Section 2:
Session 2: Continued Plant Operation

Background and Technical Basis for the ASME Section XI Process for Evaluation of Upper Head Penetration Flaws

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The recent findings of cracking in the reactor vessel head penetrations at a number of plants have prompted Section XI to develop requirements for inservice inspections of these regions. An Alloy 600 Task Group has been in operation since spring of 2002, and its goal is to keep abreast of industry inspection findings, and to develop inspection requirements for these regions. When inspections are required, a methodology is needed to deal with any indication that may be found, to determine whether a repair is required.

This paper will provide the details of the flaw evaluation rules that are now being proposed for Section XI, along with their technical basis. In addition, the status of the approval process within Section XI will be discussed.

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MAINTENANCE STRATEGY OF INCONEL COMPONENTS IN PWR PRIMARY SYSTEM IN FRANCE

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ABSTRACT

Base nickel alloys like Inconel 600 or 182 can be sensitive to high temperature primary water stress corrosion cracking. This fact is known since Corriou's works at the beginning of the sixties and its applications to the steam generator tubes in the seventies. For the RP vessel heads, the major fact of the nineties was the leak that occurred during ten years hydro test on one penetration in 1991 in the French NPP unit of Bugey. Several important decisions were taken after discovery of this leak. First of them was to understand why it appeared so quickly, then test repairs for the Bugey case, then decide to replace all cracked vessel heads considering that the repair solutions was too high cost. This is an example of EDF anticipation approach in relation to optimum safety and competitive standardized plants. In parallel, many developments were launched to establish laws for PWSCC and develop non-destructive methods to inspect the head penetrations. The conclusions obtained show the decision was good and no new leak happened on the VH penetrations. A large investigation program of understanding was launched in order to establish laws for PWSCC and predict the risk of cracking in the Inconel components. The analysis of these areas shows that the risk is less important in the other components than for VH penetrations.

INTRODUCTION

On September 1991, an important event occurred in France at the Bugey unit 3 NPP; a leak in the vessel head was discovered during the hydro test at 207 bars. It appeared that a control rod drive mechanism (CRDM) penetration had failed. Few investigations showed that the leak was produced by longitudinal cracks coming from inside the penetrations. After a destructive examination, the damage mechanism, which produced the cracks, was clearly identified and attributed to primary water stress corrosion cracking (PWSCC). In fact, for what concerns alloy 600, this problem was not a new one. Since few years, cracks had been discovered in the steam generators tubes fabricated with the same material and PWSCC in such material was already known since 1981. Later, in 1989, pressurizer alloy 600 nozzles had cracked (cracks were also discovered during ten years hydro test) and had been replaced by stainless steel ones. Nevertheless, this cracking was not expected so early in the VH penetrations as all previous studies showed an initiation after more than 10^5 hours operating.

Effects of stress, material susceptibility, and welding, and manufacturing process had been underestimated. Then Electricité de France (EDF) has decided to launch an investigation program to better understand the phenomena and has applied it on different primary system Inconel components. In parallel, due to the important cracking in VH penetrations, EDF decided at the beginning of 1993 to replace all cracked vessel heads with alloy 600 by new vessel head with alloy 690. Both aspects of the program are developed hereafter.

PHENOMENON

900 MW VH are equipped with 65 CRDM penetrations and 1300 MW VH with 78 of them. Just after discovery of the leak, many works were engaged to understand what had happened. First of them were based upon the expertise of the Bugey 4 T65 VH penetration and after this from the Bugey 3 T54 where the leak had been discovered. Crack morphology was fully analyzed and first explanations could be given [1]. Clearly, the leak was attributed to a PWSCC (see figure **1**). After VH removal and CRDM dismantling, several examinations were performed. Firstly, few non-destructive examinations, eddy current testing, visual testing, leak tests, ..., revealed longitudinal cracks in the lower part of the penetration near the weld area.

Secondly, after a destructive examination of the T54 VH penetration, the crack was initiated from inside and had a through wall extent that explained the leak.

Consequently, in 1992-1993, the analysis of the phenomenon concluded to effects of:

- Temperature and water chemistry,

- Stress level particularly for the peripheral penetrations due to the angle between the penetration and the VH and the fact the weld is not symmetrical,

- Possibly, material susceptibility.

Then it was decided to orientate research and developments in three main directions:

- Develop methods to repair the VH penetrations and study the possibility to replace vessel heads,

- Develop non-destructive methods for detection and characterization of the surface breaking cracks in order to know as soon as possible the crack initiation and measure the crack propagation,

- Launch an important investigation program in laboratory to better understand PWSCC of both alloy 600 for base metal and alloy 182 for weld metal.

SAFETY CONCERNS

For vessel head penetrations, a maintenance policy has been established and based upon a safety criterion in relation to the minimum residual ligament for a longitudinal crack initiated from inside the penetration. The NDE follow up of cracking is driven on a basis of a 3 mm / cycle crack propagation. Then for 12 months operating cycles, a 900 MW VH replacement has to be performed before reaching a value of 4 mm for residual ligament. For 18 months operating cycles this value is fixed at 6 mm.

INDUSTRIAL DEVELOPMENTS

VESSEL HEAD REPAIRS

Proposals for repairs were made immediately but due to the shape of the VH and the number of penetrations, the high dosimetry, the difficulties were important and only few tests and repairs were performed during more than one year. In fact this solution was abandoned for the benefit of a replacement solution. For EDF it was obvious that with the first results of the non-destructive inspections all VH would be concerned and then to be replaced.

VESSEL HEAD NON-DESTRUCTIVE INSPECTION METHODS

Few NDE methods were studied but the effectiveness of some of them was proved after many tests. For crack initiation, visual testing, dye penetrant testing and eddy current testing were studied. Due to the thermal sleeve inside the penetration, all three NDE methods and particularly dye penetrant testing were very difficult to implement. They needed to be removed before the inspection. The solution came with the development of "eddy current sword probes" that could be used with the sleeve. It was easy to perform the examination from inside inserting this probe between the sleeve and the penetration. Many tests were performed in EDF and CETIC facilities [1].

For crack propagation, the challenge was also very difficult. Then special "ultrasonic sword probes" were developed (maximum thickness 2 mm) and qualified using the "Time Of Flight Diffraction Technique" (TOFDT). It revealed to be the best for such flaw to be sized. The performance obtained showed a 3 mm surface-breaking crack was sized with a good accuracy on mock-ups with artificial flaws, realistic and real cracks. All results of the qualification were discussed at length [2], [3].

COMPLEMENTARY LEAK DETECTION SYSTEM

In order to prevent any new leak from another VH penetration, EDF decided to install, on the most sensitive vessel heads, N^{13} leak detection systems on the top of vessel heads.

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[1] CETIC is a common EDF and FRAMATOME facility located in Châlon sur Saone in France.

INVESTIGATION PROGRAM ON ALLOY 600 / ALLOY 182

From the experience gained with the alloy 600 steam generator tubes, many results about PWSCC were acquired. The sensitivity of the material (for instance carbon content) was known and many expertises of pulled tubes helped to understand this type of cracking. Nevertheless, the situation of VH penetration was different by the fact the level of stress can be very important due to welding process. Particularly, peripheral penetrations are subject to constrains because of the dissymmetrical welds that introduce high level of stress. This is confirmed by the NDE results (the peripheral penetrations are more cracked).

Many studies were performed and a methodology has been developed to assess the stress corrosion life of Alloy 600 components.

CRACK INITIATION

The studies undertaken to characterize the PWSCC behavior of alloy 600 have identified the factors that play the most important roles in the occurrence of the crack initiation.

Three factors appear to be essential to the susceptibility of a given part to PWSCC initiation:

1- the material properties (microstructure, composition ...),

2- the temperature,

3- the mechanical loading.

As these factors can be quantified, it has been possible to combine them in a procedure enabling the utilities to deem the risk of crack initiation by PWSCC in the components of the PWR plant primary loops made from alloy 600.

The influence of these parameters can be quantified by indexes of susceptibility: i_m, i_θ, i_σ.

The global index of susceptibility is the product of the three indexes.

The configuration of reference (global index of 1) corresponds to a tube of a "sensitive alloy 600", submitted to a mechanical loading of 450 MPa, at the temperature of 325°C.

In these conditions, the minimum time for crack initiation is about 10 000 hours.

While being arbitrary, these conditions must nevertheless match together, namely any material rated $i_m = 1$, exposed to primary water at 325°C under a stress of 450 MPa should crack in 10 000 hours or more in the laboratory or in the plant.

When the model was developed in 1992, these conditions were based on the limited experimental results and operating experience available at that time. Since then, much experimental work has been performed on steam generator tubes, vessel bottom penetrations, steam generator partition plates and reactor support pads and also much operating experience has become available. The great majority of these recent data, used to check the above reference conditions, is in good agreement with them.

Therefore, the relation between the minimum time for crack initiation and the indexes is:

$$t_i \text{ in hours} = 10000 / i_\theta \,.\, i_\sigma \,.\, i_m$$

In the application of the method to components, we have cumulated the conservatisms in the following manner:

. Material index, maximum, for a given class of material,

. Stress index based on maximal stresses determined from calculations based on models which have been checked with envelop values of measurements and results of mock-up tests,

. Temperature index based on the best knowledge of the temperature of components and on activation energy of the phenomenon derived from laboratory tests and compared to the field experience.

In these conditions, the crack initiation time corresponds to the time, minimum, for initiating a macroscopic crack. This crack is defined, in accordance to the performance of in service inspections, as a crack for which the depth is the lowest of the values of 2 mm or 5% of the thickness wall.

The crack initiation method has been used, firstly, to rank the susceptibility of stress corrosion cracking of components made in alloy 600.

