Section 3:
Session 2: Continued Plant Operation

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

Warren Bamford, Westinghouse Electric
and
Guy DeBoo, Exelon

Introduction

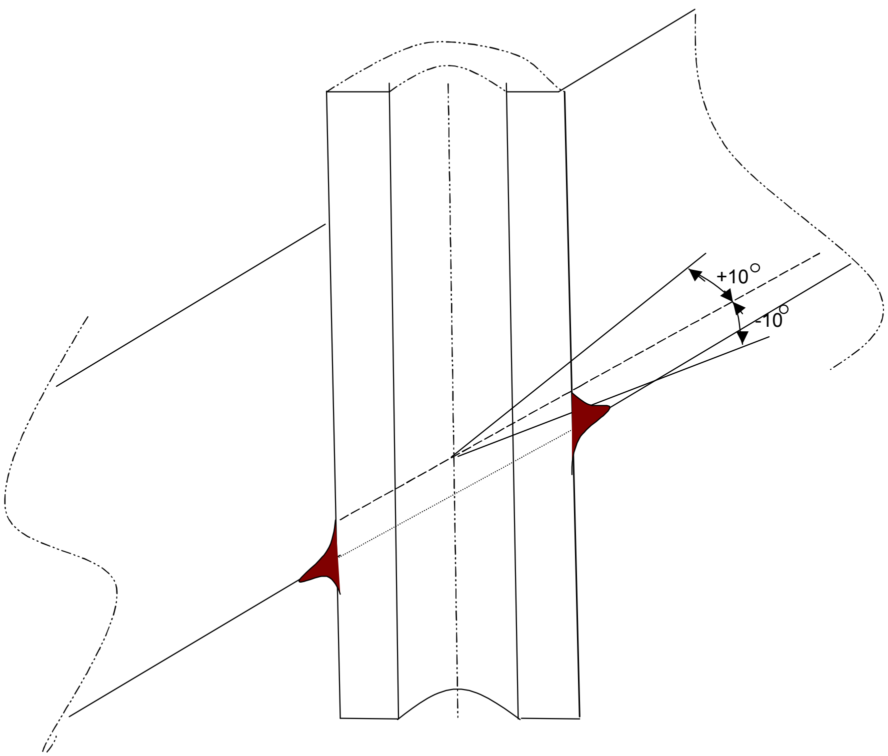
- A consistent and defendable evaluation process for the treatment of flaws in head penetrations has been developed
- The original work on these methods and acceptance criteria was done in the early 1990s, and reviewed and approved by NRC, but not codified
- In 2001, it was decided that the acceptance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

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

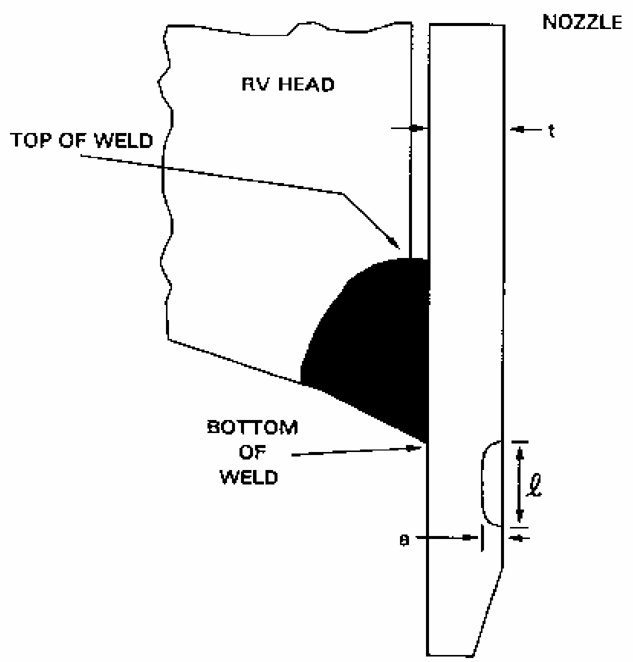
Flaw Characterization

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

Definition of “Circumferential”



Schematic of Head Penetration Geometry



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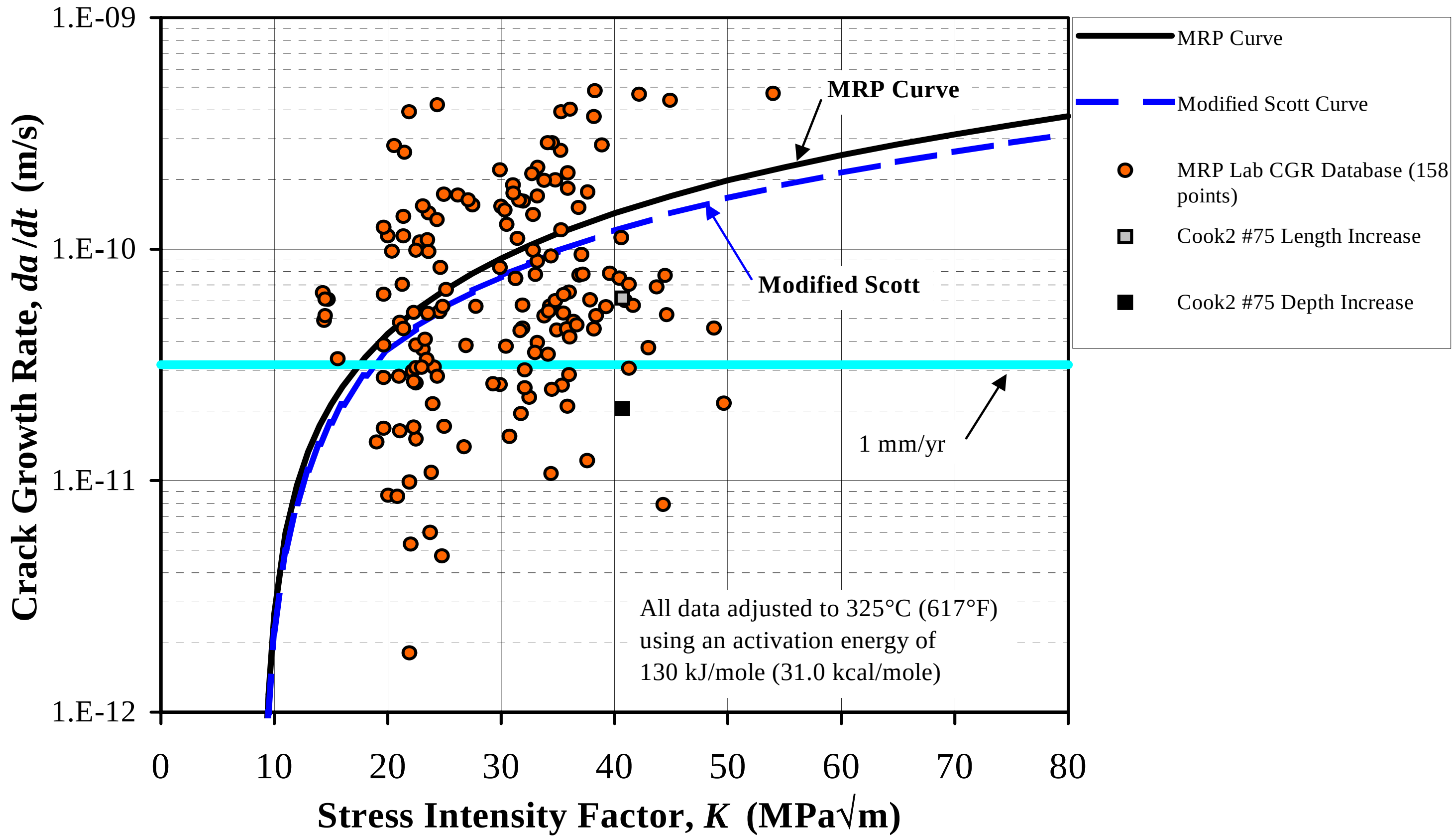
Evaluation Process

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

Stress Corrosion Crack Growth

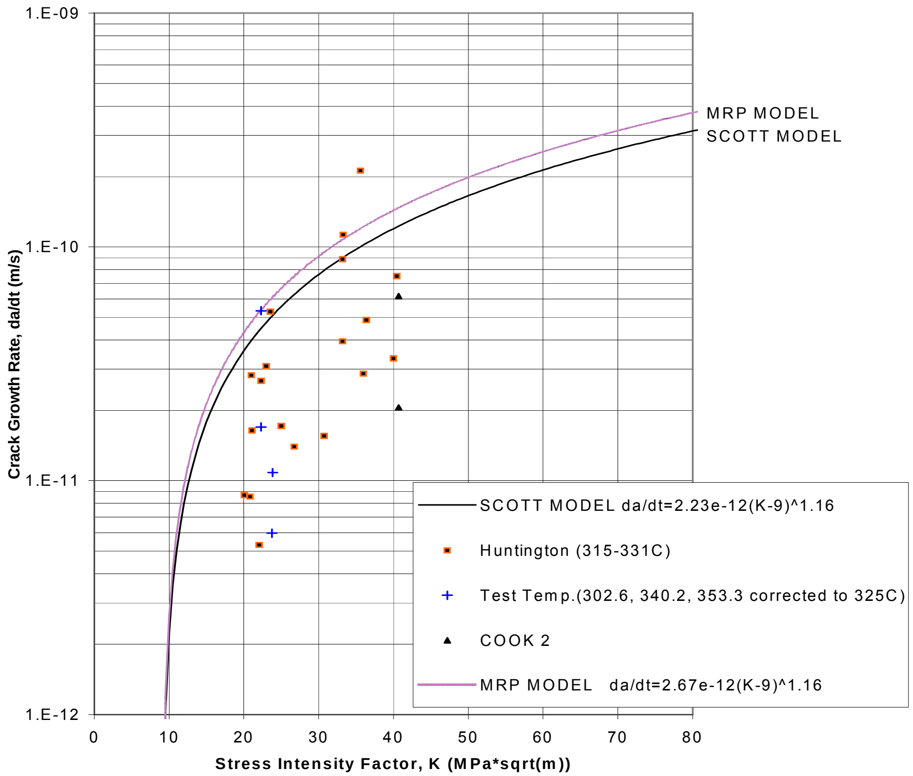
- Use EPRI MRP-55 Rev.A report as basis for growth model: Alloy 600 Base Metal
- Goal is a "Best Estimate" Prediction
- Model is higher than the mean, so it is conservative
- Additional conservations added in acceptance criteria


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

Example Calculation to Verify SCC Growth Rate

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

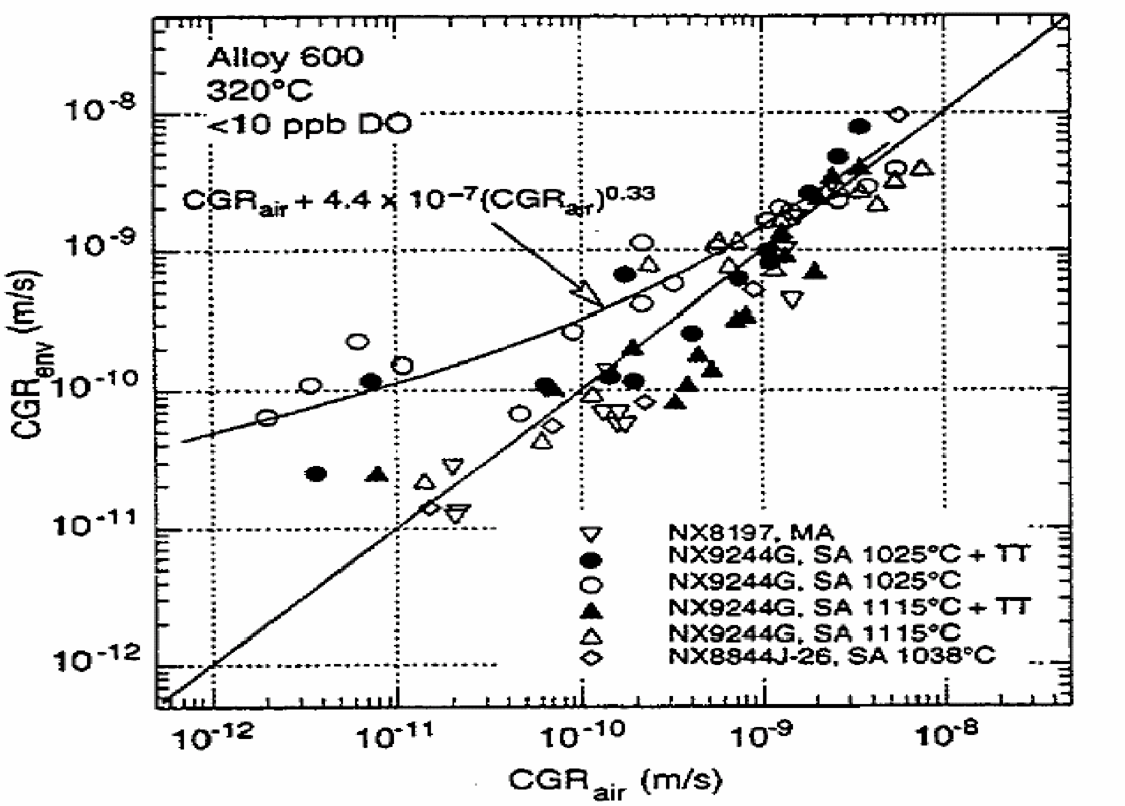
Service induced crack growth, compared with the PWSCC model



Fatigue Crack Growth

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

Argonne Model, with Data



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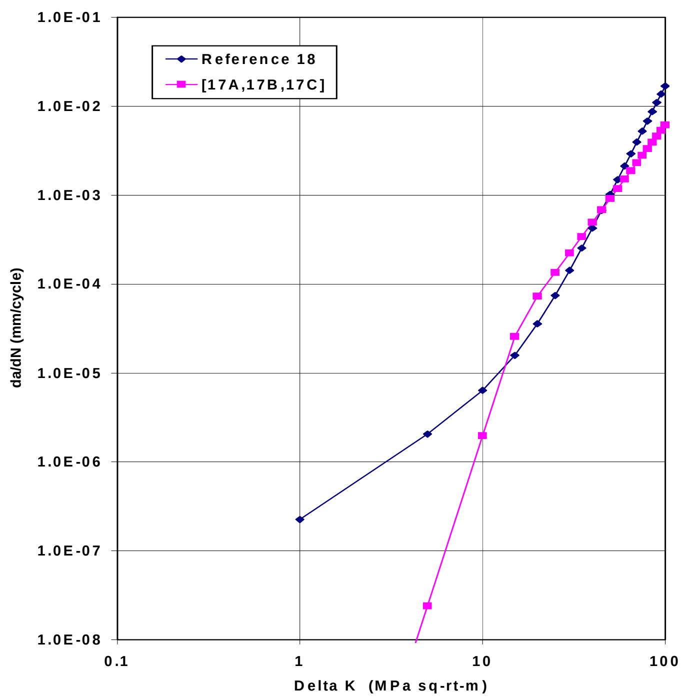
Comparison to other Fatigue Crack Growth Models



Flaw Acceptance Criteria

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

Table IWB 3663-1: Summary of R.V. Head Penetration Acceptance Criteria

Location	Axial		Circ	
	a_f	l_f	a_f	l_f
Below Weld (ID) (2)	t	No Limit	t	.75 Circ.
At and Above Weld (ID)	0.75 t	No Limit	(3)	(3)
Below Weld (OD) (2)	t	No Limit	t	.75 Circ.
Above Weld (OD)	(3)	(3)	(3)	*(3)

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

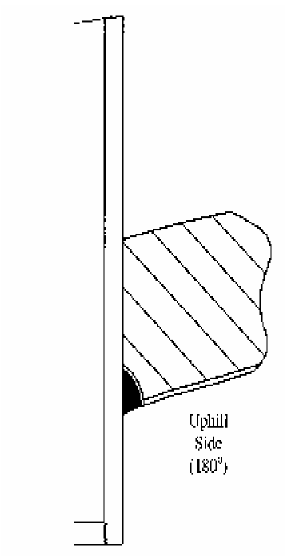
a_f = Flaw Depth as Defined in IWB 3600

l_f = Flaw Length

t = Wall Thickness of Head Penetration Nozzle

Example Application

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



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ASME Code Actions

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

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MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE

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

CONTENT

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

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

- **In France, on September 23, 1991, a leak occurred on the Bugey 3 T54 vessel head penetration;**

- **Leak was detected by acoustic emission during hydrotest (207 bar ⇒ 1.2 Pressure Design) and was estimated to 1l/h.**

- **After expertise, a mainly longitudinal crack from inside the penetration, through wall extent, was found.**

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

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

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

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- **NON DESTRUCTIVE EXAMINATION**
  - 1st NDE developments :ET
    - *Detection by Eddy current with a classical rotating probe but need to remove thermal sleeve*
  - 2nd NDE development : ET & UT
    - *Detection by Eddy current with « blade probe » without removing thermal sleeve*
    - *Characterization by ultrasonic « blade probe » using Time Of Flight Technique (TOFT)*
    - *Video probe*
- **Probes tested on mock-ups with artificial, realistic and real flaws.**
- **FIRST NDE RESULTS**
  - At the end of 1992 :
    - *✓Five 900 MW vessel heads with cracked penetrations and four 1300 MW (after 30000 to 40000 hours operating).*
  - At the end of 1994 :
    - *✓47 VHs had been inspected;*
    - *✓33 VHs out of 47 with tiny indications and very few cracks in penetrations.*

- **Alternative methods**
  - Leak detection system using N^{13} installed on about 20 vessel heads with alloy 600 penetrations to prevent new leak.
  - No leak was detected since 1991,
  - Systems dismantled when vessel heads are replaced by Inconel 690.
- **Visual testing on vessel heads**

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

REPAIRS

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

REPLACEMENT

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

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

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- **A large investigation program is launched in 1992**

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

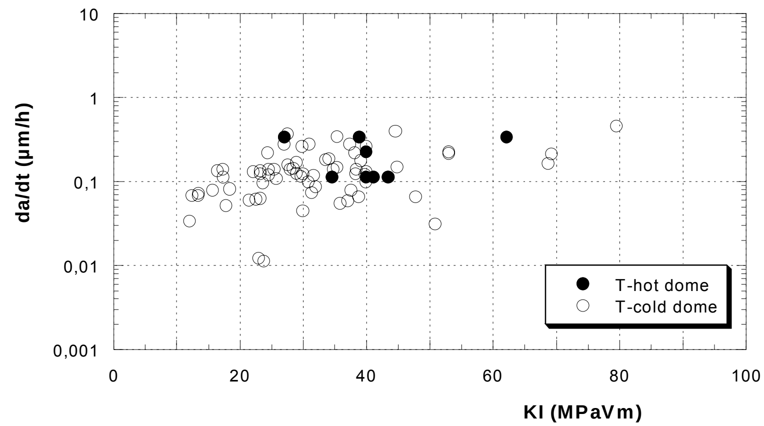
Best estimates of the temperatures at the penetration inner surface in front of the weld :

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

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

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

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



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

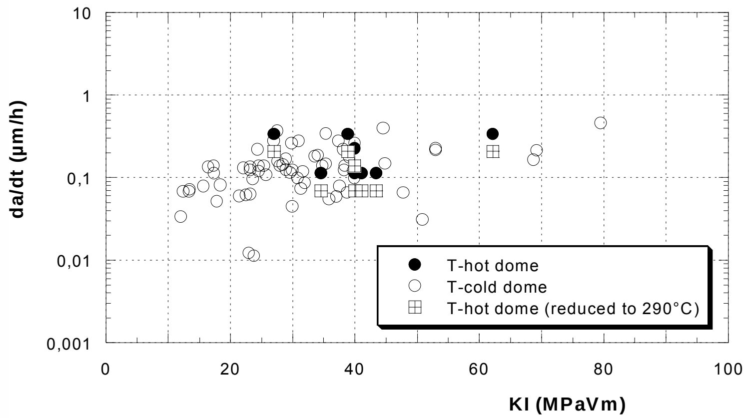
Activation energy has been deduced from **laboratory data** obtained at EDF, Framatome, CEA and ETH, between 290°C and 360°C, for which a satisfactory agreement has been obtained **(Q = 130 KJ/mol).**

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

Field data - T-hot dome data (300°C)

reduced to 290°C with Q = 130 KJ/mol

and T-cold dome data (290°C)



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❑ Crack Propagation Laws

Alloy 600 :

