Implications of Wolf Creek Pressurizer Butt Weld Indications Relative to Safety Assessment and Inspection Requirements

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REPORT SUMMARY

Background

Primary water stress corrosion cracking (PWSCC) of nickel-chromium-iron Alloy 600 material and its related Alloy 82/182 weld metals has been a concern for pressurized water reactors (PWRs) worldwide since the early 1970's. Cracks tend to initiate at high stress locations on the wetted inside surface of the susceptible material and grow axially or circumferentially into the base metal or welds. Cracks initially occurred in Alloy 600 base metal, especially in highly cold worked and strained steam generator tubes, but have subsequently been discovered at other base metal locations including pressurizer heater sleeves and instrument nozzles, steam generator tube plugs, reactor vessel top head control rod drive mechanism nozzles, and reactor vessel bottom head instrument nozzles.

In addition to cracks and leaks in Alloy 600 base metal, cracks and leaks have occurred in Alloy 82/182 butt welds. The first butt weld cracks were discovered at Ringhals 3 and 4 in 1999/2000. These were followed by leaks from a VC Summer reactor vessel outlet nozzle weld in 2000 and Tsuruga 2 pressurizer relief nozzle weld in 2003 (in the Tsuruga 2 case the cracks were in Alloy 132 weld metal which is similar to Alloy 182). These initial butt weld cracks/leaks were primarily axial and arrested when the crack propagation reached the interface with the low-alloy steel nozzle and stainless steel piping materials. A shallow circumferential crack was discovered in the leaking VC Summer reactor vessel outlet nozzle butt weld and a larger through-wall circumferential crack was found in Alloy 600 base metal adjacent to a pressurizer nozzle butt weld at Palisades in 1993.

Based on the experience with cracks and leaks in Alloy 82/132/182 butt welds, the MRP issued a safety assessment (MRP-113) in July 2004 and issued inspection requirements for Alloy 82/182 butt welds (MRP-139) in August 2005. MRP-139 requires performance demonstration initiative (PDI) qualified inspection of all Alloy 82/182 butt welds greater than 4" NPS in pressurizer locations by the end of 2007. This target date represented an expeditious implementation of MRP-139 for locations subject to pressurizer operating conditions and was the earliest practical date that PDI inspections could be accomplished given plant refueling outage schedules and available inspection/mitigation resources. Inspections of other Alloy 82/182 butt welds are to follow at one year intervals with hot leg butt welds 4-14" NPS by the end of 2008, hot leg butt welds greater than 14" by the end of 2009, and cold leg butt welds by the end of 2010. These other lower temperature locations are considered to be less susceptible to PWSCC.

In October 2006 Wolf Creek discovered significant circumferential indications in three of the six pressurizer nozzle Alloy 82/182 butt welds. Plans had been made in advance of the outage to mitigate these welds by applying full structural weld overlays. These weld overlays were performed without metallurgical examination of the indications to confirm the root cause.

Objective

The objective of this report is to document work performed by the MRP to understand the significance of the reported Wolf Creek indications and to review the MRP-113 safety assessment and the MRP-139 inspection requirements in light of this new information. The most important issue is whether there is a need to accelerate scheduled inspection and/or

mitigation of pressurizer butt welds at plants which have not yet performed PDI qualified inspections to support the continued safe operation of the plants.

Approach

A multi-step process was pursued to assess the need for accelerated inspections. First, the Wolf Creek inspection and cause evaluation reports were reviewed. Second, predictions were made of the likely future growth, and potential for rupture, of the Wolf Creek indications if they had not been mitigated including the effect of residual stress relaxation. Third, plans for future Alloy 82/182 butt weld inspections and mitigation at all domestic PWR plants were summarized. Fourth, an estimate was made of the probability of other uninspected Alloy 82/182 butt welds having critical size flaws before inspection or mitigation. Finally, the conclusions of the MRP-113 safety assessment and the MRP-139 inspection requirements were reviewed in light of the recent information.

Results

Within the scope of the subject review it was not possible to prove or disprove the presence of PWSCC in the Wolf Creek welds. Therefore, it has been conservatively assumed that the cracks are PWSCC as concluded by Wolf Creek. Refined calculations show that there is a very high probability that leakage will be detected by on-line monitoring prior to risk of rupture since critical flaw sizes are significantly larger than reported in MRP-109 and recent industry studies indicate that leakage sensitivity is much higher than was the case in the past. Another key conclusion is that the reported indications are not likely to be growing at a high rate. It is a statistical improbability that four rapidly growing cracks, all having similar depths, would be found in a single pressurizer after 18 full power years of operation. Possible reasons for a lower growth rate are that the indications are related to fabrication or are active cracks that have grown into a lower stress region. A review of utility plans shows that all pressurizer nozzle butt welds will be inspected by April 2008 and that 95% of the nozzles will be mitigated by that time. A probabilistic analysis of the inspection results to date shows that the risk of critical size flaws developing in uninspected nozzles is extremely low and there would be little reduction in probability of rupture by accelerating the currently scheduled completion of all pressurizer weld inspections within sixteen months time.

In summary, it is concluded that the industry inspection schedule remains valid, supports the continued uninterrupted safe plant operation, and that acceleration of the inspection schedule is not warranted.

Keywords

Primary water stress corrosion cracking
PWSCC
Alloy 600
Alloy 82/182
Butt welds
Wolf Creek
Pressurizer

Contents

Executive Summary

1. Evaluation of Wolf Creek Inspection Results and Fabrication Records (Section 3)
   Previously reported Wolf Creek inspection results are summarized. Significant new work was performed to compile fabrication records for the Wolf Creek pressurizer. This information shows that there were many repairs to the pressurizer butt welds, including extensive repairs from the inside surface of both the surge and relief nozzles. Review of the repair records shows extensive repairs in nozzles that had indications, as well as one nozzle with no indications. This does not support the conclusion that repairs are the sole cause of the indications. Nevertheless, it is conservatively assumed that the reported indications are PWSCC.

2. Predicted Growth of Wolf Creek Indications without Mitigation (Sections 4 & 5)
   Recent work has confirmed that circumferential PWSCC cracks would be expected to grow through-wall in a few years under the residual and applied stress assumptions used by the NRC. However, results of these calculations do not appear to agree with the observed facts. Specifically, it would be statistically unlikely for four of the five cracks to be about the same depth after about 18 years of operating time if they were all growing rapidly. Possible reasons for this behavior are that the indications are fabrication related and not growing or that they are PWSCC cracks which have grown into a zone of lower stress intensity factor due to stresses being lower than assumed.

3. Critical Flaw Size and Leak before Risk of Rupture (Section 6)
   Analyses have confirmed that the critical flaw sizes for partial-arc through-wall cracks are significantly larger than reported in the MRP-113 safety assessment and that leakage will be detected by on-line means with significant margin to rupture. Further, significant ductility of pipes with deep 360º cracks with through-wall growth over a 133º arc length was demonstrated by NRC sponsored tests (NUREG/CR-4687). This work confirms that even these types of severe cracks would exhibit detectable leakage before risk of rupture.

4. Current Utility Inspection/Mitigation Plans (Section 8)
   Utilities are working to complete PDI qualified inspections and/or mitigation of all pressurizer butt welds by the end of the next scheduled refueling outage. All plants will be inspected and/or mitigated by the end of the spring 2008 refueling outages. The status of plant plans is summarized in Table 8-1 and Figure 8-1.

5. Probability of Critical Size Flaws in Uninspected/Unmitigated Plants (Section 9)
   An evaluation has been performed to estimate the probability of a critical size crack developing in the 37 plants that have not yet completed inspections/mitigations prior to the outage at which this work is scheduled to be performed. These calculations indicate the core damage frequency (CDF) with no credit for on-line leakage detection is about 5.73E-8 per plant year. Accelerating these inspections so that all inspections are completed by the end of 2007 would only decrease the CDF to 2.50E-8 per plant year.

6. Leakage Detection and Boric Acid Corrosion (Sections 10 & 11)
   INPO has been reviewing utility leakage detection plans, has found a high level of awareness regarding leaks, and has recommended several improvements to leakage detection criteria. These recommendations have been addressed by the PWR Owners Group in recently approved standard guidelines for calculation of RCS leak rate and standardization of action levels and response guidance. The standard action levels are a combination of the following:
   - Absolute Unidentified Leak Rate in gpm.
   - Deviation from the baseline mean in gpm.
   - Total integrated unidentified Leakage in gallons.

   The action levels are constructed to complement each other with each type of Action Level providing a check of the others. The action levels are arranged into three tiers designed to address progressively larger leaks. See Section 10, Leak Detection, for details of the PWROG action level. Forty-four plants in responding to a recent survey request have identified they have existing procedural requirements that trigger corrective action at levels ≤0.3 GPM. There is no change to the conclusion in MRP-113 regarding the risk of significant boric acid corrosion from pipe butt weld leaks.

7. Conclusions (Section 12)
   The following conclusions have been reached from the recent reevaluation of the butt weld safety assessment (MRP-113) and inspection/mitigation requirements (MRP-139):
   - Nothing regarding the Wolf Creek experience invalidates MRP-113 or MRP-139.
   - MRP-113 addressed large circumferential flaws.
   - Work performed subsequent to the Wolf Creek inspections aids in the understanding of how large circumferential cracks propagate, slow or arrest near mid-wall, and continue to grow through-wall in local high stress areas. However, conservative predictions showing high crack growth rates are not consistent with finding four cracks all at a similar depth after 18 years of full power operation.
   - Critical flaw sizes are 5-8 times larger than the Wolf Creek indications.
   - Leakage will be detected before risk of rupture for all flaw conditions evaluated.
   - The risk of developing critical size flaws in uninspected pressurizer butt welds prior to completion of planned inspection/mitigation in the spring of 2008 is small.
   - The industry has made a significant commitment to inspect all pressurizer butt welds and apply mitigation where appropriate by the spring of 2008.
   - Bare metal visual inspections of butt welds during the last refueling outage, and improved on-line leakage monitoring, ensure an extremely low risk of rupture in the interim until the planned inspections and mitigations activities are completed.
   - Accelerating currently planned inspections to the fall of 2007 or the spring of 2007 is not warranted since the risk of a rupture is extremely small considering the low probability of large flaws, the large critical flaw sizes and on-line leak detection.
   - The MRP will monitor inspection experience with Alloy 82/182 butt welds during the upcoming spring 2007 inspections and will change recommendations if warranted.

1. Introduction

Primary water stress corrosion cracking (PWSCC) of Alloy 600 base metal and Alloy 82 and 182 weld metals in pressurized water reactor (PWR) plants has been a concern since initial problems were identified in steam generator tubes in the early 1970's. This experience has been widely documented in EPRI and MRP reports [e.g, 1, 2, 3] and is not repeated herein. This report focuses only on PWSCC in pressurizer Alloy 82/182[1] butt weld applications.

Pressurizers are cylindrical pressure vessels that are attached to the primary coolant hot leg by a stainless steel surge line. Pressurizers are partially filled with water which is maintained at a temperature of 650ºF by electric resistance heaters installed in sleeves at the bottom of the pressurizer. The 650ºF temperature results in a nominal internal pressure of 2,235 psig in the primary coolant system. If the system pressure rises, water from the cold leg is injected into the pressurizer through a spray nozzle in the pressurizer top head. If the pressure rises to abnormal levels it is relieved by a power operated relief valve (PORV) or safety valves that are attached to the pressurizer steam space by nozzles which penetrate the top head.[2]

Figure 1-1 shows a typical Westinghouse design pressurizer. Combustion Engineering and Babcock and Wilcox design pressurizers are similar, although the details of the heater sleeves and top head nozzle orientations differ and the Combustion Engineering and Babcock & Wilcox pressurizers also have smaller diameter Alloy 600 instrument penetrations.

Figure 1-2 shows the top head area of a typical Westinghouse pressurizer and a cutaway view through a typical relief nozzle. Safety nozzles and spray nozzles have similar cross sections, although the spray nozzles have a thermal sleeve. The relief nozzle shown has a stainless steel clad low alloy steel nozzle forging (typically A508). The forging is buttered with Alloy 182 nickel-chromium-iron, is welded into the pressurizer shell, and is then stress relieved. After stress relief, a short stainless steel safe end is welded to the nozzle by an Alloy 82/182 shop weld. The shop weld may have been subjected to repairs during the welding process and possibly again to remove unacceptable fabrication indications identified during the final code-required radiography. Weld repairs can be made from either the inside or outside surfaces even for the smaller diameter spray, safety and relief nozzles repairs as discussed in Section 3. A final stainless steel field weld is made between the stainless steel safe-end and stainless steel pipe.

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1 Alloy 82 is bare metal electrode intended for use with the gas tungsten arc welding (GTAW) process (also called the tungsten inert gas [TIG] process). Alloy 182 is coated electrode material intended for use in shielded metal arc welding (SMAW). Alloy 132, which was used in Japanese plants, is similar to Alloy 182. Alloy 82 has a greater amount of chromium (18-22%) than Alloy 132/182 (13-17%) and tests have shown it to have lower crack growth rates. Most buttering was applied with Alloy 182 material and most butt welds were made with an Alloy 82 root pass followed by multiple Alloy 182 passes to complete the weld. Accordingly, it is believed that most butt welds have a path through the more susceptible Alloy 182 material from the wetted inside surface to the outside of the weld. For convenience, these welds are designated as Alloy 82/182.

2 Wolf Creek operating practice for the past nine operating cycles involved continuous spray and heater operation resulting in a continuous outflow through the surge line.

Figure 1-3 shows the bottom head area of a typical Westinghouse pressurizer and a cutaway view through a typical surge nozzle. Fabrication of the surge nozzle is similar to that of a safety/relief nozzle except that a thermal sleeve is installed inside the nozzle bore.

Since PWSCC initiation and propagation is highly temperature dependent, and since the pressurizer is the highest temperature location in the primary system, it is the location most likely to first experience PWSCC assuming that the material susceptibility and tensile stresses are the same as at other primary system Alloy 82/182 butt weld locations. The main source of tensile stress is the weld shrinkage that occurs when making the Alloy 82/182 shop weld. When combined with weld repairs, operating pressure, differential thermal expansion between different adjacent materials, and applied piping loads, high axial and circumferential tensile stresses can occur on the wetted inside surface. Stresses on the inside surface of Alloy 82/182 butt welds are evaluated in report MRP-106.

The potential for PWSCC of Alloy 82/182 butt welds was explored in a series of MRP reports prepared between 2000 and 2005. Figure 1-4 shows a matrix of the reports and the main content of these documents is as outlined below. These documents provide further reference details regarding the development of the MRP-139 inspection plans.

- MRP-21[4]: Provides early (June 2000) information regarding crack growth rates in Alloy 182 weld metal.
- MRP-44.1 [5]: Provides a preliminary safety assessment for Alloy 82/182 butt welds following the cracks discovered in Ringhals 3 and 4 reactor vessel outlet nozzles and a leak from a VC Summer reactor vessel outlet nozzle.
- MRP-57 [6]: Provides insight into cracking of Alloy 182 butt welds in BWR plants. This information is useful regarding potential crack orientations, lengths, depths, and aspect ratios.
- MRP-33 [7]: Provides results of elastic-plastic finite element stress analyses of the Ringhals and VC Summer reactor vessel outlet nozzle butt welds.
- MRP-106 [8]: Provides results of elastic-plastic finite element stress analyses of the full range of PWR Alloy 82/182 butt welds.
- MRP-109 [9]: Provides results of the vendor safety assessment for Alloy 82/182 butt welds in Westinghouse and Combustion Engineering design plants.
- MRP-112 [10]: Provides results of the vendor safety assessment for Alloy 82/182 butt welds in Babcock & Wilcox design plants.
- MRP-114 [11]: Provides an assessment of the effect of weld repairs on crack growth in Alloy 82/182 butt welds.
- MRP-116 [12]: Provides the results of a probabilistic risk assessment of the potential for core damage resulting from butt weld PWSCC.
- MRP-115 [13]: Provides predicted crack growth rates in Alloy 82/182 weld metal as established by an international expert panel.

- MRP-113 [14]: Provides a final integrated safety assessment for Alloy 82/182 butt welds including those in pressurizer locations.
- MRP-139 [15]: Provides required initial performance demonstration initiative (PDI) qualified inspections of Alloy 82/182 butt welds and subsequent reinspection intervals.

Taken in total, the above reports document a well studied approach to the development of required inspections for all reactor coolant system (RCS) Alloy 82/182 butt weld locations. MRP-139 requires that all Alloy 82/182 pressurizer butt welds equal to or greater than 4" NPS, and the B&W pressurizer safety and relief valve nozzle welds, be inspected by PDI qualified procedures by the end of 2007. This date represented an expeditious implementation of MRP-139 for these locations and was the earliest practical completion date considering plant refueling outage schedules and the availability of PDI qualified inspection procedures and inspectors. As will be discussed in Section 8, all plants are currently scheduled to have completed these inspections by the end of April 2008 and remedial measures are planned for about 95% of the welds to prevent future PWSCC and to increase the required reinspection intervals.

Figure 1-1
Typical Westinghouse Design Pressurizer (not to scale)

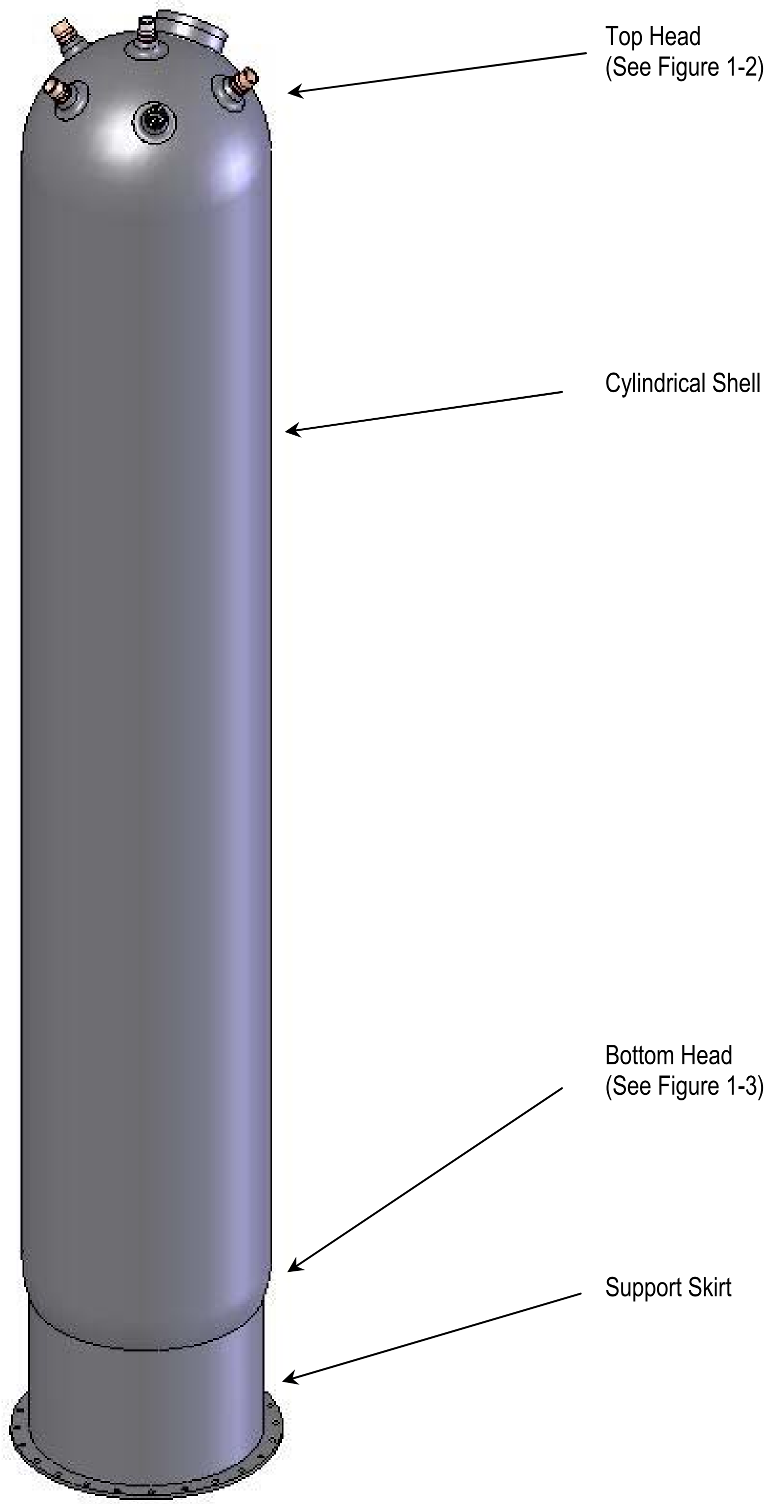
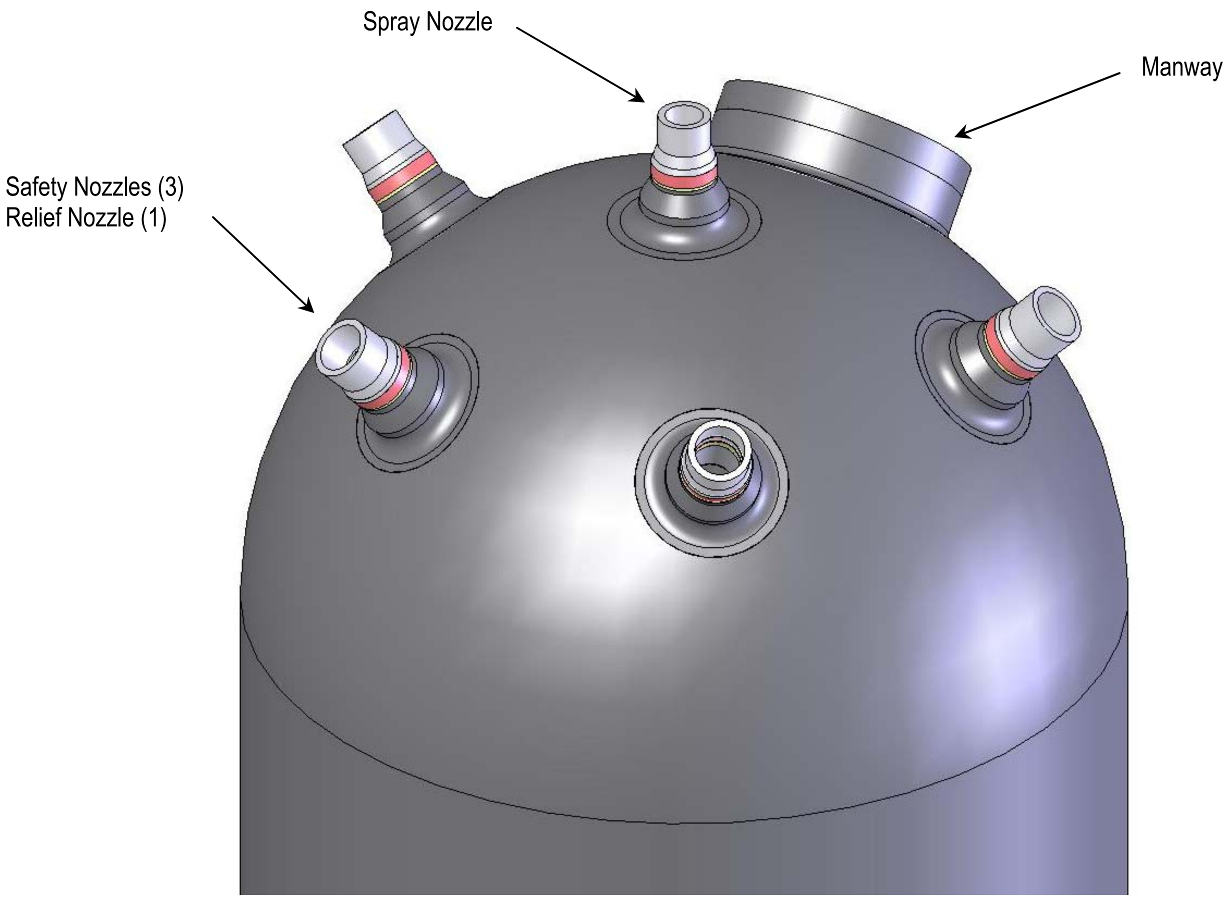


Figure 1-2
Typical Westinghouse Pressurizer Top Head and Safety/Relief Nozzle (not to scale)




