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Proceedings of the Conference on Vessel Penetration Inspection, Crack Growth and Repair

Held at
Gaithersburg Marriott at Washington Center
Gaithersburg, MD
September 29 – October 2, 2003

Volume 2 - Presentation Graphics, Part 1
Session I: Inspection Techniques, Results, and Future Developments
Session II: Continued Plant Operation
Session III: Structural Analysis and Fracture Mechanics Issues

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
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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 Nuclear 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.

FOREWORD

Stress-corrosion cracking of nickel-base alloys used in both wrought and welded vessel penetration components has been an increasing and worldwide challenge for the nuclear industry and regulatory authorities since the mid-1980s. Cracks and resultant leaks were initially discovered in components fabricated from Alloys 600 and 182 exposed to higher temperatures, particularly in pressurizer heater sleeves and nozzles. Over time, cracks and leaks have also been discovered in components operating at lower temperatures, including vessel head and bottom-mounted instrumentation penetrations.

Given the safety-significance of this issue, the U.S. Nuclear Regulatory Commission (NRC) hosted a 4-day conference on September 29 – October 2, 2003, to provide a forum for presentations and discussions concerning inspection, stress analysis, flaw evaluation, and mitigation of stress-corrosion cracks in vessel penetrations. This conference also provided a valuable opportunity for participants from several venues — regulatory, research, and plant operations — to meet face-to-face to formally and informally exchange data and concepts with the individuals who are at the forefront of the cracking issue.

As such, the conference brought together much of the worldwide expertise in the area of nickel-base alloy cracking. More than 200 individuals attended the 4-day conference, which included 45 presentations that provided a wide-ranging perspective on the issue. Many of the presentations were prepared by researchers involved in crack growth rate studies and nondestructive inspection; those presentations described successes and difficulties in developing testing and inspection procedures. Several discussed the stochastic nature and statistical analysis of cracking incidents, predictive algorithms for this type of degradation, and the prognosis for the future, including head replacement strategies, mitigation of the cracking process, and the likelihood of increased resistance to cracking of the replacement materials (Alloys 690 and 152). Other presentations were prepared by reactor component vendors, utility representatives, and regulatory participants, who described plant responses to component degradation, structural integrity evaluation, or the repair and mitigation of cracking. Many of those presentations were marked by completeness and candor in the discussion of observed problems and the related solutions. In addition, several presentations described the experiences of non-domestic institutions, providing contrasts and alternative approaches to the same problem.

The complete proceedings package consists of all conference presentations and available manuscripts, in both printed and electronic formats. The broad, public distribution of the proceedings ensures that the presentations will be subject to the greatest possible scrutiny and accreditation. As a result, the conference organizers believe that these proceedings will give readers an overview of the current status of inspection technology and crack growth rate studies, as well as an understanding of reactor safety and the economic impact of the degradation of nickel-base alloys on plant operation.

Carl J. Paperiello

Carl J. Paperiello, Director
Office of Nuclear Regulatory Research

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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. Specifically, as the weld height increased the axial stresses decreased while the hoop stresses increased. A logical consequence is that some type of medium weld height might be used in order to achieve a balance between both hoop and axial residual stresses. The session included discussion on the subject of ductile-dip-cracking, which seems to be a much larger problem for alloys 152/52 then it is 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 than PWSCC cracks. A reanalysis of LBB using PWSCC crack geometries leads to some new results. The presentation noted that it is difficult to satisfy LBB criteria using the PWSCC crack geometries. Another feature is that PWSCC could result in long circumferential surface cracks which may be more prone to failure than than the currently-utilized, simple, 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 by creating an all inclusive equation. This equation would predict failure by using past experience as a guide. Auxiliary equations would take into consideration variables such as temperature or stress, which affect 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. A discussion of the history of Alloy 600 cracking at plants in the United States and France was followed by a description of new testing techniques for stress corrosion cracking growth rates (SCCGR). This description included the design details of compliant, self-loaded compact tension (CT) specimens and the conduct of 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. The conclusion is 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 weld with 5-10 effective full power years (EFPY) cracked. Alloy 600 showed cracking in a material with 6-13 EFPY. The participants discussed 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. As a result, Obrigheim uses leakage detection systems. 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. Sweden plants replaced 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. The geometry of the component influences the choice of a particular strategy. One type of mitigation technique that has been employed is to reduce the head temperature of the vessel. This has the effect of reducing 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. The last mitigation technique discussed 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.

ACKNOWLEDGEMENTS

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 and 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

BNFL

Westinghouse

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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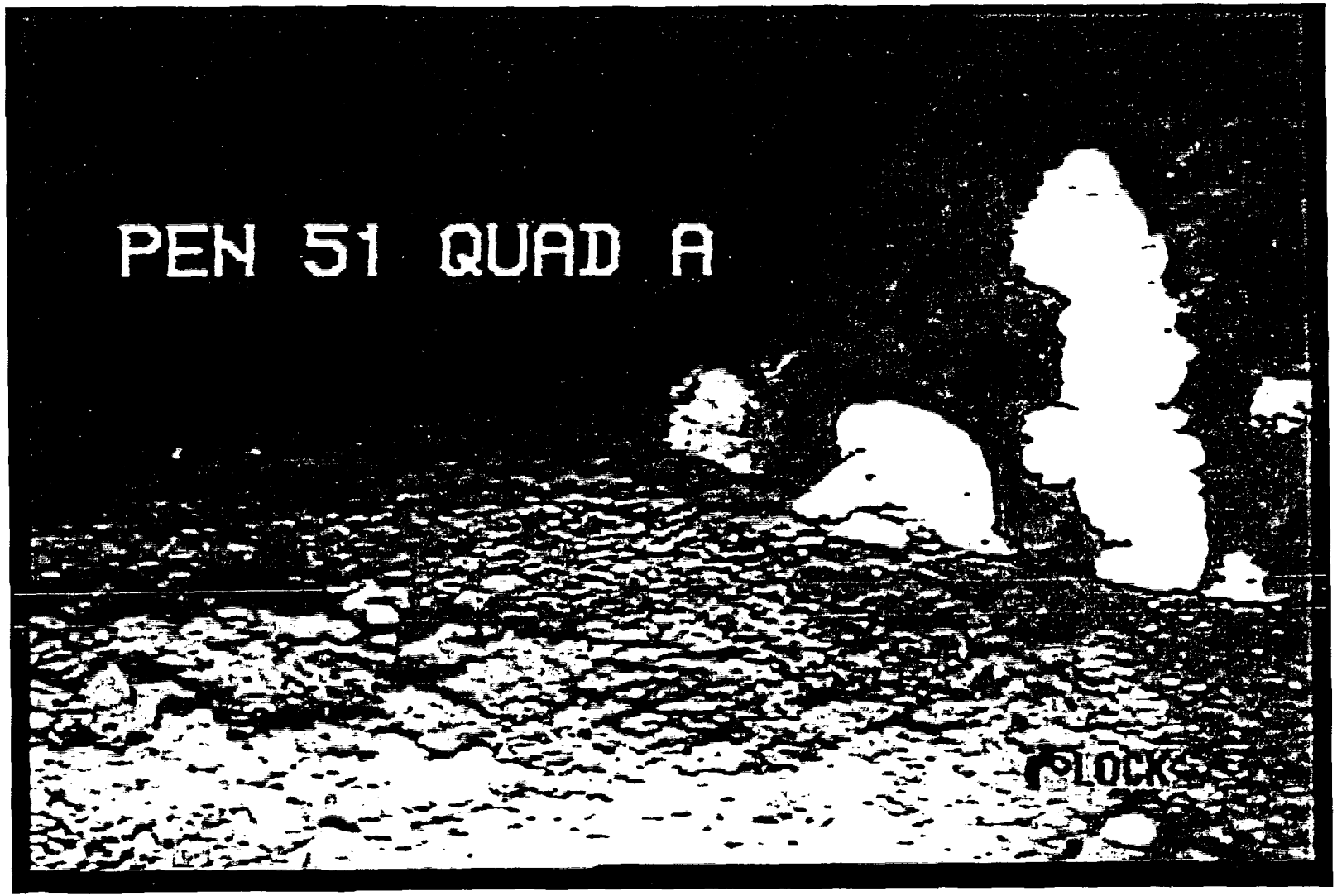

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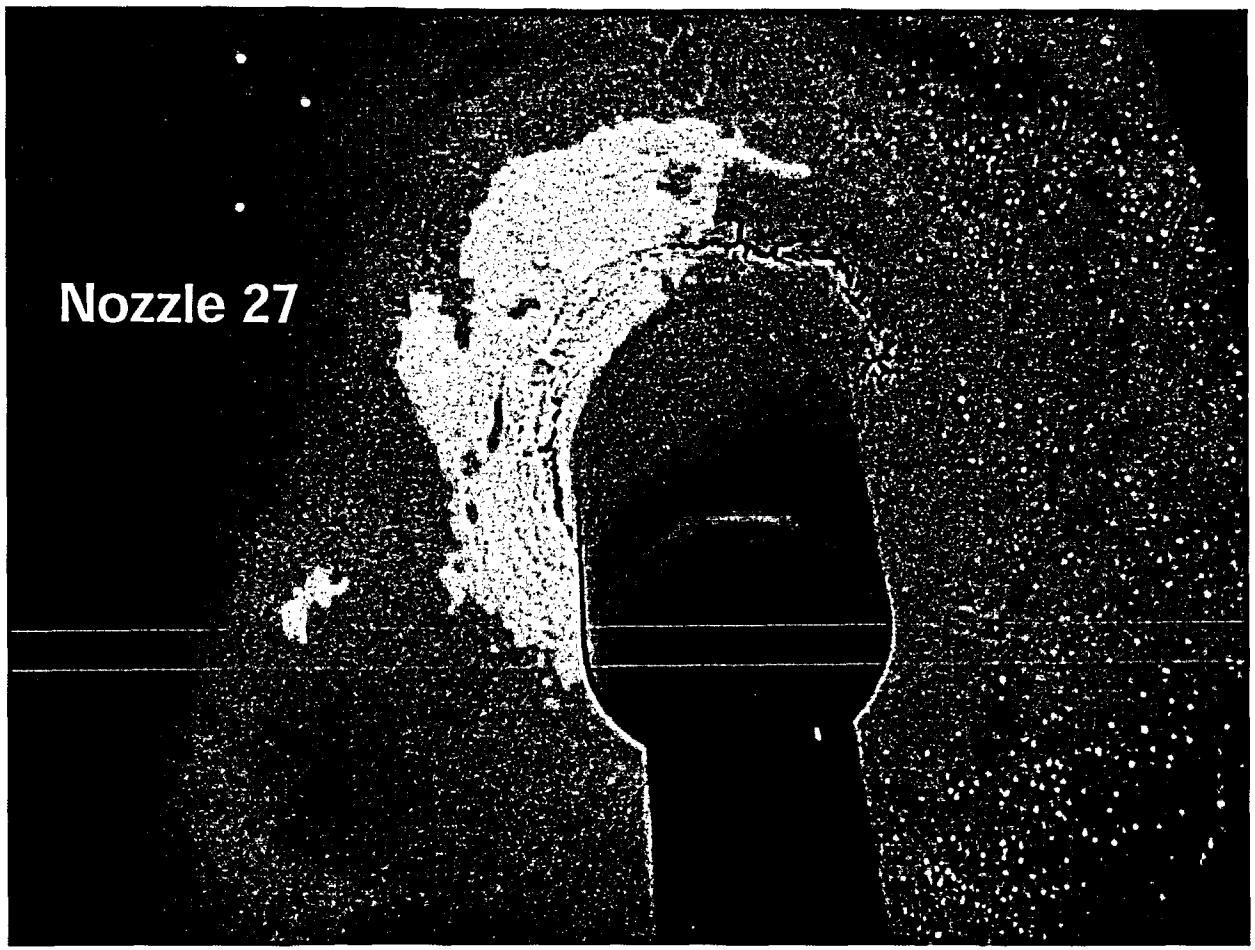
Surry Unit 1



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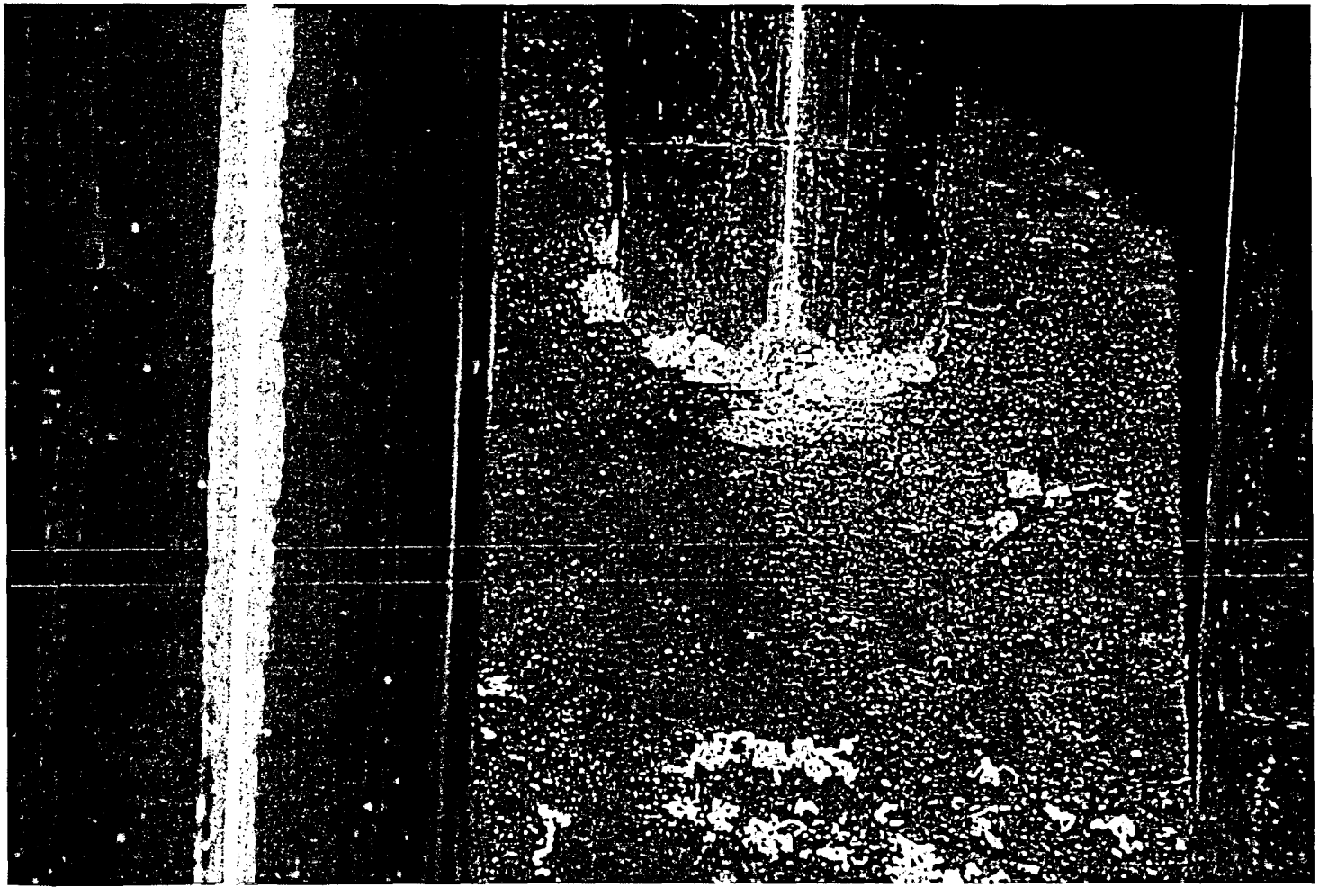
Crystal River #3



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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

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

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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

Westinghouse

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Westinghouse

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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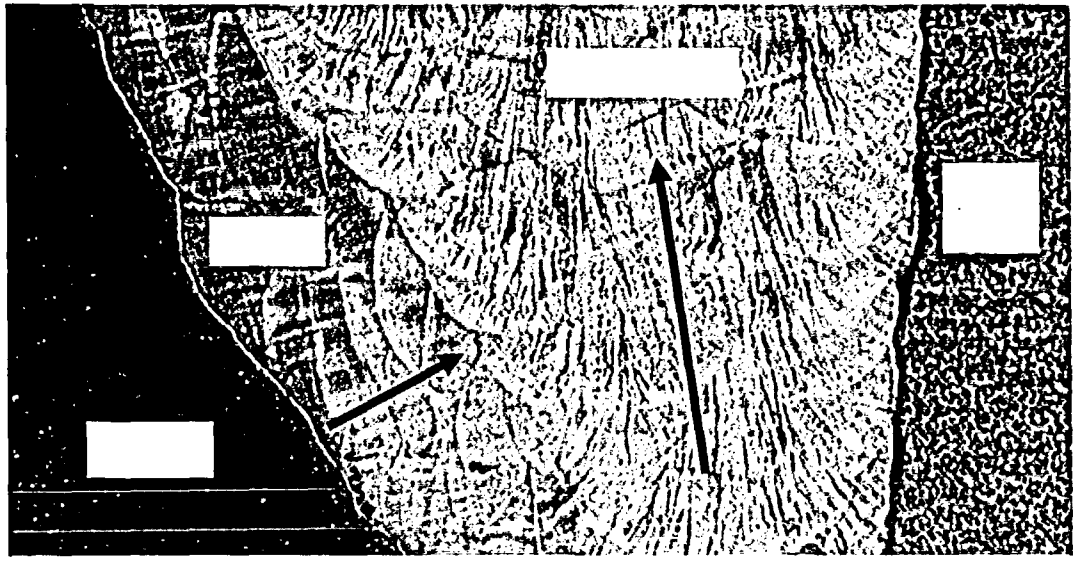
Typical Austenitic Weld Structure-Nozzle-to-Safe End

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



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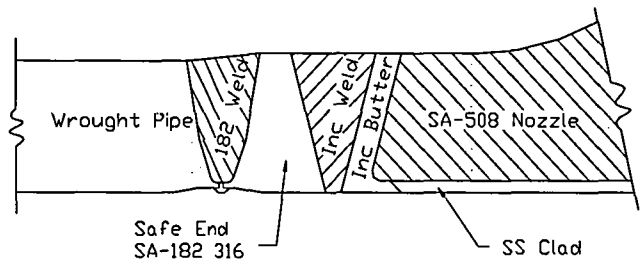
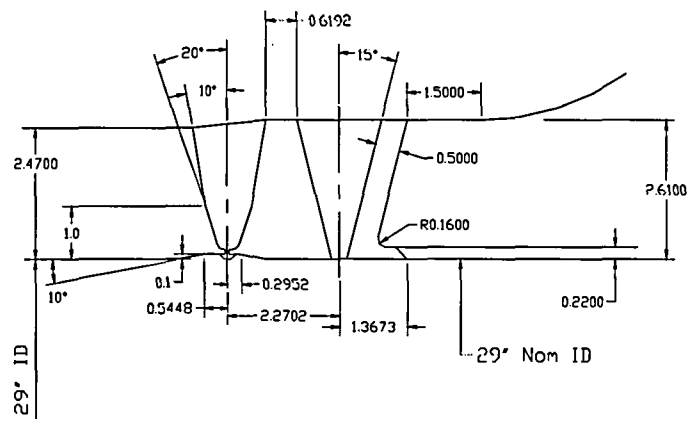
Dissimilar Metal Butt Weld Configurations





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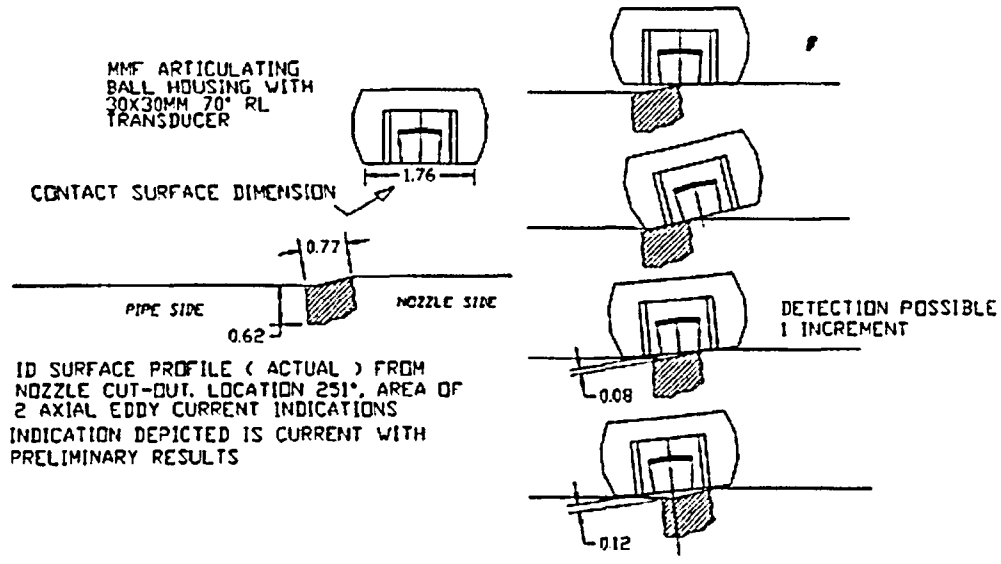
Inside Surface Effects



V.C. SUMER NOZZLE CUT-OUT SECTION AT 251°
UT PROBE ORIENTATION ALONG SURFACE GEOMETRY

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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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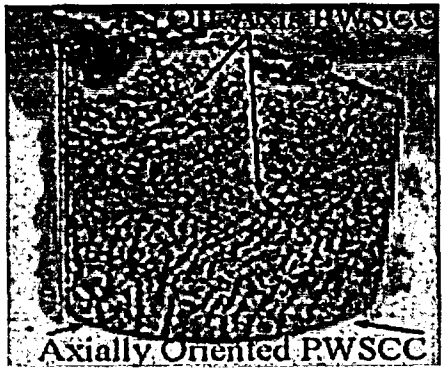
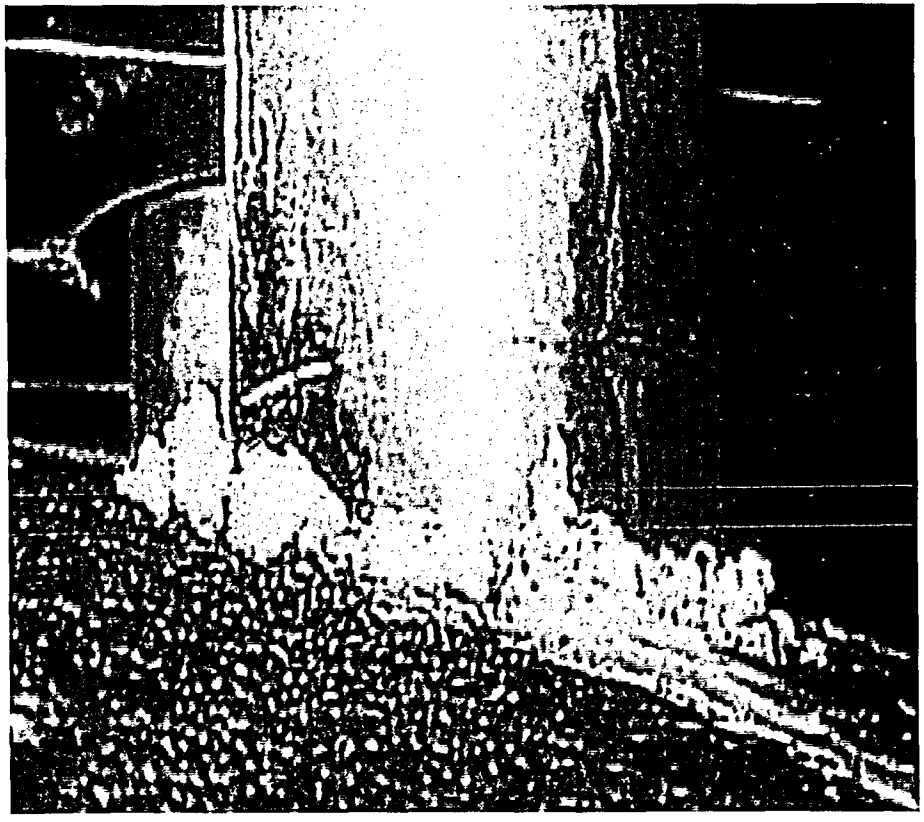
Cracking in CRDM Penetrations





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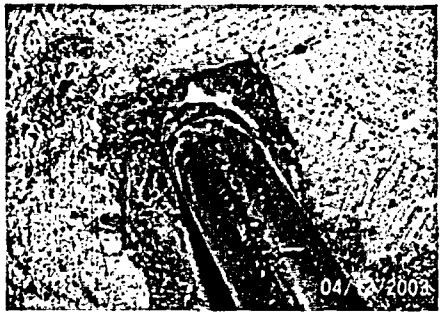
VHP Penetration, J-Groove Weld Cracking, & BMI Leak



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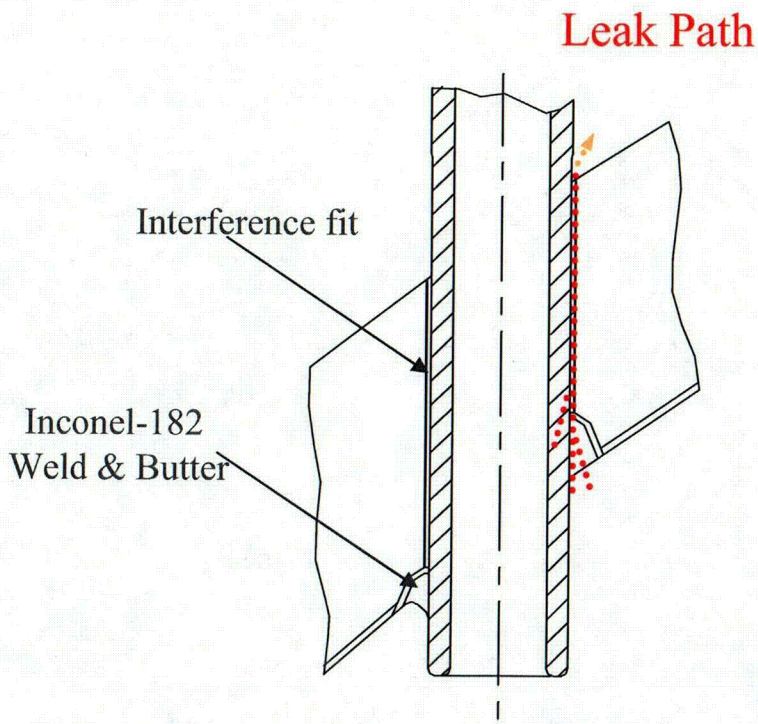
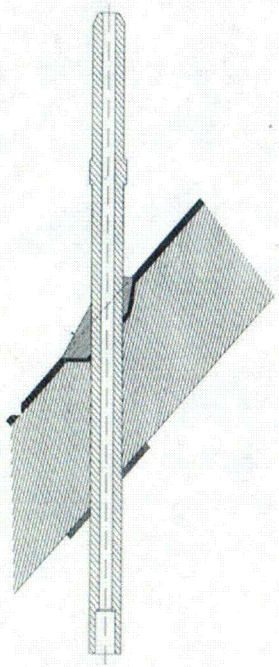
Leak Paths

Consider leak path through base metal or through weld



Top Head



Bottom Head

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C01

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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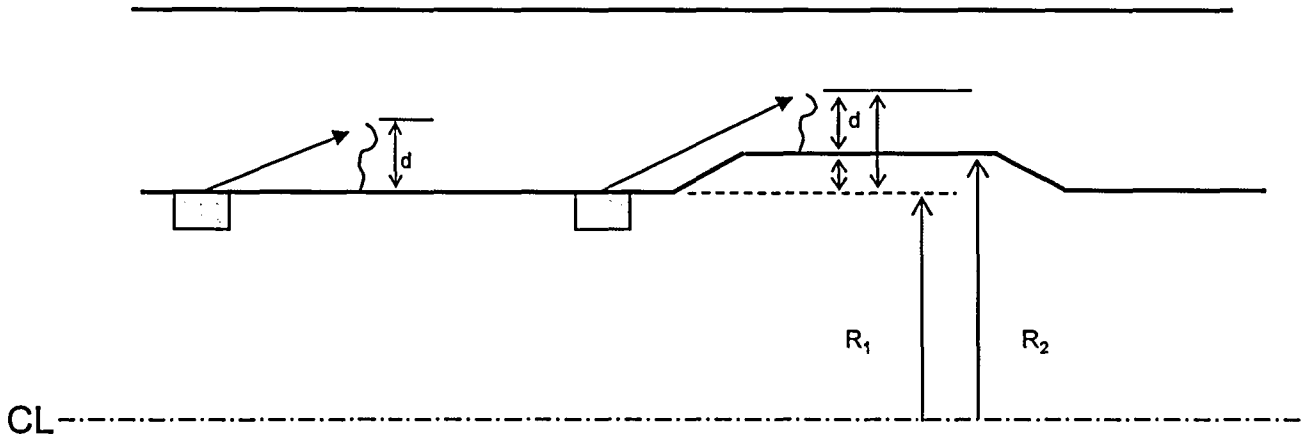
Flaw Depth Sizing-Compensation for Butt Weld Contours



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

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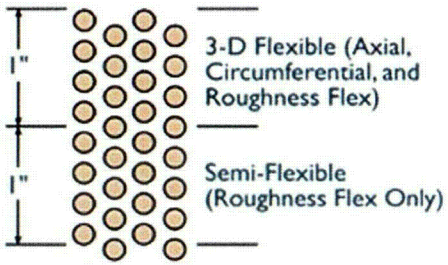
Eddy Current Array Probe for VHP J-Groove Welds

Advantages

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

Comprehensive Configuration



Coil Type: Cross-Wound

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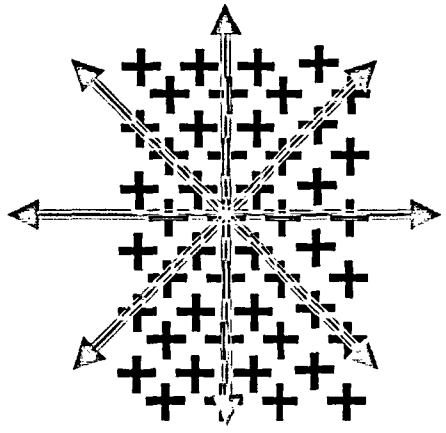
C02

Eddy Current Array Probe Configuration



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

- Cross wound impedance mode for 0°, 90° directions
- Driver-pickup mode for ± 45° 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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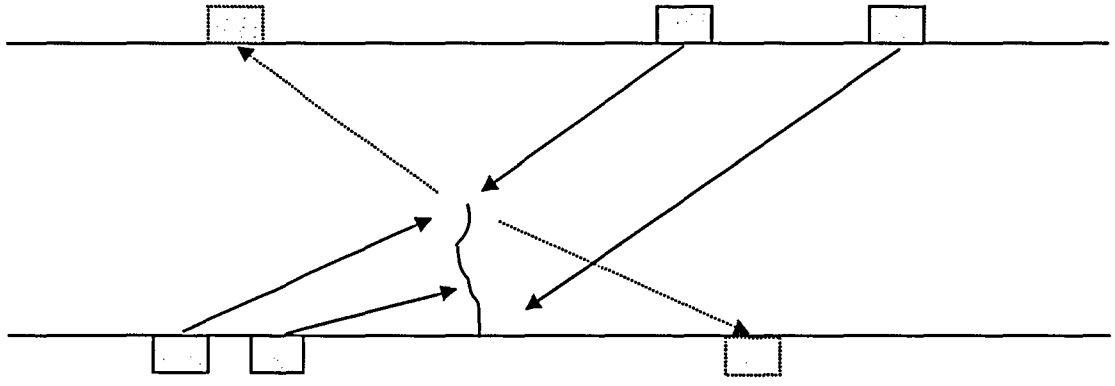
NDE Mockup Considerations

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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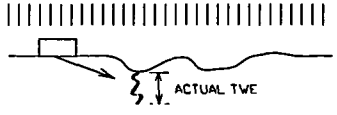
Status of Qualifications for DM Butt Welds

- 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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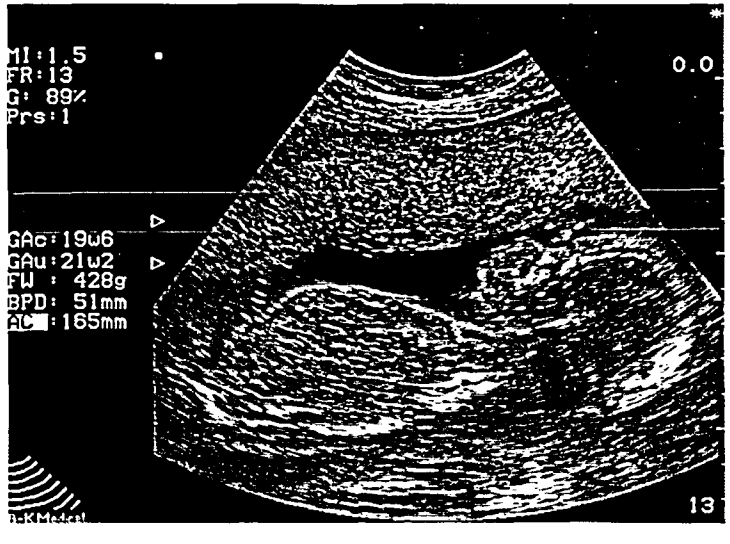
Phased Array UT Technologies for Nuclear Pipe Inspection Productivity and Reliability



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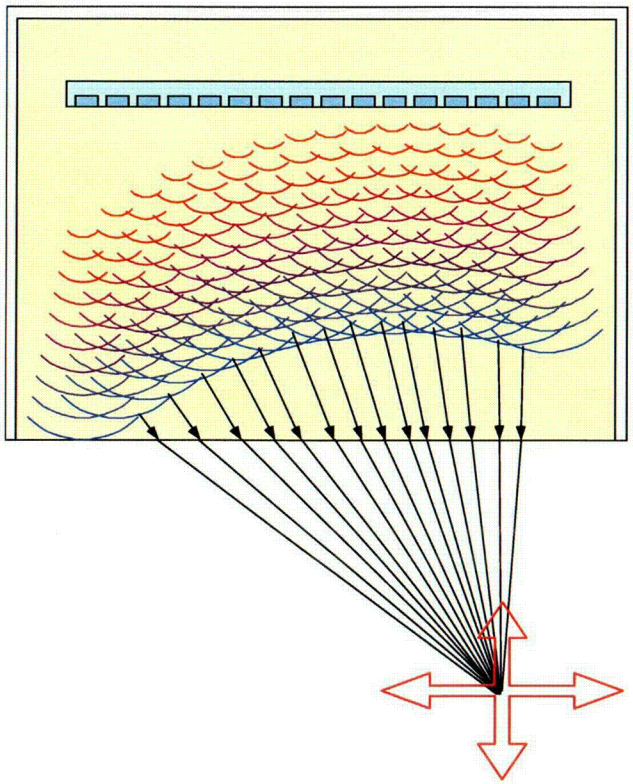
Phased arrays - Principles

Focused Angle Beam Mode



- Can focus & sweep the beam

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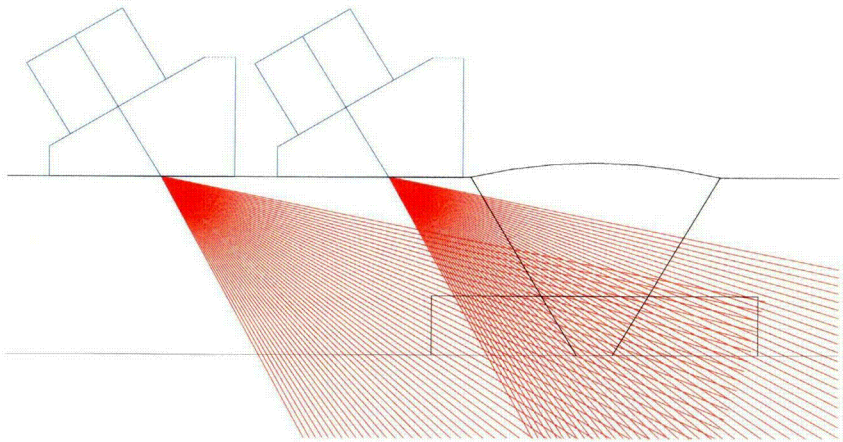
C03

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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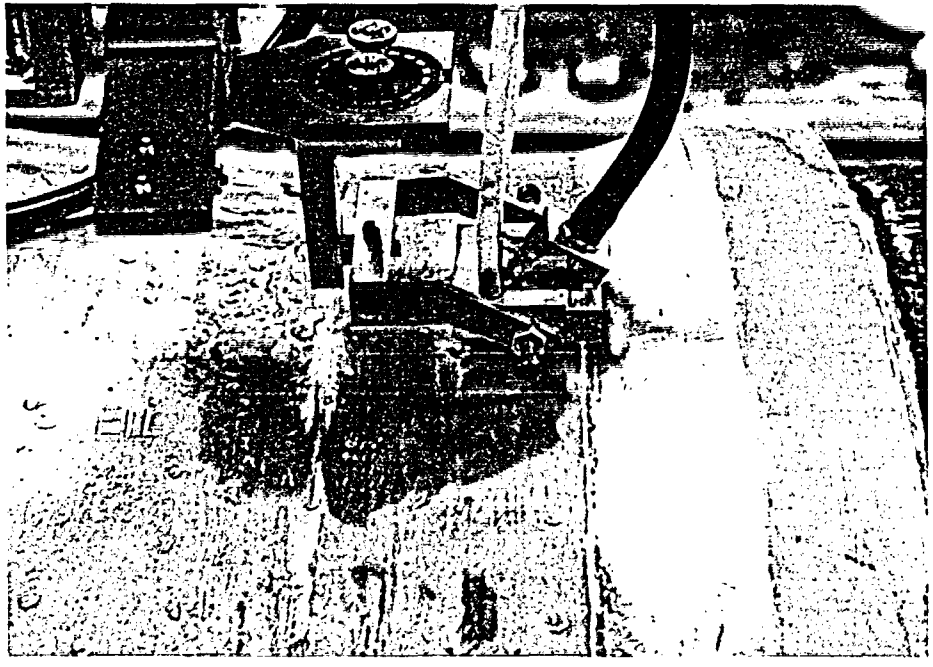
cox

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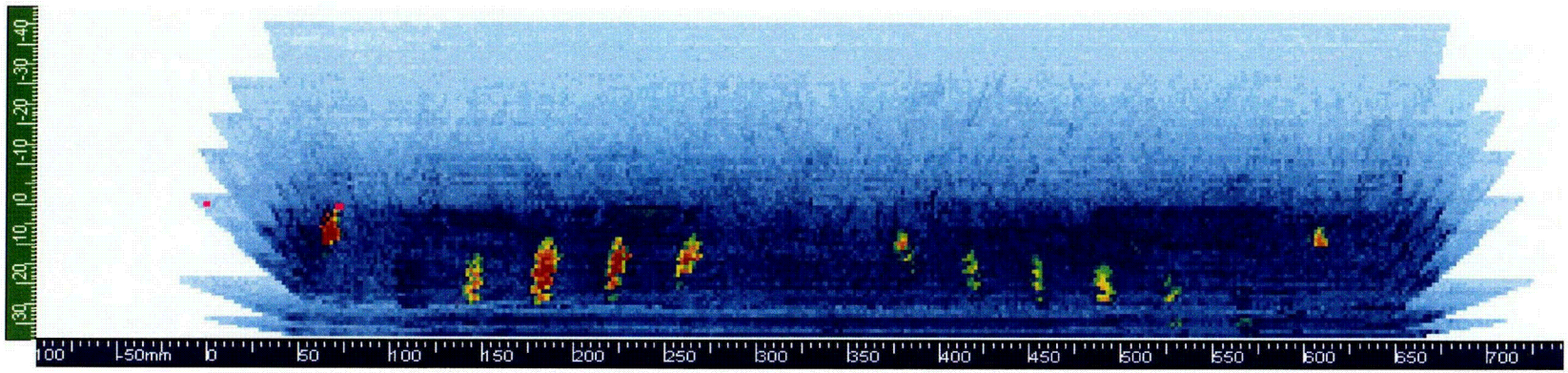
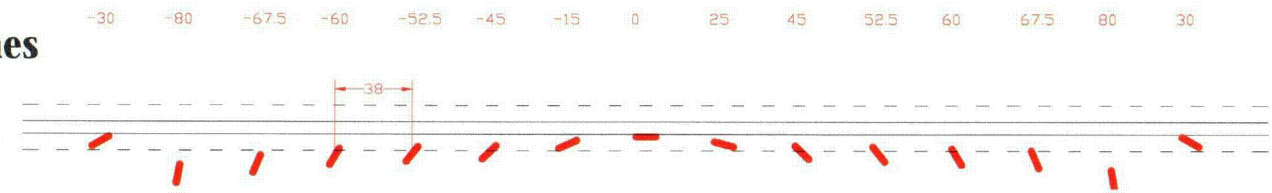
Next Step: Do It All with one 2D Array Probe