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

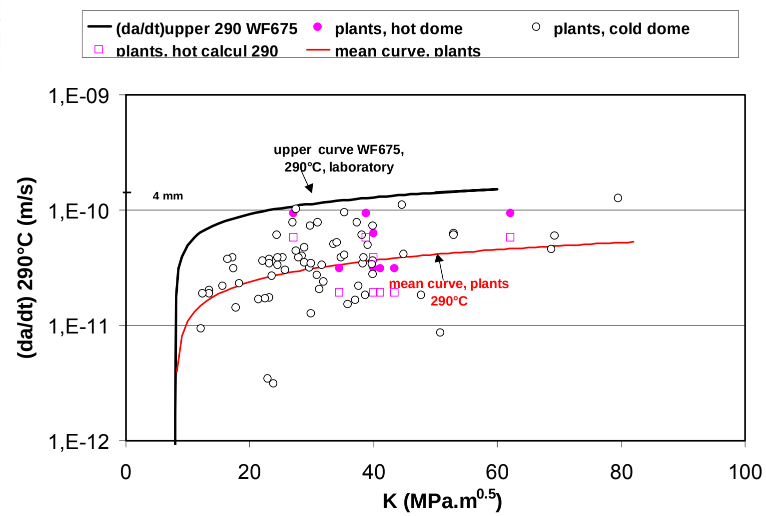
Upper bound (Field and Laboratory Data)
(290°C) : $da/dt = 0.3 \times (K - 9)^{0,30}$

(da/dt in μm/h ; K in MPa√m)

Alloy 182 :

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

Results



Characteristic Values of Crack Growth Rates in Depth

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

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

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

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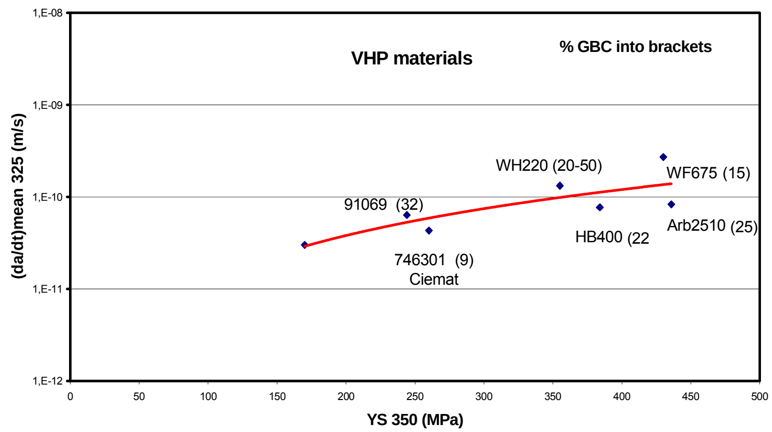
❑ Effect of yield strength on Grain Boundary Coverage (GBC):

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

For VHPs, at 325°C:

- **detrimental influence of high YS_{350} , low GBC :**
- **$(da/dt)_{mean} = 6.10^{-15}\ YS^{1.66}$ but complex effects with GBC (+ intra)?**

Laboratory results (effect of the material)



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

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

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

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

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

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

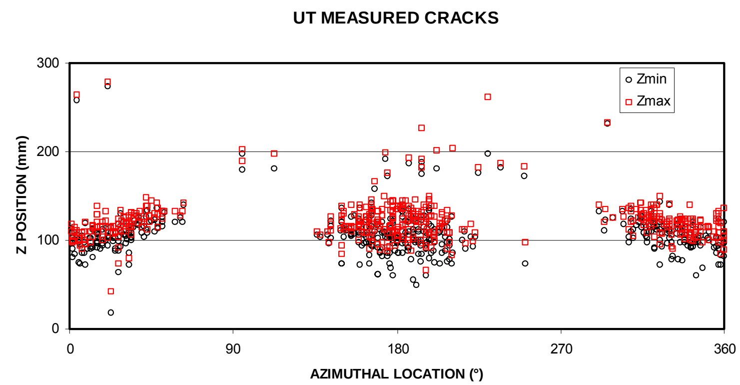
Vessel head replacement

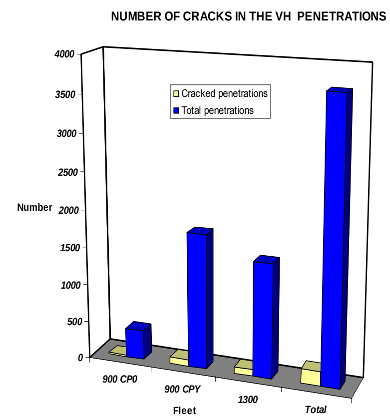
MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : NDE results

Results for VH penetrations NDE:

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

Results





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

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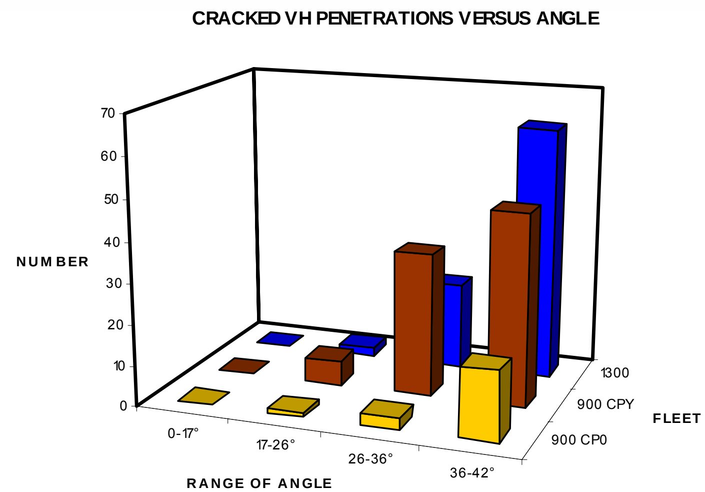
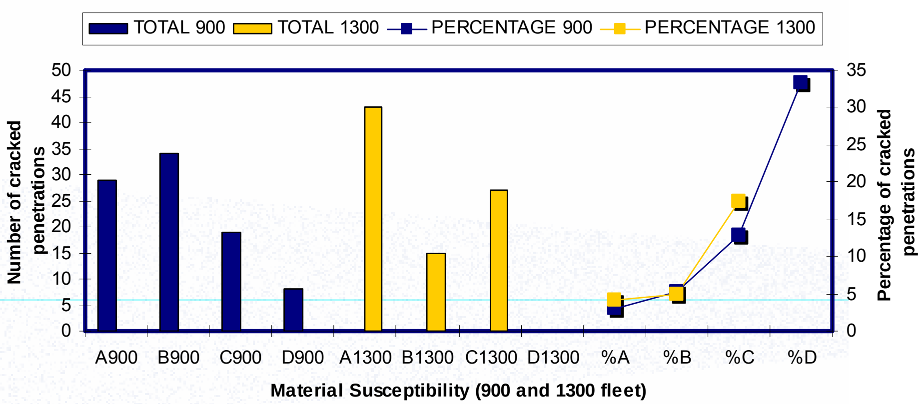
- ❑ **Importance of the set up angle of the penetration,**
- ❑ **High angle = high stress level**



- ❑ **Importance of the susceptibility of materials to PWSCC**

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



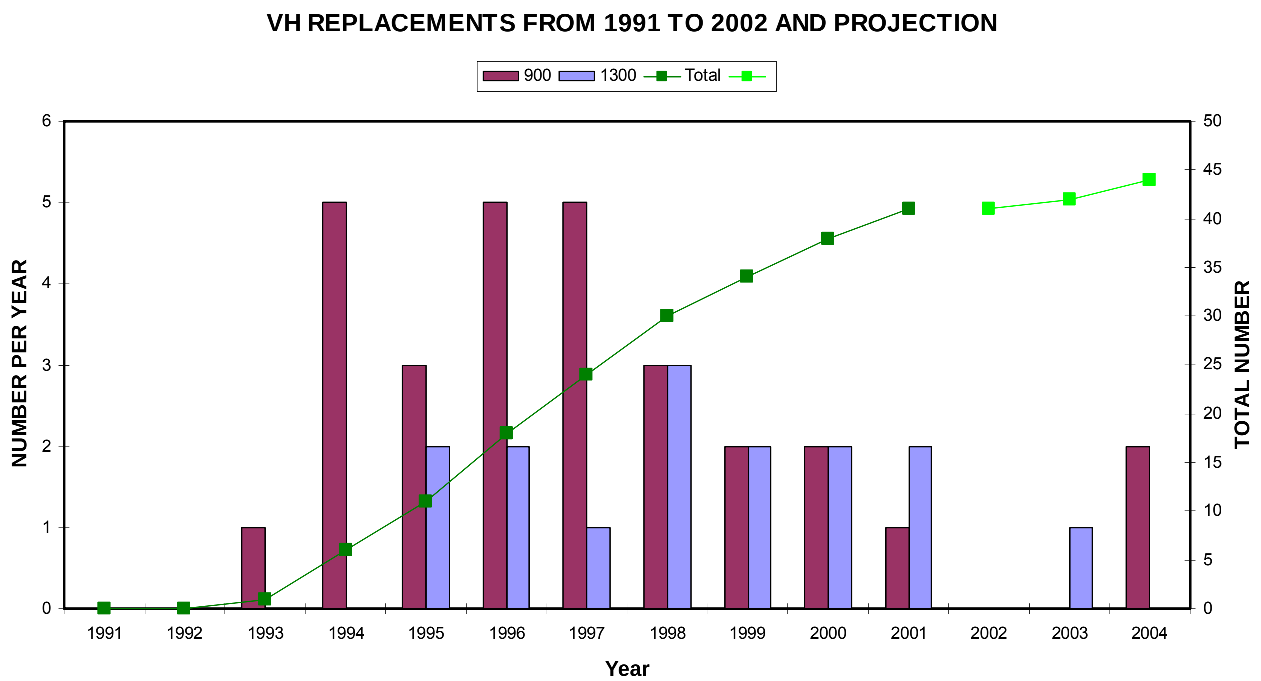
MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE : Feedback experience

EDF Electricité de France

- **Complementary examinations of J groove welds**
  - Dye penetrant testing performed on 754 welds from 11 replaced VH
  - Results : no defect detected
- **Other examinations**
  - In order to prevent any leak with boric acid corrosion on top of vessel head, a video examination of Canopy welds is performed every 10 years.
- **VHP with alloy 690**
  - 3 VHP examined by ET technique with same kind of procedure than alloy 600 VHP;
  - Results : no SCC defects detected and characterized as expected from alloy 690 SG tubes follow up (performed since 1990).

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

EDF Electricité de France



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

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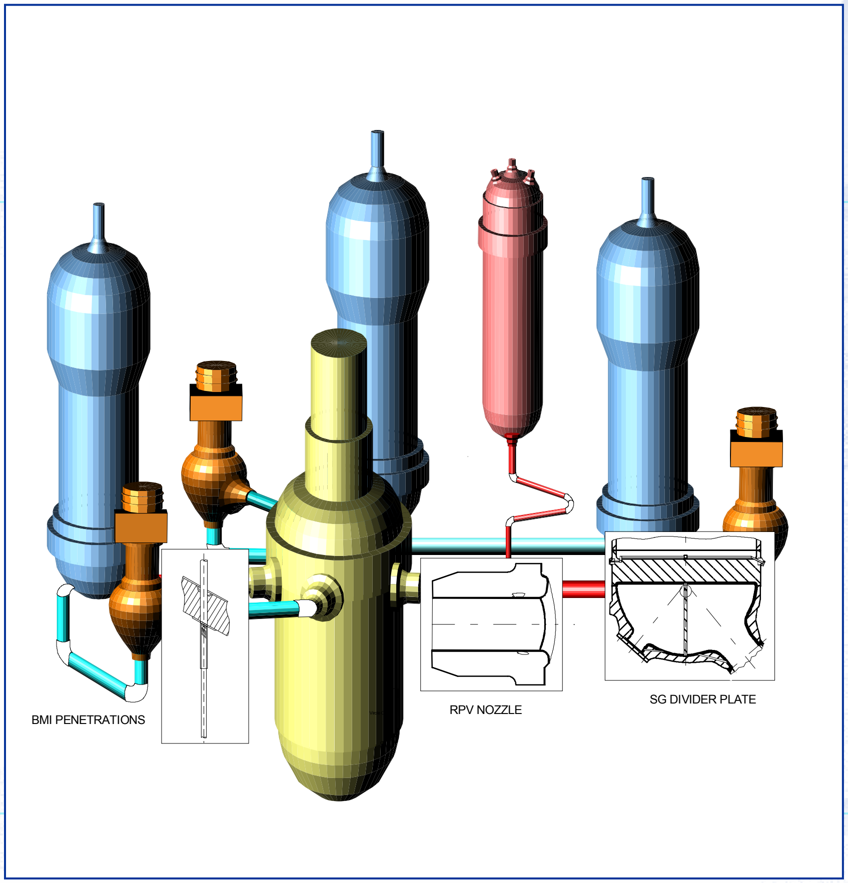
IN PRIMARY SYSTEM

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



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

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

have been inspected

No crack indication has been found in these components.

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

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

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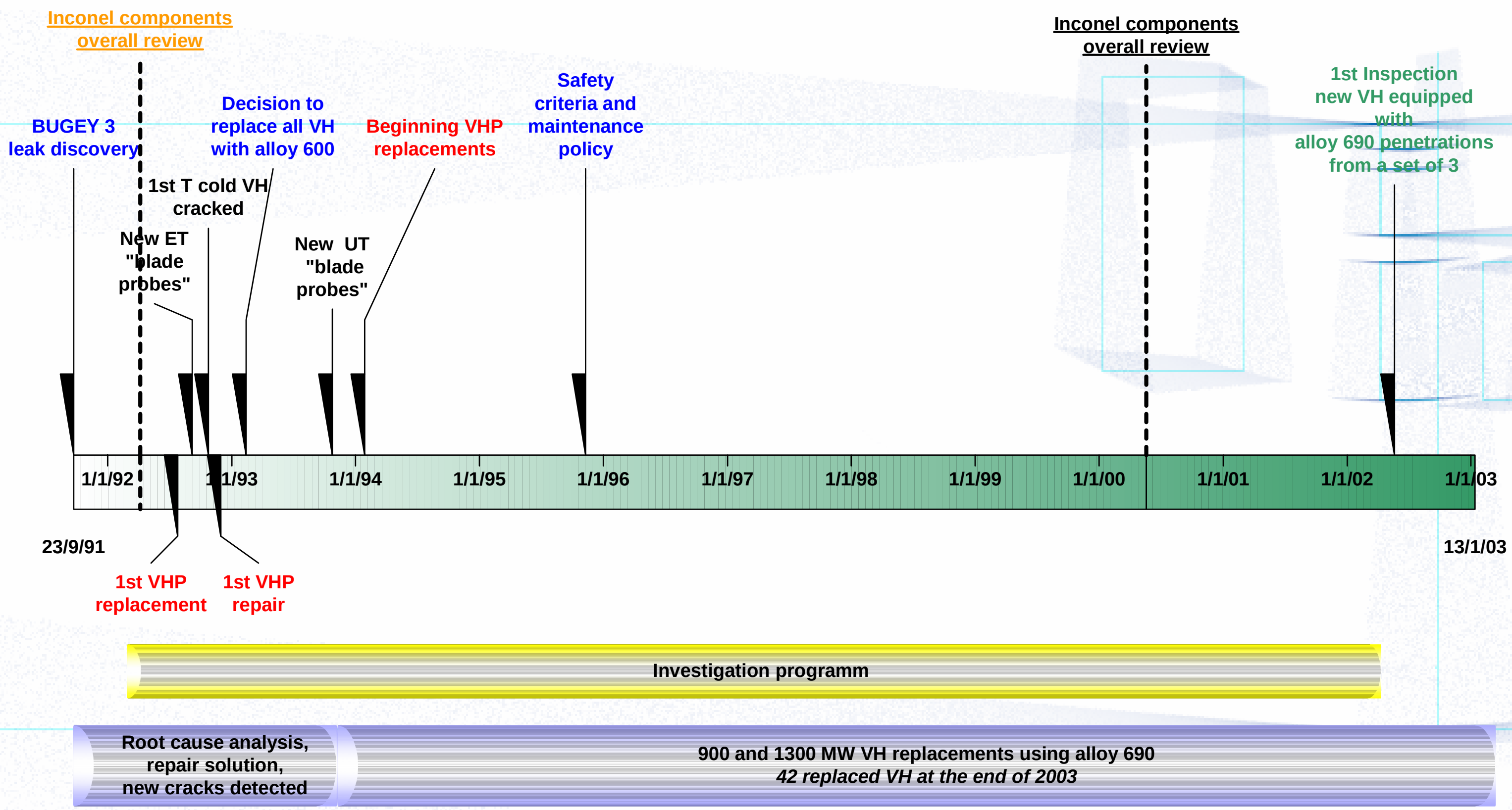
- **Since 2001, a new program has been established following French regulator's decision :**
  - 26 SG partition plates (precursors) + 9 random to be inspected up to 2008,
  - 12 RPV bottom head penetrations to be inspected up to 2008,
  - RPV hot branch nozzles repaired zones (stress relieved during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

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

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

❑ Key milestones



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

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

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

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

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

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

but

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

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Strategic Planning for RPV Head Operation

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

Vessel Head Penetration Inspection,
Cracking and Repair Conference

September 29 – October 2, 2003
Gaithersburg, MD

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

Contents

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

Objective

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

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Background
Potential Economic Consequences

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

Inputs/Constraints
Overview

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

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Inputs/Constraints
Inspection Interval Requirements

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

Inputs/Constraints
Outage Duration and Inspection/Repair Window

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

Alternative Management Approaches
Overview

- Continue to inspect and repair as necessary at intervals necessary to ensure low risk of leakage and very low risk of core damage

- Perform remedial measures to reduce risk or possibly increase inspection intervals

- Replace head at the second outage after discovery of first PWSCC

- Replace the vessel head as quickly as possible and perform NDE every 4^{th} outage

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Alternative Management Approaches
Inspection and Repair Options

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

Alternative Management Approaches
Remedial Measures Options

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

Alternative Management Approaches
Remedial Measures Effectiveness

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

Alternative Management Approaches
Remedial Measures Conclusions

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

Alternative Management Approaches
Head Replacement

- Installation of a new head is a clear success path
- New heads will be more resistant to PWSCC
  - Alloy 690 nozzles
  - Alloy 52 J-welds

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- Cost and replacement time is a function of containment building access
  - Will head fit through the equipment hatch
  - Will head fit through equipment hatch with CRDM drives preinstalled

Alternative Management Approaches
Head Replacement - Service Structure Option

- Many domestic PWR plants have original-design head service structures that require significant time for disassembly and reassembly
  - Head insulation
  - Head cooling ducts
  - CRDM cables
  - Head cooling fans
  - Missile shields

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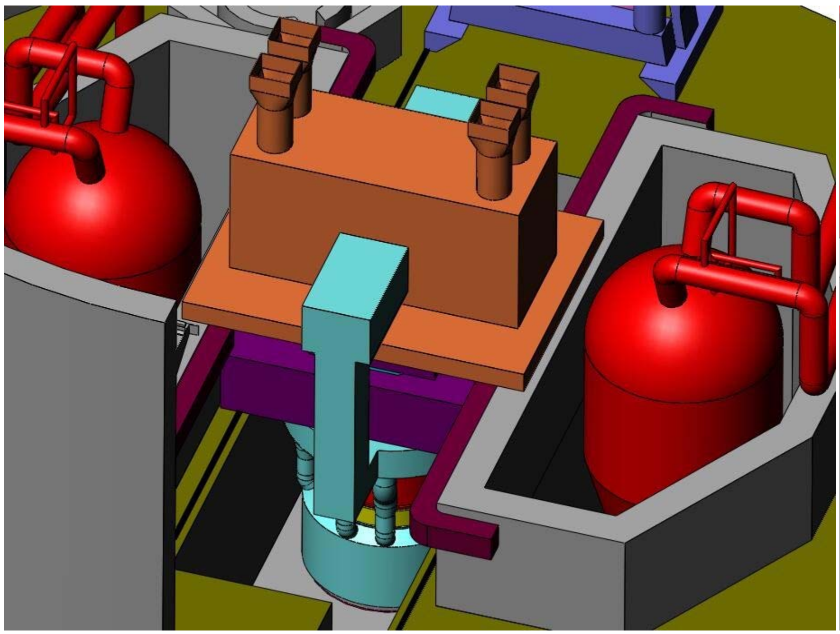
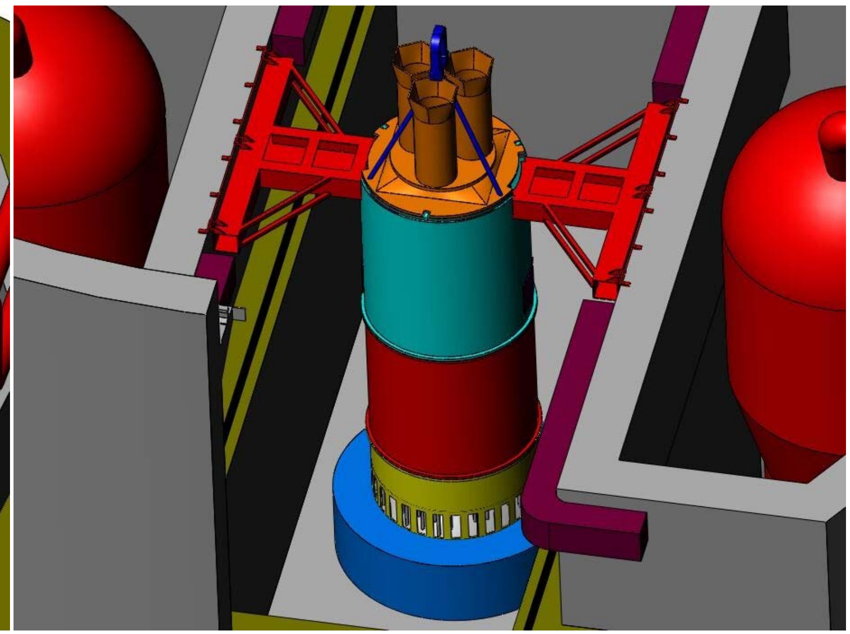
- Head disassembly and reassembly time can impact critical path
- Head replacement provides an opportunity to incorporate an integrated head service structure

