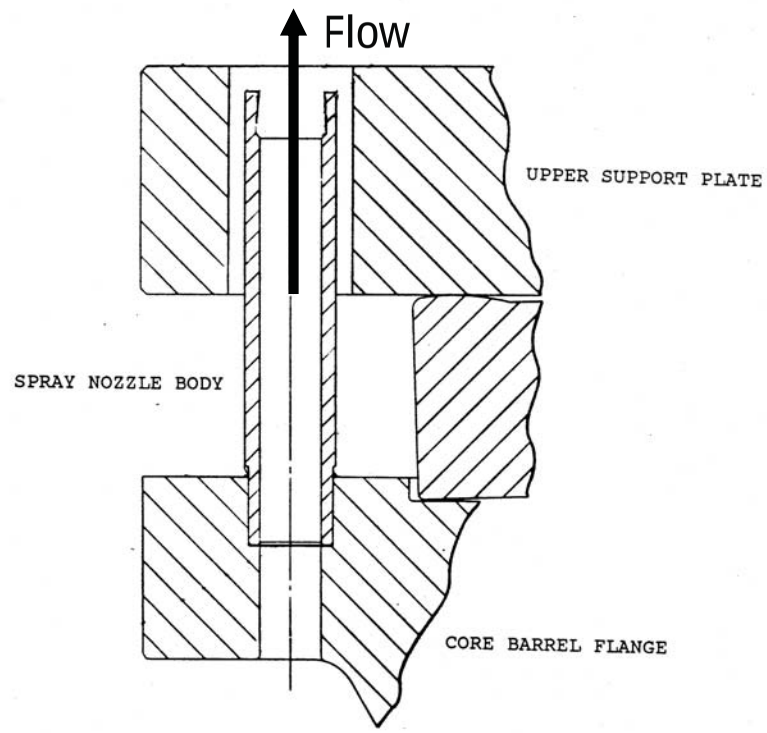
- Westinghouse has an Improved Process to Implement UHTR for the Remaining Units
  - Requires no machining in core barrel flange
  - Does not require removal of lower internals package from RV
  - Modifications performed off-critical path (outage time unaffected)

Westinghouse UHTR Field Modification Experience

- One European unit in 1992
  - Maintain LOCA margin
- Two domestic units in 2000 and 2002
  - Reduce core flow
  - Lower susceptibility to PWSCC
- A second European unit in 2003
  - Lower the risk associated with head penetration cracking
  - Provide margin to support an increase in power output
- A third European unit is scheduled for early 2004

Westinghouse Implementation Designs: Spray Nozzle Plug Removal (3 Units)

Remove specified plugs from existing flow nozzles on the core barrel flange that protrude through holes on the upper support plate flange



<u>Actual Implementation Data:</u>

Schedule: 10 hours

Exposure: 10 mR

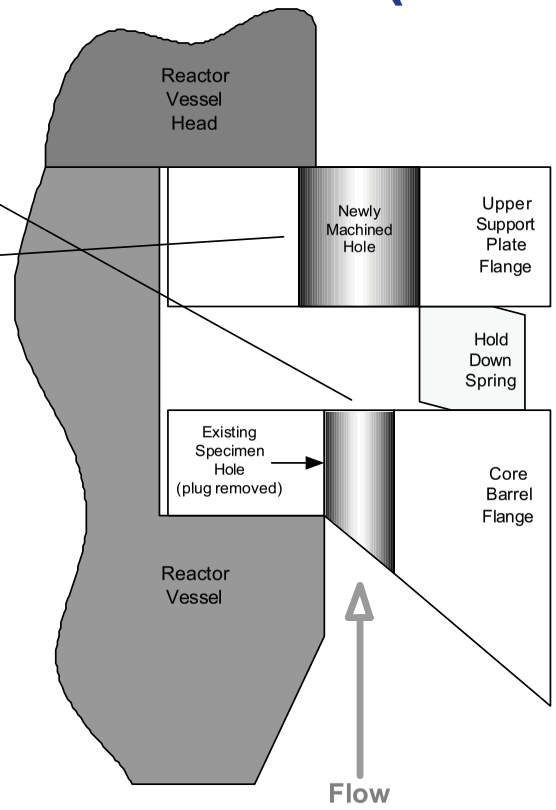
Westinghouse Implementation Designs: Upper Support Plate Modification (1 Unit)

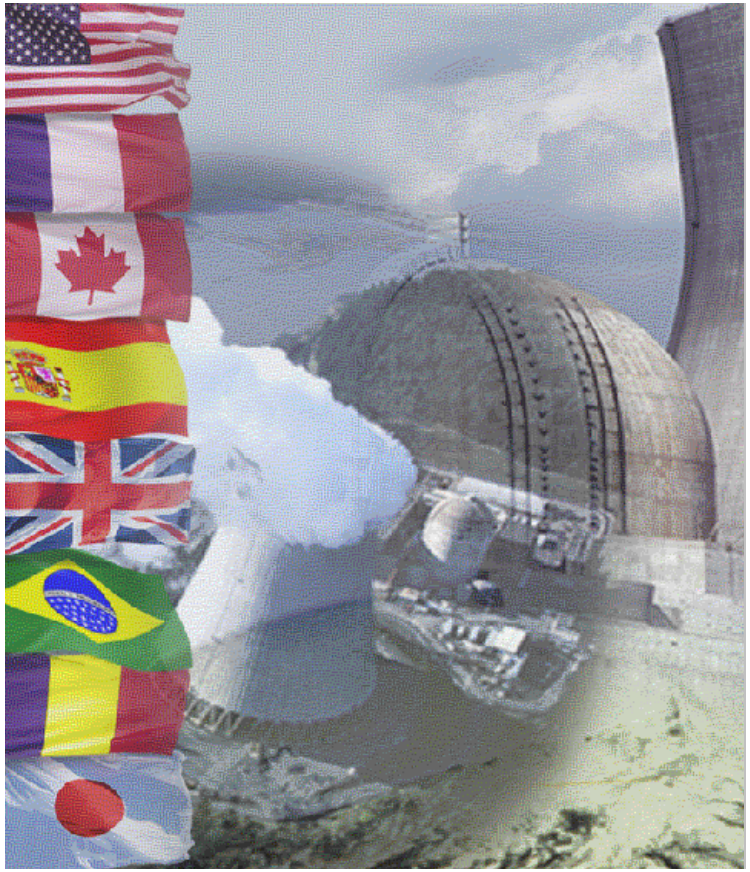
Remove a selected number of the irradiated specimen access plugs to expose specimen access holes

Electric Discharge Machine (EDM) large holes in the upper support plate above each specimen access hole location

Multiple work stations are utilized

<u>Actual Implementation Data:</u>
Schedule: 4 days
Exposure: 637 mR





Status report on the effect of zinc additions on mitigation of PWSCC in Alloy 600

John Hickling

Technical Leader – Materials Issues

Nuclear Power - Science & Technology Department, Palo Alto, CA

NRC/ANL Conference on Vessel Head Penetration Inspection, Cracking and Repairs; Gaithersburg MD, 10/2/2003

EPRI

Acknowledgements

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- Key contributions from the following EPRI colleagues are also gratefully acknowledged:
  - Keith Fruzzetti
  - Raj Pathania
  - Chris Wood
- Appreciation is expressed to John Wilson (Exelon), Rick Eaker (Duke Power) and various members of the MRP Expert Panel on PWSCC for their assistance in designing a new test program on chemical mitigation to be funded by the MRP Alloy 600 ITG Mitigation WG

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Background to PWR Zinc Addition Studies

- Zinc injection used at most BWRs to control radiation fields, but also helps to inhibit IGSCC (mainly of stainless steels)
- Lab data and German PWR experience indicated similar potential benefit for PWRs
- The objective of the field program in the USA was:
    - To evaluate the long-term effect of Zn addition in mitigating radiation fields and Alloy 600 PWSCC
    - To ensure that zinc does not have an adverse effect on fuel performance and other components
- Zinc addition demonstrations were conducted at Farley (from 1994) and Diablo Canyon (from 1998)
- Palisades uses depleted zinc to reduce radiation fields

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Interaction of Zn with corrosion films on Ni-based alloys in PWR primary water

- Long-term exposure without Zn leads to duplex oxide film:
  - inner layer is chromite spinel $(Fe,Ni,Co)Cr_2O_4$ with enriched Cr and Fe and forms by corrosion of metal
  - outer layer grows from solution and typically consists of inverse spinel ferrites such as $(Ni,Co)Fe_2O_4$
- Zn displaces Co, Ni and other cations from the normal inner spinel oxides because of its higher site preference energy
- Auger spectroscopy confirms that a large fraction of near-surface tetrahedral sites become occupied by Zn
- Concentration at surface and penetration depth appear to correlate more with exposure time than with coolant Zn level

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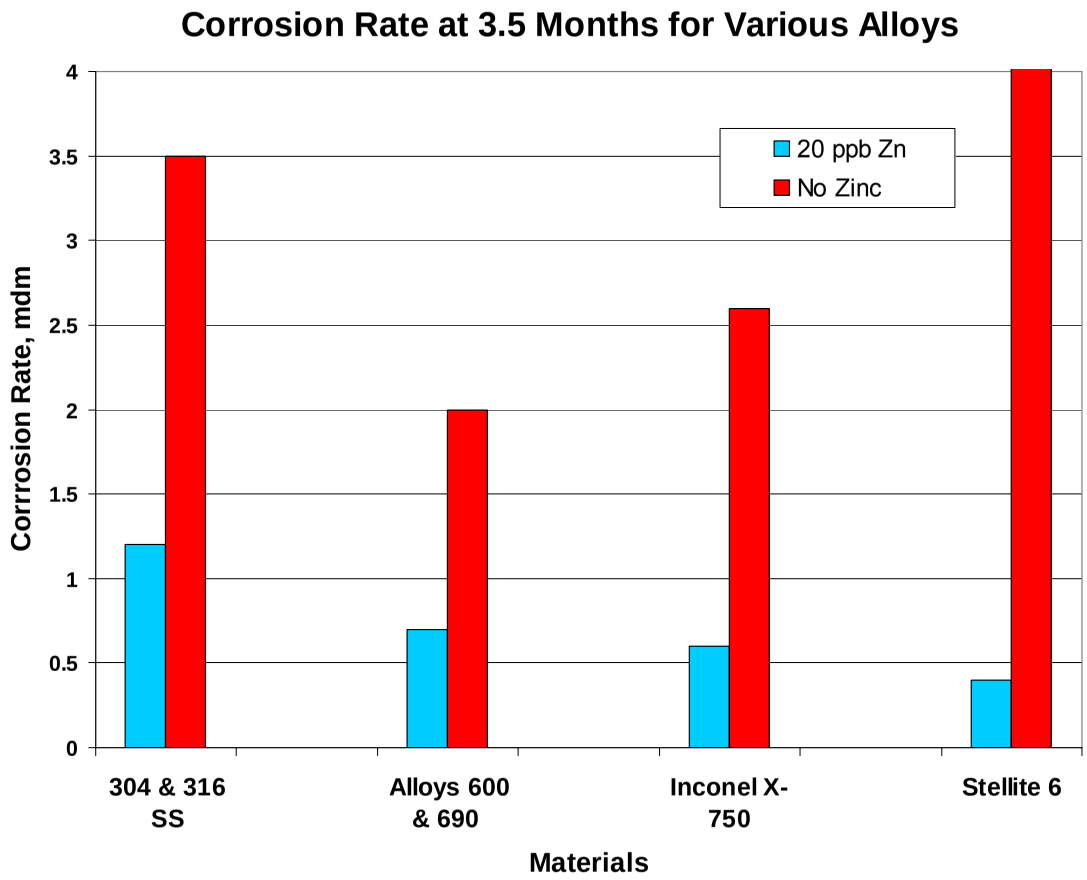
Effect of Zinc on Corrosion Rates