Typical Pressurizer Top Head Nozzle

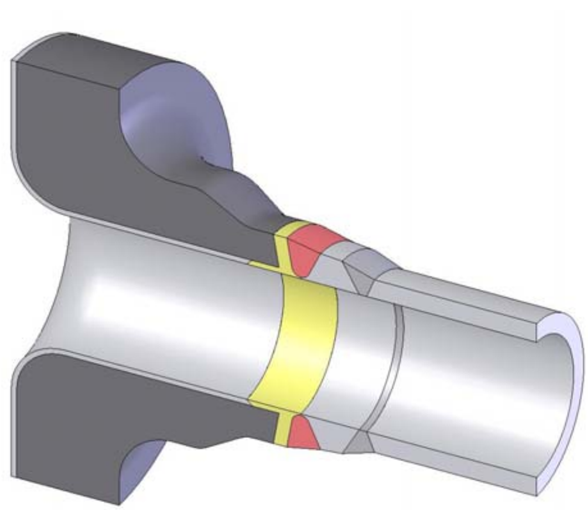
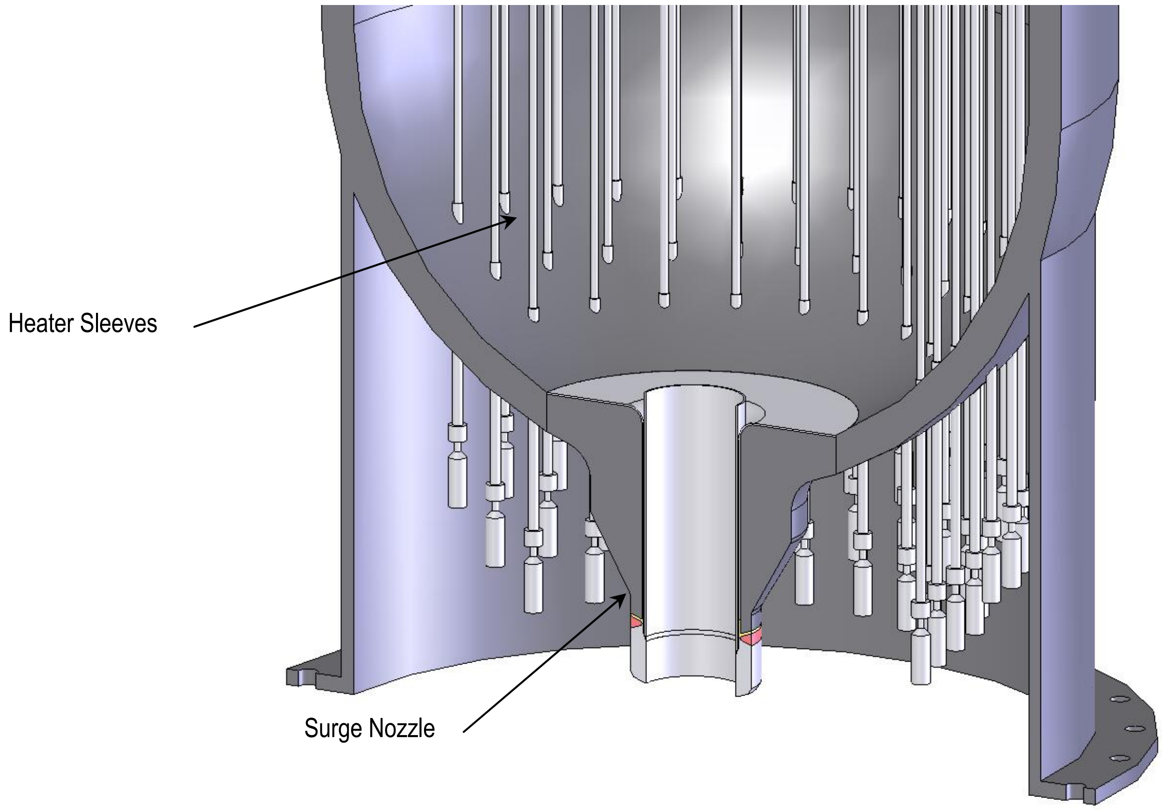
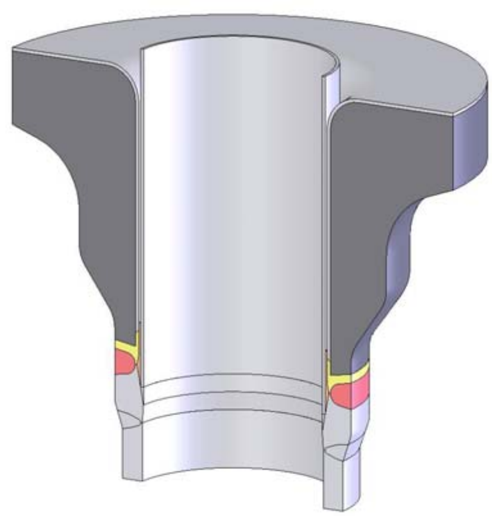

Typical Westinghouse Safety/Relief Nozzle
(see Figure 3-1 for weld details)

Figure 1-3
Typical Westinghouse Pressurizer Bottom Head and Surge Nozzle (not to scale)

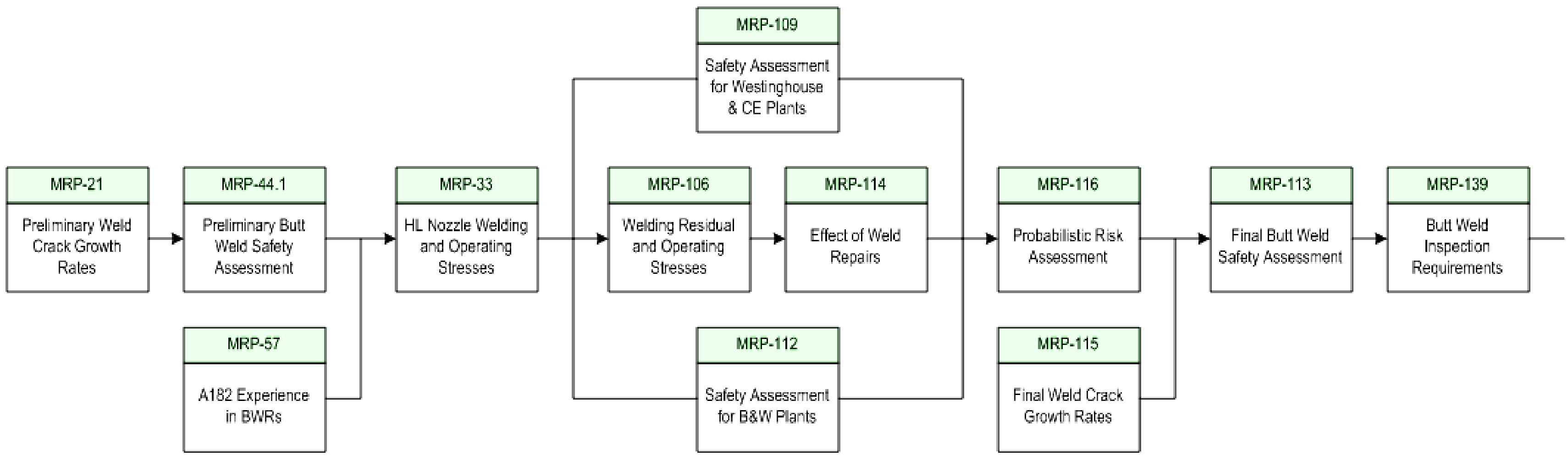


Typical Westinghouse Surge Nozzle



Typical Westinghouse Surge Nozzle
(see Figure 3-2 for weld details)

Figure 1-4
Matrix of MRP Reports on Butt Weld PWSCC



2. Experience with Pressurizer Butt Welds

Despite the high pressurizer operating temperature, and experience with PWSCC cracks and leaks in Alloy 600 pressurizer heater sleeves and instrument penetrations, there have been relatively few problems to date with Alloy 82/182 butt welds in pressurizer nozzles. The following is a brief summary of the main experience to date:

Leaks from Pressurizer Butt Welds

There have been two reports of leaks in or near dissimilar metal pressurizer butt welds in PWR plants and one somewhat related case in a test reactor.

a. Tsuruga 2 Butt Weld Leak (2003)
A leak occurred from a through-wall axial crack in an Alloy 132 pressurizer relief nozzle butt weld at Tsuruga 2 in Japan in 2003 [17]. A part-depth axial crack was discovered in a safety nozzle weld. Figure 2-1 shows cross sections through two of these cracks. The cracked welds were replaced. Alloy 132 has similar chemical and mechanical properties to Alloy 182. A root cause analysis showed that these welds had been repaired during fabrication.

b. Palisades Relief Nozzle Safe End Leak (1993)
The Palisades pressurizer is different from the typical Westinghouse pressurizer described in Section 1 in that the pressurizer safety and relief nozzles had Alloy 600 safe-ends which were welded to the low-alloy steel (LAS) nozzles and to 4 inch Schedule 120 stainless steel pipe by Alloy 82/182 butt welds. During a post refueling outage system walkdown, a leak was discovered from a circumferential through-wall crack in the heat affected zone (HAZ) of the Alloy 600 safe end. The configuration and crack location are shown in Figure 2-2.

The through-wall crack was reported to be 3.5 inches long on the outside surface and located about 0.080 inches from the weld. Using nominal dimensions, the crack arc length was approximately 90º. This weld had been examined by UT and found to be acceptable during the outage. This experience confirms the value of having delayed widespread inspections of dissimilar metal butt welds until after the inspection procedures and personnel had been PDI qualified. It also confirms the ability to detect leaks from large through-wall flaws by plant walkdowns.

c. Leak From Test Reactor Pressurizer Elbow
Bettis Atomic Power Laboratory has described a leak near the weld joining a 1-1/2 inch Schedule 80 Alloy 600 elbow to an Alloy 600 nozzle in a test reactor pressurizer [16]. The leak developed after about 20 years of service in stagnant steam at 620ºF and 1,800 psi.

Failure analysis showed that the leak resulted from a circumferentially oriented through-wall crack extending from the weld underbead through the wrought Alloy 600 base metal. Some intergranular crack branches extended into the grain growth portion of the weld heat affected zone, but none extended into the weld proper. The elbow material was heavily banded with an associated duplex grain structure, and the microstructure revealed grain boundaries that were not well decorated with carbides. No stress corrosion cracking (SCC) was observed on the elbow inside surface.

The location of crack initiation was reported to be subject to a greater amount of weld metal shrinkage and higher residual stresses than other parts of the weld. This provided an increased potential for initiation and crack growth in this localized area which ultimately resulted in a through-wall defect.

Only one of the three reported leaks occurred in the weld proper, and this leak and a related crack were axially oriented as predicted to be most probable based on finite element modeling [8]. The Palisades and Tsuruga cases support the ability to detect leaks by plant walkdowns (at Palisades they heard escaping steam) or visual inspections during outages (the Tsuruga 2 leaks were detected by boric acid deposits) prior to rupture.

Non-Leaking Pressurizer Butt Weld Indications

Twenty-nine (29) pressurizer butt welds have been inspected in the US by PDI qualified procedures through the end of 2006. Four plants have reported indications from these inspections. While details of the indications are reported below, the indication depths (when provided) should be considered "best estimates" based on limitations of the NDE qualification. These reported indications are:

- DC Cook 1 (2005): A part-depth 1.23" deep axial flaw was detected in a 1.4 inch thick 6 inch safety nozzle butt weld. The likely source of the flaw was determined to be PWSCC based on the flaw inspection response. The flaw length was not determined due to the nozzle outside surface conditions, but is believed to be limited to the width of the weld and buttering as at Tsuruga 2. This weld, and the other butt welds in Cook 1 and 2, were mitigated by a full structural weld overlay.

- Calvert Cliffs 1 (2006): A part-depth 0.1" deep by 0.6" long axial flaw was detected in a 1.3 inch thick relief nozzle butt weld. This flaw was left in place and the weld was mitigated by a mechanical stress improvement process (MSIP). Other pressurizer butt welds at Calvert Cliffs 1 and 2 have also been mitigated by MSIP. A part-depth axial flaw 0.4" deep and 2.4" long was reported in a 1.3 inch thick surge line to hot leg nozzle butt weld, but this is not counted in the database of pressurizer nozzle butt weld indications.

- Wolf Creek (2006): Circumferential indications were detected in three of the six Wolf Creek pressurizer butt welds during the Fall 2006 refueling outage. These indications are described in Section 3.

- SONGS 2 (2006): UT indications were discovered in two of the four SONGS-2 pressurizer top head nozzle welds. However, subsequent evaluations showed that these indications were not surface connected and are therefore not PWSCC. Nevertheless, full structural weld overlays were applied.

Summary Regarding Pressurizer Nozzle Butt Weld PWSCC

In summary, both axial and circumferential flaws have been detected in pressurizer nozzle butt welds or in Alloy 600 base metal adjacent to the welds. In two of the cases (Palisades and Tsuruga 2), the flaws were detected by small leaks and in the other cases the indications were detected by PDI qualified nondestructive examinations. The experience highlights the benefit of visual inspections to detect leaks at an early stage, and the potential that previously performed non-PDI qualified inspections may have missed some flaws.

Other PWR Plant Butt Weld Indications

As previously noted, the major cases involving PWSCC of other RCS butt welds were the part-depth axial cracks in the Ringhals 3 and 4 rector vessel outlet (hot leg) nozzles and the through-wall crack which led to a leak at VC Summer [14]. Two axial cracks at Ringahls 3 were both determined to be 9±3 mm in depth. After an additional approximately 8,000 effective full power hours, the first defect had grown to a depth of 13±3 mm while the second defect grew to a depth of 16±3 mm. These data were used to confirm the crack growth rate model for Alloy 82/182 weld metal [13]. In the case of VC Summer, the through-wall axial crack extended from the low alloy steel (LAS) nozzle material to the stainless steel pipe material similar to the profiles for Tsuruga 2 in Figure 2-1. VC summer also had a shallow circumferential crack in the butter on the inside of the nozzle that arrested when it reached the LAS nozzle material.

Several other part depth axial cracks have been reported in hot leg and cold leg nozzle butt welds.

Related BWR Plant Butt Weld Experience

BWR plants experienced SCC of piping early in plant life and the flaw orientations can shed some light on the potential for circumferential cracks in PWR plant butt welds.

MRP sponsored GE Nuclear Energy to document cracking experience in Alloy 182 BWR pipe butt welds [6]. Figure 2-3 shows the lengths and depths of axial cracks and the arc-lengths and depths of circumferential cracks discovered in BWR pipe butt welds. The data show that axial cracks can grow to significant lengths if not arrested by some resistant material transition (such as low-alloy or stainless steel in the case of PWSCC in PWR plants.) The data also show that most of the circumferential cracks had arc lengths less than about 75º.

The main exception to the limited circumferential crack arc length was the 360º circumferential crack at Duane Arnold. This outlier involved a unique crevice water chemistry condition that does not exist in PWR plants. As shown in Figure 2-4, a long circumferential flaw initiated at a crevice location with high residual stresses caused by a repair weld. While this crack may have started as a uniform depth 360ºcircumferential crack it ended up with the profile shown in the bottom of the figure. This crack profile is consistent with a shallow 360º crack growing in the presence of a pipe bending moment where one side has a tensile stress and the other side has a compressive stress.

Summary Regarding Dissimilar Metal Butt Weld Cracks/Indications in PWR Plants
Industry experience has shown that there is a potential for axial and circumferential cracks to develop in PWR plant Alloy 82/182 butt welds and that some of these cracks can grow to produce leaks if not inspected using qualified procedures at appropriate intervals or mitigated to prevent initiation or growth. However, the data to date from both PWR and BWR plants has shown that axial and circumferential cracks will grow to produce detectable leaks prior to rupture. The special cases of through-wall partial-arc and 360º part-depth circumferential cracks are addressed in Sections 4 and 5.

Figure 2-1
Cross Sections Through Axial Pressurizer Butt Weld Cracks at Tsuruga 2 (2003) [17]

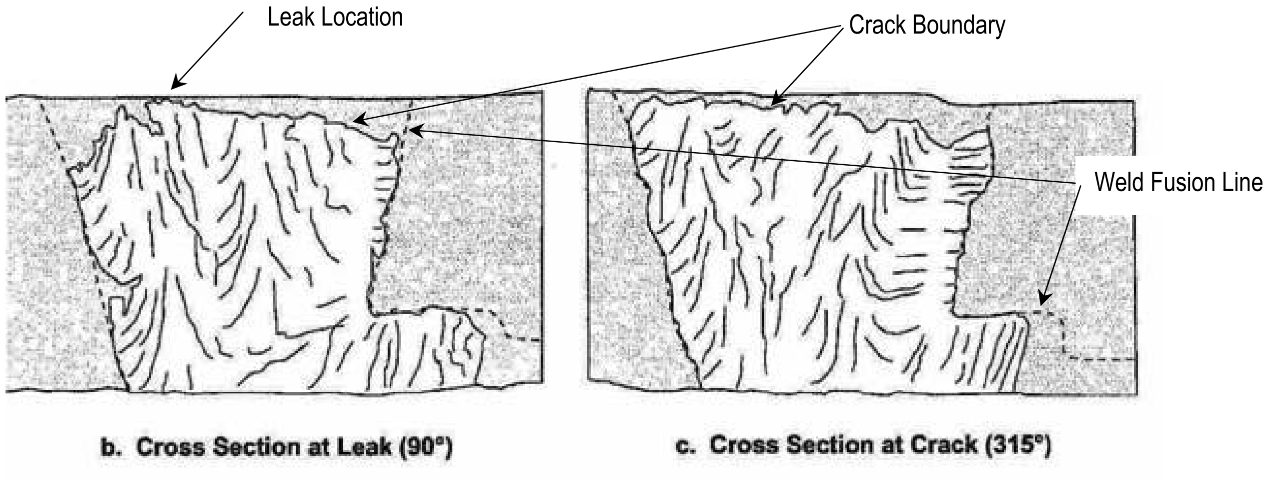


Figure 2-2
Through Wall Circumferential Crack at Palisades (1993) (not to scale)

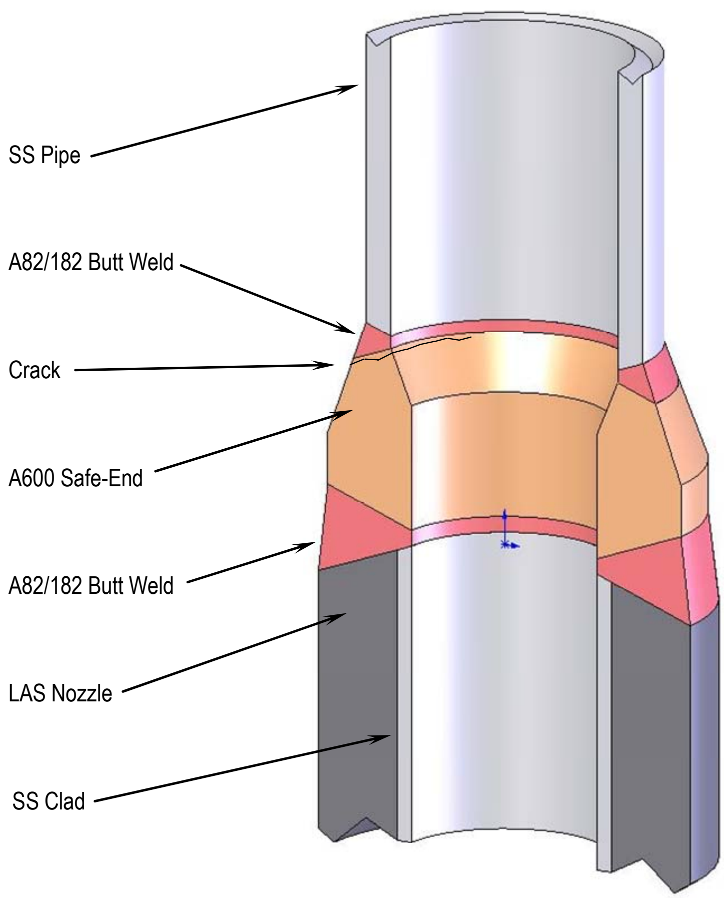
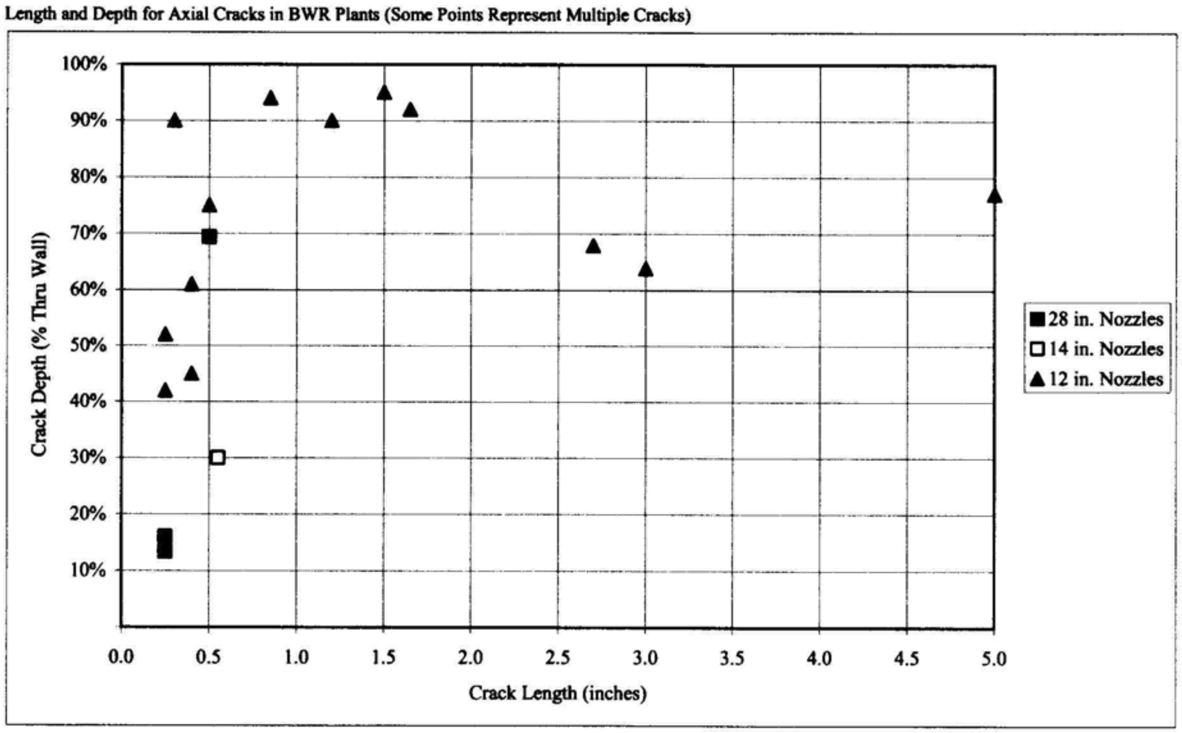


Figure 2-3
Crack Characterization in BWR Plant Alloy 182 Butt Welds



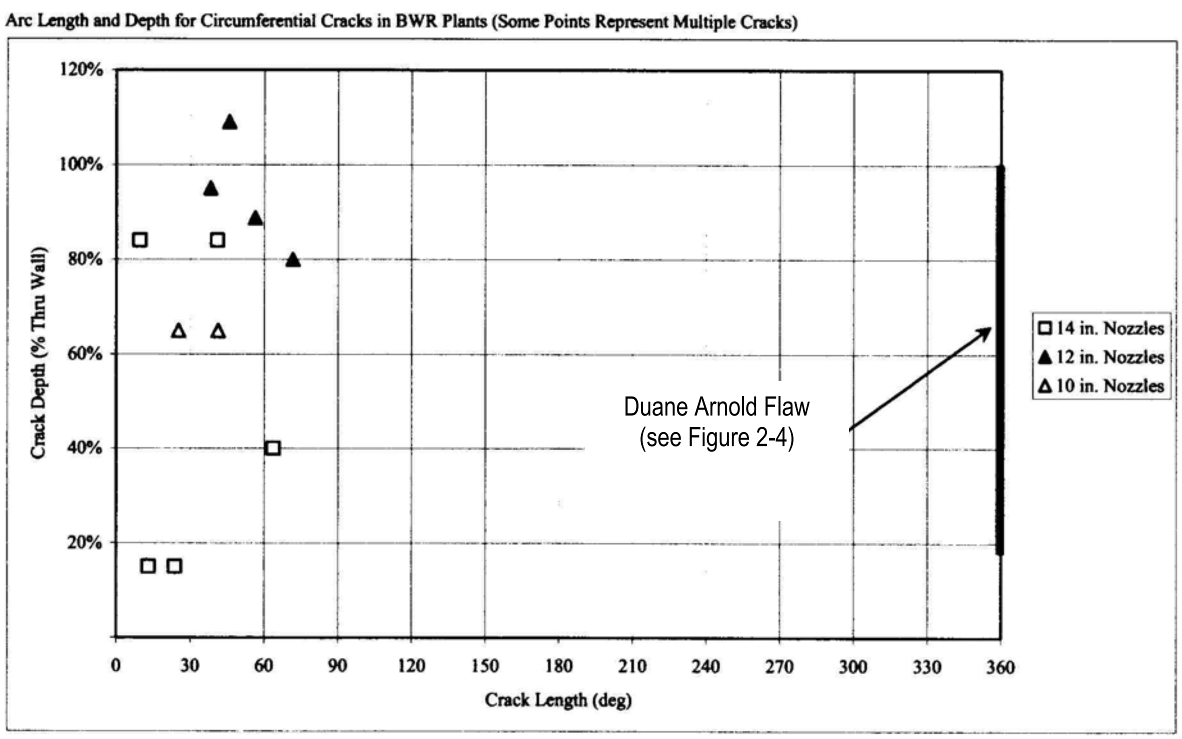
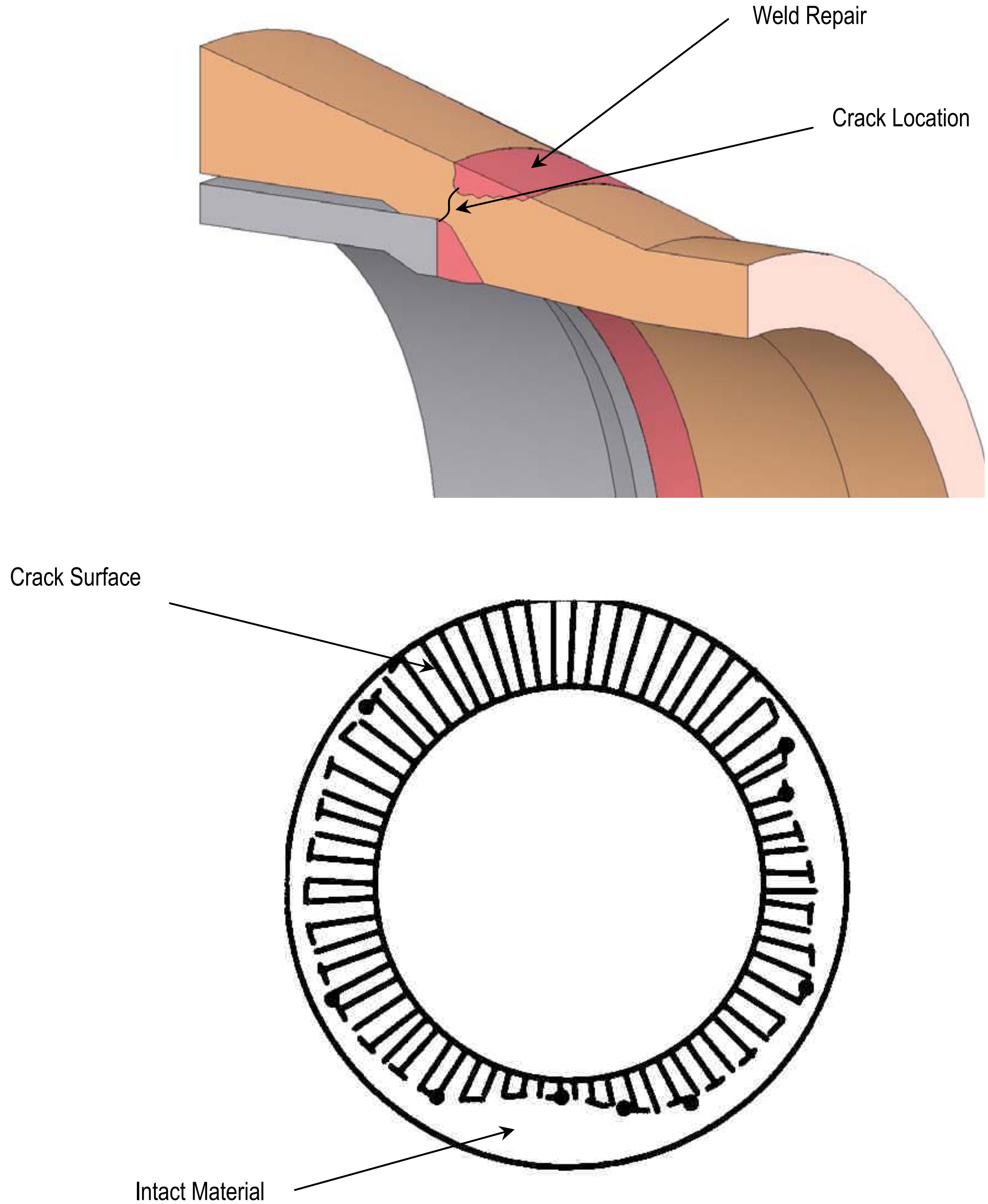


Figure 2-4
360º Flaw at Duane Arnold (not to scale)



3. Review of Wolf Creek Inspection and Root Cause Analysis Findings

The following is a summary of the Wolf Creek inspection findings and comments regarding the cause evaluation. Most of the information has been taken from a letter dated November 29, 2006 [18] from T. J. Garrett (Wolf Creek) to the USNRC providing responses to an NRC request for additional information.