Alternative Management Approaches
Head Replacement - Service Structure Option



Typical Original Structure



Conceptual Integrated Structure

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Alternative Management Approaches
Head Replacement - Service Structure Option

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

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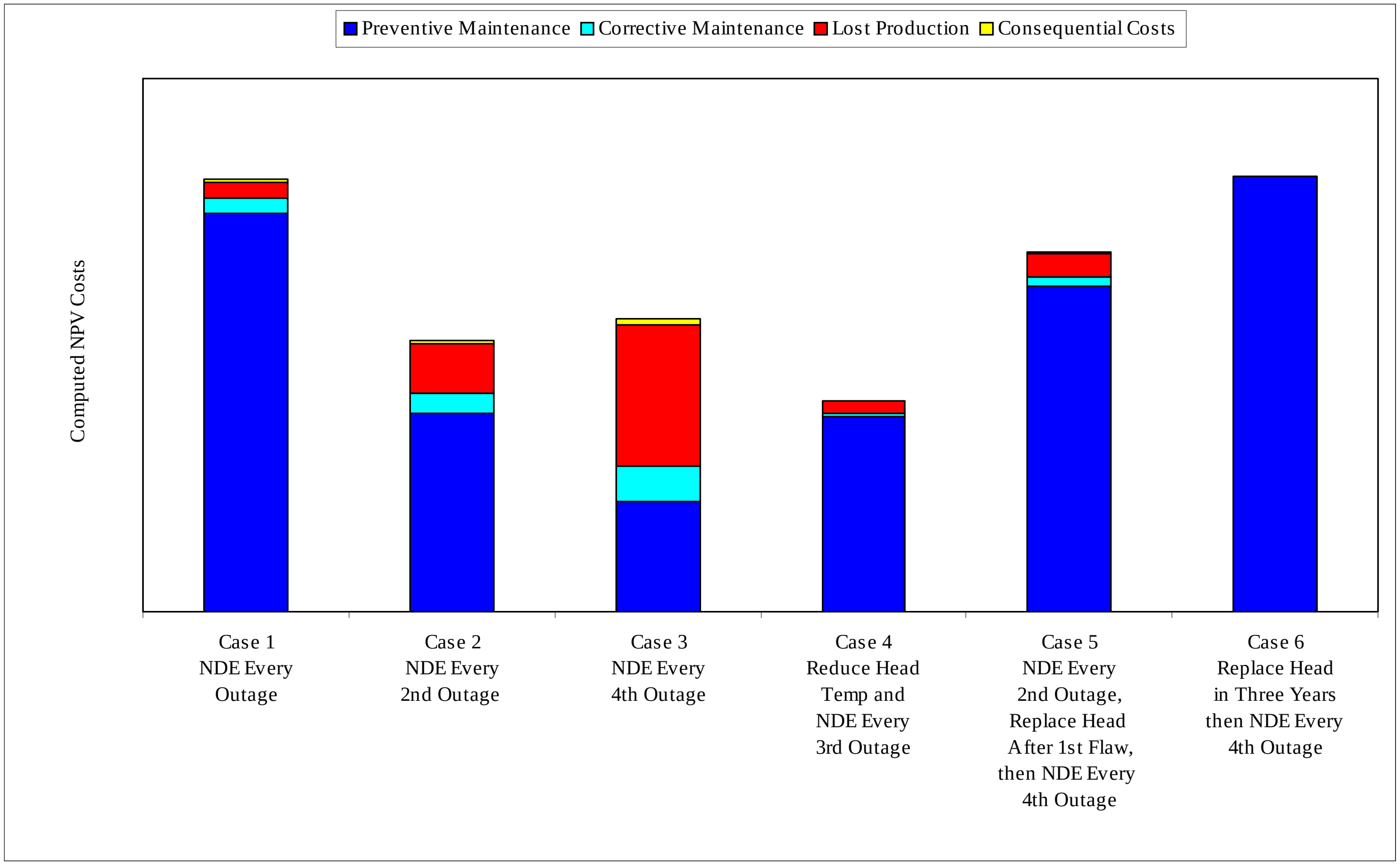
Economic Evaluations
NPV Analysis Approach

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

Economic Evaluations
NPV Analysis Software

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

Economic Evaluations
Typical Results for Moderate Susceptibility Plant



Conclusions

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

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

D. Waskey

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FRAMATOME ANP

RV Incore Nozzle FANP European History/ Experience/ Future

> **History**
  - ***In 1991, EDF initiated a programmatic campaign to examine all I-600 sensitive areas including the in-core nozzles.***

> **Experience (to Date)**
  - ***Surveillance of 18 EDF RPV (> 500 penetrations) since 1992, by Framatome.***
  - ***To date, no indications of cracks have been found.***
  - ***On-vessel time for complete inspection ~ one week***
  - ***8 more EDF inspections planned through 2009***
  - ***ECT and UT utilized***
  - ***Circ and Axial probes being further developed (0°& 45° for characterization)***
  - ***Nozzle Material and Weld fusion line inspected – not welds***

> **Future:**
  - ***EDF plans to continue examinations of one or two plants per year through 2009.***

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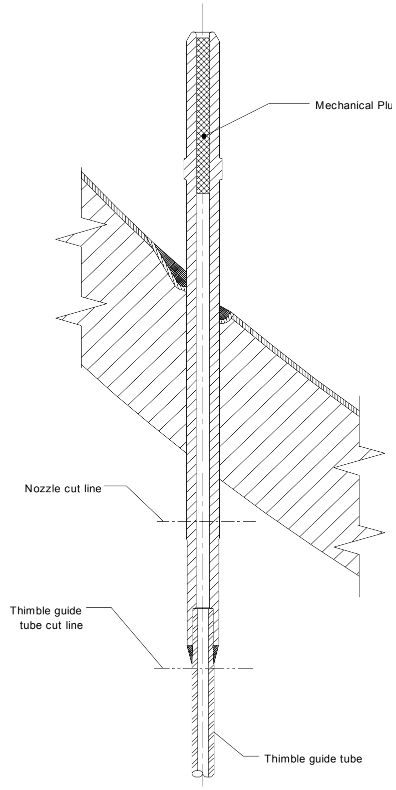
RV Incore Nozzle FANP Domestic History / Experience / Future

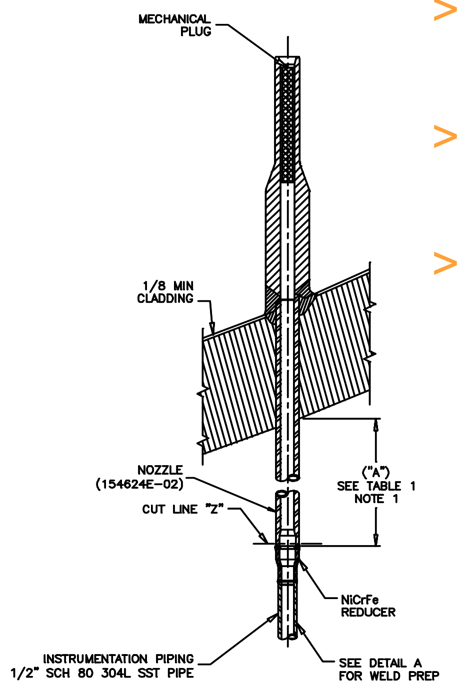
- **History**
  - During Hot Functional Testing of Oconee-1,iBMI nozzles broke.
  - Most B&W plants were field modified with thicker Alloy 600 nozzles and 182 filler material (Davis-Besse modified in shop).
- **Experience (to Date)**
  - Davis-Besse performed a bare head visual and found residue on lower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

Nozzle Repair Experience

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

BMI Nozzle Repair – Step 1





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

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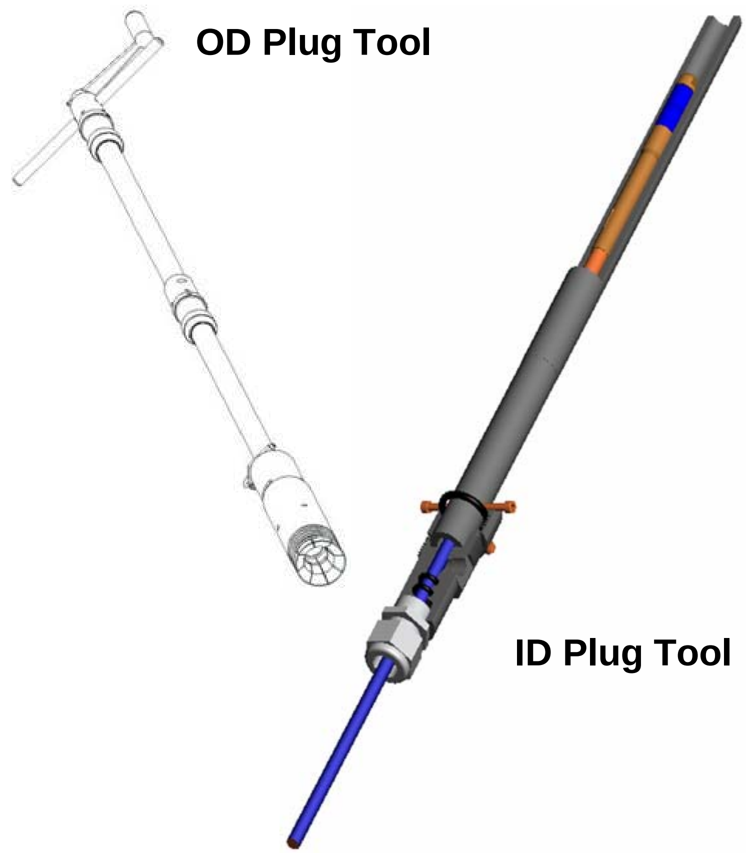
Mechanical Plug

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



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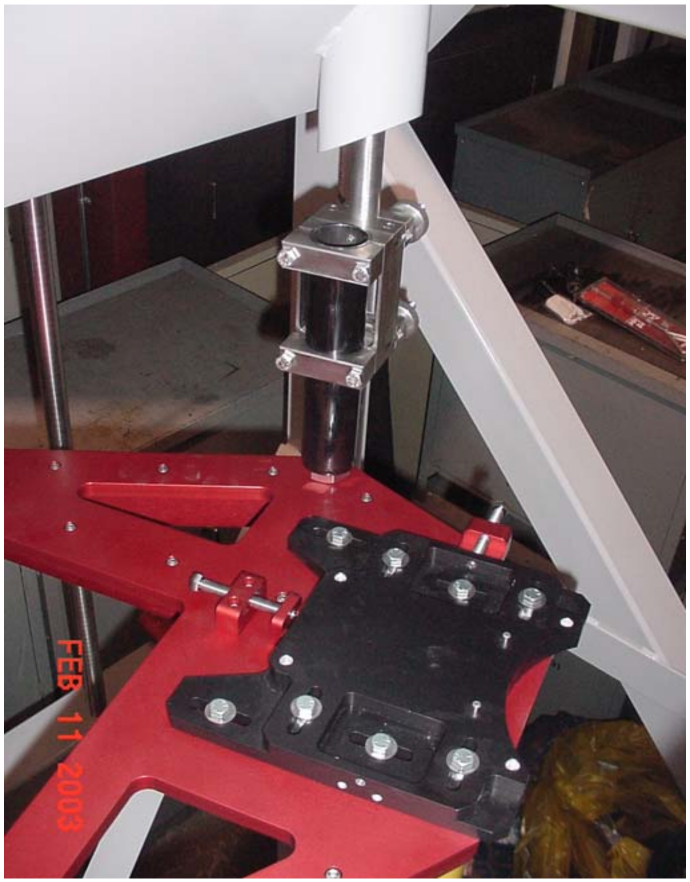
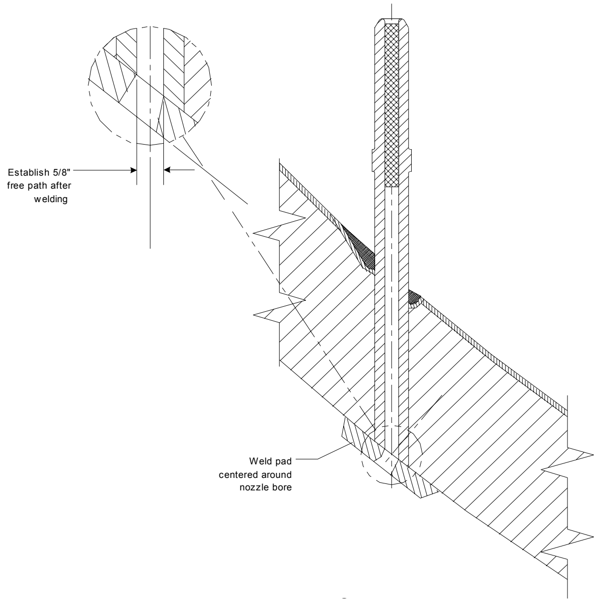
Tool Support Plate

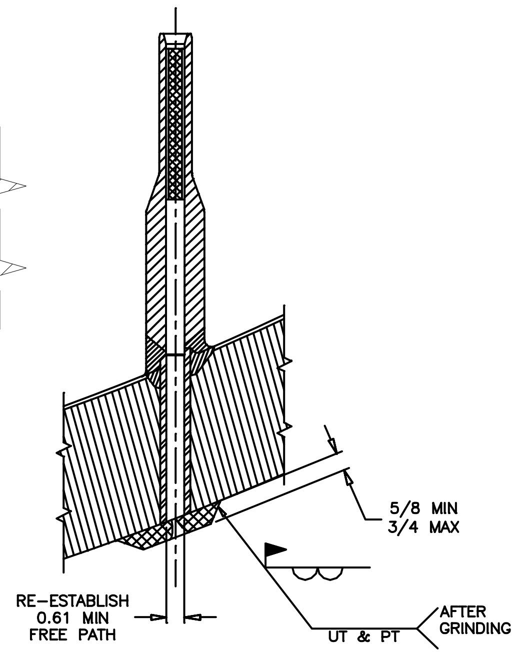


- ***Lightweight components for rapid, one-man, assembly under the RV head***
- ***Centering Plate with an alignment fixture allows for accurate alignment to nozzle bore***
- ***Common interface for weld head, machine tool, and grinder***
- ***Minimal tools required for installation and assembly***
-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

BMI Nozzle Repair – Step 2



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



FRAMATOME ANP

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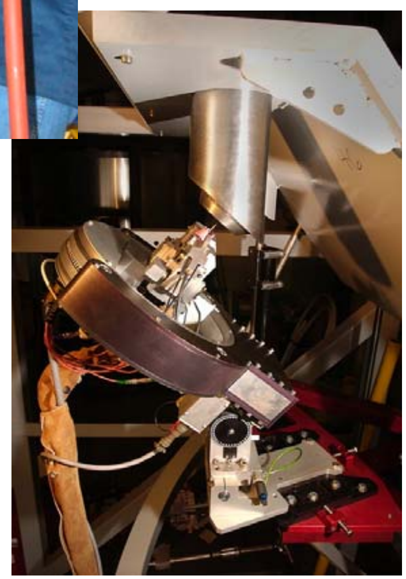
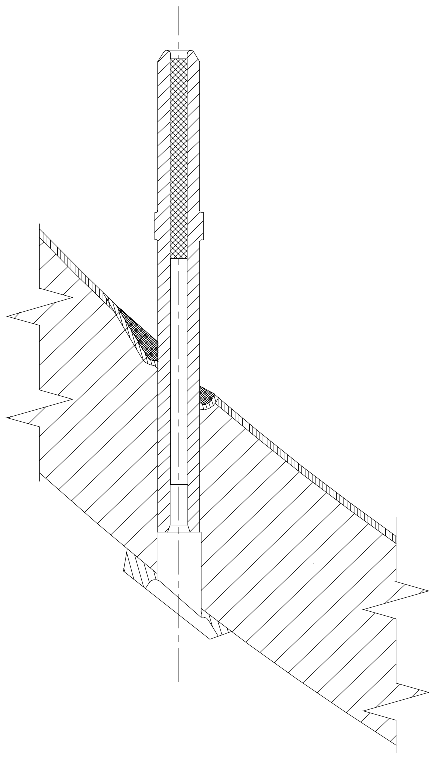
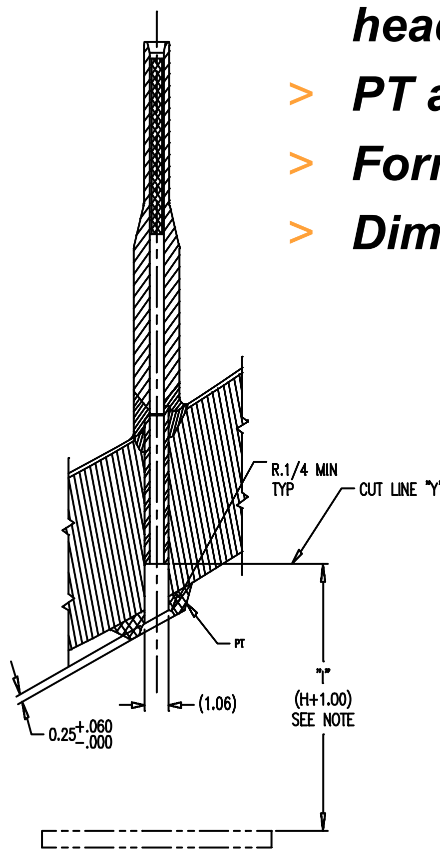
Weld Heads



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

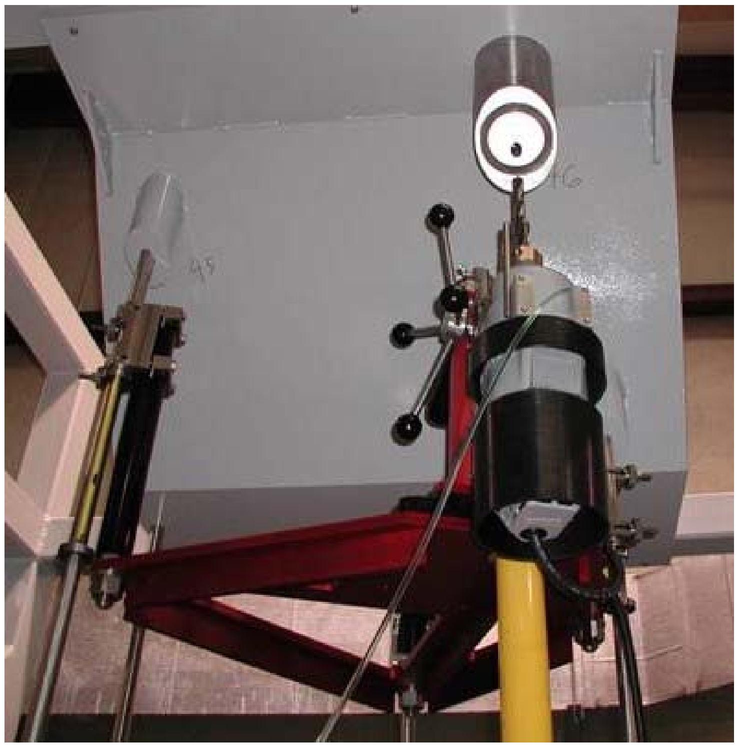
BMI Nozzle Repair – Step 3





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

Drill Tool



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

J-Prep Tool

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

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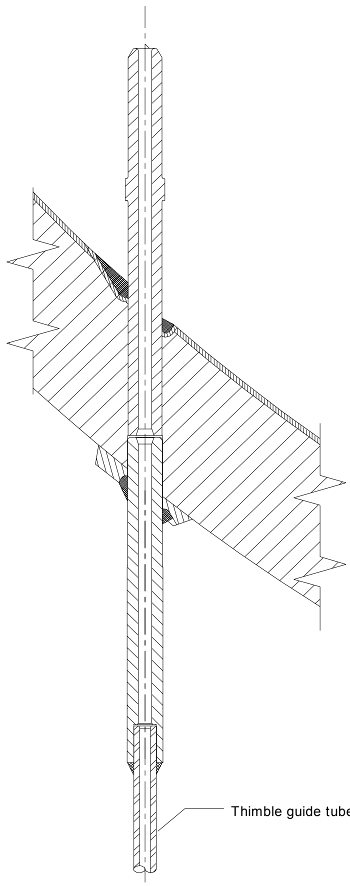
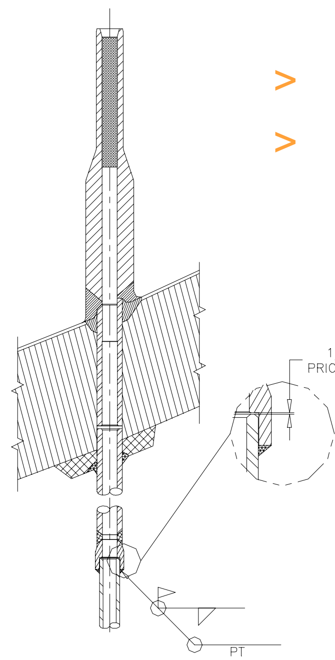
BMI Nozzle Repair – Step 4