EDM notches

10mm long

5mm deep

SS pipe 30 mm thick

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C05

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

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  - 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

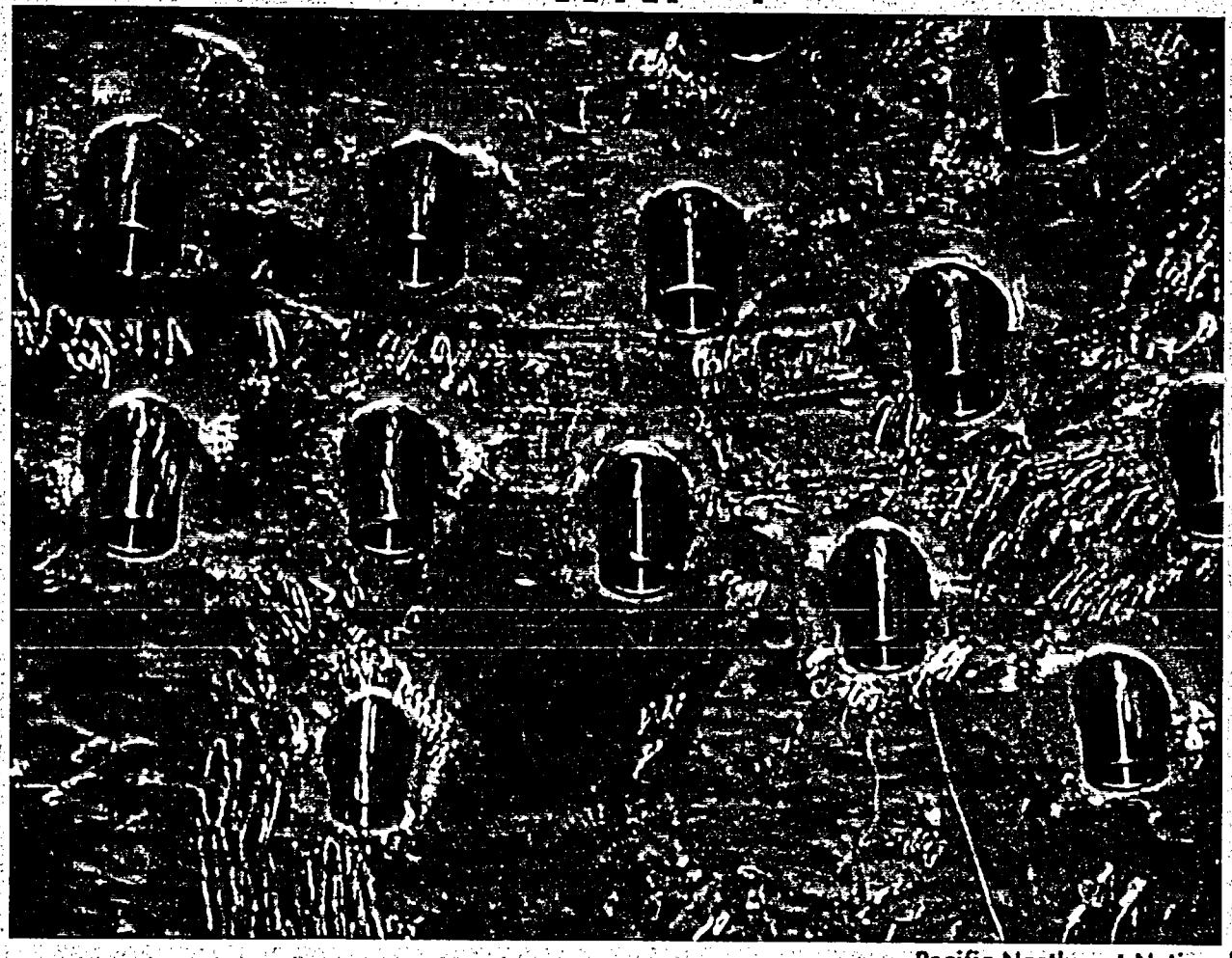
Overview of Degradation in Inconel – VHP Cont'd

- 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



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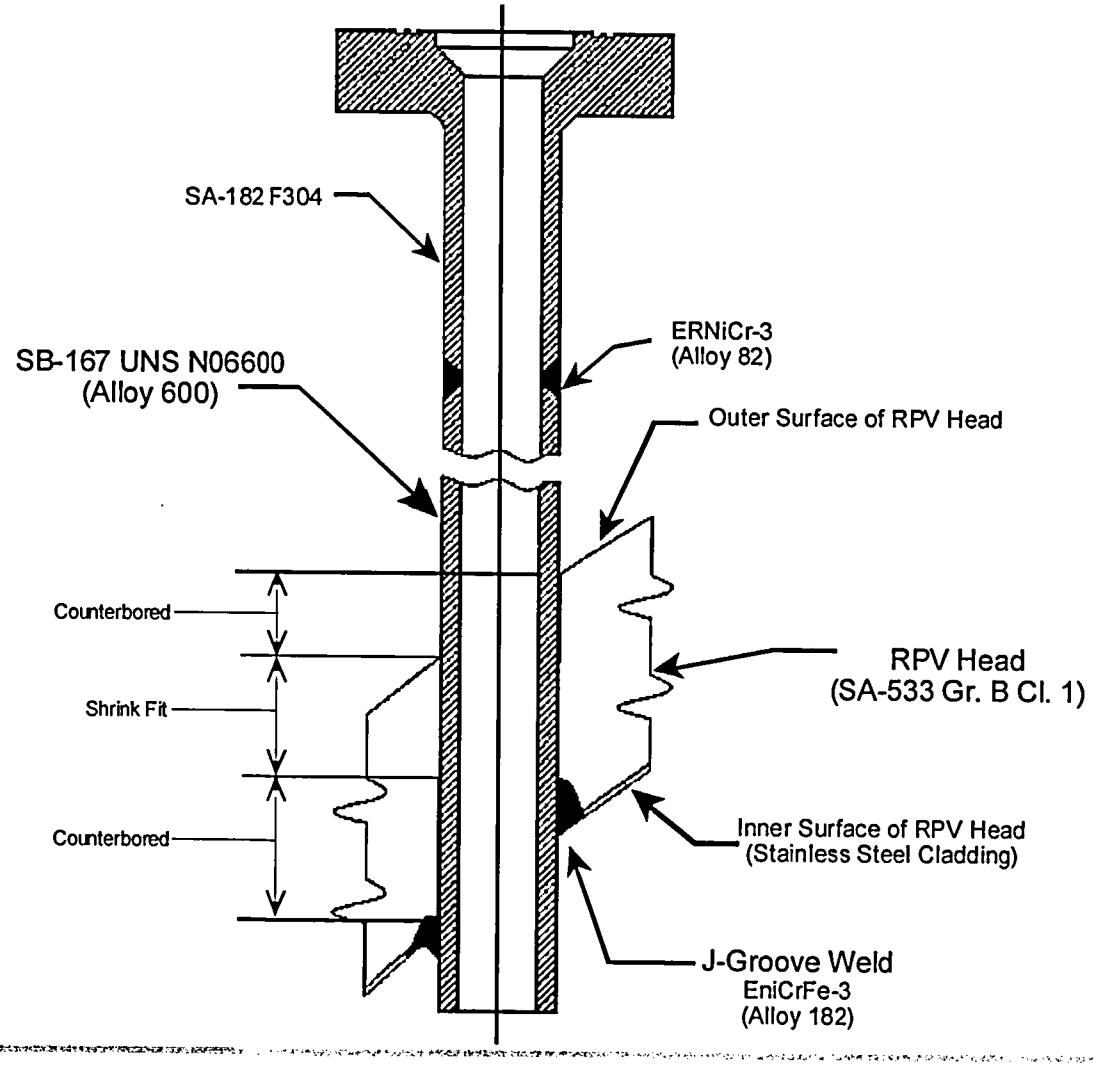
Design of B&W CRDM



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

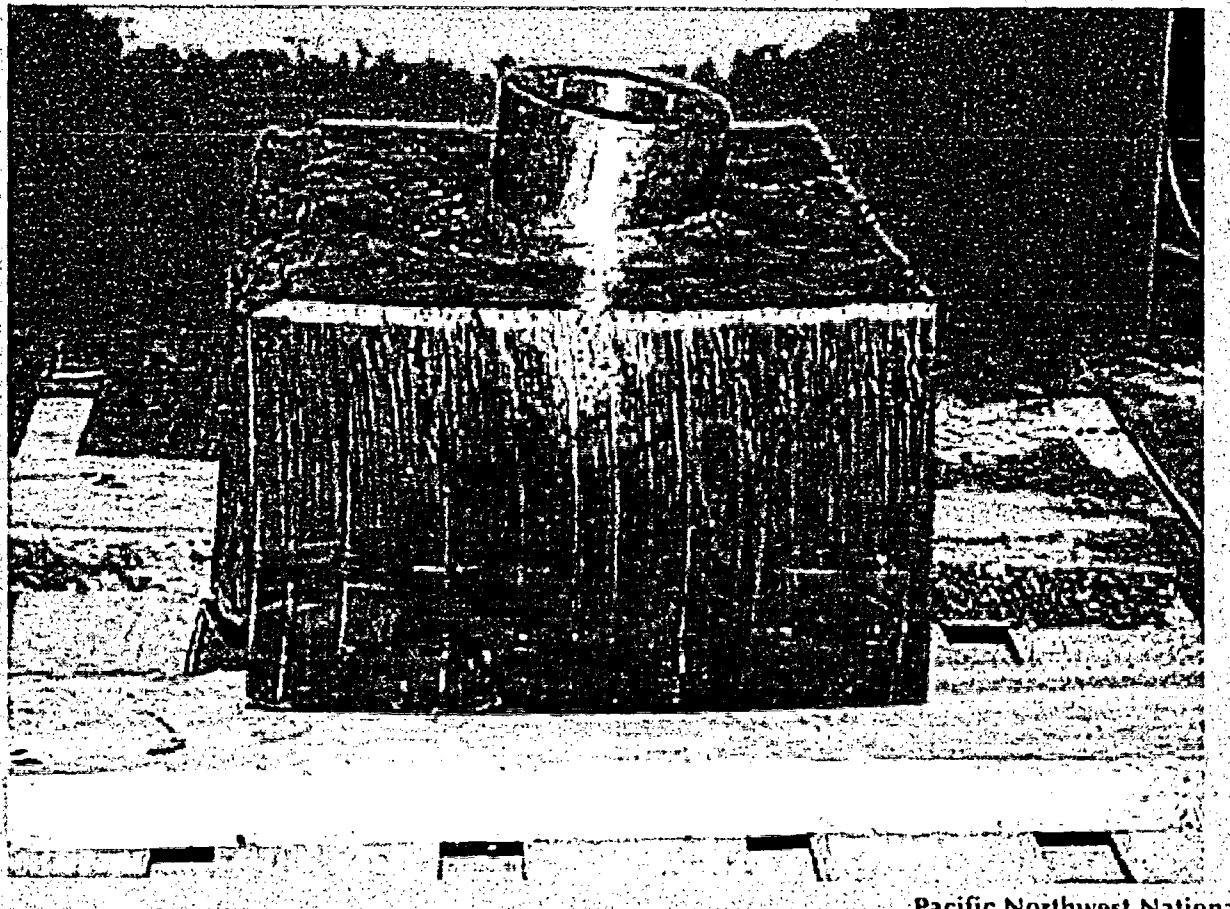
Programs Addressing NDE Effectiveness

- 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

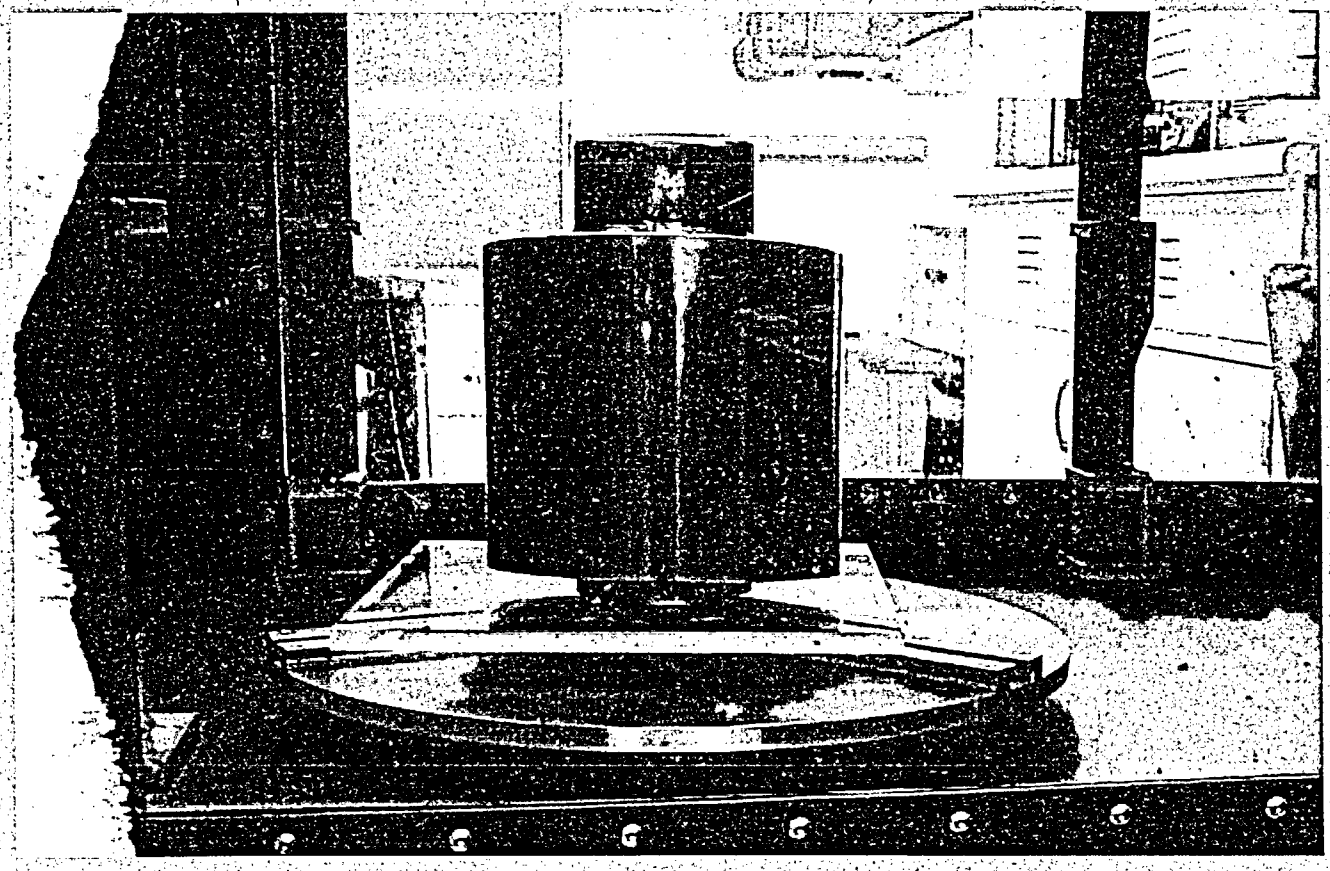
NRC Program JCN Y6604

- 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

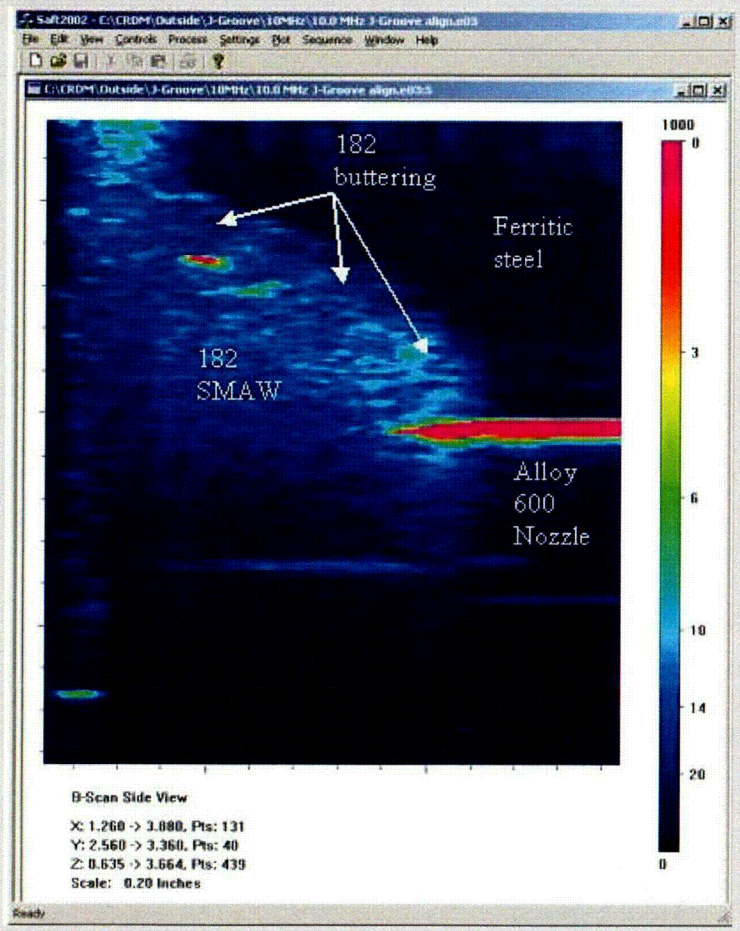
Midland CRDM Nozzle – Head Segment



CRDM prepared for Inspection



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



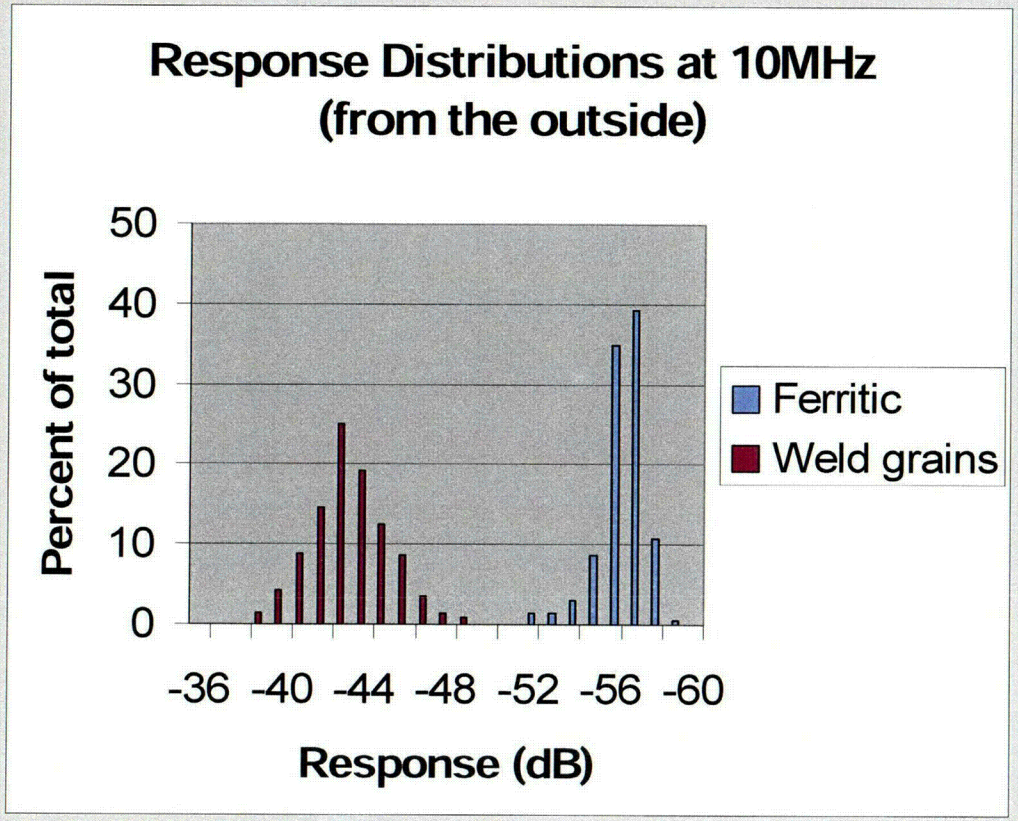
Normal incidence using 10MHz spherically focused, F8

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



C07

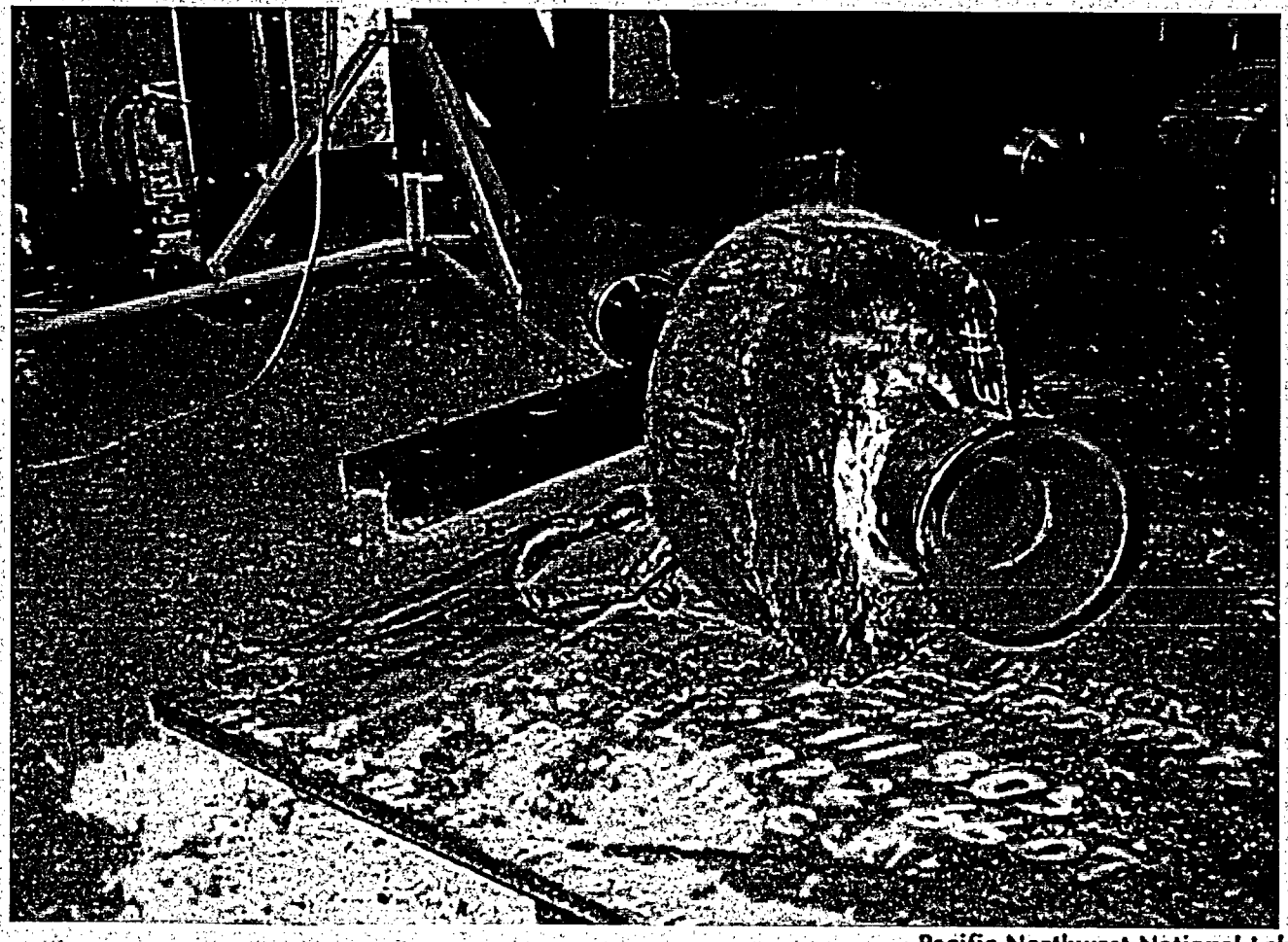
NRC Program JCN Y6534

- 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?

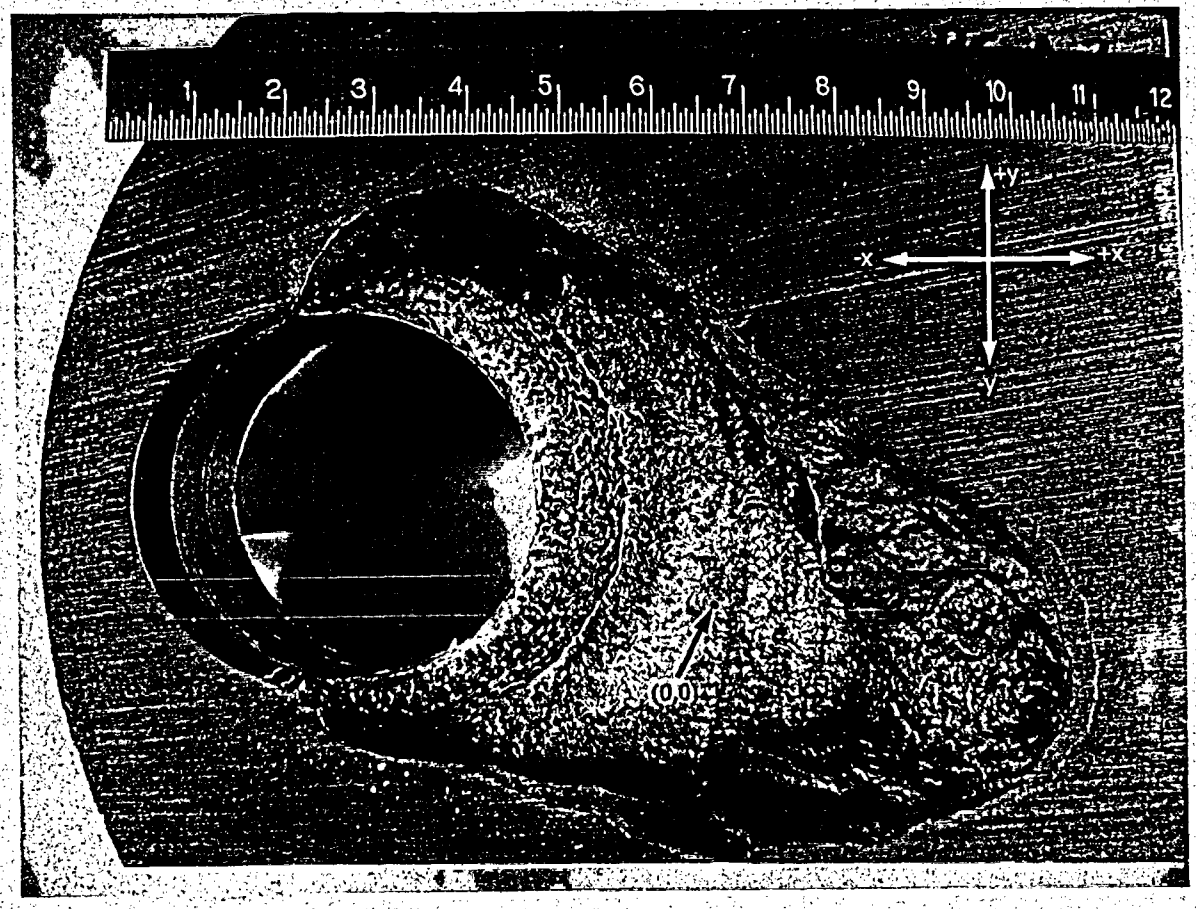
North Anna 2 Nozzle #51



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



Battelle

Pacific Northwest National Laboratory
U.S. Department of Energy 30

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

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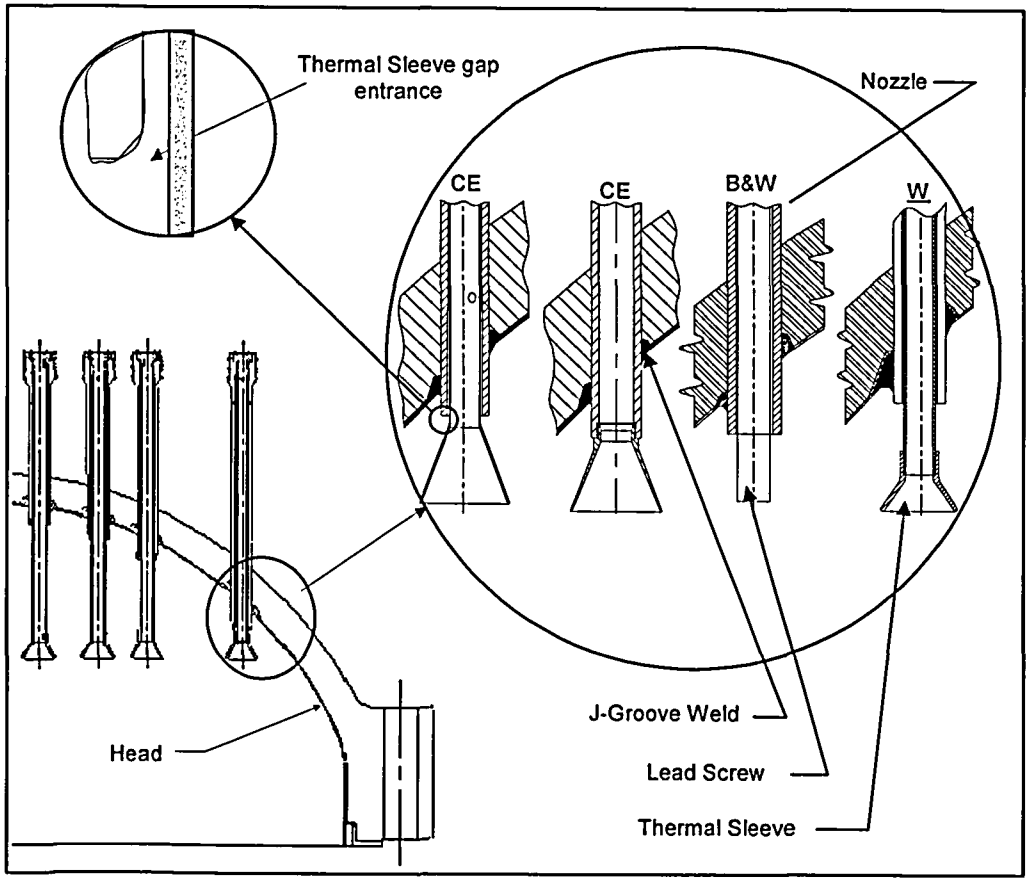
Typical CRD Nozzle Configurations



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

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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 Milsaps (864) 885-3667
Duke Energy Oconee 2	April 1996	CRDM (2)	Utility	0	2 RPT	2 RET	Barry Milsaps (864) 885-3667
Duke Energy Oconee 2	Fall 1999	CRDM (8)	Utility	0	0	8 RET	Barry Milsaps (864) 885-3667
Duke Energy Oconee 1	December 2000	CRDM (17)	Utility	16 RUT	0	17 RET	Barry Milsaps (864) 885-3667
Duke Energy Oconee 3	Spring 2001	CRDM (18)	Utility	18 RUT	0	18 RET	Barry Milsaps (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 Milsaps (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 Milsaps (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 Milsaps (864) 885-3667
Duke Energy Oconee 2	Fall 2002	CRDM (69)	Utility	65 BUT 15 RUT	7 MPT	0	Barry Milsaps (864) 885-3667
Entergy ANO - 1	Fall 2002	CRDM (31)	Utility	31 BUT	0	0	David Baumen (479) 858-4461
Total FANP Inspections To Date			**14 BHV by FANP**	**738 BUT 318 RUT**	**247 MPT 2 RPT**	**67 BET 68 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

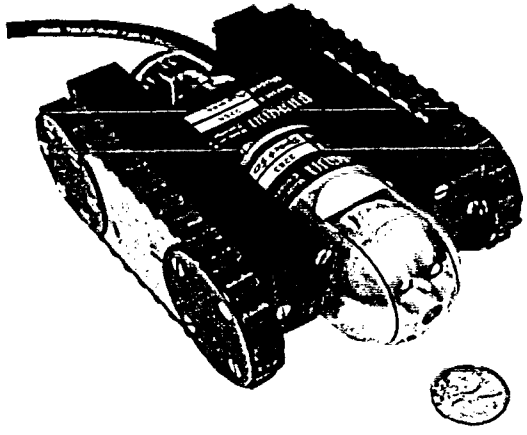
FANP has repaired 84 of the 93 RV head penetrations in the last three years.

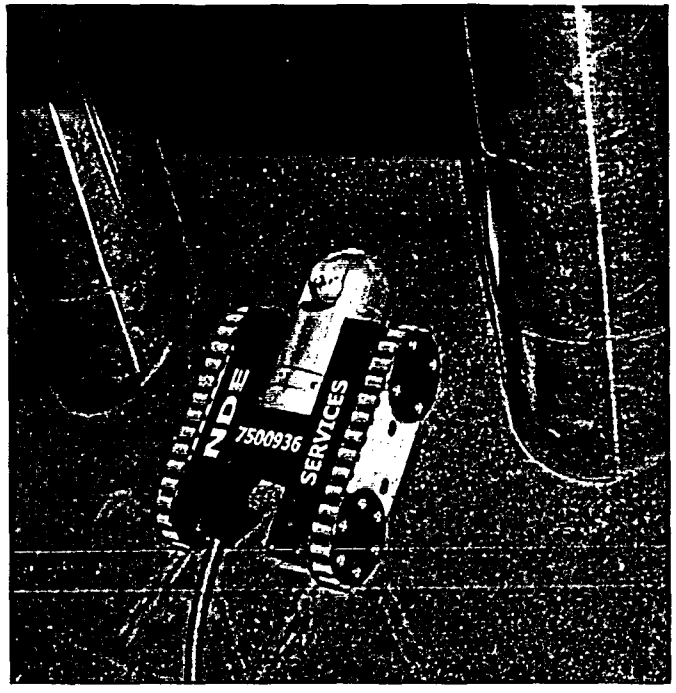
Nozzle Inspection Techniques

- > 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





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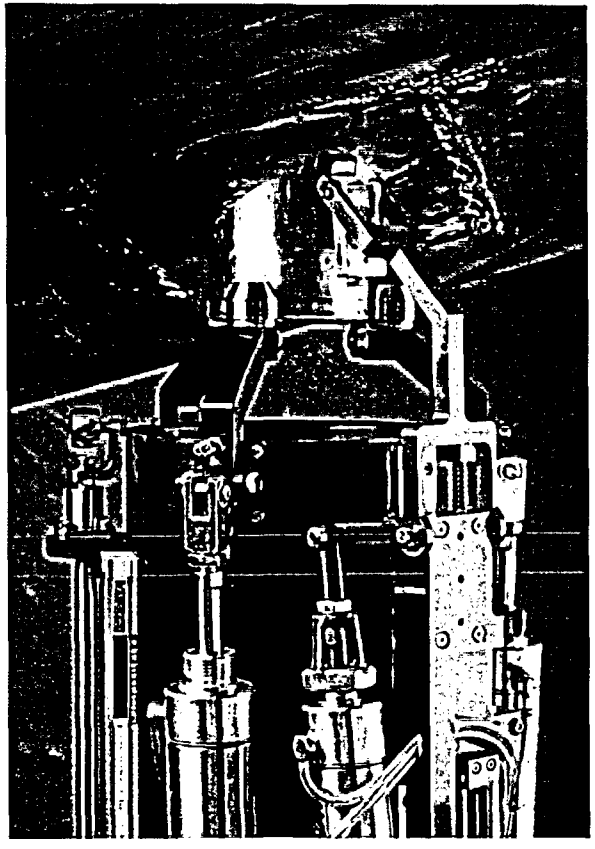
Inspection Techniques - ET

RV Head Remote ET

J-Groove Weld and Nozzle Stub Scanning



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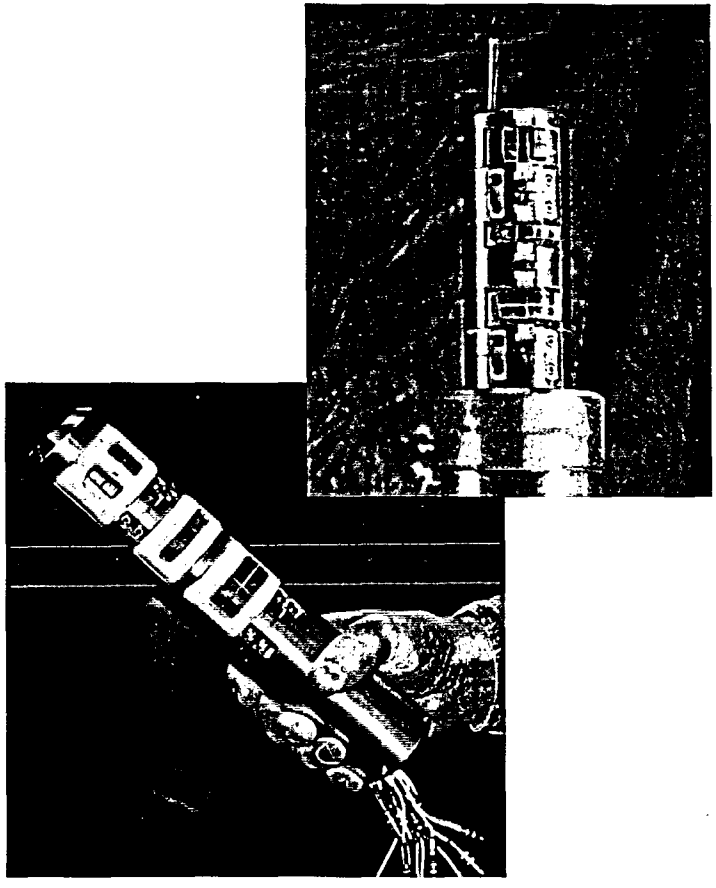
Inspection Techniques - UT

> *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*



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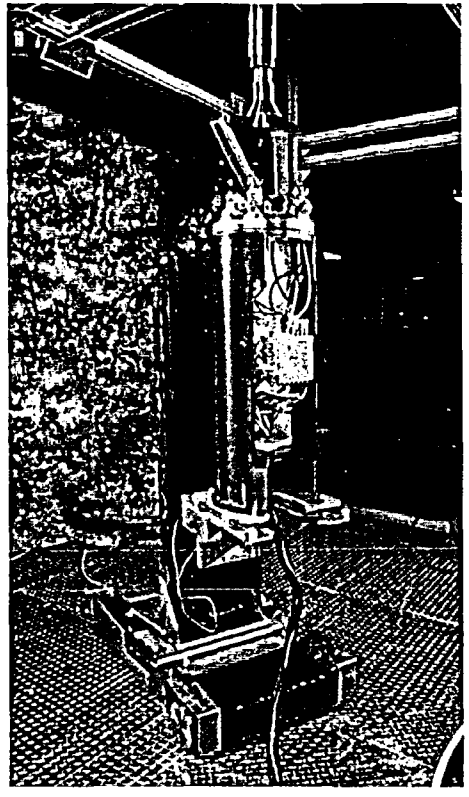
Inspection Techniques - UT