The method has then been applied to these different classes of components in order to define a maintenance strategy.

CRACK PROPAGATION

Between 1991 and 1996, 52 vessel heads have been inspected by contact eddy current.

A program of determination of in service crack propagation has been conducted on 27 penetrations from 15 vessel heads: 2 or 3 successive inspections were performed on 180 cracks [5].

The temperature of the inner surface of the penetration, in front of the weld of the penetration to the vessel head, in all configurations (cold dome, hot dome, penetration in central, intermediate or peripheral position) has been determined by calculations, studies on mock-ups and measurements on site.

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

- In cold dome: 290°C,
- In hot dome: 300°C.

The 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 the position of a penetration in the plant

Figure 2 presents the variation of the crack growth rate da / dt as a function of the stress intensity factor K for the T-hot and T-cold domes. In this representation, the points corresponding to the T-hot dome do not differ from those corresponding to the T-cold dome.

The activation energy, for crack propagation, has been deduced from laboratory data obtained between 290°C and 360°C (results EDF, Framatome, CEA and ETH for which a satisfactory agreement has been obtained (Q = 130 KJ/mol) [5].

It is not possible to deduce activation energy from available 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 (figure 2).

2 laws have been derived from field and laboratory data:

- The first law corresponds to the mean curve of field measurements:

Its expression at 290°C is:

$da / dt = 0{,}03 \times (K - 9)^{0{,}52}$ (da / dt in μm/h; K in MPa$\sqrt{m}$)

- The second law is the upper bound of results measured in field and in laboratory.

Its expression at 290°C is:

$da / dt = 0{,}3 \times (K - 9)^{0{,}10}$ (da / dt in μm/h; K in MPa$\sqrt{m}$).

Figure 3 shows a comparison of field data and laboratory data:

- Black curve representing the most sensitive heat tested in laboratory; maximum CGR is about 4 mm/year.

- Blue curve representing the average CGR coming from field measurements (VH penetrations). All values are in accordance and the most sensitive value from laboratory experiment remains above field measurement.

OTHER INCONEL COMPONENTS

Other Inconel components in the primary system were reviewed in the frame of the anticipation but taking into account results of the investigation program. Those, for which a potential risk of PWSCC was estimated, are (see figure 4):

- VH penetration J groove welds,
- Steam generator partition plate stub weld,
- Bottom head instrument penetration (BHIP),
- RPV nozzle repaired areas.

For these components, it was decided to initiate a complementary NDE program on a sample of them but taking into account material susceptibility and on the basis of previous laboratory results.

Safety evaluations were performed for each component. For instance, defects in the SG partition plate have been studied in all cases; a through wall extent crack doesn't modify SG operating conditions. For BHI penetrations, a fracture toughness study has been done considering longitudinal defect initiated from inside or outside tube penetration. For RPV nozzles, mechanical fast fracture studies show the acceptability of large defects.

Non-destructive examinations are performed during periodic outages or ten year visits (exceptionally during short outages) but using judiciously resources. For the two first ones, dye penetrant testing (PT) method was developed using an automatic tool to inspect the weld. For the second one, same techniques used for vessel head are used but adapted to the smaller diameter of the BHI penetration. A specific tool is implemented. For RPV nozzle repaired areas, detection of potential cracks is performed using eddy current probes and characterization using ultrasonic narrow beam focusing transducers. For the last one, video inspection is also performed at each ten years visit.

FEEDBACK EXPERIENCE FROM THE FIELD

A) ALLOY 600

As mentioned here above, many non destructive examinations were performed on all 54 French vessel heads with alloy 600 CRDM penetrations since 1994-1995 when ET and UT inspection procedures were finalized and stabilized. From this important set of data, few conclusions are now established and show clearly evidences. For the other areas, numerous inspections were also performed. Results are detailed hereafter.

VESSEL HEAD INSPECTION PROGRAM AND RESULTS

The inspection program is based upon the maximum CGR measured on the penetrations of a VH considered as the most sensitive. As example for 900 MW VH penetrations and 12 months cycles; the inspection policy is crack height measurement dependant: every 3 years for cracks below to 3 mm, every 2 years for cracks between 3 and 5 mm, every year for cracks above 5 mm.

In all cases, VH is replaced before reaching the safety criterion (4 mm remaining ligament for 900 MWe).

MAIN CONCLUSIONS FROM VH PENETRATIONS

Two important conclusions have to be mentioned using the experience feedback from the NDE field:

- Firstly, it is obvious that the level of stress has a major role for the initiation and propagation cracking. The main fact concerns the number of cracked VH penetrations and the circle where it belongs. Figure 5 shows that peripheral penetrations are mostly cracked compared with central ones.

- Secondly, the effect of the material susceptibility is particularly obvious for those that are classified sensitive. All VH penetrations were ranked in four categories from the less sensitive A to the most one D taking into account the material properties of each penetration. Figure 6 shows the effect of this susceptibility. Type B and C heat number are more often cracked than type A heat number but A type VH penetrations heat are more numerous. So in percentage, the value is undervalued. The effect also exists for type D but is less obvious due to the small amount of type D VH penetrations.

VHP REPLACEMENT PROGRAM

Replacement program started at the beginning of 1994. Up to now 41 VH have been replaced and 3 new ones will be installed in the next 2 years (see figure 7). As the CGR is low; it is expected to finish replacement around 2009-2010.

BHI PENETRATIONS

Fifteen RPV have been inspected up to the end of 2002. No crack indications have been discovered in the BHI penetrations at the end of 2002. Also, acoustic emission is performed during ten years visit hydro test pressure. Probes are very close to BHIP and could detect a noise due to a leak.

B) ALLOY 182

VESSEL HEAD

For J groove welds, PT examination on 754 welds from removed vessel heads was performed between 1996 and 1999. No cracks were detected in these welds.

SG PARTITION PLATES

SG partition plate (hot branch) is considered as possible precursor due to higher temperature and no stress relief from a heat treatment. Nevertheless, pressure hydro test is very favorable and decreases significantly the stress level.

Forty-two stub welds in the hot branch and twenty ix in the cold branch have been inspected. No cracks were found except in the case of a SG water box hammered by a loose part. A small crack was discovered during the SG expertise after removal as shown on figure 8.

RPV NOZZLE REPAIRED AREAS

Seven 900 MWe RPV have repaired nozzles with alloy 182. The inspections performed during the ten years visit have not revealed any cracks in the nozzles.

ALLOY 600 - VH PENETRATIONS BASE METAL ALLOY 182 - WELD METAL

Another risk is the weld metal cracking concern. In fact the Bugey 3 leak did not concern weld metal as the crack developed fully in the base metal. Taking into account international information and after the discover of a welding defect in the J groove weld on Ringhals VH, EDF decided to perform dye penetrant examinations of the J weld on several removed VH.

Eleven vessel heads (754 welds) were inspected from 1994 to 1999 and none of them were found cracked.

NEW PROGRAM

A new program has been proposed for years 2001 to 2008 following French regulator's request. This program requires inspection of :

- 26 SG partition plates (precursors) + 9 randomly chosen,
- 12 RPV bottom head penetrations

Also qualified NDE will have to be developed at the next ten years visit for RPV nozzles repaired zones and core support lugs.

CONCLUSIONS

In 1991, after discover of a leak on a vessel head penetration of Bugey NPP unit 3, numerous studies to understand the phenomenon were implemented. Several of them were in the field of expertise, others in the field of non destructive examinations in order to have all necessary tools to perform inspections The most important works were laboratory studies on both alloys 600 and 182. One of the major results concerned crack growth rates laws that can predict crack propagation.

In parallel, the maintenance policy was based upon the following key points:

- Very early, replacement of all VH equipped with alloy 600 by alloy 690. At the end of 2002, 41 of them have been replaced.

- Importance of the NDE inspections to measure cracks and determine the best instant for replacement (safety criterion).

- Importance of 2 parameters, penetration angle in the VH and material susceptibility.

For what concerns J groove welds, many PT inspections did not reveal any surface breaking cracks.

For the other Inconel components, up to now no cracks were discovered except for a very specific case in a hammered water box. For BHI penetrations, no cracking is expected before the end of life.

In conclusion, this maintenance policy was very fruitful, as no new leak has appeared up to now on vessel heads and bottom head instrumentation nozzles. It confirmed the need to anticipate and arrange strategy for the other Inconel components at the benefit of safety and competitiveness of the nuclear standardized series. EDF had a real proactive position about alloy 600/alloy 182 and more generally about Inconel components.