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

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RV Lower Head Mockup

> Originally designed for B&W Plant configuration, modified for Westinghouse design

> Includes features to hold removable coupons so that multiple repair trials can be performed at each location

> Used for machining and welding tool qualification and crew training

> CRR 03-90

FRAMATOME ANP

BMI Repair at STP

Overall Schedule for Repair

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

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

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

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BMI Nozzle Repair Code Relief Requests

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

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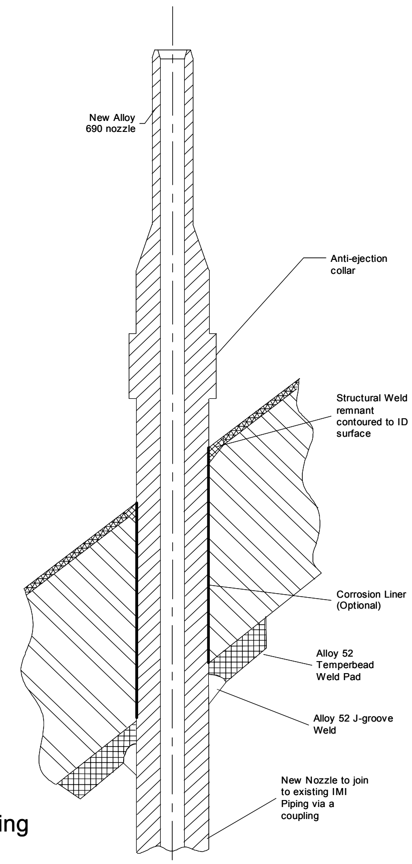
Full Nozzle Repair Concept



Patent Pending

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

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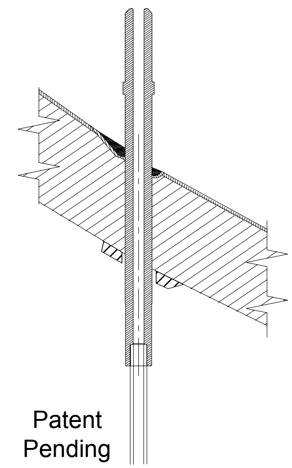
BMI/IMI Nozzle Restoration Concept

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



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Bottom Mounted Instrument Penetration

Condition Resolution

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Penetration #1

Penetration #46

Sample Analysis

Samples contained boron and elevated concentrations of lithium

Samples did not contain any iron

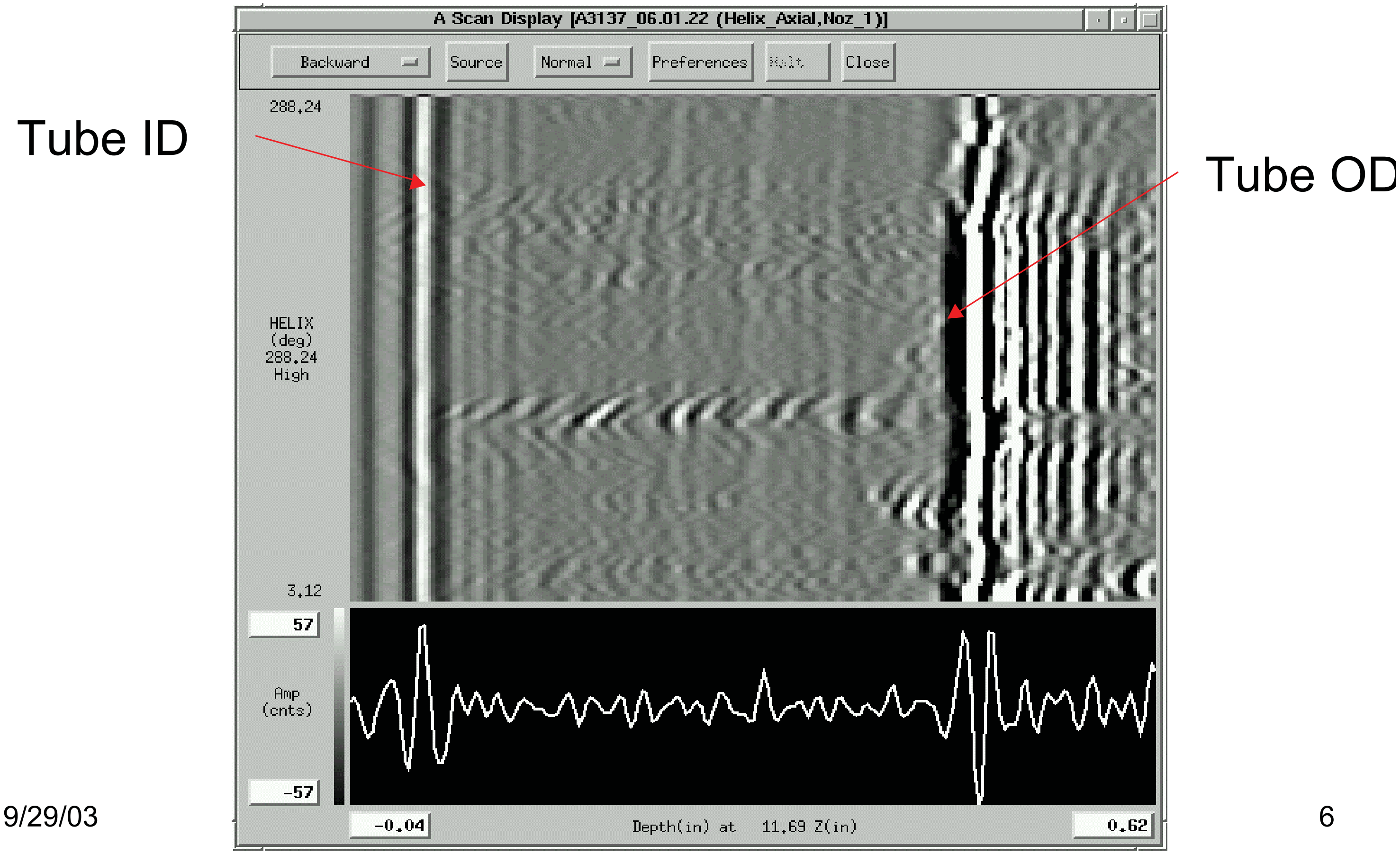
Co-58 not present; therefore > 1 year old

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

Comprehensive Examination

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

Penetration #1 Axial Probe



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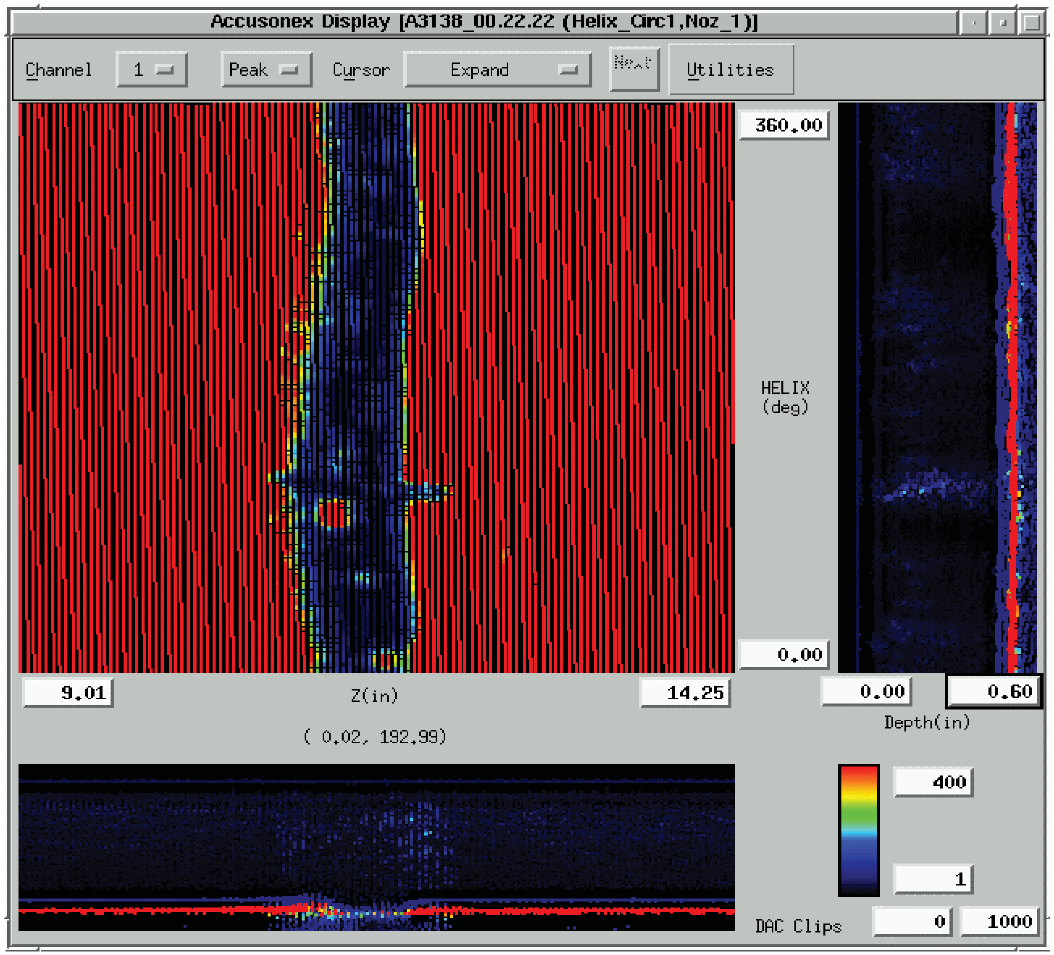
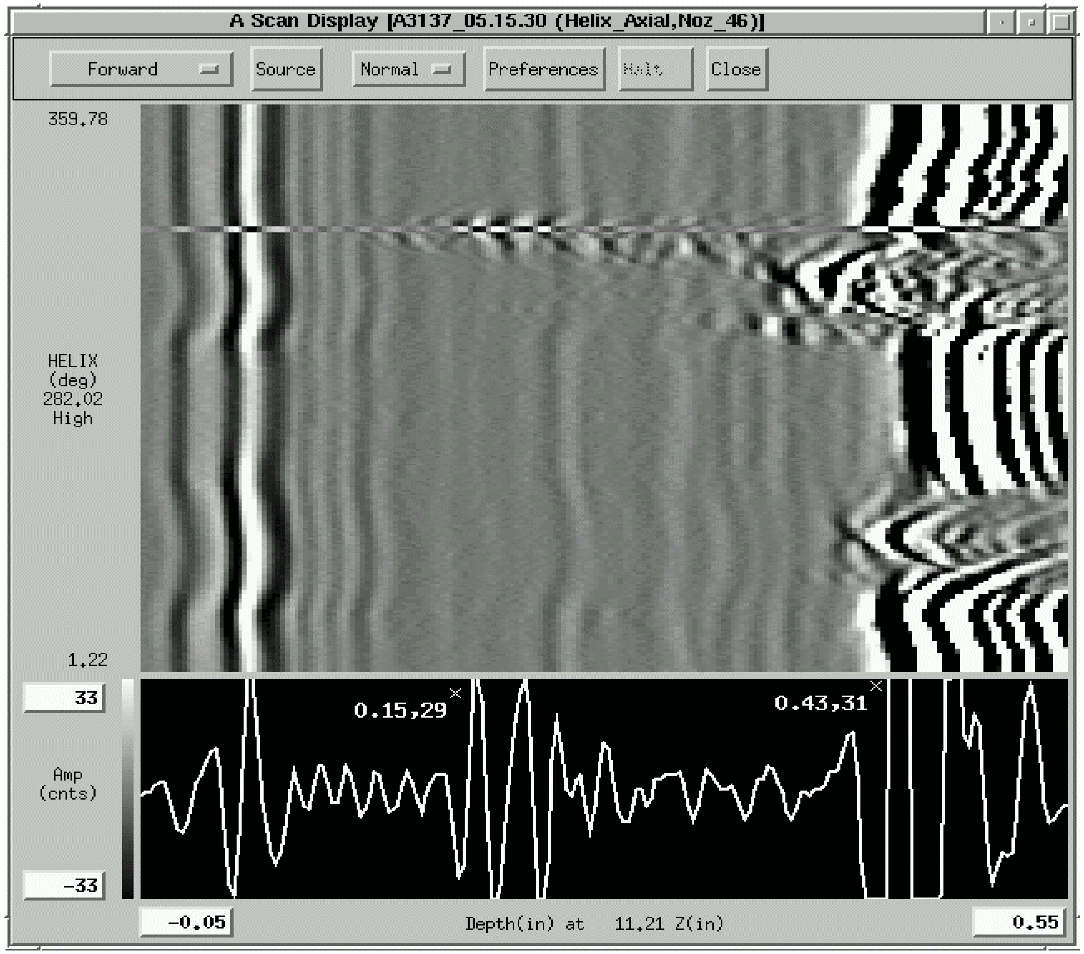
Penetration #1 Weld Profile



Penetration #46 Axial Scan



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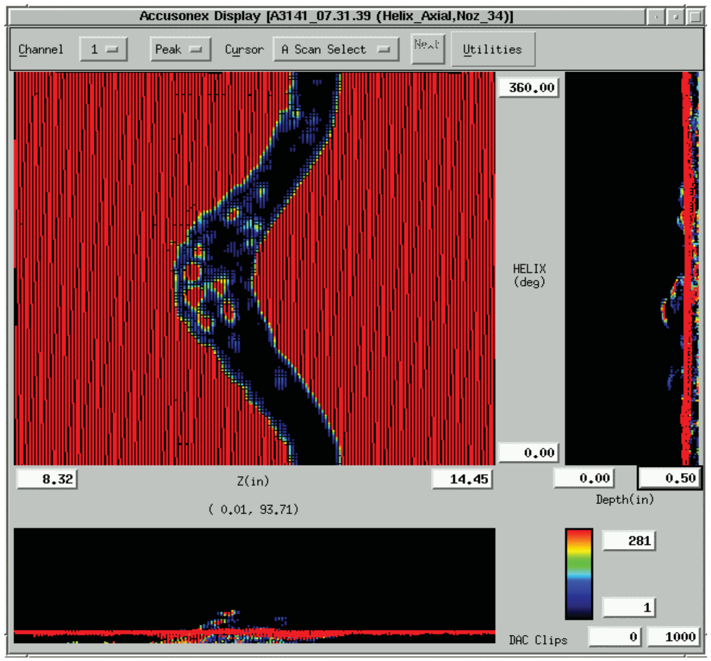
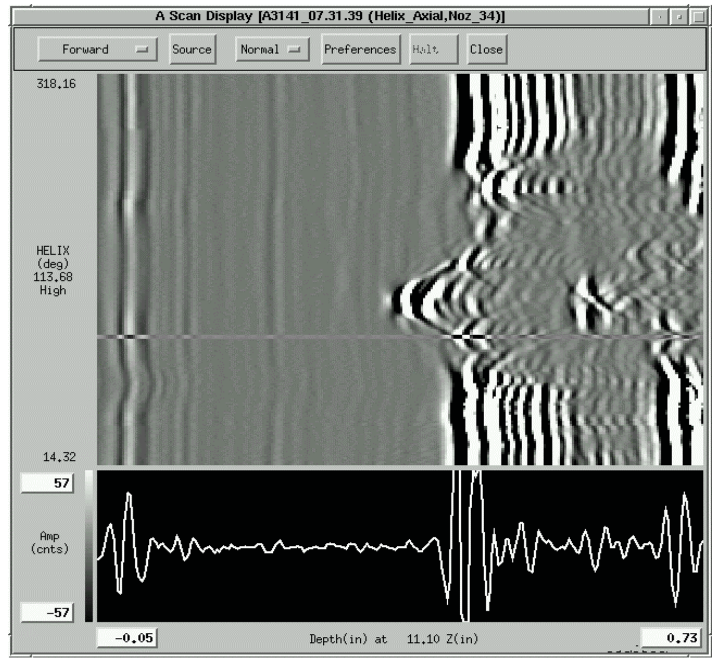
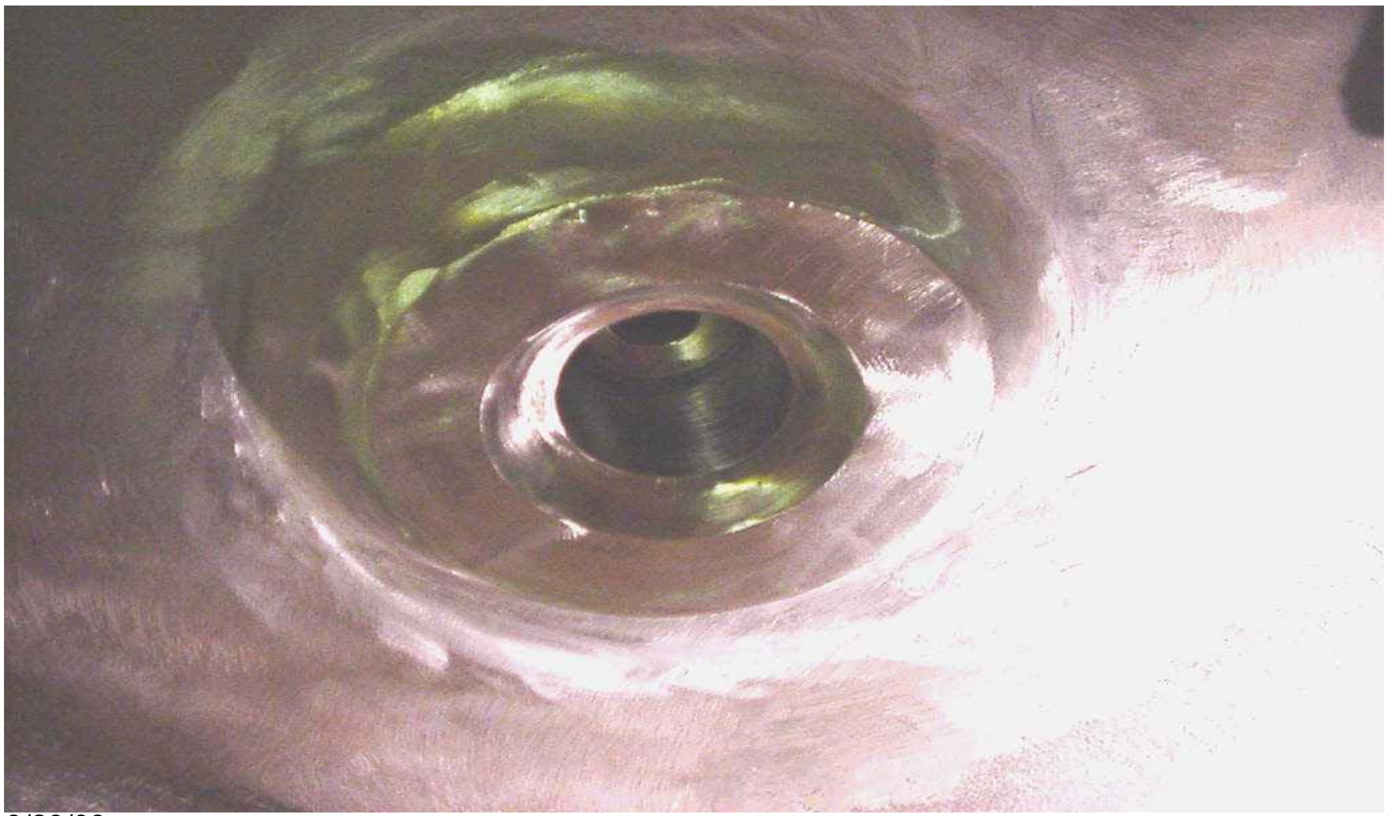
Penetration #34 Fabrication Discontinuity