(from Esposito, et. al., Proceedings of the fifth Symposium on Environmental Degradation of Materials in Nuclear Power Systems – Water Reactors, August 1991)

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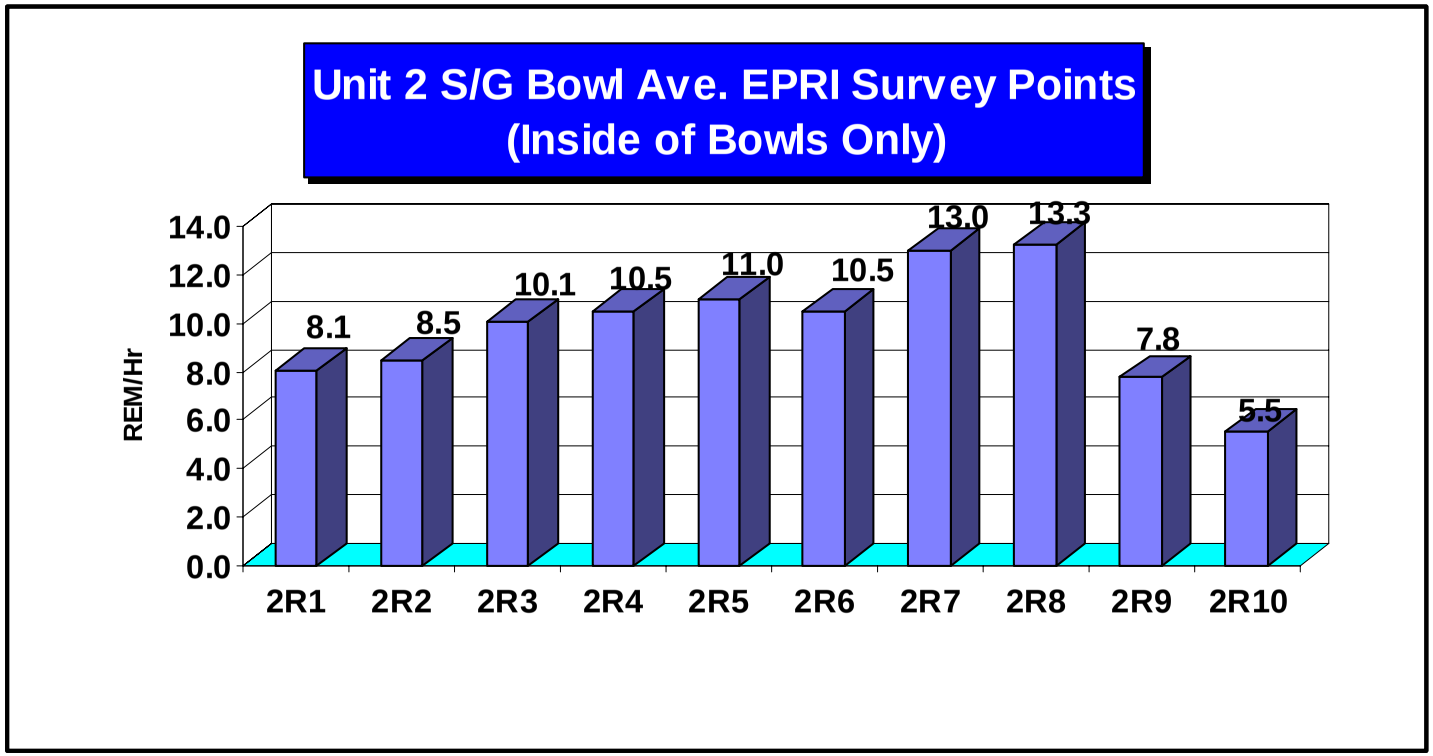
Post Zinc Dose Rate Trends: Diablo Canyon 2

(first additions during cycle 9; range 15 to 30 ppb)



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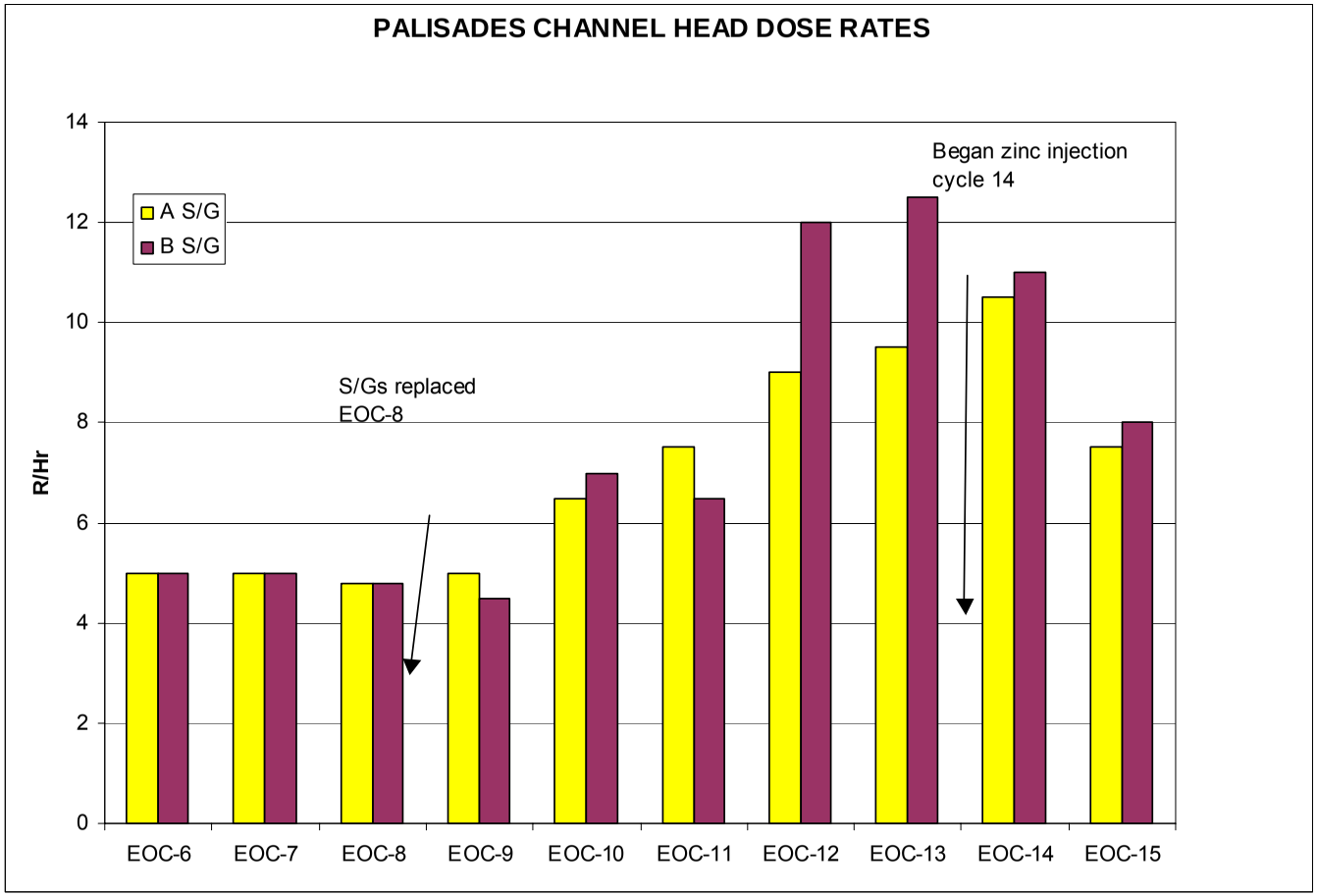
Post Zinc Dose Rate Trends: Palisades
(levels up to 10 ppb)



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PWR Primary Water Stress Corrosion Cracking of Nickel-based Alloys (600/182/82)

- Main factors affecting PWSCC are materials, material condition, stress and temperature
- Water chemistry in the normal operating range has a relatively small effect:
  - Lithium, boron, pH (minimal effect on initiation or growth)
  - Dissolved hydrogen (minor effect over current field levels but important influence on CGR shown in laboratory studies)
- Zinc injection has potentially significant mitigation benefit
- Laboratory data will be considered for time to initiate cracks and for growth rate of pre-existing cracks
- EPRI Materials Reliability Program (MRP) is starting additional CGR measurements in the near future to examine all of the above chemistry issues using advanced testing techniques