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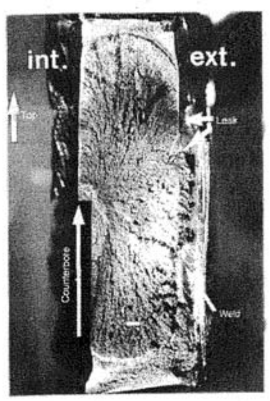

Fig. 1: TWE crack in T54 VH penetration

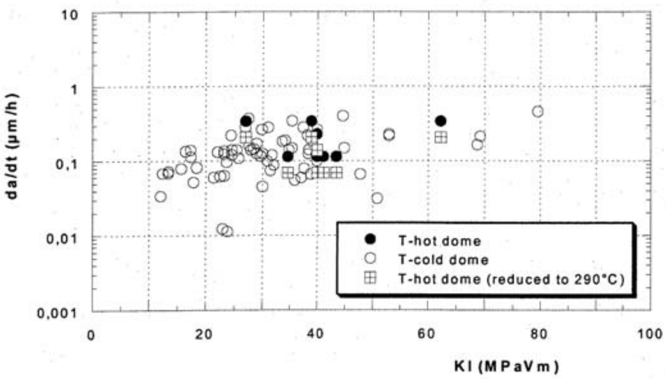

Fig 2 : Field data - T-hot dome data (300°C) reduced to 290°C with Q = 130 KJ/mol and T-cold dome data (290°C)

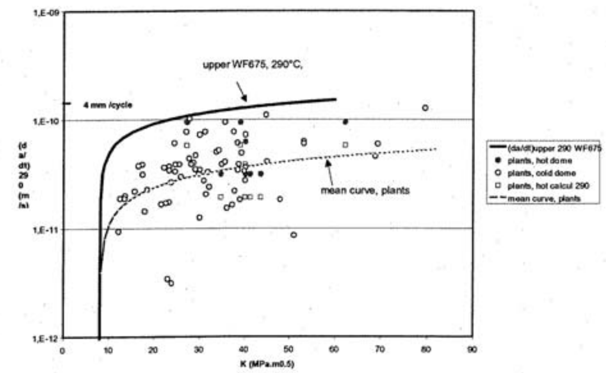

Fig. 3 : Comparison between laboratory and field experience

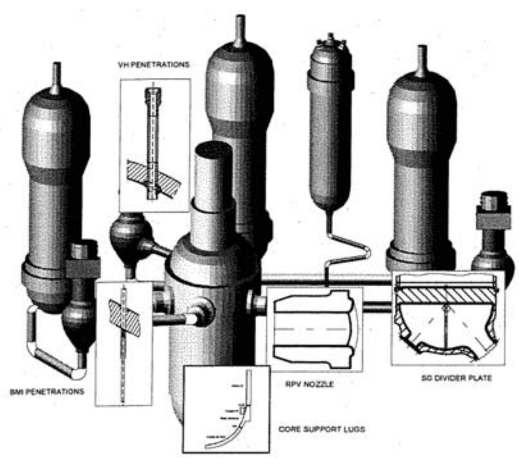

Fig 4 : Inconel components in primary system

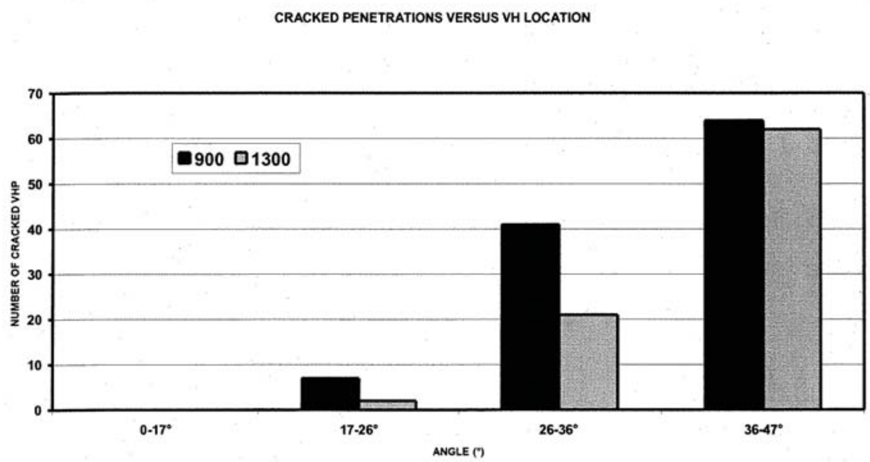

Fig. 5 : Importance of the "angle effect" versus VH penetrations cracking

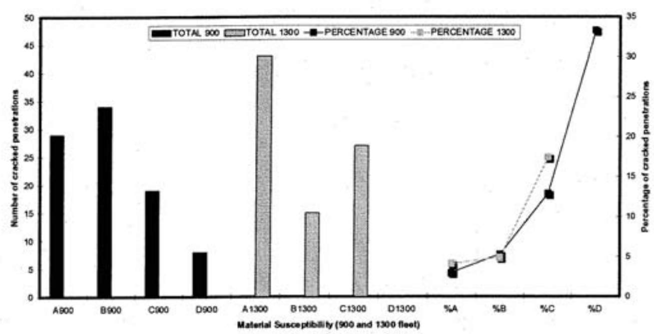

Fig 6 : Importance of the material susceptibility versus VH penetrations cracking (percentage values are given versus the total number of penetrations in standardized plant series 900 or 1300)

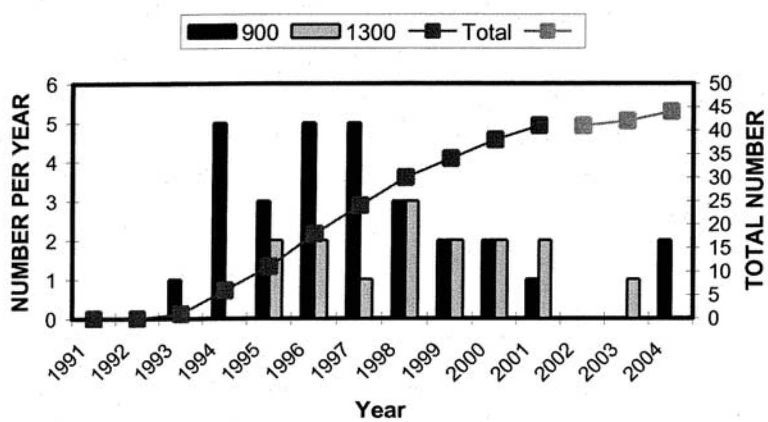

Fig. 7 : Vessel head replacement since 1993

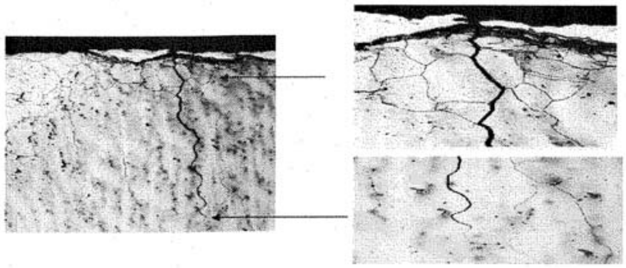

Fig. 8 : Expertise from a removed part of a hammered steam generator channel.

Strategic Planning for RPV Head Operation

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Abstract: Utilities are faced with difficult economic choices in managing PWSCC of RPV head penetrations. Inspections are expensive, especially if required on a frequent basis; if leaks are discovered during an outage when no inspections are performed, and no provision to perform repairs has been made, repairs can lead to significant lost production; repairs and remedial measures are expensive and, depending upon conditions, may result in future cracks or leaks; and head replacements are expensive. Life cycle management planning has been performed for a moderate susceptibility plant to determine the most attractive long-term strategy. This work has been based on predictive modeling and net present value economic analyses. The approach described can help a utility determine the best management strategy for its plant.

BACKGROUND

The economic consequences of managing RPV head nozzle PWSCC can be significant. For example:

- EdF is replacing all of its RPV heads.
- Cracks and leaks in nozzles in several domestic plants have resulted in significant outage extensions and repair costs.
- Boric acid corrosion resulting from a PWSCC leak at the Davis-Besse plant has led to over a 20 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.

The purpose of this paper is to review issues associated with developing a strategic plan for managing RPV head PWSCC at a moderate susceptibility plant. The strategic plan must:

- Ensure an extremely low risk of core damage. For purposes of this paper, it is assumed that this objective can be met by meeting the core damage risk criterion of NRC Regulatory Guide 1.174. Analyses to determine the risk of core damage are discussed in another DEI paper[1] presented during the same NRC-ANL conference during which this paper was presented.
- Ensure a low risk of leakage.
- Select a strategic plan that results in the lowest practical net present value (NPV) cost.

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[1] G. White, S. Hunt, and N. Nordmann, "Risk-Informed Evaluation of PWR Reactor Vessel Head Penetration Inspection Intervals." *Vessel Head Penetration Inspection, Cracking and Repairs Conference*, U.S. NRC and ANL, September 29 – October 2, 2003.

INPUTS AND CONSTRAINTS

There are a number of constraints that apply to establishing a cost effective strategic plan. Issues that should be addressed include:

- The current condition of the vessel head must be established by non-destructive examination. The head must be free of cracking to remain in the moderate susceptibility category.
- The rate of future PWSCC initiation and growth should be predicted based on industry experience and modeling that accounts for differences between the subject plant and relevant industry peers.
- Non-destructive examination intervals should be selected such that there is a low risk of leakage and extremely low risk of core damage.
- Planned refueling outage durations can have a significant effect on establishing a strategic plan. For example, plants with short refueling outages will have little time for inspections or repairs without extending the outage, and plants in a long outage, such as for steam generator replacement or 10 year ISI, may have longer time available for inspections or repairs.
- The time and cost for nozzle inspections and repairs.
- The time and cost for replacement head procurement and installation. For example, inspections may show the need for immediate replacement while there may be a long delay to obtain a suitable replacement head.
- Potential remedial measures, including an assessment of their cost and effectiveness.
- Special attention should be given to the possibility of discovering leaks from a nozzle at an inopportune time such as during a mid-cycle outage conducted for another purpose, during system leak checks at the end of a refueling outage, or during a regular outage when a leak is discovered but no provisions have been made in advance for inspections or repairs.

NRC inspection requirements such as EA-03-009, *Issuance of Order Establishing Interim Inspection Requirements for Reactor Pressure Vessel Heads at Pressurized Water Reactors*, are obviously significant inputs to strategic planning. It is necessary to comply with the order or to obtain relaxation from the requirements based on appropriate technical assessments.

ALTERNATIVE MANAGEMENT APPROACHES

There are four main alternative management approaches for RPV heads. These are:

- Continue to inspect and make repairs as necessary to ensure a low risk of leakage and an extremely low risk of core damage.
- Perform remedial measures to reduce the risk of PWSCC and possibly to increase the inspection intervals.
- Replace the head as soon as possible after discovery of the first PWSCC.
- Replace the vessel head as quickly as possible and perform NDE at increased intervals based on materials in the new head.