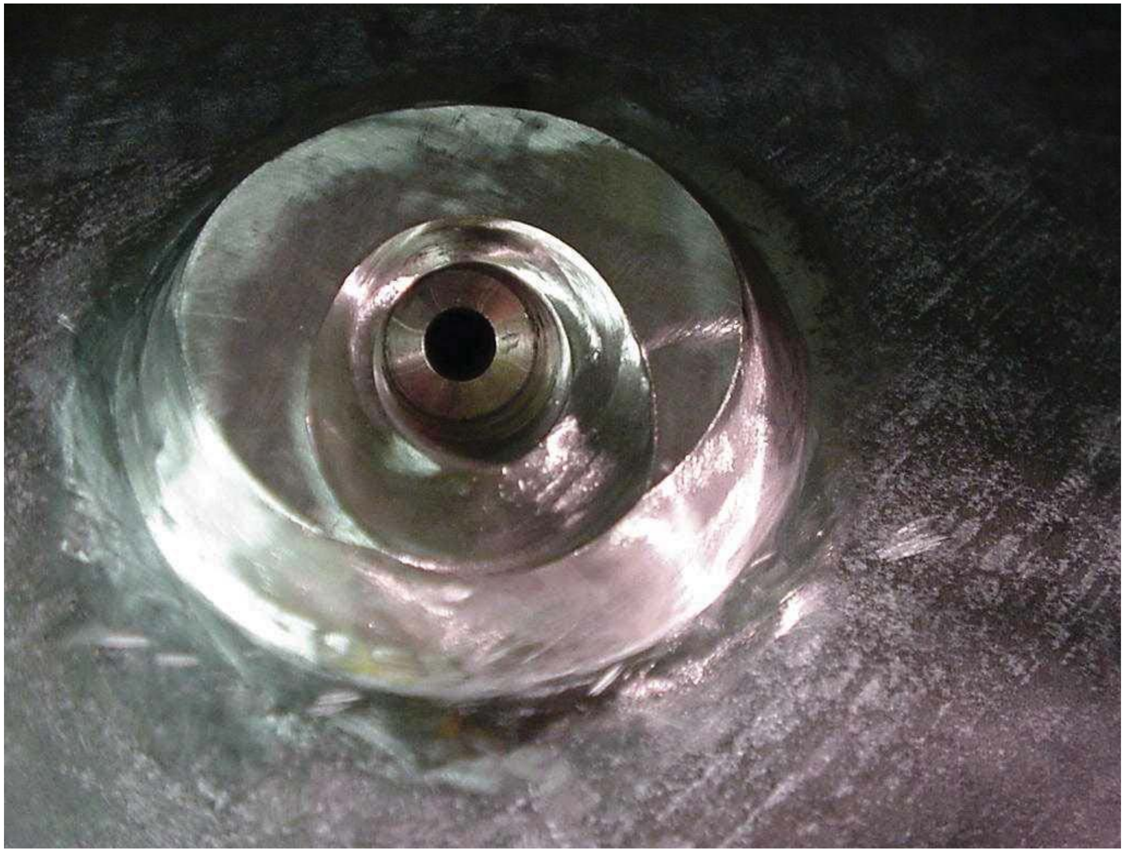


Penetration #1 Weld Pad



Penetration #1 Final Weld

Penetration #46 Weld Pad



Penetration #46 Final Weld

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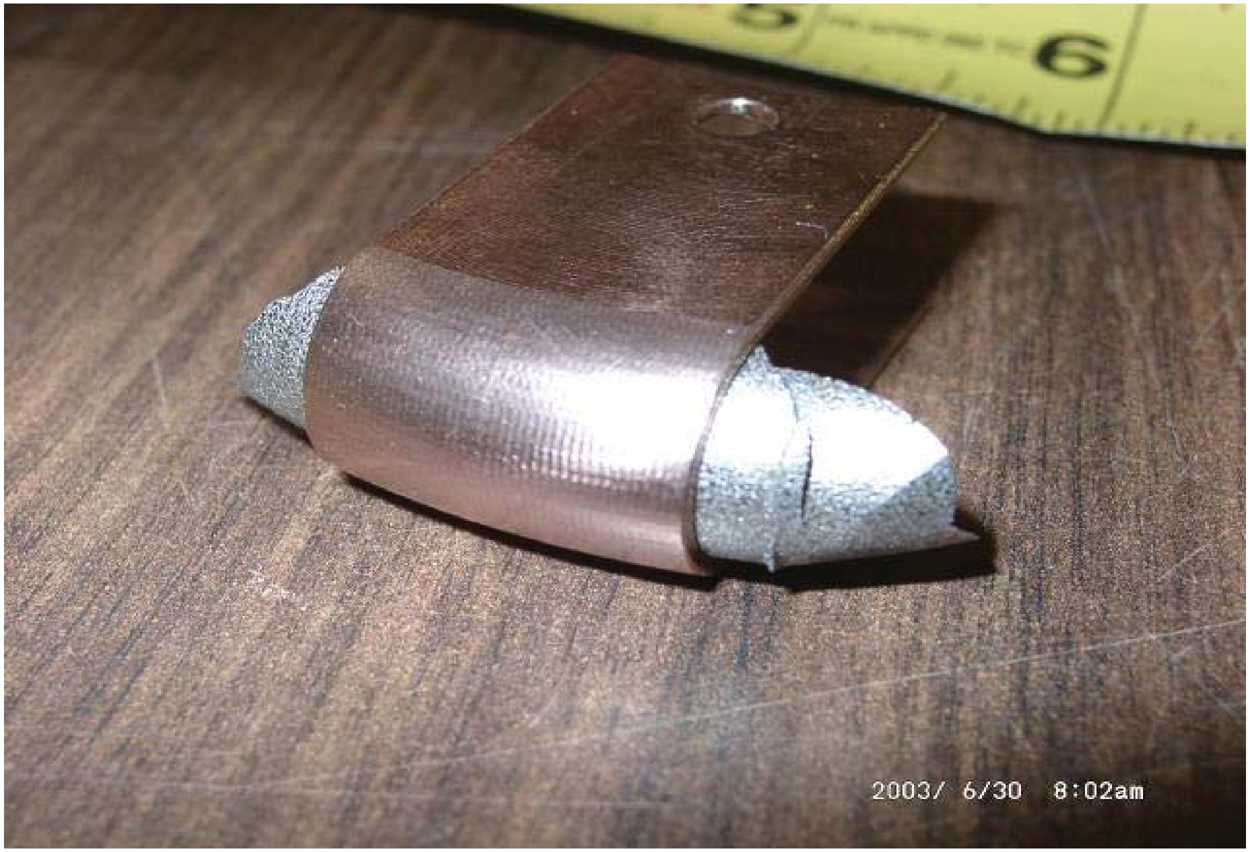
Boat Sample Electrode



Boat Sample Mockup

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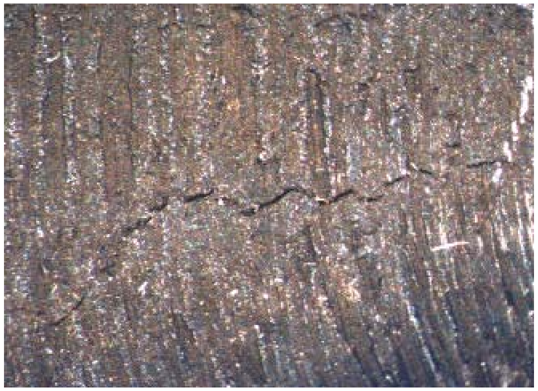
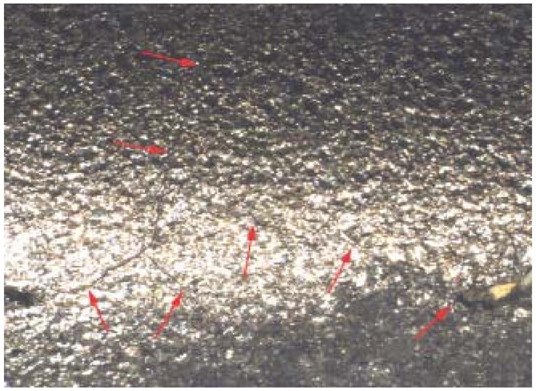
Penetration #1 Boat Sample

4X



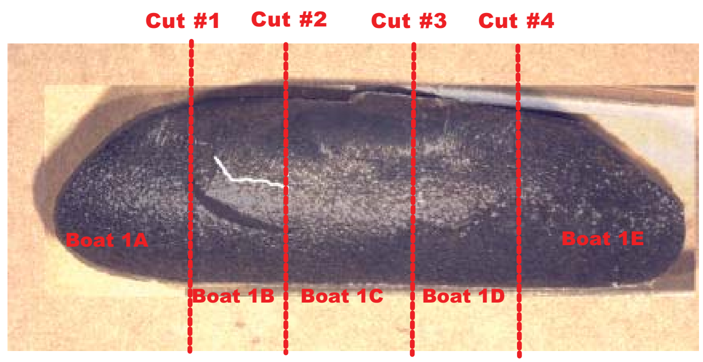
30X

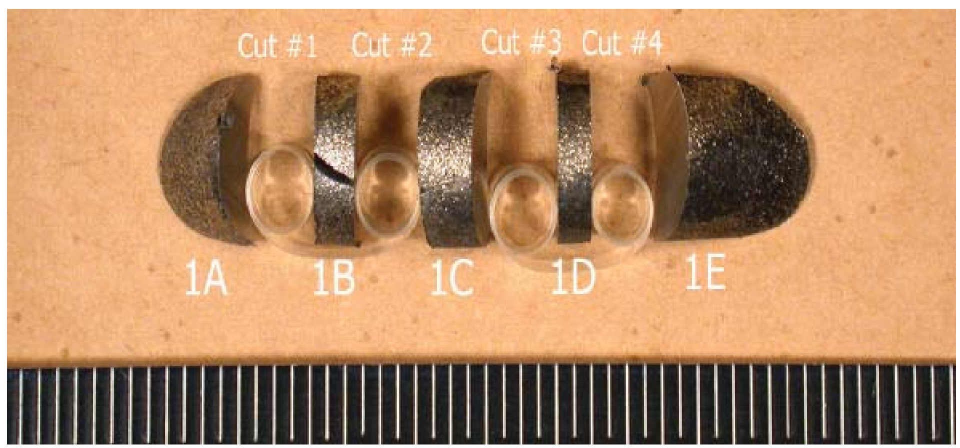
4X



15X

Boat Sample Sectioning





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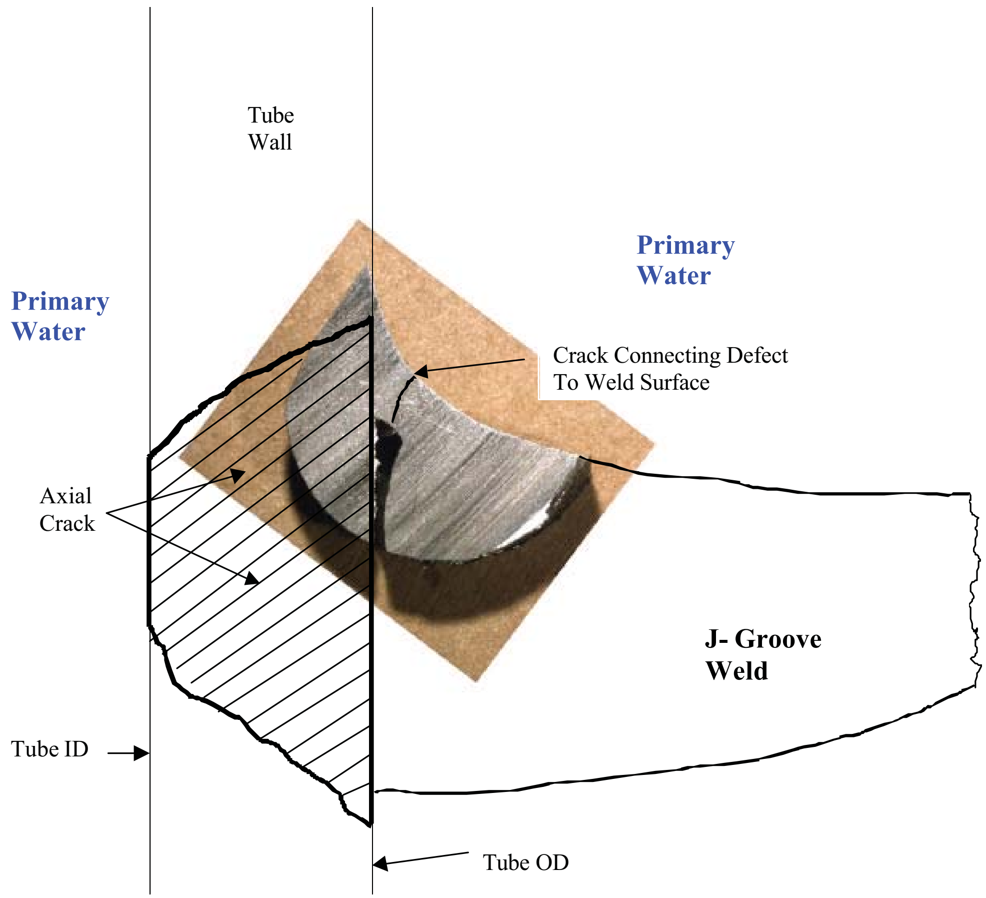
Boat Sample Analysis



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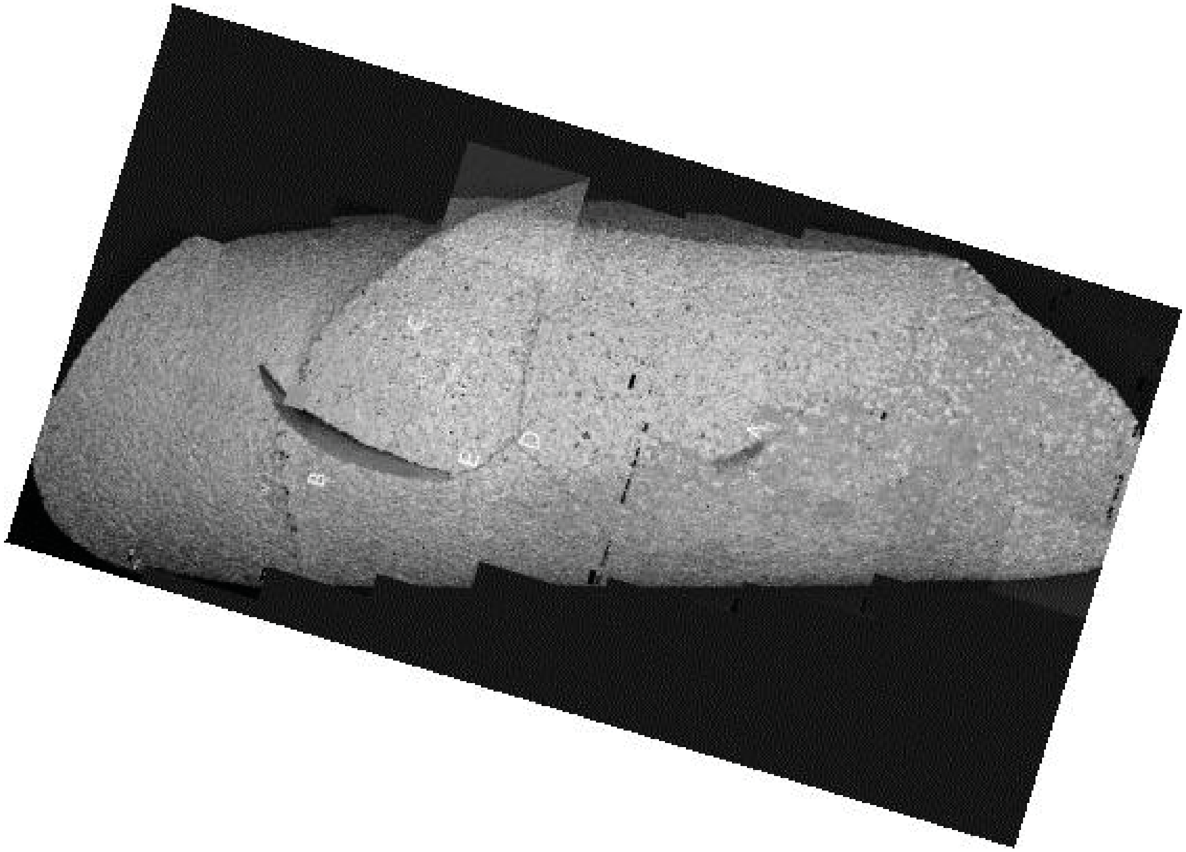
Boat Sample SEM/EDS As-Received



Boat Sample X-Ray Radiography

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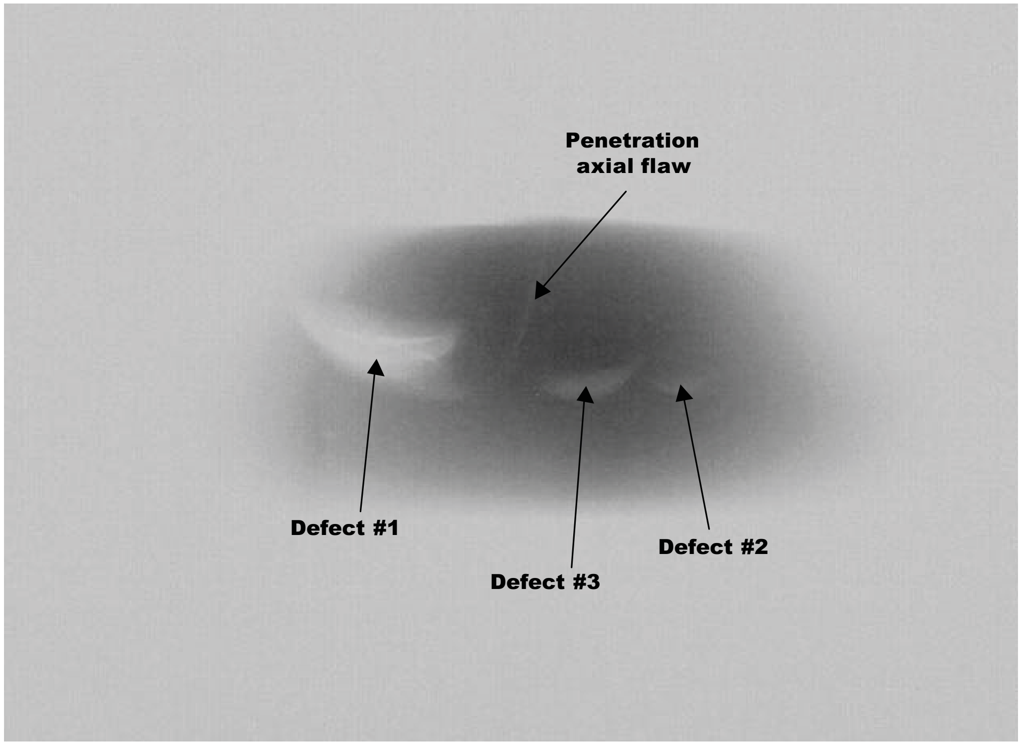