Wolf Creek Butt Weld Configurations

Figures 3-1 and 3-2 are best estimate illustrations of cross sections through the Wolf Creek safety/relief and surge nozzle welds. These figures were created from a general understanding of the joint configuration, photographs of the completed welds, measurements of the completed welds taken to establish the joint configuration, and plots of UT findings reported to the NRC [18].

An interesting feature that may have affected the potential for PWSCC in the surge nozzle is the surge nozzle safe-end fill in weld which is Alloy 182 material deposited after welding the safe-end to the nozzle.

The spray nozzle has a thermal sleeve but it does not have Alloy 82/182 build-up under the safe-end to nozzle weld as noted for the surge nozzle. The other Wolf Creek pressurizer nozzles do not have thermal sleeves.

Summary of Wolf Creek Inspection Findings

Prior to performing scheduled full structural weld overlays during the fall 2006 refueling outage Wolf Creek performed ultrasonic inspections of the six Alloy 82/182 pressurizer nozzle butt welds.

The manual UT procedure and inspection personnel were qualified in accordance with ASME Code, Section XI, Appendix VIII, Supplement 10 and PDI requirements and the surface conditions were such that the inspection could achieve 90% coverage for both axial and circumferential flaws. The procedure was qualified for detection and length sizing of circumferential flaws and the detection of axially oriented flaws located in the base metal or weld. The procedure was not qualified for depth sizing in either the circumferential or axial directions. Personnel performing the examinations were qualified for detection only. While not qualified per PDI requirements, informational sizing was performed to provide an approximation of indication length and depth. The examination techniques applied to estimate the through-wall extent of the indications were capable of detecting the presence of flaw indications throughout the examination volume.

All five top head nozzle welds and the bottom head surge nozzle were examined. No indications were found in the Spray, Safety A and Safety B nozzle welds. The indications found in the Safety C, Relief, and Surge nozzle welds are summarized in Table 3-1 and Figure 3-1 and were characterized as branched with multiple facets. No indications were found in the adjacent stainless steel butt welds. It is especially interesting to note that the reported maximum depths of four of the five indications fall in the range of 23-31%. This apparent uniformity would be statistically improbable for rapidly growing cracks in nozzles after about 18 full power years of operation. Several possible explanations for the apparent uniformity of indication depth are provided later in this section and in Section 5 of this report.

An independent review of the findings, including hands-on examination, was performed by personnel from the EPRI NDE Center. The review concurred with the observation of the original examiner that the reflector responses were consistent with the presence of flaws. The reviewer also confirmed that the transducers used for previous inspections in 1993 and 2000 were unlikely to have found the current indications.

Results of Prior Inspections
The pressurizer surge nozzle butt weld was last inspected in 1993 and the five top head nozzle butt welds were last inspected in 2000. None of these inspections showed reportable indications. However, the inspections in 1993 and 2000 were performed prior to the ASME Code, Section XI, Appendix VIII, Supplement 10 and PDI requirements coming into force. Industry experience suggests that these examinations may not have been capable of detecting the current indications.

Fabrication Records and Weld Repairs
Detailed shop fabrication records were not available to Wolf Creek at the time of their causal evaluation and will be discussed later in this section. However, the final acceptance radiographs for the nozzles with detected flaw indications were retrieved, digitized and enhanced for use in the causal evaluation. These radiographs were reviewed along with the original reader sheets to determine if there were any fabrication flaws or weld repairs in the areas of the current indications. Results of this review are shown in Figure 3-1 and are summarized as follows:

- Safety C Nozzle: There were no reported repairs. However, there may have been in-process repairs prior to submittal for final acceptance radiography.
- Relief Nozzle: There were a number of repairs to the weld and buttering. As shown in Figure 3-1 there is some overlap of the repaired region and the large circumferential flaw indication. The maximum depth of the flaw was recorded in the overlap region between the repaired area and the flaw indication.
- Surge Nozzle: There were repairs to the surge nozzle weld and buttering. However, the reference point for the radiograph locations no longer exists such that it is not possible to correlate the repair locations with the locations of the current indications.

Probable Cause of Indications Identified by Wolf Creek
Wolf Creek was not able to establish a positive root cause. This is because no metallurgical samples were taken to permit laboratory examination. Because of the inside diameter location, characterization of the flaws (origin, depth and location), and likely damage to the surge nozzle thermal sleeve, WCNOC concluded that obtaining samples for laboratory analysis was impractical. Plans had been made prior to the outage to perform full structural weld overlays of all six pressurizer nozzles and this was accomplished without removing specimens.

As documented in the letter to the NRC, Wolf Creek identified several possible causes for the indications. These possible causes and conclusions reached are as follows:

- PWSCC: PWSCC is the only one of the possible mechanisms that is unique to Alloy 82/182 nozzle butt welds. The cracks must initiate at the wetted inside surface and propagate outward through the weld. PWSCC is also the only one of the possible mechanisms that can produce cracks characterized as branched with multiple facets. One factor that is not consistent with PWSCC is that most cracks in Alloy 82/182 butt welds to date have been axially oriented such as occurred at the VC Summer reactor vessel outlet nozzle and Tsuruga 2 pressurizer butt weld leaks. However, the possibility of circumferential cracks has been recognized and was evaluated in MRP-113 [14].
- Fatigue: Fatigue cracks are most likely to occur at the outside surface of the smallest diameter cross section with the greatest stress concentration. Further, the safety and relief nozzles at the top of the pressurizer are not exposed to significant fatigue loading. Finally, fatigue cracks would not be branched or multi-faceted in the manner reported for the Wolf Creek indications.
- Fabrication Defects: Fabrication defects, or false reflectors from repair excavations or some ID anomaly, including defects associated with weld repairs, are a potential source of the reported indications. Defects of this type are most likely to be associated with the root pass which is the most difficult to perform. However, the completed welds were radiographed and, as noted in the previous section, the enhanced radiographs do not show fabrication related defects consistent with the reported indications.
- Weld Repairs: Experience at VC Summer and Tsuruga 2, and analysis work in reports MRP-106 and MRP-114 have confirmed that weld repairs have the potential to create high tensile hoop and axial stresses on the wetted inside surface of Alloy 82/182 butt welds. Further, fabrication radiographs confirm that weld repairs were made to the relief and surge nozzle welds. While there is no direct evidence that repairs were made to the Safety C weld, it is quite possible that in-process weld repairs were made before submitting the nozzle for final radiography. In-process repairs are not necessarily reported.

Based on the available evidence, Wolf Creek concluded that the most probable cause of the indications is PWSCC resulting from high stresses caused by weld repairs.

Subsequent Information Regarding Wolf Creek Pressurizer Weld Repairs

On December 15, 2006 Westinghouse completed a review of the Wolf Creek pressurizer fabrication records to identify the types of repairs that were made to the subject Alloy 82/182 butt welds [19]. This document described a process of cross checking design and fabrication information including design drawings, weld procedures, material specifications, engineering changes made during the fabrication process, quality assurance records, and fabrication records such as weld logs and shop travelers. Table 3-1 is a brief summary of the major repairs reported. Further details are provided in the referenced report. The most significant points regarding the recent inspection findings are as follows:

- The pressurizer surge nozzle was subjected to repair activities after the pressurizer was completed, sealed, and installed on the rail car for shipment to the site. Specifically, it was discovered that a minor repair weld to the nozzle SS clad had not been PT inspected after post weld heat treatment (PWHT). As a result, the pressurizer was opened up, the thermal sleeve removed by grinding, the cladding was inspected, and then the thermal sleeve was reinstalled using A82 weld metal.

- There were many weld indications in the relief nozzle buttering which required repeat repair cycles, including some to the ID surface.
- There were several repairs to the ID surface of the Safety Nozzle "A" and "B" safe end butt welds confirming that repairs were made to the ID of nozzles down to 6 inch NPS.

It is interesting to note that repairs are reported to the Spray Nozzle welds and Safety Nozzle A and B welds where no indications were discovered, and no repairs were reported for the Safety Nozzle C welds where indications were discovered. This indicates that the repairs are not the sole cause of the indications detected unless some in-process repairs were not reported.

Conclusions Regarding Probable Cause of Wolf Creek Indications

While there are a number of potential causes for the observed indications, none can be directly proven. Given the available evidence, and the lack of metallurgical specimens, the indications have been treated as though they are PWSCC flaws.

Table 3-1
Summary of Major Repairs to Wolf Creek Pressurizer Butt Welds [19]

Defect Location and Description	Repair Description
Surge Nozzle Welds	
1. Not enough weld build-up on buttering	A182 added
2. During Repair #1 RT found (2) OD indications	Indications removed, repaired with A182, PT
3. Safe end RT showed (1) ID flaw 0.20/0.44	Indication removed, repaired with A82, PT/RT
4. Cuts made in surge nozzle SS clad to check thickness	Cuts repaired with 308L and inspected
5. With completed PZR on rail car it was discovered that Repair #4 had not been PT inspected after PWHT	Unpacked PZR, thermal sleeve removed by grinding, Repair #4 weld removed/inspected/rewelded with 308L & 309L, local PWHT, PT of repair, and thermal sleeve reinstalled by A82 weld
Spray Nozzle Welds	
6. PT indications found on build-up prior to PWHT	Indications removed, repaired with A82, PT
Safety Nozzle "A"	
7. Butter grindouts to 1/8" needed to clear PT	Repaired with A182, PWHT, PT
8. Safe end RT showed (2) ID flaws 0.34/1.25, 0.34/0.875	Indications removed, repaired with A82, PT/RT
Safety Nozzle "B"	
9. Safe end RT showed (6) ID flaws 0.5/1.0 to 0.75/2.5	Indications removed, repaired with A82, PT/RT
10. Repair #9 did not include proper cleaning step	Repairs #9 removed, repaired with A82, PT/RT
11. SS safe end ID too large	Added 308L to ID, machined, PT
Relief Nozzle	
12. Butter grindouts needed to clear PT	Repaired with A82/182, PWHT, PT
13. Butter and clad RT showed (1) ID flaw 0.44/0.5 and (1) OD flaw 0.44/1.0	Indications removed, repaired with A82, PWHT, PT/RT
14. Additional butter OD flaw (1) 0.75/1.0	Indication removed, failed RT, additional material removed, repaired with A182, PT/RT, PWHT
15. Additional butter ID flaws (3) 0.75/0.75 to 0.75/2.25	Indications removed, repaired with A82
16. Additional butter OD flaws after PWHT 0.75/0.5 to 0.75/2.25	Indications removed, repaired with A82, PT
17. ID of butter and cladding damaged during Repair #16. PT of damaged area showed ID indications	Clad weld repaired with A82, ground to clean up surface, PT
18. Safe end RT showed (1) OD flaw 0.5/1.25	Indication removed, weld repaired with A82,PT/RT
19. Safe end RT showed (1) ID flaw 0.5/0.5	Indication removed, weld repaired with A82, PT/RT
20. Safe end ID exceeded drawing maximum	Applied 308L buildup, machined, PT
21. PT after PWHT and hydro showed ID indications 1.88" long, 2.38" wide and 0.50" deep	Indication removed, weld repaired with A82,PT

Notes:
(1) Sequence numbers agree with Reference Repair Numbers in Westinghouse evaluation.
(2) See complete Westinghouse evaluation for further details.
(3) Code for flaws is Depth / Length.

Figure 3-1
Best Estimate Cross Section Through Wolf Creek Safety/Relief Nozzle Weld (not to scale)

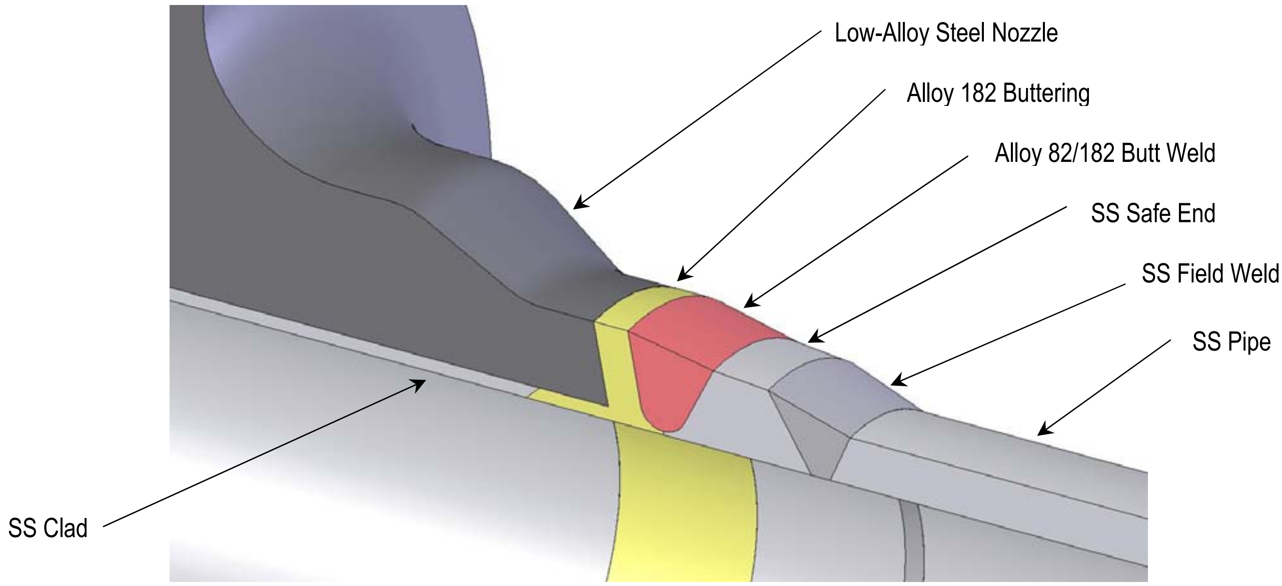


Figure 3-2
Best Estimate Cross Section Through Wolf Creek Surge Nozzle Weld

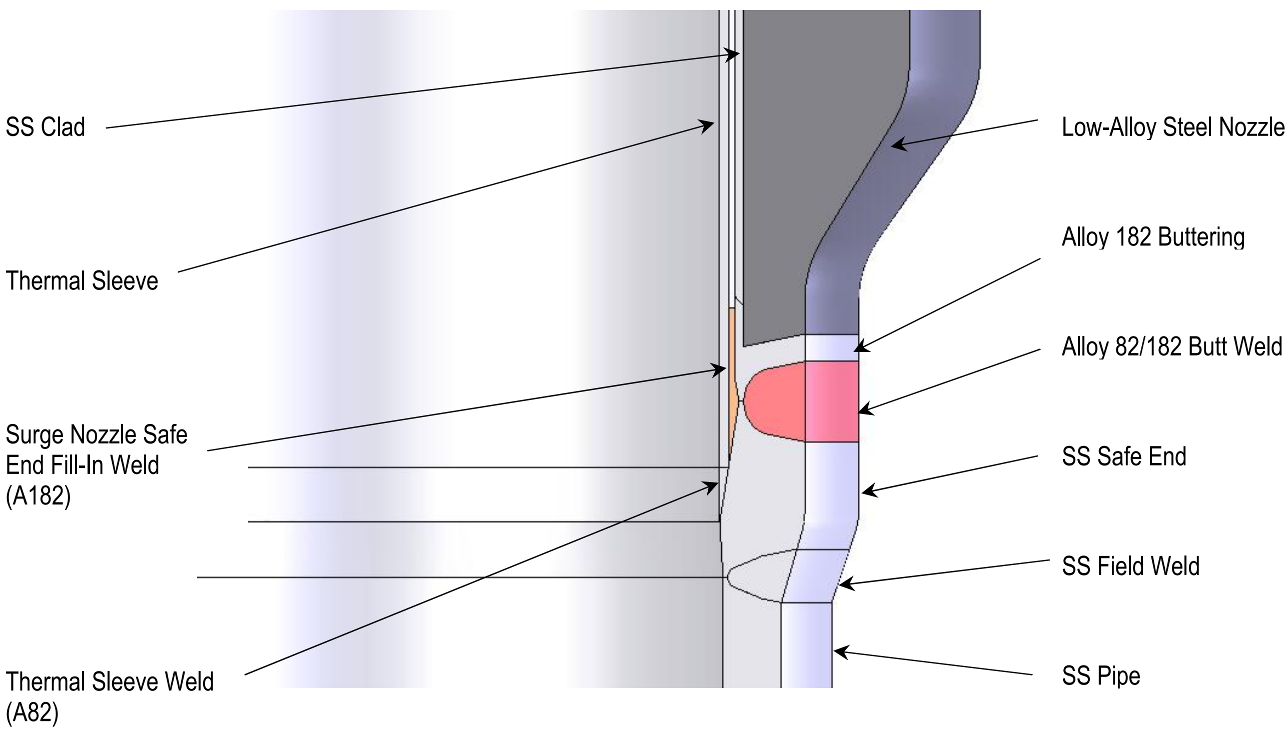


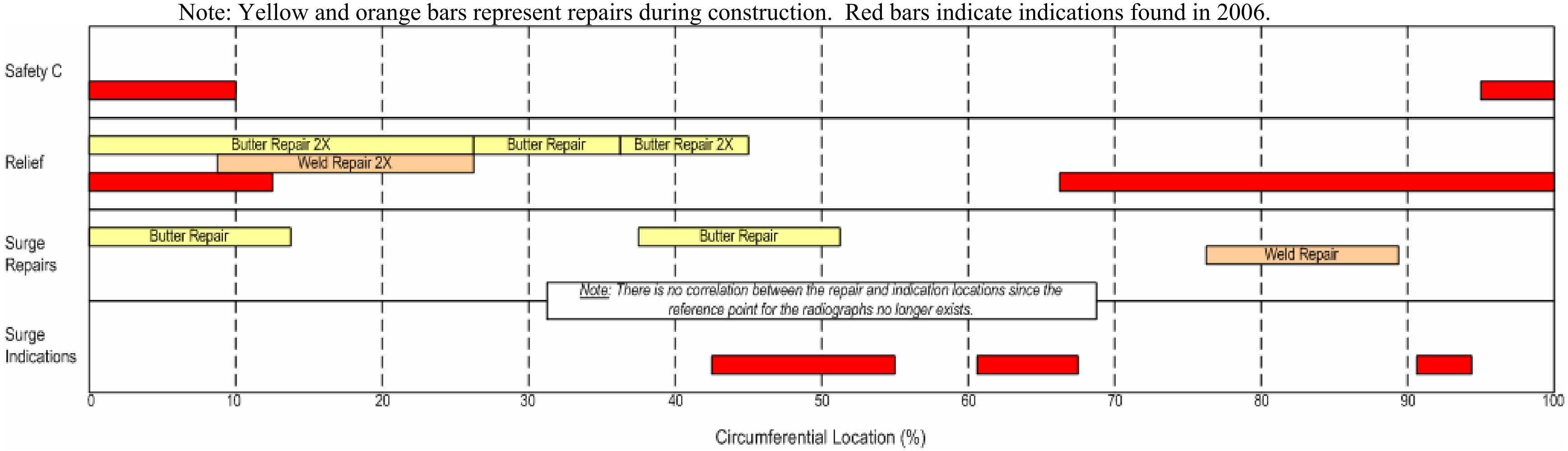
Table 3-1: Summary of Wolf Creek 2006 Indications during Plant Construction

Nozzle	Circumference (in)	Outside Diameter (in)	Thickness (in)	Inside Diameter (in)	2006 Indications OD Lemgth (inches)	Arc Length (2) (deg)	Average Depth (1) (%)	Depth (in)	Aspect Ratio (3)	Area Lost (%)
Safety C	25.0	7.96	1.32	5.32	3.75	54	23	0.30	8	3.5
Relief	25.0	7.96	1.32	5.32	11.50	166	26	0.34	22	12.0
Surge	47.0	14.96	1.45	12.06	1.00	8	<10 (4)	---	---	---
	47.0	14.96	1.45	12.06	2.75	21	25	0.36	6	1.5
	47.0	14.96	1.45	12.06	5.00	38	31	0.45	9	3.3
				Surge Nozzle Totals =>	8.75	67				4.8

[Yellow box] Highlighted data represents values reported to the NRC by Wolf Creek. Other values are calculated by geometry.
(1) Average depth from 45 and 60 degree UT probe angles.
(2) Calculated from OD length and circumference.
(3) Calculated from ID arc length and depth.
(4) Indication found but no measurable depth could be determined.

Figure 3-3: Summary of Wolf Creek 2006 Indications Relative to Weld Repairs

Note: Yellow and orange bars represent repairs during construction. Red bars indicate indications found in 2006.



4. Predicted Growth of Wolf Creek Flaws without Mitigation

The following is a summary of work performed during December 2006 to develop a better understanding of how the Wolf Creek cracks ended up at the size they were at the time of detection and how they might have grown in the future if they had not been mitigated by the structural weld overlays. A key question of interest is why all of the cracks are of similar depth after about 18 full power years of operation if they were all growing rapidly at the time of detection?

NRC Calculations Reported at November 30, 2006 Technical Meeting

On November 30, the NRC staff presented the results of crack growth calculations investigating past and hypothetical future growth of circumferential indications that were reported in three of the Wolf Creek pressurizer nozzle-to-safe-end dissimilar metal welds [20]. Because of limited time for crack growth calculations to be performed, the NRC reported that the calculations reflected some conservative assumptions.

A review of the NRC analysis showed several possible conservatisms:

- First, the NRC calculations assumed initially supplied dimensions of the nozzle weld that result in higher stresses than would result from the final dimensions provided in the Wolf Creek response to the NRC request for additional information.
- Second, the NRC calculations conservatively assume that the axial end-cap pressure load on the end of the nozzle is calculated using the outside diameter at the weld. In fact the pressure only acts on the inside diameter and this reduces the applied axial force.
- Third, the NRC has conservatively assumed linear elastic superposition of stresses which results in peak stresses at the inside surface above the material yield strength. This conservatism will be addressed later in this section.
- Fourth, NRC has conservatively assumed that welding residual stresses are not modified by the growth of cracks.

The need to make conservative assumptions is understood realizing the extremely short time available to perform calculations, and that information needed for more refined calculations was not immediately available.

Independent MRP Calculations to Assess Crack Growth around Full 360º Circumference

Independent elastic superposition fracture mechanics calculations were performed for the case where a shallow (5% through-wall) 360º circumferential flaw has initiated on the inside surface of the butt weld by some mechanism. The objective of this work was to determine the likely propagation of the assumed initial flaw to assess the potential for deep 360º flaws to develop which could lead to sudden rupture with no advance warning by a leak from a through-wall crack. These calculations included several of the same conservatisms made by the NRC including use of linear superposition of stresses, and not considering the effect of residual stress relaxation with crack growth.

The through-wall welding residual stress distribution was assumed to be the same as reported by the NRC and shown in Figure 4-1. This residual stress distribution for Alloy 182 weld metal with a yield strength of 54 ksi was scaled up from test data for stainless steel welds shown in Figure 4-2. The nozzles were also assumed loaded by 2,235 psi internal pressure and operating pipe reaction loads. Pipe axial and moment loads on the relief nozzles were 5.41 kips and 277 kip-inches. Pipe axial and moment loads on the surge nozzles were -3.31 kips and 1,638 kip-inches respectively. These are the same pipe loads that were assumed by the NRC.

The MRP fracture mechanics calculation results shown in Figures 4-3, 4-4 and 4-5 were calculated using the following approach.

- Through-Wall Stress Distributions
  Figure 4-3 shows the through-wall stress distributions for the relief and surge nozzles. The stresses shown are the sum of the residual stresses in Figure 4-1, the pressure end-cap load stress based on thick-wall model, the pipe axial load stress, and the pipe bending stress. Results are plotted for locations ranging from +90º (most tensile bending stress) to -90º (most compressive bending stress). A constant pressure stress of 2,235 psi is also applied to the wall thickness to account for pressure acting on the crack face. These data show that the stresses vary significantly through the wall thickness and around the circumference.

- Stress Intensity Factors
  Stress intensity factors were determined using influence functions for complete circumferential cracks in pipes contained in the SmartCrack software [21]. The influence functions are combined with the stresses to obtain the stress intensity factors by numerical integration, which is performed directly by the SmartCrack software. The influence functions are included in the NASA FLAGRO software [22] as model SC06. The solution is applicable to cylinders with *OD/t* from 2.2 to 2000 (R_I/t from 0.1 to 1000), and are based on information discussed in Reference [23]. Values of *a/t* from 0.02 to beyond 0.9 are included. The FLAGRO software was run for a wide variety of R_I/h and *a/t*, for stresses that varied as x^n, where *x* is the distance from the inner pipe wall. Values of *n* from 0 through 6 were considered. This provided a large set of "data" from which coefficients in the functional form of the influence function used in Reference [24] were evaluated. These coefficients define the influence function for a given R_I/t, and are contained in the SmartCrack software. The crack was taken to be an interior surface crack that conservatively extended completely around the circumference and was subjected to axisymmetric stresses equal to those provided for the angular location being analyzed. Figure 4-4 shows the stress intensity factors through the thickness and at 30º increments around the circumference for the relief and surge nozzles. It is important to note that the stress intensity factors are high at the inside surface at all locations but decrease significantly approaching mid-wall. In many cases, the stress intensity factors approach zero or go negative approaching mid-wall. The stress intensity factors obtained from the SmartCrack software are compared to those obtained from the solution of Cheng and Finnie [25] which was used in BWRVIP-14-A [26] to determine the K solutions for the BWR shroud vertical welds. Similar to the K solution in References [22, 23, 24], Cheng and Finnie K solutions cover a very wide range of R/t ratios, from 1 to 500. The comparison of the K solution from SmartCrack and that of Cheng and Finnie is shown

in Figure 4-5. As can be seen from this figure, the comparison is very good providing confidence in the K solutions.