> *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*



Blade Pro e it
umoR C Manipulator

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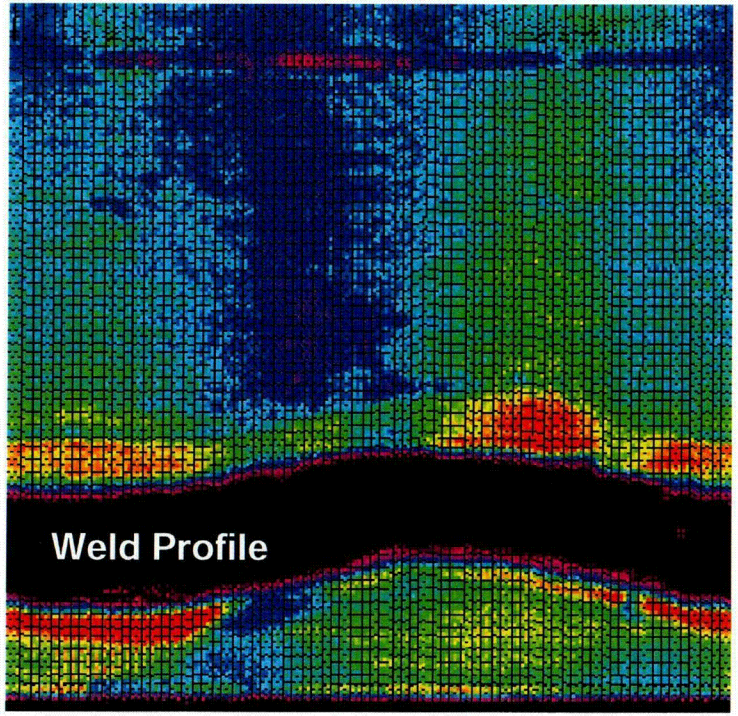
Leak Path Detection

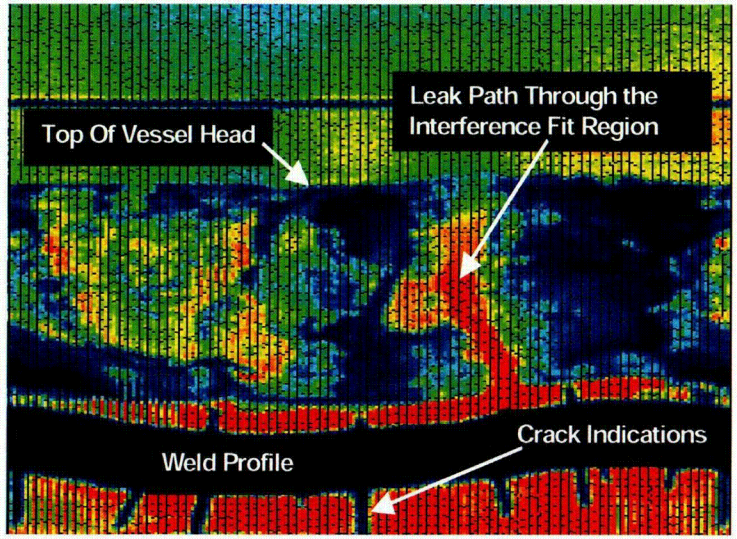
> *What is it?*
- *UT Image of the Amplitude Profile Resulting From Changes in Reflectivity of the Nozzle Backwall in the Interference Fit Region of the Nozzle*
- *Sees Changes in the Geometry of the Interference Fit Caused by Erosion/Corrosion of Head Material*
- *Patterns Form in the C-scan Image Indicative 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

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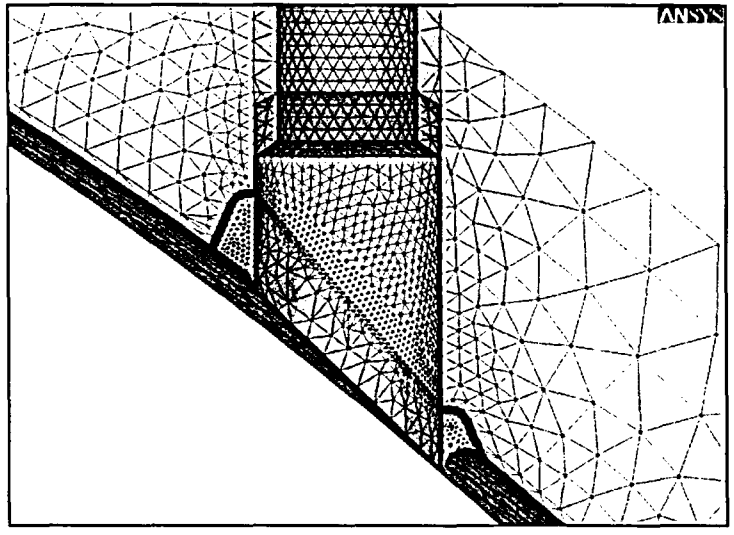
C08

Framatome ANP Repair Approaches

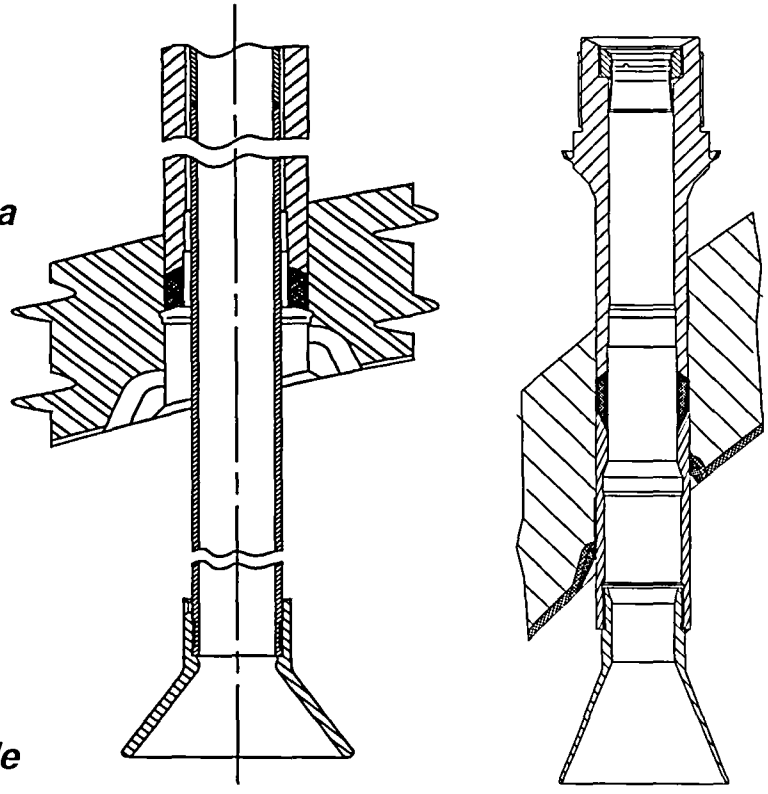
> *Remote ID Temper Bead (IDTB) Process - Recommended*
  - *Good contingency approach to be prepared for any failure event*
    - *Structural Weld Defects*
    - *Nozzle ID Defects*
    - *Nozzle OD Defects*
    - *Multiple Defects in Nozzles With Multiple Failure Modes*
    - *Maximizes Repair Life 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

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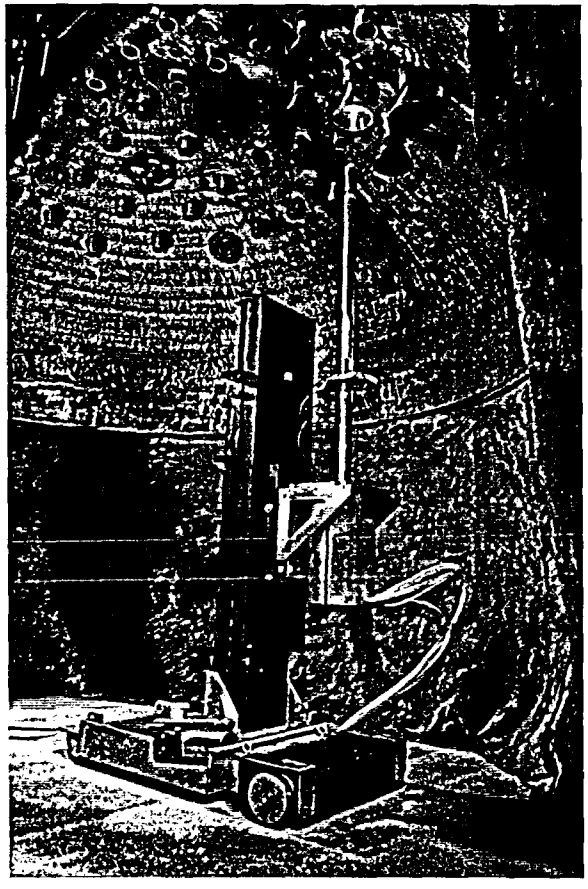
Head Mockups



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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

EPRI

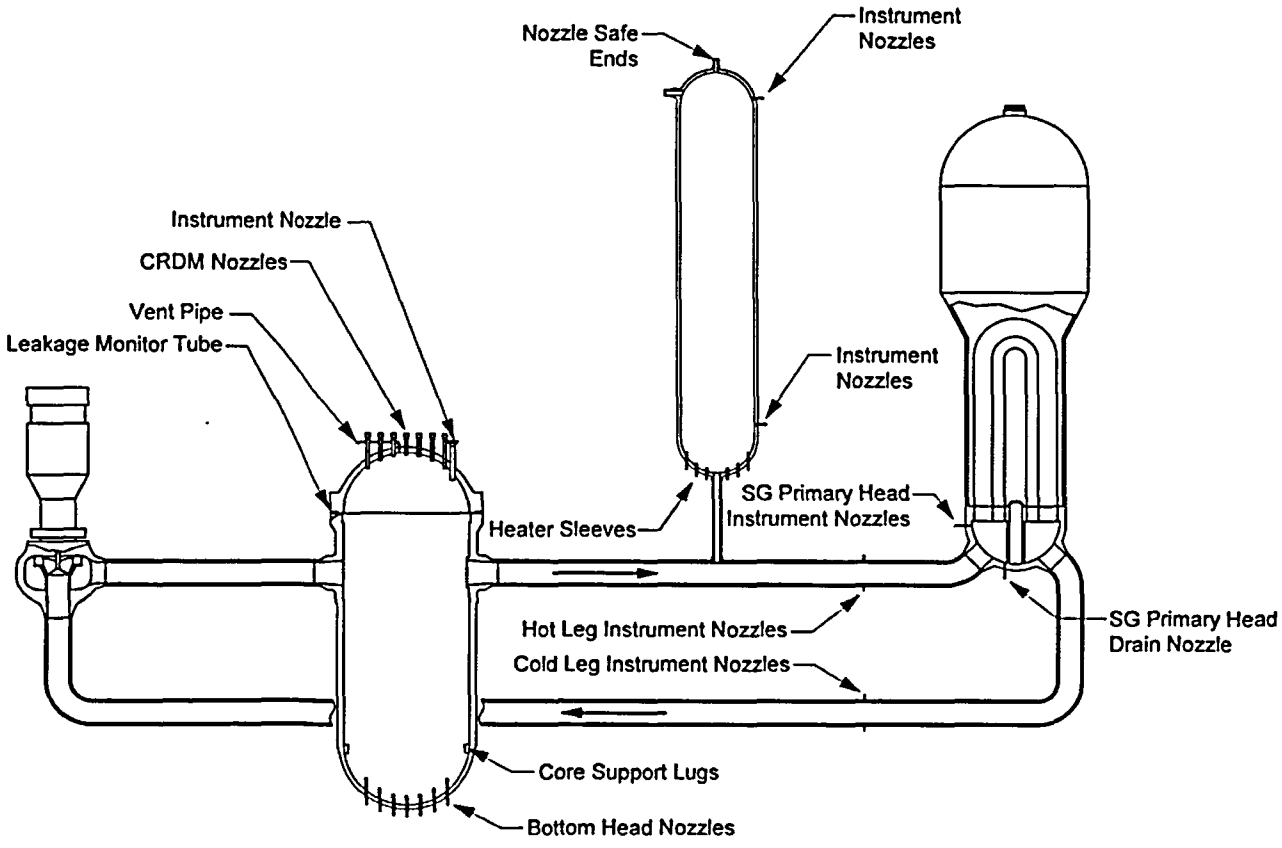
Topics

- 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

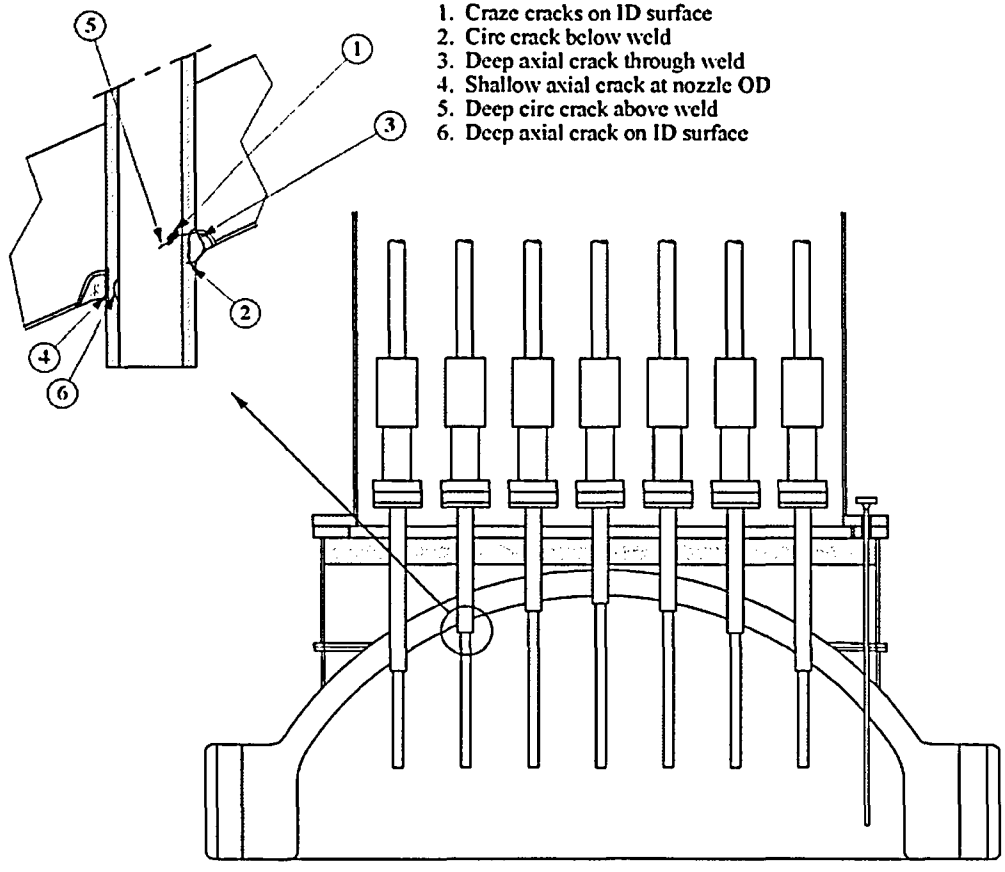
Uses of Inspection Summary Statistics

- 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 00

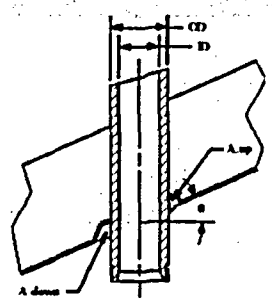


Introduction
Typical PWR RV Head Nozzle PWSCC

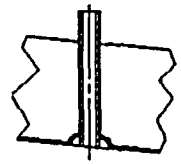


Introduction
Penetration Types

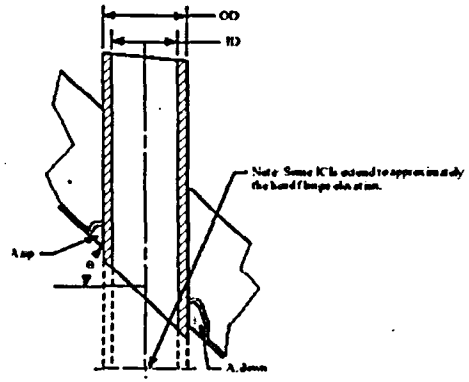
- 69 operating PWR units in the U.S.
- J-groove nozzle designs (all Alloy 600)
  - 3871 CRDM nozzles (55 units)
  - 1090 CEDM nozzles (14 units)
  - 94 in-core instrument (ICI) nozzles (11 units)
  - 59 vent line nozzles (59 units)
  - 16 small-bore thermocouple nozzles (2 units)
  - 8 auxiliary head 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

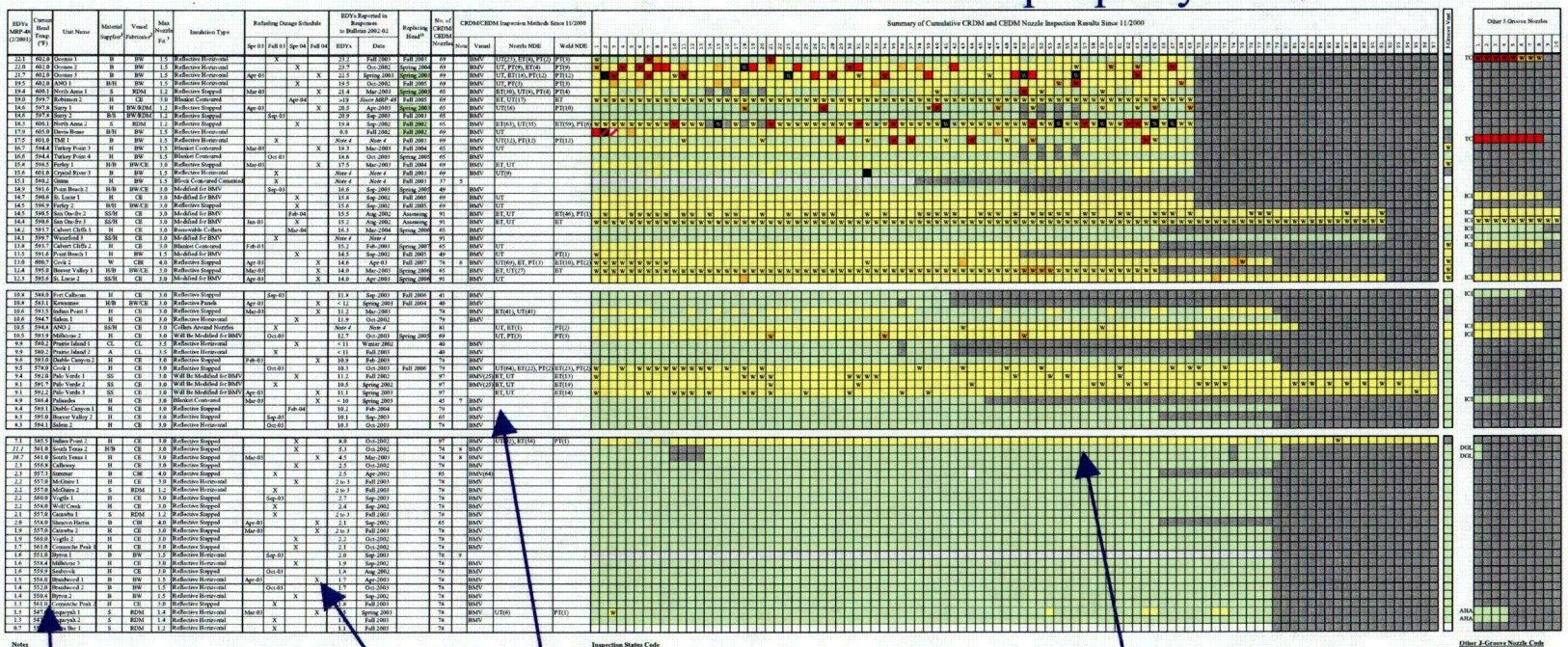
Introduction
MRP Database

- 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 →



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

Types of inspections performed

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

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

EPRI

C09

Introduction
NRC Chart for Tracking Insp. Results[1]

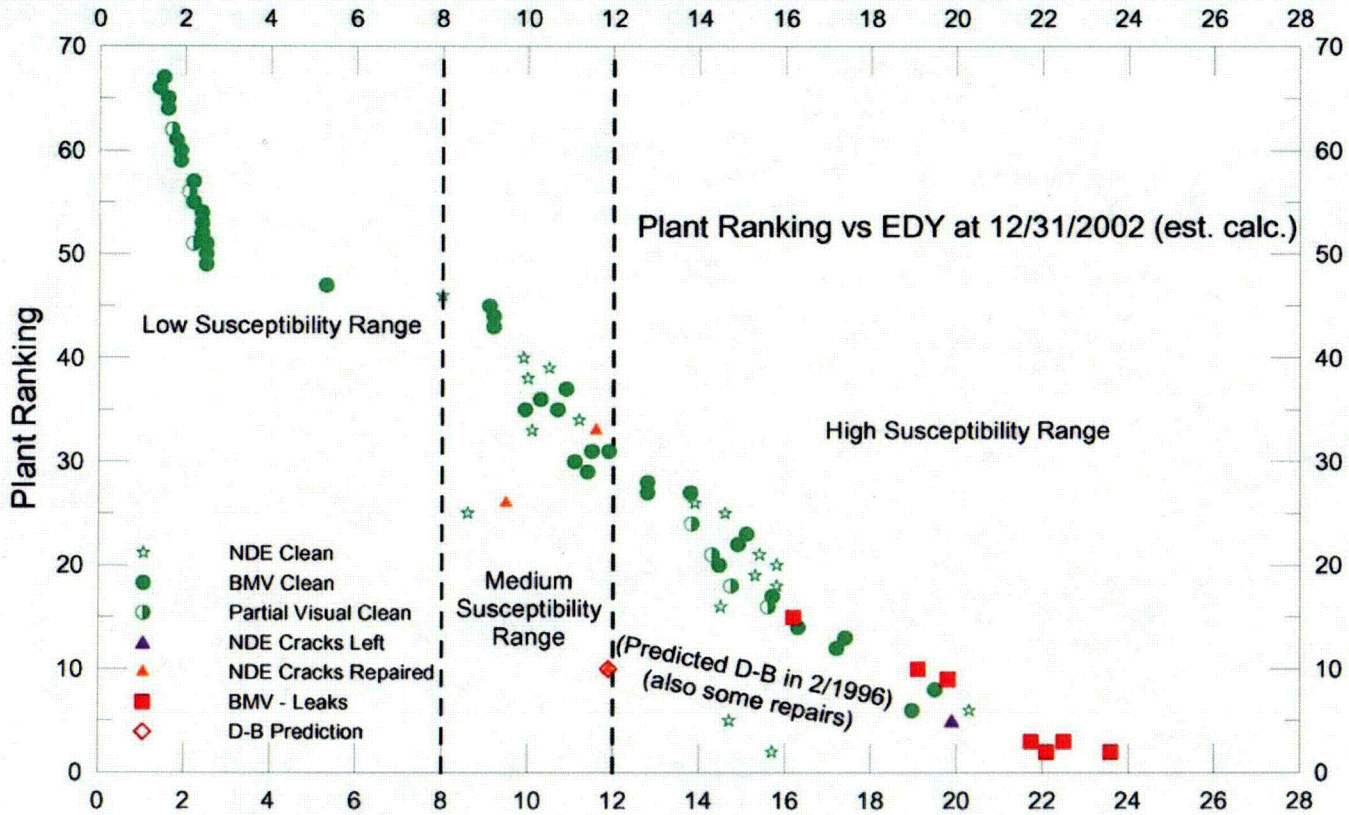


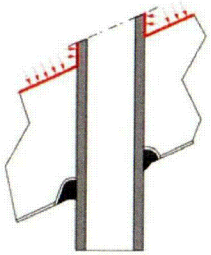
Figure 1. Ranking of domestic plants according to the EDY formula, showing results of inspections, evidence of leakage, and repairs. Many plants are shown with multiple symbols, indicating a "clean" inspection at inspection opportunity, followed by a different finding at a subsequent inspection (e.g.,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

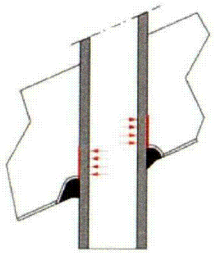
[1]Attachment to Memo, L. Marsh, "Use of the 'EDY' Formula – Susceptibility Model Critique," NRR-2002-018 User Request & LLTF Recommendations Action Plan, July 14, 2003

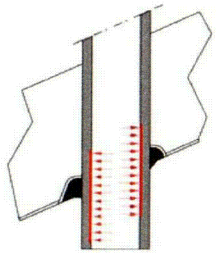
C10

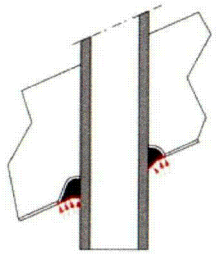
Introduction
Inspection Techniques

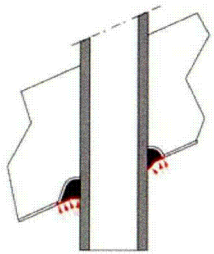
- Inspection techniques include visual inspections for leaks and surface and volumetric NDE of the nozzle,
  J-groove attachment weld, and interference fit zone

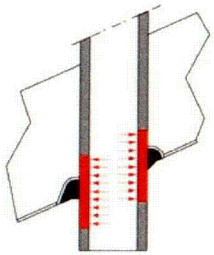


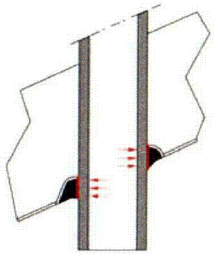


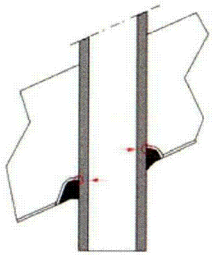


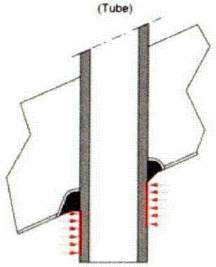


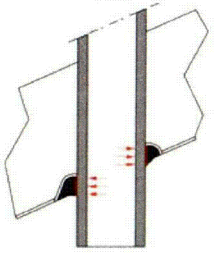


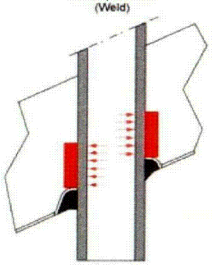












C11

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%

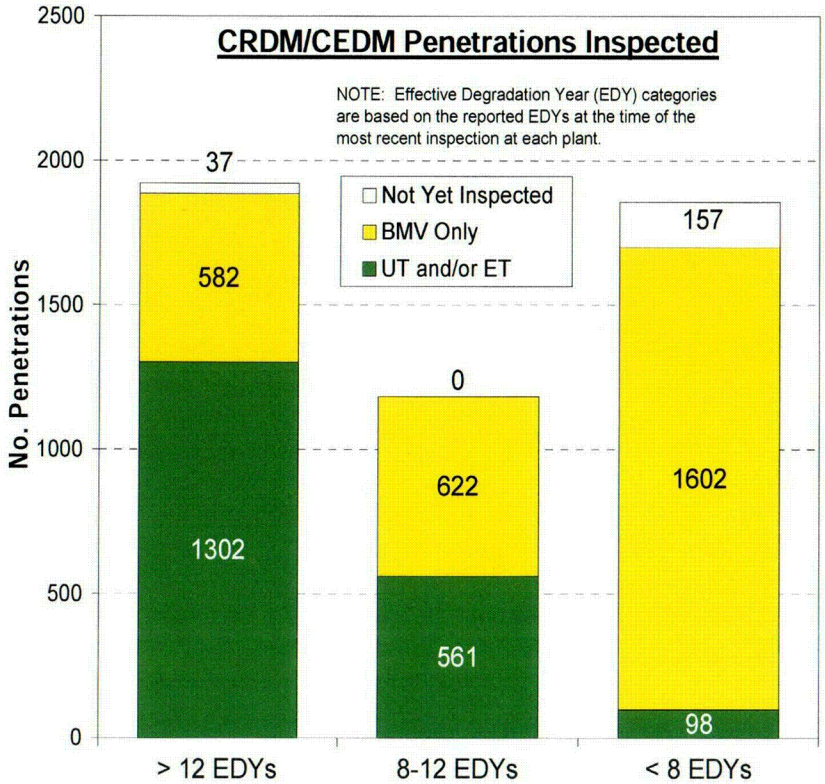
Cracking Detected
Summary

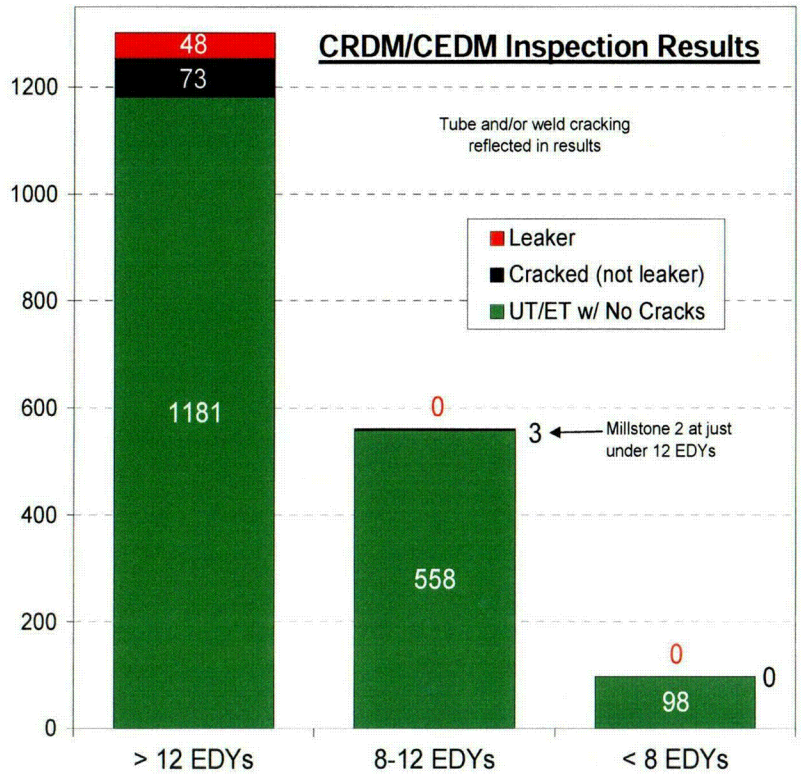
- About 51 CRDM nozzles have been found to be leaking:
  - All in the "> 12 EDY" category
  - 40 of 483 (8.3%) CRDM penetrations in 7 B&W plants
  - 11 CRDM penetrations in 3 heads fabricated by Rotterdam Dockyards, all due to weld cracking
- Little or no wastage has been detected except for the Davis-Besse 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

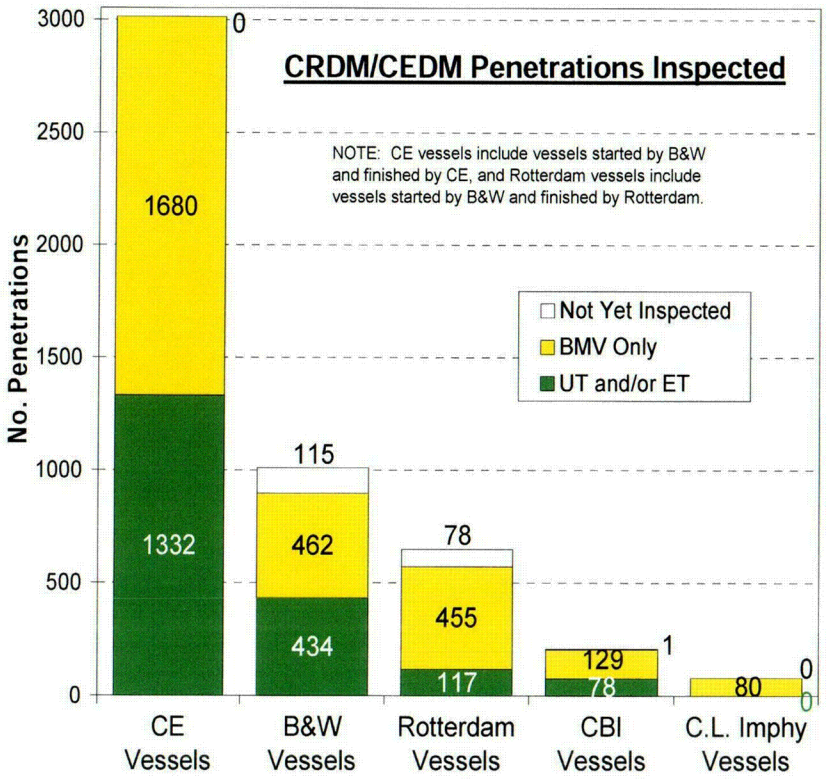
Subpopulation Statistics
By EDY Group

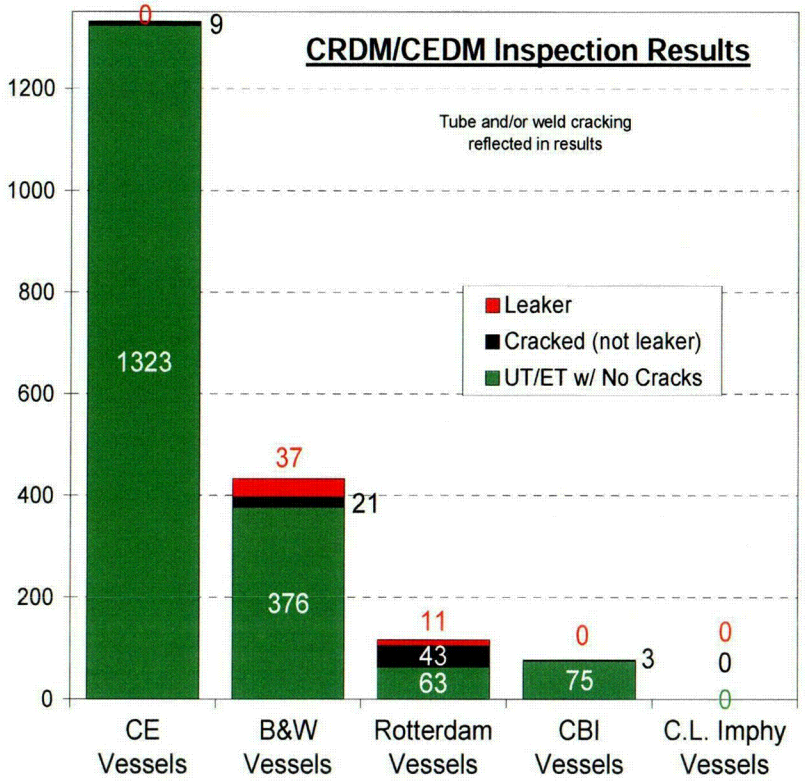




C12

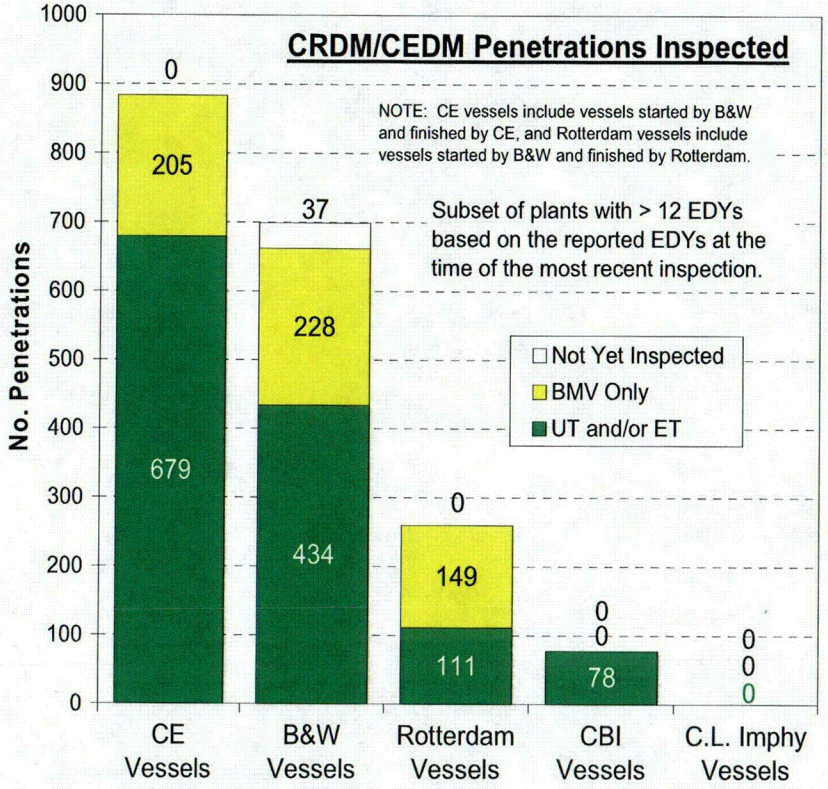
Subpopulation Statistics
By Head Fabricator (All EDY)

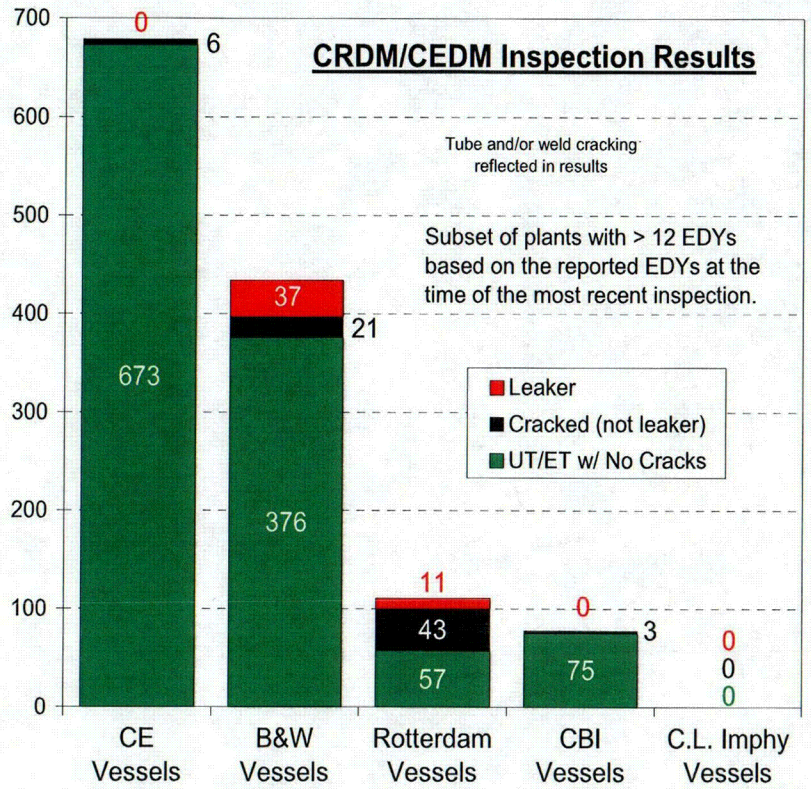




C13

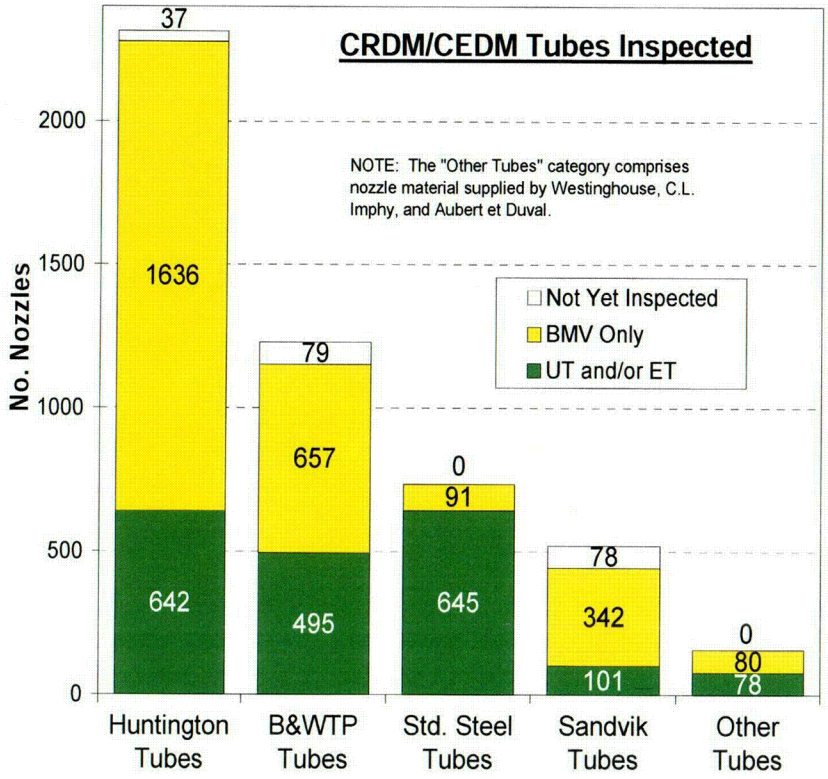
Subpopulation Statistics
By Head Fabricator (>12 EDYs)