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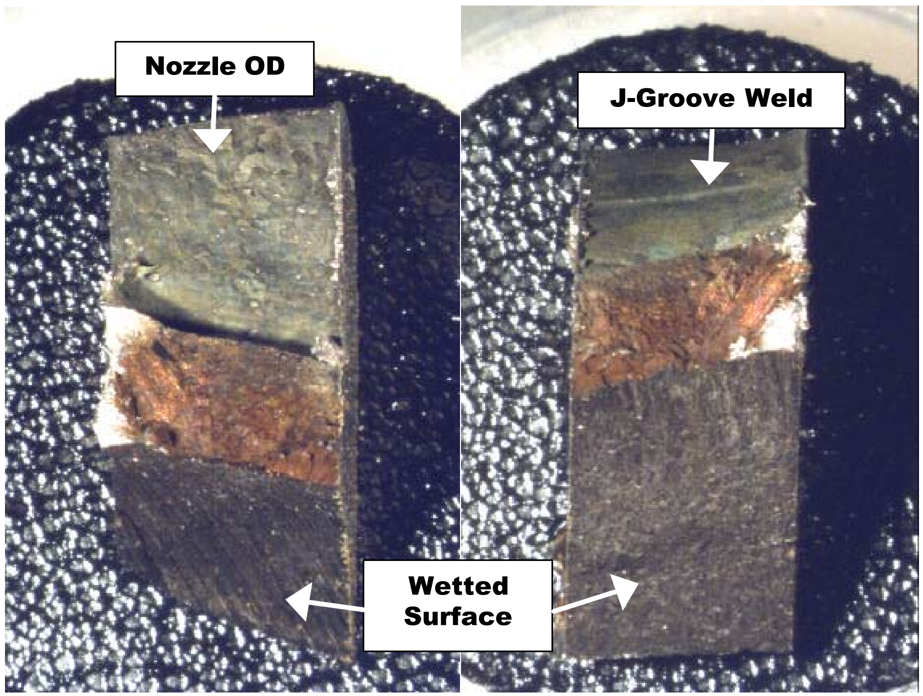
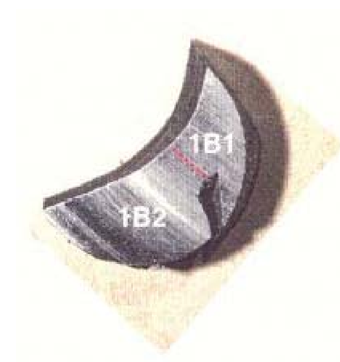
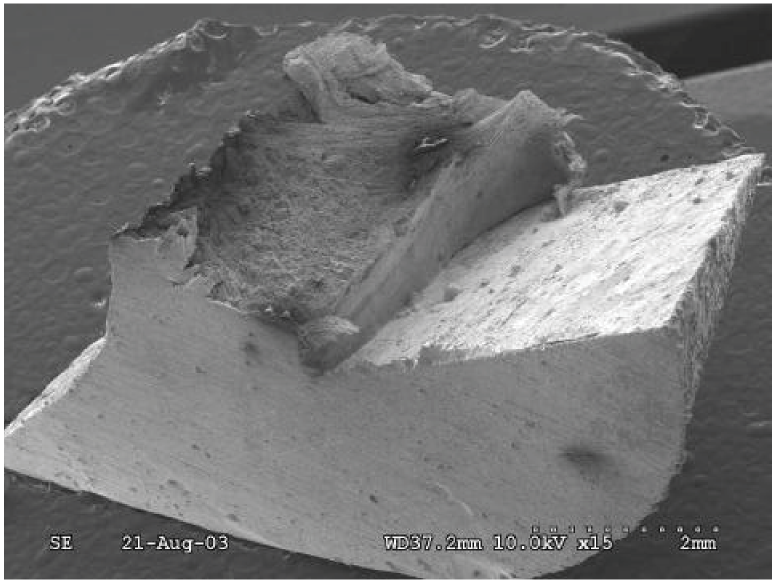
Boat Sample Open Crack - 1B1 & 1B2



Piece 1B1 **Piece 1B2**



Boat Sample Open Crack - 1B1



Boat Sample Progressive Grinds
1C & 1C2

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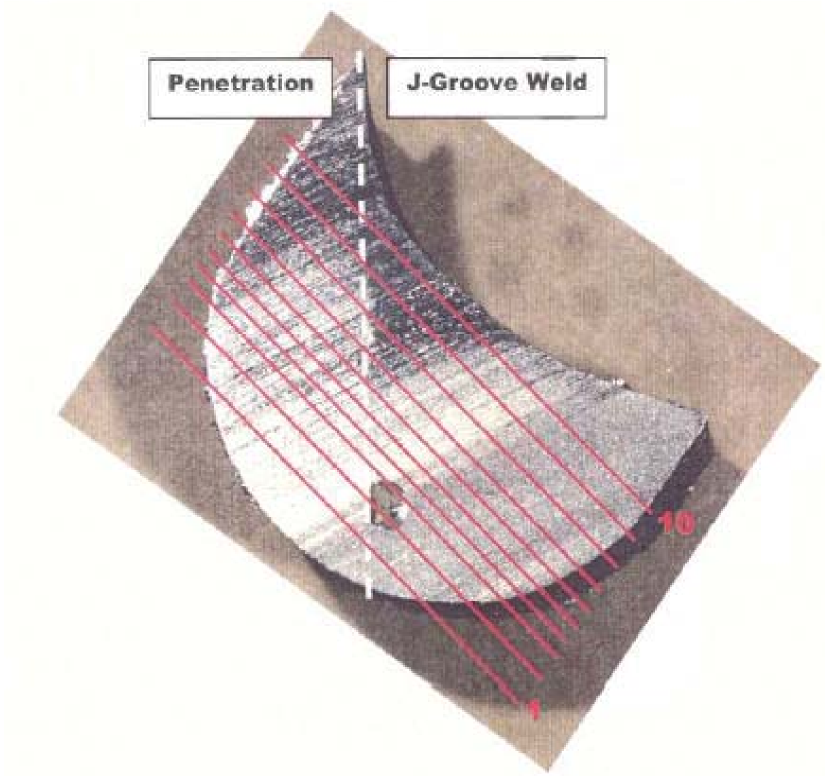
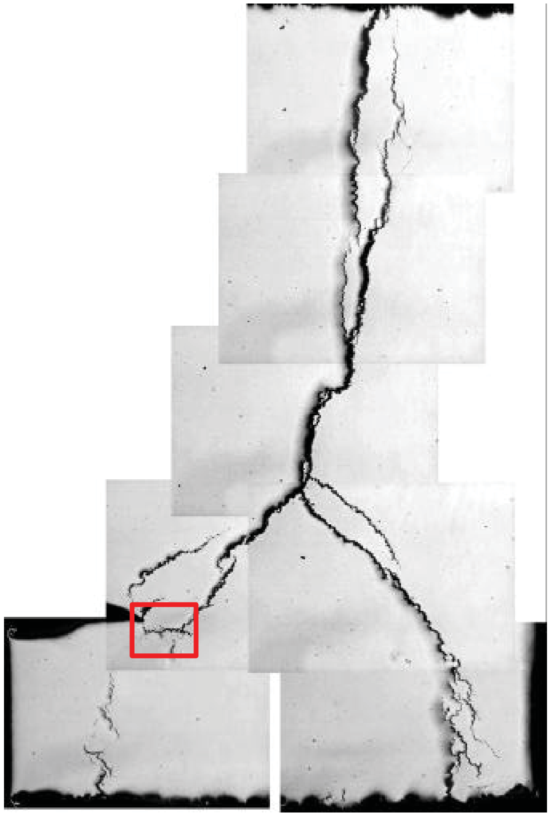
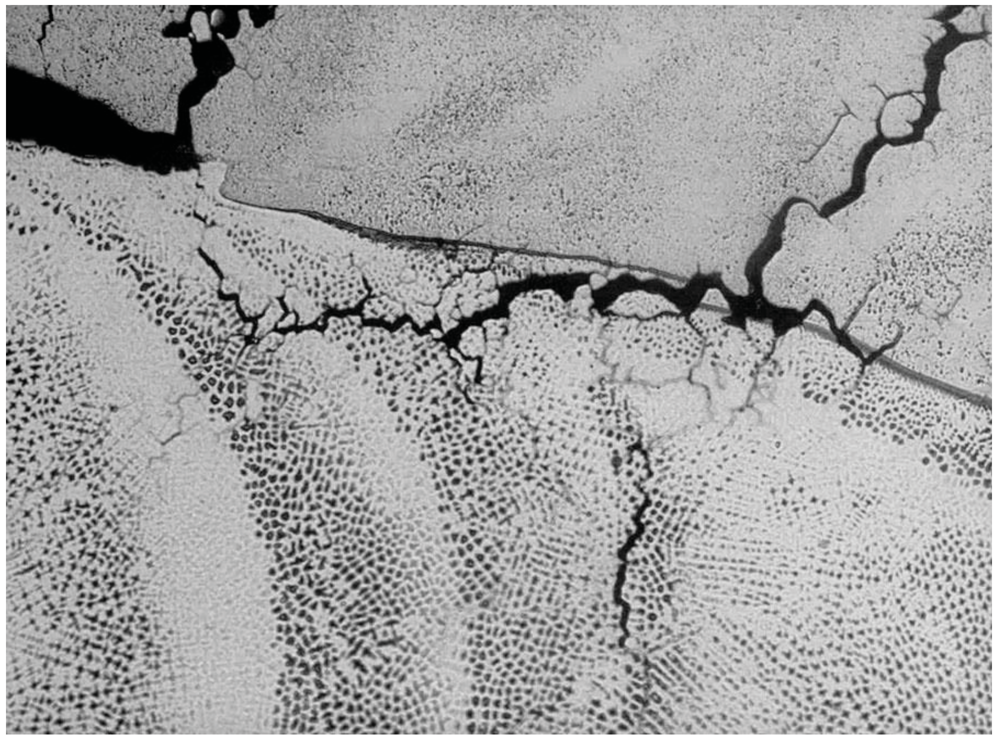


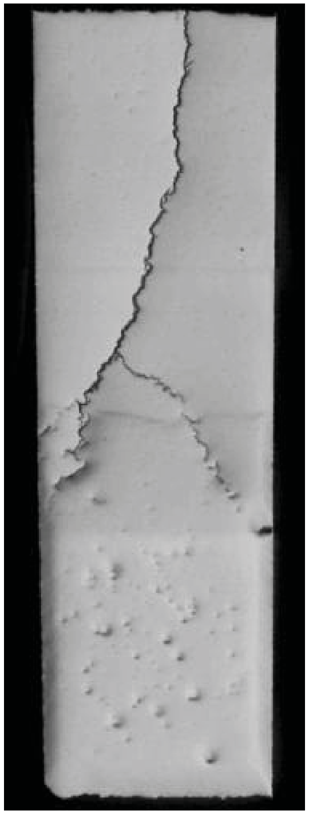
Face #1



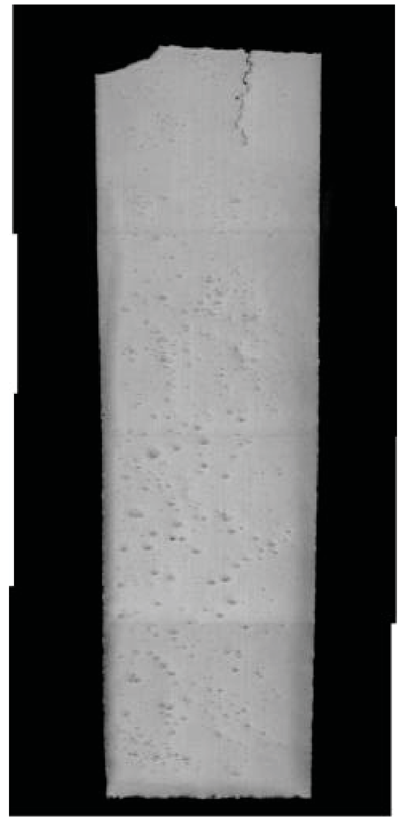
Intergranular Crack



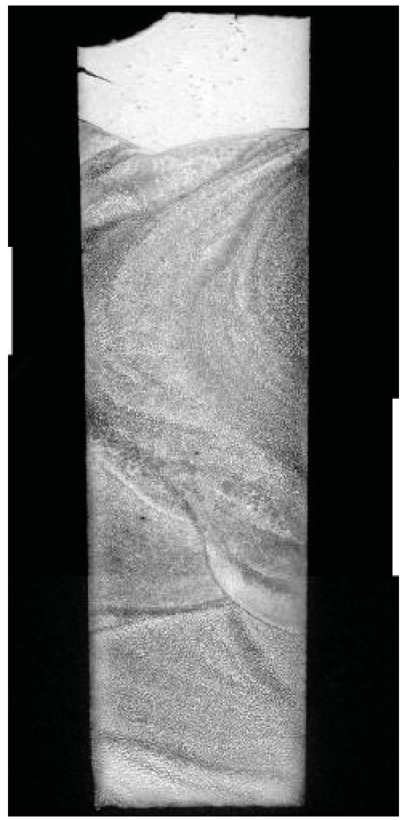
Face #3



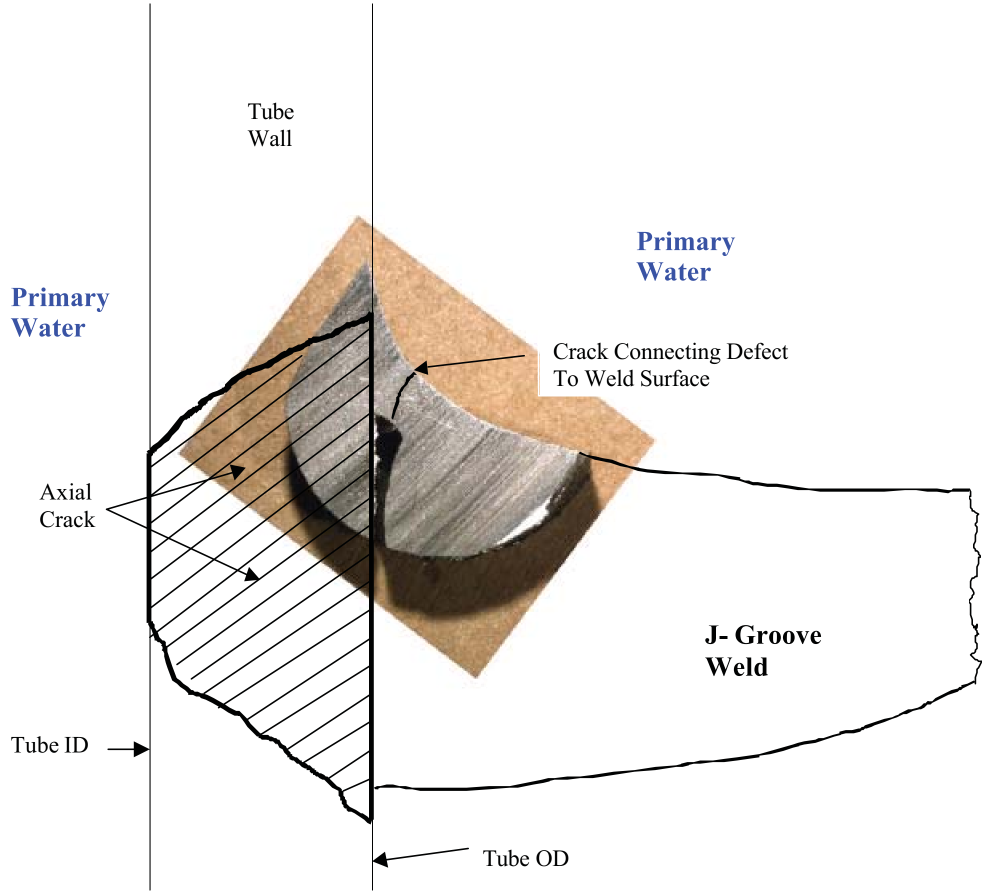
Face #9



Face #10



Boat Sample Analysis



Conclusions

- The Alloy 600 BMI nozzles are susceptible to PWSCC and will crack under the right conditions. PWSCC is possible even at T_{cold}.
- The SMAW process used to construct the J-groove welds is prone to leaving weld defects in service and creating high residual stresses.
- Visual bare metal examination of the BMI nozzles is an effective mechanism for detecting leakage long before flaws become structurally significant.

Future STP Inspections

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

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Westinghouse

A BNFL Group company

BNFL

Westinghouse

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The Embedded Flaw Process for Repair of Reactor Vessel Head Penetrations

Warren Bamford

Paul Kreitman

Westinghouse Electric Company

September 2003

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

BNFL

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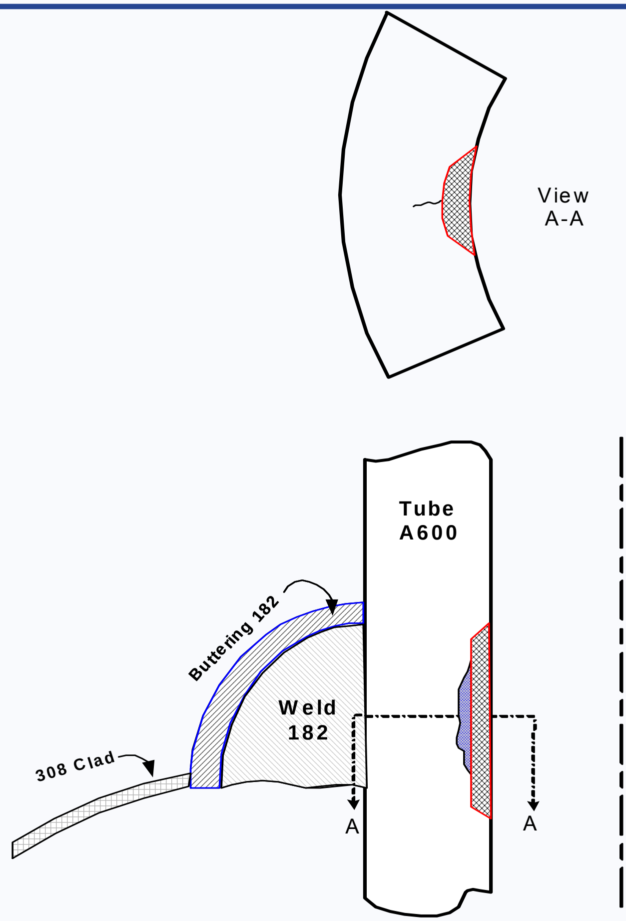
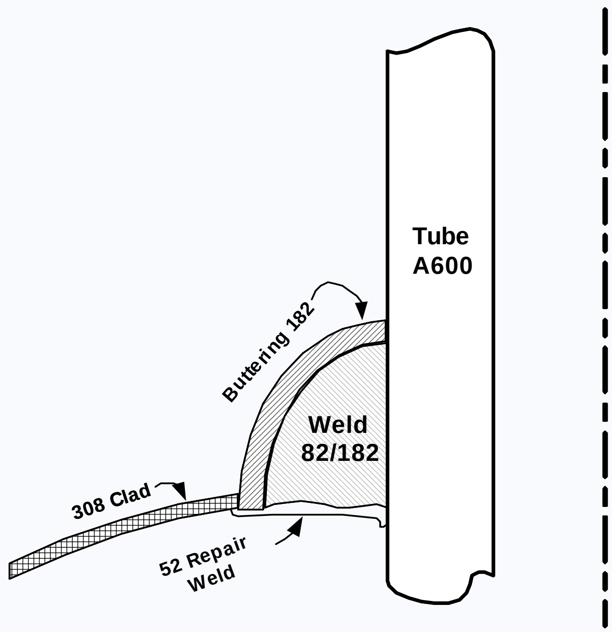
Embedded Flaw Repair: Tube ID



BNFL Westinghouse

Embedded Flaw Repair: J-Groove Weld



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Introduction

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

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Attributes

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

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

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

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Depth of Weldment for Embedded Flaw

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

  where S = distance from flaw to surface

  a = half width of embedded flaw

- **Set width of flaw (2a) equal to penetration thickness (0.625 in.)**
- **Weld thickness (S) is then 0.125 inches**
- **For smaller flaws the weld thickness can be smaller**

WOG Program/Qualification Summary

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

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Embedded Flaw Repair Process

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

Alloy 52

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

Alloy 52 - SCC Resistance

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

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Embedded Flaw Service Experience: D C Cook Unit 2

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

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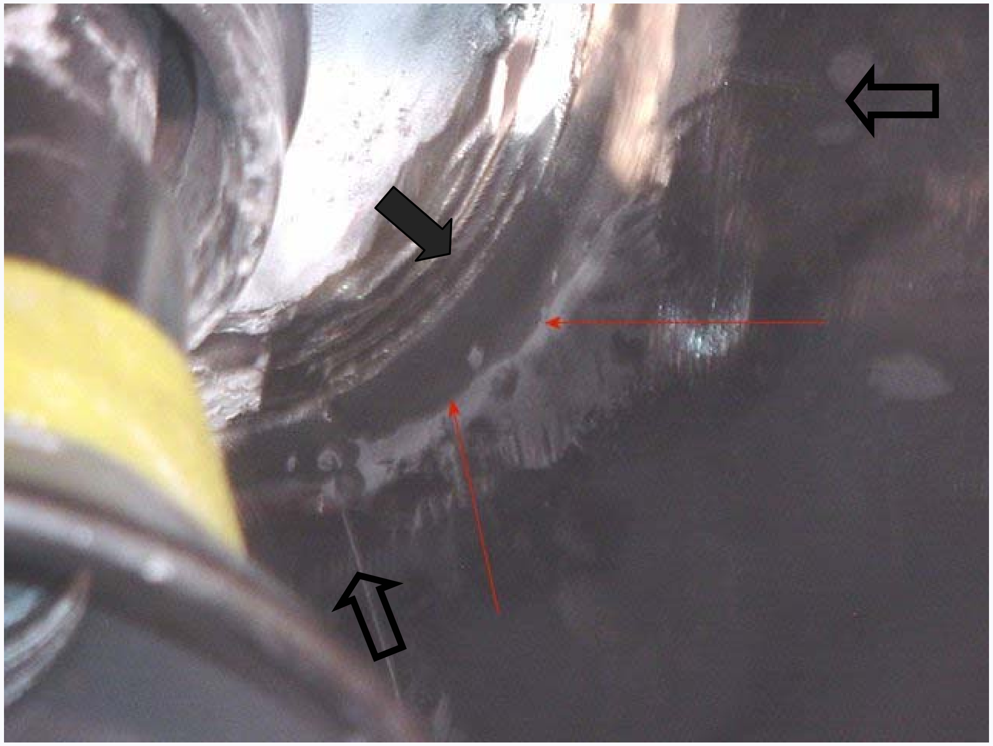
North Anna Implementation