- Crack Growth Calculations
  Crack growth was calculated using the deterministic curve for Alloy 182 welds from MRP-115 that was established with the input of a panel of international experts including representatives from the NRC and NRC contractors. This curve has no stress intensity factor threshold so cracks are predicted to grow as long as the stress intensity factor remains positive. If the stress intensity factor drops below zero, cracks will arrest. Figure 4-6 shows results of crack growth calculations using this approach for both the relief and surge nozzles.

Several observations can be made from these results:

- The time for a 30% through-wall crack to grow through-wall at the side of the nozzle with the highest bending tensile stress ranges from about 1.5 years for the surge nozzle to about 6 years for the relief nozzle.
- At locations of lower axial stress, such as over the 120-180º opposite to the point of highest bending tensile stress, the cracks are predicted to arrest somewhere between 40 and 60% through wall. This result points out the sensitivity of these calculations to relatively small differences in applied stress.
- The results appear to predict the same basic type of behavior that was observed at Duane Arnold (see Figure 2-4) where the crack broke through on one side, probably due in part to tensile bending stresses, and remained at shallow depth 180º opposite.

Obviously, local conditions such as deep weld repairs could also contribute to a crack breaking through to the outside surface, but as reported in MRP-114, this would only be expected to occur over the arc length of the weld repair.

Conservatism in Linear Superposition Models under High Residual Stresses
Both the NRC and MRP calculations reported above have been based on linear superposition of stresses to create a third order polynomial fit to the through-wall stress distribution. However, if the welding residual stress alone is at tensile yield strength on the inside surface, superimposing additional tensile stress terms will result in assumed stresses above the material tensile yield strength. This, in turn, will result in conservatively high crack stress intensity factors and crack growth rates. This effect was explored during the early 1980's and the potential conservatism is summarized in NUREG-1061, Volume 1 [27]. Figure 4-7 shows a plot from NUREG-1061 which shows the effect of elastic-plastic behavior in limiting the peak stress for the case of a welding residual stress distribution similar to that assumed by the NRC and MRP and an axial tensile stress of 18 ksi.

Conclusions
In summary, the work in this section suggests that:

- Conservative calculations by the NRC and MRP show that cracks can grow from 30% through-wall to produce a leak at locations of high bending or weld repair stresses in a few years using the deterministic crack growth model for Alloy 182 weld metal from MRP-115. Note that these conclusions are essentially identical to the reported times (1.1-

4.1 years) from initiation to leakage reported for Westinghouse pressurizer nozzle butt welds in the MRP-113 safety assessment.

- Growth of deep 360º circumferential flaws is unlikely in the presence of pipe bending moments.
- Under conditions of applied pipe bending loads, shallow 360º flaws would be expected to grow through wall on one side and grow at a much slower rate on the opposite side producing the same basic type of crack profile as exhibited at Duane Arnold even though the initiating mechanism for the 360º crack would be completely different
- If the applied stresses at Wolf Creek are lower than assumed in the NRC and MRP analyses due to lower than reported piping loads, lower than assumed residual stresses, or shakedown of stresses during hydro test or initial operating cycles, the data suggest the possibility of cracks arresting near mid wall thickness. This may explain why 4 of the 5 Wolf Creek indications were detected at 23-31% depth after 18 years of operation. The Wolf Creek results would clearly not be expected for the case of rapidly growing cracks.

Figure 4-1
Welding Residual Stress Distribution Assumption of NRC Crack Growth Calculation for Wolf Creek Relief Nozzle Based on ASME Published Data

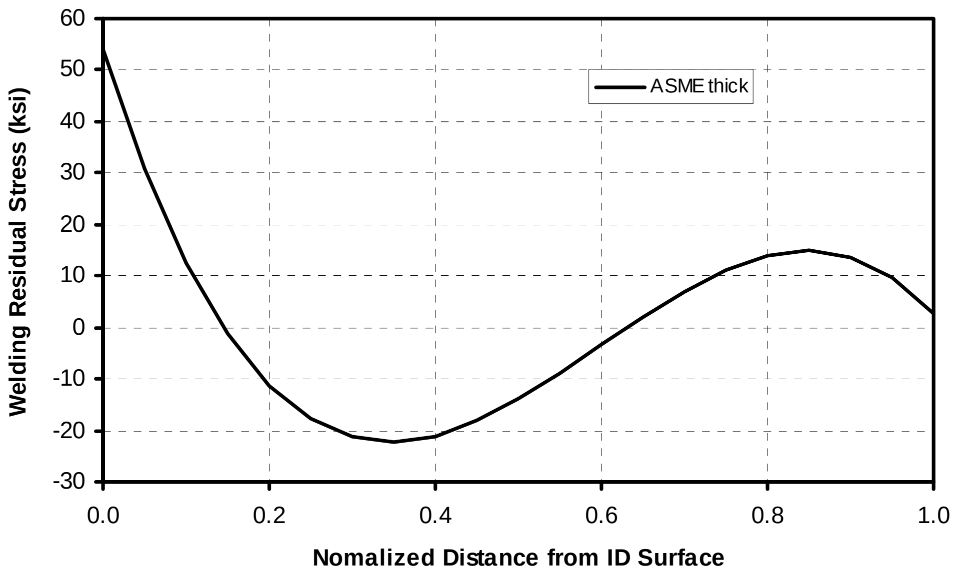


Figure 4-2
ASME Welding Residual Stress Distributions: (a) Figure from NUREG-0313 [28], and (b) ASME figure [29]

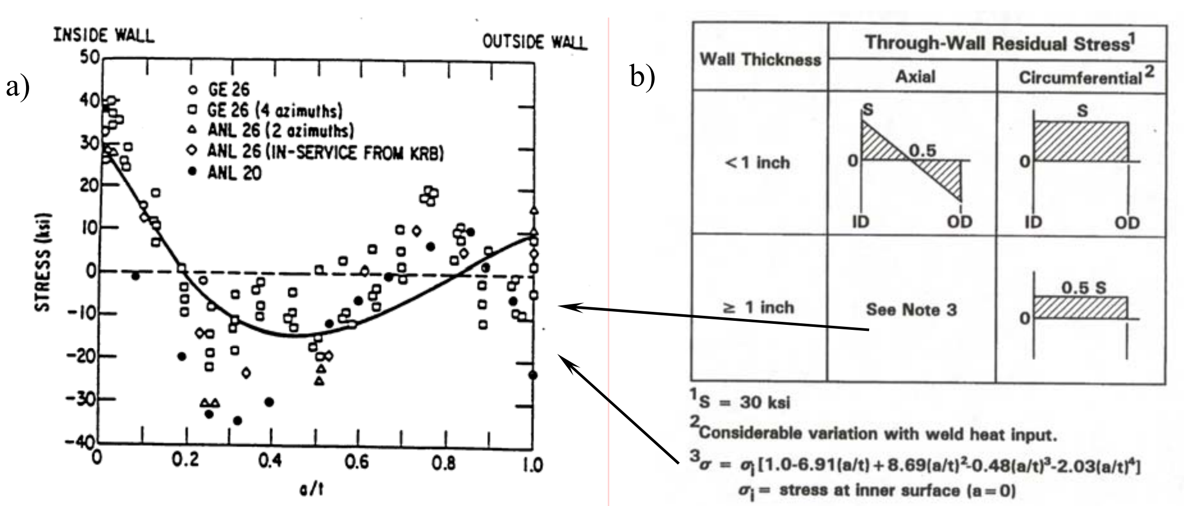
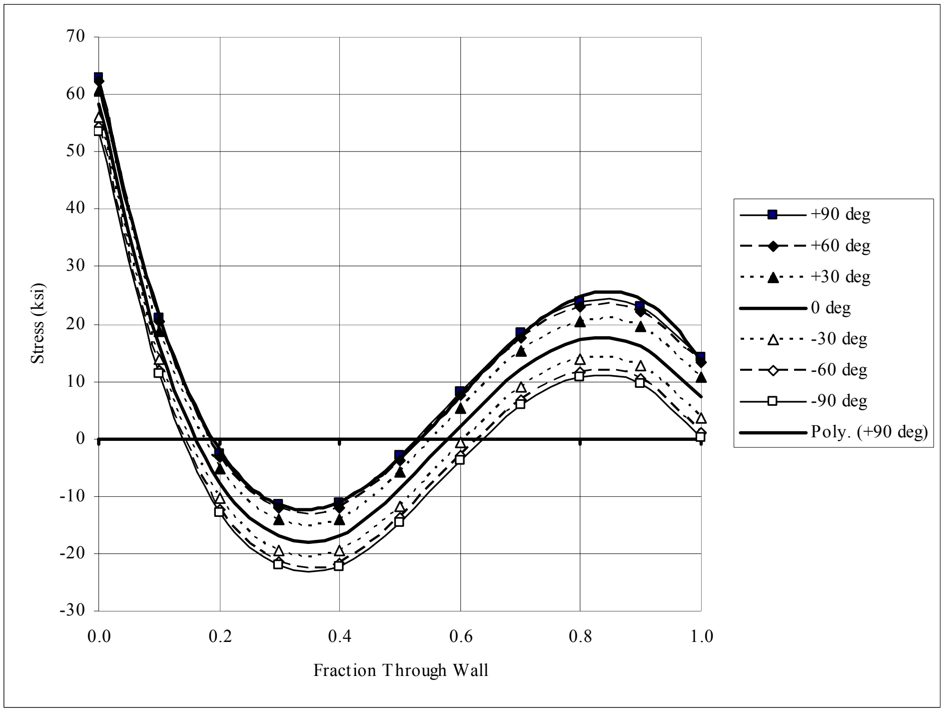


Figure 4-3
Assumed Through Wall Stress Distributions (Residual + Pressure + Pipe Force + Pipe Moment)

Relief Nozzle Stress Distributions



Surge Nozzle Stress Distributions

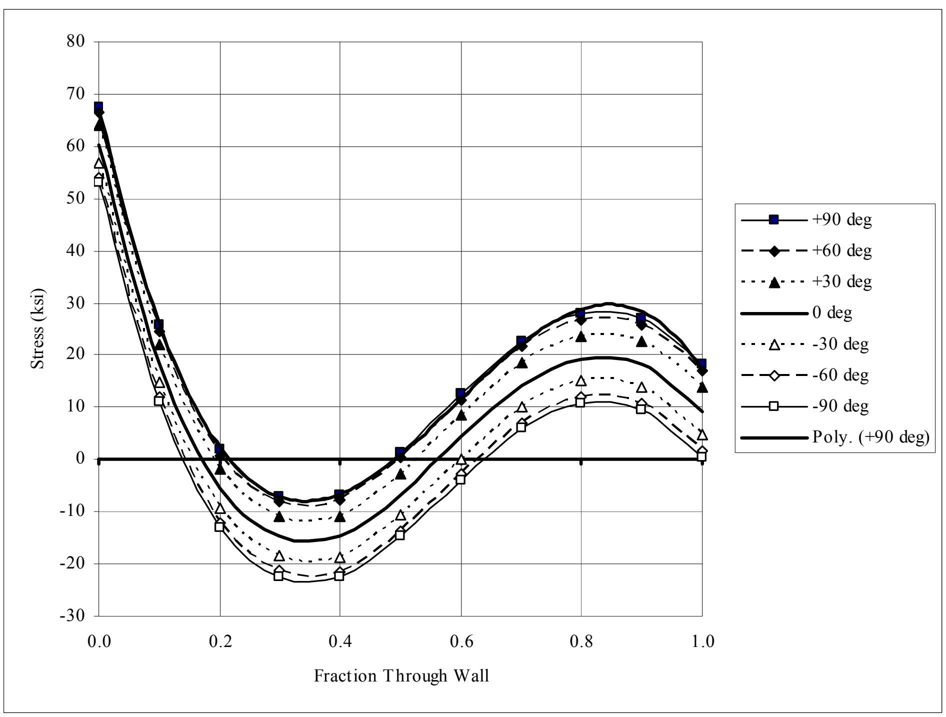
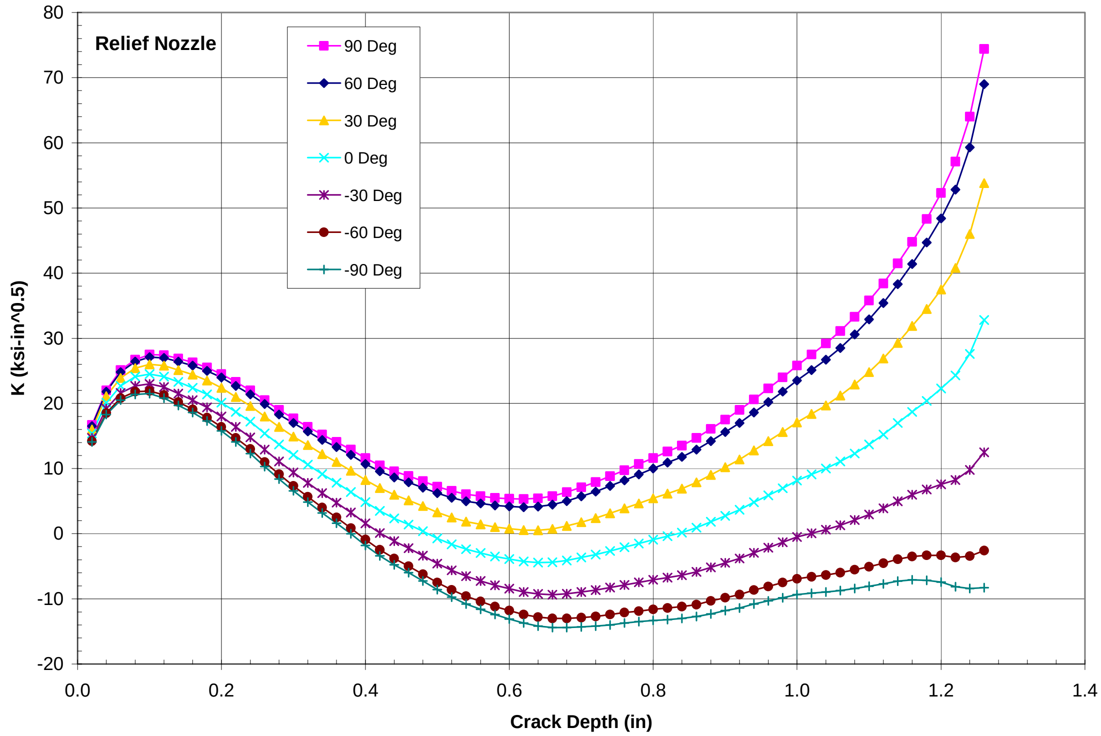


Figure 4-4
Stress Intensity Factors



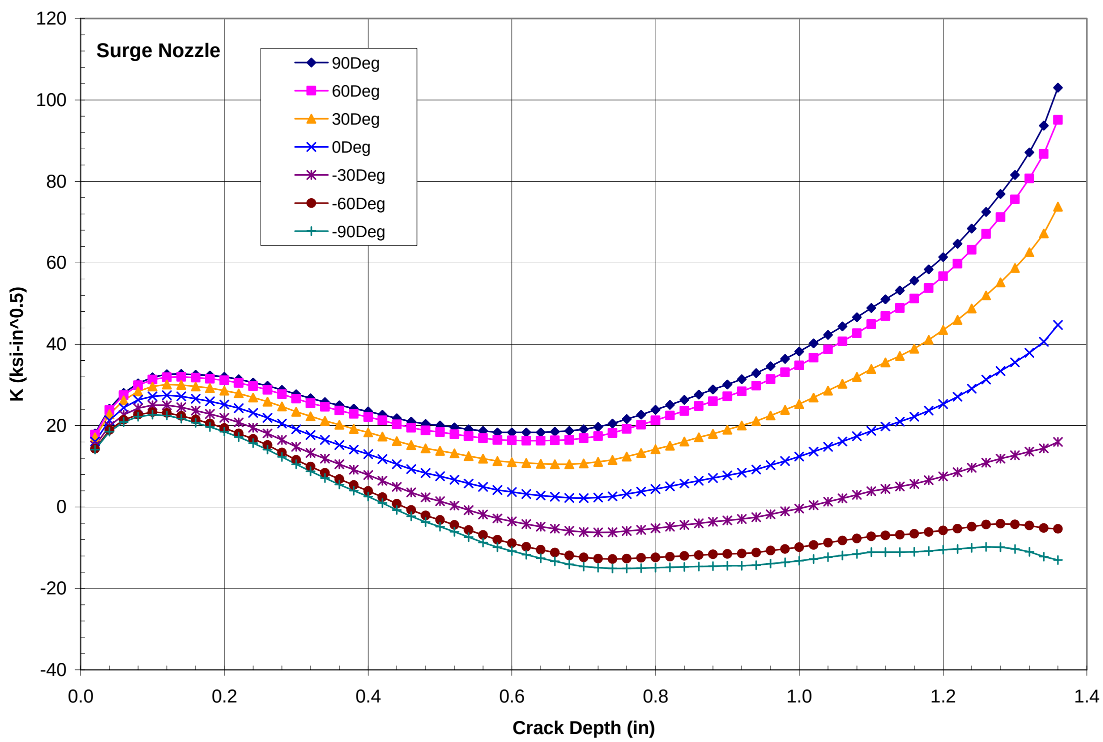


Figure 4-5
Comparison of Relief Nozzle Stress Intensity Factor Results from SmartCrack with the Solution of Cheng and Finnie

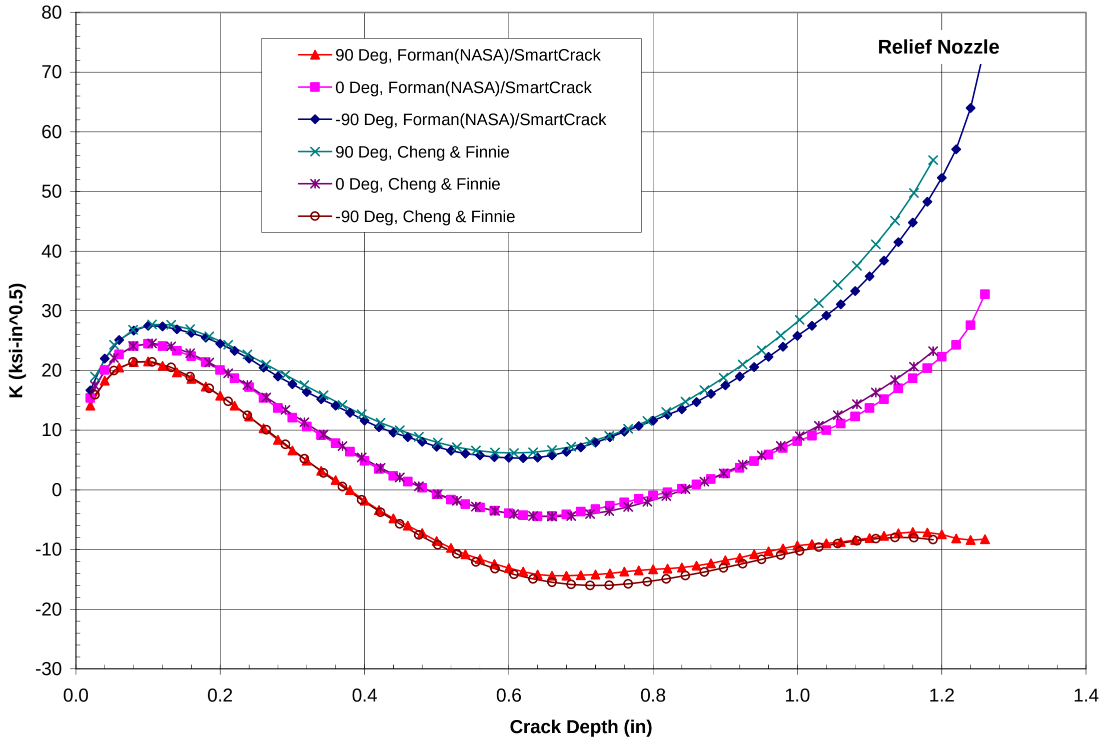
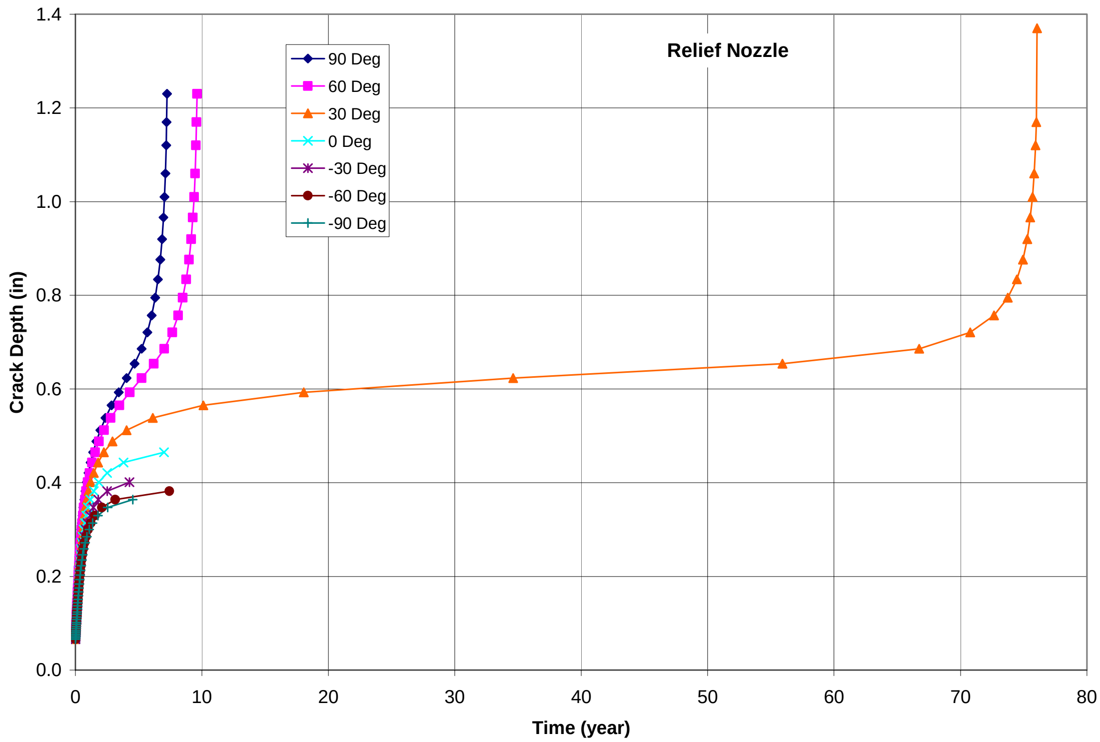


Figure 4-6
Crack Growth Calculations



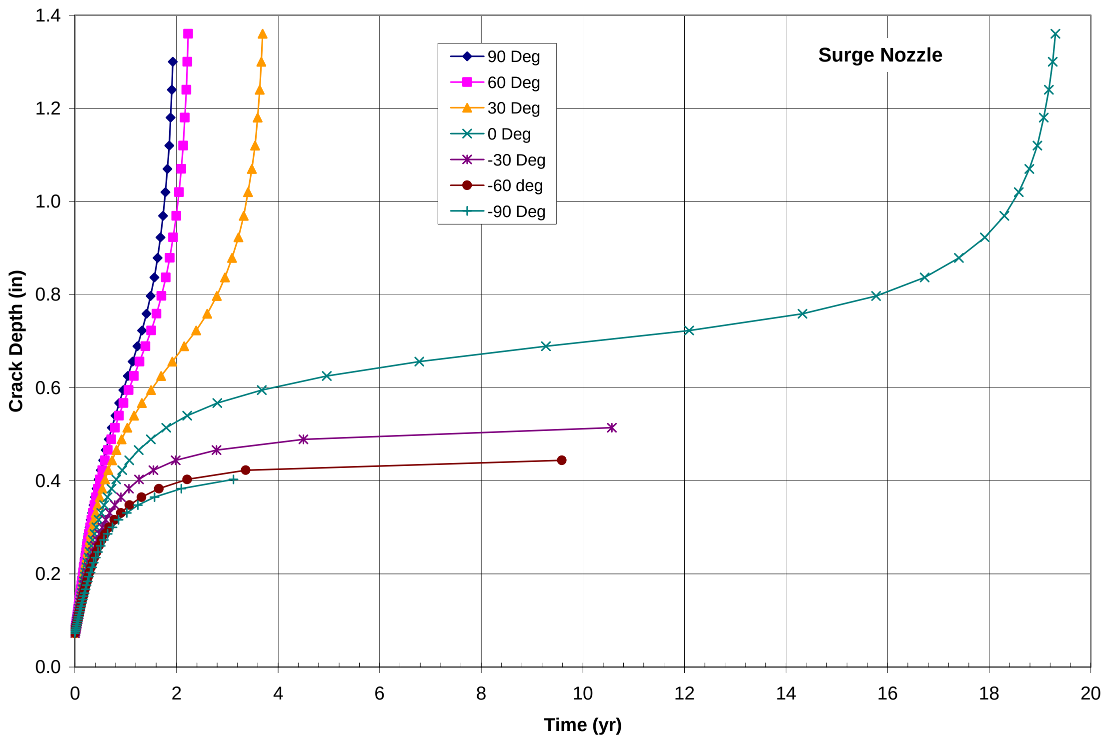


Figure 4-7
Effect of Elastic-Plastic Behavior in Redistribution of Applied welding Residual and Operating Stresses [27]

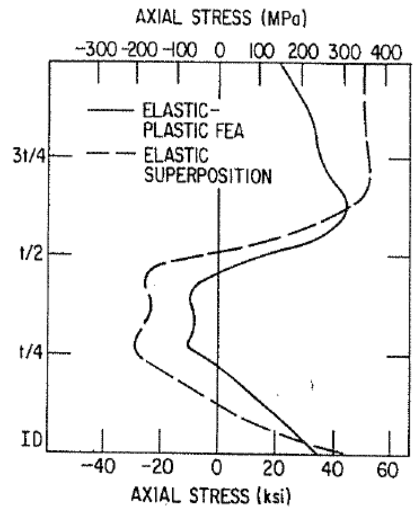


Figure 6.6 Comparison of elastic-plastic solutions for throughwall axial stresses with simple elastic superposition, 18-ksi applied load.