Comments on each of these approaches are as follows:

Inspect and Repair as Necessary

Inspection and repair methods are currently available to support the first alternative. The main nondestructive examination methods are volumetric NDE (UT) of nozzles plus volumetric examination for leakage paths through the annulus, or eddy current examination of the entire wetted surface of the nozzle and weld to show absence of cracks. Repair methods that have been used include removing shallow surface flaws, embedding deeper flaws, and removing the lower part of the nozzle and rewelding the bottom of the remaining nozzle to the head using a temper bead technique.

Remedial Measures

A number of remedial measures have been proposed for RPV head nozzles including:

- Modification of the internals flanges to increase bypass flow and thereby reduce the temperature of the vessel head. Some utilities have already performed this modification.
- Surface treatment of the nozzle and weld surfaces by shot peening or water jet conditioning to reduce the tensile stresses and, in the case of water jet conditioning, to remove small preexisting flaws.
- Nickel plating the nozzle and weld surfaces to keep the primary water coolant from contacting the Alloy 600 materials.
- Applying Alloy 152 weld overlays on the nozzles and welds.
- Roll expanding the nozzles into the vessel head to provide a redundant load path above the J-groove weld, and then conditioning the rolled surface to reduce the potential for new cracks.
- Application of a new structural weld between the nozzle and low-alloy steel vessel head, either on the top surface of the head or after boring out the lower part of the nozzle.
- Mechanical stress improvement.
- Zinc injection.

EPRI has sponsored testing of many of these remedial measures.[2] Upon completion of the testing, the remedial measures were ranked in terms of effectiveness. The three main categories were:

- 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

To date, the main remedial measure applied in the field has been modification of the internals to increase the bypass flow and thereby reduce the head temperature. The lower head temperature should reduce the rates of crack initiation and growth based on the thermal activation energy. However, experience in France suggests that PWSCC may occur at head temperatures close to the

[2] *Materials Reliability Program: An Assessment of the Control Rod Drive Mechanism (CRDM) Alloy 600 Reactor Vessel Head Penetration PWSCC Remedial Techniques (MRP-61)*, EPRI, Palo Alto, CA: 2003, 1008901.

reactor cold leg temperature. This is especially significant given the PWSCC at the South Texas Project Unit 1 bottom mounted instrument nozzles at a temperature of about 565ºF. The South Texas Project experience shows that poor material properties and weld defects can result in PWSCC at temperatures lower than otherwise expected.

Finally, while remedial measures may reduce the rates of PWSCC initiation and growth, and thereby reduce the cost of future repairs, it may be difficult to take credit for the improvement in the form of increased inspection intervals.

Head Replacement

Installation of a new RPV head with improved nozzle and weld materials is a clear success path that has been taken in France and has been announced by many plants in the United States. The Alloy 690 nozzles and Alloy 52 J-groove welds in these heads should provide better service life than the original heads with Alloy 600 nozzle base material and Alloy 182 welds. In addition to the cost of the new head, consideration must be given to:

- Access provisions for getting the new head into containment.
- Whether the head will be installed with new CRDM drives.
- Disposal of the old head.

One variation on head replacement is to use this as an opportunity to replace the original design reactor head service structure with an improved service structure that requires less effort to disassemble and reassemble every outage. Figure 1 shows a typical original design head service structure and one possible configuration for an improved head service structure. As shown, the original design requires disassembly and removal of the following parts at the beginning of every refueling outage:

- Head insulation
- Head cooling ductwork
- CRDM cables
- Head cooling fans
- Head missile shield

An integrated head service structure, such as shown in Figure 1, can be developed for most plants. In this arrangement, most of the above listed components are integrated in such a manner that only one main lift is required after disconnecting the electrical cables to the CRDM drives.

While an integrated head service structure can reduce the required manpower, it may not result in a reduction of refueling outage critical path time since other constraints can establish the point in time at which the head can be removed and replaced. Nevertheless, there a number of significant benefits of an integral head service structure including:

- Freeing up labor and crane time inside containment during normal refueling outages.
- Reducing the risk of personnel injury by eliminating many crane lifts.
- Cutting several days off of the time required to perform a rapid head disassembly and reassembly such as for a leaking RPV flange o-ring seal or internals inspection after a slow rod drop test, etc.

ECONOMIC EVALUATIONS

In most cases, strategic plans will include some level of economic evaluation. A deterministic "best-estimate" approach can be used for these evaluations, provided the analysis includes sufficient detail and includes costs over the remaining plant life. In some cases, utilities may elect to perform a Monte Carlo type probabilistic analysis to provide better information of the range and probability of possible costs.

Regardless of the type of economic evaluation, the analysis should include the following:

- The risk of future cracks and leaks for each alternative considered.
- The cost of performing planned (preventive maintenance) work.
- The cost of making repairs (corrective maintenance).
- The value of lost production.
- The value of consequential risks.
- The potential risk that leaks will be discovered at inopportune times such as during a mid-cycle outage or during a system leak check at the end of an outage.
- The planned operating life, including life extension.
- The discount and inflation rates.

Guidance on developing strategic plans is provided in EPRI report 1000806, *Demonstration of Life Cycle Management Planning for Systems, Structures, and Components with Pilot Applications at Oconee and Prairie Island Nuclear Stations*. Deterministic type economic analyses can be performed using the LcmVALUE version 1.0 software prepared as part of the EPRI LCM demonstration program.

Figure 2 shows typical results of net present value calculations for a moderate susceptibility plant. The figure shows the discounted net present value cost over the remaining plant life including preventive maintenance, corrective maintenance, value of lost production and consequential costs.

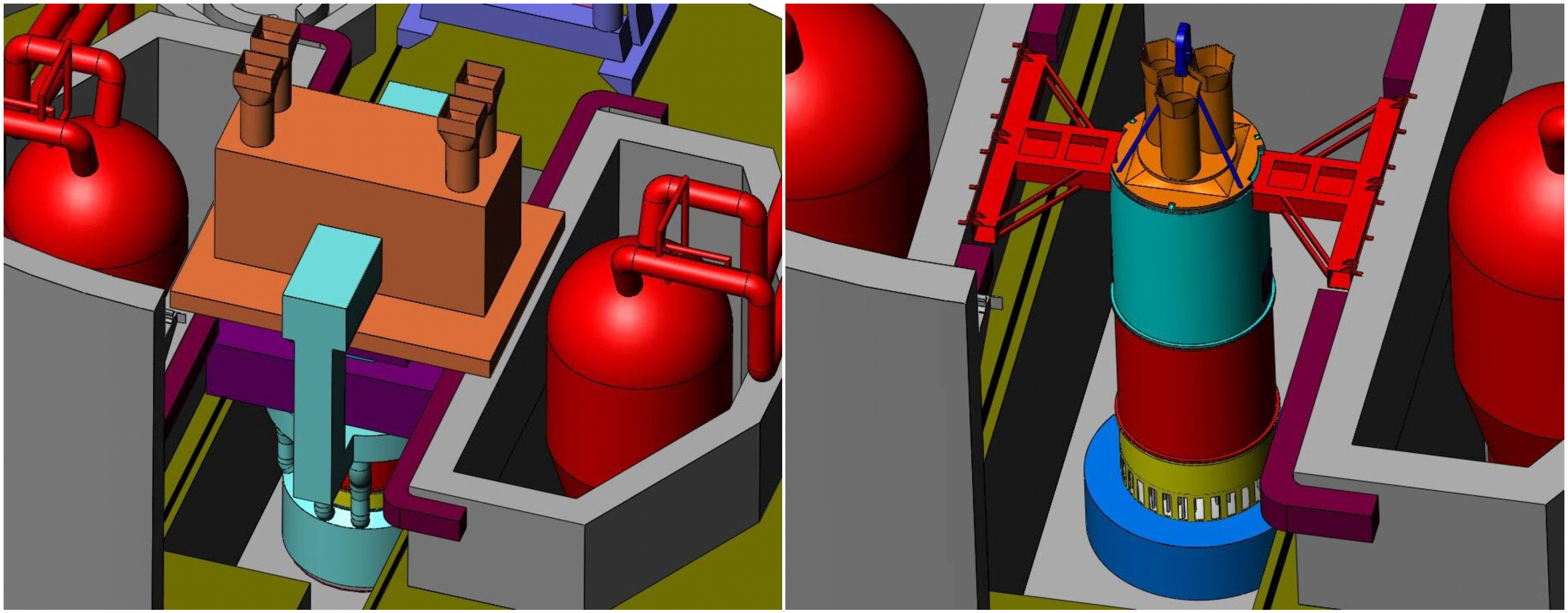
CONCLUSIONS

For the sample case presented, the optimum alternative appears to be bare metal visual inspections of the RPV head every refueling outage with nondestructive examinations of the nozzles and J-groove welds every second refueling outage.

- 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 EDYs.
- 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.