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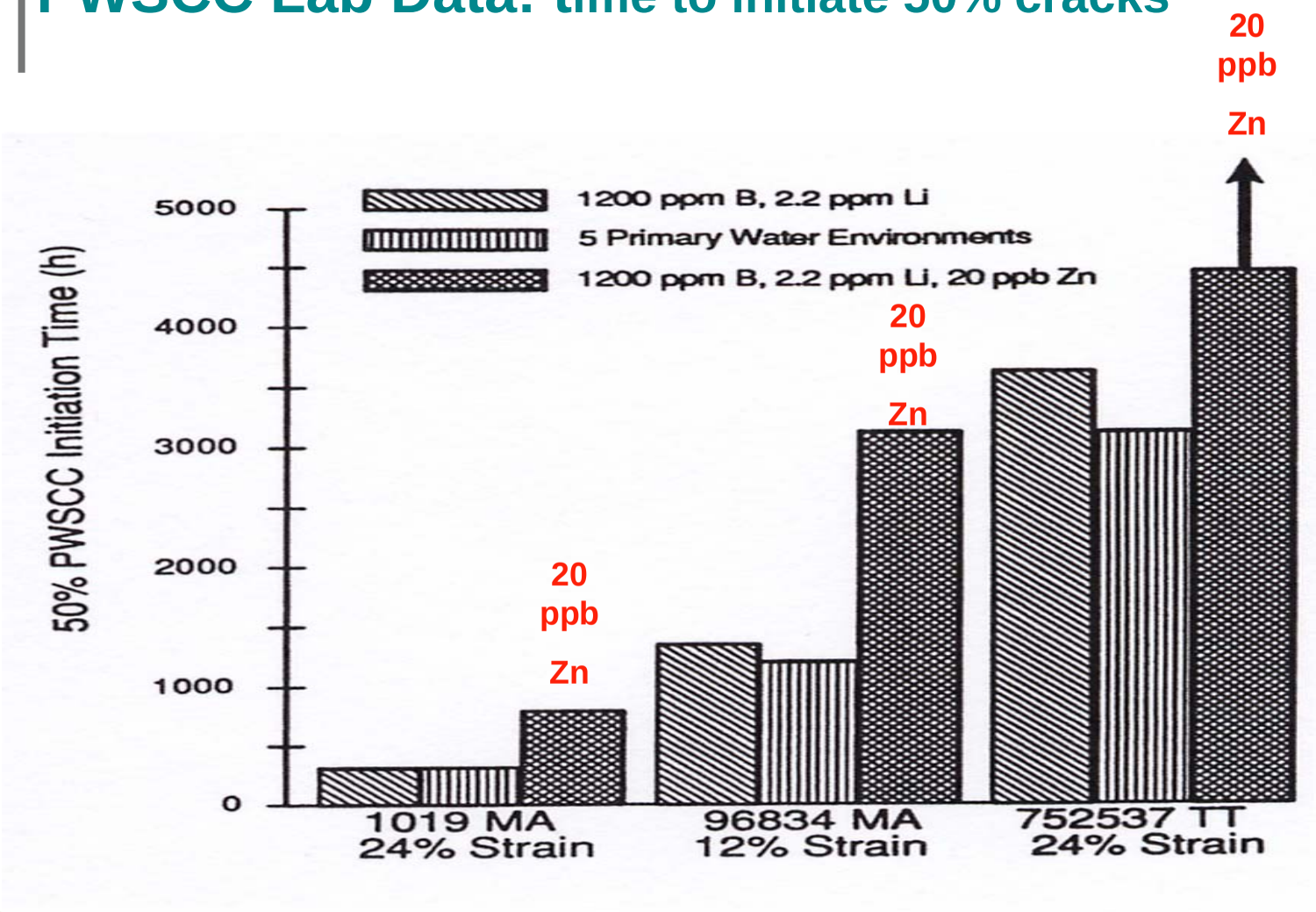
PWSCC Lab Data: time to initiate 50% cracks



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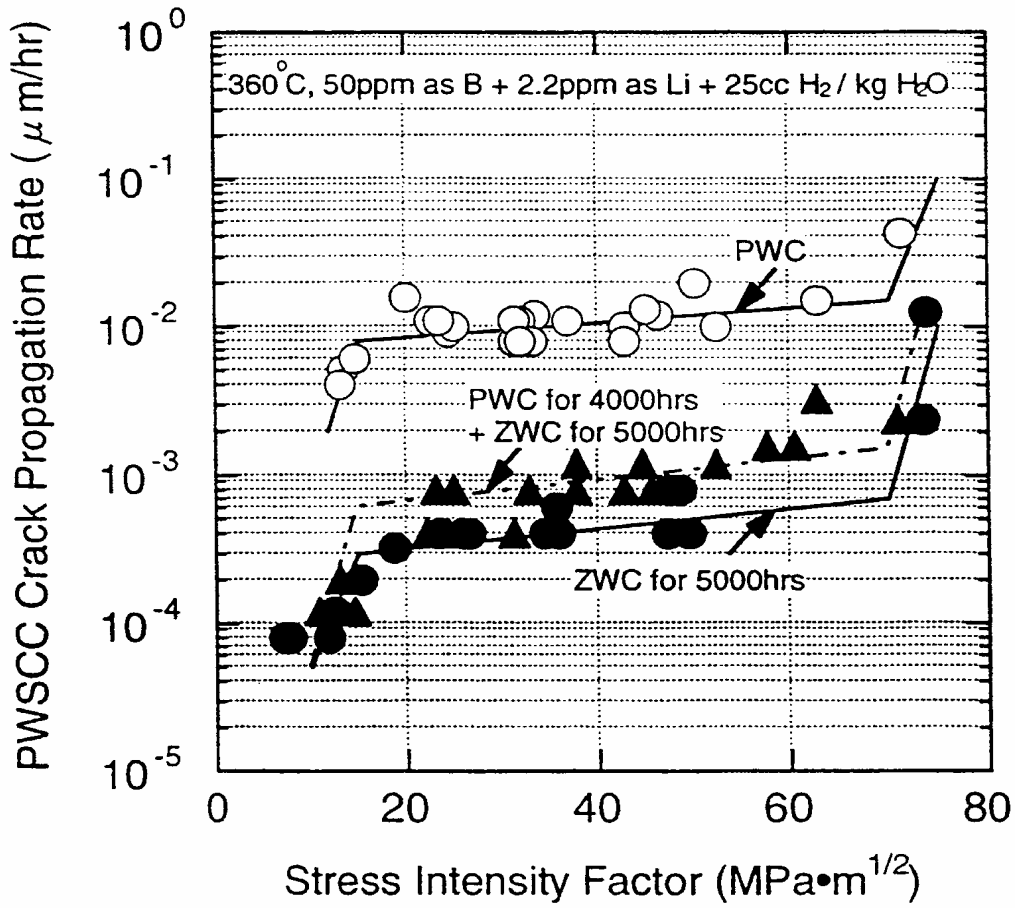
PWSCC Lab Data on CGR with and without Zn addition (10 ppb) to primary water



Kawamura et al. (1998) using DCB specimens from plate material

SSRT also showed a beneficial effect of Zn additions (factor of ~ 2x on PWSCC depth)

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Other PWSCC Lab Data on CGR in fracture mechanics specimens is less conclusive

- In a test at 330C, Gold et al. (1994) found that 20 ppb Zn lowered the CGR of a pre-cracked SG tube specimen under dead-weight loading at high K by a factor of ~ 3x
- In further tests on CRDM material at lower K values, no crack growth was found when Zn (50-250 ppb) was present
- Airey et al. (1996) found no apparent effect of 40 ppb Zn in extended tests at high K levels using WOL & CT specimens
- Further tests in the same program, reported in 1999, gave the same result at lower K levels
- Tests by Morton et al. (1997) also failed to show a beneficial effect of Zn, even when added at high levels (~ 100 ppb)

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Possible explanation for apparent lack of beneficial effect from Zn in CGR testing

- Morton et al. found Zn had been absorbed into the chromite spinel films on the free surfaces but was NOT present at the crack tip, where they reported mainly cubic NiO present
- In contrast, Kawamura et al. report finding the spinel at the crack tips in their work, which would be consistent with the beneficial effect observed
- Recent high-resolution ATEM studies indicate that crack tip oxides in Ni-based alloys are complex and may vary both according to the environment and the crack growth rate
- Possible that effective introduction of Zn into the crack tip films requires more time than is often allowed in testing
- Would be consistent with the work of Andresen on factors affecting Zn incorporation in Alloy 600 cracks in BWR water

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US field data with regard to Zn and PWSCC

- Diablo Canyon Units 1 & 2 provide the best opportunity to assess the effect of Zn additions on PWSCC (of SG tubing)
- Plugging/repair actions at the TTS locations have become manageable over recent cycles and do not appear to represent a threat to SG reliability
- Trends at the tube/TSP locations are also encouraging, particularly the decrease in the # of new indications
- It is tempting to interpret this as a Zn effect!
- May be correct, but the data are ambiguous because of of a number of factors, such as changes in inspection practice and equipment, limited and intermittent periods of zinc injections, modified plugging criteria, etc.

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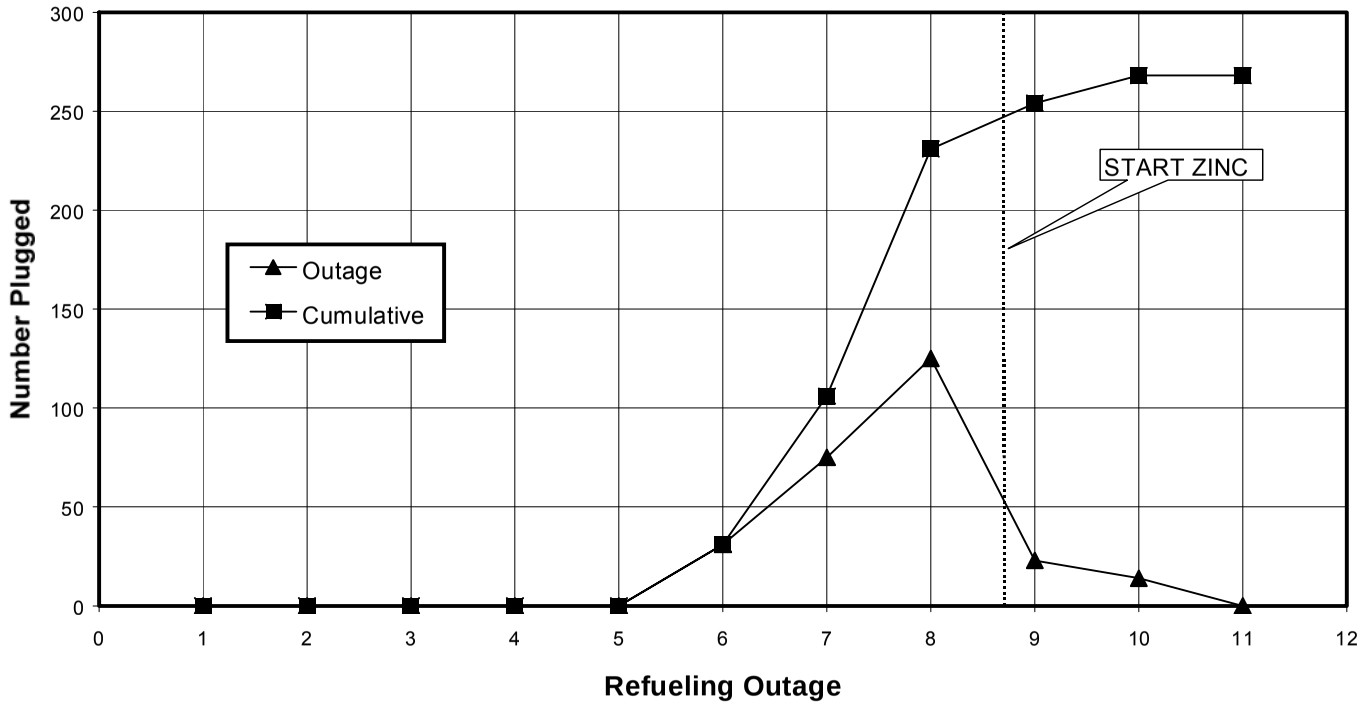
Example for Diablo Canyon Unit 1: SG tube plugging for PWSCC at TSP locations