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

Etched Region of Penetration 62



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

SER on Embedded Flaw Repairs

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

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SER on Embedded Flaw Repairs

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

SER Requirements

- **Inspections are consistent with those for a structural weld, requiring both UT and surface exams in most cases**

- **Inspections must be performed by qualified inspectors**

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- **Licensees must demonstrate that a plant-specific application is bounded by the WCAP (15987, Rev. 2), including the ASME Code fracture mechanics evaluation contained in Appendix C of the WCAP (see SER paragraph 3.6)**

Conclusions

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

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A BNFL Group company

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

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

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

EPRI

Contents

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

Background

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

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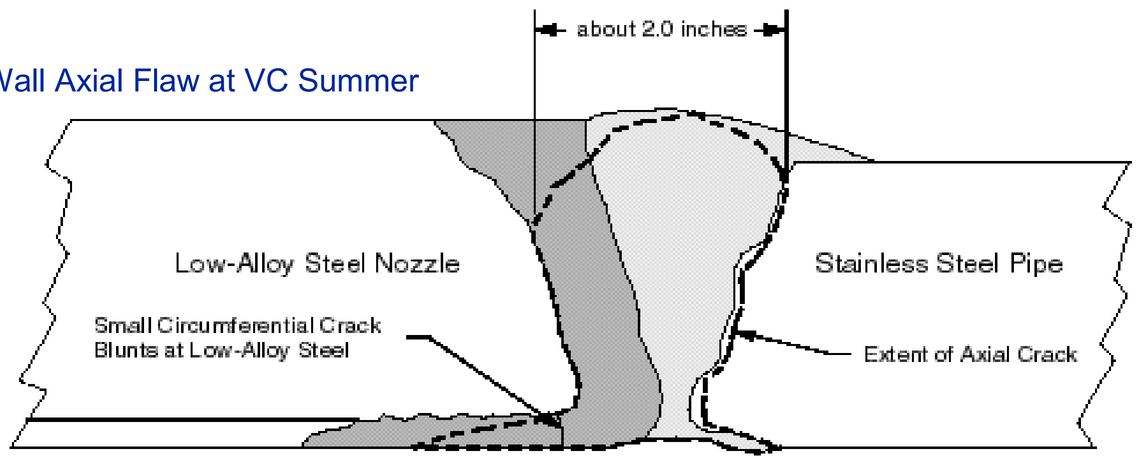
Through-Wall Axial Flaw at VC Summer



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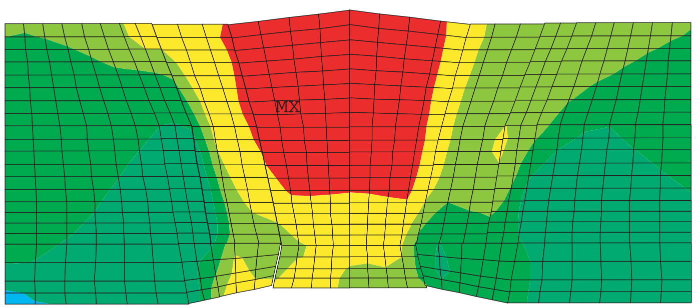
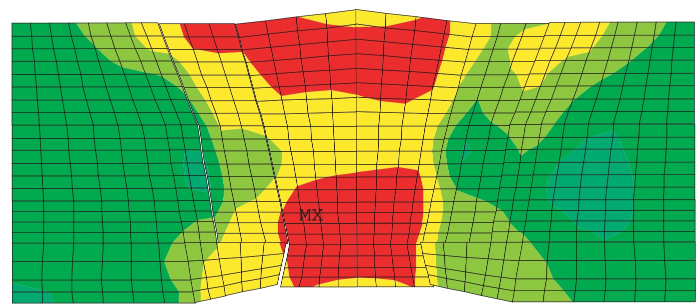
Background

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



Operating Hoop Stress – As Designed

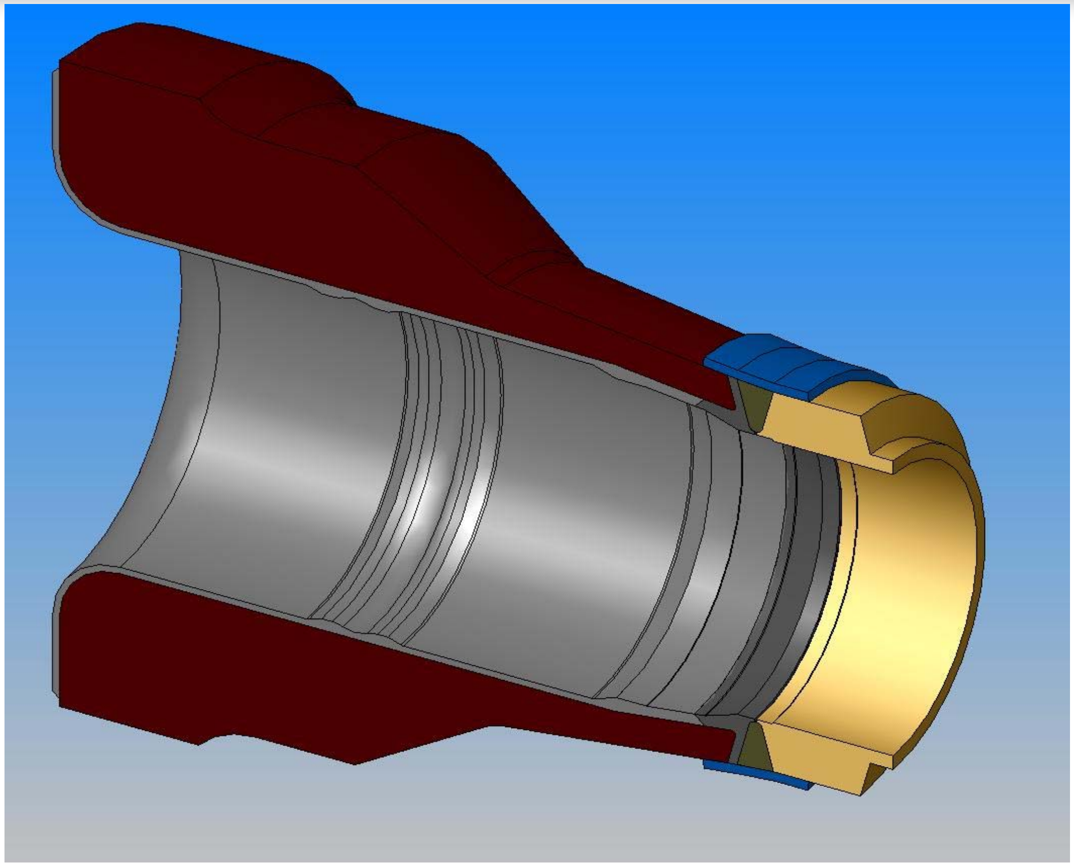


Operating Hoop Stress – With ID Repair

Weld Overlay to Reduce Tensile Stress

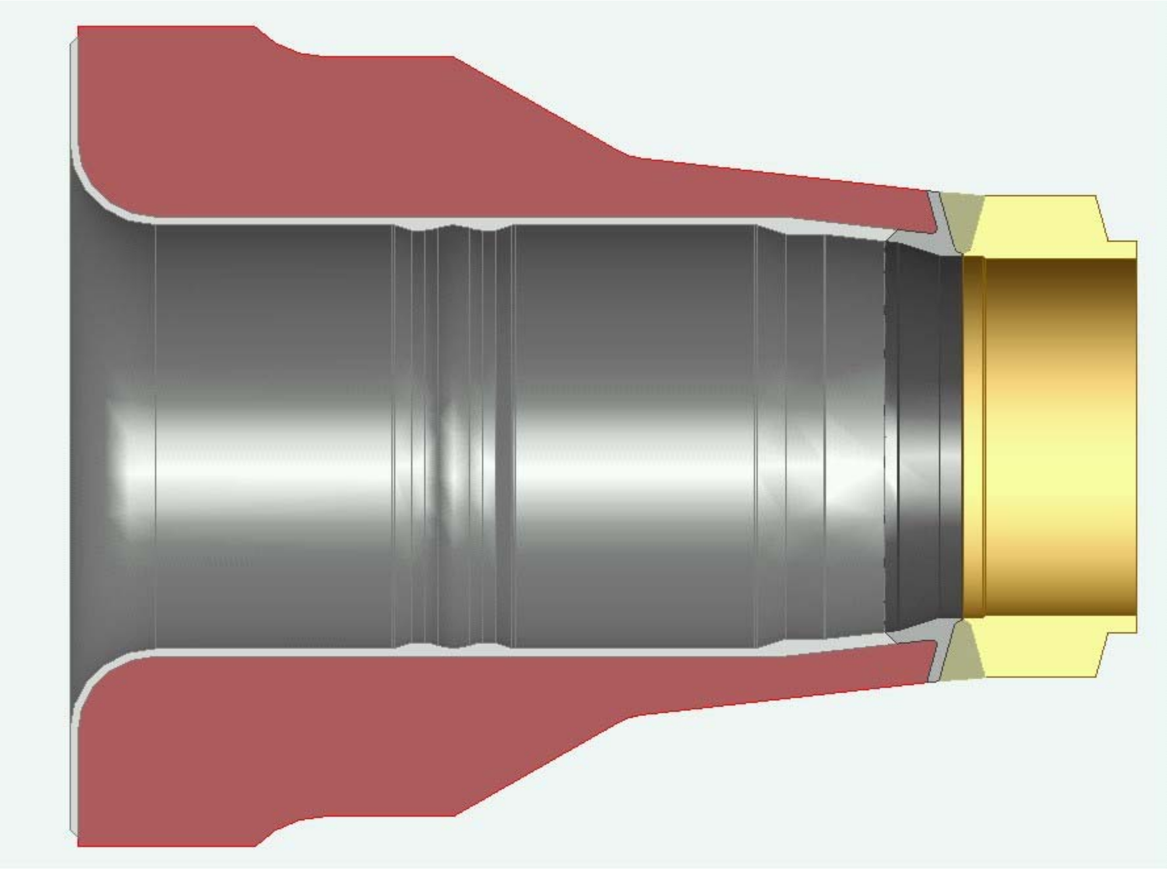
- A weld overlay applied to the outside of a nozzle/pipe at the butt weld will reduce tensile stresses on the inside surface of the weld
  - Weld shrinkage causes a reduction in nozzle/pipe diameter and a resultant reduction in tensile stress
  - Reduced tensile stresses will delay the time to PWSCC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

Weld Overlay to Reduce Tensile Stress



Weld Overlay Applied to Typical Pressurizer Surge Nozzle Butt Weld

Finite Element Model
Typical Pressurizer Surge Nozzle



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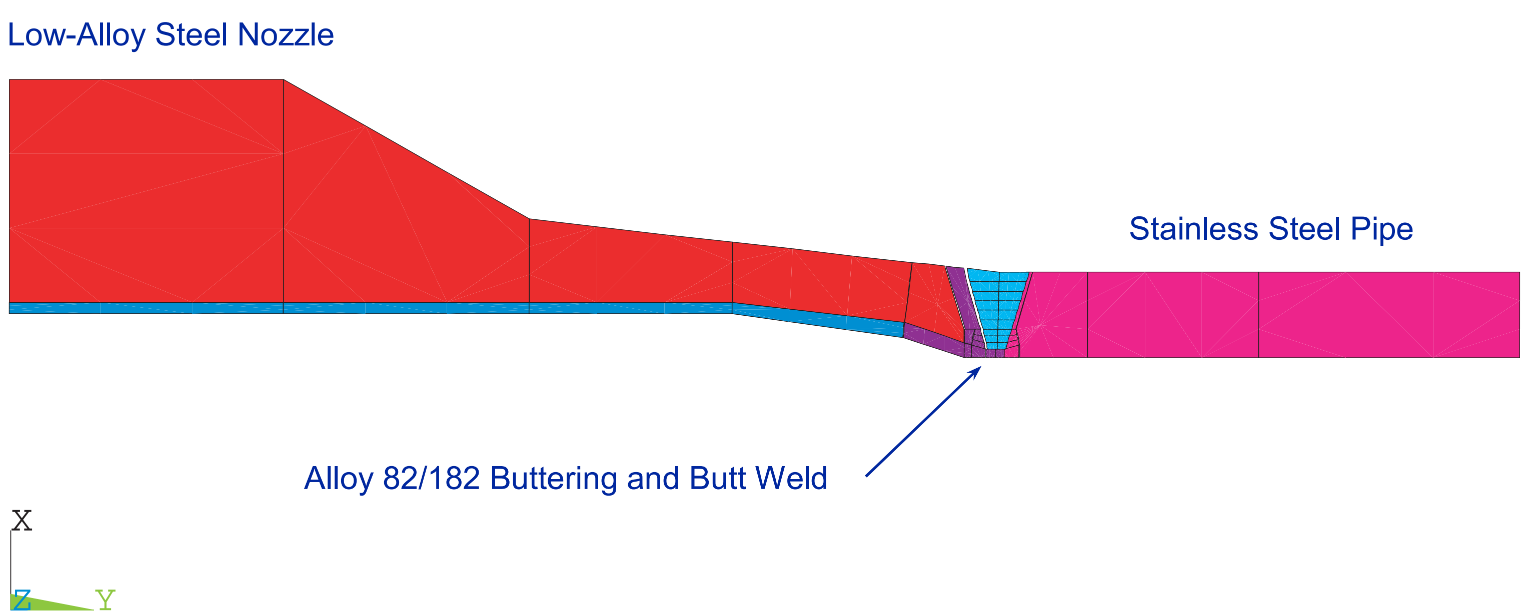
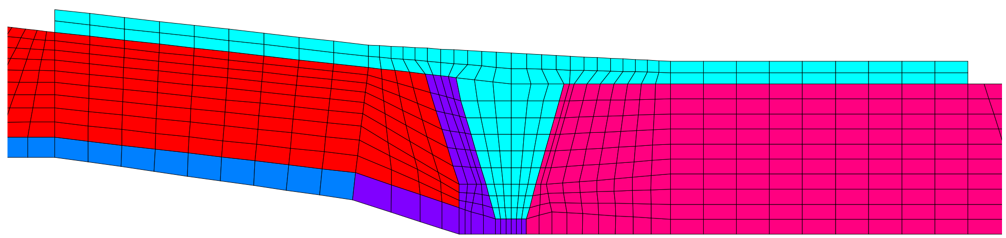
Finite Element Model
Overall Finite Element Model

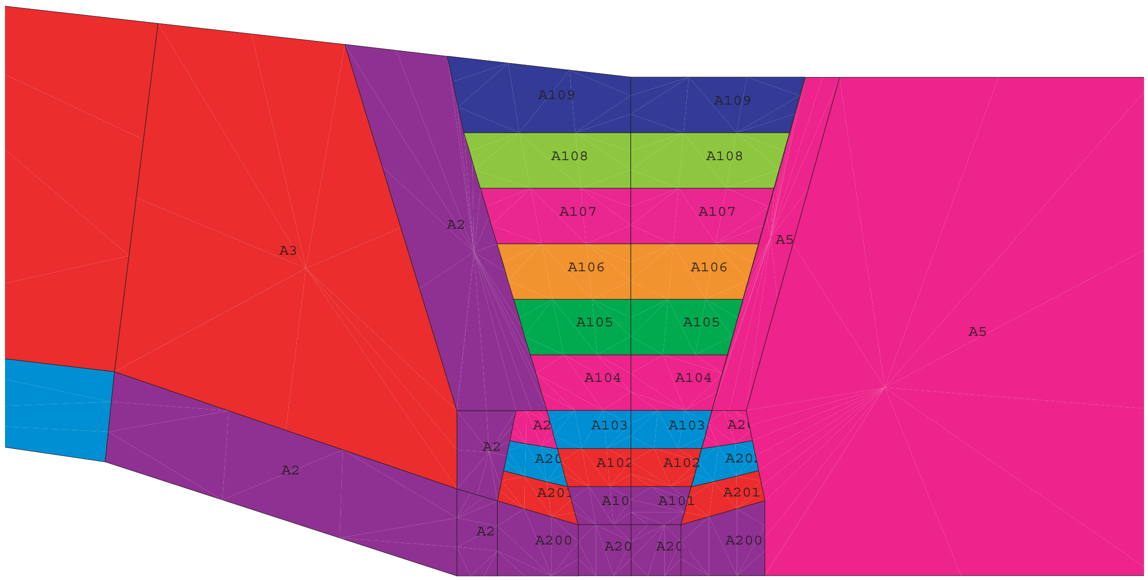


Finite Element Model
Finite Element Model with Weld Overlay



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

Finite Element Model
Weld Elements



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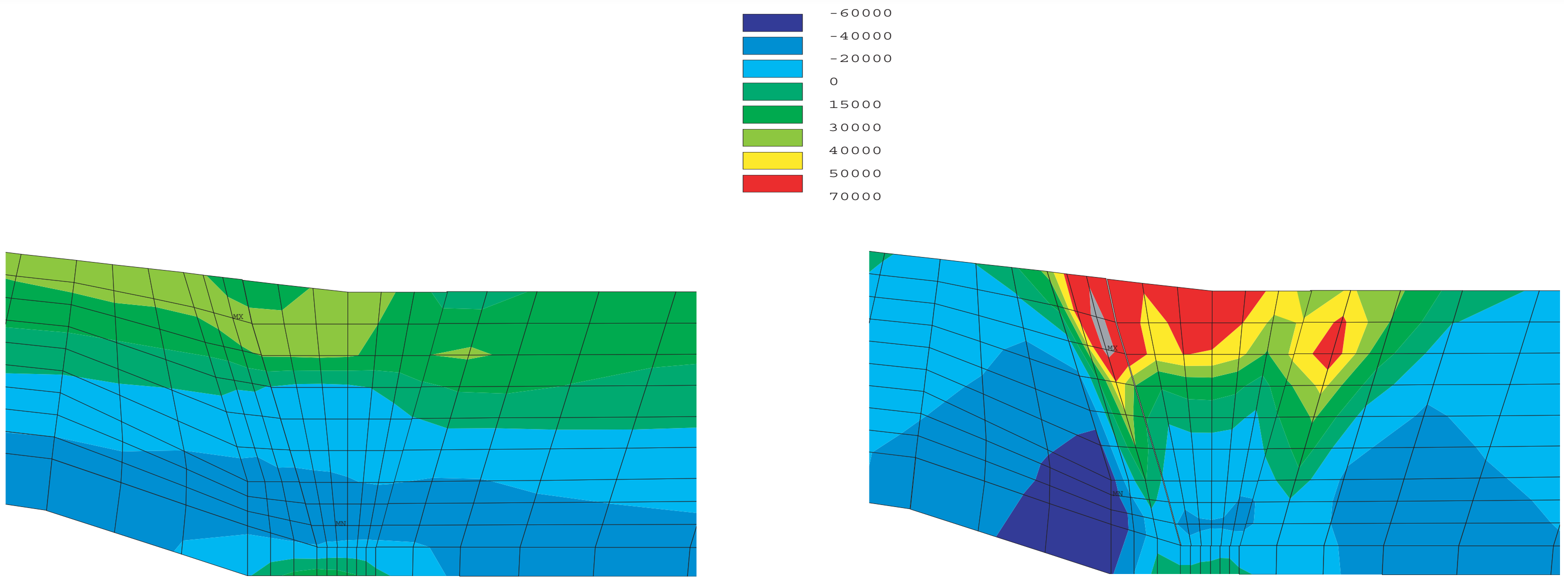
Finite Element Model
Analysis Approach

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

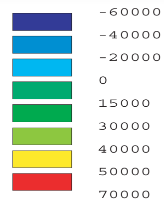
Welding Residual Stresses
As-Designed

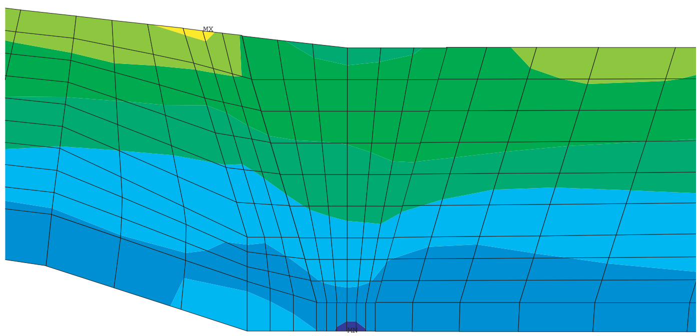


Axial Stress

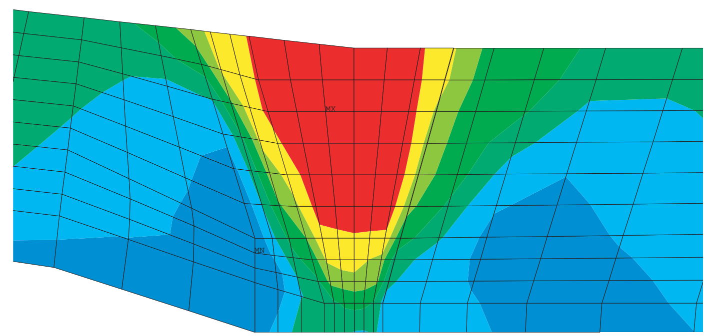
Hoop Stress

Operating Stresses *As-Designed*





Axial Stress
(-2.7 ksi max)