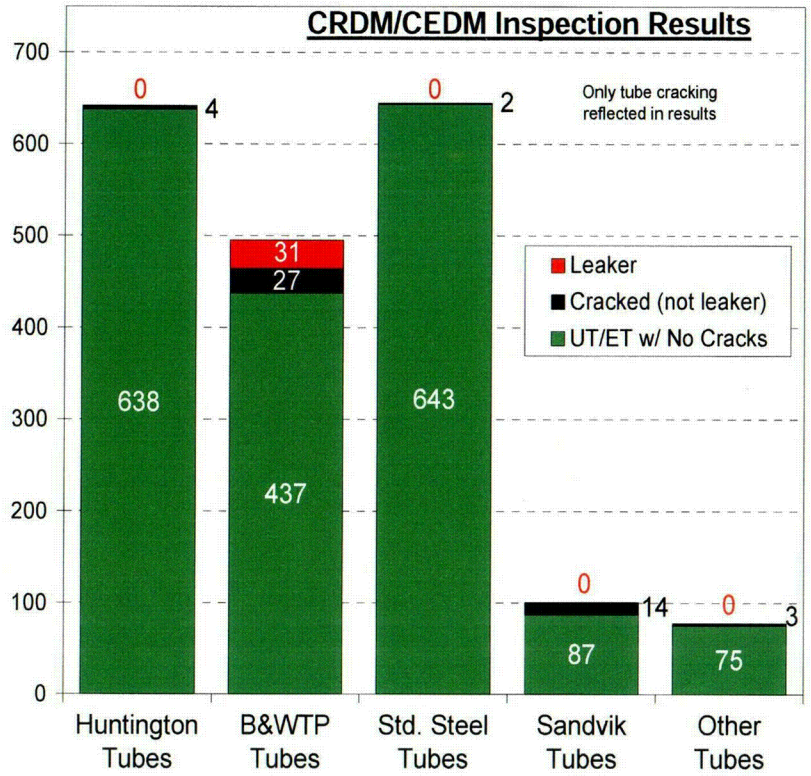




C14

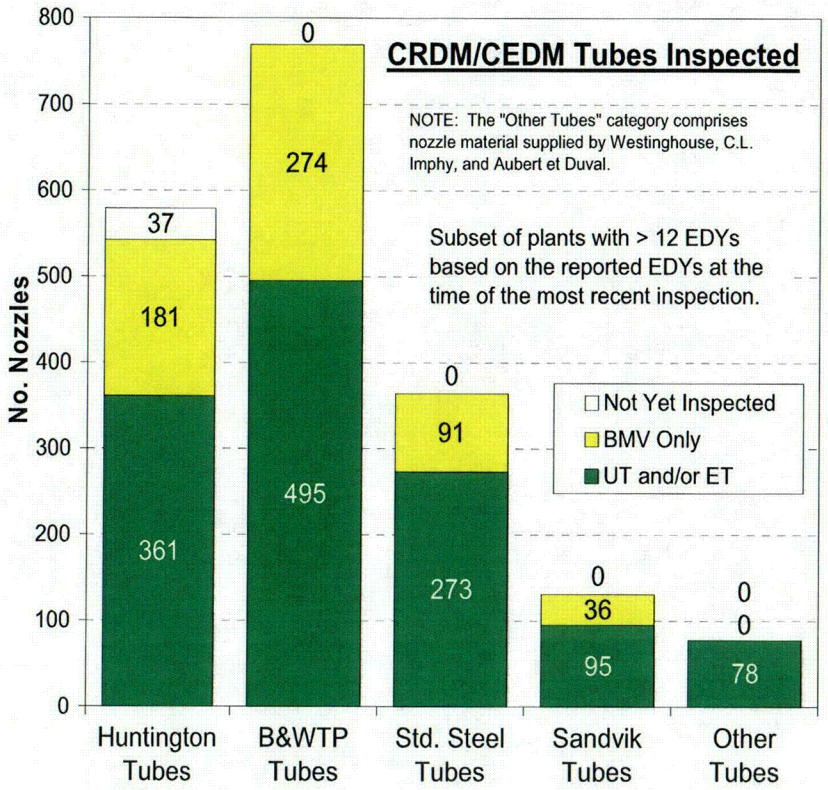
Subpopulation Statistics
By Nozzle Mat'l Supplier (All EDY)

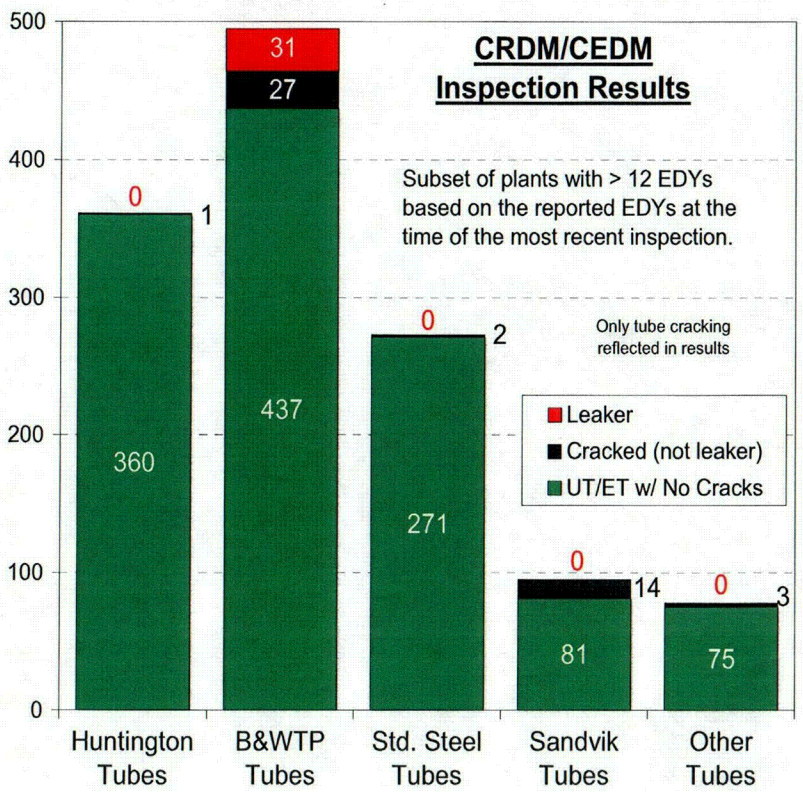




C15

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





C16

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

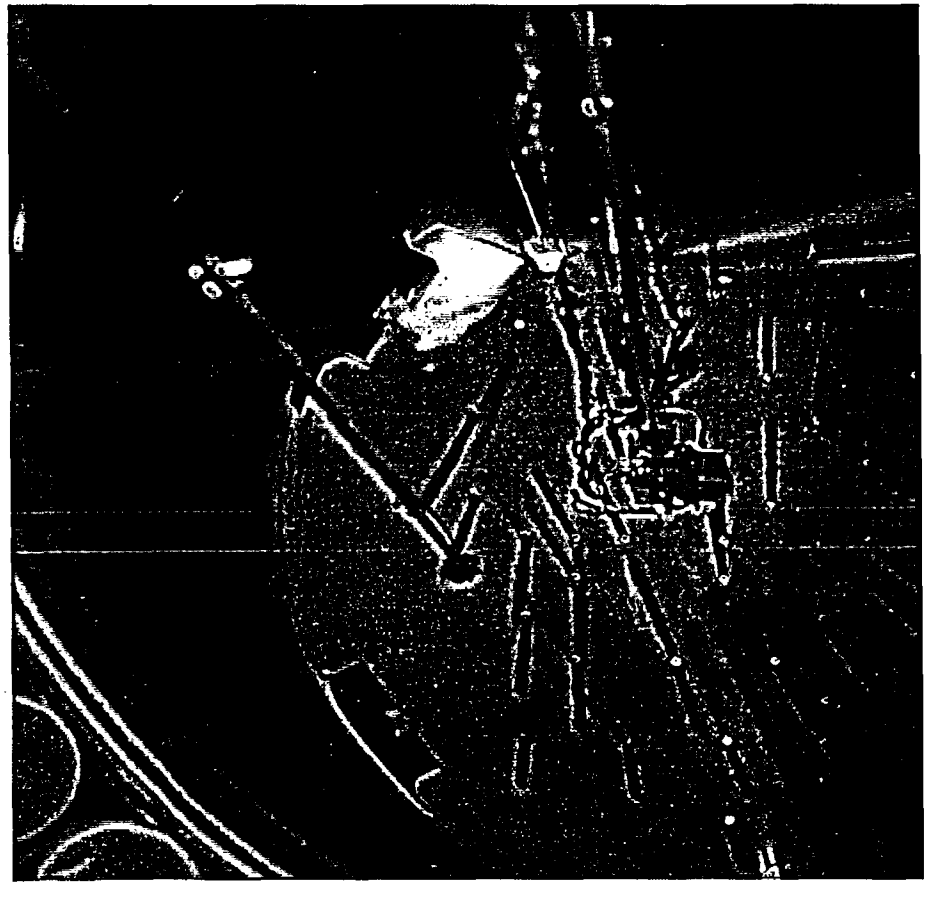
- 27 units have refueling outages this fall:
  - 5 will replace their heads with new heads having Alloy 690 material
  - About 6 plants in the "8-12 EDY" and "> 12 EDY" categories are expected to perform nonvisual inspections of all nozzles
- After fall 2003, it is expected that:
  - BMV and/or nonvisual 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

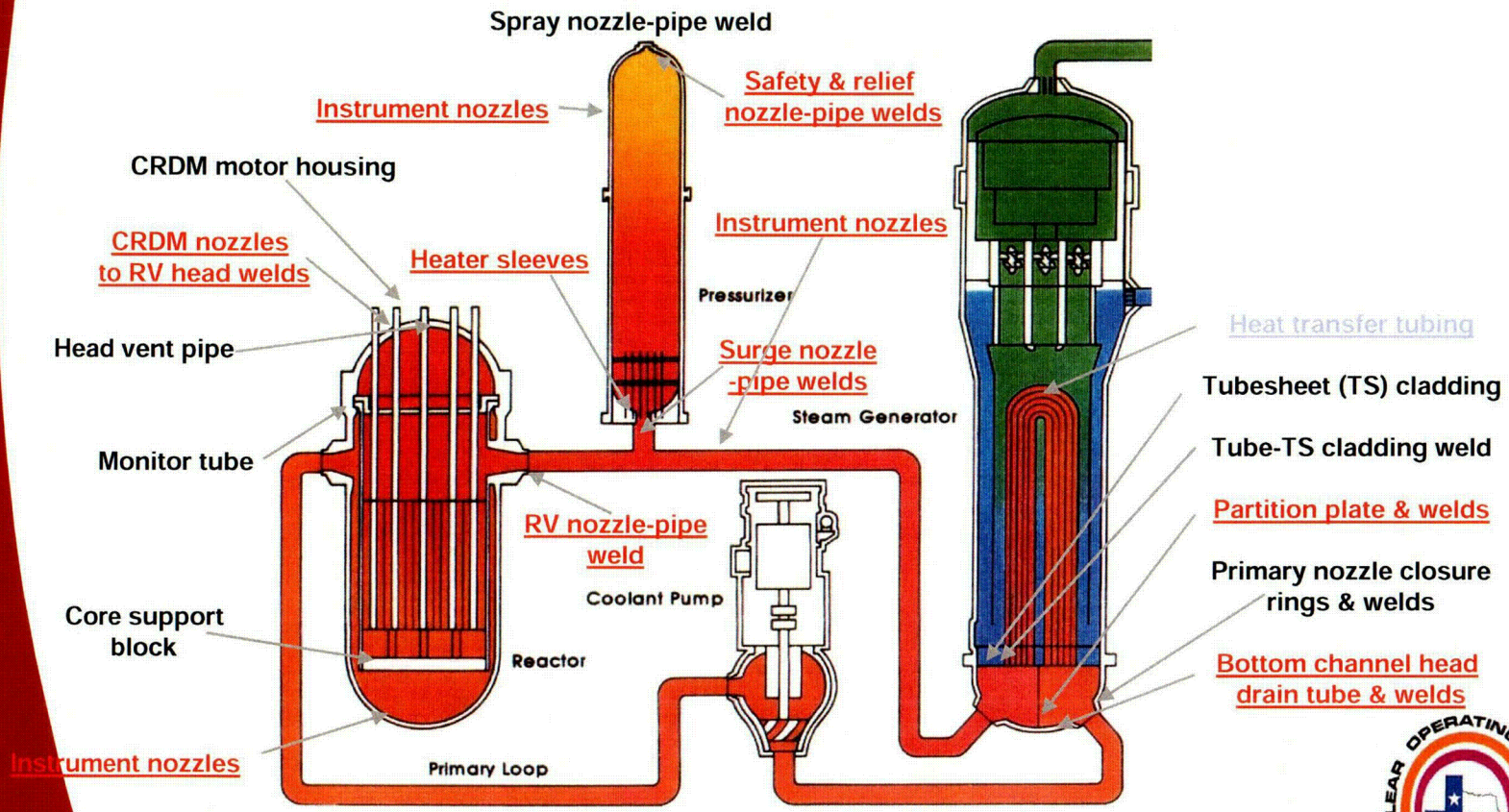
- Time at temperature is an important susceptibility factor
- The head fabricator and nozzle material supplier are also significant factors
  - Relatively little nozzle cracking has been detected in heads fabricated by CE using nozzle material supplied by Huntington Alloys or Standard Steel
  - No weld 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.



Typical Alloy 600 locations



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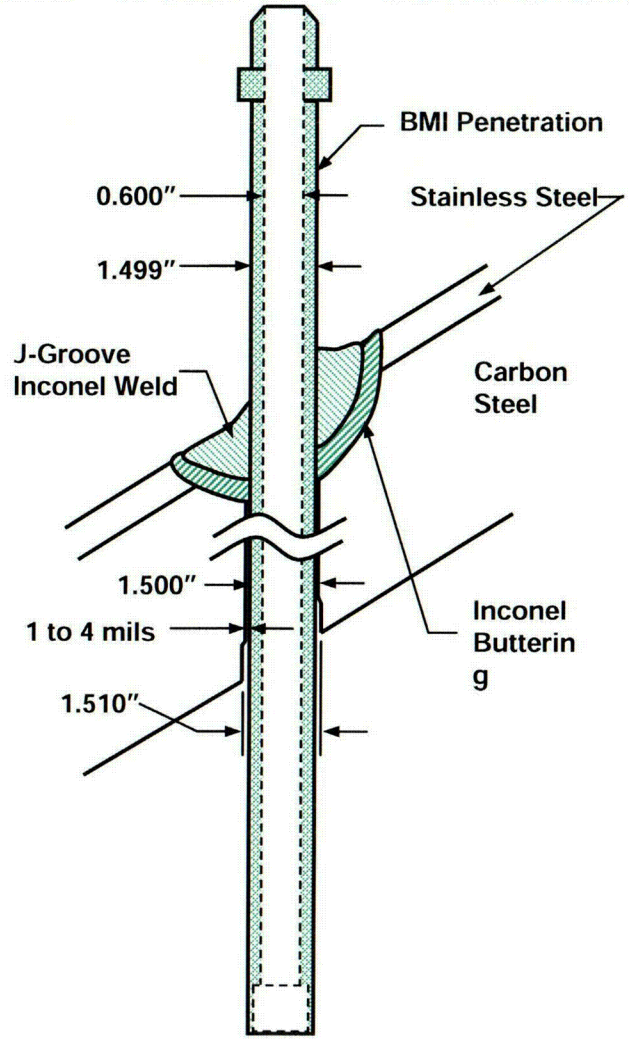
BMI Guide Tube Penetration



C18

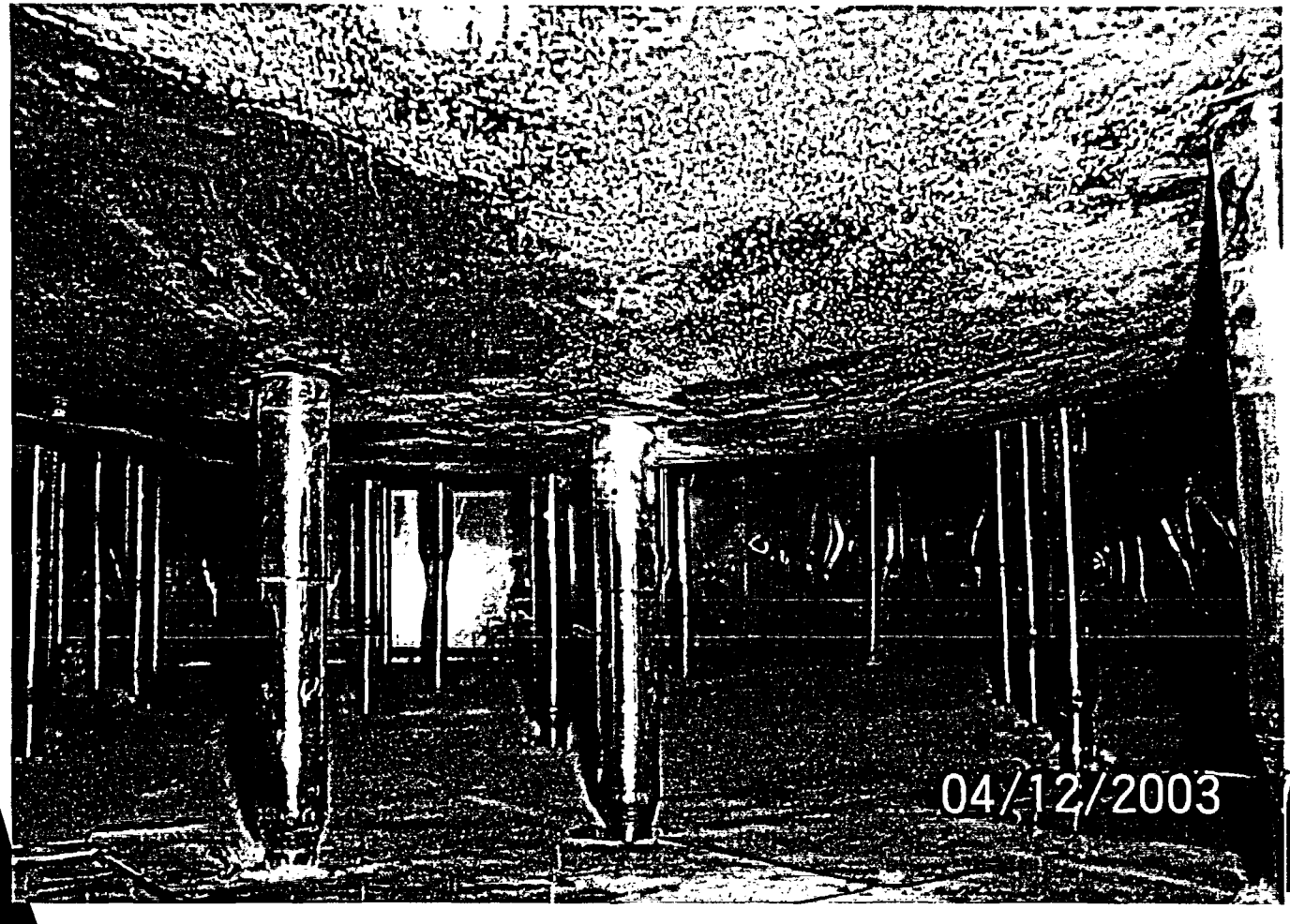
In France, EDF commissioned development of BMI ultrasonic inspection methods and has performed more than 500 examinations since 1992. Framatome has participated in all of these examinations. The 4 columns represent the type of UT examinations performed. Until the South Texas project, no confirmed leaking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

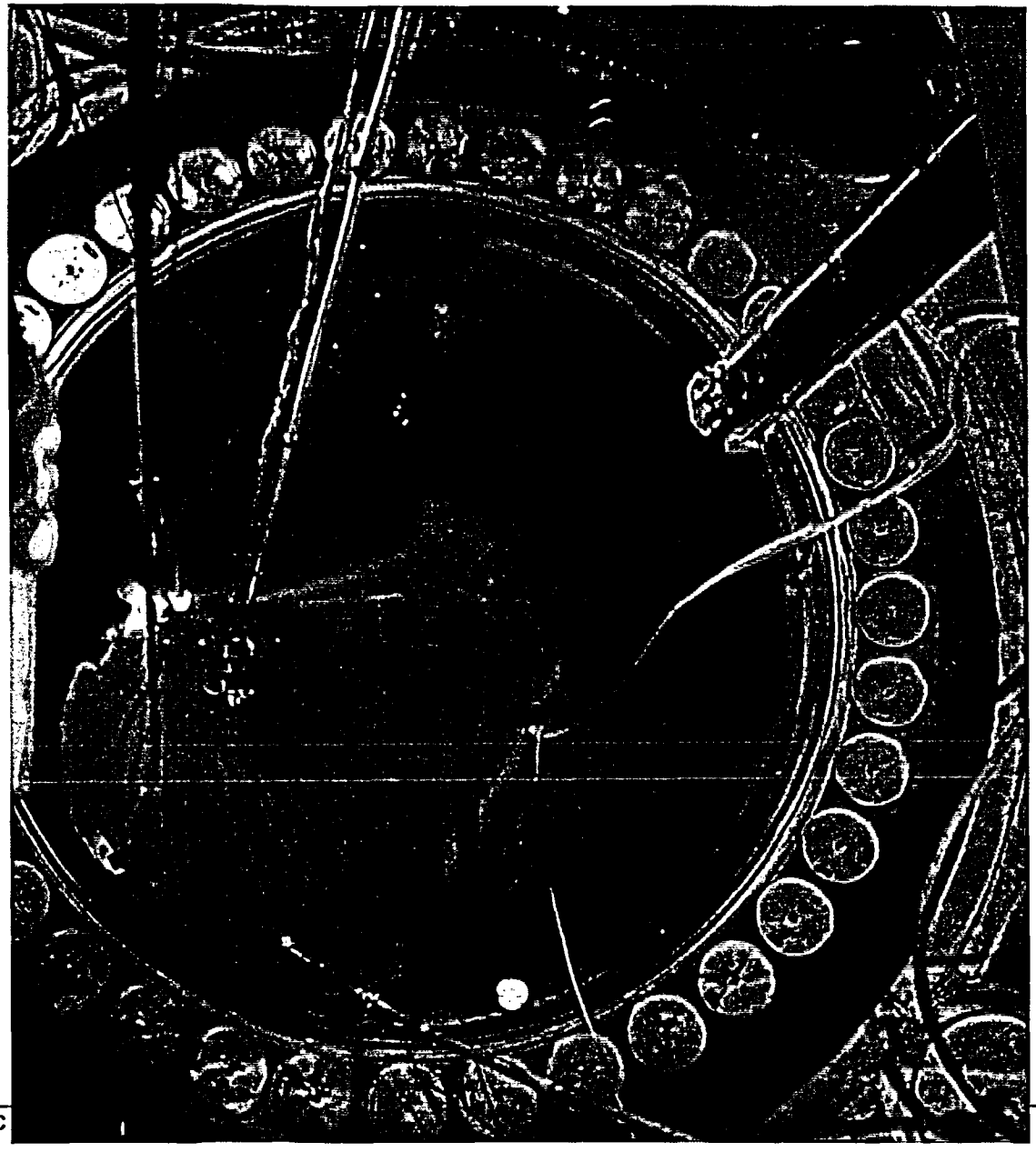
Plant - Unit	TOFD C	TOFD L	OL 0° base	OL 0° Comp.
TRICASTIN 1	49	22		
BUGEY 3	50	50		
FESSENHEIM 2	50	50		11
BUGEY 2	50	50		16
NOGENT 1	58	58		26
BLAYAIS 3	50	50		22
BUGEY 3	50	50	50	
TRICASTIN 2	50	50	50	
GRAVELINES 4	50	50	50	
PALUEL 1	58	58	?	?
FLAMANVILLE 1	58	58		13
GRAVELINES 1	50	50		3
SOUTH TEXAS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

Comprehensive Examination Performed Using Industry Experts

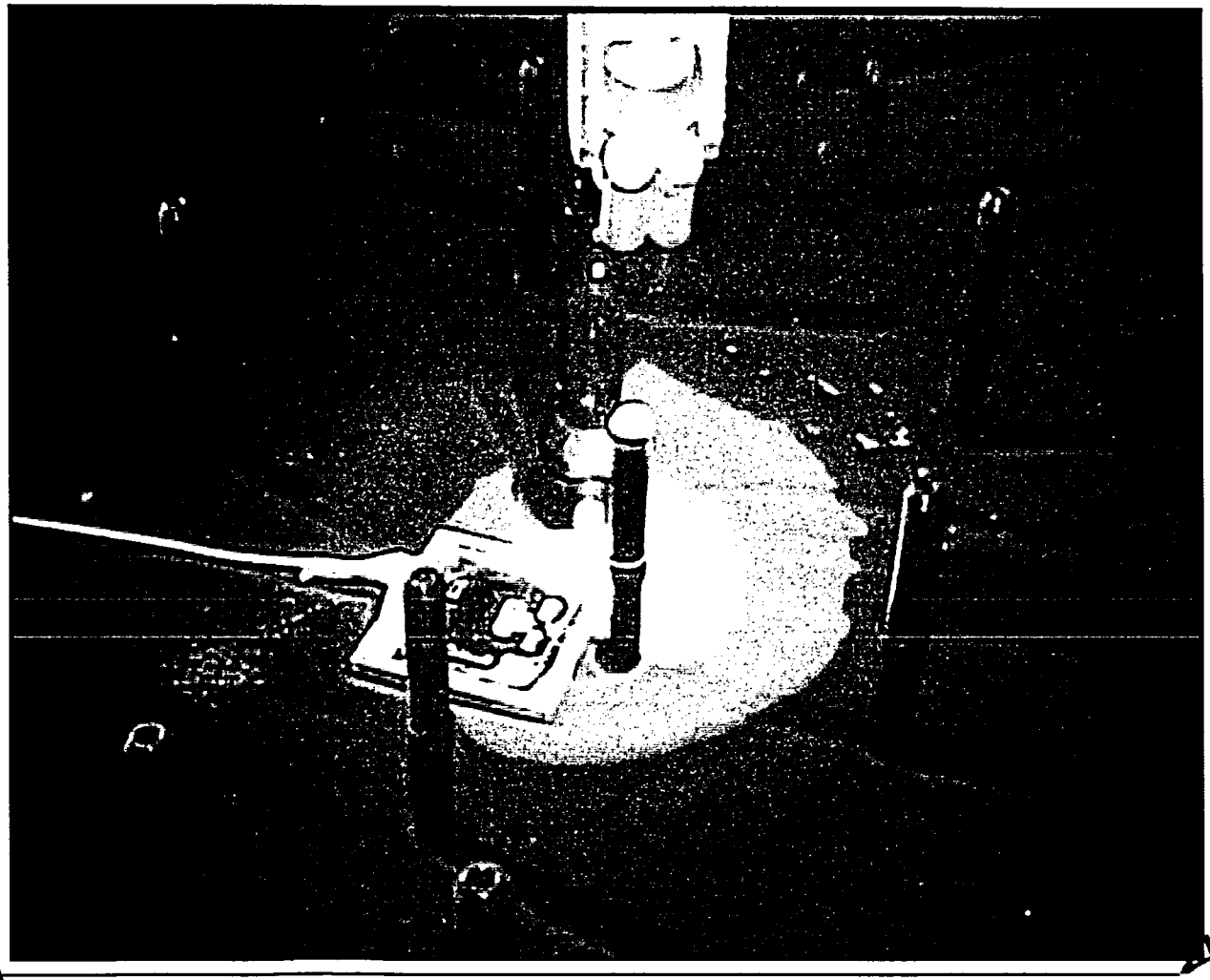
- UT from penetration tube ID
- Enhanced visual exam of J-groove weld surface
- Volumetrically interrogate vessel base metal for wastage
- ET from penetration tube ID
- ET of J-groove weld surface
- Profilometry
- Borescope examinations
- Helium tests
- Metallurgical analyses of removed nozzle remnants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

Unit 1 Reactor Vessel Bottom Head

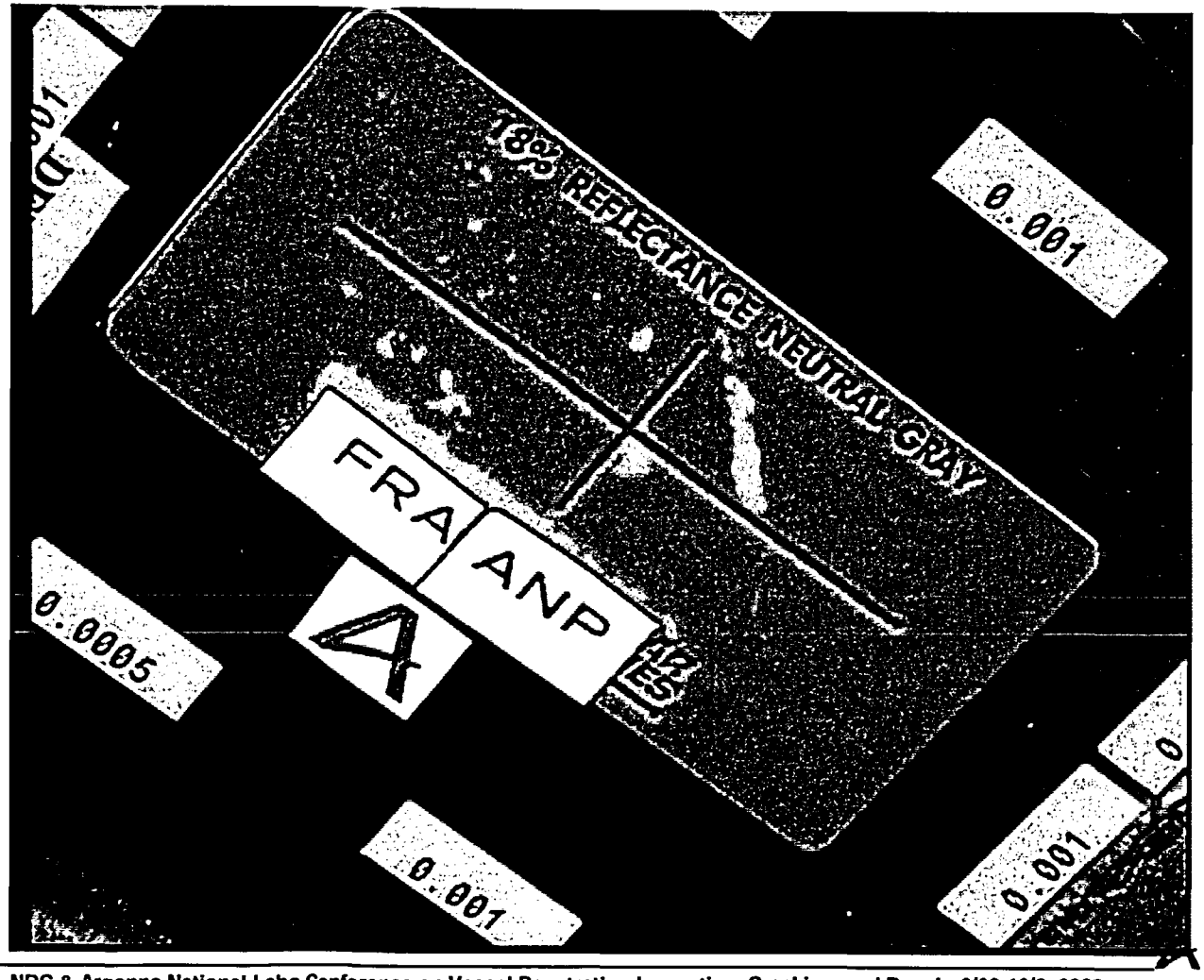




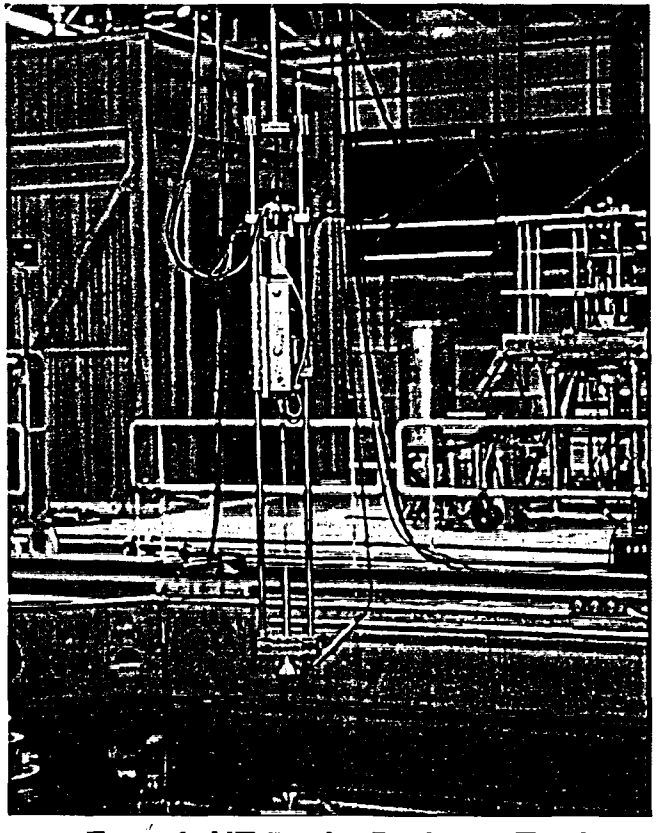
Penetration Overview



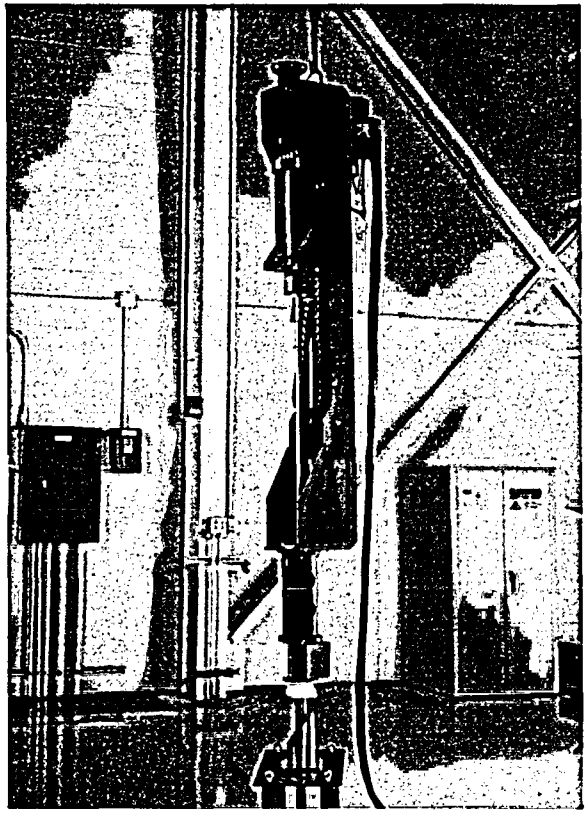
Enhanced Visual



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.