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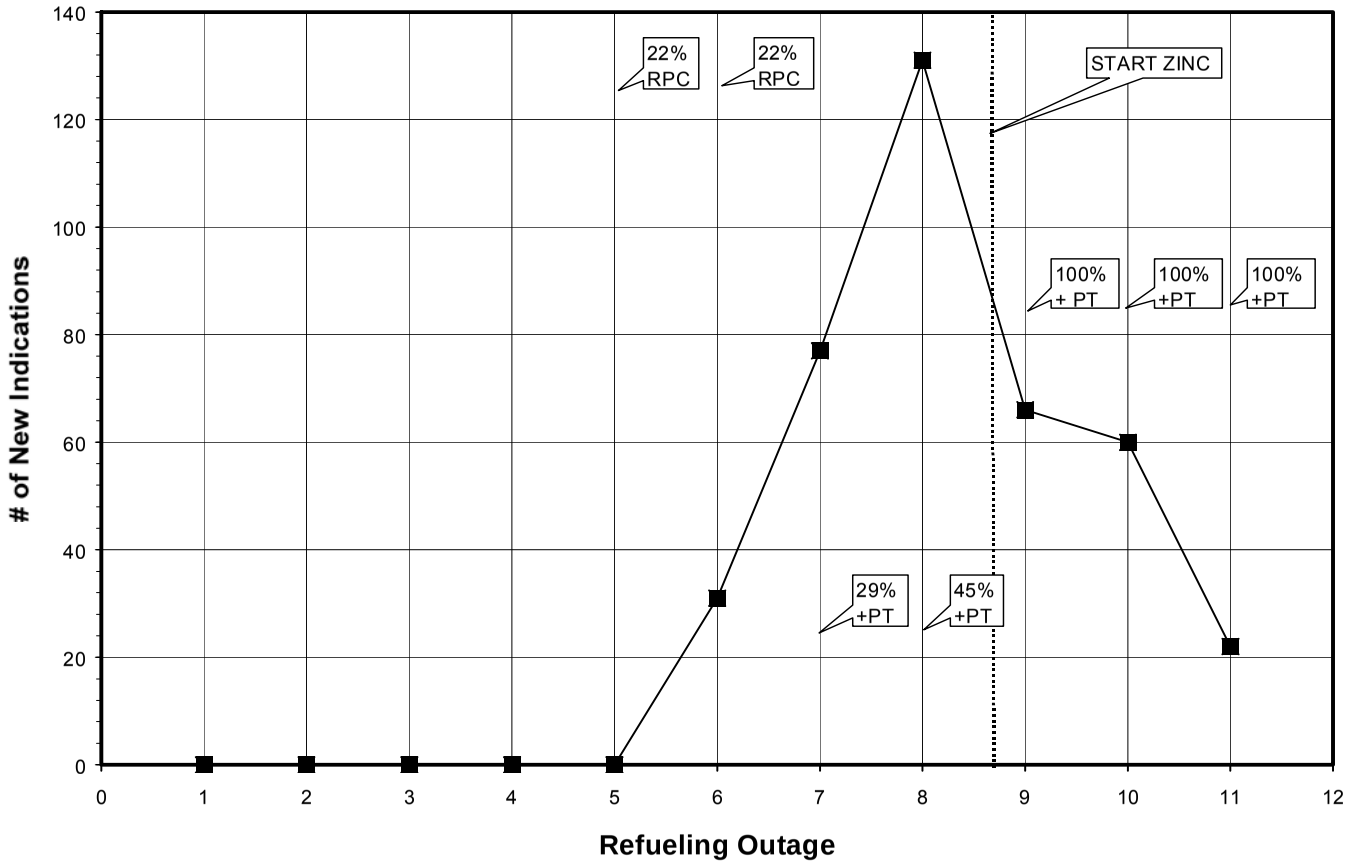
Example for Diablo Canyon Unit 1: new indications of PWSCC at TSP locations



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Zinc Effects on PWSCC: Summary

- Strong laboratory evidence exists to support the position that zinc inhibits the ***initiation*** of PWSCC in Alloy 600
- Less conclusive laboratory evidence suggests zinc may be effective in inhibiting the ***propagation*** of PWSCC
- Zinc incorporated in corrosion films on Alloy 600 tubing
  - Too early to assess effect on PWSCC in plants because of complications involving NDE data
- More field eddy current inspection data needed to confirm Zn injection mitigates PWSCC crack initiation and/or growth
- Continuous injection of 20-35 ppb of zinc acetate is currently the most promising chemistry mitigation technique

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Zinc – Fuels Issues

- Increase in Zircaloy fuel cladding oxidation measured at Farley 2 after cycle 10
  - Detailed root cause analysis showed higher oxidation caused by higher thermal duty and measurement bias
- Subsequent oxide measurements at Farley 2 showed lower values on once- and twice-burned fuel
  - Confirms no effect of zinc
- Recent scrapes at Palisades showed no evidence of zinc silicates, following operation with Zn ~ 9 ppb & silicates up to 2.5 ppm

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Overall conclusions on adding Zinc in PWRs

- Farley, Diablo Canyon and Palisades show significant reductions in PWR shutdown radiation fields with Zn additions
- No adverse effects of Zn additions observed on Zircaloy or ZIRLO fuel cladding corrosion
- Need to resolve potential issues associated with Zn injection on fuel performance in high duty plants
- Latest Chemistry Guidelines (June 2003) recommend PWRs should consider implementing 5-10ppb Zinc
  - reduce radiation buildup
  - prepare plant to gain benefits of zinc to mitigate PWSCC, if this is confirmed to be effective
- New MRP crack growth measurement program to start soon

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CONFERENCE ON VESSEL HEAD PENETRATION INSPECTION, CRACKING AND REPAIRS
Gaithersburg, MD – Sept. 29-Oct. 2, 2003

An Assessment of MSIP for PWSCC Mitigation of PWR Thick Wall Piping Welds by Instrumented Monitoring of Full-Scale Mock-up Test

GUTTI RAO[1], MANU BADLANI[2], EDWARD RAY[1], and THOMAS DAMICO[2]

[1]Westinghouse Electric Company, LLC
[2]AEA Technology

BNFL

Westinghouse

OBJECTIVES

- To validate analysis and confirm applicability of MSIP for thick wall PWR piping
  - Verify that the desired MSIP load locations and range of radial contractions achieve permanent compressive residual stresses at the nozzle ID surface at the nozzle-to-safe-end weld
- To verify post-MSIP OD surface profile satisfies inspection acceptability

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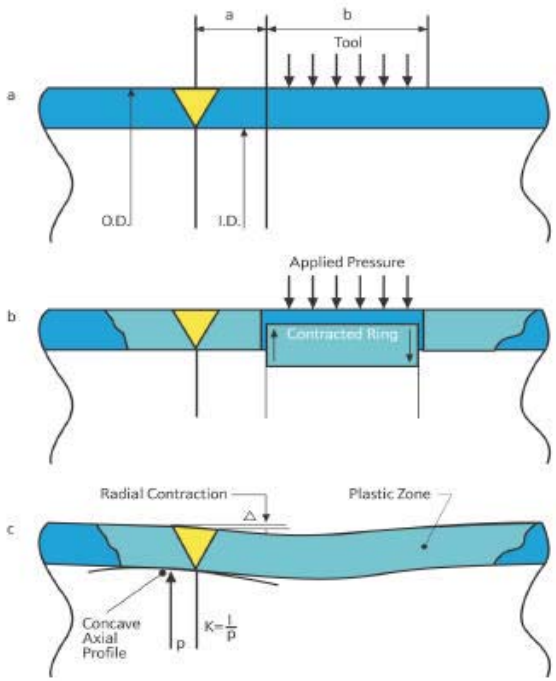
QUALIFICATION PROCEDURES

- Detailed qualification procedures were developed for:
  - The MSIP tooling, calibration, testing, data recording and documentation
  - Strain gauge instrumented monitoring of the MSIP testing, including strain gauge positioning and mounting procedures, strain gauge calibration and data recording, and documentation

1102

MSIP TECHNOLOGY

- **Patented (AEA) process that prevents/mitigates SCC in piping and nozzle weld joints**
- **MSIP**
  - Mechanically contracts the pipe on one side of weldment
  - Replaces residual tensile stresses with compressive stresses
- **Verified by Argonne National Laboratory & EPRI**
- **Accepted by the NRC (NUREG 0313, Rev. 2)**



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MSIP VERIFICATION TESTS

- The MSIP loading (pipe squeezing) of the mockup nozzle weld region was accomplished by the application of hydraulic pressure through the MSIP tool clamp rings, mounted on the OD surface at predetermined positions
- A planned sequence of two pipe squeezes were applied to obtain the desired data and accomplish the desired radial displacements and the ID surface strains
  - The maximum pressure generated by the MSIP tool was increased to obtain minimum specified contraction and generate acceptable residual stress redistribution in the nozzle-to-safe-end weld region upon unloading
  - Additional loading of the tool was applied to reach the maximum specified contraction and achieve the desired condition in the weld region following removal of the tool
- Post-MSIP OD profile was measured