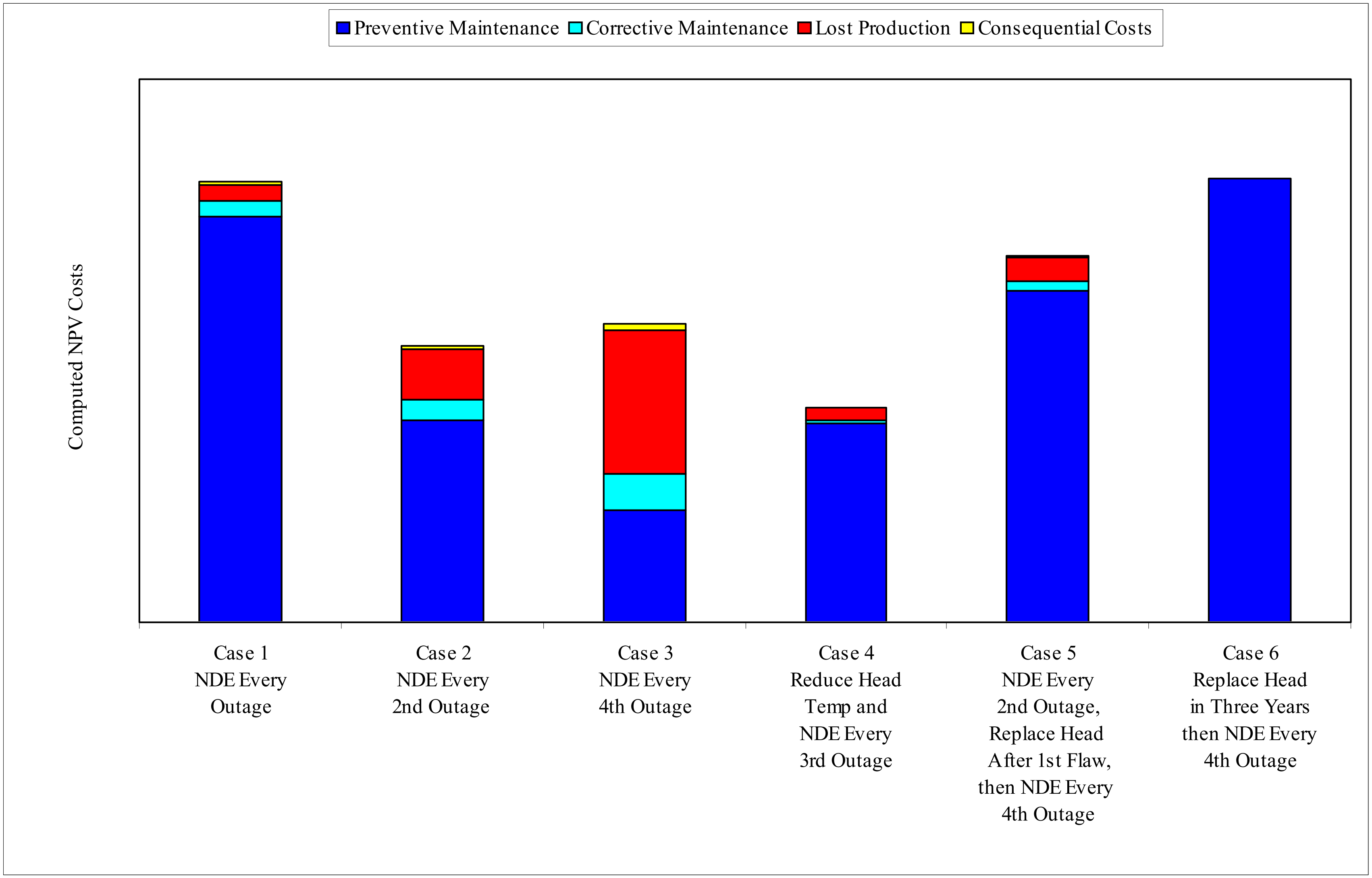
These results are plant specific, and other plants may have different constraints that would affect the optimum solution.

Figure 1
Head Replacement – Integrated Head Service Structure Option



Typical Original Structure | **Conceptual Integrated Structure**

Figure 2
Typical Strategic Planning Results for Moderate Susceptibility Plant With No PWSCC



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

S. Thomas, South Texas Project, and
R. Payne, D. Schlader, and D. Waskey, Framatome ANP, Inc.

Following a visual inspection that revealed a small amount of a powdery substance around two penetrations in the lower reactor pressure vessel (RPV) during a regular refueling and maintenance outage, Framatome ANP was contracted to perform inspection and repair of the South Texas Project (STP) Unit 1 RPV. This was the world's first indication of the possibility of a similar issue with the lower RPV that has affected the RPV heads for several years.

After extensive inspection of all 58 BMI nozzles, two nozzles were identified for repair. Repair technology implemented on other similar nozzle designs was modified for the two specific STP nozzle locations. Tooling was designed, fabricated, tested, and qualified over a short time period to respond to the emergent need at STP. The teaming between STP and Framatome ANP led to a successful first time implementation of repair on BMI nozzles.

The repair approach, associated tooling, and processes utilized at South Texas will be presented.

Manuscript was not available for publication in the Proceedings

South Texas Project Experience with Alloy 600 Bottom Mounted Instrument Penetration Cracking

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Abstract

The PWSCC susceptibility of the two PWR units at the South Texas Project has been considered low. Although the bottom mounted instrument (BMI) penetrations are Alloy 600 base metal with Alloy 82/182 welds, PWSCC was not expected at T_{cold} temperatures of the bottom head. Nevertheless, on April 12, 2003, routine visual inspections in Unit 1 discovered boron deposits at two BMI penetrations. Subsequent examinations revealed five axial cracks in the Alloy 600 tubes of the two leaking penetrations and no cracks in the tubes of any of the other 56 penetrations. The two leaking penetrations were repaired utilizing a "half-nozzle" design concept. Although ID initiated PWSCC was originally suspected as the initiating mechanism, several facts are inconsistent with a classical PWSCC scenario. Analysis of a boat sample confirms the presence of welding defects at the tube/J-groove weld which could be responsible for initiating the cracks and explain why the extent of cracking was limited to the two nozzles.

Background

On April 12, 2003, STP performed a scheduled visual inspection of the Unit 1 reactor vessel bottom head during the closing stages of 1RE11. The inspection, which has been performed routinely since startup, revealed deposits on two of the 58 bottom mounted instrument (BMI) penetrations. Chemical and spectrographic analysis determined the deposits to contain of boron and elevated concentrations of lithium consistent with reactor coolant system (RCS) leakage. Isotopic analysis detected no Co-58, indicating the deposits were at least one year old, and the ratio of Cs-134 to Cs-137 showed the deposits to be about 3-5 years old.

Evaluation and Repair

An extensive NDE campaign involving UT examination of all 58 BMI nozzles detected 5 axial cracks in the two leaking penetrations, three in Penetration #1 and two in Penetration #46. One crack in Penetration #1 penetrated the ID of the nozzle and extended from just above to just below the J-groove weld. The other two cracks were small and just penetrated the OD of the nozzle. Neither of the cracks in Penetration #46 penetrated the ID of the tube, as verified by a supplemental ET examination. One crack extended from just above to just below the J-groove weld. The UT examination also discovered a number of "discontinuities" at the tube/J-groove weld interface in the same general area of the cracks in Penetrations #1 and #46. Several other penetrations exhibited similar discontinuities, but no cracks.

In an effort to positively identify the leak path, a helium leak test was performed on the two leaking penetrations by pressurizing the annulus between the nozzle and the vessel. No bubbles were observed in Penetration #46. In Penetration #1 a small helium bubble was observed about every two seconds rising from a location outside the nozzle in the J-groove weld fillet at the tube interface.

Penetrations #1 and #46 were repaired utilizing a “half-nozzle” repair which relocated the pressure boundary to the exterior of the vessel with an ambient temperbead weld pad, new J-groove weld, and new Alloy 690 nozzle.

The details of deposit analyses, the NDE campaign, and nozzle repairs have all been previously discussed in public presentations. The remainder of the discussion in this paper will focus on the cause of the cracks.

Metallurgical Sampling

To facilitate metallurgical analysis of the actual cracks, boat samples were removed from Penetrations #1 and #46 employing an Electric Discharge Machining (EDM) cutting technique. In the case of the BMI nozzles inside the reactor pressure vessel, the boat sample excavations could not be repaired. The desire for the largest possible boat sample was balanced against conservative structural limitations. A number of mockups were constructed to test the remotely operated equipment.

The boat sample from Penetration #46 was designed to capture as much tube material as possible in an attempt to harvest a portion of a crack not connected to the ID of the nozzle. The margins for error associated with positioning the EDM equipment through 70 feet of water resulted in a shallow cut in Penetration #46. The resulting undersized sample was either inadvertently discarded or completely consumed in the margins of the EDM cutting tool. The boat sample from Penetration #1 captured material and defects from the J-groove weld and J-groove/tube interface, as designed.

Boat Sample Results

The boat sample from Penetration #1 contained a portion of the large through-wall axial crack in the tube, three “discontinuities” which were confirmed to be lack of fusion resulting from slag inclusions, and one crack at the helium bubble location which connects the surface of the J-groove weld to the largest area of lack of fusion.

Axial Crack in Penetration Wall

Earlier UT results identified an axial crack in Penetration #1 which penetrated the ID of the nozzle and extended from just above to just below the J-groove weld. The boat sample from Penetration #1 captured a part of the upper portion of this crack in the region of the tube/J-groove weld interface. The intergranular nature of this crack exhibits classical PWSCC characteristics. The extent of the crack was examined by progressively grinding away thin layers of the section of the boat sample. The orientation of the ground surface was such that more weld material and less tube material was exposed at each successive grind. The initial exposed surface consisting of nearly all tube material exhibits this crack which extends through the tube material and just into the weld material where the crack ends. As successive layers are ground away, exposing more weld and less tube, the crack becomes smaller and smaller. The final ground surface, which consists almost entirely of weld material, reveals no crack at all in the weld and a small vestige of crack in the remaining small bit of tube.