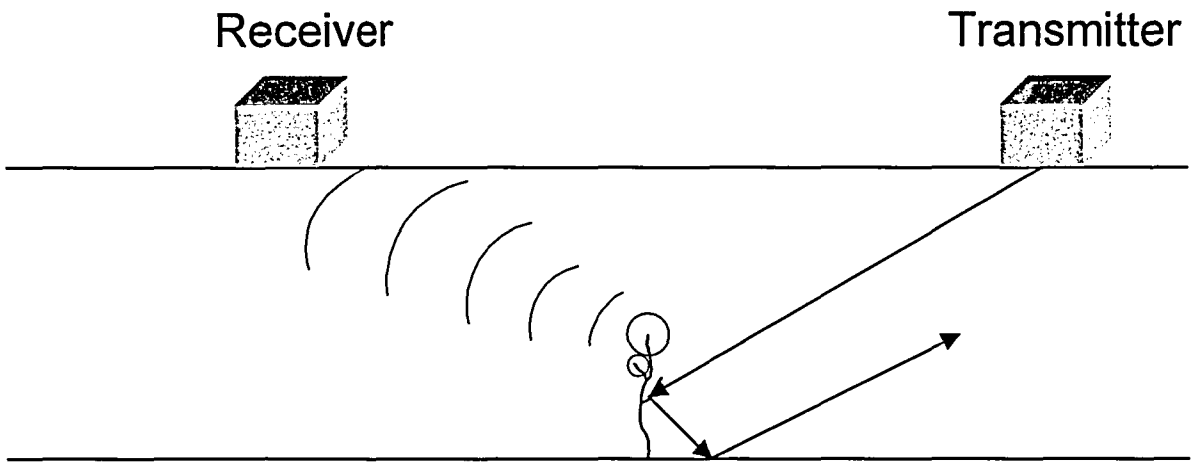


French UT Probe Delivery Tool



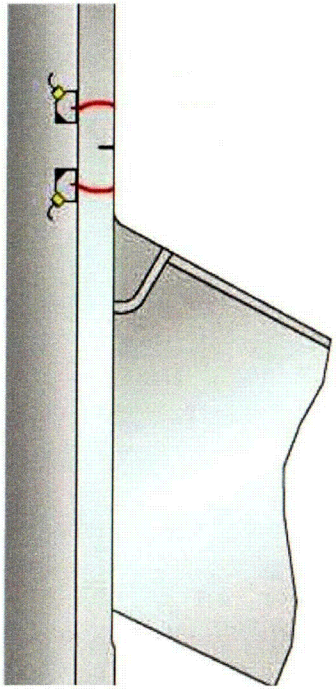
US UT Probe Delivery Tool

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

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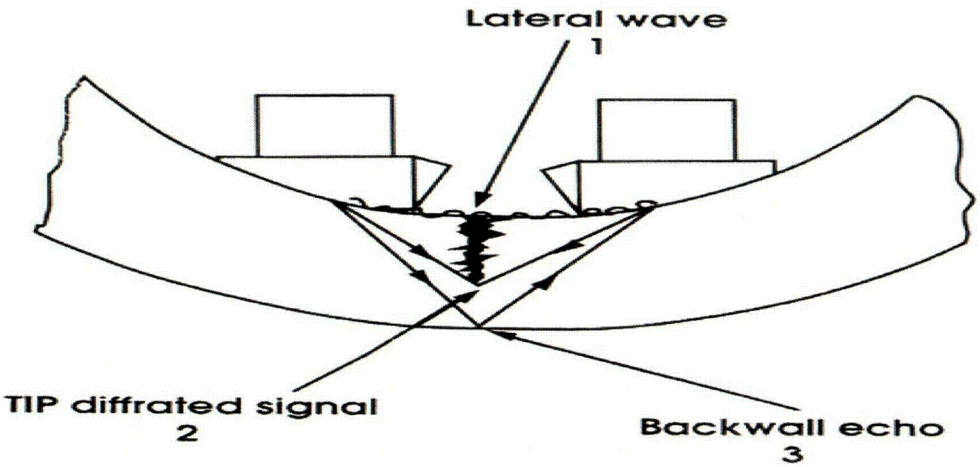
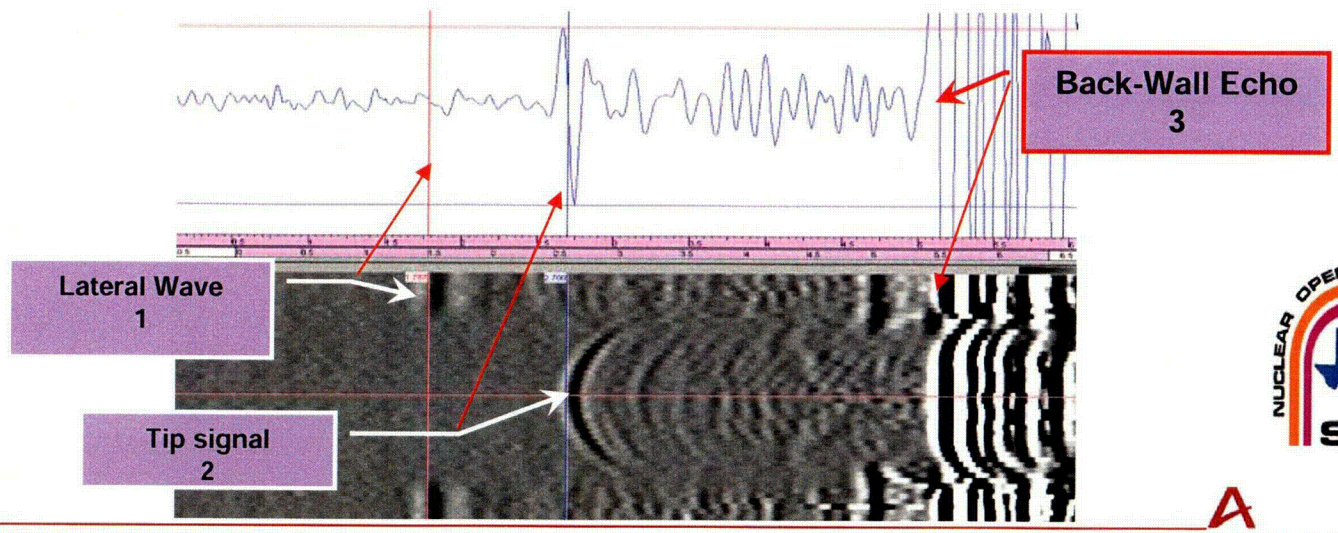
TOFDT (Time Of Flight Diffraction Technique)





C20

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

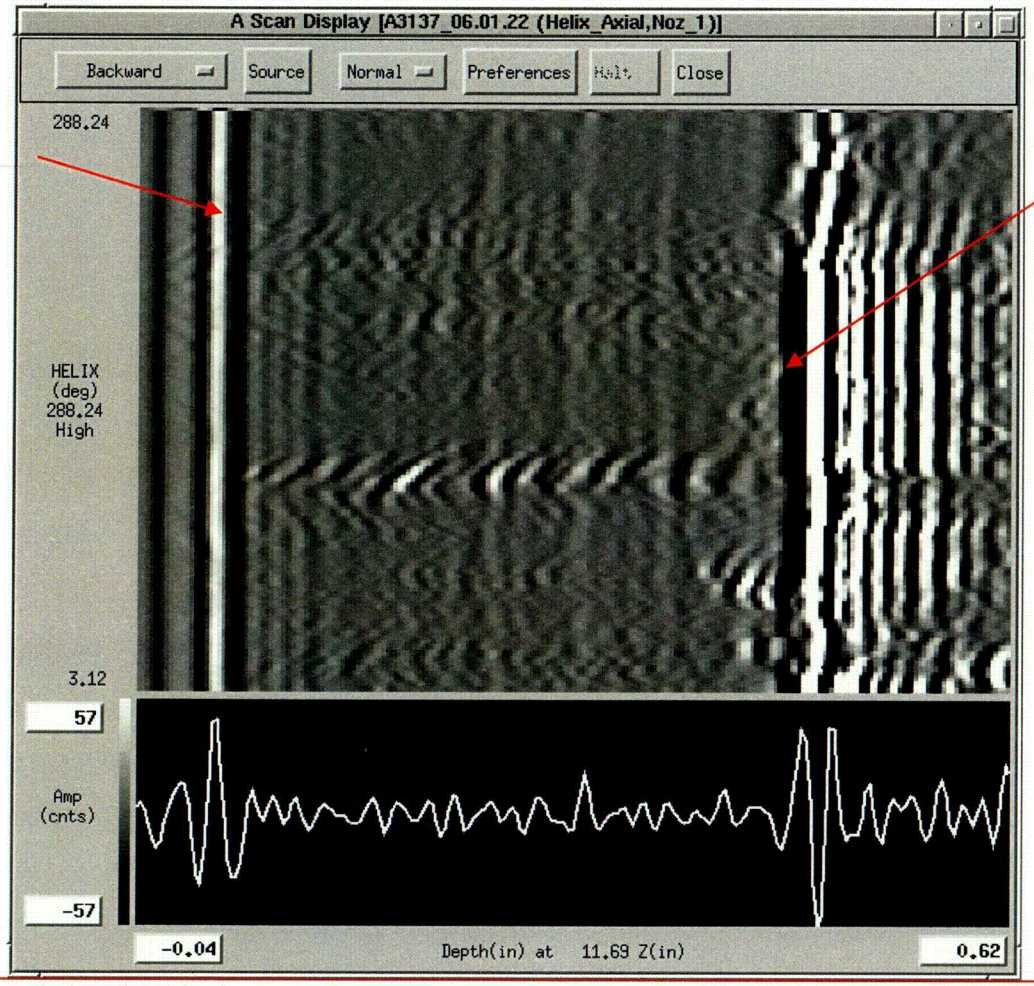
Demonstration Protocol (cont'd)

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

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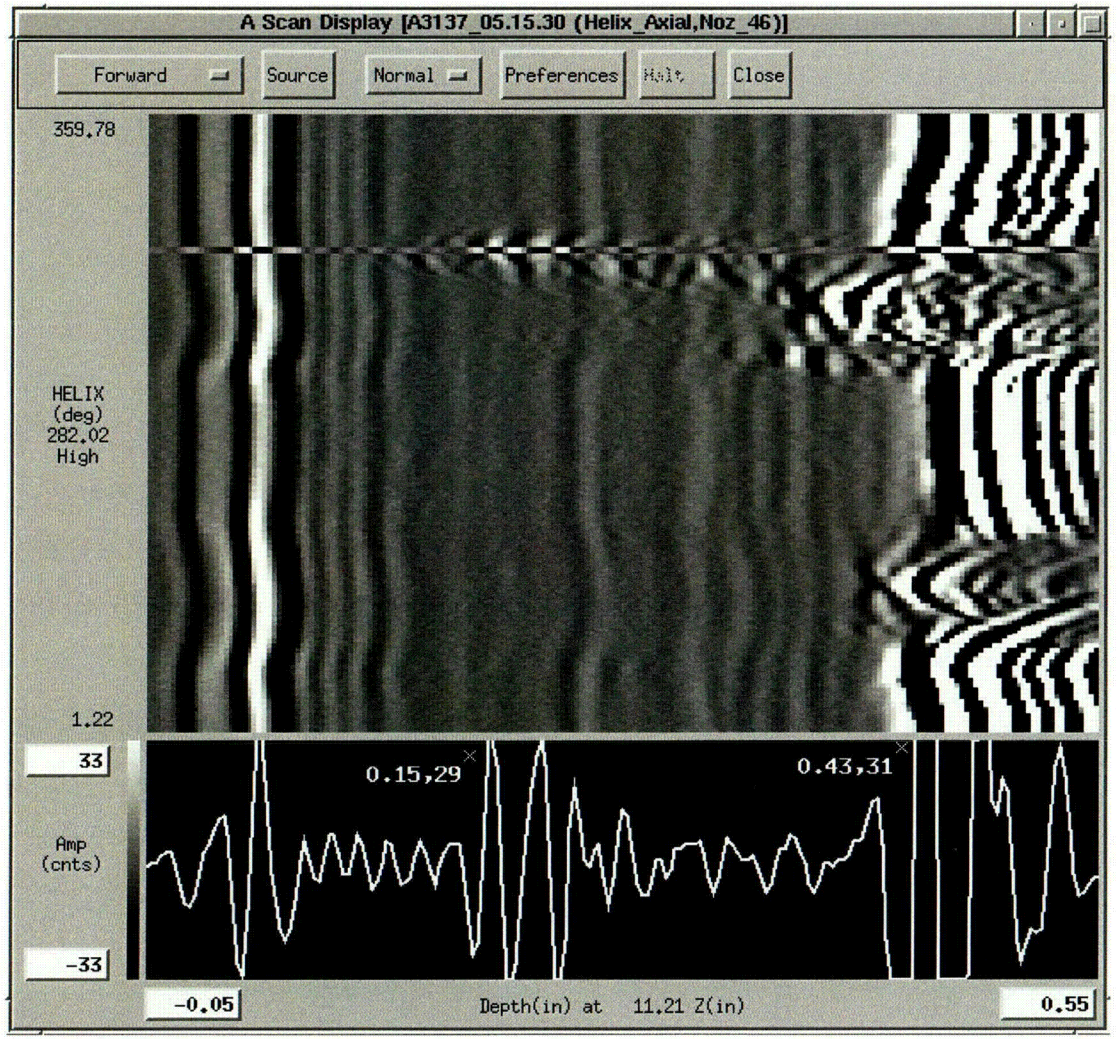
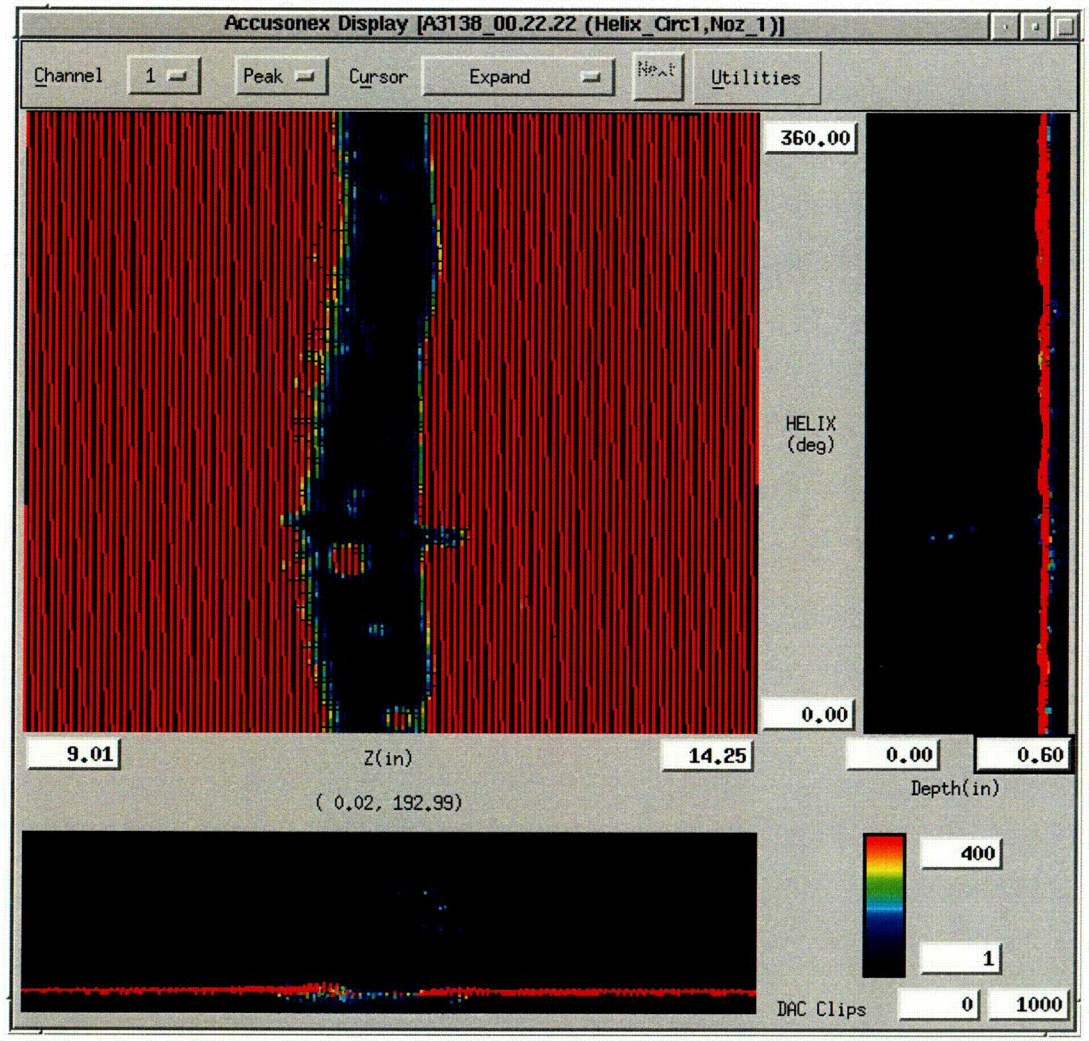
C21

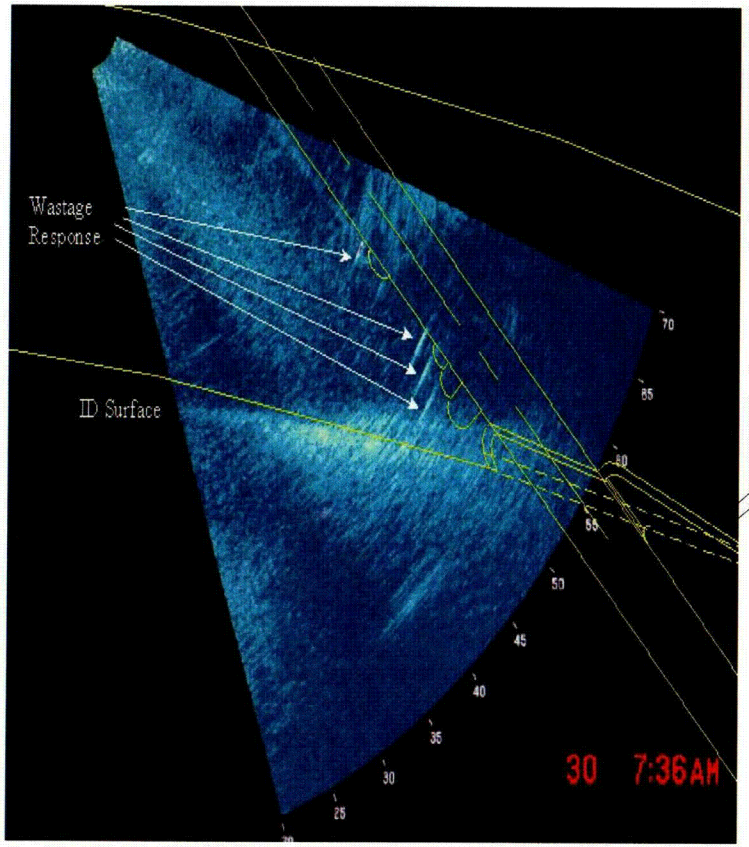
Penetration #46 Axial Scan

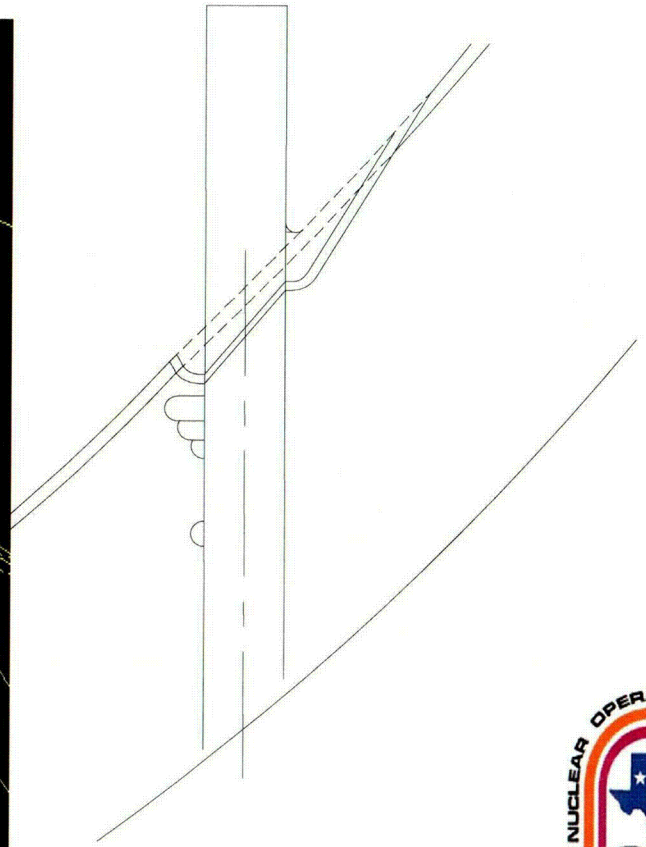


Penetration #1 Weld Profile



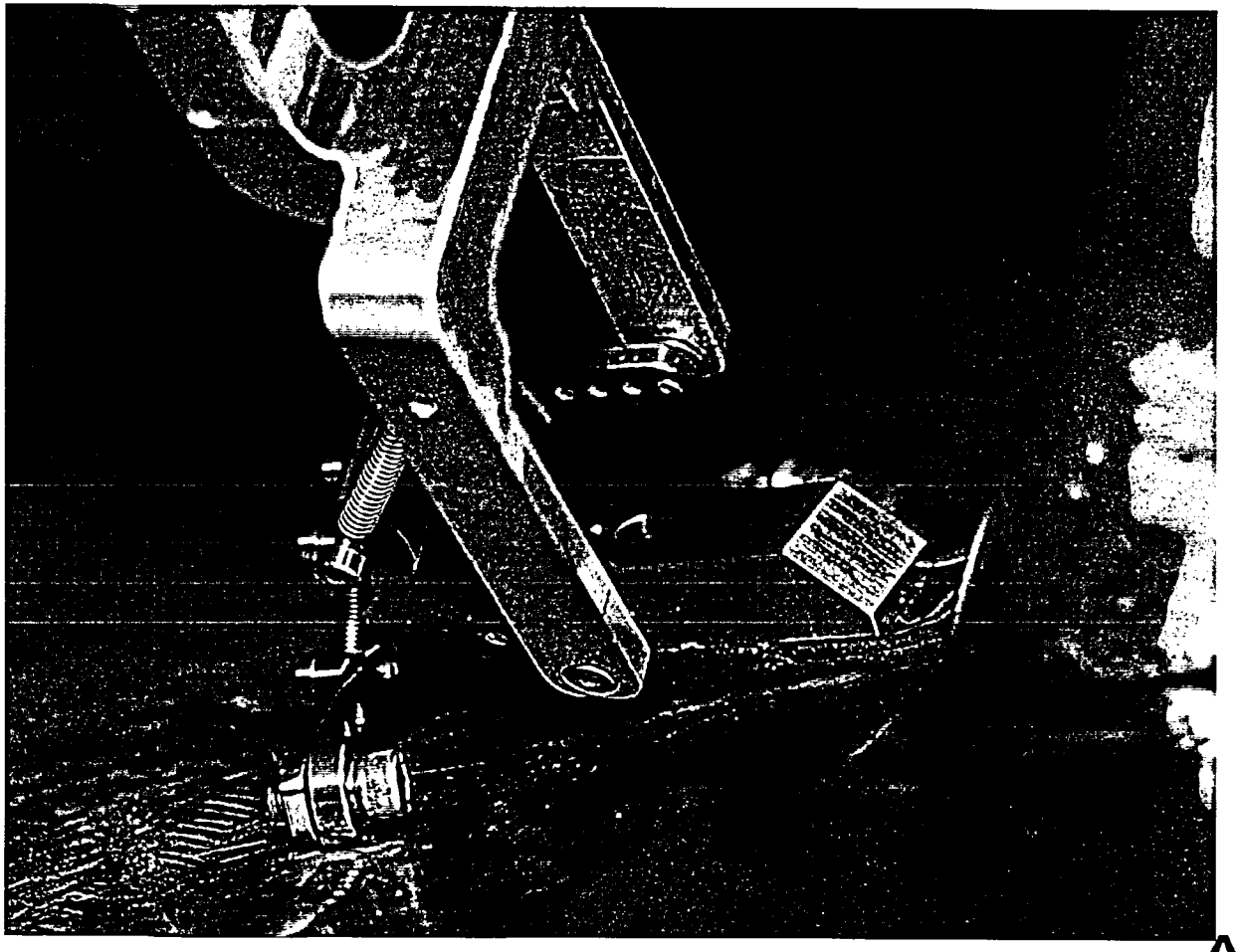
Phased Array UT to Identify Wastage



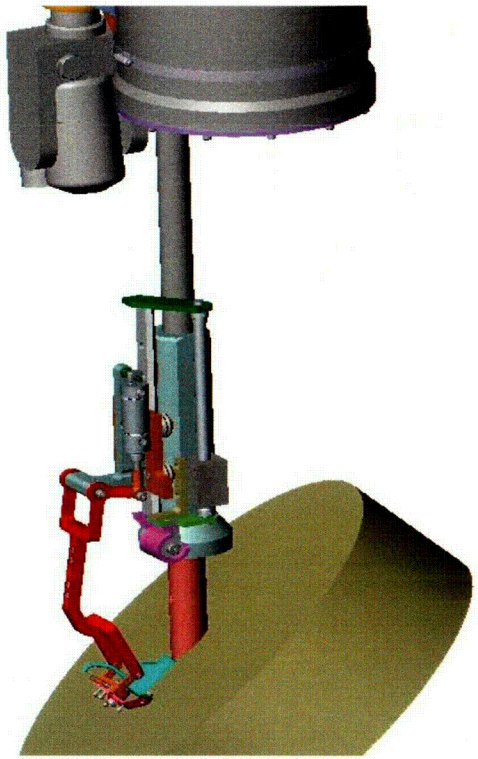


C24

Eddy Current J-Groove Probe



Incore J-Groove Eddy Current



C25

Examination Matrix

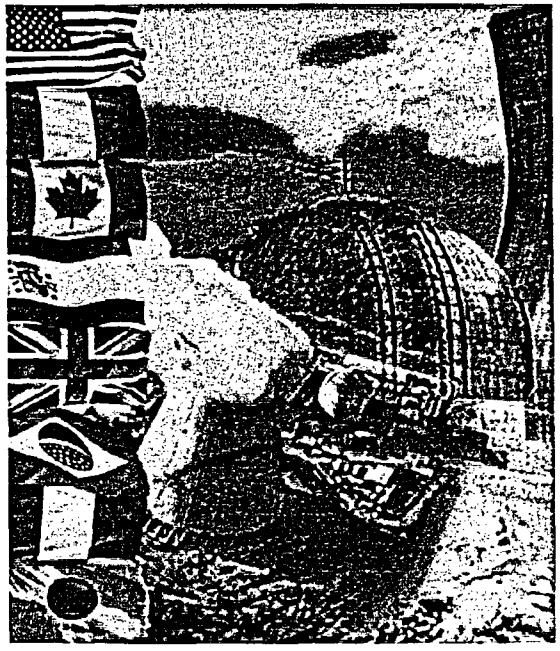
Techniques	Benefits
UT - circ	Most beneficial tool to detect and size flaws of different depths, lengths, and orientation.
UT - axial	Very beneficial to detect and size flaws
UT - 0	Good tool to discriminate between weld defects and cracks
EVT-1	Beneficial to detect surface indications with 0.0005 inch 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

EPRI

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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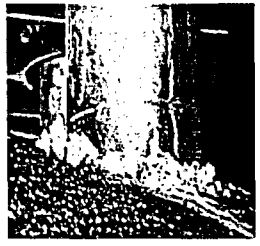
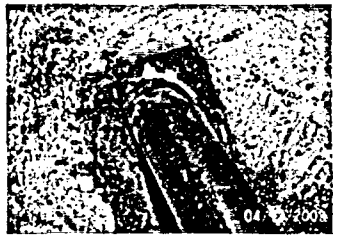
MRP Visual Examination Guidance

- 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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EPRI

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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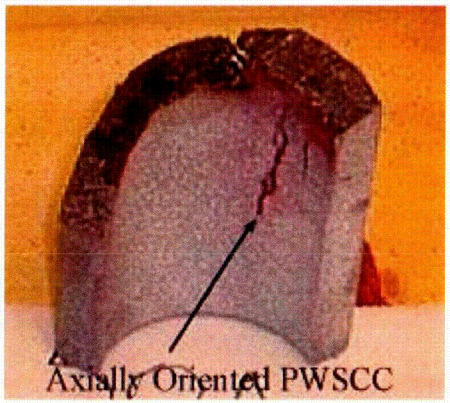
Oconee Specimens

- 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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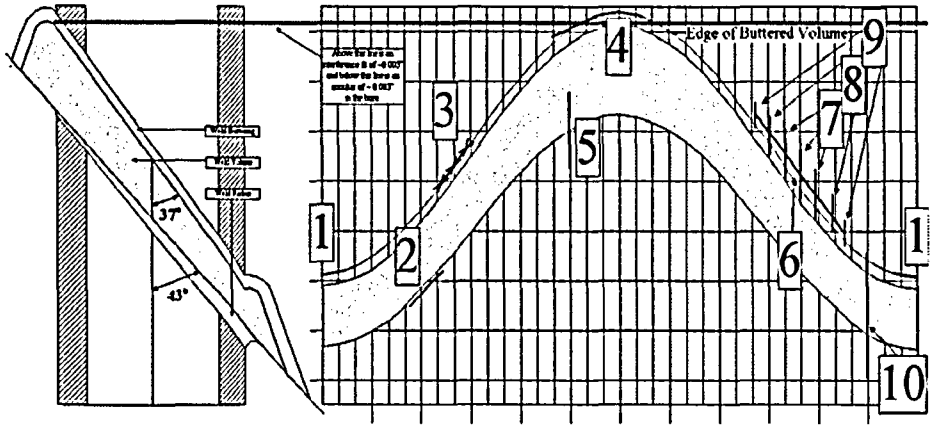
2001 Full-Scale Mock-up



♦#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

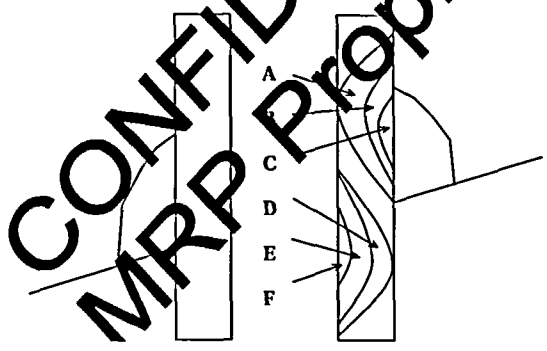
Example Detailed Summary Table

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
EPRI Demonstrations conducted for 97-01 ID flaws									
BP TOFD for Axial flaws (7 mks)					D, S	D, S	M	EN 241 GEN 3 (1)	02/1994
BP TOFD for Circ Flaws (7 mks)					D, S	D, S	M	EN 241 GEN 3 (1)	02/1994
BP ID ET					D, S	D, S	N/A	(1)	02/1994
BP TOFD for Axial flaws (7 mks)					D, S	D, S	M	EN 241 GEN 3 (1)	02/1994
BP ID ET					D, S	D, S	N/A	(1)	02/1994
BP TOFD for Axial (7 mks)					D, S	D, S	M	ID 061 (1)	12/1996
BP ID ET					D, S	D, S	N/A	ID 061 (1)	12/1996
BP TOFD for Axial flaws 10 mks PCS 10 w/RD Tech System					D, S	D, S	M	PB 447, Rev. 3 05/08/2000 (1)	05/2000
BP TOFD for Axial flaws 6 mks PCS 18 w/RD Tech System					D, S	D, S	M	PB 447, Rev. 3 05/08/2000 (1)	05/2000
BP TOFD for Circ flaws 10 mks PCS 10 w/RD Tech System					D, S	D	N/A	PB 447, Rev. 3 05/08/2000 (1)	05/2000
BP TOFD for Circ flaws 6 mks PCS 18 w/RD Tech System					D, S	D	M	PB 447, Rev. 3 05/08/2000 (1)	05/2000
BP ID ET					D, S	D	N/A	(1)	05/2000
Weld mapping demonstrations conducted for MRP ID flaws									
BP TOFD for Axial flaws 6 mks PCS 18 & PCS 24 w/RD Tech System	(4)	(4)	(4)	(4)	(4, 5)	(4, 5)	M	EMUT 02, Rev. 0, 09/2001 (6)	09/2001
BP TOFD for Circ flaws 6 mks PCS 18 & PCS 24 w/RD Tech System	(4)	(4)	(4)	(4, 5)	(4, 5)	(4, 5)	M	EMUT 02, Rev. 0, 09/2001 (6)	09/2001
BP PE for Circ flaws w/RD Tech System	(4)	(4, 7)		N/A	N/A	N/A	N/A	EMUT 02, Rev. 0, 09/2001 (6)	09/2001
BP TOFD for Axial flaws 6 mks PCS 18 w/Intraspect System	(4, 5)		OR	(4, 5)	(4, 5)	(4, 5)	M	EMUT 02, Rev. 0, 09/2001 (6)	01/2002
BP TOFD for Axial flaws 6 mks PCS 24 w/Intraspect System	OR		D	(4, 5)	(4, 5)	(4, 5)	M	EMUT 02, Rev. 0, 09/2001 (6)	01/2002
BP TOFD for Circ flaws 6 mks PCS 18 w/Intraspect System	(4, 5)	(4, 5)	OR	(4, 5)	(4, 5)	(4, 5)	M	EMUT 02, Rev. 0, 09/2001 (6)	01/2002
BP TOFD for Circ Flaws 6 mks PCS 24 w/Intraspect System	OR	D	D	(4, 5)	(4, 5)	(4, 5)	M	EMUT 02, Rev. 0, 09/2001 (6)	01/2002
BP TOFD (only 5 mks PCS 24 demonstrated) w/Intraspect System	OR	D	D	(4, 5)	(4, 5)	(4, 5)	M	EMUT 02, 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)



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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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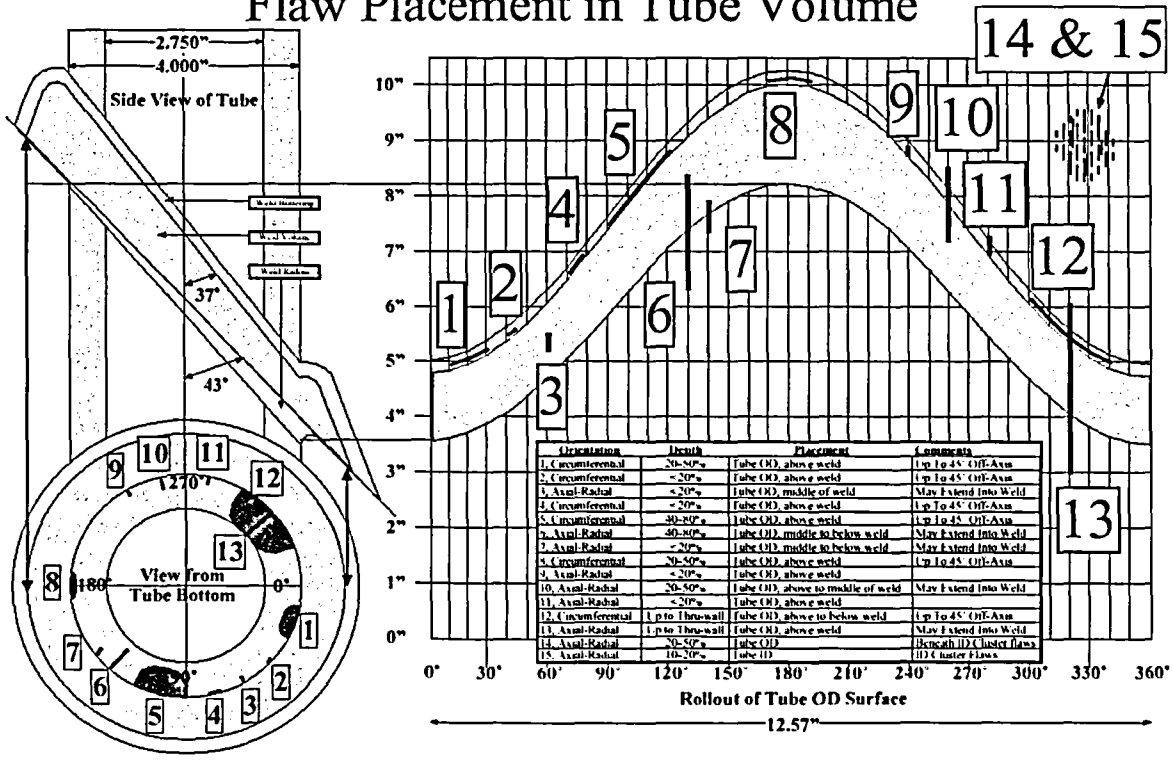
2002 Mock-up – Tube Flaws- Schematic

MRP CRDM Generic Mockup Layout for Flaw Placement in Tube Volume



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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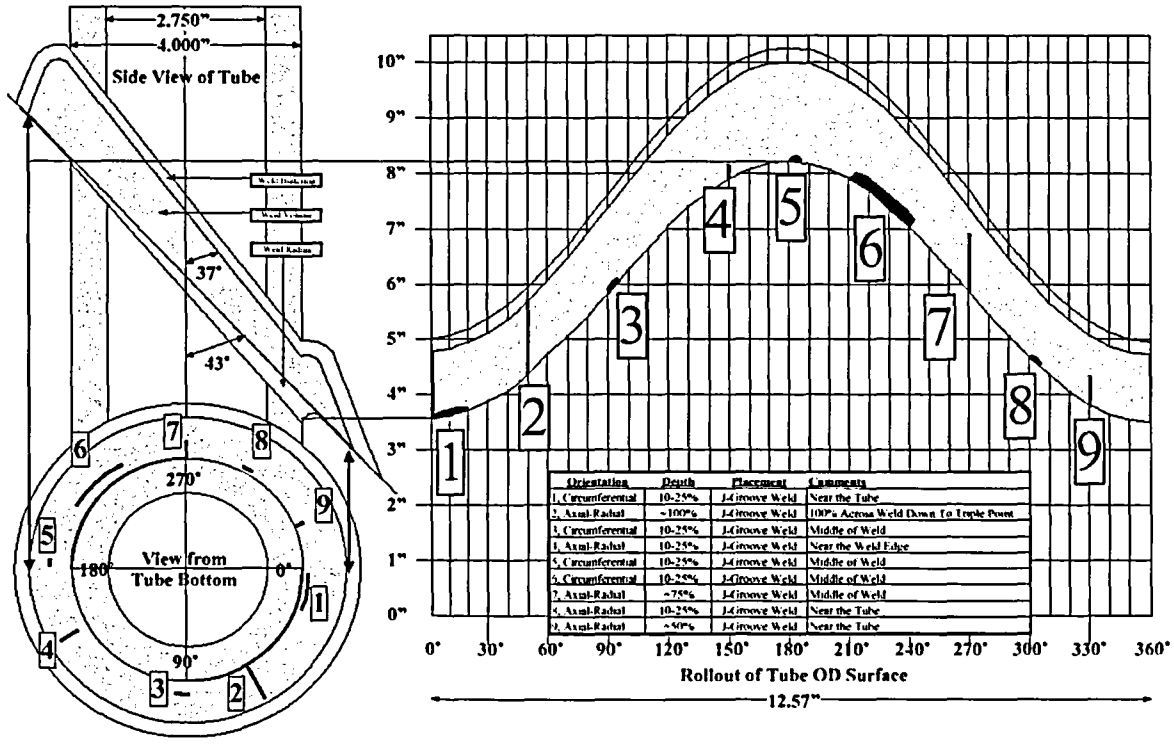
2002 Mock-up – Weld flaws-Schematic

MRP CRDM Generic Mockup Layout for Flaw Placement in J-Groove Weld Volume



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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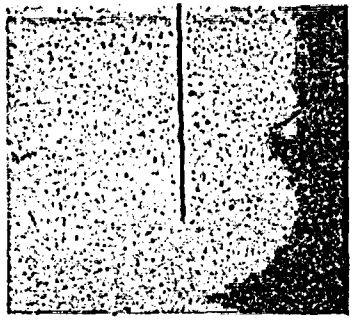
Manufactured Flaws - CIP

- 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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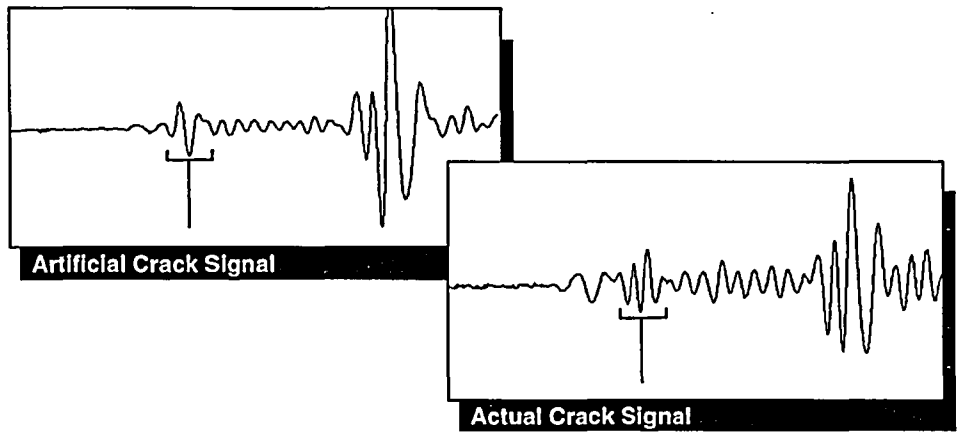
Manufactured Flaws – CIP cont..