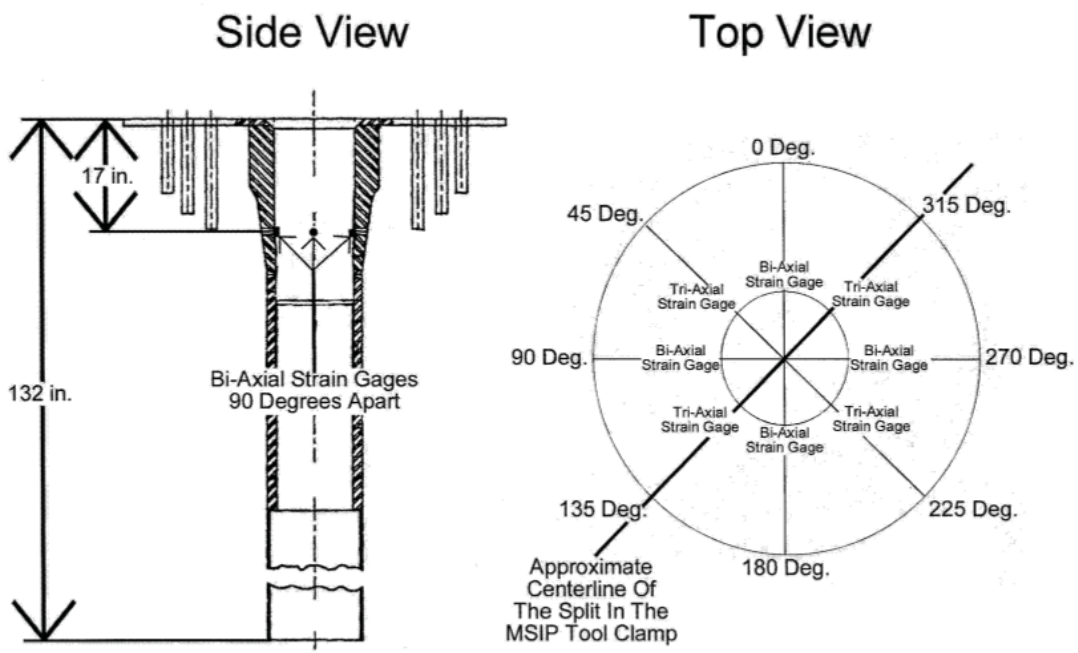
PRESURIZER SURGE NOZZLE MOCK-UP FOR TIHANGE 2

Pressurizer Surge Nozzle Mock-up for Tihange 2

STRAIN GAUGING

- ID strains at the weld were monitored by employing:
  - Single electrical resistance strain gauges applied at each of the eight measurement locations situated 45 degrees apart on the ID surface at the weld
  - Bi-axial strain gauges were applied at the 0, 90, 180 and 270 degree positions with the grids aligned in the hoop and axial directions. Strain gauge rosettes were applied to the 45, 135, 225 and 315 degree positions.

SCHEMATIC ILLUSTRATION OF POSITIONS OF BI-AXIAL AND TRI-AXIAL STRAIN GAUGES NEAR WELD REGION AT THE ID SURFACE



Schematic Illustration of the Positions of Bi-axial and Tri-axial (Rosette) Strain Gauges Near the Weld Region at the ID Surface

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ILLUSTRATION OF INSTALLED STRAIN GAUGES AND STRAIN MEASURING INSTRUMENTATION AT GIRARD SITE PRIOR TO MSIP LOAD TEST

Illustration of the Installed Strain Gauges and the Strain Measuring Instrumentation at the Girard Site, Prior to MSIP Load Test

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ILLUSTRATION OF INSTRUMENTED STRAIN GAUGES INSTALLED ON ID SURFACE NEAR WELD LOCATION OF MOCK-UP PRESSURIZER NOZZLE

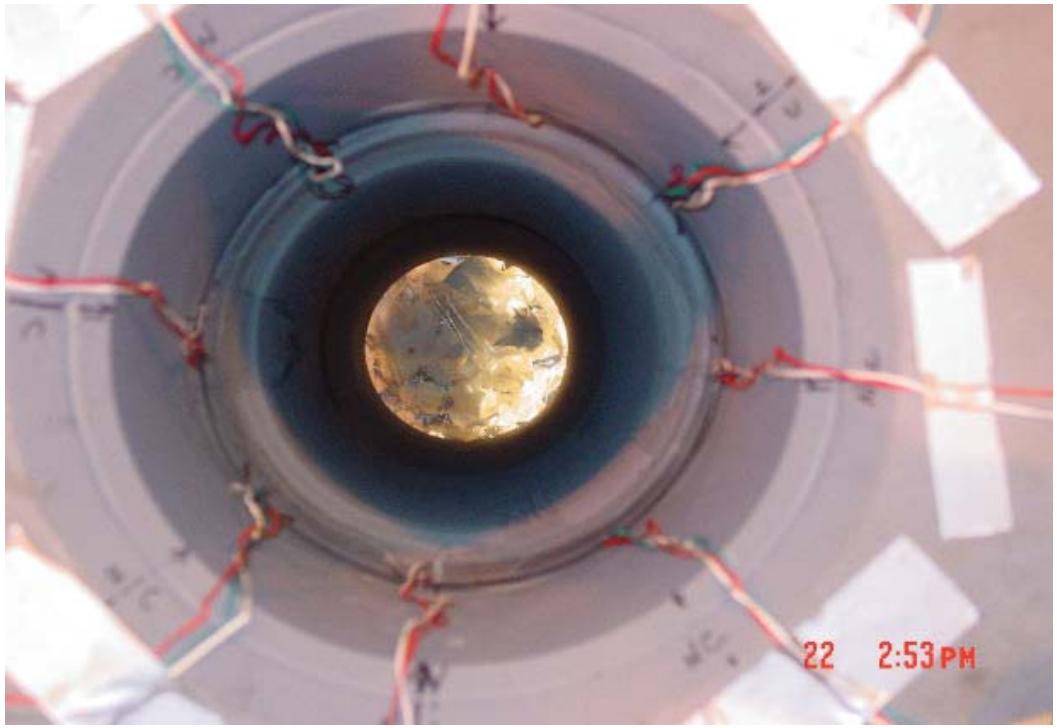

Illustration of the Instrumented Strain Gauges Installed on the ID Surface Near the Weld Location of the Mockup Pressurizer Nozzle

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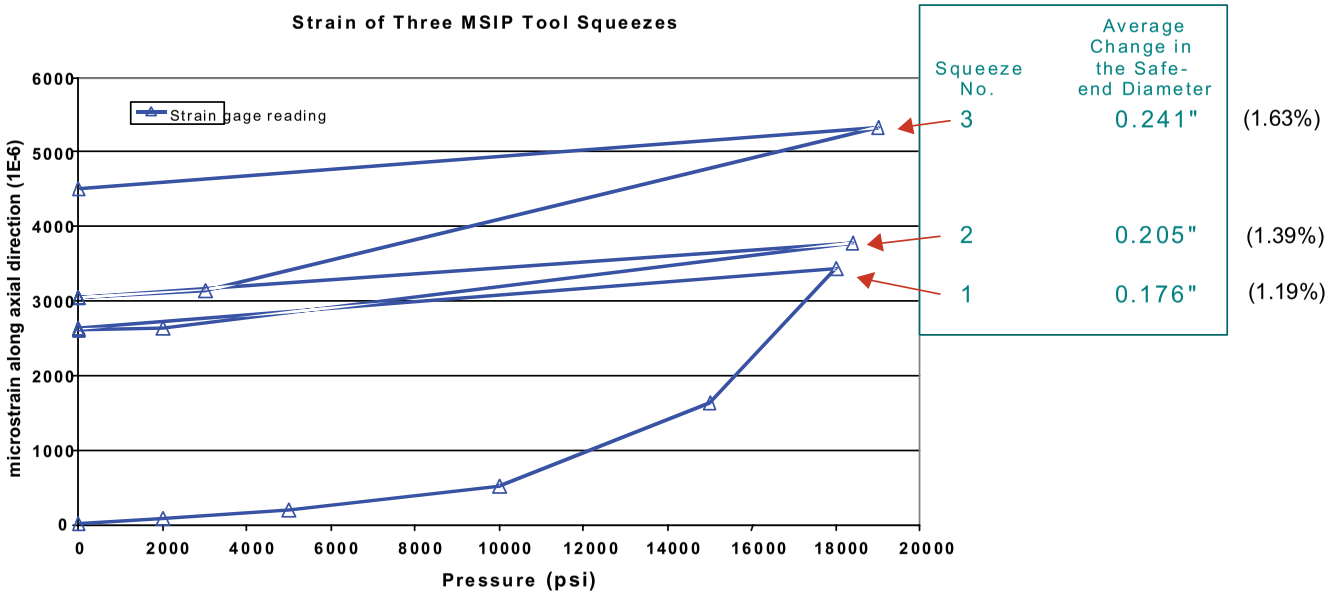
STRAIN GAUGE RESULTS

- MSIP generated desired compressive strains in inner weld region
- Hoop strains were fairly axisymmetrical
- Axial strains were fairly axisymmetric except for the 135 and 270 degree positions which showed significantly higher magnitudes of compressive strain
- Compression maintained throughout MSIP application

1110

SAFE-END DIAMETER CHANGES ASSOCIATED WITH THREE MSIP SQUEEZES

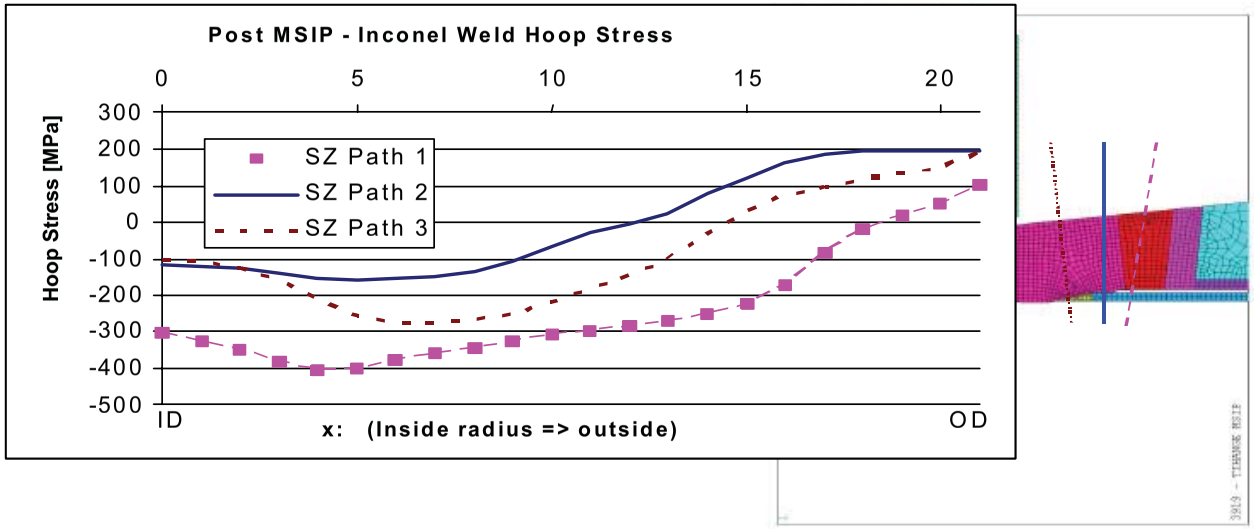


Safe-end Diameter Changes Associated with the Three MSIP Squeezes

1111

POST MSIP-THROUGH WALL HOOP STRESS

Analytical Results



Post MSIP-Through Wall Hoop Stress

1112

CONCLUSIONS

- Tihange 2 MSIP qualification program demonstrated that the MSIP process was very effective in generating compression at the weld location
- Demonstrated that the MSIP process works well in thick-walled PWR applications
- Demonstrated that the post-MSIP OD profiles are acceptable for in-service inspections
- MSIP can be an effective part of a proactive Alloy 600 mitigation program

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Section 7:
Session Summaries

United States Nuclear Regulatory Commission

CONFERENCE ON VESSEL HEAD PENETRATION INSPECTION, CRACKING, AND REPAIRS

Sponsored by
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Session I: Inspection Techniques, Results, and Future Developments

Chairpersons: S. Doctor, Pacific Northwest National Laboratory
D. Jackson, U.S. Nuclear Regulatory Commission

United States Nuclear Regulatory Commission

NDE of Austenitic Materials - A Review of Progress and Challenges

Frank V. Ammirato, EPRI NDE Center

- Based on recent events, presented industry's progress on addressing PWSCC
- Provided a status of development of mockups and performance demonstrations
- Highlighted advanced NDE technology to improve inspection reliability
  - UT Phased Array
  - ET Arrays

United States Nuclear Regulatory Commission

Inspection Reliability of Reactor Vessel Head Penetrations

Steven R. Doctor, PNNL

- PWSCC failure in Inconel Alloy 600\182\82 is a generic problem
- NDE programs should have goal of preventing leaks, not finding leakage
- There are a number of studies, nationally and internationally, that are addressing issues of NDE reliability
  - NRC
  - EPRI/MRP
  - JRC/Petten
  - Finland

United States Nuclear Regulatory Commission

The Evolution of Inspection and Repair Approaches for Reactor Vessel Head Penetrations

Dan M. Schlader, Framatome ANP, Inc.