The axial crack in the tube appears to grow from the EDM surface out toward the tube/J-groove interface since it branches and connects two of the three voids. Crack growth in the tube toward the defects at the OD of the tube could indicate ID initiated PWSCC. However, neither of the two cracks in Penetration #46 connects to the ID of the tube. A supplemental ET examination of the ID surface was performed specifically to confirm the UT results that the flaws did not penetrate the ID. ET established that the cracks did not connect to the ID. Based on this fact STPNOC has concluded that the PWSCC axial crack in the tube is OD initiated. The crack most likely originated on the OD of the tube in the highly stressed region of the flooded weld defects.

Unless the cracks in Penetration #46 resulted from a different mechanism than the large crack in Penetration #1, the cracks must be OD initiated, since the flaws in Penetration #46 do not connect to the ID. The fact that the leakage in both penetrations appeared at the same time and are about the same age, suggests a single mechanism, and it seems too coincidental that two separate mechanisms could produce such similar results and be so closely connected in time.

Three Discontinuities

X-ray examination of the boat sample revealed three discontinuities or voids located at the tube/J-groove weld interface. Material found in the voids contained elements found in weld electrode coatings indicating that the voids were areas of lack of fusion resulting from weld slag inclusions. The peripheries of the LOF flaws contain a number of short cracks to a depth of 1 or 2 grains. Although hot cracking in the weld material is a likely possibility, these intergranular cracks also appear in the nozzle, where hot cracking is not possible. Therefore, STPNOC has concluded that this cracking is PWSCC resulting from flooding of the LOF voids.

J-Groove Weld Crack

The crack in the weld that connects the surface of the J-groove weld to the largest area of lack of fusion is singular and unique. The 0.2-inch long crack spans an 80 mil-thick ligament separating the lack of fusion void from the surface of the J-groove weld in the ground fillet transition at the tube/J-groove weld interface. The length of the crack spans and is limited to the width of the lack of fusion void. The section of the boat sample containing this crack was broken in the laboratory to expose the crack face for examination. Tenacious deposits obscured the crack face, and gradually more aggressive attempts to remove the deposits also attacked and distressed the metal surface. The crack exhibits some intergranular characteristics. The nature of the oxide deposits could be indicative of hot cracking. Fatigue and stress corrosion could also be factors in the development of this crack. In the final analysis, the precise mechanism responsible for initiating and propagating this crack could not be determined from an examination of the crack surface.

Conclusions

The root cause is the use of Alloy 600 combined with nozzle manufacturing and installation methods that further increased the susceptibility of the metal to stress corrosion cracking when in contact with primary water.

The following discussion outlines the most likely sequence of events. The SMAW process used to construct the J-groove welds produced slag inclusions on the interface between the Alloy 600 tube and the weld. Already located in highly stressed areas on the OD of the penetration, these weld defects acted as stress risers. Early in the life of the vessel, a solitary crack developed that connected a lack-of-fusion or slag inclusion weld defect to the surface of the weld and primary water. Once the 80 mil-thick ligament was cracked and the lack-of-fusion void became flooded with primary water, all of the requisite conditions to support stress corrosion cracking existed. Minute cracks developed in both the tube and weld material around the edges of these flooded defects. One of these cracks propagated in the tube material, but not the weld. Consistent with the analytically predicted residual stresses, the crack was axially oriented.

Although there are other possible theories regarding the crack development scenario, several points are very clear regardless of the specific sequence of events.

1. The Alloy 600 BMI nozzles are susceptible to PWSCC and will crack under the right conditions. Even at Tcold, PWSCC is possible.

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

Note: The South Texas Project did not identify any materials or fabrication techniques unique to the construction of Unit 1 that contributed to the cracking.

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

Development and Justification of a Repair Process for Flaws in Reactor Vessel Upper Head Penetrations

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In preparation for the inspections of reactor vessel upper-head penetrations, which began in 1992, a repair process was developed for embedding the flawed region behind an Alloy 52 weld, to ensure that the flaw was isolated from the water environment. The weld itself is composed of a material that is immune to stress corrosion cracking, and the weld is just thick enough to qualify the flaw as an embedded flaw according to the rules of Section XI of the ASME Code.

The initial concept was intended for application to the inside surface of the head penetration tubes, and the NRC approved the process in 1996. In the year 2000, as degradation was found on the tube outer diameter, and in the attachment welds, the process was revised to cover these regions as well.

This paper will discuss the development of the repair process, as well as its application for several repairs that have been completed in operating plants. The service experience for these repairs has been excellent. The steps that have been taken to assure the quality and integrity of the weld repair will also be discussed.

Manuscript was not available for publication in the Proceedings

Weld Overlay Deposit on Alloy 82/182 Butt Welds to Reduce ID Surface Stresses

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D. Covill, *Progress Energy, Raleigh, NC*

Abstract: PWSCC has been detected in Alloy 82/182 butt welds in plants in the US and Europe. The most significant incident to date resulted in leakage from a reactor vessel hot leg outlet nozzle at VC Summer during the fall of 2001. A potentially attractive remedial measure for Alloy 82/182 butt welds is to apply weld overlay on the outside of the butt weld to reduce the tensile stresses on the inside surface. Finite element analyses have been performed of pressurizer-surge-nozzle butt welds in the as-designed condition and with inside surface repairs ranging from a 30° partial arc to a full 360° weld repair. The effect of weld overlay cladding on inside surface stresses has been assessed.

This paper presents work sponsored by the Electric Power Research Institute (EPRI), Materials Reliability Program (MRP), Alloy 600 Issue Task Group.

BACKGROUND

PWSCC cracks have been discovered in reactor pressure vessel (RPV) inlet and outlet nozzle to primary coolant pipe butt welds at VC Summer and Ringhals. Figure 1 shows the VC Summer nozzle and weld configuration with the main PWSCC cracks superimposed. An axial crack propagated completely through the weld and arrested at the low-alloy steel nozzle and the stainless steel pipe. This crack led to a leak that was discovered during a refueling outage. A small circumferential crack in the Alloy 182 cladding blunted when it reached the low-alloy steel nozzle material.

The root cause investigation at VC Summer concluded that the subject weld had been subjected to several repairs, including a repair weld to the inside surface after completion of the entire weld. Figure 2 shows results of stress analyses performed for EPRI of the VC Summer weld. The left side figure shows the operating condition hoop stress, including the effect of welding residual stresses, for the as-designed case without repairs to the ID surface. The right side figure shows that making a weld repair to the ID surface after completing the entire weld, significantly increases the inside surface hoop stress and therefore increases the potential for PWSCC. Figure 2 also shows the stress contours used for all of the stress plots in this paper.

It should be noted that the operating condition stresses in this paper represent the combined effect of welding residual stresses, hydrostatic testing (provides some mechanical stress relief) and operating pressure and temperature. The operating condition results do not include the effect of piping forces and moments. These were not included since they vary significantly from plant to plant.

WELD OVERLAY TO REDUCE TENSILE STRESSES

A weld overlay applied to the outside surface of a butt weld will reduce the tensile stresses on the inside surface of the weld. Specifically weld shrinkage causes a reduction in diameter at the weld and a resultant reduction in tensile stress. Reducing tensile stresses will delay the time to PWSCC crack initiation and the growth rate of any preexisting cracks.

While weld overlays can also be used to provide a redundant load path around a cracked weld, the subject work was not focused upon creating a redundant load path.

Figure 3 shows a typical pressurizer surge nozzle assumed for this evaluation and Figure 4 shows a weld overlay applied over the weld to reduce ID surface stresses. The overlay assumed for this study had a thickness of 17% of the nominal pipe wall thickness and a length 5.5 times the nominal pipe wall thickness.

FINITE ELEMENT MODEL

Finite element analyses of the surge nozzle were performed using the ANSYS finite element software. Figure 5 shows the overall finite element model, Figure 6 shows the mesh in the area of the weld and overlay and Figure 7 shows the weld passes assumed for the calculation. The area assumed for the weld repair is outlined in this figure.

The finite element modeling was performed using the following basic methodology:

- The weld was simulated using ten passes in layers from the ID to the OD.
- Thermal analyses were performed for each pass to determine the welding temperatures and these temperatures were input to the stress analysis as a function of time to determine the welding residual stresses.
- After completion of the main weld, the backgouge weld repair was simulated by analytically removing from the inside surface already completed weld elements.
- The backgouged area was repaired assuming that four passes were applied to the inside surface.
- The completed weld joint was subjected to hydrostatic test conditions that act to reduce peak stresses.
- Finally, the operating pressure and temperature were applied.

WELDING RESIDUAL AND OPERATING CONDITION STRESSES

Figure 8 shows the welding residual stresses, operating condition stresses for the as-designed case with no ID weld repair, and operating condition stresses with the assumed ID weld repair. Axial stresses are plotted on the left and hoop stresses are plotted on the right. Also reported for each case are the maximum axial and hoop stresses on the ID surface for the operating condition cases. These results show that the maximum hoop stresses exceed the maximum axial stresses and that a weld repair to the ID surface after completing the main weld significantly increases both the axial and hoop stresses on the ID surface. These results are for a 2D axisymmetric model.

Figure 9 shows results for a 3D model with the weld repairs performed for partial arcs of 30º, 60º, and 90º. These results show similar stresses to the case for a 360º repair, although the axial stresses tend to be slightly higher. On this basis it is assumed that the effectiveness of the overlay can be evaluated using the 2D axisymmetric model.

Figure 10 shows the effect of applying weld overlay for both the as-designed case and the case with a 360º ID weld repair. In both cases the axial and hoop stresses are significantly reduced. This should have a beneficial effect on both crack initiation and growth.

SUMMARY OF RESULTS

Table 1 summarizes the analysis results.

CONCLUSIONS

The conclusions of the analysis are as follows:

- Repairs to the ID surface of a butt weld after completing the through-wall weld increases both the axial and hoop stresses on the ID surface.
- Partial-arc ID repairs also produce higher hoop and axial stresses in the inside surface.
- Weld overlay applied to the outside surface of the butt weld reduces the hoop and axial stresses on the ID surface and should therefore reduce the susceptibility to PWSCC initiation and growth.
- 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 increase in axial ID stress due to bending occurs at a location where the material is not susceptible to PWSCC.