- 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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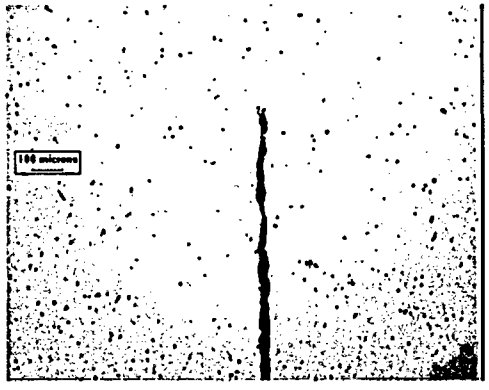
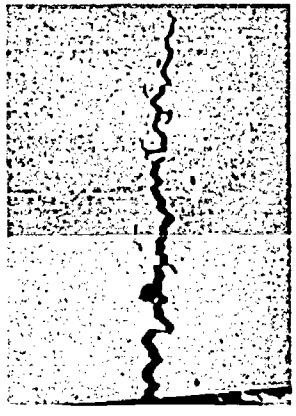
CIP Flaw Mock-ups – Technical Basis

- 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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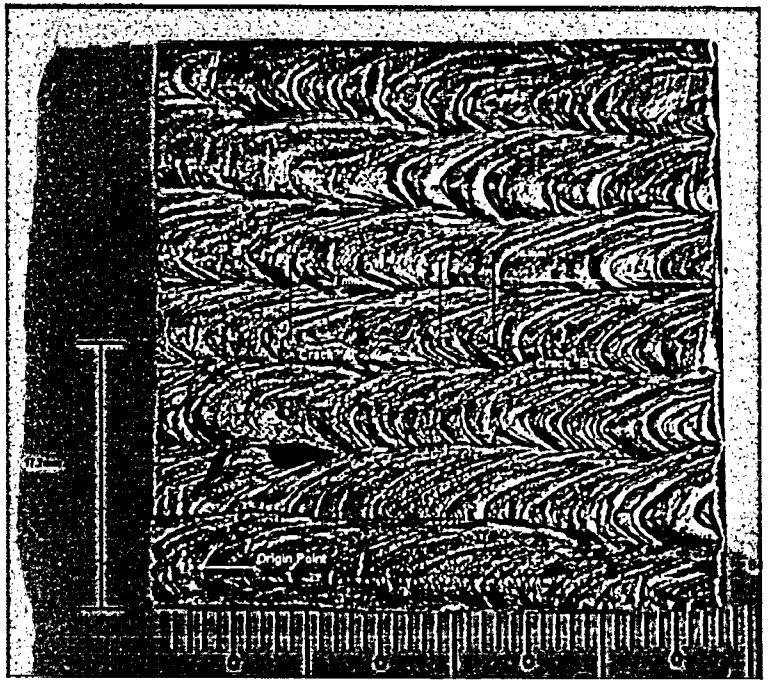
Stress Corrosion Weld Crack Specimens

- 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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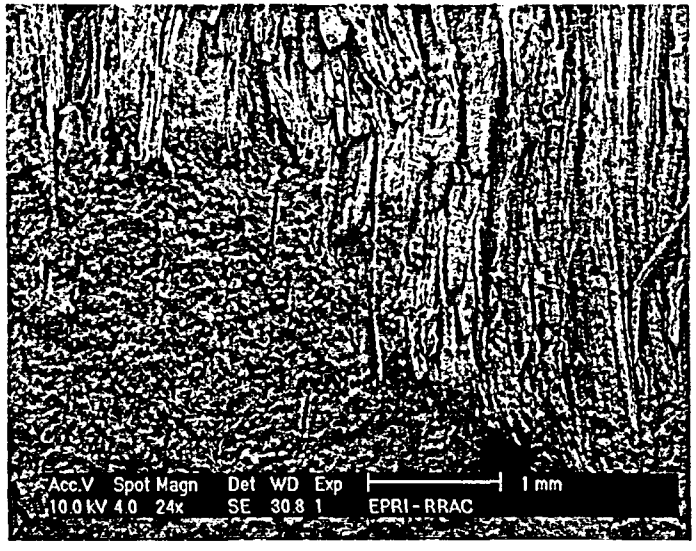
Stress Corrosion Weld Cracks

- 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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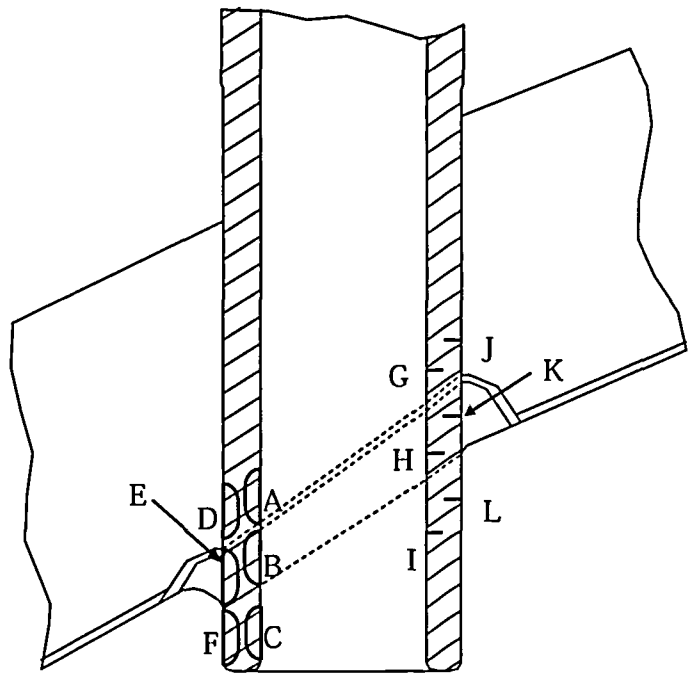
2002 Demo Tube Flaw mock-up "J"

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



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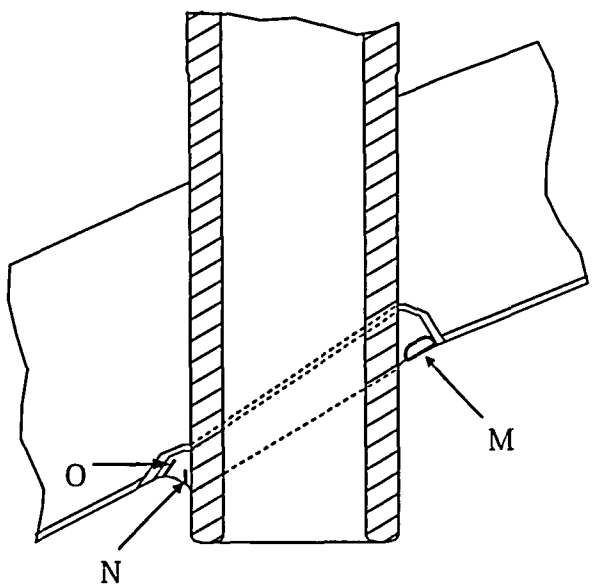
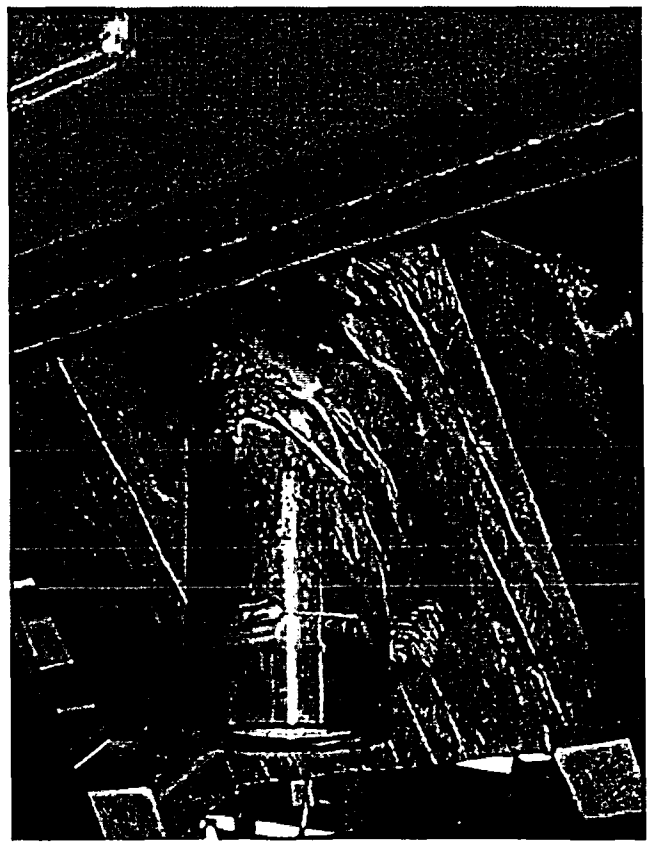
2002 Demo Weld Flaw Mock-up "K"

- CIP flaws for UT from inside surface of tube





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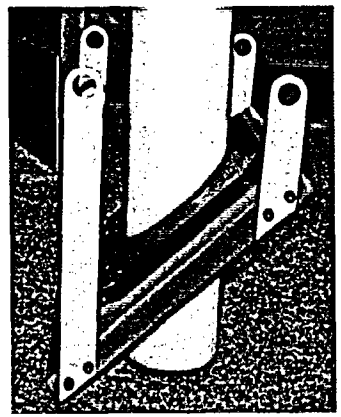
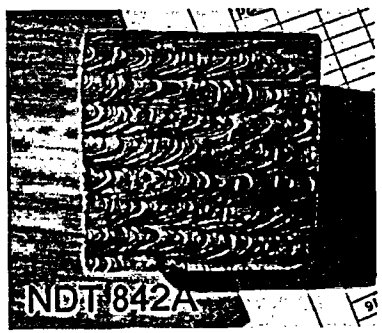
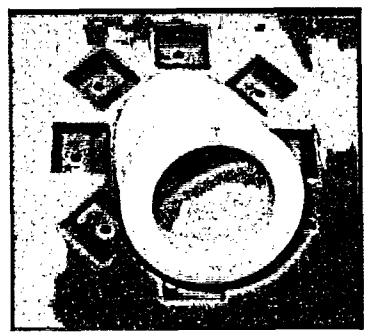
2002 Demo Weld Flaw Mock-up "L"

- 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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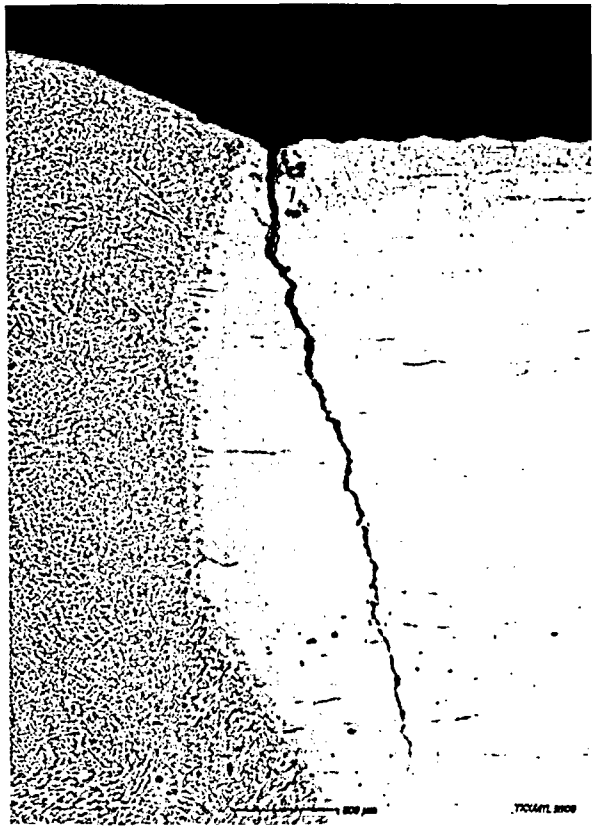
Production of realistic flaw in Alloy 600 for qualification purposes

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

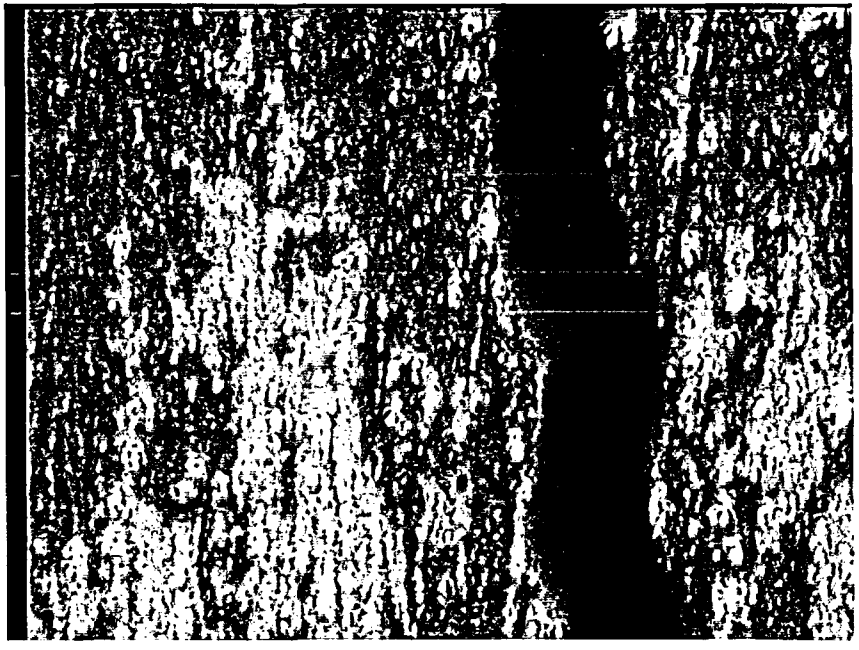
Controlled loading - controlled cracks



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

Controlled loading - controlled cracks

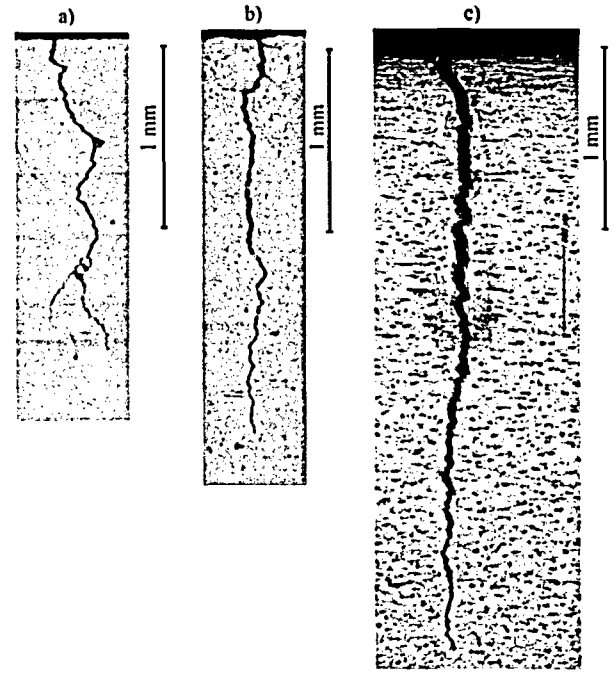
- Thermal fatigue loading
  - Crack closes during heating
  - Crack opens during cooling



How does a True Flaw look like?

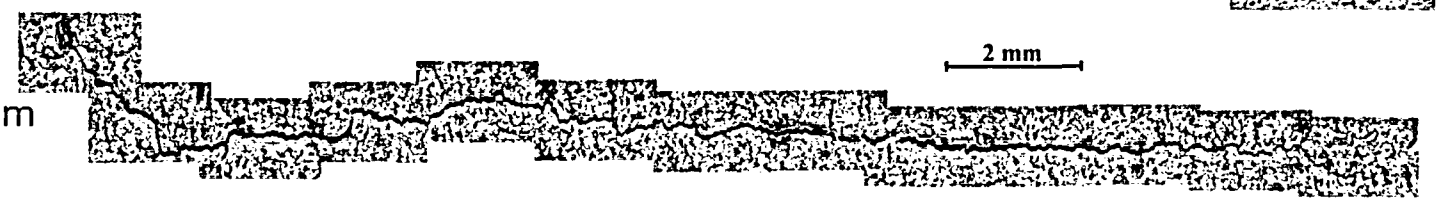
Austenitic stainless steel

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



L= 8 mm

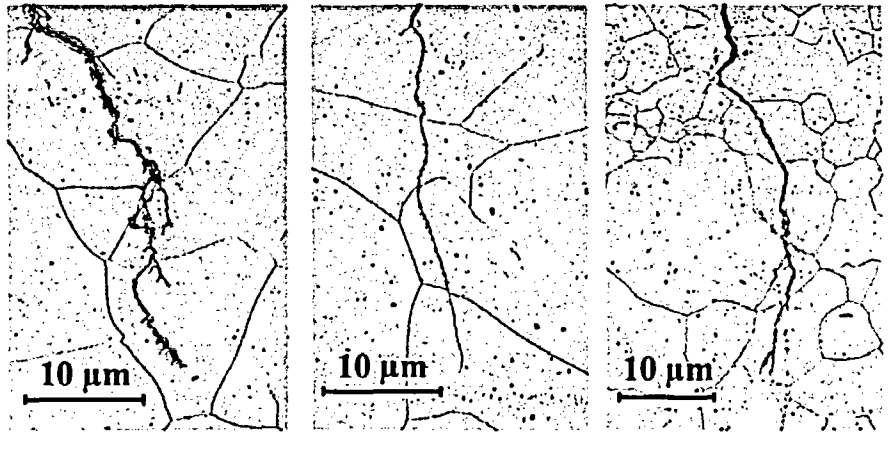
L= 20 mm

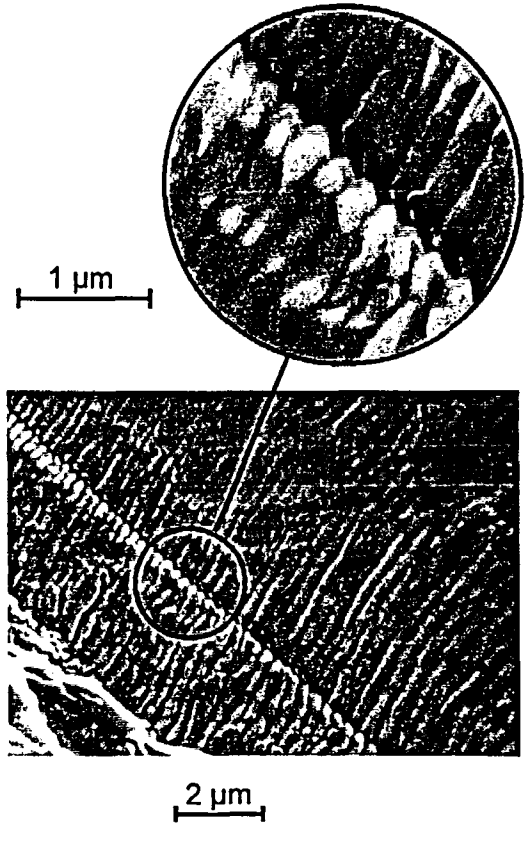


How does a True Flaw look like?

Austenitic stainless steel

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





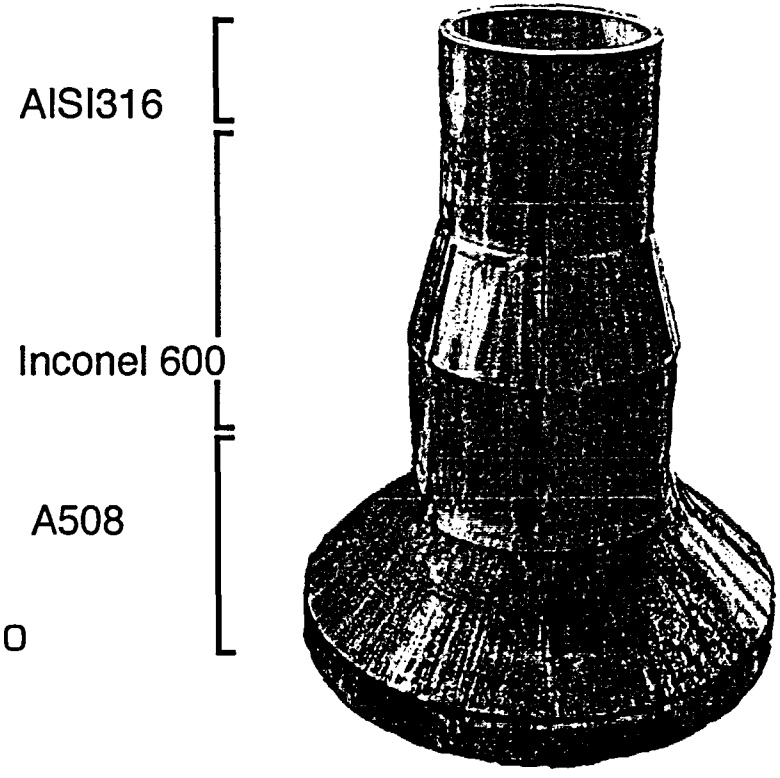
True Flaw for Inconel 600

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

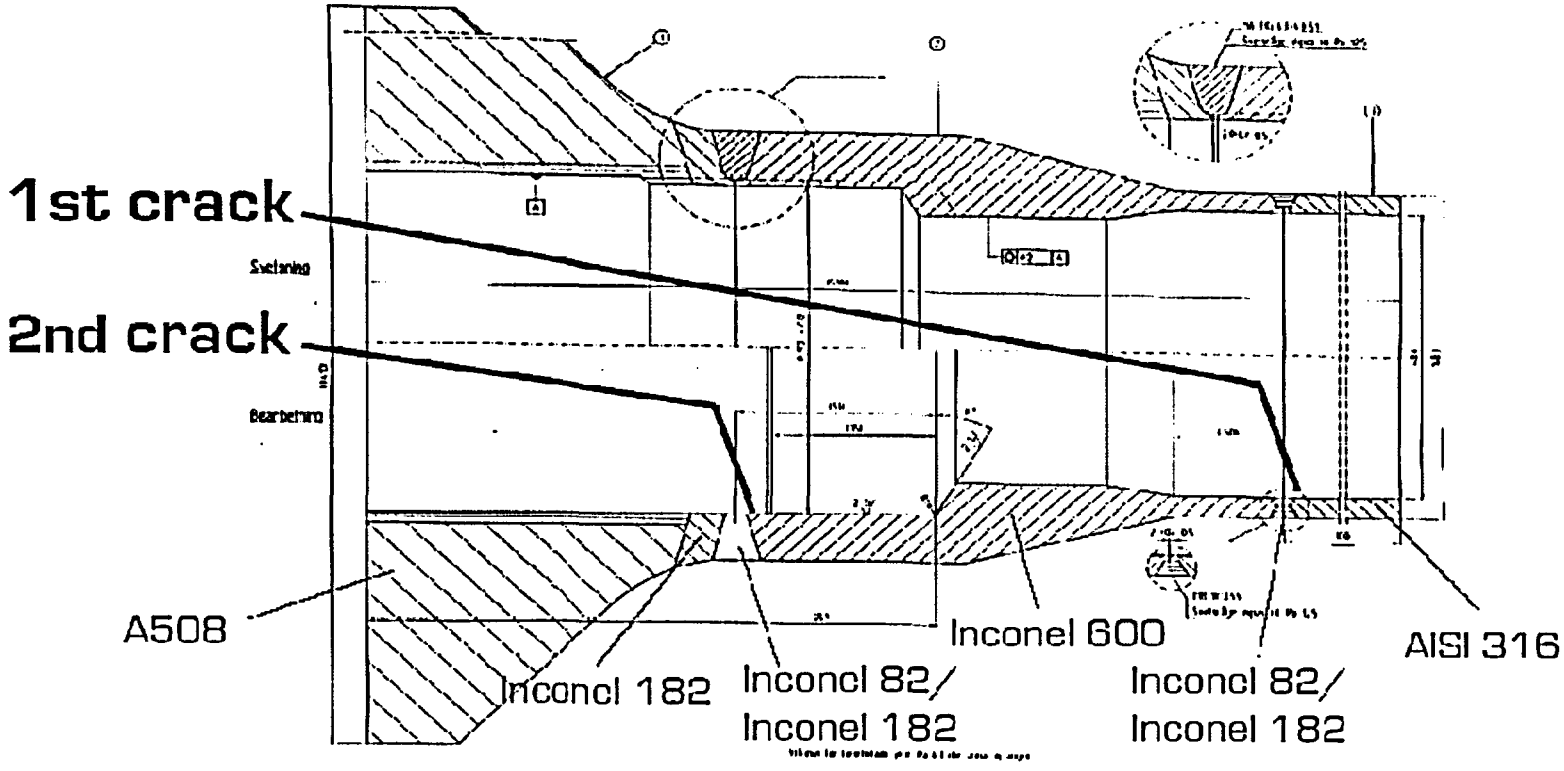


True Flaw for Inconel 600

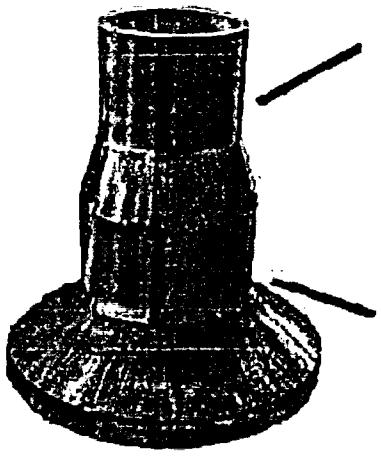
True crack production

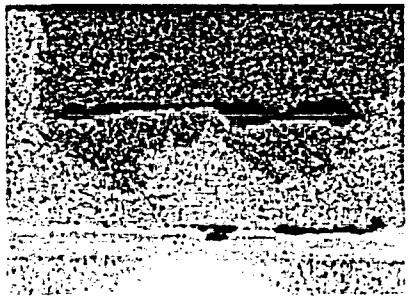
- 2 cracks in the HAZ of welds
- At the inner surface of the nozzle
- 1st crack in AISI 316 vs. Inconel 600 weld
  - In AISI 316
- 2nd crack in Inconel 600 vs. A508 buttering weld
  - In Inconel 600

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

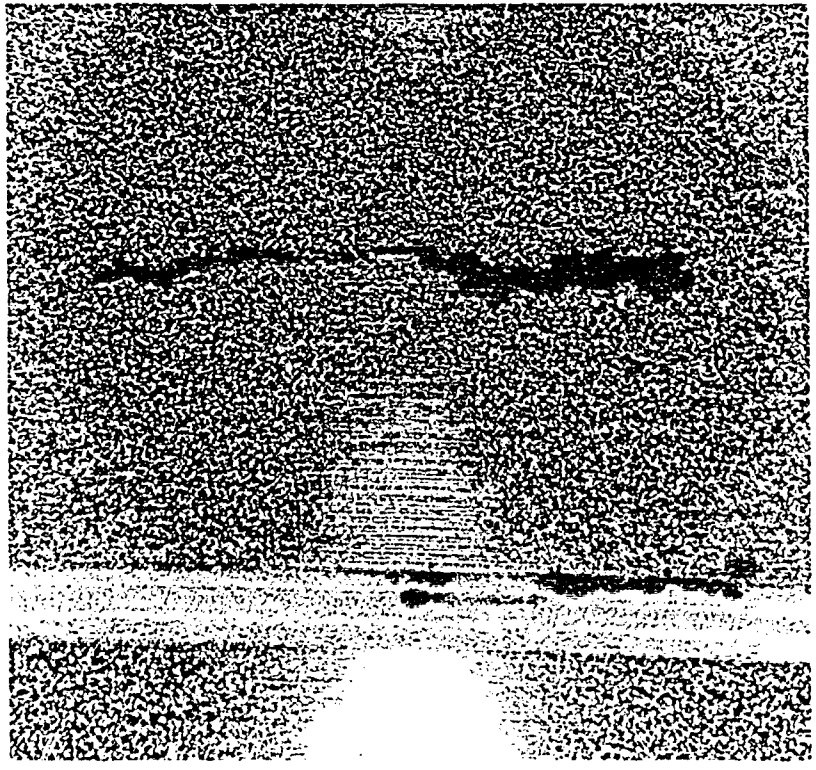
- HAZ of the buttering weld
- 14,2 mm x 5 mm
- Size controlled by the process and confirmed by UT

True Flaw in Inconel 600 Safe-End

Dye penetrant test

- Crack in the of Inconel 600

=> 14,2 mm x 5 mm

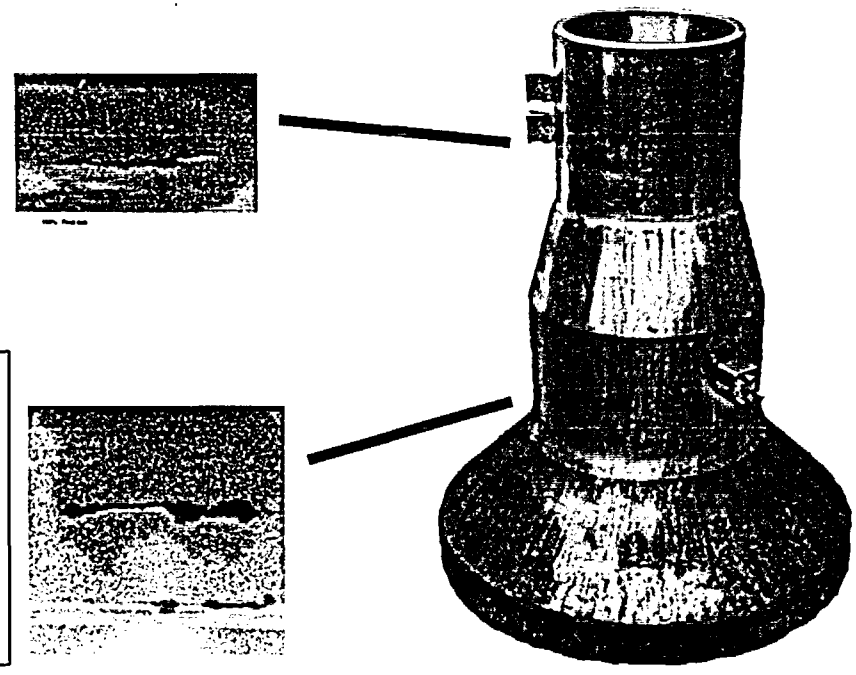


10 mm

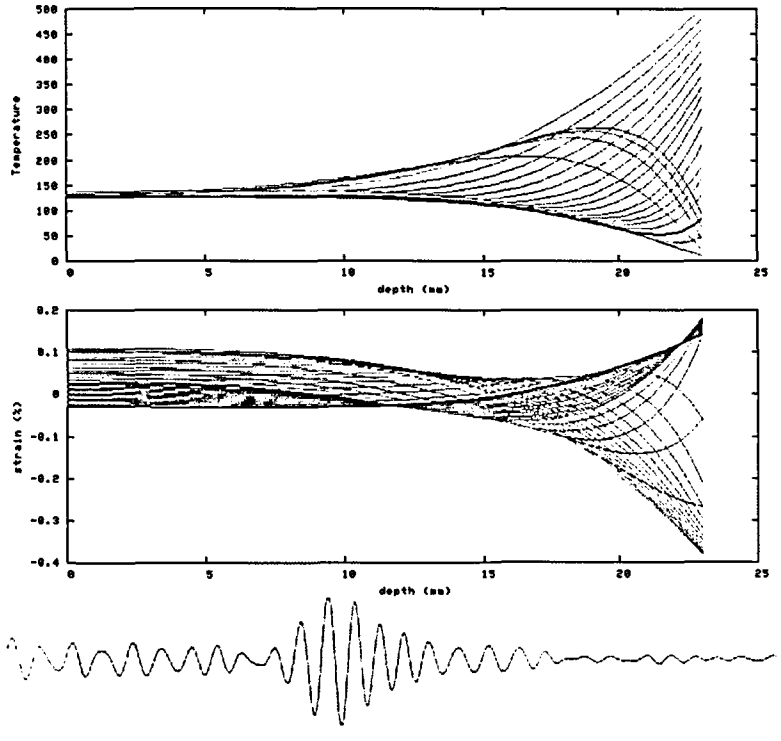
Arrangements for in-situ UT measurements

Two UT probes
- Transverse wave
- 55° and 70°

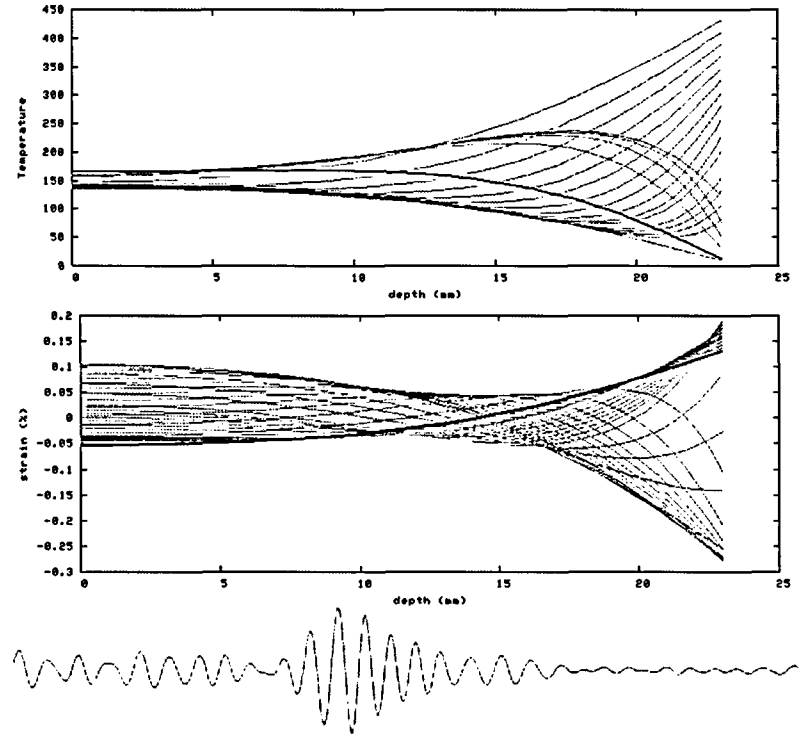
One UT probe
- Transverse wave
- 41°
- 1.5 MHz



Applied loads - results



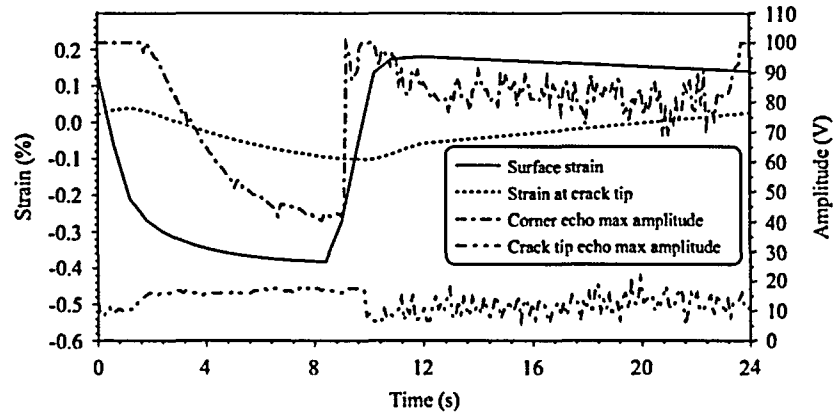
B1

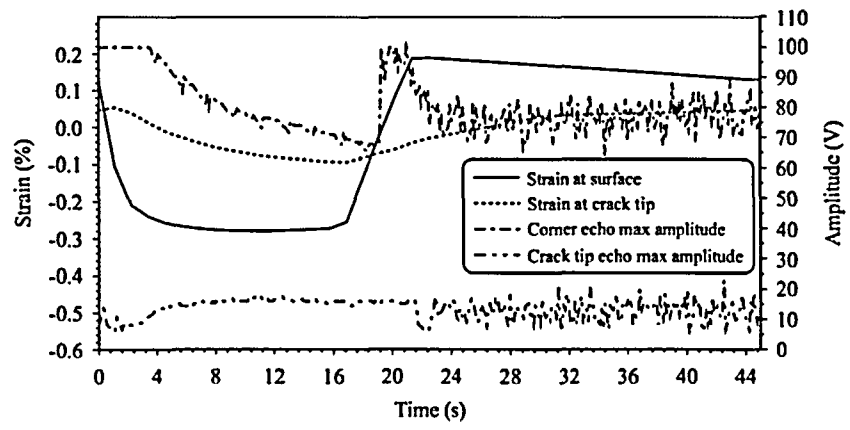


B2

Loading alters amplitude

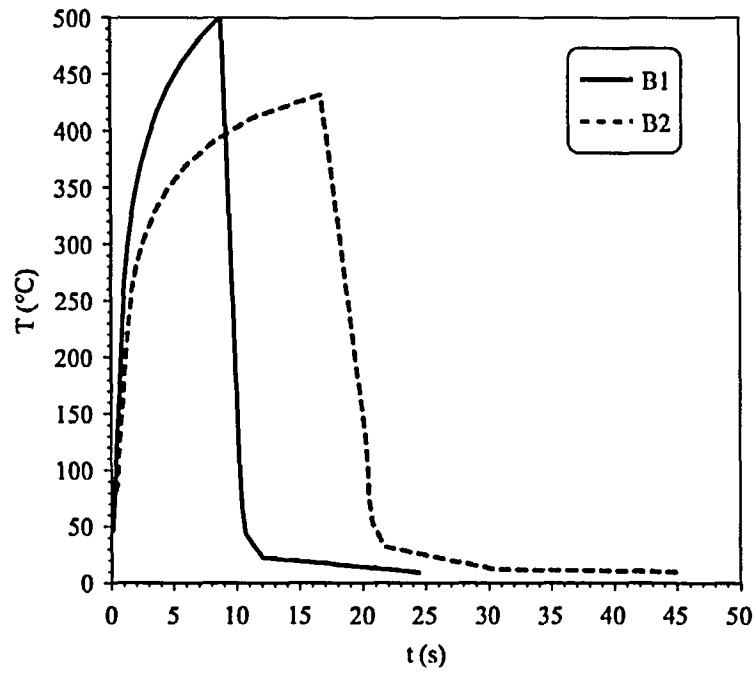
- Compression during heating decreases corner echo amplitude
- Tip echo amplitude increases during heating





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

BNFL

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 Pressuri ed 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)

Ob ectives

- 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.