- Presented overview of evolving and advanced technology to facilitate improved and faster NDE inspections, identifying VT robotic system and scanners
- Discussed remote repair methods

United States Nuclear Regulatory Commission

Inspection Techniques, Results and Future Developments, Summary of U.S. PWR Reactor Vessel Head Nozzle Inspection Results

Glenn White, Dominion Engineering, Inc.

- Presented a summary of a large amount of inspection data
- Discussed findings from a statistical analysis of the inspection data
- Identified significant factors
  - Time at temperature
  - Head fabricator
  - Nozzle material supplier

Inspection Technology for In-Core Penetrations
Michael Lashley, STP Nuclear Operating Company

- Provided an overview of the many NDE technologies that were rapidly deployed to assess the integrity of the BMI issue
- Discussed the benefit of each NDE technology for the BMI inspections

United States Nuclear Regulatory Commission

EPRI MRP Alloy 600 RPV Head Penetration Inspection Demonstration Program

C. Thomas Alley, Duke Energy Cooperation

- Reviewed industry's program (MRP) that was developed to build test specimens and to demonstrate inspection technology as new failure sites were found
  - Flaws in tubes
  - Flaws in J-groove weld
  - BMI nozzle

Production of Realistic Flaw in Alloy 600 Qualification Purposes

Mika O. Kenppainen, Trueflaw Ltd.

- Presented advanced flaw production method of representative service induced cracks
- The method is a thermal fatigue cracking process
- Provided research results of the cracking method and the applicability to alloy 600
- Flaws can be introduced into full-scale components

United States Nuclear Regulatory Commission

Generic Guidance for an Effective Boric Acid Inspection Program for Pressurized Water Reactors

T. R. Satyan Sharma, American Electric Power Co.

- Provided information on how industry's boric acid corrosion control programs can be updated to take advantage of industry experience to better manage this degradation process
- This guidance does not apply to the reactor vessel heads which is covered under MRP-75

United States Nuclear Regulatory Commission

Risk-Informed Evaluation of PWR Reactor Vessel Head Penetration Inspection Intervals

Glenn White, Dominion Engineering, Inc.

- Used risk-informed evaluation to determine ISI re-inspection frequency of the vessel head penetrations
- Re-inspection every second or third operating cycle
- Issue raised during question session regarding whether risk measures should be CDF or avoiding leakage

United States Nuclear Regulatory Commission

Reactor Vessel Head Penetration Inspection Technology, Past, Present and Future

John P. Lareau, Westinghouse Electric Co. LLC

- Describes the evolution of NDE technology for the inspection of vessel head penetration to speed up these inspections and make them more reliable
  - UT
  - ET
  - J-groove weld scanner

Summary

- PWSCC and Inconel is a complex problem
- Generic to the entire industry
- Rapid evolution of NDE technology and systems
- Reactionary response to events as opposed to a proactive comprehensive program
- Progress is being made but additional work is still required to address the issue of NDE reliability for VHP

CONFERENCE ON
VESSEL HEAD PENETRATION INSPECTION, CRACKING, AND REPAIRS

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Session II: Continued Plant Operation

Chairpersons: **A. Hiser, Jr., U.S. Nuclear Regulatory Commission**
W. Bamford, Westinghouse Electric Company, LLC

Continued Plant Operation

- These were the best presentations of the meeting!
- Analytical and Repair Approaches to allow continued operation
- Also actual application at South Texas

Evaluation Methods

- Now developed for upper head penetrations
- To appear in 2004 edition of Sect. XI, and also a code case
- NRC has endorsed this methodology in a letter of April 2003

French Maintenance Strategy

- Excellent Summary
- French programs are strongly proactive

Strategic Planning for Operation after Repair or Mitigation

- A methodology was developed to compare various options for VHP
- Comparison included repair costs, down time, and is based on net present value
- Optimum Solution was head temperature reduction
- The next best solution was NDE every other outage, with BMV every outage

South Texas BMI Issue

- Excellent summary of the incident, and utility response to it
- STP had help and advice from a number of other utilities
- Repair is now complete, and the plant is back at power
- The evaluation of the boat sample showed that the cracking started in the Weld (in the considered opinion of the author)
  - large lack of fusion area
  - ductile failure of a small ligament to the surface
  - water invasion of the lack of fusion
  - cracking of the BMI tube from the OD

Embedded Flaw Repair - VHP

- Originally developed in 1993
- First implemental at DC Cook 2 in 1996, and ID
- Good service experience after 6-7 years
- Technique now adapted for OD and J-groove welds
- NRC endorsed with SER in 2003

Weld Overlay on Pipe Welds

- Looked at thickness and lengths needed to establish compressive Stresses
- Similar idea to the BWR Weld overlay technique
- PWR pipes are much thicker

United States Nuclear Regulatory Commission

CONFERENCE ON VESSEL HEAD PENETRATION INSPECTION, CRACKING, AND REPAIRS

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Session III: Structural Analysis and Fracture Mechanics Issues

Chairman: G. Wilkowski, Engineering Mechanics Corporation of Columbus

No Information Available

Session Summary

IV: Crack Growth Rate Studies for the Disposition of Flaws

- total 12 presentations-

Tetsuo Shoji

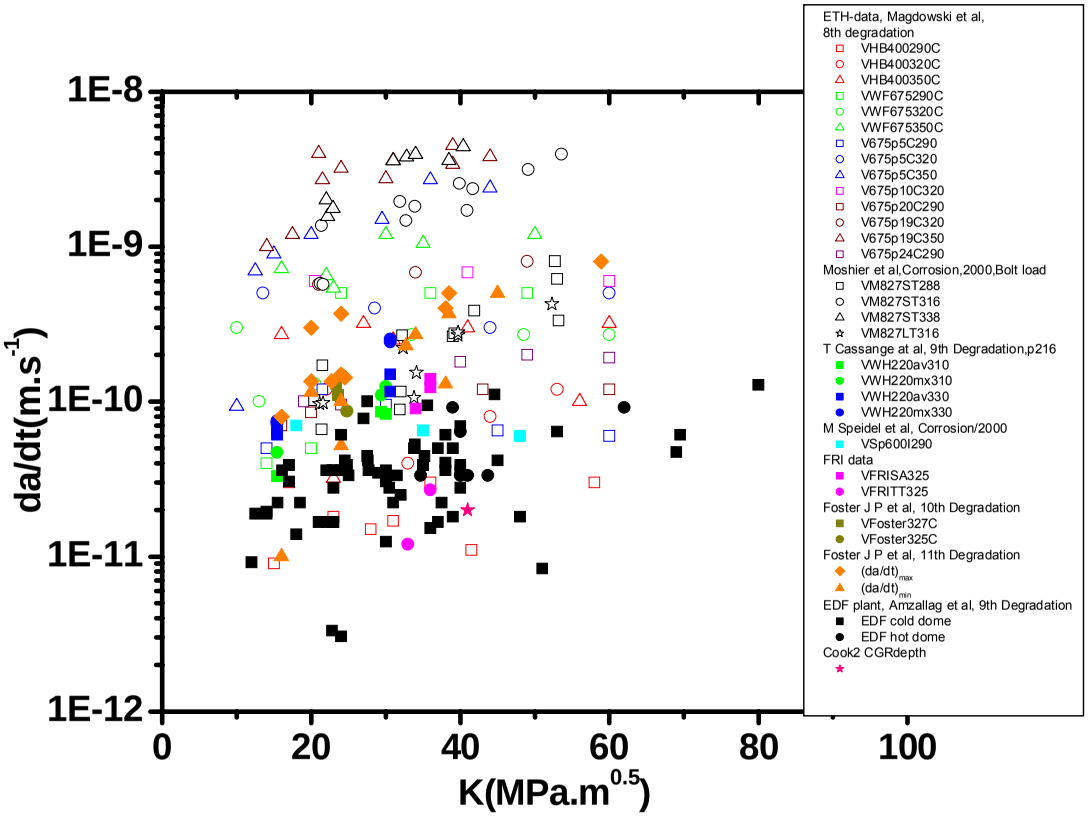
Regulatory Experience and Prognosis on Nickel-Base Alloy PWSCC in VHP and RPV Head Degradation

- Allan Hiser, Jr(NRC) gave a historical review of the axial and circumferential cracking in the US plants and NRC Bulletins and Orders.
  - Order EA-03-009-February 2003
    - Mandates inspection for all PWRs
    - Possible modifications based upon a technical basis
  - Other Consideration
    - Avoid significant events
    - Leakage from thermocouple nozzle(Alloy 690 plug and 152 weld)
  - Bulletin 2003-02:Information Request(LHP)

- Guy Turluer(IRSN/DES) presented French approach for PWSCC prevention and treatment.
  - Recognition of Generic effects - Inconel Zone Review
  - Specific features
    - French Nuclear Organizations & Practices
    - Effectiveness of Decennial Complete Visits(DCV)
  - Specific features of Nickel base Alloys PWSCC
    - Crack initiation can be stochastic processes
    - Uncertainties in stress assessment, residual stress, transients and cycling etc.
  - Proactive program to preclude any leak in the main primary circuit-no other CRDM leak after Bugey 3.
    - Regulatory hydro-test at 1.2 times the design pressure
    - Extensive ISI
    - Conservative Screening Criteria