Finally, it should be noted that the subject analysis is not intended to represent an actual weld overlay design. The purpose of the work was to demonstrate the beneficial effect of weld overlays.

Table 1
Summary of Analysis Results

- 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

Figure 1
Locations of Cracks in VC Summer Hot Leg Outlet Nozzle Weld

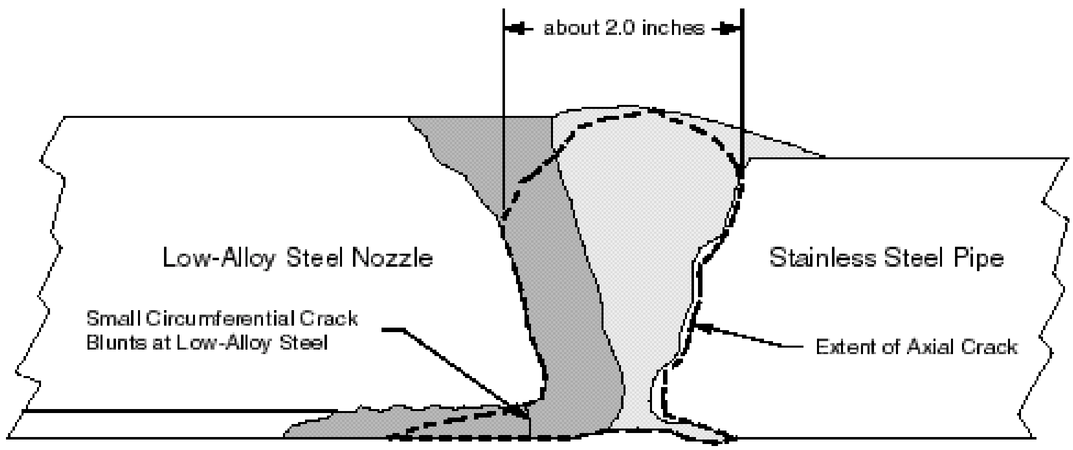


Figure 2
Effect of ID Weld Repairs on Butt Weld Operating Hoop Stress

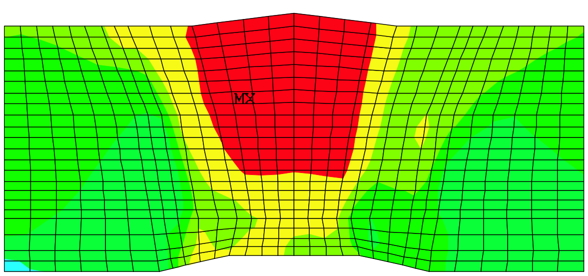
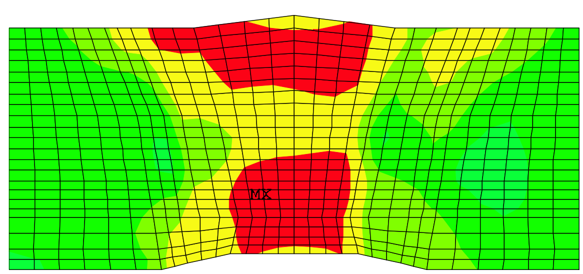
As-Designed Condition	With ID Repair to Completed Weld
	

Figure 3
Pressurizer Surge Nozzle Cross Section

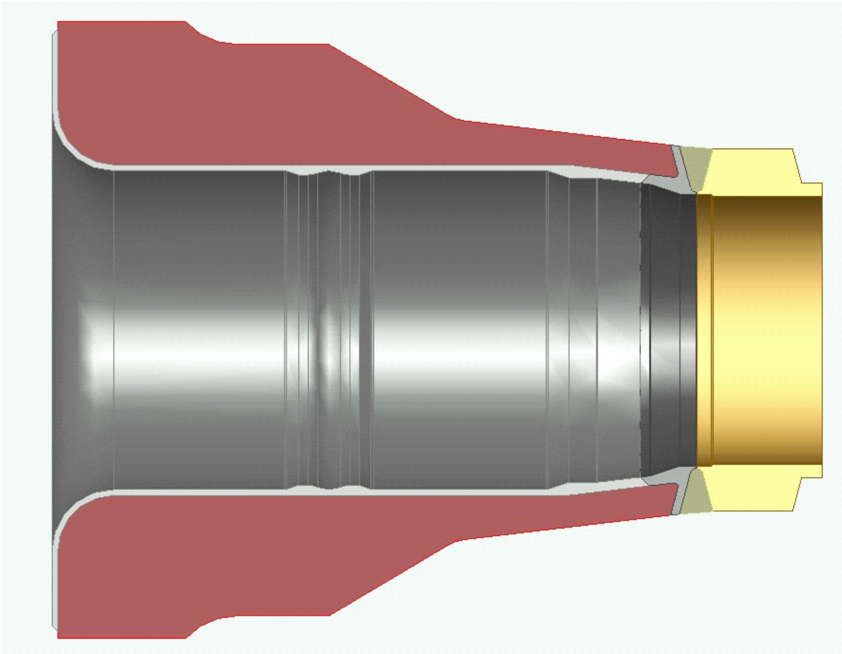


Figure 4
Pressurizer Surge Nozzle with Weld Overlay to Reduce Tensile Stress

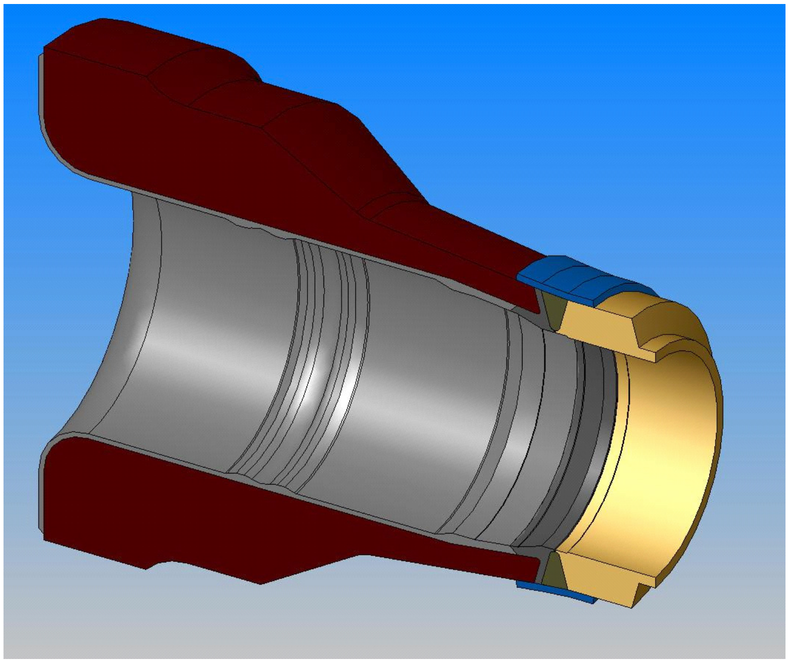


Figure 5
Pressurizer Surge Nozzle – Overall Finite Element Model

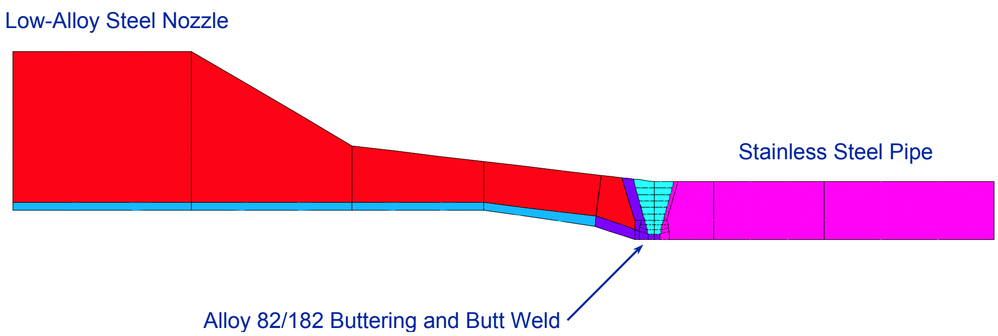


Figure 6
Pressurizer Surge Nozzle – Mesh in Area of Weld and Overlay

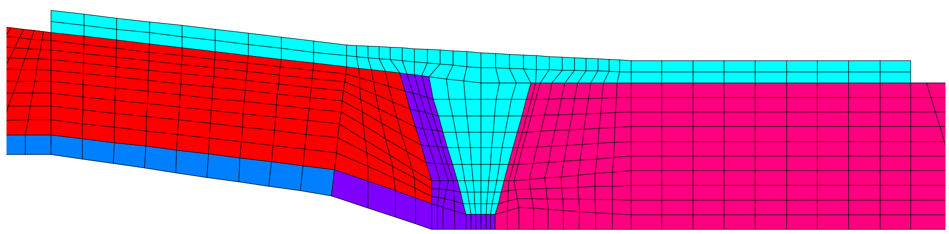


Figure 7
Pressurizer Surge Nozzle – Weld Passes Modeled

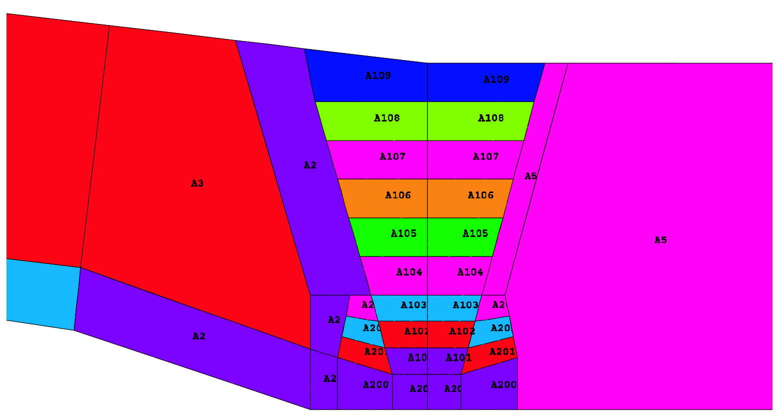


Figure 8
Welding Residual and Operating Stresses With and Without 360º ID Weld Repair