Ob ectives

- 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 2001-0, 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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5.8	Typical BACC Issue Documentation Form	5-46

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

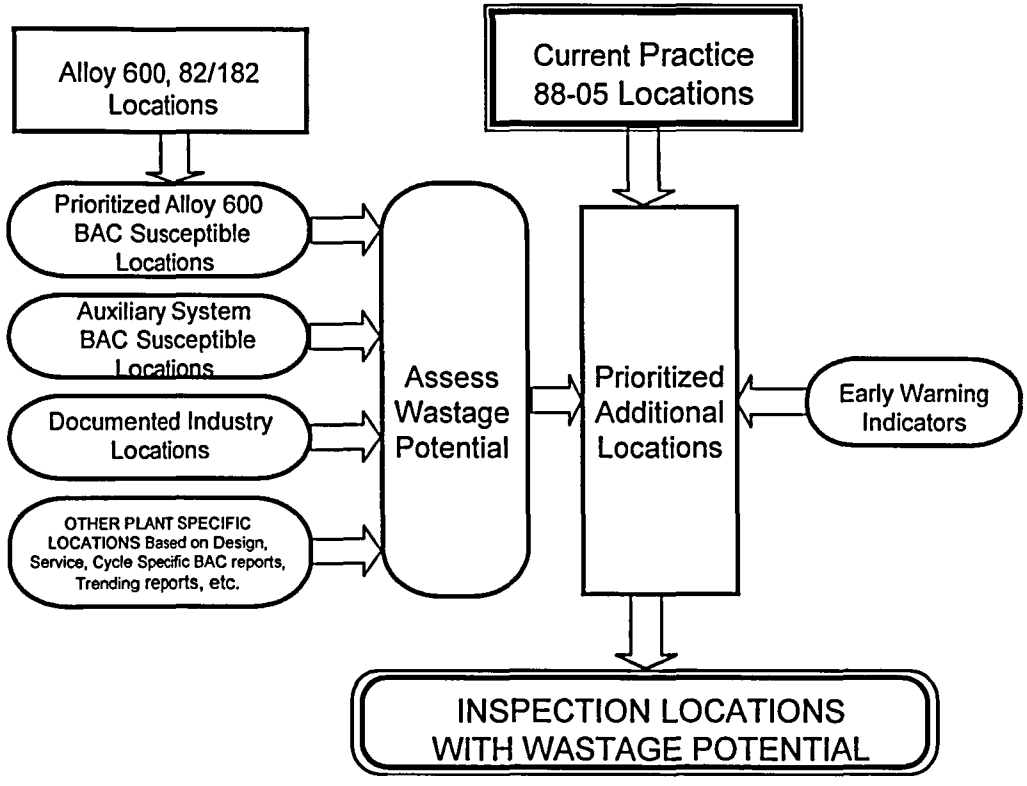
Inspection Locations

- 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

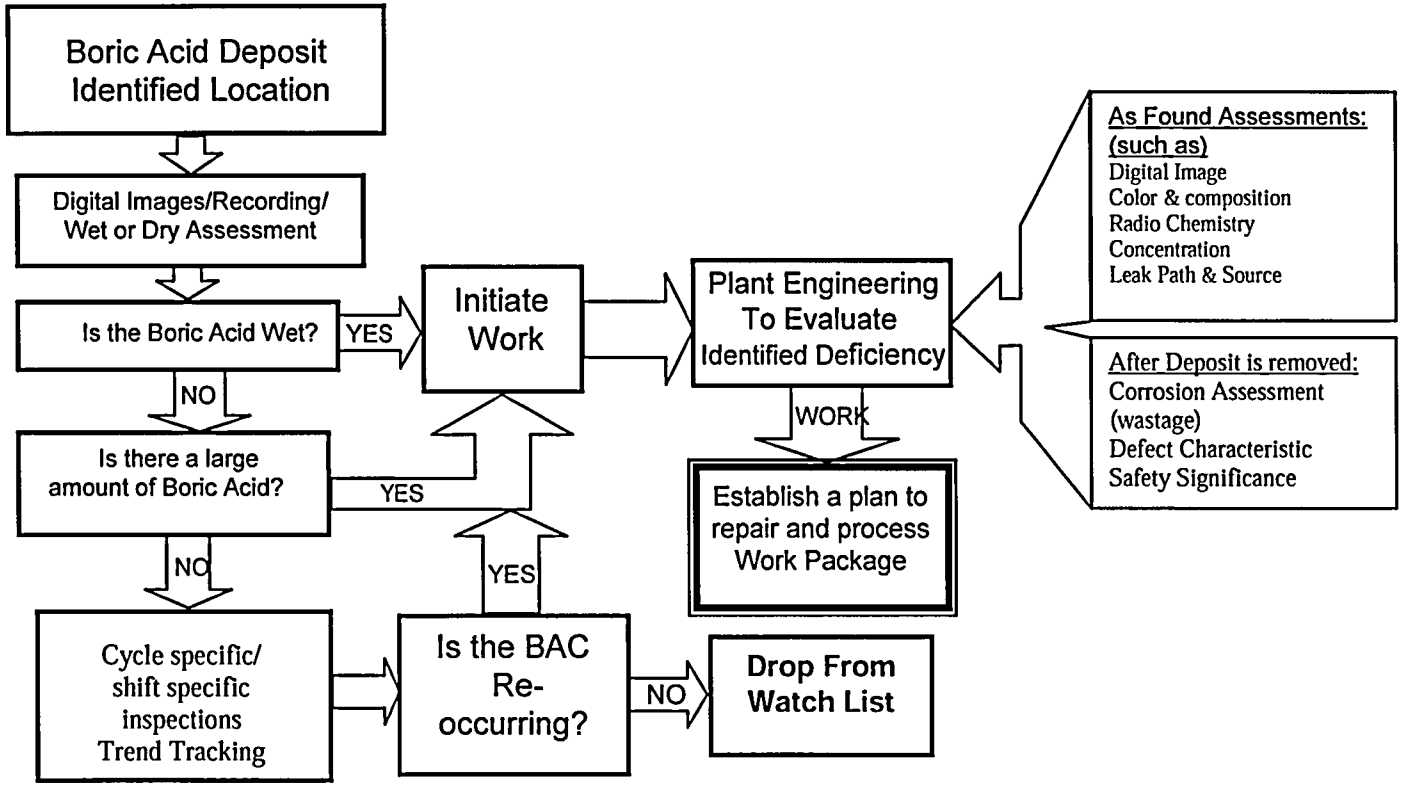
Examples of Systems Containing Boric Acid

- Reactor Coolant System
- Chemical and Volume Control System
- Safety In ection System
- Residual Heat Removal Shutdown Cooling System
- Reactor Plant Sampling System
- Spent Fuel Pool Cooling and Purification System
- Containment Depressuri ation System
- Containment Spray System
- Reactor Plant Vent and Drain System
- Li uid Waste Disposal System
- Gaseous Waste Disposal System

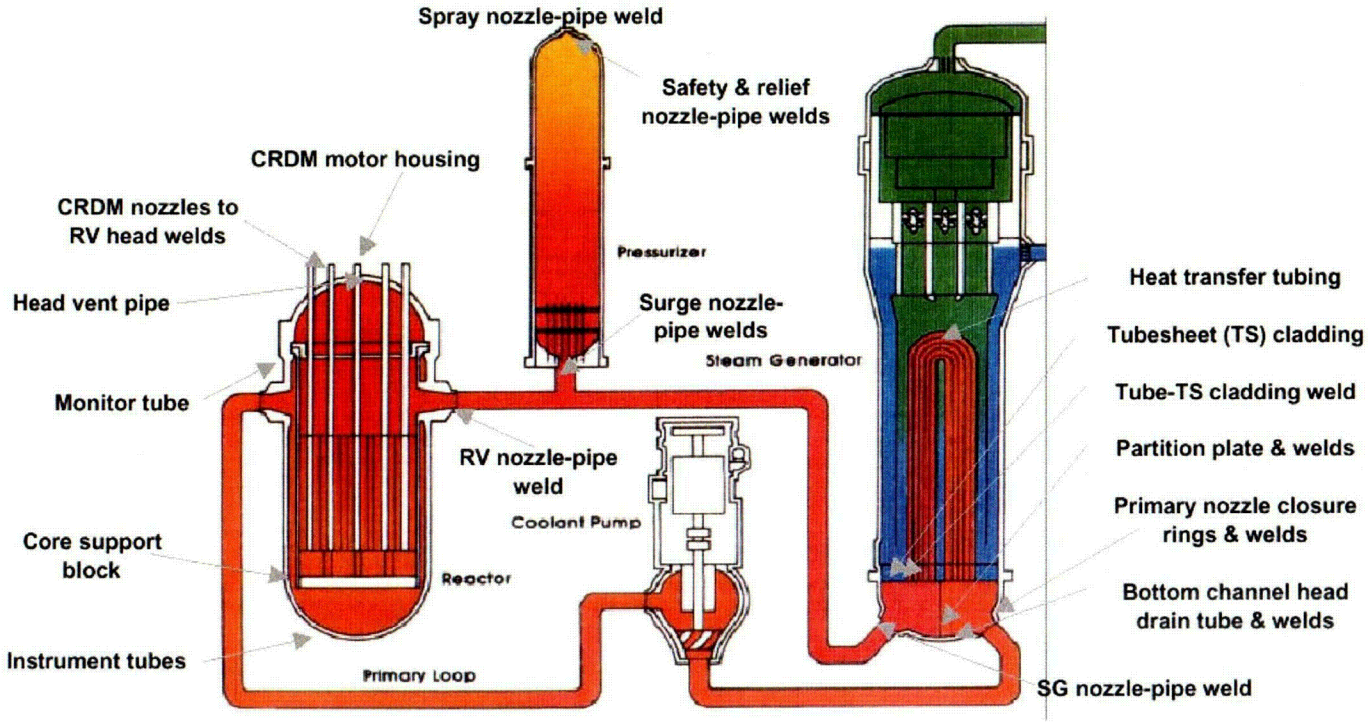
Identification of Inspection Locations with Wastage Significance



Criteria for Boric Acid Deposit Assessment



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



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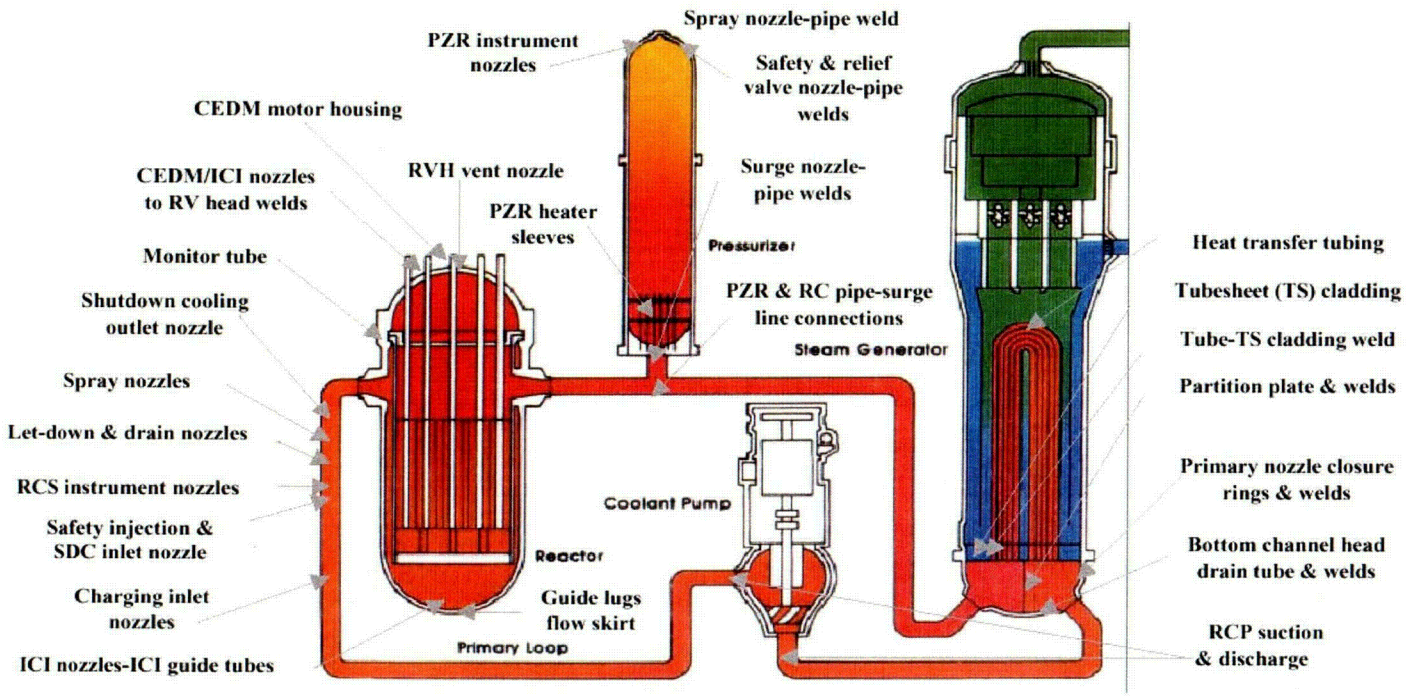
Alloy 600 and Alloy 82 182 Locations in the Primary Pressure Boundary Components of CE PWR Units



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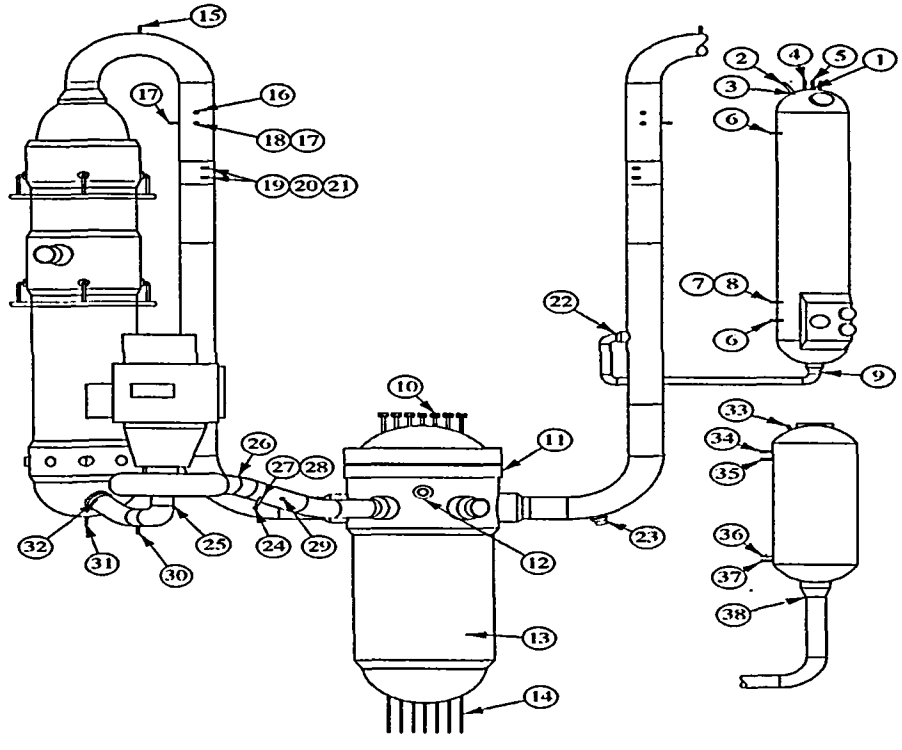
General Locations of Alloy 600 Type Materials in the B&W 177-FA Design Reactor Coolant System Prepared by DEI



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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:
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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

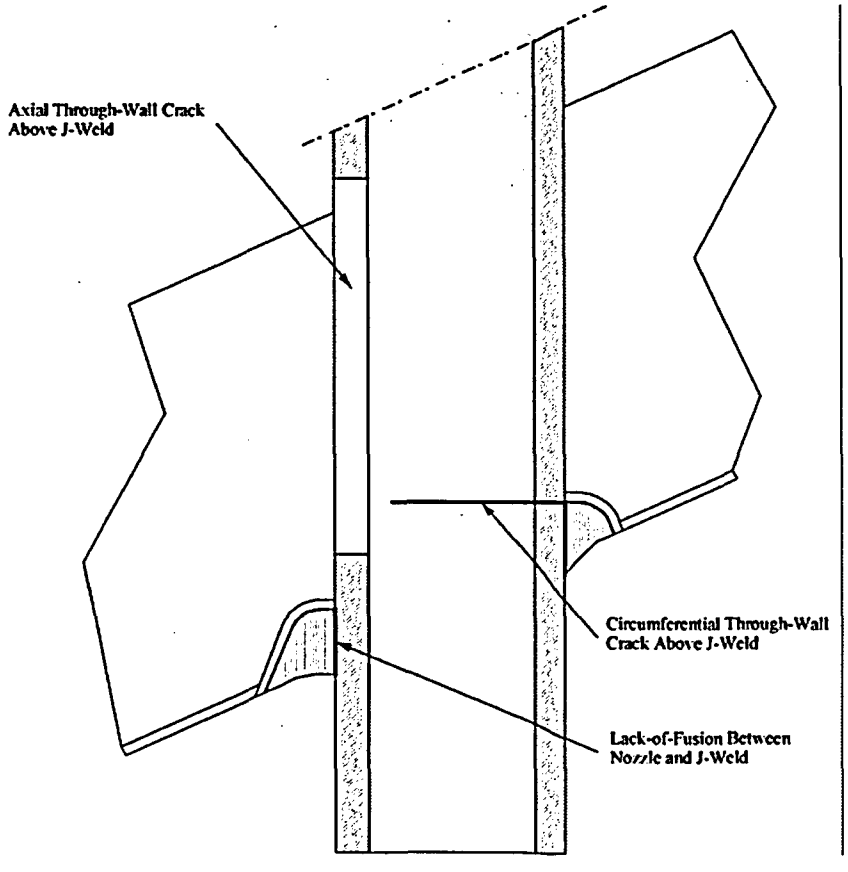
Purpose of Evaluation

- 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

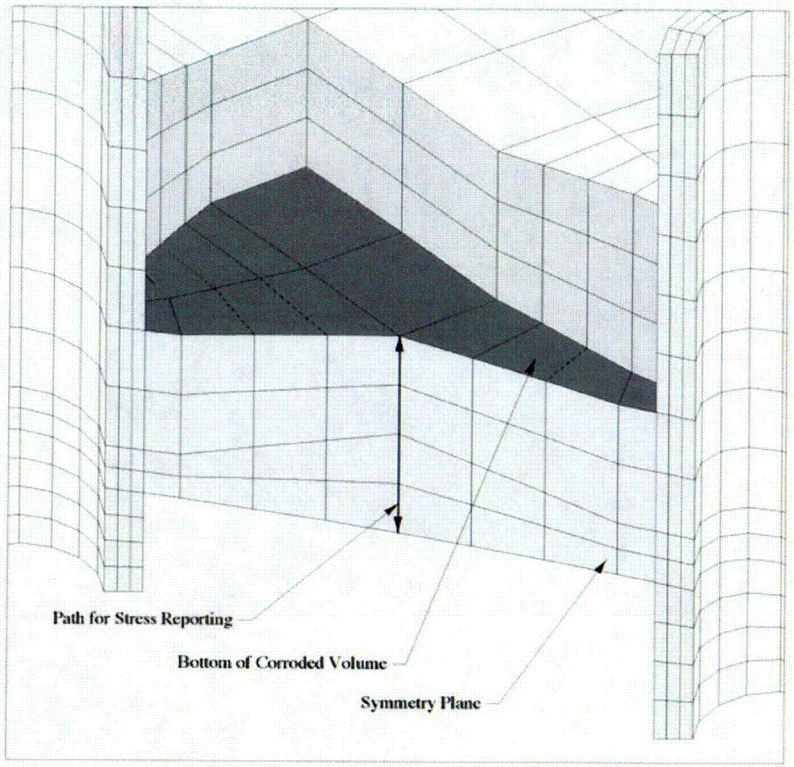
Flaw Tolerance Evaluation
Tolerance to Cracking



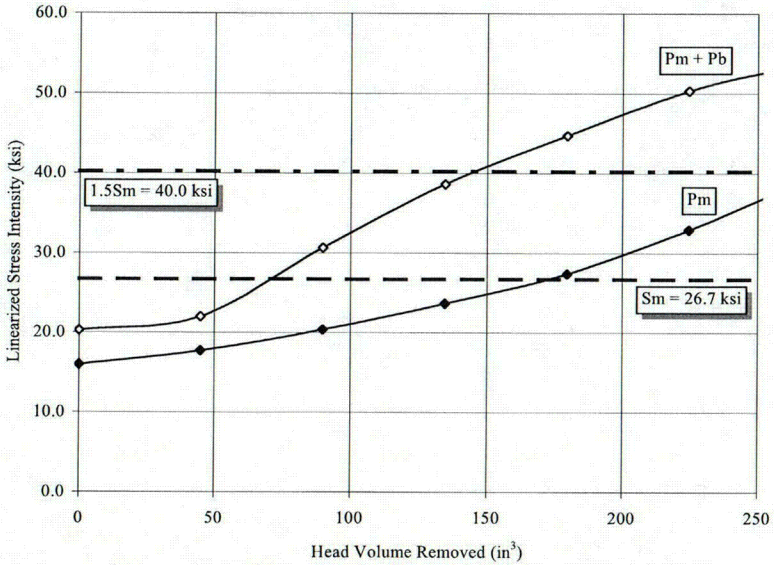
Typical Results for CRDM Nozzle

	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

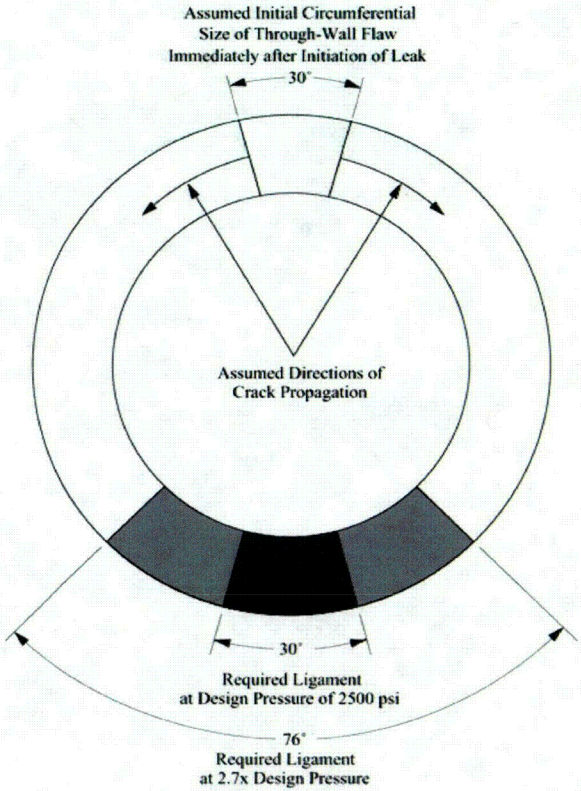
Flaw Tolerance Evaluation
Summary

- 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

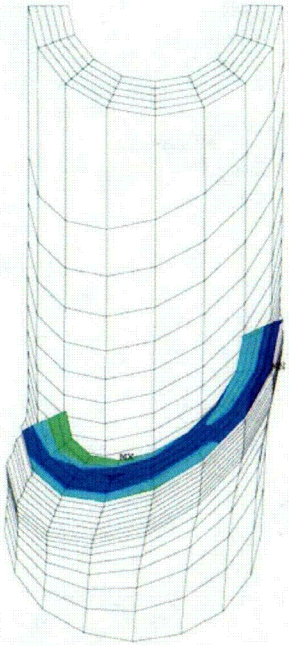
Deterministic Nozzle Ejection Assessments

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°

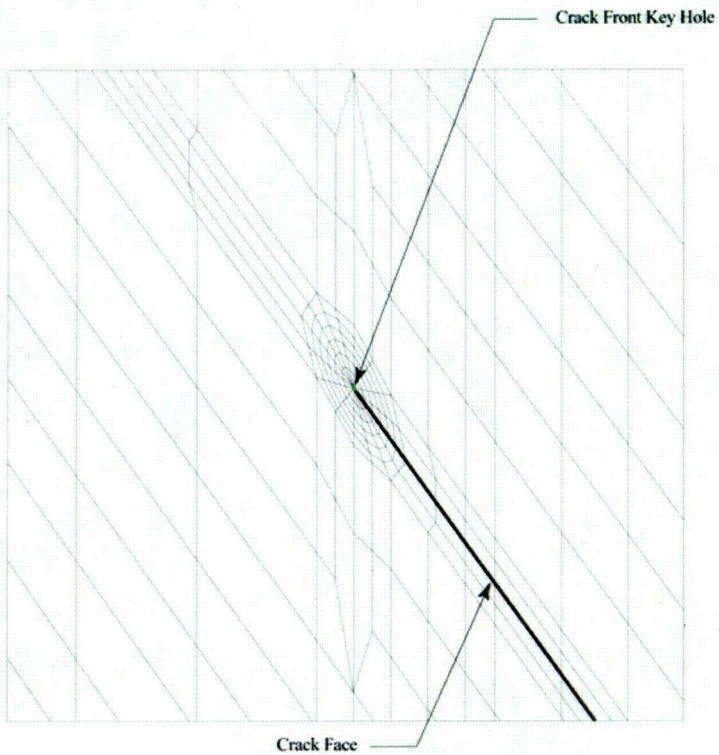


Example of Operating Stress Perpendicular to Circ Crack Plane

Stress Intensity Factor Calculation

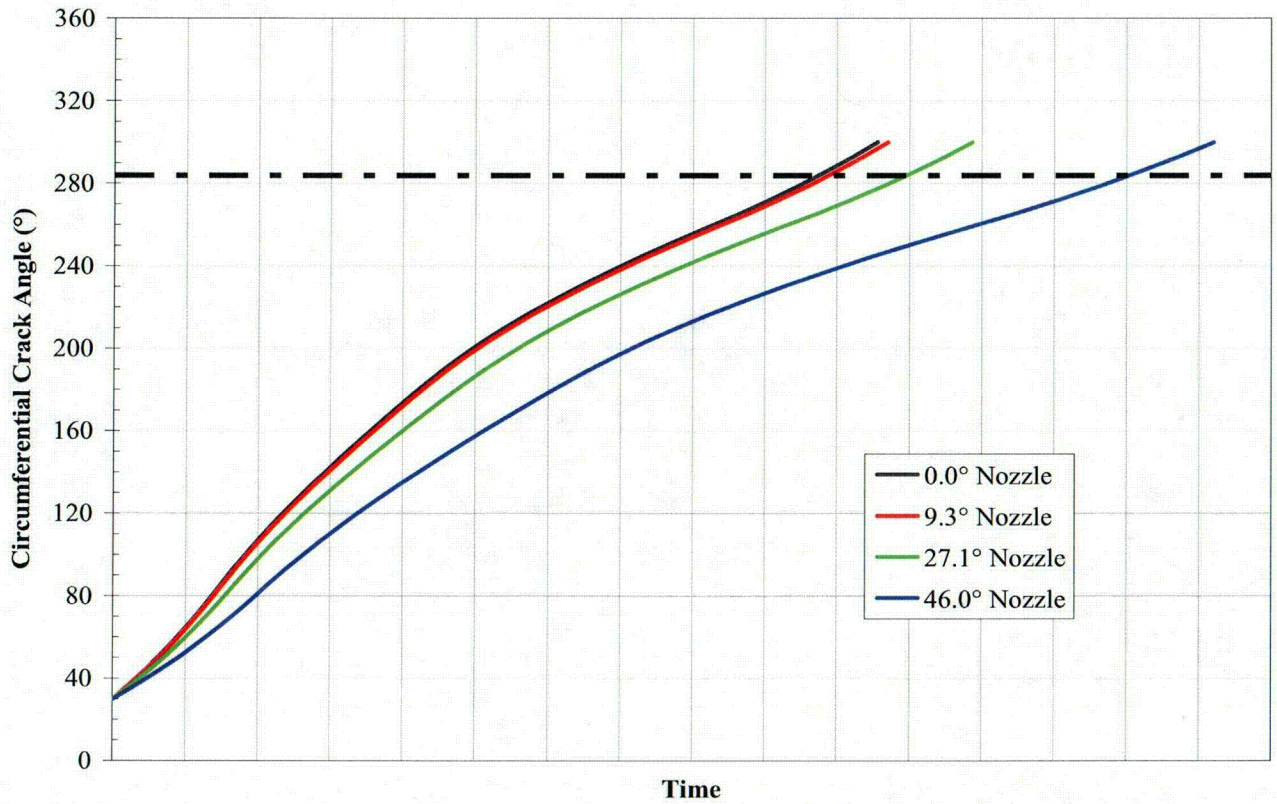
Example Fracture Mechanics Analysis for Nozzle Circ Cracks

180° Downhill-Centered Crack

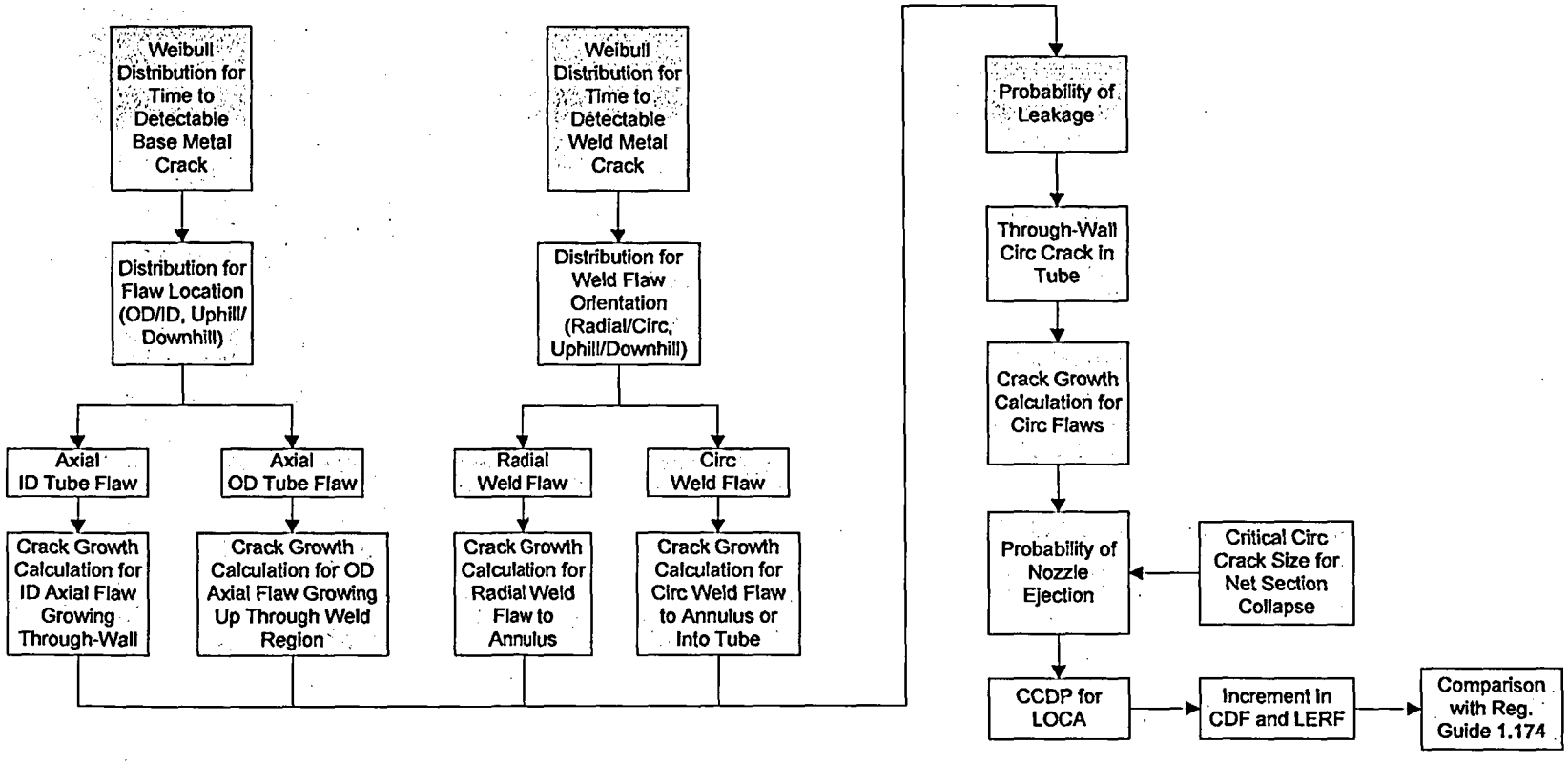


Crack Mesh Detail

Deterministic Nozzle Ejection Assessments
Example Results

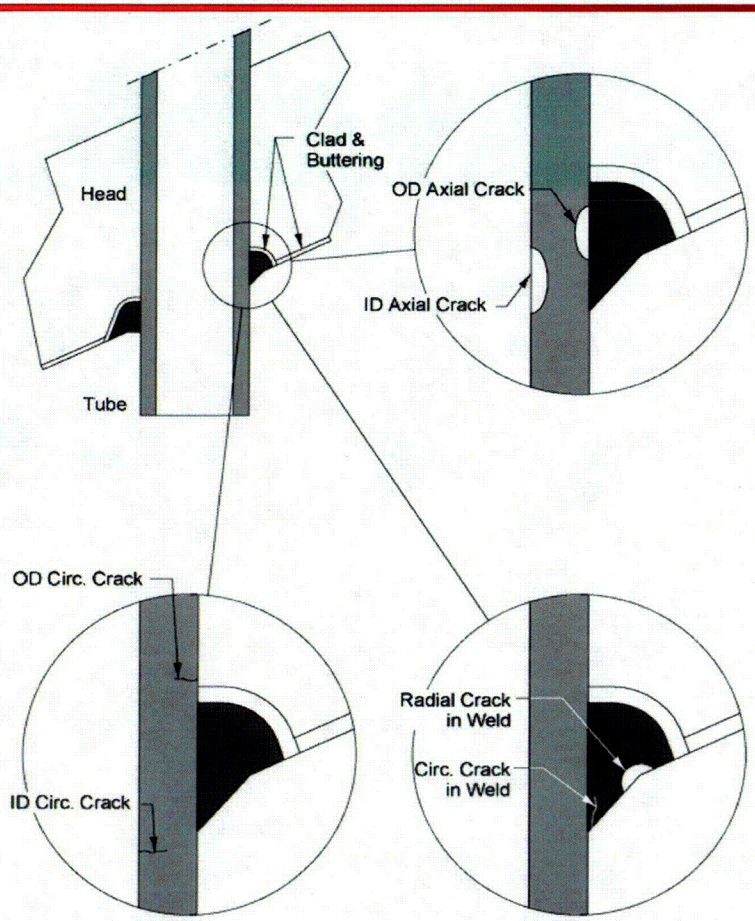


Probabilistic Nozzle Ejection Assessments
Simplified Simulation Model Flowchart



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



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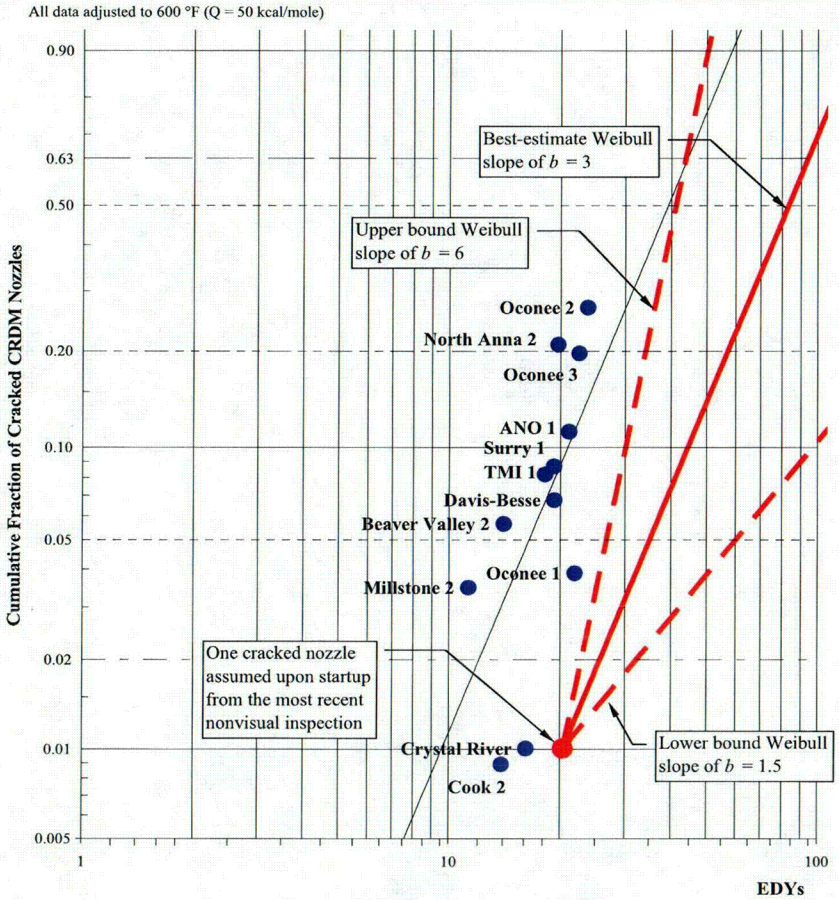
Probabilistic Nozzle Ejection Assessments
Weibull Statistical Modeling of Crack Initiation

- 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



Risk-Informed Evaluation of PWR Reactor Vessel Head Penetration Inspection Intervals 14

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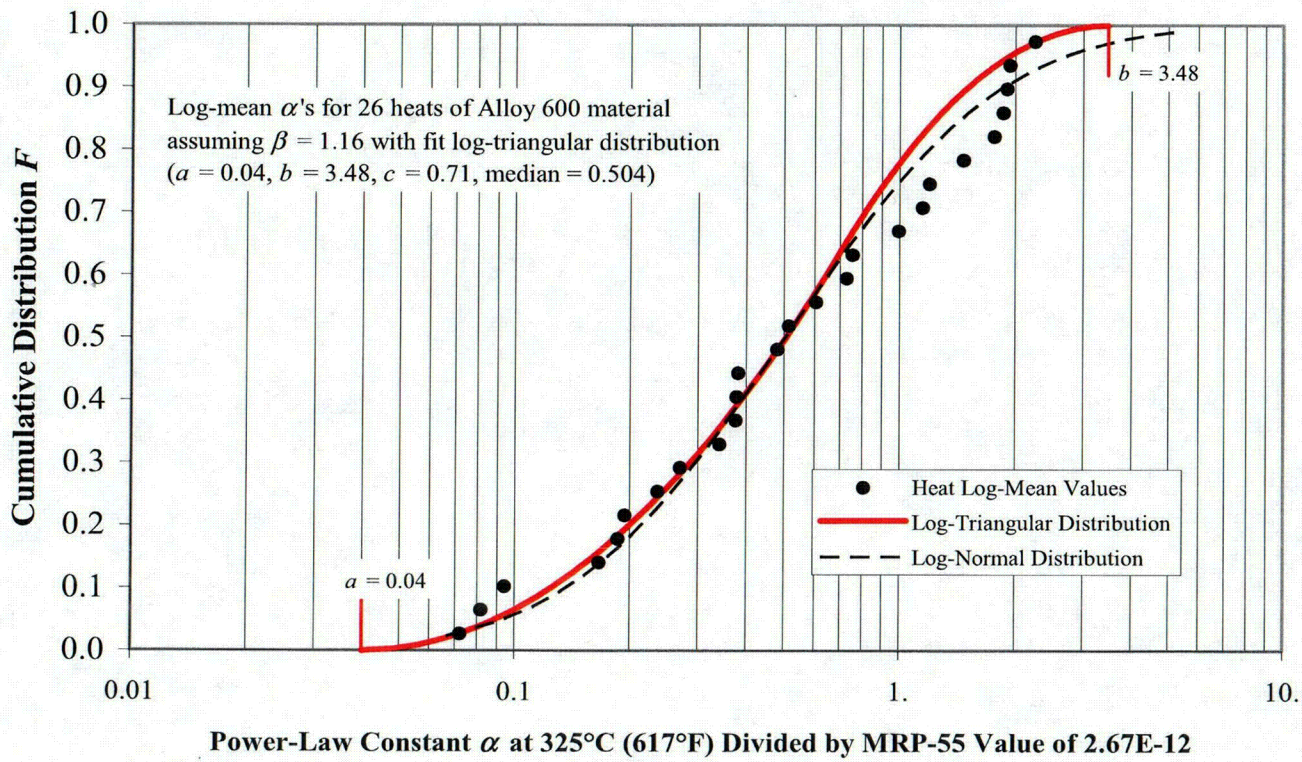
Deterministic Nozzle Ejection Assessments

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

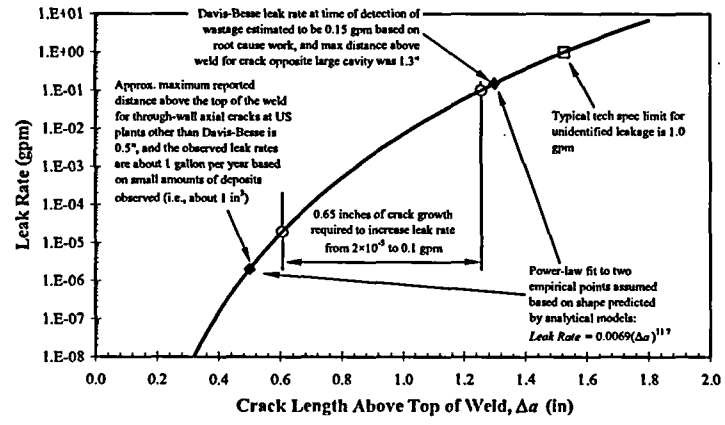


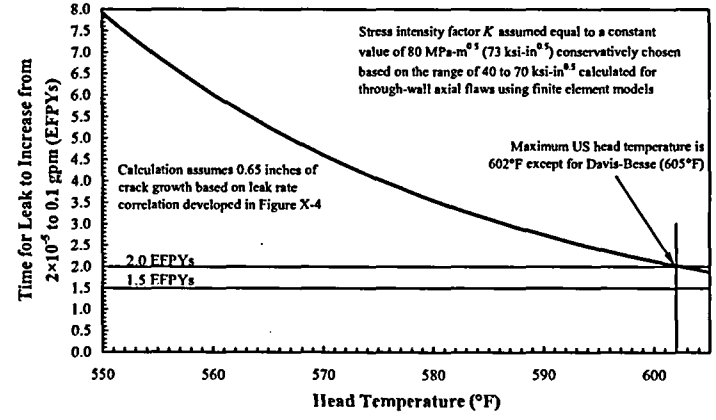
Probabilistic Nozzle Ejection Assessments
Assessment of Results

- 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

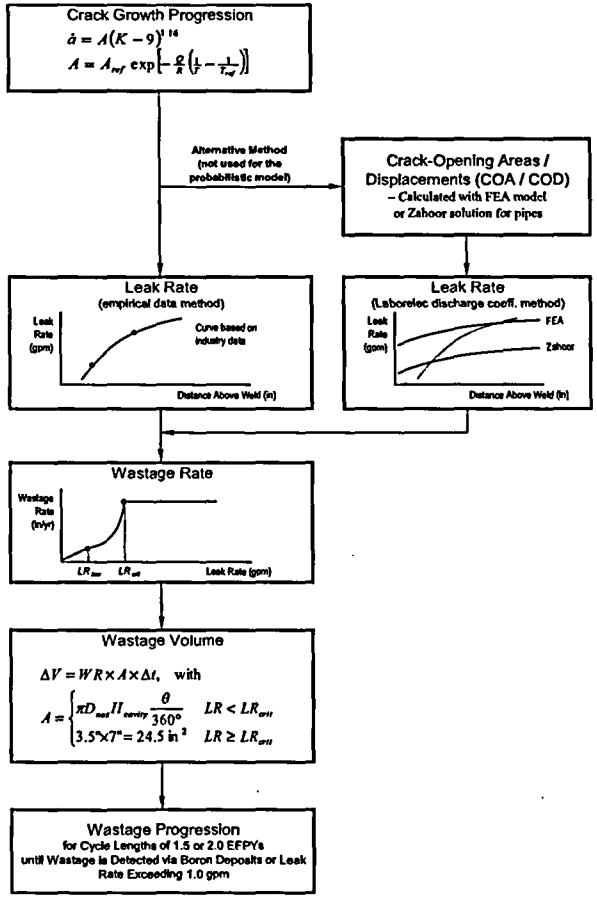
- The methodology presented in Appendices C, D, and E of MRP-75 may be used to evaluate the potential for wastage
- The MRP is revising the MRP-75 wastage assessment on the basis of bare metal visual (BMV) inspections being performed each refueling outage
- The methodology is based on the time for the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