5. Review and Refinement of NRC Crack Growth Calculation for Relief Nozzle

On November 30, the NRC staff presented the results of crack growth calculations investigating past and hypothetical future growth of the circumferential indications that were reported in three of the Wolf Creek pressurizer nozzle-to-safe-end dissimilar metal welds, assuming mitigation was not applied [20]. Recently MRP supported crack growth calculations using a finite element analysis (FEA) approach to calculate stress intensity factors for comparison with the crack growth time results presented by the NRC. The advantage of the FEA approach is that it could be applied to the actual low radius-to-thickness ratio (Ri/t = 2.00) for the Wolf Creek relief nozzle dissimilar metal weld versus extrapolation of available stress intensity factor correlations for higher Ri/t ratios. The FEA approach was also used to consider the potential effect of redistribution and relaxation of welding residual stress with crack growth, which is not possible through use of standard stress intensity factor correlations based on the superposition principle. The circumferential indication reported for the Wolf Creek relief nozzle was the largest indication reported relative to the weld cross sectional area.

Purpose and Assumptions of MRP Crack Growth Calculation

The purpose of the MRP calculation is to evaluate the effect of the following two assumptions in the NRC calculations for the relief nozzle:

- The NRC calculations were reported to be based on a stress intensity factor correlation developed by Anderson [30] for which the smallest covered Ri/t ratio is 3. In addition, for Ri/t of 3, the largest covered c/a ratio is 8. Extrapolation of the Anderson results to a geometry outside of the covered range necessarily results in some uncertainty in the predicted stress intensity factor.

- Standard stress intensity factor expressions based on the superposition principle for semi-elliptical part-depth and for through-wall circumferential flaws in a cylindrical wall with an arbitrary through-wall axial stress distribution and applied global bending moment were applied in the NRC calculations. This approach does not consider the potential effect of stress redistribution and relaxation on the crack-tip stress intensity factor and time for growth to leakage or rupture.

All other assumptions of the NRC crack growth calculations were maintained in the MRP calculation in order to isolate the effects of these two assumptions. The MRP calculations assumed the same basic loading as the NRC calculation (see Figure 5-1 for resulting stress) and same axisymmetric welding residual stress distribution based on a 54 ksi stress on the inside surface that the NRC assumed (see Figure 5-2). This distribution was developed as part of the NRC calculation based on the “thick-wall” stress data shown in Figure 5-3 from stress measurements performed on BWR piping weld mockups [28, 29]. The MRP crack growth calculation is based on the same basic dimensions and magnitude load assumptions (welding residual stress, deadweight, pressure, and thermal piping expansion) that were input to the NRC calculations for the relief nozzle, and the MRP calculation is also based on the MRP-115 [13] crack growth rate equation for Alloy 182 weld material, applied for an operating temperature of 650°F.

Approach of MRP Crack Growth Calculation

To calculate the stress intensity factor input to the crack growth calculation, a three-dimensional FEA technique was applied that explicitly calculates the effect of the presence of the crack on the stress field. This general procedure has been previously applied to evaluation of crack-tip stress intensity factors for PWR components including CRDM nozzles and pressurizer heater sleeves. A description of this general methodology, including model validation cases, has previously been submitted to the NRC in connection with evaluations of hypothetical circumferential flaws in pressurizer heater sleeves [31]. The inputs to and results of the FEA calculation are discussed below:

- *Dimensions*. The calculation assumed identical basic dimensions as were assumed by the NRC: outside diameter of 7.75 inches and wall thickness of 1.29 inches. These dimensions result in slightly conservative high stresses in comparison with the latest available dimensions reported by Wolf Creek based on recent measurements.

- *Loads*. As discussed above, the DEI calculation assumed identical loading conditions for crack growth as the NRC calculation. The total applied axial force was 52.33 kips (resulting in a 2.00 ksi axial stress) based on deadweight, thermal expansion axial force, and end cap pressure). The total effective global bending moment (M_{eff}) was 277.5 in-kips based on deadweight and piping thermal expansion, with applied torsion (T) acting to increase the effective moment as follows:

$$M_{eff} = \sqrt{M_x^2 + M_y^2 + \left(\frac{\sqrt{3}}{2}T\right)^2} \qquad [5\text{-}1]$$

  The welding residual stress distribution assumed by the NRC was applied in the FEA model as a thermal load. Figure 5-2 shows the good agreement attained between the NRC assumed distribution and the actual distribution attained in the FEA model. Finally, crack face pressure (2.235 ksi) was applied directly on the crack face in the FEA model. It is noted that local thermal expansion stresses due to material mismatch (i.e., Q-stress) were not applied in the model, as is understood to be the case for the NRC calculation. Such stresses must average close to zero across the wall as they must be self-balancing on the overall weld cross section.

- *FEA Model*. The FEA model is illustrated in Figure 5-4. Consistent with the NRC calculation, a basic cylindrical component geometry and semi-elliptical surface crack geometry are assumed to approximate the loading of the flaw located in the relief nozzle dissimilar metal weld. Also, consistent with the NRC calculation, it is conservatively assumed that the center of the crack is aligned with the maximum tensile bending stress location. As shown, the model assumes two symmetry planes. The axial dropoff in the simulated residual stress is shown in Figure 5-5. The thermal load assumed to produce this simulated residual stress profile is applied over a 1.0-inch axial distance in the model, corresponding to a total 2.0-inch axial extent considering the symmetry plane at the crack plane. The stress dropoff shown is conservative given the reported axial extent of the subject weld and buttering. The model loading was explicitly checked to verify that it was as intended.

- *FEA Model Validation*. As a validation step, the model was applied for the parameters described above, but for a larger diameter resulting in a Ri/t ratio of exactly 3. (The applied axial force and global moment were increased to result in the same nominal axial stress values as for the main model.) A semi-elliptical crack geometry was assumed with a crack aspect ratio (2c/a) of 16. This component and crack geometry permitted direct comparison of the calculated stress intensity factor with the result of the Anderson correlation without any extrapolation or interpolation for multiple Anderson cases. As a standard superposition approach, the Anderson correlation does not consider the potential effect of relaxation of localized residual stresses.

  The results of this comparison are shown in Tables 5-1 and 5-2. The comparison in Table 5-1 is based on the residual stress distribution assumed in the NRC calculation. Table 5-2 makes the same comparison but based on the actual attained simulated welding residual stress distribution, which as shown in Figure 5-2 differed slightly from the target distribution. Table 5-2 shows that the FEA technique results in somewhat conservative stress intensity factor values for the surface location, and slightly conservative values for the deepest point location. No effect of relaxation of the simulated residual stress is apparent in these results. Hence, it is concluded that for the modeling assumptions made, residual stress relaxation does not have a significant role in the calculated stress intensity factor. Based on past experience, it is expected that residual stress relaxation would tend to have a significant effect for deep crack growth for circumstances such as high axial tensile residual stress through the wall over a partial arc and with a more limited axial extent of high tensile residual stress. Such circumstances may apply to practical situations reflecting weld repair over a partial arc region of the weld circumference.

- *FEA Model Results*. The results of the main matrix of FEA cases investigated are shown in Table 5-3. The FEA stress intensity factors shown in this table were applied in the crack growth calculation. These results are compared in the table to the predictions of the Anderson correlation, where a second order log-space extrapolation was applied to determine geometry influence coefficients applicable to the relief nozzle weld geometry of Ri/t = 2.004. A greater degree of extrapolation was required for crack aspect ratios (2c/a) greater than 16. Because of these required extrapolations, there is increased uncertainty in the comparison of these FEA results versus the Anderson results. However, the comparison with the Anderson results shows consistent behavior versus the previous comparison in Tables 5-1 and 5-2, with no significant effect of residual stress relaxation apparent.

  Another comparison of FEA results versus predictions using the Anderson superposition results is shown in Figure 5-4. These FEA results were generated with the previously assumed loads but with no simulated welding residual stress applied. The uncharacteristic behavior for case 20 in this table is believed to be due to the relatively high degree of extrapolation required to produce Anderson predictions for 2c/a = 30.

Finally, three additional cases were investigated for a part-depth crack geometry having a uniform depth. These are cases 34, 35, and 36 at the bottom of Table 5-3. These supplemental cases were considered to investigate the effect of the compressive global bending stress on flaw growth on the side of the weld opposite the maximum tensile bending stress location. These cases are discussed under Discussion below.

Results of MRP Crack Growth Calculation

Through interpolation among the FEA cases shown in Table 5-3, the time for growth of the detected relief nozzle indication to through-wall leakage was calculated. In the same manner as for the NRC calculation, the growth in depth was calculated based on the assumption that the flaw aspect ratio changes with growth in the length direction driven by the surface stress intensity factor (K-driven case) and based on the assumption of a constant aspect ratio (constant c/a case[3]). The result of the crack growth calculation is shown in Figure 5-6. Approximately, 4.4 years of growth is required for the relief nozzle indication to reach through-wall in either case. This is about 1.8 years longer than the K-driven NRC case. The reason for this difference remains unexplained at this time because (1) residual stress relaxation effects do not appear to be significant for the particular set of FEA assumptions made and (2) the FEA results appear reliably high versus the extrapolated Anderson results. Note that the time for growth backwards in time to a hypothetical initial flaw depth of 0.040 inches is similar to the corresponding NRC results.

Figures 5-7 and 5-8 show some additional results associated with the crack growth calculation. The development of crack aspect ratio with growth in depth is shown in Figure 5-7, and Figure 5-8 shows the stress intensity factors applied to calculate the crack growth rate based on interpolation of the FEA results. Note that because of the nonlinear nature of the MRP-115 crack growth rate equation (with power-law exponent on stress intensity factor of 1.6), the crack growth time is most sensitive to the minimum in the Kdeep curve of Figure 5-8. Two additional FEA cases not shown in Table 5-3were performed to confirm that this minimum value is insensitive to the assumed crack aspect ratio.

Discussion

The crack growth results based on the FEA stress intensity factor calculation predicts about 4.4 years from the initial 26% depth to through-wall depth (leakage) for the case of K-driven growth and for the case of constant crack aspect ratio, assuming the “54ksi” welding residual stress distribution. The reason for the difference between this result and the results presented by the NRC staff on November 30 is unexplained at this time.

Regarding time for crack growth to rupture, the calculation shows similar behavior as the NRC result presented on November 30. If one assumes development of the cracked cross sectional area (i.e., the criticality factor) on the basis of an assumed semi-elliptical crack geometry, then the critical crack size (on the order of 220° to 240° for a through-wall flaw per the NRC calculation for the relief nozzle weld) may be reached at about the same time as the flaw grows through wall. This behavior is due to the growth around much of the inside diameter surface that

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[3] For the constant c/a case, the Kdeep value for the semi-elliptical crack FEA cases with the highest c/a for each a/t value evaluated were applied once the total crack length is projected to reach 360° per the constant 2c/a = 21 assumption.

is predicted due to the moderately high stress intensity factor values at the crack free surface (Ksurf) location given the relatively high welding residual stress assumed near the inside weld surface. However, the compressive bending stresses on the half of the pipe cross section opposite the assumed location of the crack center would tend to lead to development of a crack geometry different from the idealized semi-elliptical shape in which the crack is more shallow near its ends than according to the semi-elliptical geometry. This type of flaw geometry would be expected to result in significantly increased time to rupture, likely with detectable leakage being produced prior to rupture for the case of the relief nozzle weld.

The calculation results shown in Figure 5-9 were produced to investigate the likely crack shape development. This figure shows the calculated stress intensity factor around the crack front for a uniformly deep crack geometry centered at the circumferential position with maximum tensile bending stress (cases 34, 35, and 36 in Table 5-3). Stress intensity factor results are presented to an angle of approximately 150° from the point of maximum bending stress; beyond this point, the constant depth flaw shape rounds off as it approaches its maximum extent of 175° at the surface. Figure 5-9 illustrates how as crack growth proceeds on the compressive side of the bending neutral axis, relatively small stress intensity factors are expected, retarding the growth rate and changing the crack geometry. Analysis of changing crack shape with time is feasible using the FEA approach, but was not investigated.

The general tendency for asymmetric loading such as applied moments to drive cracks through-wall before reaching a mechanically unstable size is discussed in Section 4. It is emphasized that the idealized axisymmetric welding residual stress loading assumed in the MRP and NRC calculations is not realistic in practice given standard welding practices and the likely role of weld repairs.

Table 5-1
FEA Fracture Mechanics Validation Cases for Relief Nozzle Dissimilar Metal Weld Inside Diameter Scaled up to Ri/t = 3 for Direct Comparison to Anderson Correlation [30] Based on NRC Assumed Welding Residual Stress Distribution (with Scaled up Loading Resulting in Comparable Axial Stress Distribution)

						Anderson (ksi-in$^{0.5}$)		DEI FEA (ksi-in$^{0.5}$)		Deviation	
No.	crack	Ri/t	a/t	2c/a	2θ (deg)	Ksurf	Kdeep	Ksurf	Kdeep	Ksurf	Kdeep
V1	semi-elliptical	3	0.2	16	61.1	19.8	19.5	28.7	21.1	8.9	1.6
V2	semi-elliptical	3	0.4	16	122.2	24.0	6.7	31.9	9.0	7.8	2.3
V3	semi-elliptical	3	0.6	16	183.3	25.5	10.3	30.8	12.5	5.4	2.1
V4	semi-elliptical	3	0.8	16	244.5	25.0	29.6	27.9	29.9	2.9	0.3

Table 5-2
FEA Fracture Mechanics Validation Cases for Relief Nozzle Dissimilar Metal Weld Inside Diameter Scaled up to Ri/t = 3 for Direct Comparison to Anderson Correlation [30] Based on Actual FEA Welding Residual Stress Distribution Attained (with Scaled up Loading Resulting in Comparable Axial Stress Distribution)

						Anderson (ksi-in$^{0.5}$)		DEI FEA (ksi-in$^{0.5}$)		Deviation	
No.	crack	Ri/t	a/t	2c/a	2θ (deg)	Ksurf	Kdeep	Ksurf	Kdeep	Ksurf	Kdeep
V1	semi-elliptical	3	0.2	16	61.1	18.6	18.9	28.7	21.1	10.1	2.2
V2	semi-elliptical	3	0.4	16	122.2	22.6	6.9	31.9	9.0	9.3	2.1
V3	semi-elliptical	3	0.6	16	183.3	23.8	9.5	30.8	12.5	7.0	3.0
V4	semi-elliptical	3	0.8	16	244.5	23.3	26.5	27.9	29.9	4.6	3.4

Table 5-3
Matrix of FEA Fracture Mechanics Cases Investigated for Relief Nozzle Dissimilar Metal Weld Dimensions and Loading with Comparison of Results to Anderson Correlation [30] Based on NRC Assumed Welding Residual Stress Distribution Extrapolated Down to Ri/t = 2.004

						Anderson ($ksi\text{-}in^{0.5}$)		DEI FEA ($ksi\text{-}in^{0.5}$)		Deviation	
No.	crack	Ri/t	a/t	2c/a	2θ (deg)	Ksurf	Kdeep	Ksurf	Kdeep	Ksurf	Kdeep
1	semi-elliptical	2.004	0.1	5	14.3	25.2	20.8	31.0	22.4	5.9	1.6
2	semi-elliptical	2.004	0.1	10	28.6	20.7	23.7	24.9	25.7	4.2	2.0
3	semi-elliptical	2.004	0.1	15	42.9	16.1	24.2	22.3	26.7	6.2	2.5
4	semi-elliptical	2.004	0.1	21	60.0	13.5	24.8	19.8	27.3	6.4	2.5
5	semi-elliptical	2.004	0.1	25	71.5	12.1	25.2	19.3	27.4	7.3	2.1
6	semi-elliptical	2.004	0.1	30	85.8	10.3	25.7	18.1	27.5	7.9	1.8
7	semi-elliptical	2.004	0.1	50	143.0			15.3	27.8		
8	semi-elliptical	2.004	0.2	5	28.6	32.1	14.1	38.2	15.3	6.1	1.2
9	semi-elliptical	2.004	0.2	10	57.2	26.6	17.1	32.1	18.5	5.5	1.4
10	semi-elliptical	2.004	0.2	15	85.8	20.9	18.0	28.4	19.5	7.4	1.5
11	semi-elliptical	2.004	0.2	21	120.1	17.7	19.0	25.4	20.1	7.7	1.1
12	semi-elliptical	2.004	0.2	25	143.0	16.0	19.7	23.5	20.3	7.5	0.6
13	semi-elliptical	2.004	0.2	30	171.6	13.8	20.5	22.4	20.5	8.6	0.0
14	semi-elliptical	2.004	0.2	50	285.9			22.3	20.5		
15	semi-elliptical	2.004	0.3	5	42.9	35.5	6.0	41.2	7.9	5.7	1.9
16	semi-elliptical	2.004	0.3	10	85.8	29.4	8.6	34.9	10.5	5.5	1.9
17	semi-elliptical	2.004	0.3	15	128.7	23.1	9.7	30.7	11.4	7.7	1.7
18	semi-elliptical	2.004	0.3	21	180.1	19.7	10.9	27.3	11.9	7.5	1.0
19	semi-elliptical	2.004	0.3	25	214.4	18.1	11.7	25.4	12.1	7.3	0.4
20	semi-elliptical	2.004	0.3	30	257.3	16.0	12.6	23.8	12.2	7.8	-0.3
21	semi-elliptical	2.004	0.4	10	114.4	30.6	3.1	35.7	5.8	5.0	2.7
22	semi-elliptical	2.004	0.4	15	171.6	23.5	4.2	31.1	6.6	7.5	2.4
23	semi-elliptical	2.004	0.4	21	240.2	20.5	5.4	27.3	6.9	6.9	1.6
24	semi-elliptical	2.004	0.4	25	285.9	19.1	6.1	25.4	7.0	6.3	0.9
25	semi-elliptical	2.004	0.4	30	343.1	17.5	7.0	23.6	7.0	6.1	0.0
26	semi-elliptical	2.004	0.5	24	343.1	19.7	4.4	25.7	6.0	6.0	1.7
27	semi-elliptical	2.004	0.6	20	343.1	21.2	7.5	27.2	9.2	6.0	1.7
28	semi-elliptical	2.004	0.7	10	200.1	30.9	14.3	33.0	15.6	2.1	1.3
29	semi-elliptical	2.004	0.7	17.14	343.1	21.6	15.2	27.9	16.1	6.3	0.9
30	semi-elliptical	2.004	0.8	10	228.7	29.2	24.6	31.5	25.0	2.3	0.4
31	semi-elliptical	2.004	0.8	15	343.1	22.5	25.6	28.5	25.9	6.0	0.3
32	semi-elliptical	2.004	0.9	10	257.3	27.7	34.7	29.8	38.3	2.1	3.6
33	semi-elliptical	2.004	0.9	13.33	343.1	23.3	35.9	28.8	39.9	5.5	4.0
34	uniform depth	2.004	0.7	17.49	350.0			7.2*	16.5		
35	uniform depth	2.004	0.8	15.30	350.0			2.2*	26.9		
36	uniform depth	2.004	0.9	13.60	350.0			1.3*	42.5		

*The Ksurf values for the uniform depth crack geometry are for a position 150° from the point of max bending stress.

Table 5-4
Selected FEA Cases from Table 5-2 for Case of No Welding Residual Stress Loading for Comparison to Anderson Correlation [30] Extrapolated Down to Ri/t = 2.004

						Anderson (ksi-in$^{0.5}$)		DEI FEA (ksi-in$^{0.5}$)		Deviation	
No.	crack	Ri/t	a/t	2c/a	2θ (deg)	Ksurf	Kdeep	Ksurf	Kdeep	Ksurf	Kdeep
3	semi-elliptical	2.004	0.1	15	42.9	2.6	6.2	2.9	6.4	0.4	0.2
15	semi-elliptical	2.004	0.3	5	42.9	7.2	9.9	7.8	10.1	0.6	0.2
18	semi-elliptical	2.004	0.3	21	180.1	2.4	12.2	2.3	12.1	-0.1	-0.1
20	semi-elliptical	2.004	0.3	30	257.3	1.5	13.0	0.6	12.2	-0.9	-0.8

Figure 5-1
Assumed Axial Stress Loading on Wolf Creek Relief Nozzle (Deadweight, Pipe Thermal Expansion Force and Moment, End Cap Pressure Load, and Assumed Welding Residual Stress Distribution per Figure 5-2)

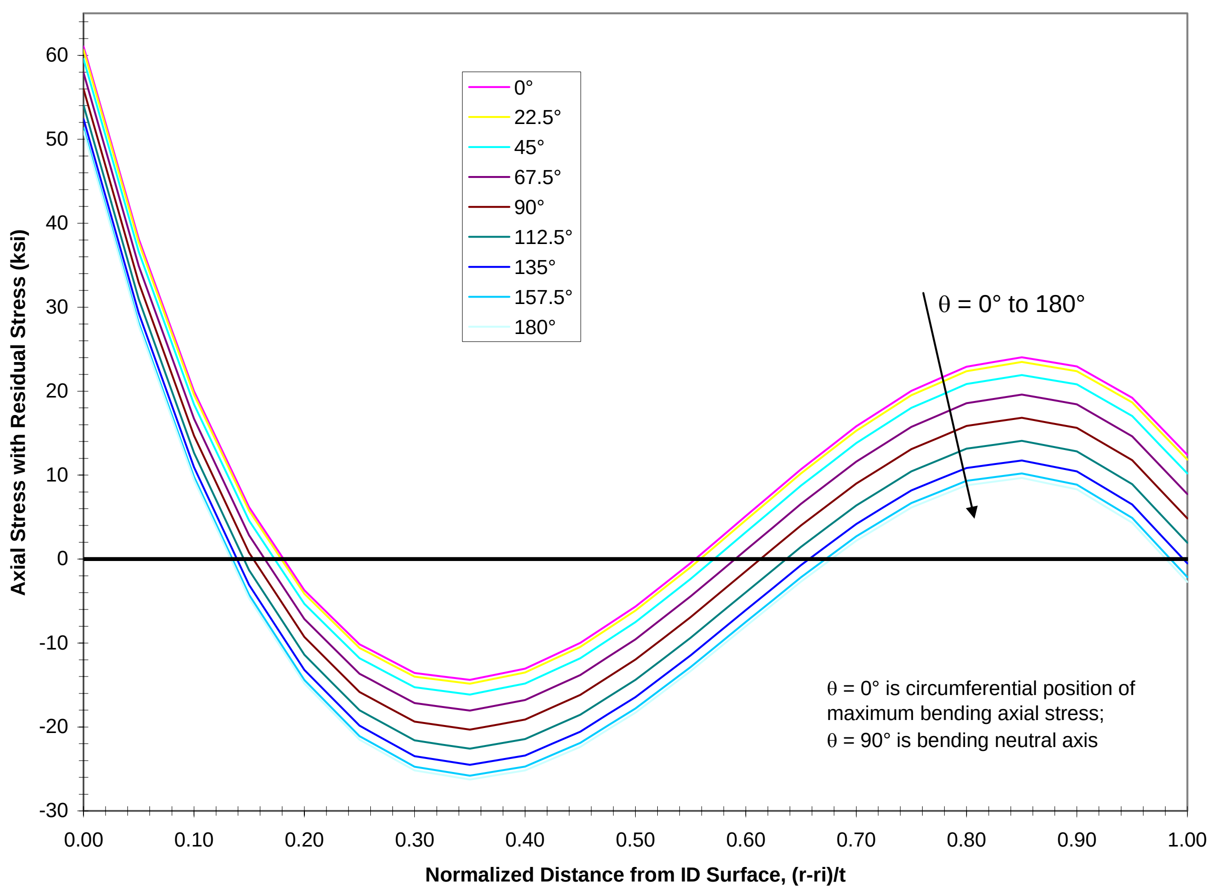


Figure 5-2
Welding Residual Stress Distribution Assumption of NRC Crack Growth Calculation for Wolf Creek Relief Nozzle Based on ASME Published Data

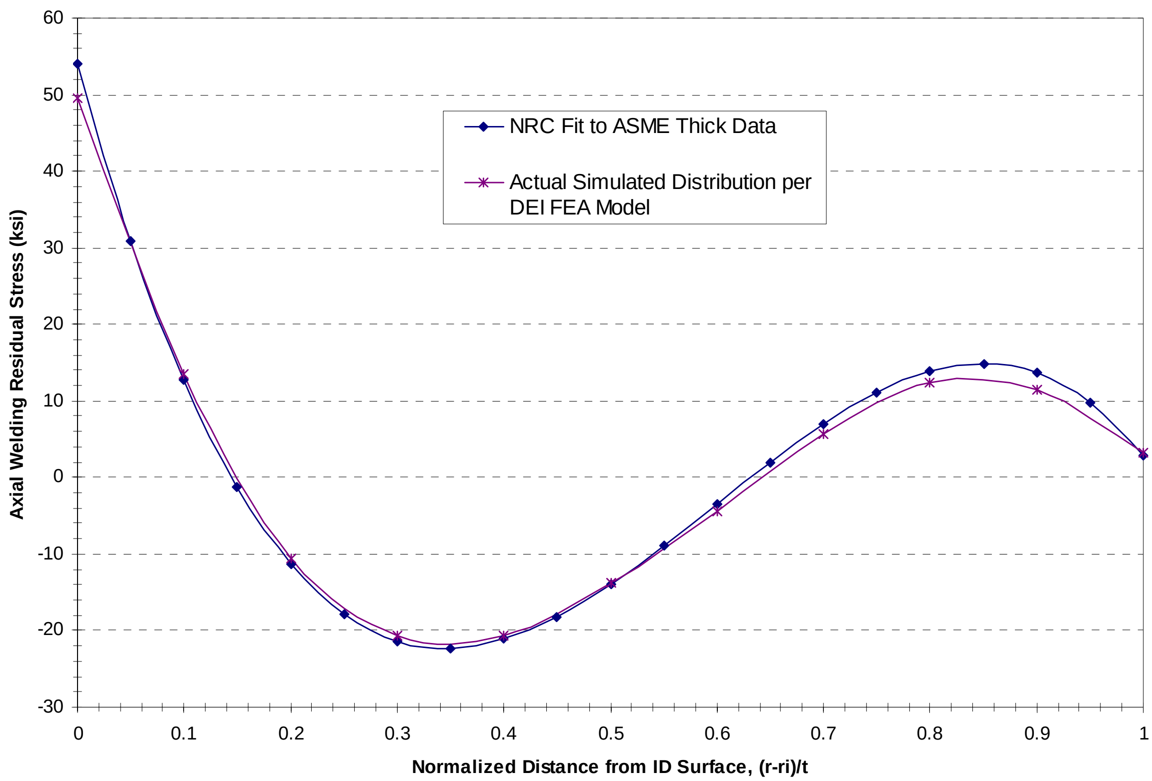


Figure 5-3
ASME Welding Residual Stress Distributions: (a) Figure from NUREG-0313 [28], and (b) ASME figure [29]