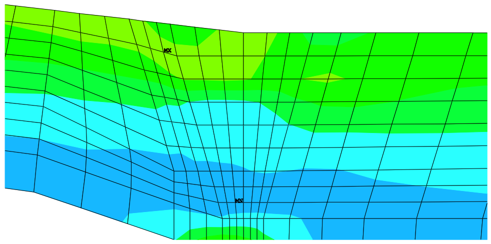
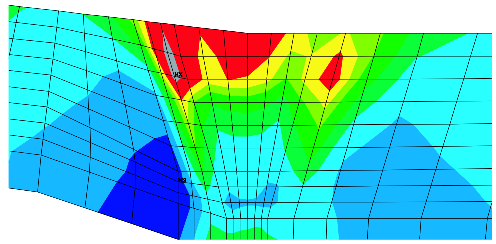
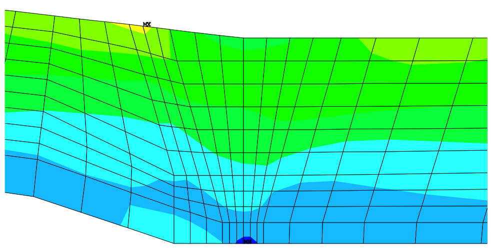
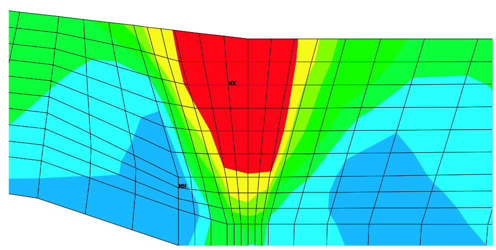
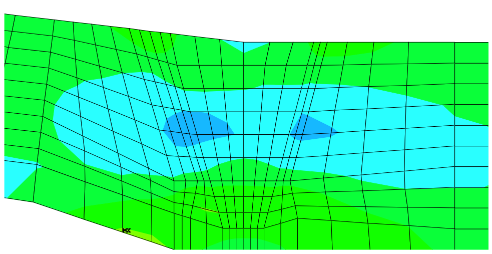
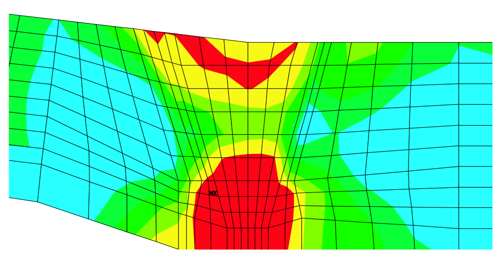
Condition	Axial Stress	Hoop Stress
Welding Residual Stresses		
Welding Residual and Operating Stresses – As Designed	 -2.7 ksi Max ID Stress	 9.0 ksi Max ID Stress
Welding Residual and Operating Stresses – With 360º ID Weld Repair	 32.5 ksi Max ID Stress	 52.8 ksi Max ID Stress

Figure 9
Welding Residual and Operating Stresses With Partial-Arc ID Weld Repairs

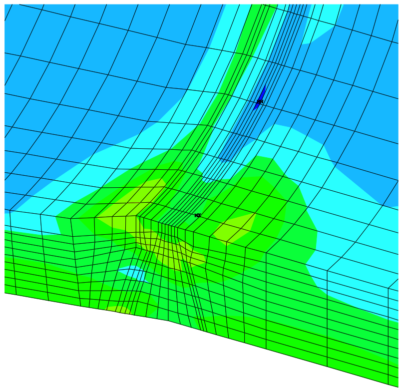
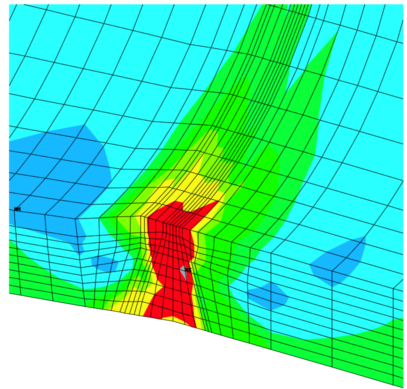
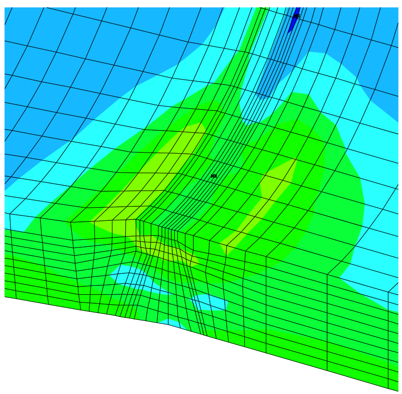
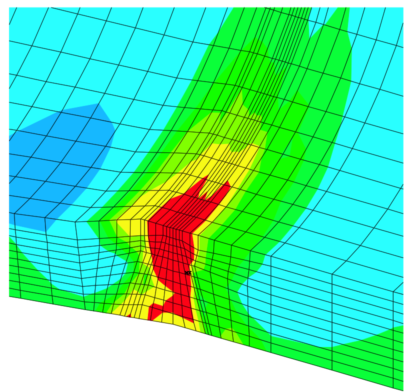
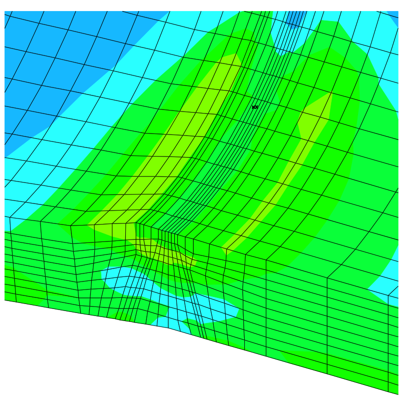
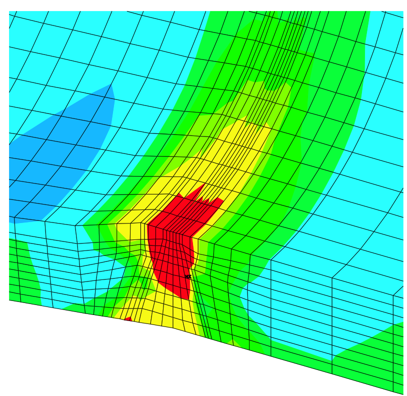
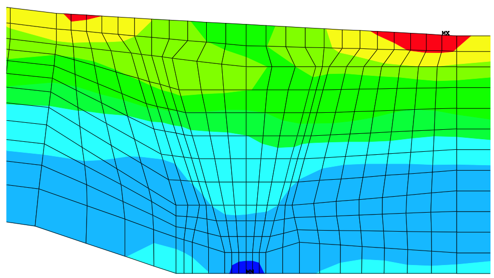
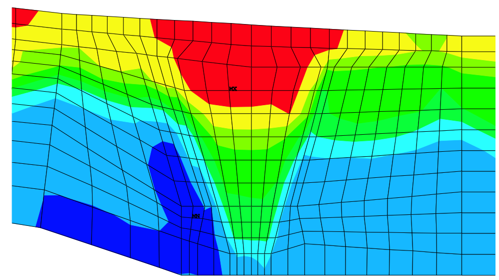
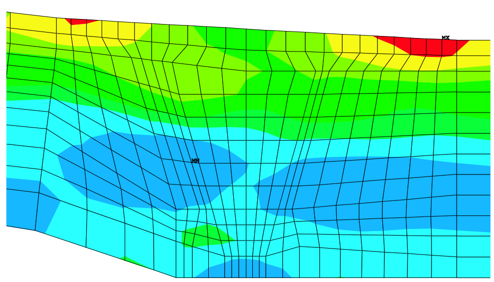
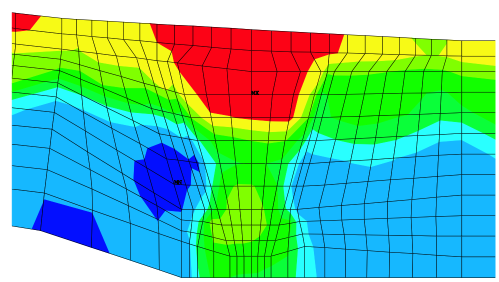
Condition	Axial Stress	Hoop Stress
Welding Residual and Operating Stress 30° Arc ID Repair	 39.9 ksi Max ID Stress	 54.6 ksi Max ID Stress
Welding Residual and Operating Stress 60° Arc ID Repair	 38.6 ksi Max ID Stress	 52.6 ksi Max ID STress
Welding Residual and Operating Stress 90° Arc ID Repair	 40.2 ksi Max ID Stress	 52.0 ksi Max ID Stress

Figure 10
Welding Residual and Operating Stresses With Overlay Deposit

Condition	Axial Stress	Hoop Stress
Welding Residual and Operating Stresses With Overlay – As Designed	 -8.6 ksi Max ID Stress	 -23.2 ksi Max ID Stress
Welding Residual and Operating Stresses With Overlay - 360º ID Weld Repair -	 1.7 ksi Max ID Stress	 19.9 ksi Max ID Stress