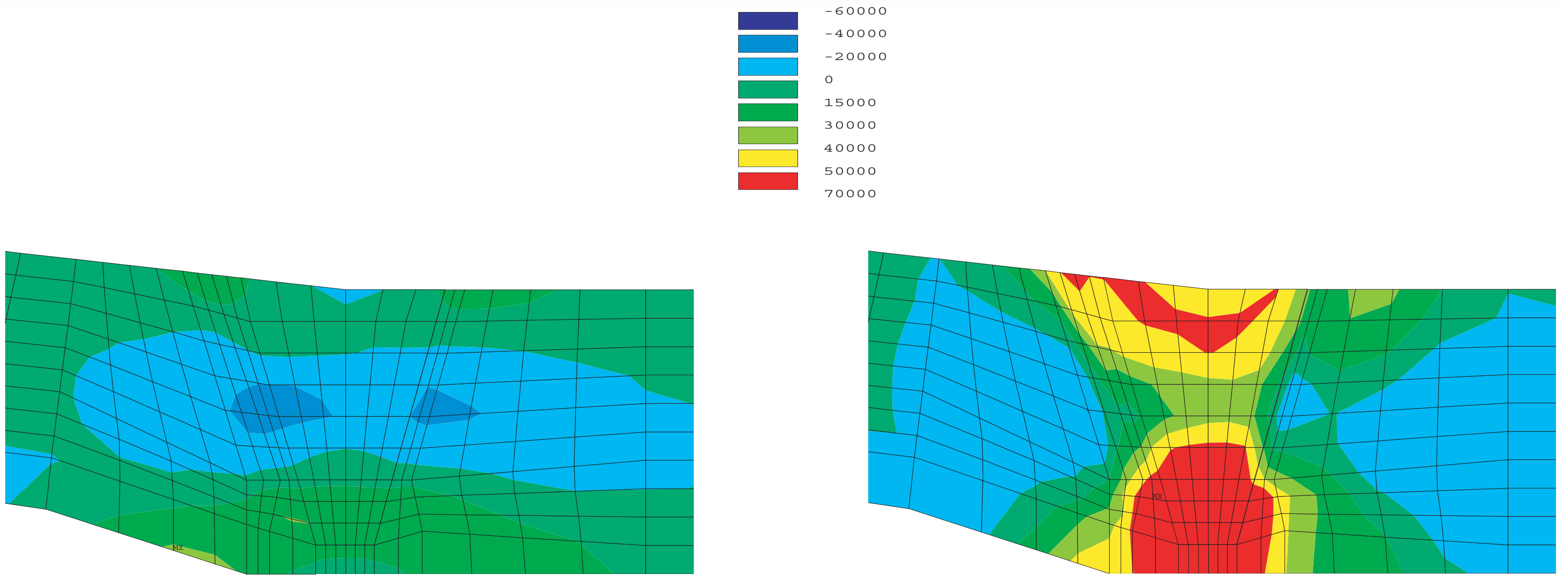


Hoop Stress
(9.0 ksi max)

Notes: For all cases:

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

Operating Stresses
With ID Weld Repair (360°)



Axial Stress
(32.5 ksi max)

Hoop Stress
(52.8 max)

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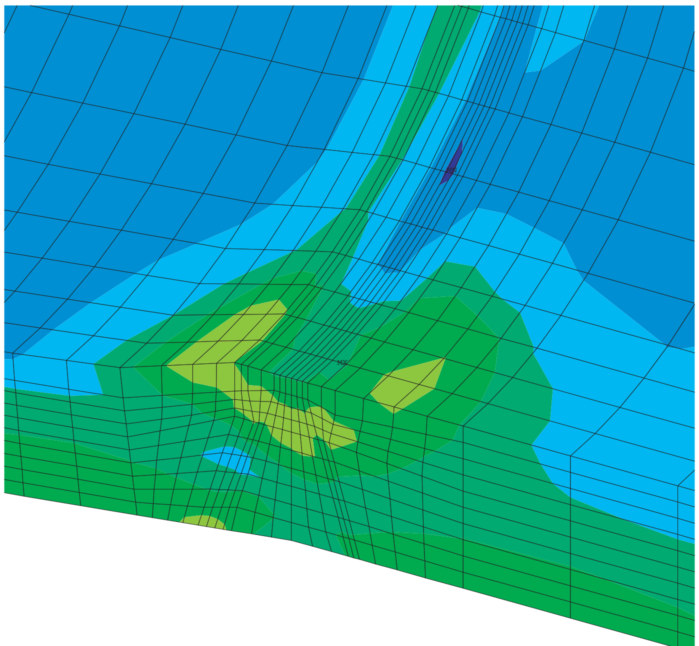
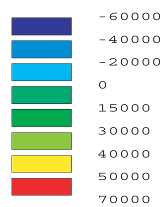
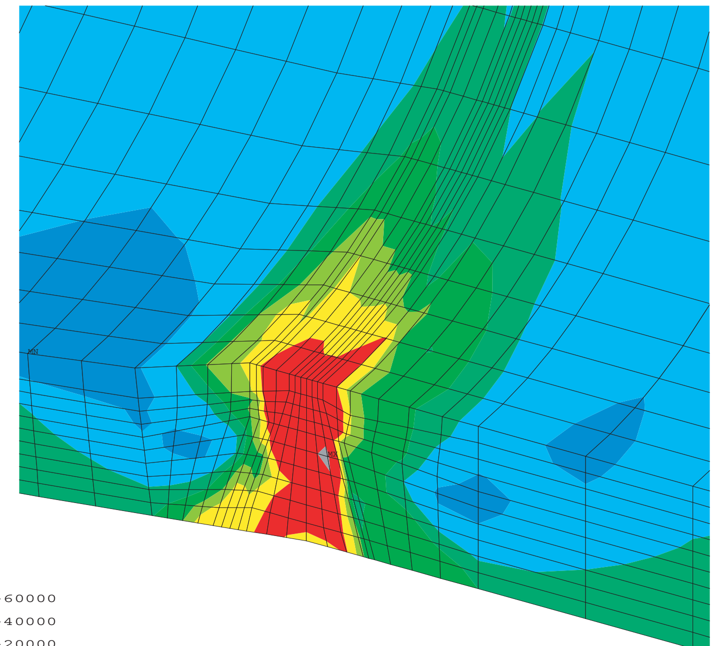
Operating Stresses
With ID Weld Repair (30° Arc)



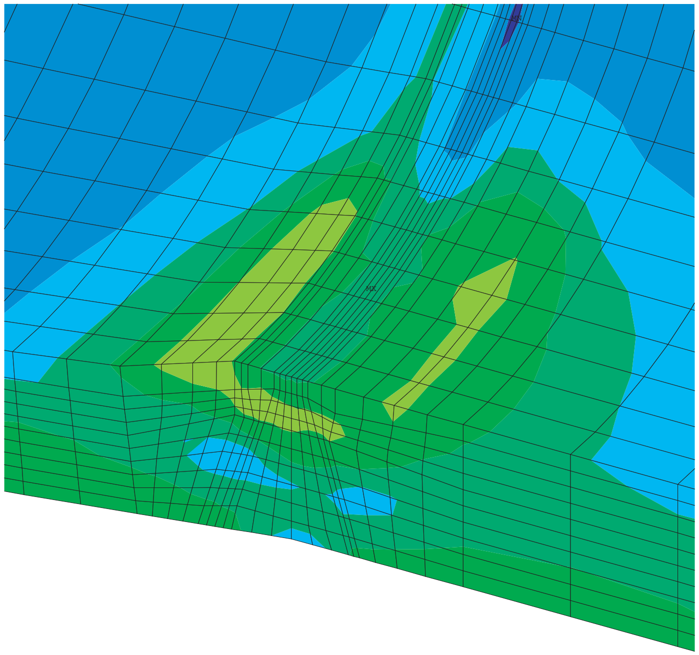
Axial Stress
(39.9 ksi max)



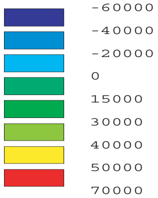


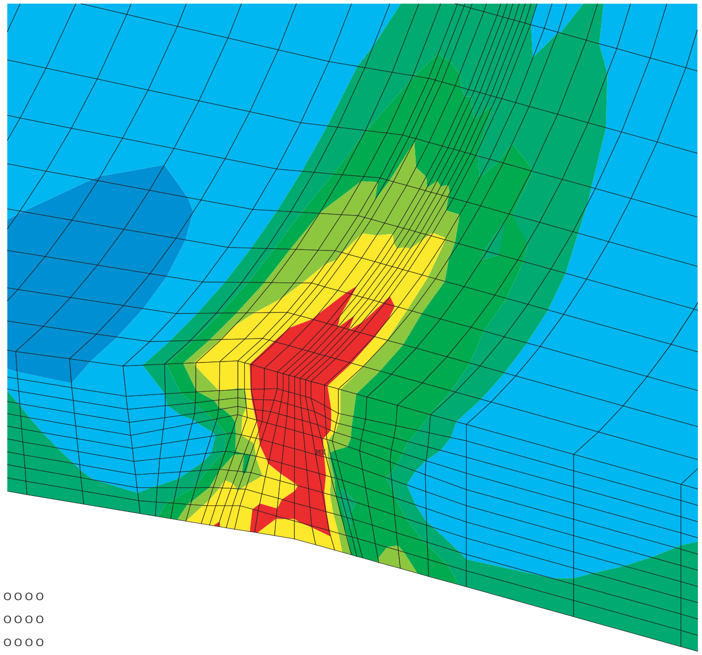
Hoop Stress
(54.6 ksi max)

Operating Stresses
With ID Weld Repair (60° Arc)



Axial Stress
(38.6 ksi max)





Hoop Stress
(52.6 ksi max)

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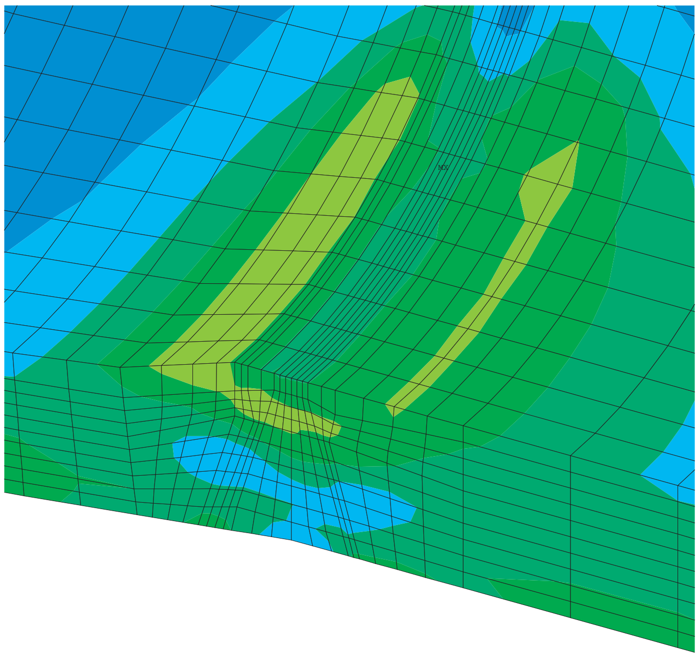
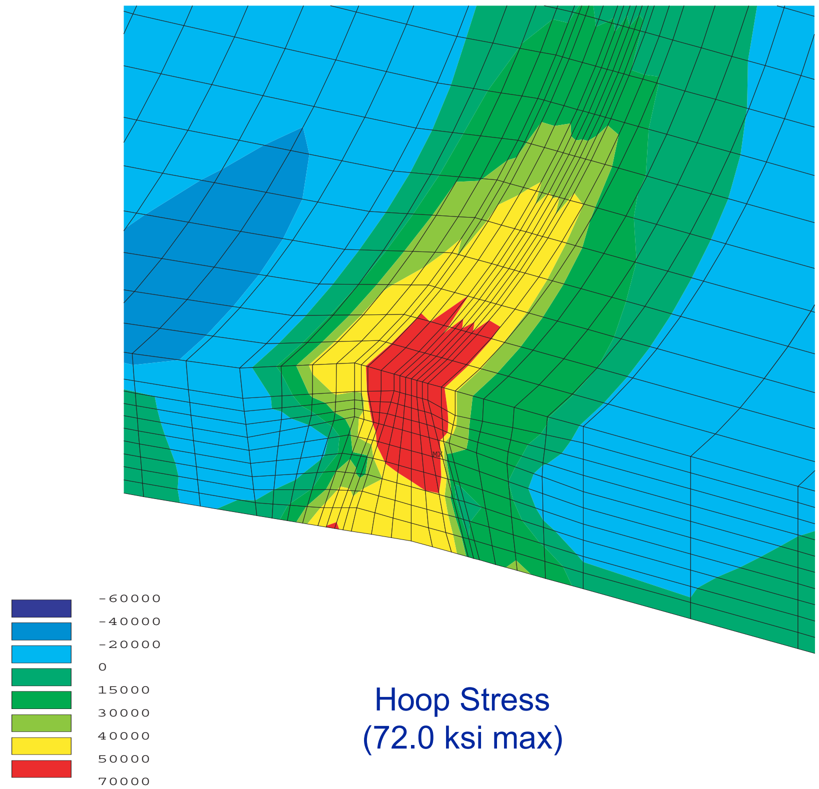
Operating Stresses
With ID Weld Repair (90° Arc)



Axial Stress
(40.2 ksi max)



Hoop Stress
(72.0 ksi max)

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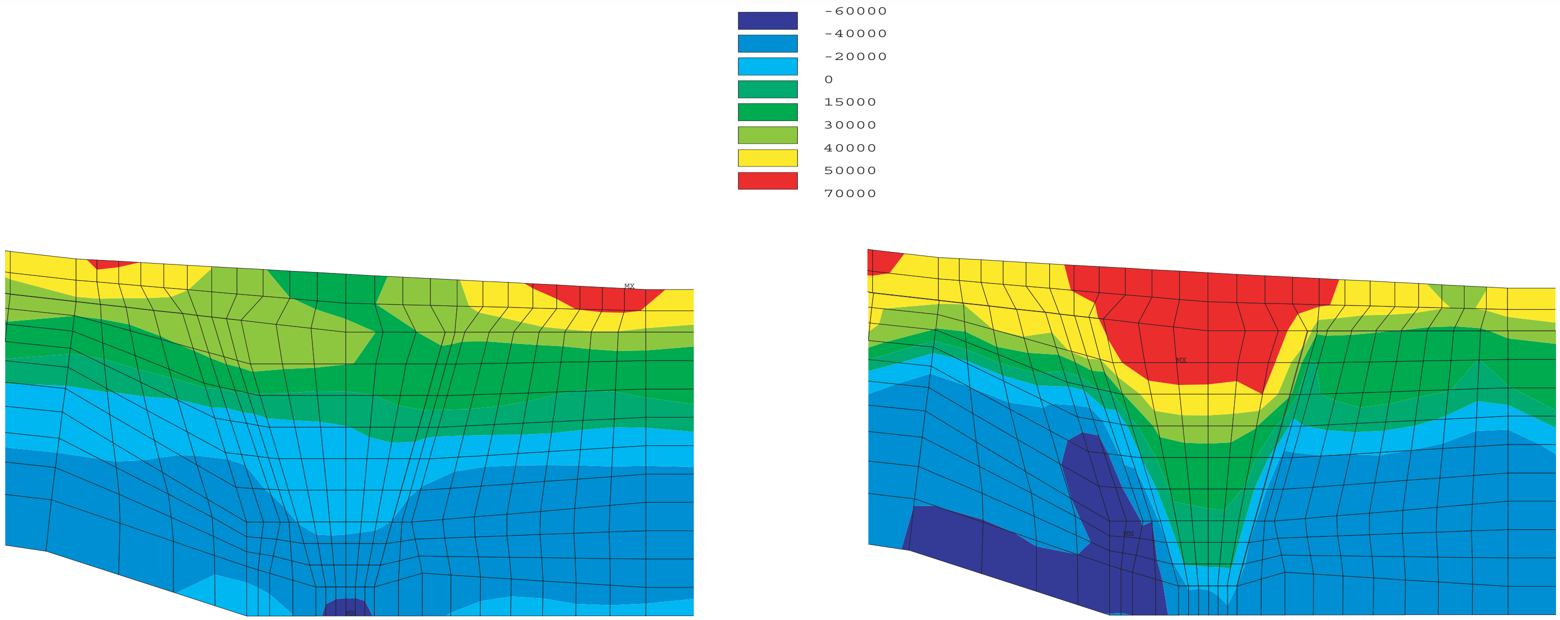
Operating Stresses
With Weld Overlay – As-Designed



Axial Stress
(-8.6 ksi max)

Hoop Stress
(-23.2 ksi max)

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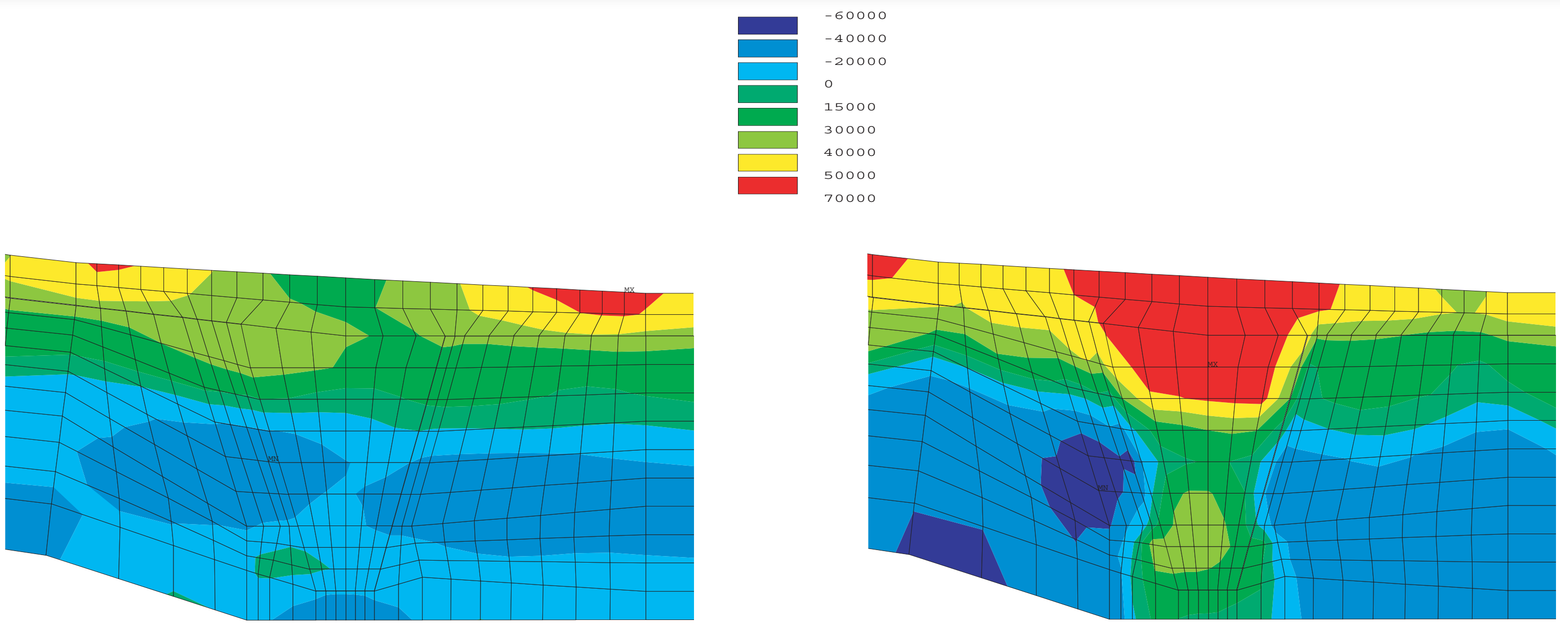
Operating Stresses
With Weld Overlay – 360° ID Repair



Axial Stress
(1.7 ksi max)

Hoop Stress
(19.9 ksi max)

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Summary of Analysis Results
Operating Condition Stresses

- As-Designed (no weld repair)

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

- With 360° ID Weld Repair

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

EPRI

Conclusions

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