Literature Survey

Existing CGR Data-Laboratories & Plants



CGRs of Alloy 600 in PWR environments

- Lab. data:

-thick plate material

-fracture mechanics specimen

- Plant data: EDF & Cook 2

>Huge scatter of the data in da/dt vs K

SCCGRs -New testing methodology

- Steven Attanasio (Lockheed Martin Co.)
  - Compliant Self-Loaded CT specimens
    - Qualified with data
- Tetsuo Shoji(Tohoku University)
  - Accelerated tests suggested from the mechanism with an clearly defined acceleration factor
    - Increase σy or hardness, or decrease in **n,** strain hardening coefficient
    - Higher dK/dt condition-specimen design or Rising Load SCC tests
    - Smaller m, slow passivation or oxide growth rate (Increase in crack tip oxidation rate constant, κa

SCCGRs –Evaluation Procudures

- Steven Attanasio (Lockheed Martin Co.)
  - Maximum or Average SCCGR?
    - Correlation between Max./Ave. ratio(R)
    - SCCGR data can be reasonably reported as SCCGRave + R
- Toshio Yonezawa(MHI)
  - Examination of periodic unloading for crack tip activation
    - Effective to start crack grow but not so for straight crack front

SCCGRs
-alloys182,152,132,82,52 comparison-

- Steven Attanasio (Lockheed Martin Co.)
  - Alloy 182 SCCGRs >Alloy 82 SCCGRs
- Toshio Yonezawa(MHI)
  - Alloy 132 SCCGRs ~ Alloy 182 SDCCGRs
  - SCCGRs in TS and LS specimens X3~10 > LT
- George Young(Lockheed Martin Co.)
  - In Alloy 600, SCCGRs in HAZ X30 >> Base plate
    - Due to loss of grain boundary Cr carbides
    - Residual local plastic strain from welding
    - DH effects is ~2.8X > base plate

SCCGRs
-alloys182,152,132,82,52 comparison-

- Richard Jacko(WH)
  - Alloy 52M showed no crack initiation even under an aggressive and accelerated cocndition
  - Crack initiation occurred
    - Alloy 182 equivalent to 5-10 EFPY
    - Alloy 600 equivalent to 6-13 EFPY
  - The V.C. Summer Alloy 82 and 182 showed a similar SCCGRs to the general industry database.

SCCGRs
-alloys182,152,132,82,52 comparison-

- Gutti Rao(WH)
  - CRDM Penetration crack at Alloy 182/82 J-Weld at Ringhals 2 and North Anna 2 originated from the original fabrication of the J-Weld buttering and lack of fusion at the Low Alloy Steel Interface is a main contribution to cracking.
  - There was a Wastage Pocket in the Low Alloy Steel at the interface

SCCGRs –DH effects

- Steven Attanasio (Lockheed Martin Co.)
  - Max. SCCGR at Ni/NiO by CER
    - X750 HTH, Alloy 600
- George Young(Lockheed Martin Co.)
  - In Alloy 600, SCCGRs in HAZ X30 >> Base plate
    - DH effects is ~2.8X > base plate
- Il Soon Hwang(Seoul National University)
  - In-situ Raman Spectroscopy system developed and successfully applied to oxide analysis in PWR
  - Ni/NiO equilibrium agreed with CER data by Attanasio et al.

SCCGRs –Temperature effects

- Yoshito Nishikawa (INSS)
  - Alloy 132(SMAW) and 82(TIG)
  - Alloy 600/132 HAZ and Alloy 600/82 HAZ
  - Accelerated SSRT
  - Activation Energy
    - 179-188 kJ/mol for weld metals
    - 148-156 kJ/mol for HAZs
- George Young(Lockheed Martin Co.)
  - In Alloy 600, SCCGRs in HAZ X30 >> Base metal
  - Activation energy for Alloy 600 HAZ ~ Base metal
    - 125 kJ/mol +_47kJ/mol for HAZ & 145+_18kJ/mol for BM

SCCGRs –Models

- Steven Attanasio (Lockheed Martin Co.)
  - Three empirical models seem reasonable(R^2=0.55).
    - MRP without threshold, K dependence not fixed
    - MRP with threshold, K dependence not fixed
    - MRP with threshold, K dependence
- Tetsuo Shoji(Tohoku University)
  - Proposal of theoretical formulation based upon crack tip mechanics and oxidation kineics
    - Significance of σy and dK/dt and other parameters
    - K dependence depends upon σy and m,oxidation kinetics parameter

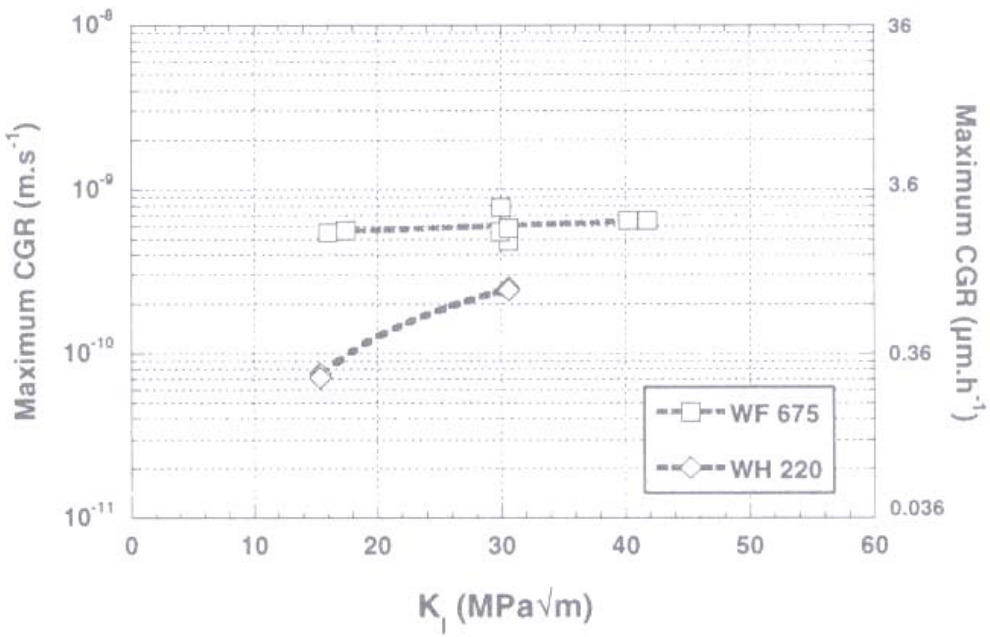
SCCGRs –Models

- Michael Hall, Jr (Bettis APL)
  - Hydrogen Assisted Fracture Model
  - Describe a sensitivities of Alloy 600 to K, T, C% and σy
  - Suggesting a comprehensive dfata sets obtained on single heats of Alloy 600 required
  - Important dependence of CGR on crack growth orientation

SCCGRs –Models

- Martin Pattison(MetaHeuristics LLC)
  - Data analysis by an Artificial Neural Network
  - Relative Effect of Variables
    - Temperature(factor of 3)
    - Lithium concentration(factor of 10)
    - Applied stress intensity factor, K(factor 10~300)
    - Yield strength(factor 30)
    - CGR was much more sensitive to K for the specimens with a low yield strength(Agree with FRI model)

Different K dependence



T. Cassagne, et al
9th Degradation,
PWR, 330^{0}C

Two types of CGR-K curves

- WF 675, CGR plateau, YS(WF675)= 468MPa
- WH 220, moderate increase of CGR with K, YS(WH220)= 394MPa

SCCGRs –Lifetime Prediction

- Tetsuo Shoji(Tohoku University)
  - Possible crack growth retardation under the condition of negative dK/dt, which might be relevant in crack growth under compressive residual stress field
- George Young(Lockheed Martin Co.)
  - Need to consider PWSCC of the HAZ separately from the base metal and weld metal
  - Other Nickel-base alloys which rely on grain boundary Cr-rich precipitates for PWSCC resistance(e.g.A690) may show increased susceptibility to PWSCC in the HAZ

SCCGRs –Lifetime Prediction

- Il Soon Hwang(Seoul National University)
  - Fluctuation of DH in PWR may weaken oxide integrity and accelerate PWSCC
  - Stabilize and/or lower DH may provide a mitigation in PWSCC

Summary

- **Hardening is harmful not only initiation but also in propagation**
  - Surface finish, fabrication strain, weld strain, weld shrinkage strain etc.
  - No data on resistant materials such as Alloy690, 52 etc
- **Resistant microstructure might be altered in HAZ and may show a susceptibility**

- **Need qualified acceleration tests with a quantitative acceleration factor**
  - Data on resistant materials
  - Easy to back calculate the SCCGRs for realistic condition and plant application
  - Need qualification by Regulatory Authorities
- **Physical or Mechano-chemical models provide a tool for sorting out complex crack growth characteristics and provide a basis for development of higher confidence Disposition Curves of Flaws.**

United States Nuclear Regulatory Commission

CONFERENCE ON VESSEL HEAD PENETRATION INSPECTION, CRACKING, AND REPAIRS

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Session V: Mitigation of Nickel-base Alloy Degradation and Foreign Experience

Chairmen: S. Fyfitch, Framatome ANP, USA
P. Scott, Framatome ANP, France

Foreign Experience

- Belgian Activities on Alloys 600 and 182 Issues
  R. Gérard and Ph. Daoust, Tractebel Engineering, Brussels, Belgium
- German Experience with Vessel Head Penetrations
  K. Degmayr, Framatome ANP, Erlangen, Germany
- Activities on Alloy 600 Cracking of PWRs in Japan
  M. Toyoda, S. Asada, and N. Hori, Kobe Shipyard and Machinery Works, Mitsubishi Heavy Industries, Ltd, Japan
- RPV Heads: Inspection vs. Exchange Strategies for Ringhals PWR Units 3 and 4
  P. Efsing, Ringhals AB, Sweden

Session V:
Foreign Experience Summary

- Proactive approach being taken at Belgium reactors to inspect all Alloy 600/182/82 locations and repair, mitigate, or replace components as needed before leakage occurs
- German RPV heads
  - Obrigheim only RPV head with Alloy 600 nozzles; stress relieved with RPV head; expected to have low susceptibility
  - All other RPV heads contain different design with carbon steel nozzles clad with Nb-stabilized SS
  - Leak detection systems in place to identify any leakage should it occur

[Note: French experience and approach summarized in Session IV]