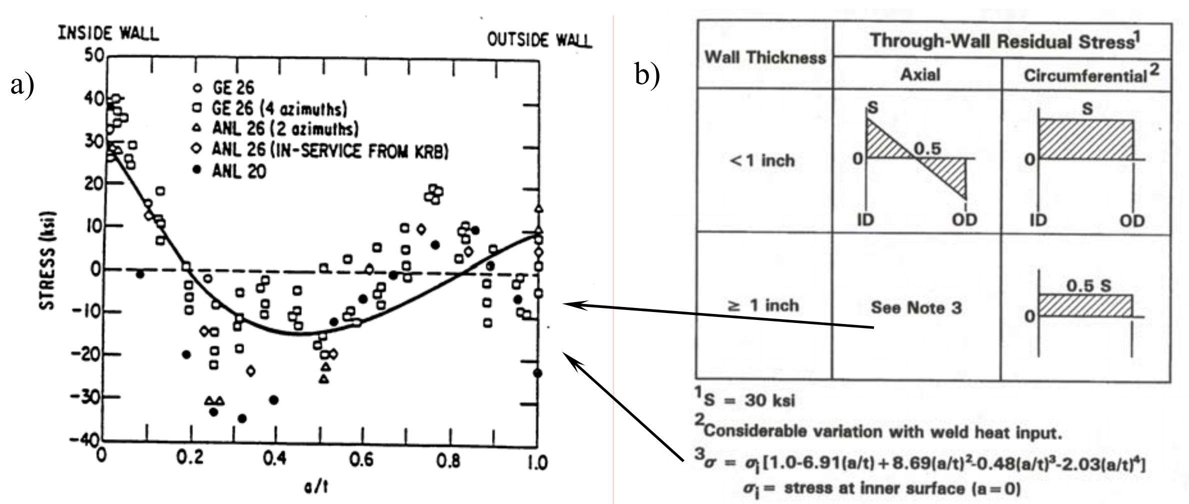


Figure 5-4
FEA Fracture Mechanics Model for the Wolf Creek Relief Nozzle

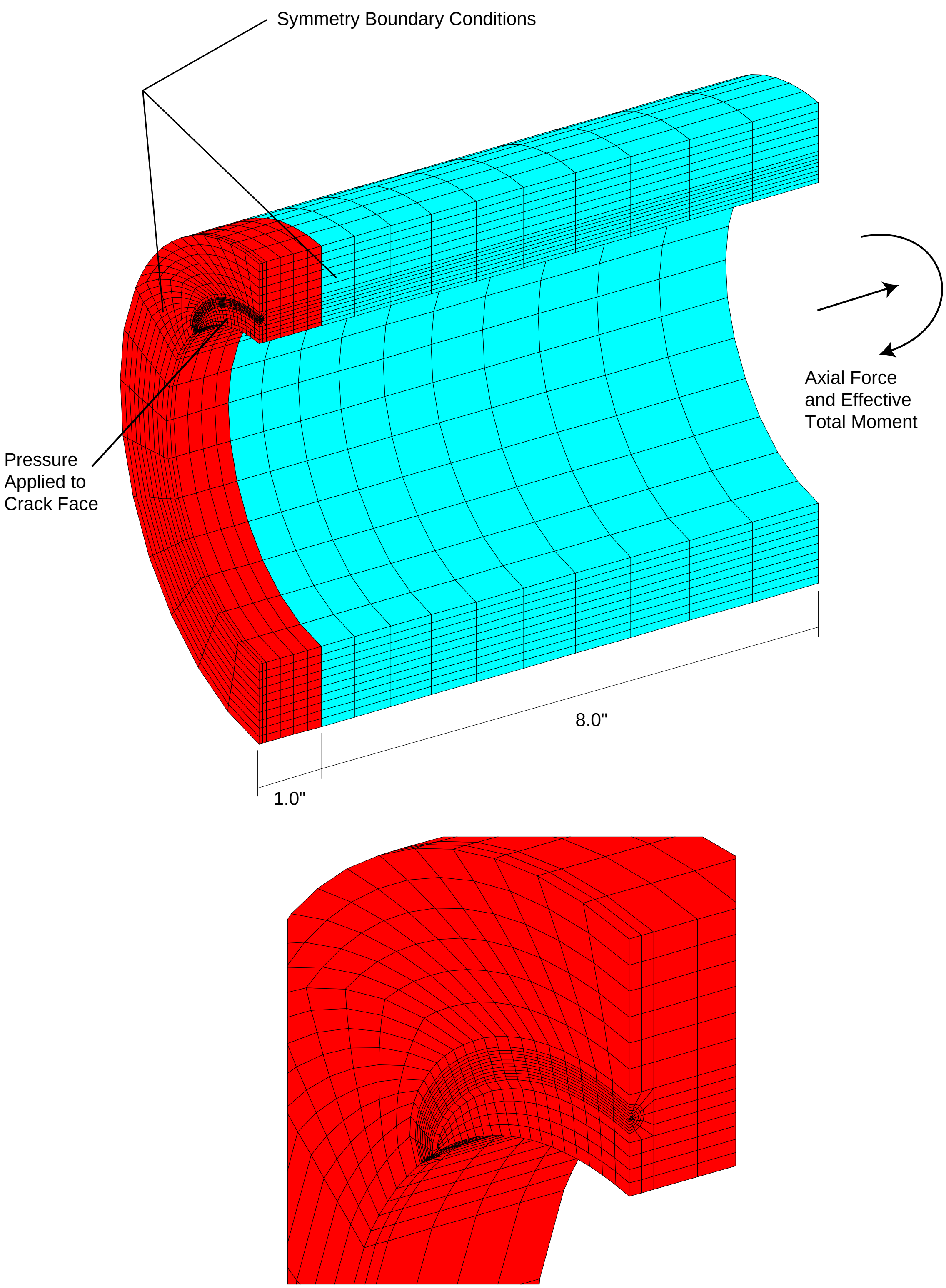


Figure 5-5
Axial Extent of Imposed Thermal Stress Simulating Welding Residual Stress Loading

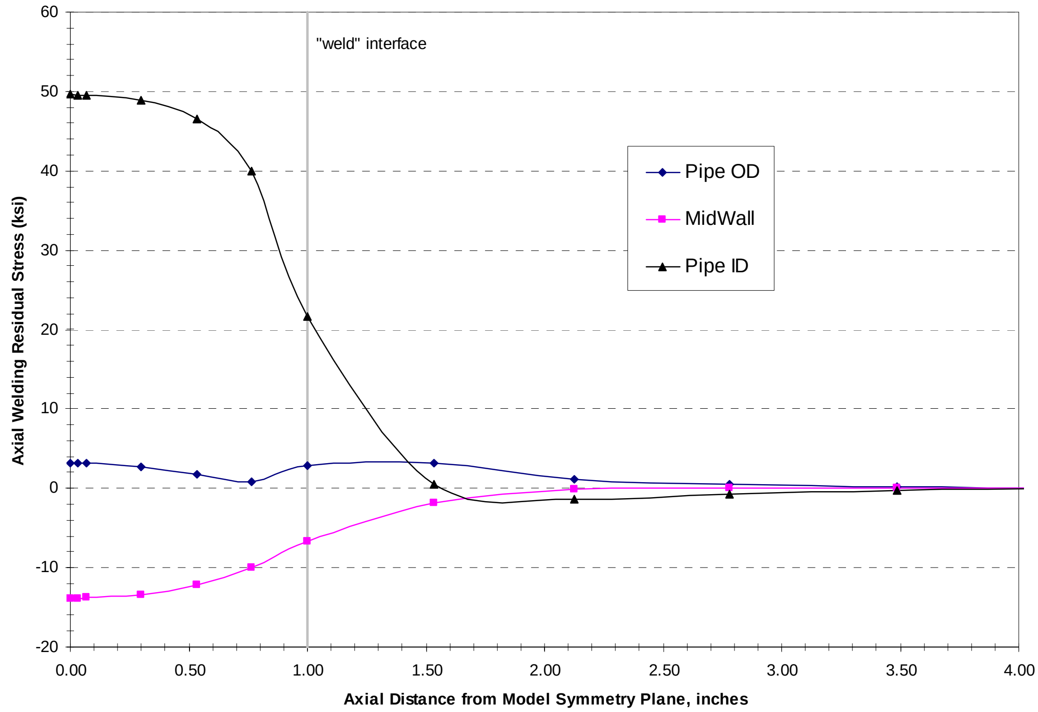


Figure 5-6
Predicted Growth in Depth Direction of Relief Nozzle Indication Based on FEA Model Stress Intensity Factor Results and MRP-115 Crack Growth Rate Equation for Alloy 182

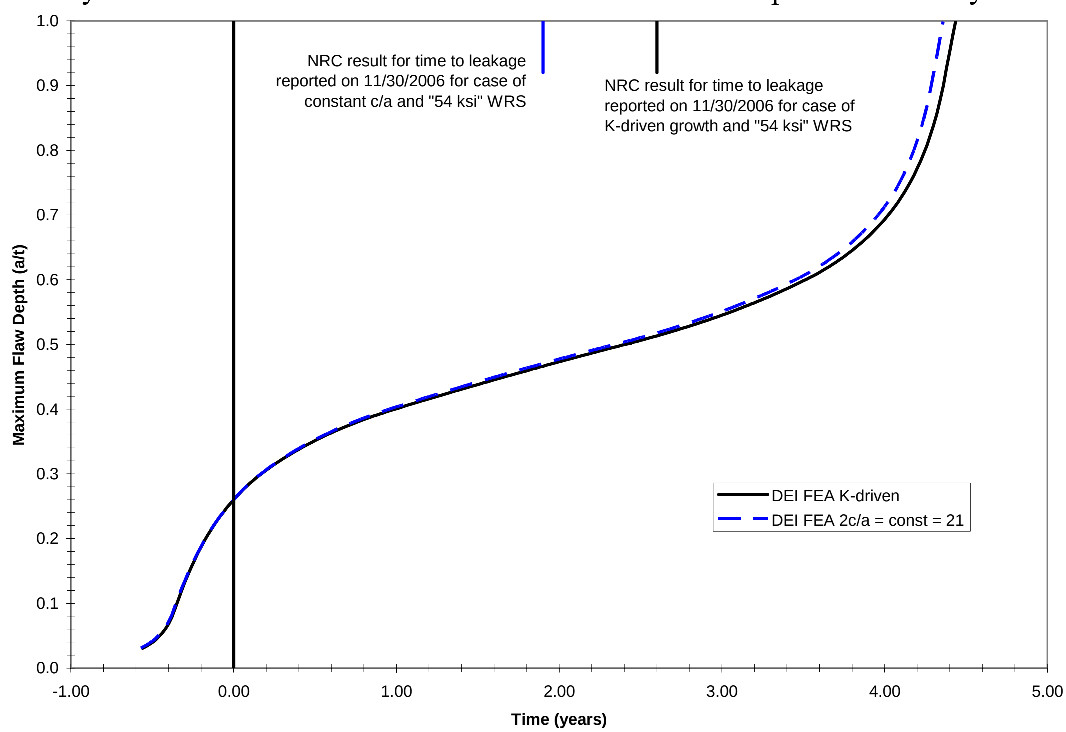


Figure 5-7
Predicted Aspect Ratio Development for Relief Nozzle Indication Based on FEA Model Stress Intensity Factor Results and MRP-115 Crack Growth Rate Equation for Alloy 182

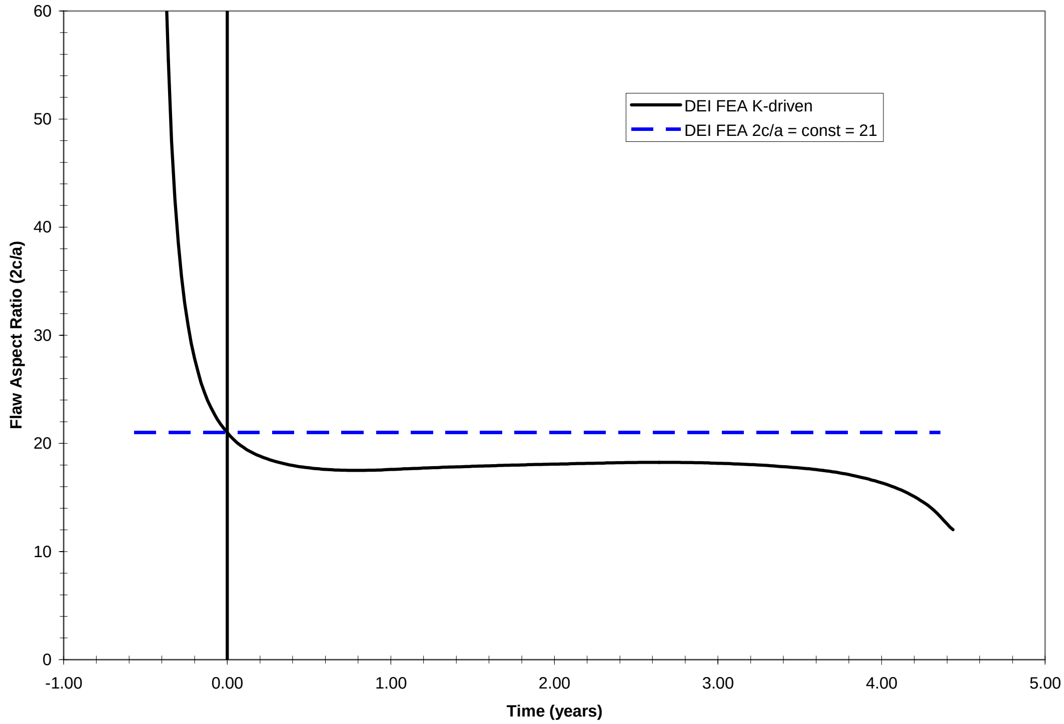


Figure 5-8
Crack-Tip Stress Intensity Factors for Calculation of Growth of Relief Nozzle Indication Based on Interpolation between FEA Model Case Results

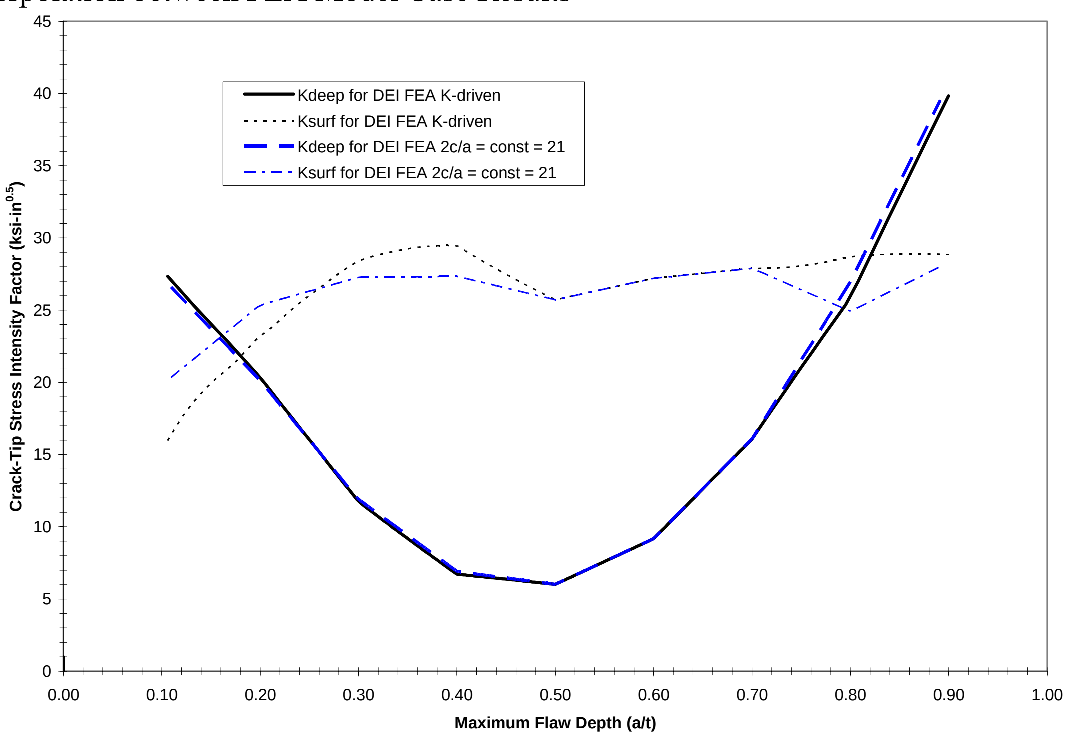
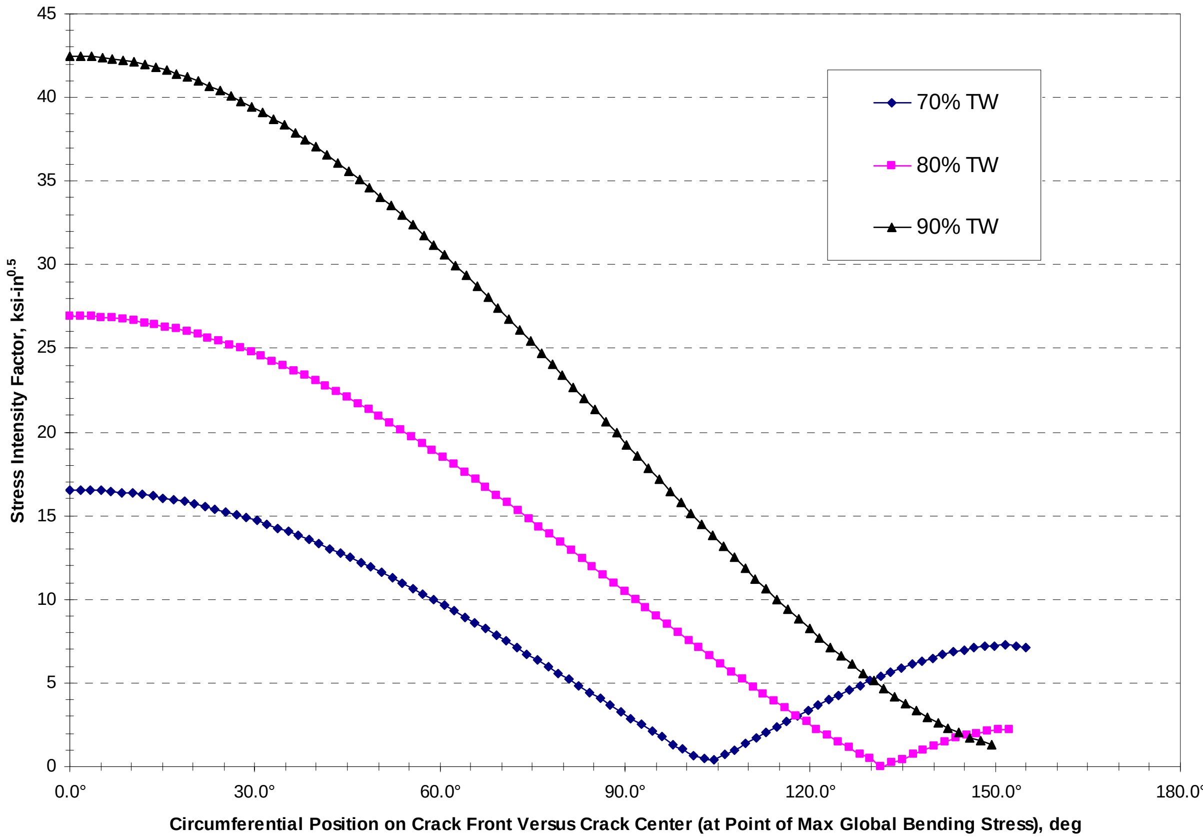


Figure 5-9
FEA Crack-Tip Stress Intensity Factor around Crack Front for Case of Uniform Depth Crack Geometry with Total Length of 350°



6. Critical Flaw Size and Leakage Detection before Risk of Rupture

A key factor in the industry safety assessment of Alloy 82/182 butt welds has been that, while it is possible that leaks may occur until such time as all welds have been inspected by PDI qualified methods and/or mitigated to prevent crack initiation and growth, the critical flaw sizes for ductile materials such as Alloy 600 and Alloy 82/182 weld metal are sufficiently large that it is highly probable that leaks will be discovered by on-line leak detection methods prior to a significant risk of rupture developing. The purpose of this section is to reassess this key factor based on the Wolf Creek inspection findings.

Flaw Orientation

Three types of PWSCC flaws are of interest in Alloy 82/182 butt welds:

- Through-Wall Axial Flaws
  Most flaws in Alloy 82/182 butt welds in both PWR and BWR plant butt welds have been axially oriented. Calculations in reports MRP-109, 112 and 113 have confirmed that there is no risk of reaching critical size axial flaws in Alloy 82/182 PWR butt welds since axial cracks are arrested at abutting stainless steel and low-alloy steel materials as shown in Figure 2-1 for the case of cracks in the Tsuruga 2 pressurizer safety and relief nozzles. The crack which led to a leak at VC Summer had a similar profile. The critical flaw length for axial cracks is significantly greater than the axial length of the Alloy 82/182 welds, or for the welds plus the Alloy 600 base metal for the small number of plants with Alloy 600 safe-ends. Based on this knowledge, the critical sizes for axial flaws were not investigated further in this update.

- Through-Wall Partial-Arc Flaws
  Through-wall partial-arc circumferential flaws have received primary attention in past MRP analyses. Calculations in reports MRP-109, 112 and 113 have confirmed that for the case of through-wall, partial arc flaws, leakage will be detected prior to risk of rupture. Work in the following paragraphs of this section takes another look at the critical size and the predicted leakage for partial-arc circumferential flaws.

- Part-Depth 360º Flaws
  The Wolf Creek experience indicates the potential for long part-depth continuous or intermittent circumferential flaws. Fracture mechanics calculations in Section 4 show that potentially high tensile stresses on the inside surface can lead to this type of flaw in the presence of some initiating mechanism such as machining marks, long weld repair, etc. However, calculations in Section 4 also show that growth of these cracks through-wall will tend to occur on the side of the nozzle with high tensile welding stresses while the crack depth remains shallow on the side with compressive bending stresses. This is similar to cracks which were reported at Duane Arnold (see Figure 2-4). Results of test work on this type of crack configuration are reported.

Critical Through-Wall Partial-Arc Circumferential Flaw Sizes Reported in MRP-113

The summary safety assessment report for PWR plant Alloy 82/182 butt welds (MRP-113), documents the vendor calculated critical sizes for through-wall partial-arc circumferential flaws. The limiting critical flaw sizes for the pressurizer nozzle butt welds are summarized in Table 6-1.

Table 6-1
Summary of Controlling Vendor Calculated Partial-Arc Through-Wall Critical Flaw Sizes for Pressurizer Nozzles

Plant NSSS Supplier	Arc-Length of Critical Size Through-Wall Flaws from MRP-113		
	Surge Nozzles	Spray Nozzles	Safety/Relief Nozzles
Westinghouse Plants	115º	144º	144º
Combustion Engineering Plants	126º	72º	130º
B&W Plants	93º	211º	188º

Westinghouse and AREVA report that the calculations included the effects of dead weight, internal pressure, thermal expansion, thermal stratification loads, and safe shutdown earthquake loads. AREVA noted in MRP-112 that their calculations also include the effect of through-thickness thermal gradients and differential thermal expansion between the Alloy 182, low-alloy steel and stainless steel parts. Westinghouse states that the intact section properties (area and section modulus) are based on dimensions of the attached pipe which is smaller than the cross section through the Alloy 182 butt weld.

A review of these calculations shows several potential sources of conservatism. For example:

- The wall thickness at the weld is typically larger than the nominal wall thickness of the pipe
- The typical as-deposited yield strength of the Alloy 182 weld metal is significantly higher than the ASME Code specified minimum yield strength of Alloy 600 material
- The critical flaw size calculations typically included secondary stresses such as produced by through-thickness thermal gradients and differential thermal expansion between the three nozzle materials (low-alloy steel, Alloy 182, stainless steel). These loads would apply to calculating crack growth under operating conditions but not to the critical flaw size.
- While seismic loads would apply to critical size flaws over the plant life, the probability of a seismic event prior to inspection/mitigation of the pressurizer butt welds in combination with a near critical size flaw is extremely low

Leakage from Through-Wall Partial-Arc Cracks

Figure 6-1 shows the results of leakage calculations for through-wall partial-arc cracks in the Wolf Creek relief and surge nozzles using the PICEP software. The leak rate for the top head relief nozzle was calculated using properties for saturated steam. The leak rates for the bottom head surge nozzle were calculated using subcooled water at 600ºF. Since PICEP calculates leakage for fatigue cracks rather than PWSCC cracks the length of the crack has been increased by the same factor of 1.69 that was determined in MRP-140 to produce an equivalent leak rate for PWSCC morphology.

Critical Size Through-Wall Partial-Arc Circumferential Cracks for Wolf Creek Relief and Surge Nozzle Butt Welds

Limiting through-wall partial-arc cracks for the Wolf Creek relief and surge nozzles were calculated using the method in the EPRI Ductile Fracture Handbook [32] for a flawed pipe under axial loading. The material properties used for calculating the material flow stress are taken from Section II, Part D of the ASME Code for Alloy 600 base metal at 650ºF.

In addition to the leak rates, Figure 6-1 shows critical flaw sizes reported by the vendors in MRP-113, upper bound (UB) and lower bound (LB) critical flaw sizes reported by the NRC during the November 30, 2006 meeting, and critical flaw sizes calculated using the Ductile Fracture Handbook. This figure also shows the typical Technical Specification leak rate of 1 gpm. These calculations show:

- Critical flaw sizes reported by the NRC and calculated using the Ductile Fracture Handbook are significantly larger than reported in MRP-113.
- There is significant margin between the size flaw that would be detected by the 1 gpm Technical Specification limit and the critical flaw size.
- Further reduction in the on-line leakage detection limits would improve the margin further.