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

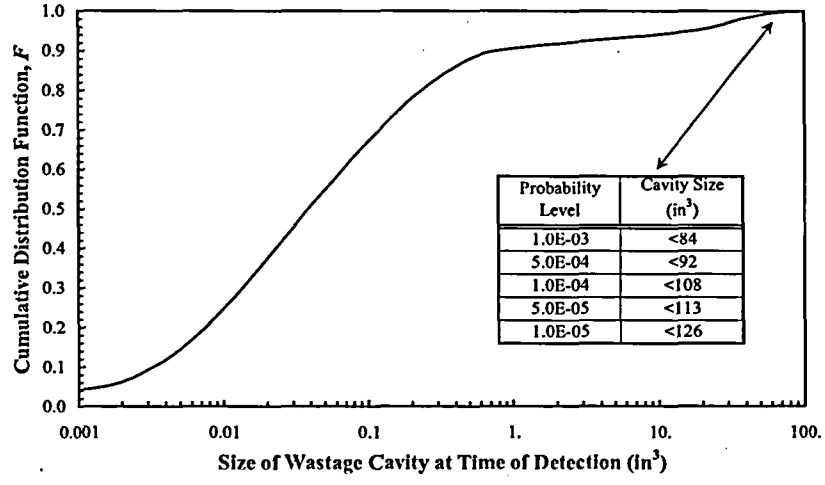
- The probabilistic wastage assessment of MRP-75 considers relatively wide tolerance bands for the key model parameters:
  - Point within operating cycle that wastage begins
  - Stress intensity factor driving crack growth
  - Crack growth rate distribution
  - Leak rate as a function of axial crack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

J. P. Lareau

D. C. Adamonis

Westinghouse Electric Company

BNFL

Westinghouse

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

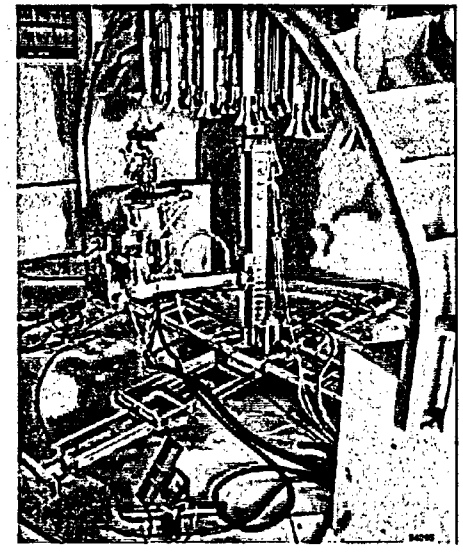
RPVH Inspection Technology

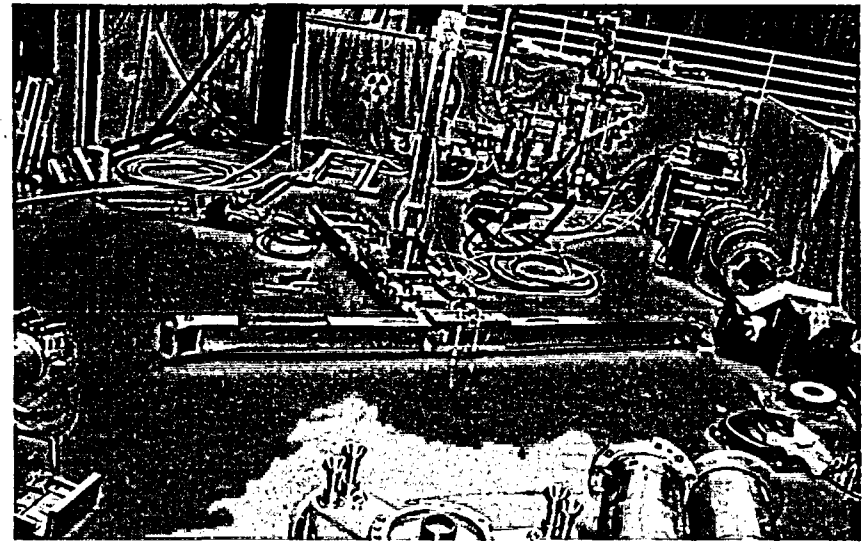
- NRC Bulletins 02-02 and 03-02
  - Emphasis changes to Nozzle OD and Weld
  - Ultrasonic volumetric exam or wetted surface exams required
- Additional Inspection Equipment Required
  - Open Housing Scanner (ET and UT)
  - Weld and Nozzle OD Scanner (ET)

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

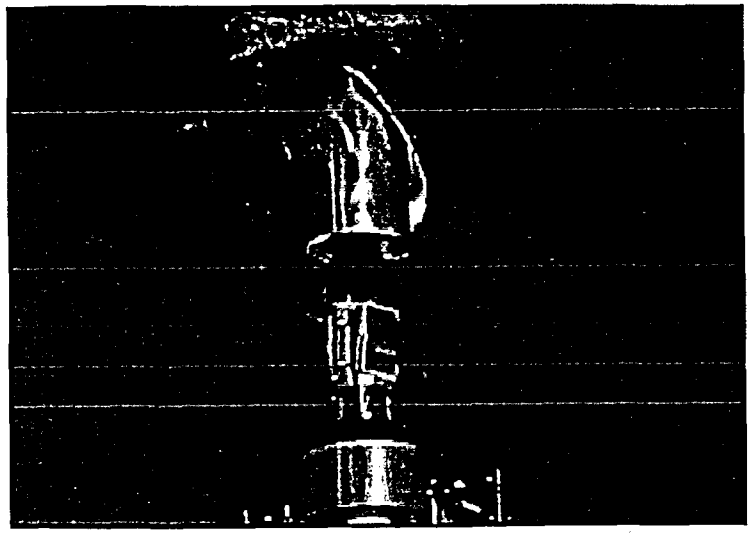
Under the Reactor Vessel Head Inspection and Repair Equipment Delivery System

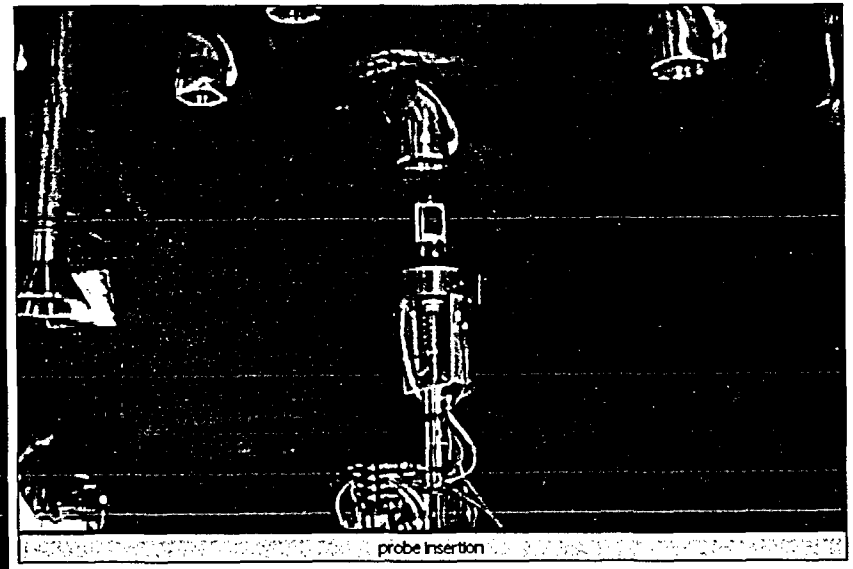




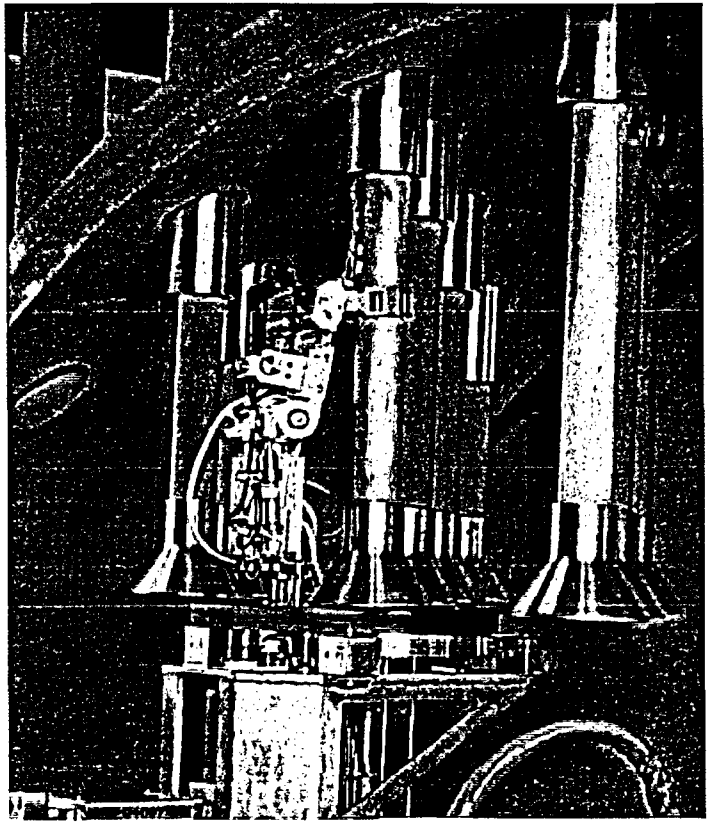
- End-effectors for under-head penetration inspection and repair are delivered by the "DERI" manipulator system
  - 5 systems available in the Westinghouse system
  - Over 140 RV Head inspections performed with the DERI/eddy current gap scanner
  - Change out of end effectors is performed remotely

Open Housing Scanner Offers Eddy Current and TOF Inspection Capability



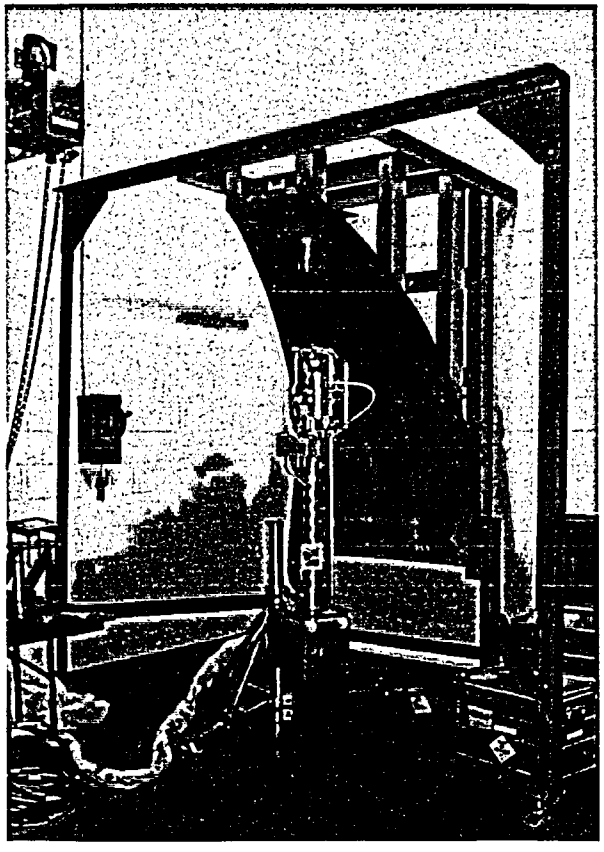


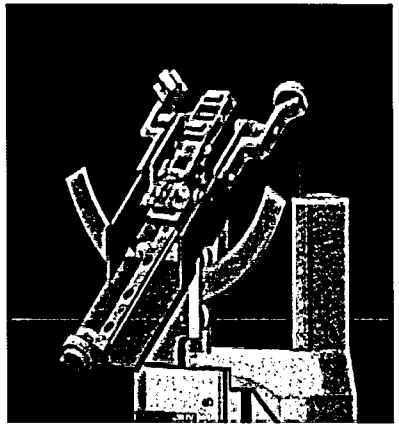
Gapscanners for Sleeved Penetrations

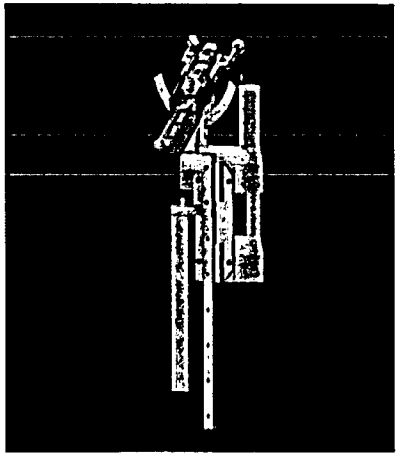


- Blade probes are delivered into the annulus between the the ID surface of the penetration and OD surface of the thermal sleeve, on the order of 0.125 inches
- The Gapscanner end effectors can be used with a variety of eddy current and ultrasonic blade probes for inspection and characterization
  -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

J-Weld and Penetration Tube OD EC Inspection



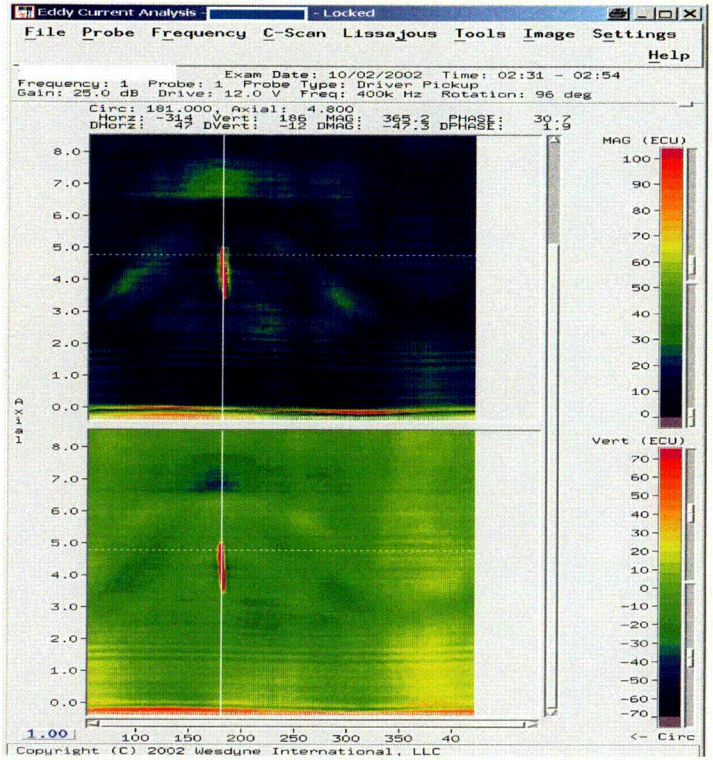


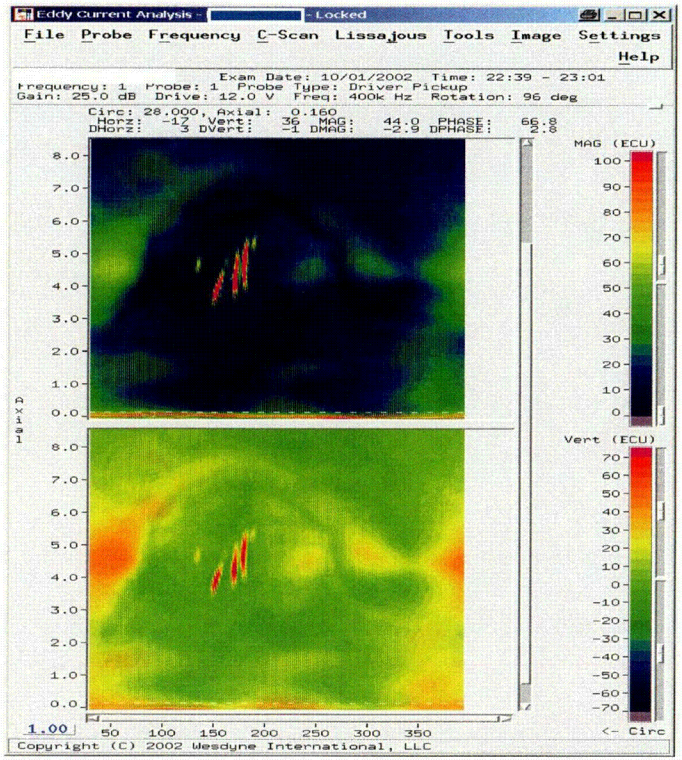


"Grooveman" is used to perform eddy current inspections of the J-weld and penetration tube OD surface

"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





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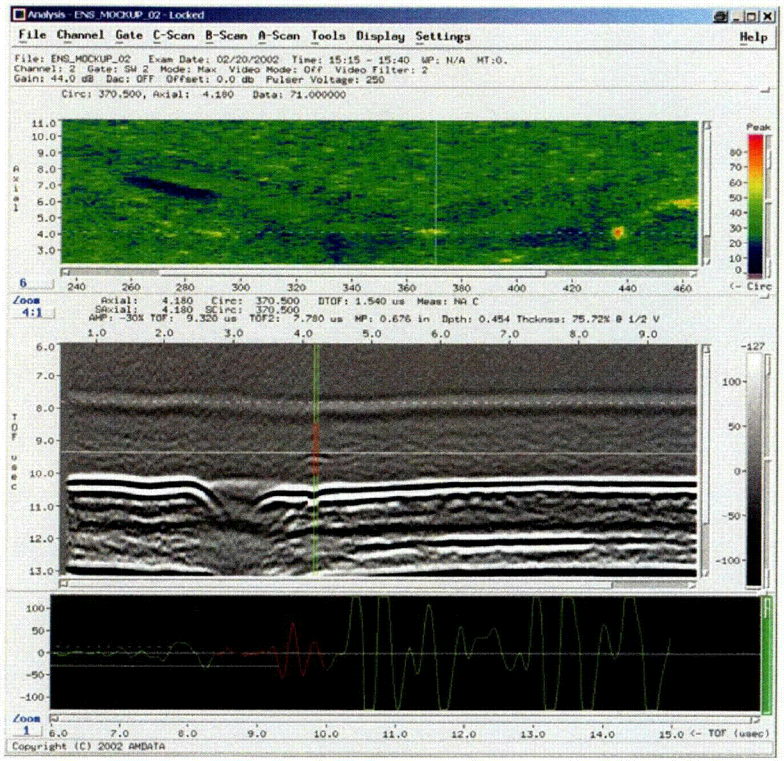
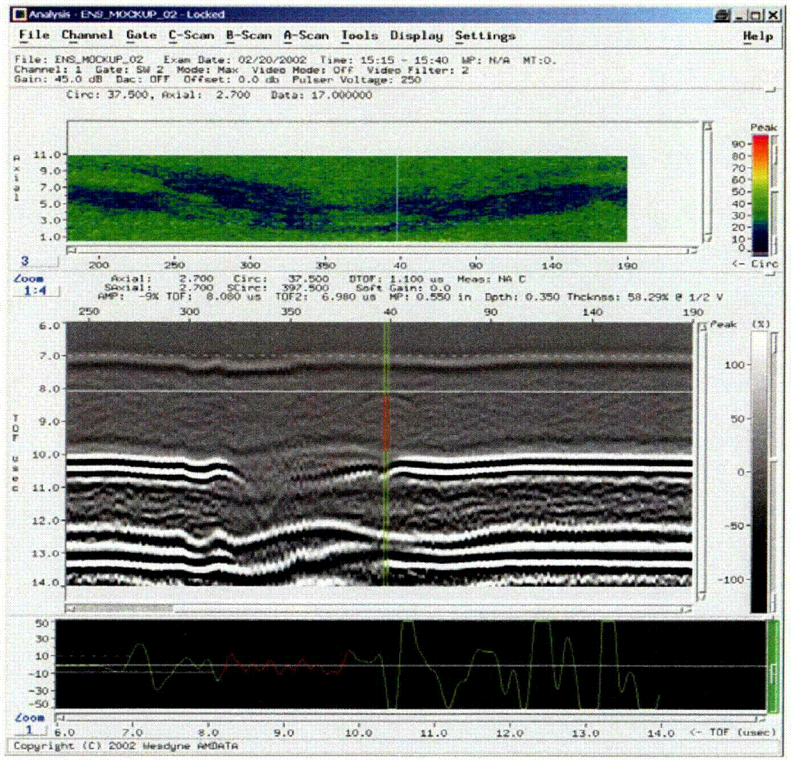
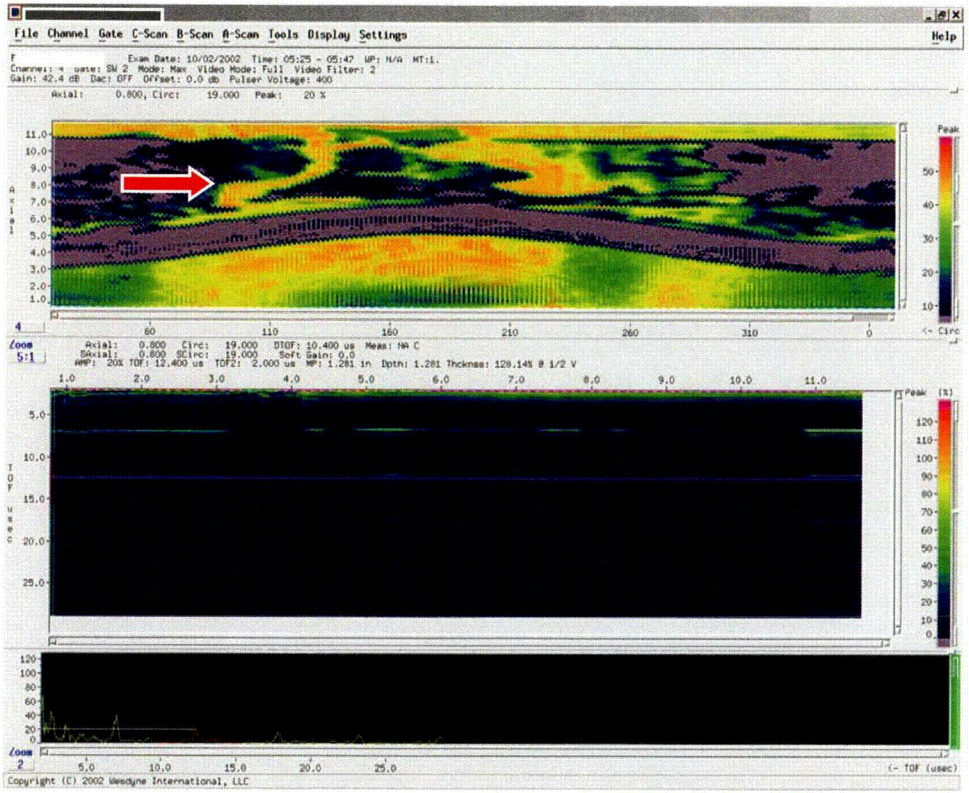
PCS24 TOFD UT Results



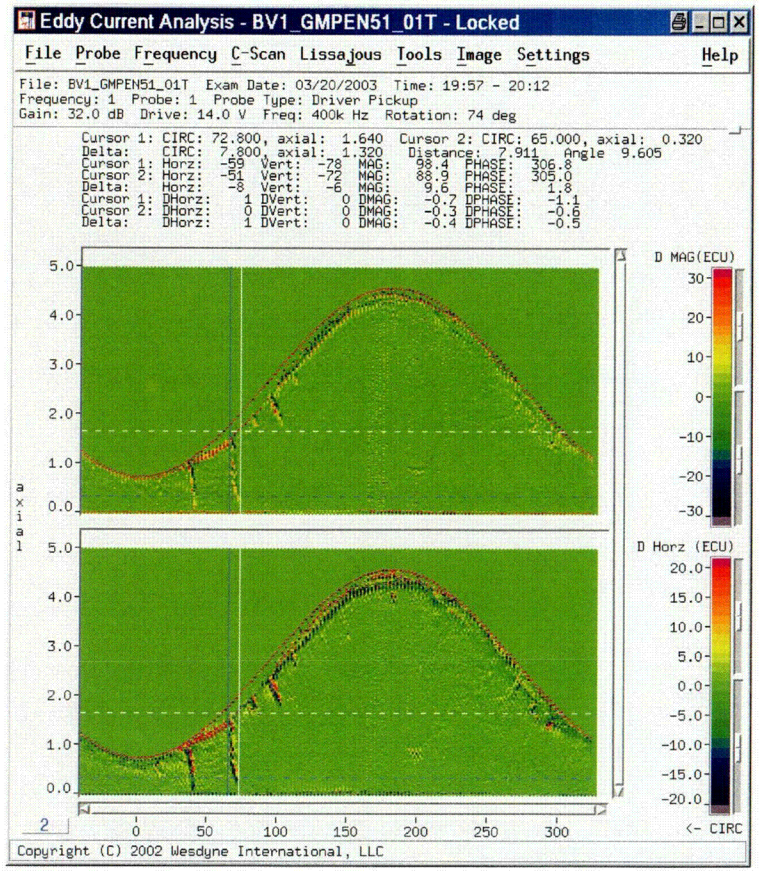


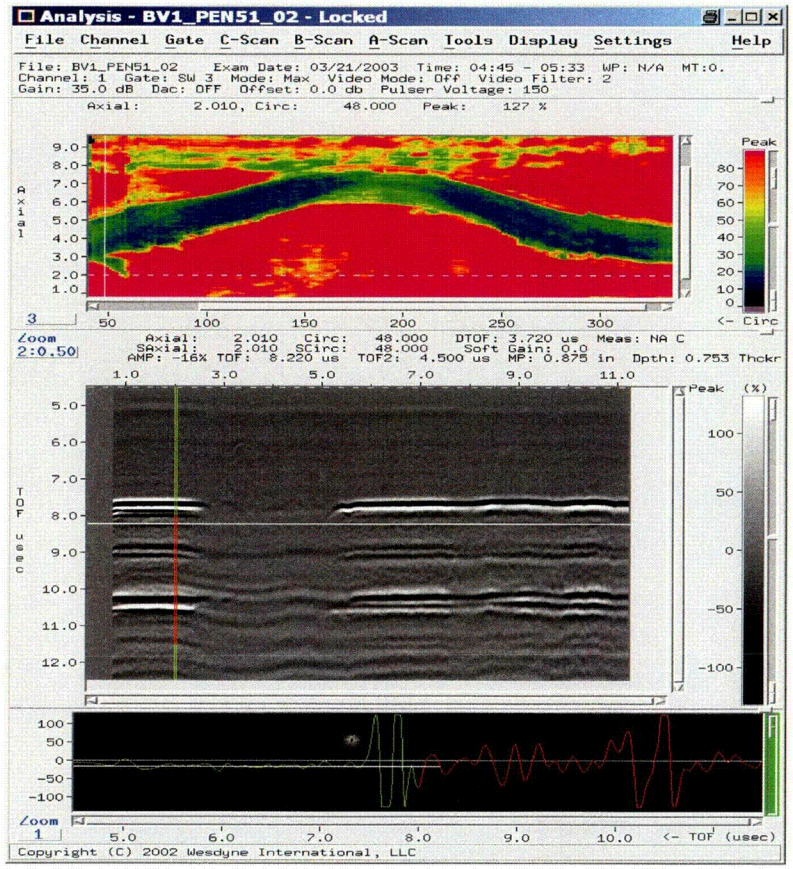
Leak Path Identification



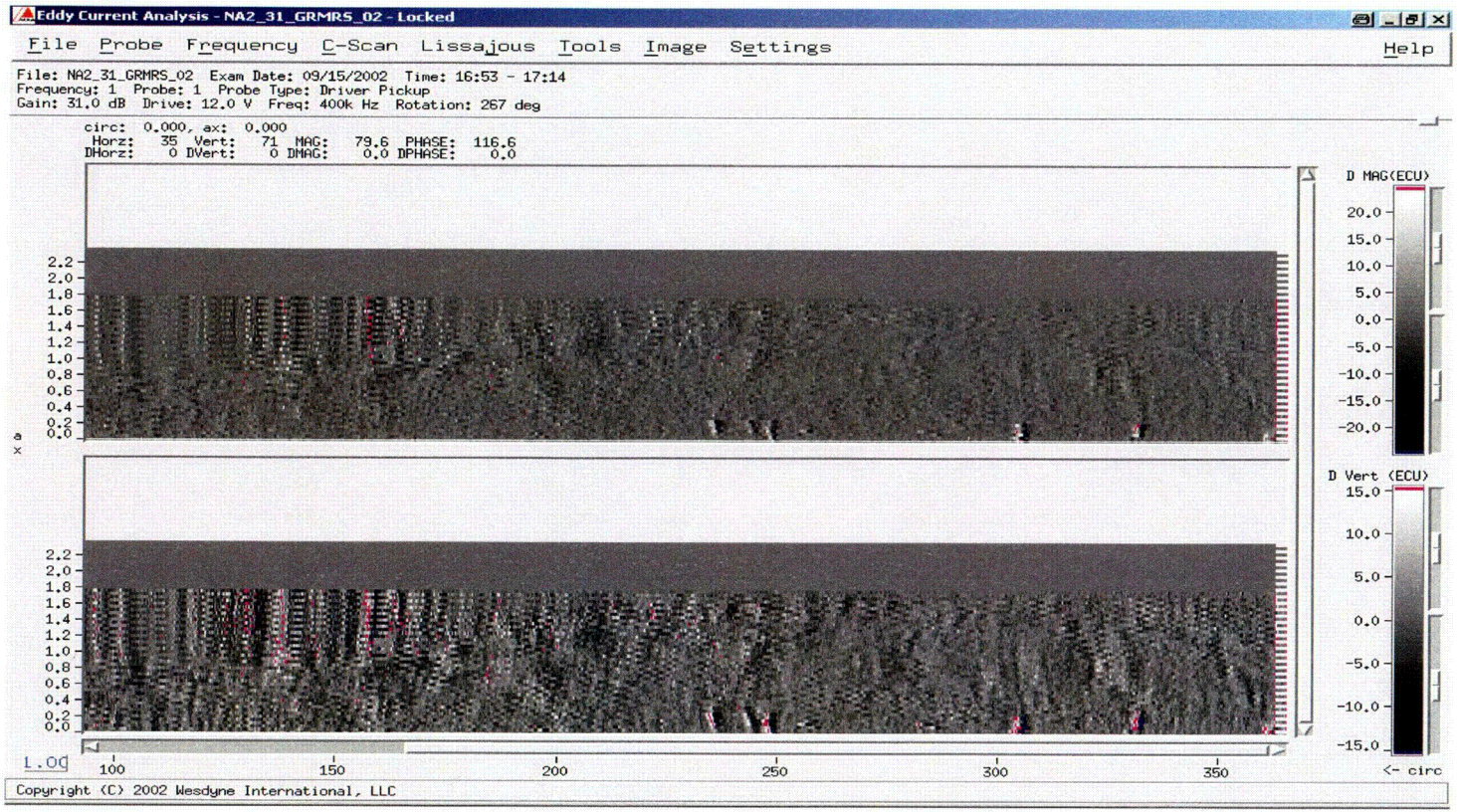
- Not applicable to BMI inspections
- Possible leak path identified with straight beam, high frequency ultrasonics
- Leak path leads to loss of shrink fit integrity and a resulting increase in reflectivity
- Diagnostic tool rather than a primary inspection method

Penetration Tube OD ECT and ID TOFD Results



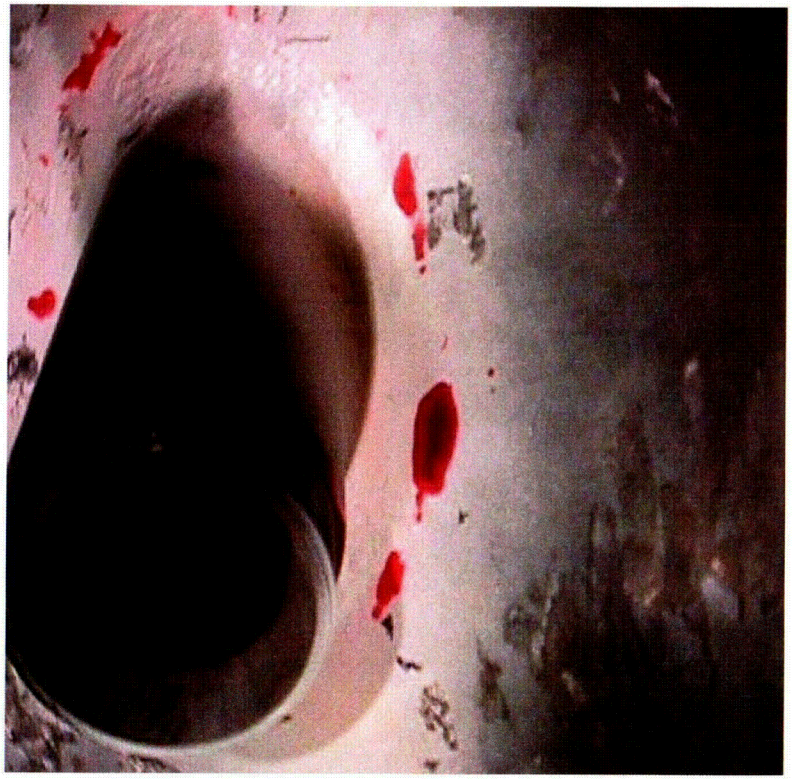


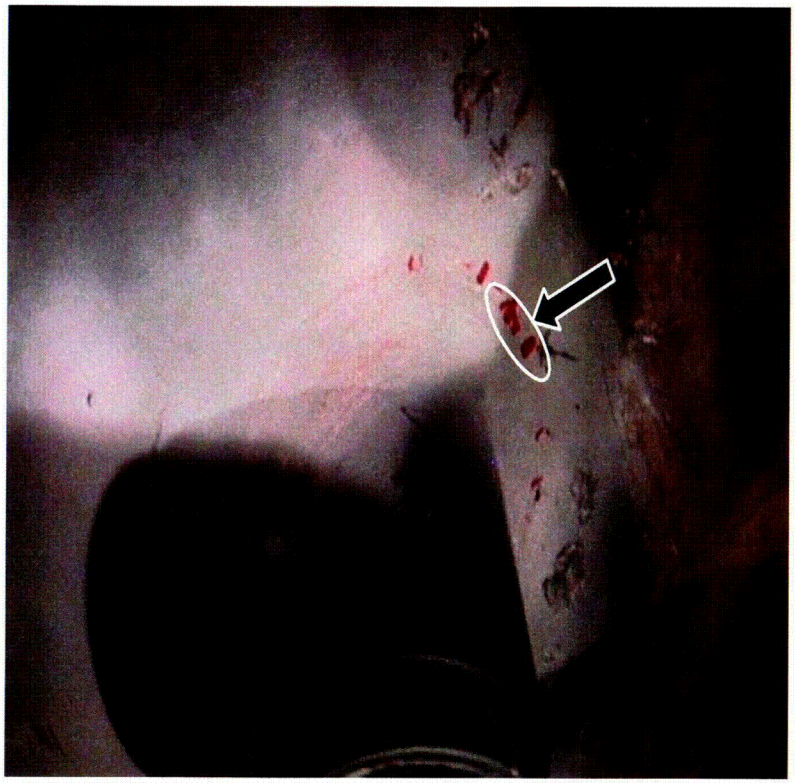
J-Groove Weld ECT Results



C40

Reactor Vessel Head PT Results





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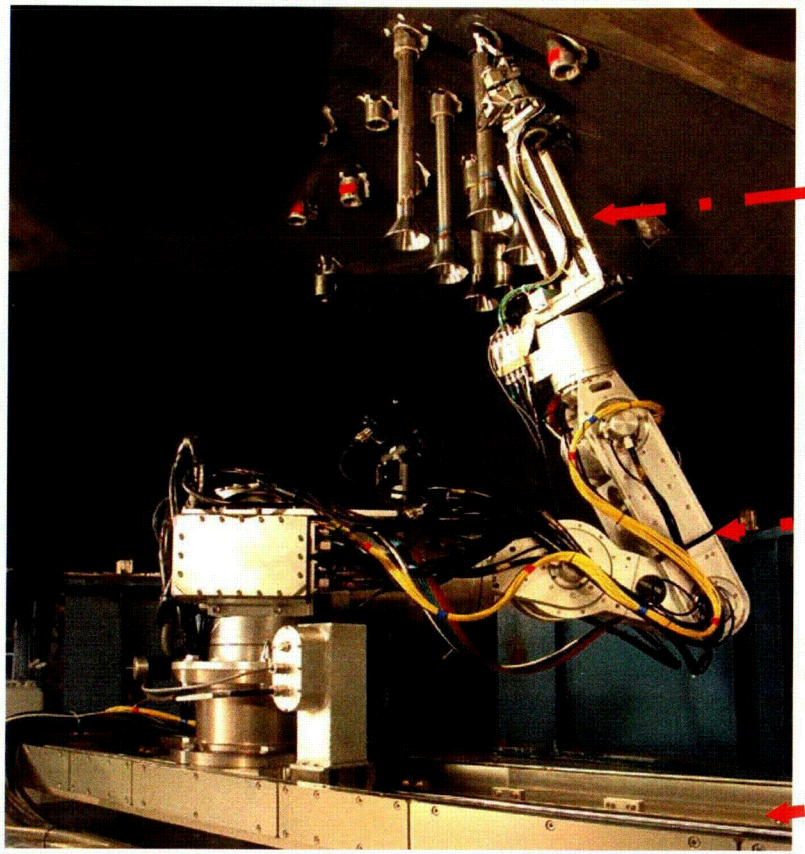
RPVH Inspection Technology

- 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

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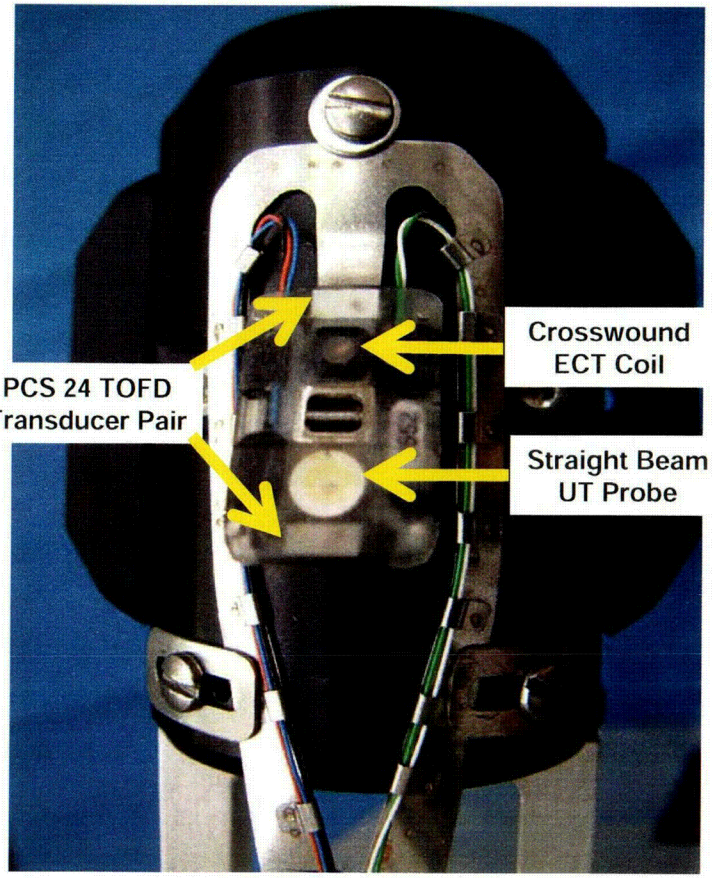
Westinghouse Triple Combo Blade Probe



- 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

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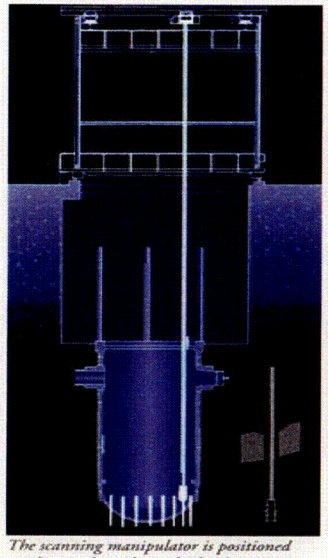
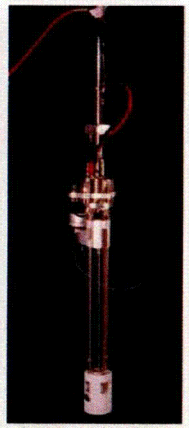
Bottom Mounted Instrumentation Inspection



The scanning manipulator is positioned on the nozzle with a ridgid pole system.



Bottom nozzle inspection manipulator

The manipulator positioned on a nozzle.

ET / UT probe for defect detection (left)
UT pulse echo probe for socket weld inspection
UT TOFD probe for defect sizing (right)

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