Session V:
Foreign Experience Summary

- **Japanese RPV Alloy 600 activities:**
  - RPV head nozzles: inspections performed on 17 plants; T_{cold} conversion performed on newer plants; older plants replaced RPV head
  - BMI nozzles: inspections performed on 6 plants; minor indication found at Takahama #1 (to be inspected again); WJP performed on 5 plants
  - Hot leg nozzle welds: inspections performed on 5 plants; use of WJP or Alloy 690 cladding (under development)
- **Ringhals RPV Head Activities:**
  - Inspections performed; some indications identified; defect tolerance evaluated; conclusion: replace RPV heads

Session V: Mitigation of Nickel-base Alloy Degradation Summary

- Alloy 600 PWSCC Mitigation: Past, Present, and Future
  S. Fyfitch, Framatome ANP, Inc., Lynchburg, VA
- A Reactor Vessel UPPER Head Temperature Reduction Program to Prevent and Mitigate Alloy 600 Cracking
  D. R. Forsyth and P. L. Strauch, Westinghouse Electric Company LLC
- Status Report on the Effect of Zinc Additions on Mitigation of PWSCC in Alloy 600
  J. Hickling, R. Pathania and C. Wood, EPRI, Palo Alto, CA
- An Assessment of MSIP as a PWSCC Mitigative Technique by Instrumented Monitoring of ID Strains During the Full Scale Mock Up Demonstration Test of Pressurizer Nozzle Weld at Tihange Unit 2 Station
  G. Rao, Westinghouse Electric Company, Pittsburgh, PA

Summary Mitigation of Nickel-base Alloy Degradation

- Replacement with Alloys 690/52/152 mostly used today
- Three categories of mitigation techniques: mechanical surface enhancement (MSE), environmental barriers or coatings, and chemical or corrosion potential (ECP) control
- Very geometry dependent, many techniques not effective if cracking present, utilities need to evaluate a variety of techniques, one is rarely applicable to all locations, cost-benefit analyses need to be performed, most techniques require further developmental efforts

Summary Mitigation of Nickel-base Alloy Degradation

- Many cold head design plants in operation in W-fleet (30); upper head temperature reduction performed at three additional; two others planned
  - Benefits: reduced accumulation rate of EDY and possibly number of required inspections; reduced risk of cracking; increases peak clad temperature margin; slightly increases RCS flow and increases SG tube plugging margin; early implementation may extend life into license renewal

Summary Mitigation of Nickel-base Alloy Degradation

- **Zinc additions:**
  - Favorable experience with zinc controlling radiation fields
  - Field tests in USA to evaluate long term effects on mitigating PWR radiation fields, evaluating effect on PWSCC, and ensuring no adverse effect on fuel or other components
  - Mitigation of radiation fields demonstrated
  - Worthwhile favorable influence on lab PWSCC initiation times
  - PWSCC lab data on CGR in fracture mechanics specimens is less conclusive; field data ambiguous
  - No adverse effects observed on fuel cladding corrosion but need to resolve potential issues associated with high duty plants

Summary Mitigation of Nickel-base Alloy Degradation

- Program performed to confirm applicability of MSIP to thick wall PWR piping, verify analysis and inspectability
- Qualification testing with mockup of Tihange 2 pressurizer surge line nozzle
- MSIP generated required compressive strains in inner weld region
- Post MSIP profiles were acceptable for in-service inspections
- MSIP can be a potential part of a proactive Alloy 600 mitigation program

Section 8:
Panel Discussion

NRC Perspective on the Management of Materials Degradation

Dr. Richard Barrett, Director
Division of Engineering
Office of Nuclear Reactor Regulation
Nuclear Regulatory Commission
October 2, 2003

ALLOY 600 ISSUES

- Cracking frequently identified and repaired in pressurizer heater sleeves and instrument nozzles
- Hot leg weld cracking – V.C. Summer
- Upper head nozzle cracking – ANO, Oconee, etc.
- Upper head wastage – Davis-Besse
- Lower head nozzle cracking – South Texas Unit 1

RECENT NRC ACTIONS

- Bulletin 2001-01: Upper head inspections for high-susceptibility plants
- Bulletin 2002-01: Adequacy of boric acid corrosion control programs
- Bulletin 2002-02: Bare metal visual and non-destructive examinations of upper heads
- NRC Order EA-03-009
- Bulletin 2003-02: Lower vessel head inspections

FUTURE NRC NEEDS

- More complete and realistic technical basis for inspections and repairs
  - ♦ Crack initiation and growth rates
  - ♦ Susceptibility models
  - ♦ Alloy 600 and 690
- Continued progress on inspection methods
- Regulatory requirements that accommodate materials differences, evolving technical information, and emerging inspection methods

SUMMARY

- Frequency and significance of materials degradation issues are growing
- Research community must continue to develop technical basis for inspections and repairs
- Industry must be prepared to provide comprehensive approaches in a timely manner
- NRC will continue in its regulatory role and will take necessary actions based on its evaluation of the available information

INTEGRATED INSPECTION MODEL FOR MANAGING MATERIALS ISSUES

- Inspection Scope
- Inspection Method
- Acceptance Criteria
- Inspection Frequency

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Integrated Inspection Model (con't)

- Inspection Scope
  - How Many Components to Look at
  - How Much of Each Component to Look at
  - Expansion Criteria
    - *Based on statistical evaluations to provide the reliability necessary to maintain desired level of component reliability and an acceptable level of overall risk*

Integrated Inspection Model (con't)

- Inspection Method
  - Inspection Technology (e.g., VT, PT, ECT, UT, ….)
  - Technique and Personnel Qualification (Detection and Sizing)
    - *Based on performance demonstration with defined level of reliability*

Integrated Inspection Model (con't)

- Acceptance Criteria
  - Defined Failure Point
  - Applicable Margins
    - *Margins account for uncertainties e.g., in inspection methods, degradation rates, failure criteria*

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Integrated Inspection Model (con't)

- Inspection Frequency
  - Degradation Rates
    - Performance Based?
    - *Requires integration of reliability of inspection method, degradation rates and acceptance criteria to maintain desired level of component reliability*

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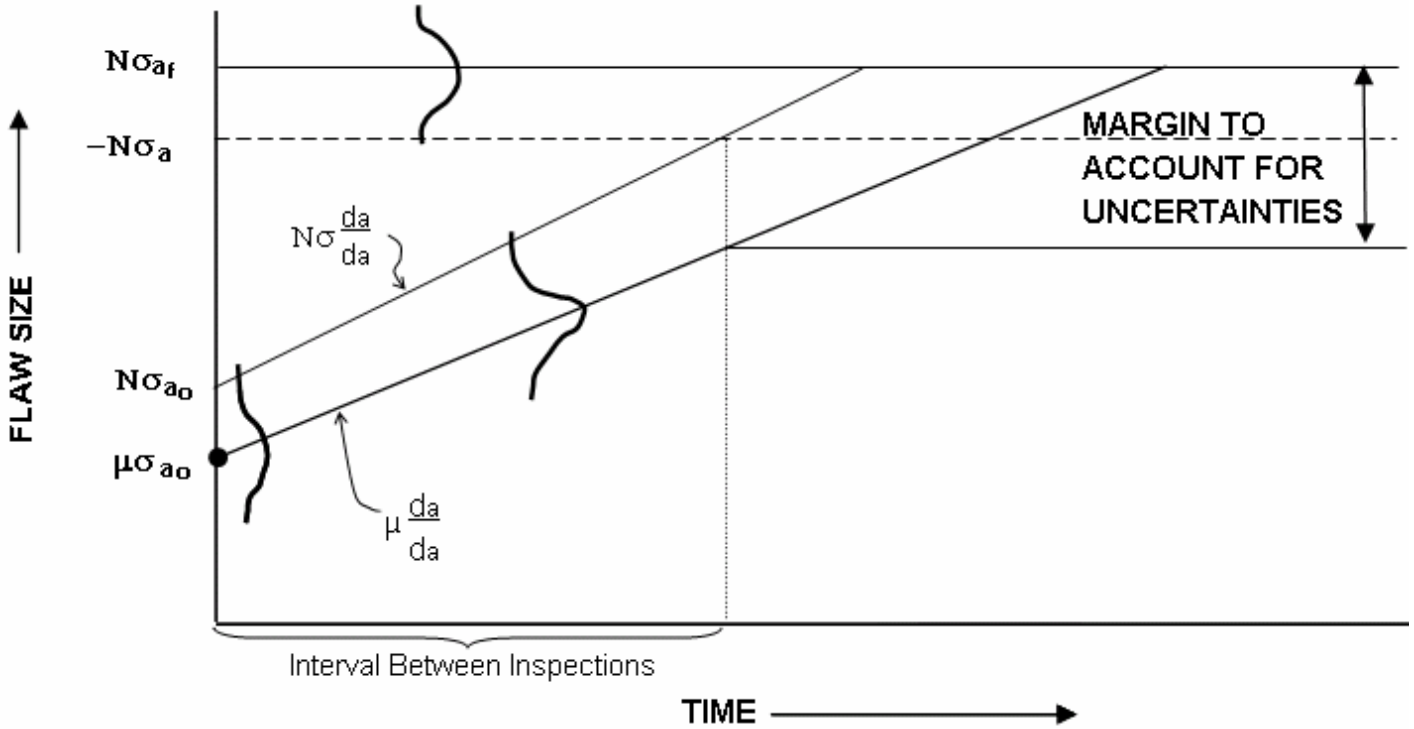
INTEGRATED INSPECTION MODEL



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IMPORTANCE OF IMPLEMENTATION

- The Best Research and Technical Work Will Be for Naught If:
  - Results Are Not Put Into an Implementable Format (e.g., Code or Guidance Document)
  - Implementation Is Not Monitored to Ensure Effectiveness

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10. SUPPLEMENTARY NOTES

Conference held September 29 - October 2, 2003 in Gaithersburg, Maryland, USA

11. ABSTRACT *(200 words or less)*

These two volumes of proceedings contain the visual projections (in Volume I), and the contributed manuscripts (in Volume II) from the Conference on Vessel Head Penetration, Crack Growth and Repair, held a t the Gaithersburg Marriott at Washingtonian Center on September 29 – October 2, 2003. The conference was co-sponsored by the U. S. Nuclear Regulatory Commission and Argonne National Laboratory. Over two hundred attend ees were provided with 45 presentations, divided into five sessions: (I) Inspection Techniques, Results, and Future Deve lopments, (II) Continued Plant Operation, (III) Structural Analysis and Fracture Mechanics Issues, (IV) Crack Growth Rate Studi es for the Disposition of Flaws, and (V) Mitigation of Nickel-Base Alloy Degradation and Foreign Experience. The confer ence opened with a plenary session including presentations giving the overview from the NRC Office of Regulatory Research, a nd an overview of nickel-base alloy cracking issues worldwide. The conference closed with a panel session consisting of ind ustry representatives and NRC management discussing the prognosis for future issues in this area of concern.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

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