Critical Size of Part-Depth 360º Flaws

NUREG/CR-4687 [33] describes a series of tests on 6" carbon steel, stainless steel and Alloy 600 pipes under moment type loading at 550ºF to simulate the behavior of the Duane Arnold type flaw under limit loading conditions. The pipe test specimens were machined on the inside to simulate the Duane Arnold crack as shown in Figure 6-2. Figure 6-3 shows the test fixture. Figure 6-4 shows typical test results in which the crack has opened up a large amount prior to rupture. Selected results are reported in Table 6-2. It is clear from the figures and test data that the critical flaw sizes are very large and that there will be significant advance warning by gradually increasing leakage before risk of rupture.

Reason for Short Predicted Time between Leak and Rupture for B&W Relief Nozzles

During the meeting between the NRC, NEI and MRP on November 30, a question was raised regarding the significant difference in time from a 1 gpm leak to the critical flaw size between Westinghouse/CE relief nozzles and B&W relief nozzles.

While the Westinghouse/Combustion Engineering and B&W relief nozzles have the same name, they are significantly different. As shown in Figure 6-5, the B&W nozzle design is very stubby with 4.5 inch OD, 2.5 inch ID, and thickness of 1 inch, resulting in an R/t ratio of 3.5 (based on the mean radius). It has a moment loading due to SSE and Anchor Movement of 126.4 in-kips.

CE relief nozzles, on the other hand, have 3.68 inch OD, 2.62 inch ID and thickness of 0.53 inch. These nozzles have an R/t ratio of 5.94 and a bending moment of 191 in-kips.

Since the R/t ratio of the B&W design is one half that of the CE design, any direct comparison of the analytical results for these two nozzles is not meaningful. Because of the very stiff design, the calculated through wall critical flaw length is large. This stiffness acts to restrict the opening of a through-wall flaw, which results in a rather long flaw being needed to produce a 1 gpm leak.

Conclusions Regarding Critical Flaw Size and Leakage before Rupture
The preceding calculations have demonstrated that the critical flaw size for partial-arc through-wall flaws such as occurred in the Palisades nozzle tend to be large and that leakage will be detected prior to risk of rupture as was confirmed by the Palisades crack. The analyses and reported tests also show that, in the event that a uniform depth 360º crack were to initiate and grow into a similar profile as at Duane Arnold, that leakage would be detected prior to rupture as was the case at Duane Arnold.

Table 6-2
Summary of NUREG/CR-4687 Tests of Pipes with Duane Arnold Type Flaws [33]

	Tests					
Parameter	304 SS		Alloy 600		Carbon Steel	
Pipe OD (in)	6.625	6.625	6.625	6.625	6.625	6.625
Wall Thickness (in)	0.570	0.570	0.435	0.435	0.560	0.560
Crack Depth/Wall Thickness (a/t)	0.31	0.63	0.34	0.61	0.31	0.64
Thru-Wall Arc (deg)	133	133	133	133	133	133
Area Lost (%)	58	80	60	79	58	81
Yield at 550F (ksi)	20.1	20.1	28.5	28.5	46.4	46.4
Tensile at 550F (ksi)	65.2	65.2	88.4	88.4	90.0	90.0
Flow Stress at 550F (ksi)	49.0	49.0	67.2	67.2	78.4	78.4
Test Results						
- Maximum Load (kips)	27.9	18.2	26.5	19.5	33.1	33.1
- Stress at Max Load, Pb/Sm	0.979	0.639	0.970	0.587	1.102	0.662
- Crack Opening Angle	15	12	18	12-15	5-6	6
- Pipe Kink Angle (deg)	---	7	9	7	---	3
- Crack Opening Area (in^2)	12.4	10.6	16.5	14.7	4.0	6.5

Figure 6-1.a
Predicted Leakage vs. Critical Flaw Size for Wolf Creek Pressurizer Relief Nozzles

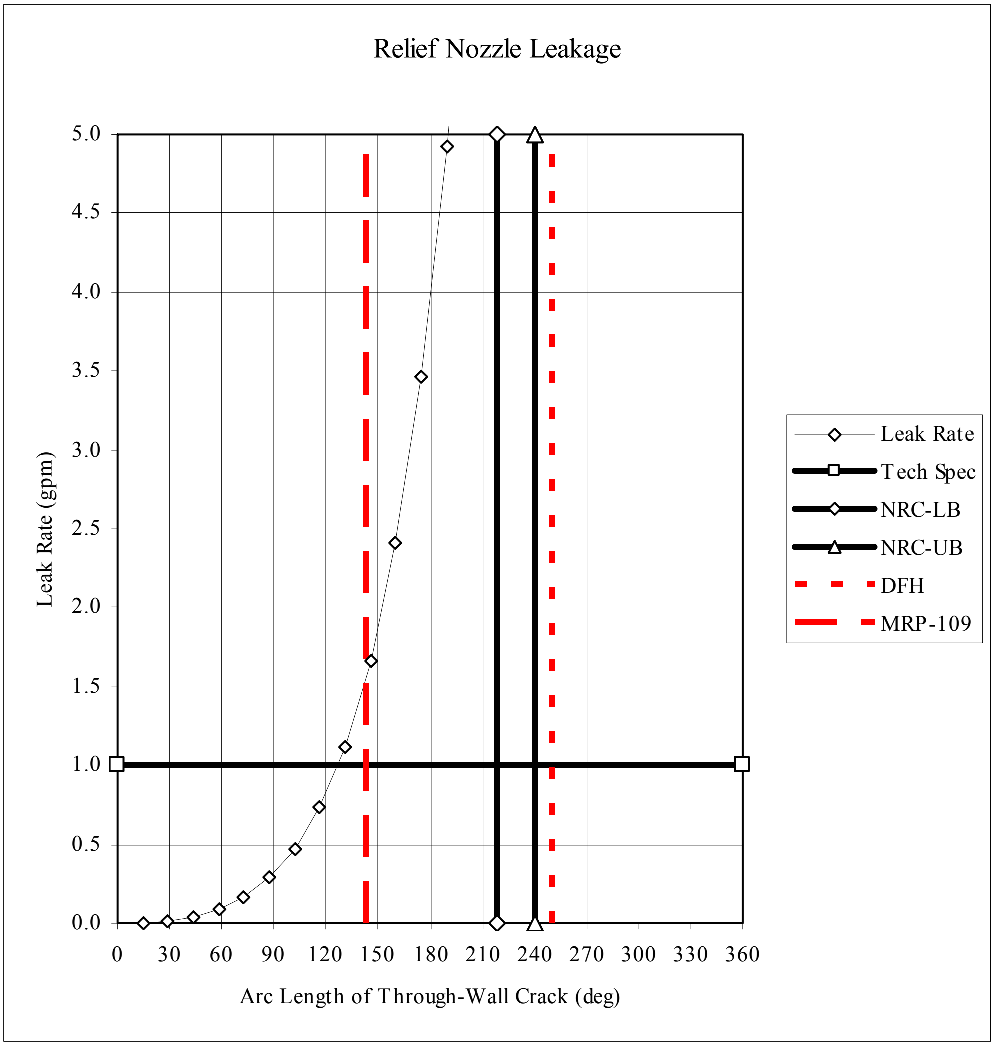


Figure 6-1.b
Predicted Leakage vs. Critical Flaw Size for Wolf Creek Pressurizer Surge Nozzles

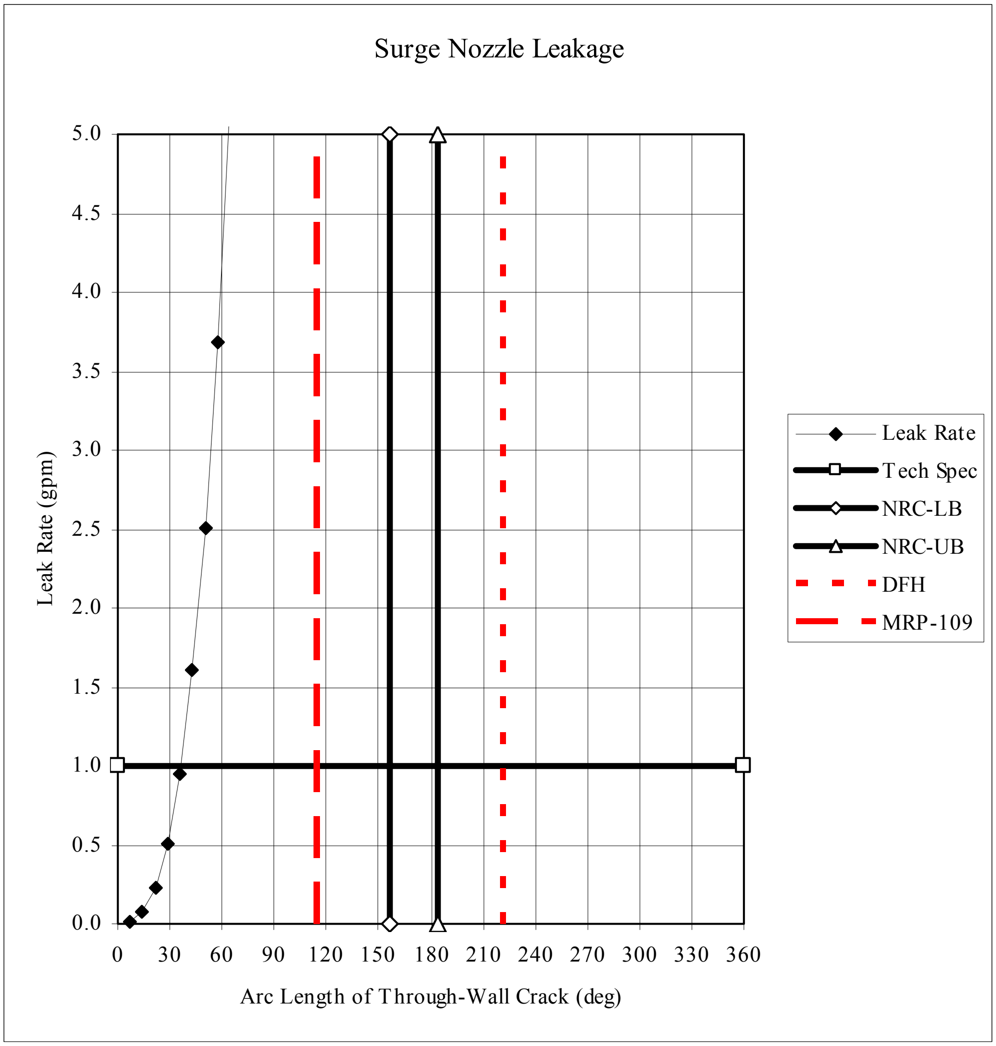


Figure 6-2
Duane Arnold Crack Profile and Simulated Complex Crack for NUREG/CR-4687 Tests [33]

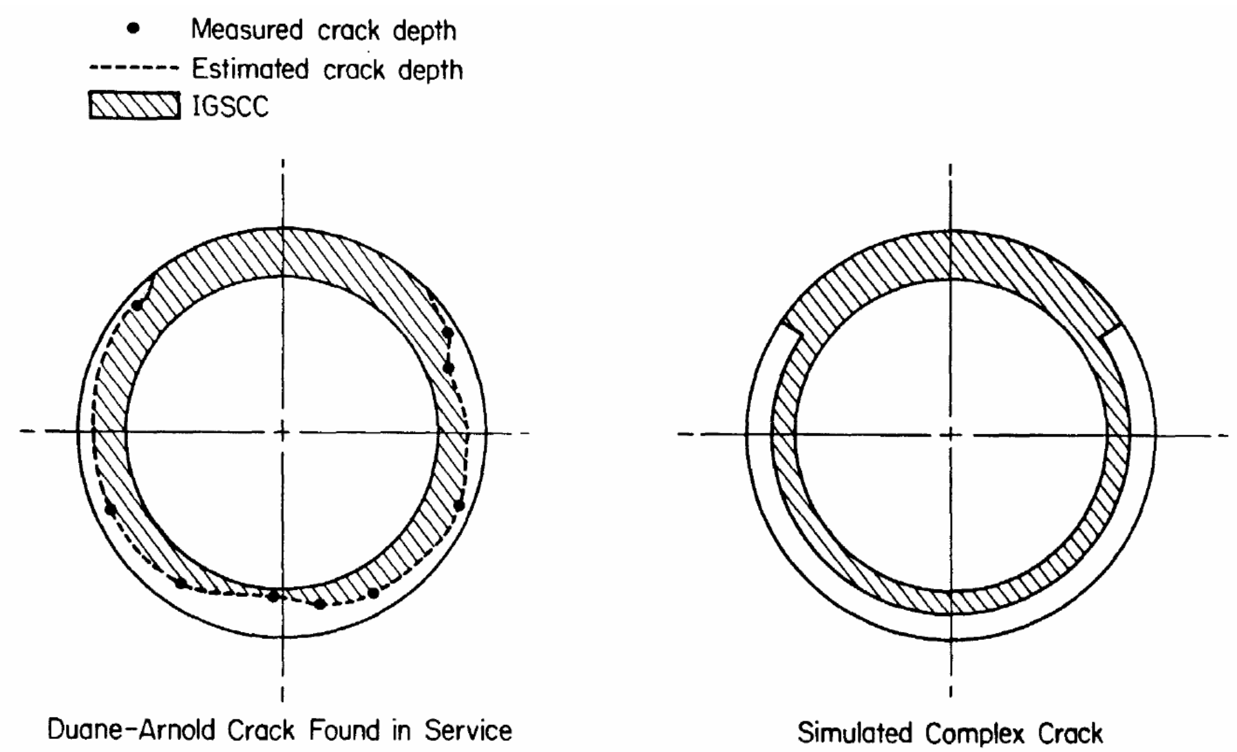


Figure 6-3
Fixture for NUREG/CR-4687 Tests [33]

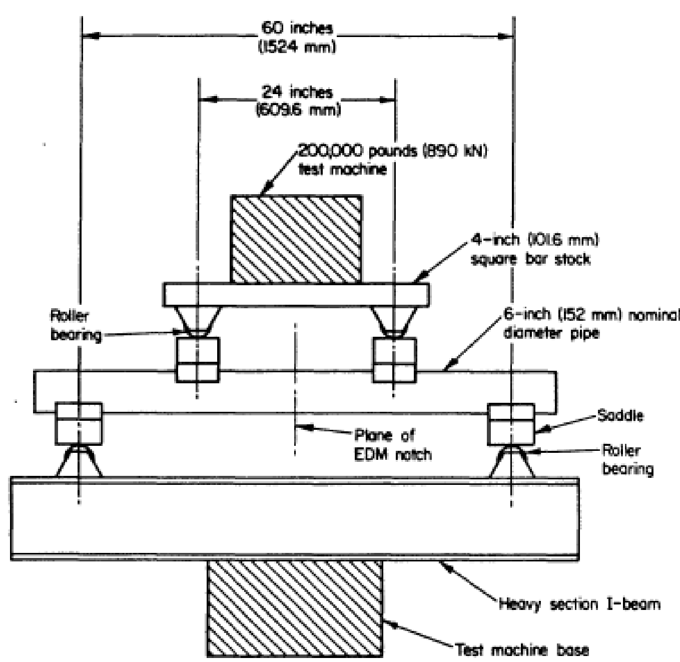
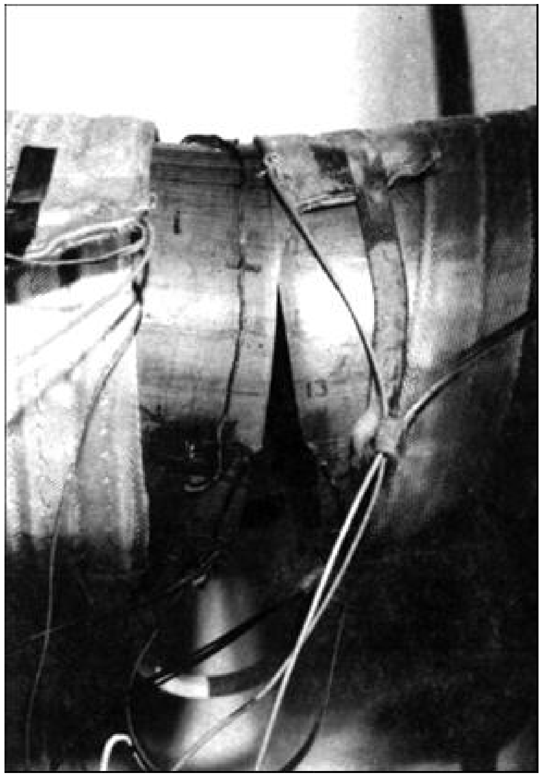


Figure 6-4
Figures from NUREG/CR-4687 Tests [33]



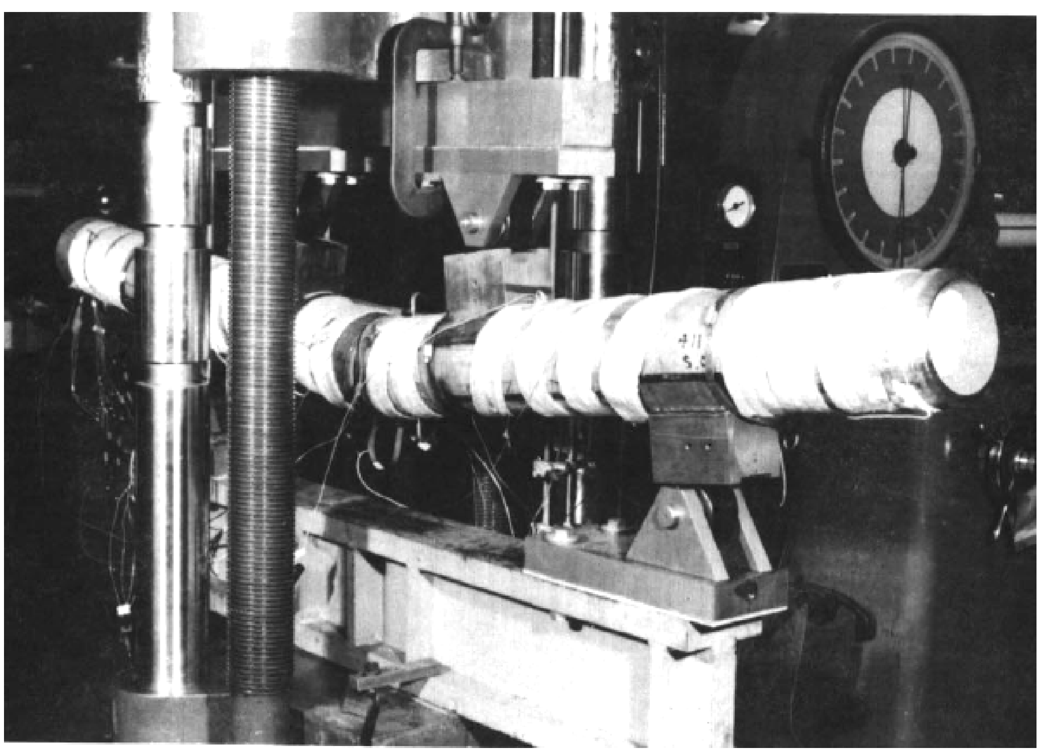
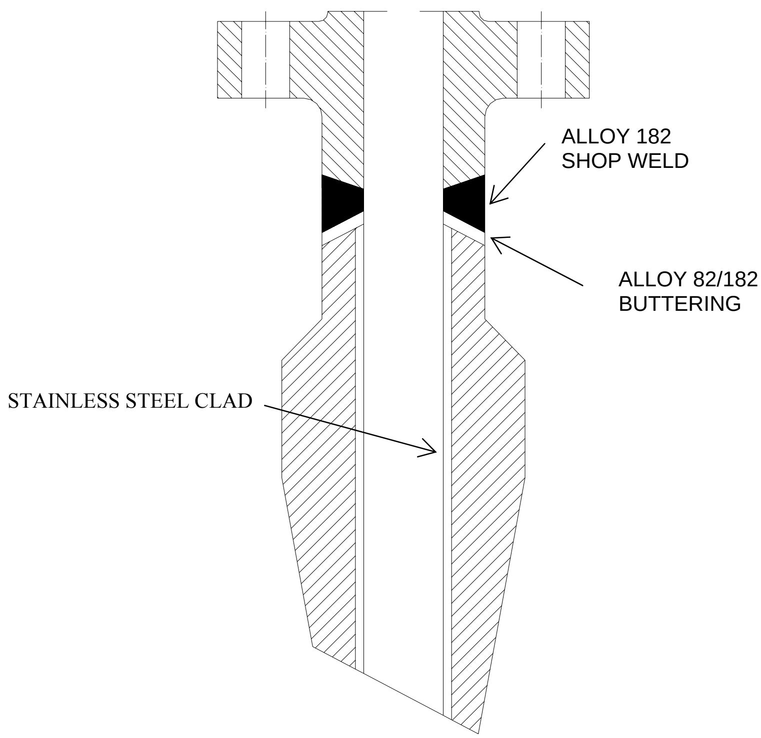


Figure 6-5
B&W Relief Nozzle Configuration (not to scale)



7. Update of MRP-109 Calculations for Larger Aspect Ratio Cracks

To examine the impact of the Wolf Creek indications on the Safety Case published in MRP-109, a series of additional calculations were carried out, and the results will be discussed in this section. Only circumferential flaws will be addressed. For information on axial flaws, the reader is referred to MRP-109.

The same loadings used for MRP-109 were used here, and the calculations were done using the same assumptions, with two exceptions, the flaw shape and the PWSCC crack growth model. Instead of covering all the plants, the single most limiting plant for each of the pressurizer nozzles was chosen which will provide a conservative assessment. This is a different approach than used by the NRC, where Wolf Creek plant specific loads were used.

As with MRP-109, calculations were carried out both with and without residual stresses. The residual stresses used were those contained in the technical basis for pipe flaw evaluation, and are shown in Figure 4-2 of this report.

The calculations discussed here have considered all the appropriate loadings, including dead weight, thermal expansion, thermal stratification, welding residual stress, and pressure. The loadings were updated to include all known design changes to the system. Such changes include, where appropriate, the following:

- Steam generator replacement and uprating
- Steam generator snubber elimination
- Steam generator center of gravity and weight revisions

The following load combinations were considered for circumferential flaws:

- Thermal normal–100 percent power
- Dead weight
- Steady state pressure

The crack growth calculations were carried out using the steady state loadings which exist at the three locations of interest. The initial crack depth for part through-wall cracks was assumed to be that depth which would lead to a stress intensity factor of 9.5 MPa-m$^{0.5}$. This value is above the threshold value of 9 MPa-m$^{0.5}$, for the MRP-21 model, thereby ensuring crack growth occurs. This is important regardless of the crack growth model used. For the MRP-115 model, although there is no threshold for crack growth, the growth rate at low values of K is very slow, so this could give a false sense of security.

The results of the crack growth calculations are shown in Tables 7-1 and 7-2. Aspect ratios of 6:1, 10:1, 20:1, and 30:1 were used, to envelope the range of aspect ratios which could realistically occur. The results show that the aspect ratio has very little impact on the time required for a postulated flaw to progress through the pipe wall. Thus, it may be concluded that the safety case report, MRP-109, findings are unchanged..

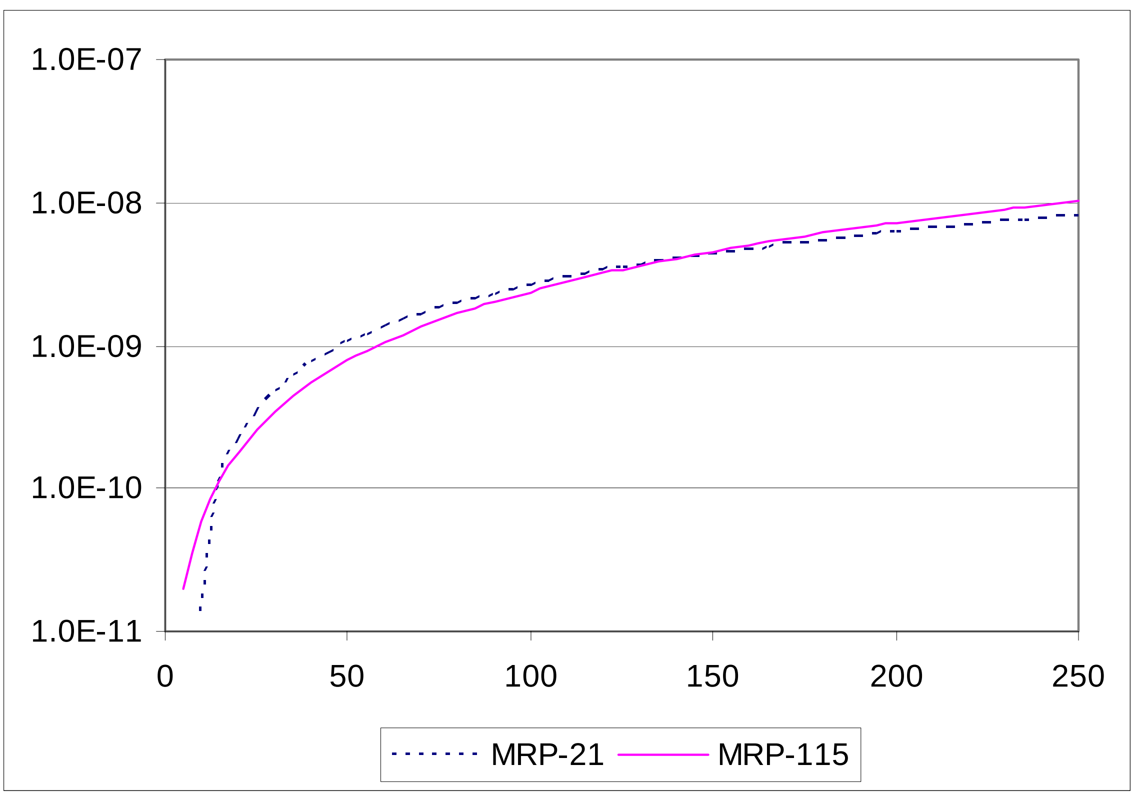
Table 7-1
Impact of Larger Aspect Ratio on Time to Failure for Westinghouse plants (using MRP-21)

Location	Years to leak (6:1)	Years from 1 GPM to Critical	Total 6:1	Total 10:1	Total 20:1	Total 30:1
Surge	**1.4**	**2.6**	**4.0**	**3.7**	**3.4**	**3.4**
Safety Relief	**4.1**	**5.6**	**9.7**	**7.8**	**7.5**	**7.4**
Spray	**1.1**	**2.6**	**3.7**	**3.4**	**3.3**	**3.2**

Table 7-2
Impact of Larger Aspect Ratio on Time to Failure for Westinghouse plants (using MRP-115)

Location	Years to leak (6:1)	Years from 1 GPM to Critical	Total 6:1	Total 10:1	Total 20:1	Total 30:1
Surge	**2.1**	**2.6**	**4.7**	**4.1**	**3.8**	**3.7**
Safety Relief	**2.3**	**5.6**	**7.9**	**7.7**	**7.6**	**7.7**
Spray	**1.1**	**2.6**	**3.7**	**3.4**	**3.3**	**3.3**

Figure 7-1
PWSCC Crack Growth Models used in the Evaluation



8. Current Utility Inspection/Mitigation Plans

As previously noted, MRP-139 requires PDI qualified examinations of pressurizer butt welds 4" NPS and greater, and the B&W pressurizer safety relief nozzle welds (see figure 6-5), prior to the end of 2007. Table 8-1 shows the current utility plans to complete the required inspections as well as plans for nozzles ≥2" NPS but <4" NPS. The table is organized to best highlight differences in the planned inspection timing and mitigation.

As shown in Table 8-1, plants are grouped in seven categories with some small amount of overlap as noted below. These main categories are:

- Plants which do not have Alloy 600/82/182 materials in pressurizer nozzle butt welds
- Plants which have already replaced pressurizers and the new pressurizers use improved materials with greater resistance to PWSCC
- Plants which have already mitigated the pressurizer butt welds by mechanical stress improvement process (MSIP) or full structural weld overlays
- Plants which have completed PDI qualified inspections. (Note: This list includes some duplicate plants with the previous category which have also mitigated. This is done so that the actual pre-mitigation inspection data points are clearly identified.)
- Plants planning to perform inspections, and possibly mitigations, during the Spring 2007 outage season
- Plants planning to perform inspections, and possibly mitigations, during the Fall 2007 outage season
- Plants planning to perform inspections, and possibly mitigations, during the Spring 2008 outage season

Figure 8-1 shows another way of viewing the work that has been accomplished to date and is remaining to be performed over the next 16 months.

Within each category, plants are listed in approximate order of decreasing plant operating hours through the end of January 2006. The operating hours were estimated by dividing the total plant production (MW-hr) through the end of January as reported by Platts *Nucleonics Week* by the current plant capacity (MW)[4]. No adjustments are made for changes in capacity over plant life. Plants above the double line in each category have more operating hours than Wolf Creek at the time the circumferential indications were discovered and plants below the line have fewer operating hours than Wolf Creek.

These data show that by the end of the spring 2008 outage season (approximately end of April 2008) all pressurizer nozzle butt welds will have been PDI inspected and about 95% of the welds

[4] Since all pressurizers operate at essentially the same temperature, there is no need to correct for differences in operating temperature as was the case for reactor vessel top head nozzles. Table 8-1 could also have reported effective full power years (EFPYs) but data in *Nucleonics Week* allowed the approximate operating time to be computed more quickly, and small differences between the methods will have no significant effect on the order of plant operating times.

will have been mitigated by mechanical stress improvement (MSIP) or full structural weld overlays.

Table 8-1
Current Plans for Pressurizer Butt Weld Inspections and Mitigation

Category and Plant	1,000 hrs 2/1/06	Spray	Surge	Safety Relief (# affected)
No Alloy 600 Welds				
- Ginna	244			
- Prairie Island 1	224			
- Point Beach 1	218			
- Point Beach 2	215			
- Kewaunee	212			
- Robinson 2	207			
- Surry 1	203			
- Surry 2	201			
- Indian Point 2	167			
- Indian Point 3	150			
- Diablo Canyon 1	149			
- Turkey Point 3	138			
- Turkey Point 4	134			
- Salem 1	105			
- Salem 2	92			
Pressurizers Replaced - No Alloy 600 Welds				
- Ft. Calhoun	178	Rep Fall 06		
- Millstone 2	159	Rep Fall 06		
- ANO-2	147	Rep Fall 06		
- St. Lucie 1	147	Rep Fall 05		
Alloy 600 Welds Mitigated as of December 2006				
- Oconee 1	211	FW - IN	FW - IN	FW - IN (3)
- Cook 1	170	FW - IN	FW - IN	FW - IN (4)
- San Onofre 2	161	FW - IN		FW - IN (3)
- San Onofre 3	158	FW - IN		FW - IN (3)
- McGuire 2	153	FW - IN	FW - IN	FW - IN (4)
- Wolf Creek	150	FW - IN	FW - IN	FW - IN (4)
- Palisades	149		MS - IN	RepNz (PORV)
- Catawba 1	147	FW - IN	FW - IN	FW - IN (4)
- Cook 2	146	FW - IN	FW - IN	FW - IN (4)
- Sequoyah 2 *	144	*FW - IN*	FW - IN	*FW - IN (4)*
- Calvert Cliffs 1	142	PI - MS	PI - MS	PI - MS (2)
- Byron 1	133	FW - IN	FW - IN	FW - IN (4)
- Beaver Valley 2	127	FW - IN	FW - IN	FW - IN (4)
- Millstone 3	121	FW - IN (F05)		
- South Texas 1	118		FW - IN	
Alloy 600 Welds PDI Inspected Pre-Mitigation as of December 2006				
- Prairie Island 2	222	No A600	No Mit	No A600
- Farley 2	174	No Mit 05		No Mit (1)
- San Onofre 2	161	FW S06	FW F07	FW F07 (3)
- San Onofre 3	158	FW F06	FW F08	FW (3)
- Crystal River 3	157	No Mit 05 (2)		
- Davis-Besse	153	PI - FW S08	PI - FW S08	PI - FW (3)
- Wolf Creek	150	FW F06	FW F06	FW (4)
- Palisades	149	No Mit	MS - IN	ID PT (3) (<4")
- Sequoyah 2 *	144		FW F06	
- Calvert Cliffs 1	142	MS	MS	MS (2)
- Calvert Cliffs 2	137	MS		MS (2)
- Watts Bar	76	No Mit	No Mit	No Mit (4)

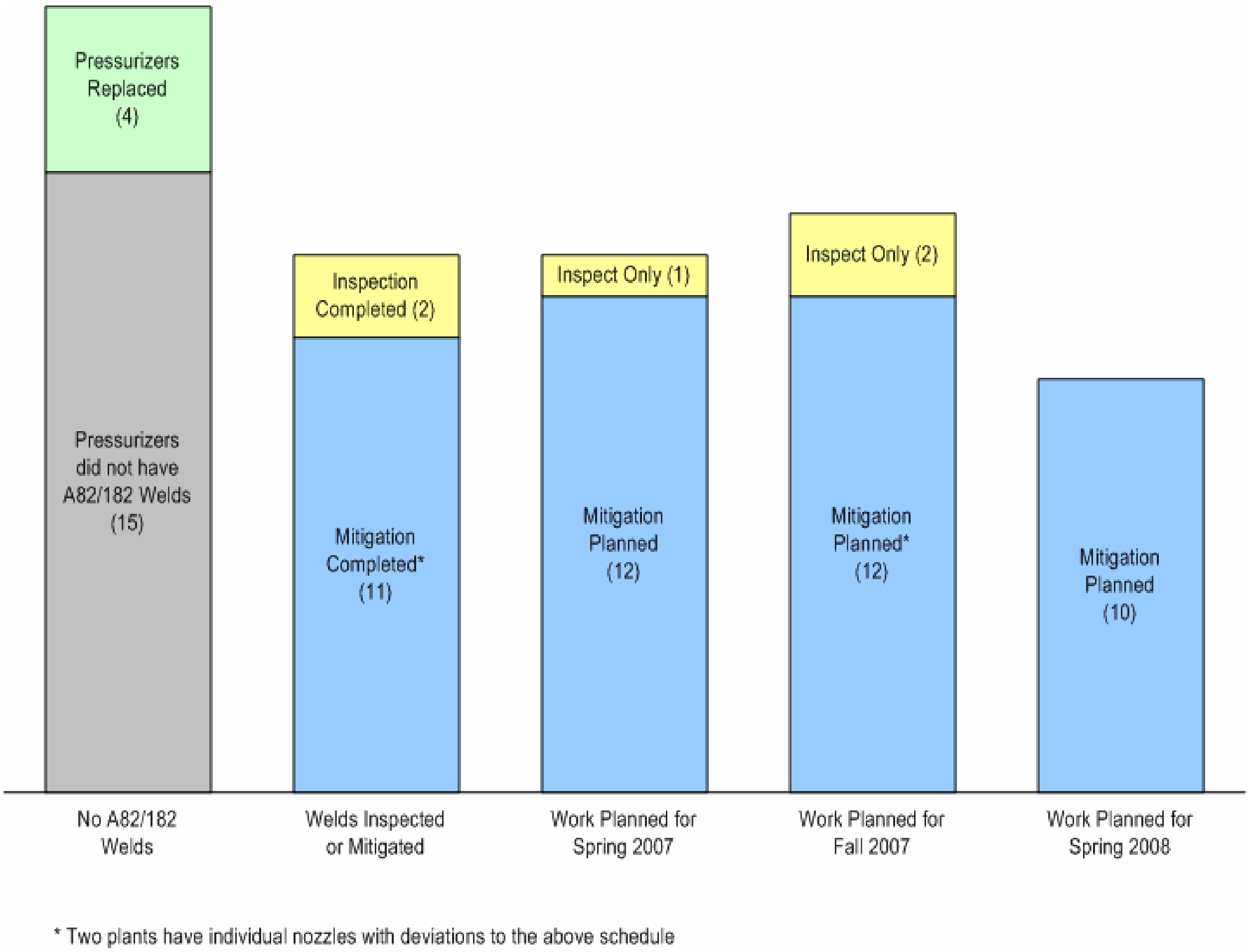
Category and Plant	1,000 hrs 2/1/06	Spray	Surge	Safety Relief (# affected)
Inspections/Mitigation Planned Spring 2007 (Next RFO)				
- Oconee 2	210	FW - IN	FW - IN	FW - IN (3)
- ANO-1	181	FW - IN	FW - IN	FW - IN (3)
- North Anna 2	179	FW - IN	FW - IN	FW - IN (4)
- Farley 2	174		PI - No Mit	PI - No Mit (3)
- McGuire 1	153	FW - IN	FW - IN	FW - IN (4)
- Callaway	149	FW - IN	FW - IN	FW - IN (4)
- Calvert Cliffs 2	137	PI - MS	PI - MS	PI - MS (2)
- Byron 2	131	FW - IN	FW - IN	FW - IN (4)
- Vogtle 2	129	FW - IN	FW - IN	FW - IN (4)
- Palo Verde 1	122	FW - IN	FW - IN	FW - IN (4)
- Millstone 3	121		FW - IN	FW - IN (4)
- Comanche Peak 1	116	FW - IN	FW - IN	FW - IN (4)
- South Texas 2	114	FW - IN	FW - IN	FW - IN (4)
Inspections/Mitigation Planned Fall 2007 (Next RFO)				
- Oconee 3	206	FW - IN	FW - IN	FW - IN (3)
- Farley 1	192	FW - IN	FW - IN	FW - IN (4)
- North Anna 1	184	FW - IN	FW - IN	FW - IN (4)
- TMI	181	PI - No Mit	PI - No Mit	Repl Noz (3)
- Beaver Valley 1	168	FW - IN	No A600	FW - IN (4)
- San Onofre 2	161		PI - FW - IN	
- Crystal River 3	157	FW - IN	FW - IN	FW - IN (3)
- Palisades	149			ID PT (2) (<4")
- Catwaba 2	141	FW - IN	FW - IN	FW - IN (4)
- Shearon Harris	136	FW - IN	FW - IN	FW - IN (4)
- Palo Verde 3	126	FW - IN	FW - IN	FW - IN (4)
- Braidwood 1	124	FW - IN	FW - IN	FW - IN (4)
- St. Lucie 2	111	PI - No Mit	FW-IN	PI - No Mit (3) FW - IN (1)
Inspections/Mitigation Planned Spring 2008 (Next RFO)				
- Summer	154	FW - IN	FW - IN	FW - IN (4)
- Davis-Besse	153	PI - FW - IN	PI - FW - IN	PI - FW - IN (3)
- Diablo Canyon 2	147	FW - IN	FW - IN	FW - IN (4)
- Vogtle 1	142	FW - IN	FW - IN	FW - IN (4)
- Waterford 3	140	FW - IN	FW - IN	FW - IN (3)
- Braidwood 2	129	FW - IN	FW - IN	FW - IN (4)
- Palo Verde 2	119	FW - IN	FW - IN	FW - IN (4)
- South Texas 1	118	FW - IN		FW - IN (4)
- Comanche Peak 2	96	FW - IN	FW - IN	FW - IN (4)
- Seabrook	95	FW - IN	FW - IN	FW - IN (4)
Inspections/Mitigation Planned beyond Spring 2008				
- San Onofre 3	158		Complete F2006 FW attempt	
- Palisades	149			ID PT (1) (<4")

Code:
- [grey] = No Alloy 600 Type Weld Material
- [light green] = Indication(s) Dispositioned as Fabrication-Related
- [orange] = Indication(s) Dispositioned as Weld Cracks
- [pink] = PDI Examinations Complete but with Limitations
- [purple] = PDI examination Complete for MRP-139 (>90% Circ)
- [blue] = Westinghouse
- [green] = Combustion Eng
- [yellow] = Babcock & Wilcox

PI Pre-mitigation PDI exam
IN Post-mitigation PDI exam
MS Mech. Stress Improvement
FW Full Structural Weld Overlay
* Outage still in progress - Surge pre & post-mitigation PDI exam complete, two safety nozzles overlay and PDI exam complete as of 12-14-06

* As of December 18, 2006, Sequoyah 2 has completed the planned structural weld overlay and the post-overlay NDE.

Figure 8-1
Chart of PWR Plant Pressurizer Nozzle Butt Weld Inspection/Mitigation Status



9. Probability of Critical Size Flaws in Pressurizer Nozzle Welds

As of the end of 2006, approximately 32 pressurizer nozzle butt welds have been inspected using procedures and operators qualified to performance demonstration initiative (PDI) criteria and where the geometry is such that there is 90% coverage of the inner 1/3 of the wall thickness. In addition, other inspections have been performed in accordance with PDI qualified procedures in which some limitations were present, but which were still considered meaningful examinations. Other meaningful data can be gleaned from inspections of non-pressurizer, Alloy 82/182 butt welds and leakage experience. Further, analysis work in Section 6 shows that the critical flaw sizes are large and that it is highly likely that leaks will be discovered by system walkdowns and on-line leakage monitoring well before flaws reach their critical size.

This section describes a relatively simple probabilistic model that has been used to estimate the probability of a critical size flaw occurring in the remaining uninspected nozzle butt welds prior to planned inspections and or mitigation of all such welds under the planned MRP-139 inspection program.

Flaw Size Distribution at the End of 2006

Inspection results for a total of 41 Alloy 82/182 butt welds were included in this probabilistic assessment, as summarized in Table 9-1. Seven of these were reported as having circumferential indications, ten as having axial indications, and the remaining 24 were reported as being clean. Note that axial indications in this table are listed as having zero circumferential length, and that the database includes three non-pressurizer nozzles (hot and cold leg drain nozzles) that contained flaw indications. A plot of the data, in terms of indication depth divided by thickness (a/t) and indication length divided by circumference (l/circ) is provided in Figure 9-1. This plot also contains loci of critical flaw sizes for a typical surge and safety nozzle under normal operating conditions (without seismic loads). In this plot, nozzles with axial indications appear on the vertical axis, and clean nozzles are plotted randomly in a 10% box in the lower left hand corner, which corresponds to the approximate detectability threshold of the examinations.

A "Criticality Factor" (CF) was computed for each of the nozzles in Table 9-1 (last column), by multiplying the reported indication lengths and depths and dividing the product by the approximate cross sectional area of the nozzle at the flaw location. CF corresponds, approximately, to the percentage of circumferential cross sectional area that is lost due to the observed indications, assuming that they are cracks with a depth equal to their maximum reported depth over the entire length of the indication. A cumulative distribution of the criticality factors was then developed using median rank regression [34]. The individual data points are illustrated in Figure 9-2, along with exponential and Weibull fits of the data.

Predicted Flaw Size Distributions at Next Three Outage Seasons

The flaw size distribution in Figure 9-2 represents a snapshot in time at the end of the fall 2006 outage season. It is considered appropriate to treat the data in this manner, since the plants bracket the Wolf Creek nozzles in terms of operating time, and since there are other factors that contribute to butt weld PWSCC that tend to discount the effect of operating time on the PWSCC degradation mechanism.

In order to evaluate future failure probabilities associated with various inspection programs, it is necessary to project the data into the future considering potential crack propagation due to PWSCC. A conservative crack growth projection was developed for this purpose using preliminary crack growth analyses of the Wolf Creek indications performed by the NRC and its contractors [35]. Criticality factors were computed versus time from projected increases in crack lengths and depths provided by the NRC for the Wolf Creek surge and relief nozzles, using their "K-dependent" cases with worst case residual stress assumptions. The resulting criticality factor increases at six, twelve, and eighteen months into the future were added to the current flaw size distribution as illustrated in Figure 9-3. Note that this figure conservatively increases all flaw sizes in the distribution by the maximum rates computed for the Wolf Creek indications. Figure 9-3 utilizes the Weibull fit for these projections, since it was found to be more conservative than the exponential fit.

Probability of Rupture as Function of Flaw Size

Also shown in Figures 9-2 and 9-3 is a distribution of critical flaw sizes predicted to cause pipe rupture (i.e. a fragility curve). This distribution was estimated in terms of the criticality factor (CF) from critical flaw size data provided by the NRC [35]. NRC provided two critical flaw sizes each for partial-arc, through-wall flaws in the Wolf Creek surge and safety/relief nozzles. These were 156° of circumference (with SSE seismic) and 184° (normal operation w/o seismic) for the surge nozzle and 219° (with SSE seismic) and 240° (normal operation w/o seismic) for the safety/relief nozzle. These correspond to percentages of circumference equal to 43.3%, 51.1%, 60.8%, 66.7%, respectively, which can also be equated to CFs, since the flaws are assumed through wall over their entire length. Criticality factors were only computed based on through wall flaw calculations, which is a conservative assumption, since nozzles can generally sustain larger cracked percentages of circumference for part-through-wall flaws than for through-wall flaws.

The mean and standard deviation for the above rupture CFs were computed as 55.5% and 10.3%, respectively, from the four NRC computed values, and critical flaw sizes were assumed to be normally distributed to produce the critical flaw size distribution shown in Figures 9-2 and 9-3. While this approach is not totally rigorous, and is based upon a small number of critical flaw size computations, the resulting distribution (mean of 55.5% and standard deviation of 10.3%) is considered reasonable and conservative for purposes of this scoping analysis. It implies that 50% of the nozzles would fail at a CF of 55.5%, and that ~0.1% would fail at ~25%, which is considered an extreme lower bound critical flaw size, including the effects of SSE seismic loads. It thus builds into the analysis, in an approximate manner, the relatively low probability of a seismic event occurring during the evaluation period. One final adjustment was to truncate the distribution at 25%, to avoid having Monte Carlo results biased by occasional critical flaw sizes from the extreme lower tail of the normal distribution. (Considering the ductility of Alloy 82/182 weld metal, there is virtually no chance of a Section III Class 1 nozzle rupturing with 75% or more of it's circumferential cross sectional area intact.)

Probability of Rupture versus Time

Rupture probability was then calculated via convolution integral of the two flaw distributions in Figure 9-2, adjusting the observed flaw distribution for PWSCC flaw growth as shown in Figure 9-3. The calculations were conducted using Monte-Carlo sampling from the two distributions, and recording a failure for each simulation in which the flaw size selected from the observed (or future projected) flaw distribution exceeded that from the critical flaw size distribution. A total of 1 x 10^8 simulations were performed for each time period, which is more than sufficient for convergence considering the resulting failure probabilities. The results are presented in Table 9-2. These results correspond to the predicted cumulative failure probability (per nozzle) as a function of time over the next 18 months. Incremental failure probabilities for each six month period were also computed, and recorded in the last column of the table, from the differences of the cumulative results at each time period.

Sensitivity of the results to the various distributions was also evaluated. Based on discussions with an NRC expert, a flaw size distribution was developed based only on nozzles that contained circumferential flaws, and factored by the frequency of inspected nozzles that had circumferential flaws (7/41). This distribution was combined with a less conservative fragility curve, and resulted in lower probabilities than those reported in Table 9-2.

Predicted Pressurizer Nozzle Butt Weld Rupture Frequency at Next Three Outages
Table 9-3 presents the key results of this study, interpreted in terms of the numbers of nozzles projected to be examined at various times under the currently proposed industry response to MRP-139. The first four rows of the table present the approximate numbers of plants and nozzles to be inspected and/or mitigated through spring 2008. These data are interpreted from Table 9-1, and include planned inspections/mitigations in each outage season, as well as the remaining numbers of plants/nozzles at the beginning of each period. The raw Monte Carlo probability data from Table 9-2 are entered in rows 5 and 6 (shaded), and multiplied by the applicable numbers of uninspected, unmitigated nozzles in row 7. Finally, the results are adjusted to give the weld rupture and core damage frequencies, per plant per year, in rows 8 and 9. The adjustments included dividing by the remaining number of plants in each time period, plus a time factor adjustment to put the data on a per-year basis. Core damage frequency (CDF) was computed by multiplying by the conditional core damage probability given a pressurizer nozzle LOCA, assumed to be 10^{-3}.

It is seen that the resulting CDFs are quite small, increasing from 3.26 E-8 to 2.7 E-7 with time until all pressurizer nozzles are inspected under the MRP-139 program. All computed CDF values are well below the target value of 1.0 E-6 in RG 1.174.

Effect of Accelerated Inspections in Reducing Risk of Rupture and CDF
Finally, the probabilistic analysis results were used to evaluate the potential benefits of accelerating the inspections relative to the schedule proposed by the industry in response to MRP-139. These results are summarized in Table 9-4, comparing the current MRP-139 program to two accelerated programs:

1. A program in which the Spring 2008 examinations are rescheduled for Fall 2007
2. A program in which all inspections are rescheduled for Spring 2007

The average failure frequencies for these two programs, as well as for the current MRP-139 program, were computed by multiplying the Monte Carlo failure probabilities times the total number of remaining plants in each six month period and then summing the results for all periods. The failure frequencies were then adjusted to the standard "per plant, per year" basis by dividing by the total number of affected plants (50) and normalizing to one year (x 12/18). The results indicate relatively modest gains in rupture and core damage frequencies associated with accelerated inspection programs, and as previously noted, the core damage frequencies are already within NRC guidelines under the MRP-139 inspection schedule.

In the last two rows of Table 9-3, an attempt is made to estimate the industry impacts to achieve these relatively modest benefits. As previously mentioned, any acceleration of the MRP-139 schedule would result in forced shutdowns, and rough estimates of the associated reductions in rupture frequencies are provided in Table 9-3.

Summary and Conclusions

The following is a summary of the work performed and the main conclusions:

- A significant data base of PDI qualified inspections and other meaningful data sources on Alloy 82/182 pressurizer nozzle butt welds exists as of the end of the 2006 outage season (41 of 279 nozzles). These inspection results were used to develop an expected distribution of nozzle flaws at the current time.
- The resulting nozzle flaw distribution was projected (conservatively) into the future based on NRC PWSCC crack growth computations for the Wolf Creek surge and relief nozzle indications.
- A critical flaw size distribution (at which nozzle rupture is predicted) was also developed based on NRC computations for Wolf Creek. This distribution takes into account the low probability of a seismic event occurring during the remaining time period until all nozzles are inspected/mitigated.
- The distributions were evaluated using Monte Carlo methods to determine the probability of a nozzle rupture versus time.
- The resulting probabilities were multiplied by the applicable numbers of remaining uninspected/unmitigated nozzles to estimate nozzle rupture frequencies. The rupture frequencies and associated core damage frequencies predicted under the proposed industry inspection schedule (MRP-139) are small and well below associated NRC guidance (R.G. 1.174).
- The rupture probabilities were also used to estimate the benefit of accelerated inspection schedules, over and above the proposed industry inspection program. The risk improvements are shown to be modest, while the impact of forced shutdowns required to perform these inspections would be large.
- Where uncertainties in the evaluation process were encountered, conservative assumptions were taken.

Table 9-1
Plant Inspection Data Used in Probabilistic Analysis

Plant	Inspection Date	Nozzle	Crack Depth (a)	Crack Length (l)	a/t	l/circ	Criticality Factor
Tihange 2	2002	Surge	0.600	0.000	43%	0%	0.00%
Tsuruga	2003	Relief	1.000	0.000	100%	0%	0.00%
Tsuruga	2003	Safety	0.900	0.000	90%	0%	0.00%
TMI	2003	Surge	0.585	0.000	45%	0%	0.00%
Millstone 3	2005	Spray	0.220	3.750	24%	20%	4.86%
Calvert 2	2005	CL Drain	0.056	0.628	10%	10%	1.00%
Calvert 2	2005	HL Drain	0.392	0.000	70%	0%	0.00%
DC Cook	2005	Safety	1.232	0.000	88%	0%	0.00%
Farley 2	2005	Safety	0.000	0.000	0%	0%	0.00%
Farley 2	2005	Spray	0.000	0.000	0%	0%	0.00%
Wolf Creek	2006	Relief	0.335	7.700	26%	32%	8.21%
Wolf Creek	2006	Surge	0.465	7.000	31%	15%	4.60%
Wolf Creek	2006	Safety	0.297	2.500	23%	10%	2.36%
Calvert 1	2006	Surge	0.400	2.400	31%	6%	1.84%
Calvert 1	2006	HL Drain	0.100	0.450	27%	5%	1.33%
Wolf Creek	2006	Safety	0.000	0.000	0%	0%	0.00%
Wolf Creek	2006	Safety	0.000	0.000	0%	0%	0.00%
Wolf Creek	2006	Spray	0.000	0.000	0%	0%	0.00%
SONGS 2	2006	Safety	0.420	0.000	30%	0%	0.00%
SONGS 2	2006	Safety	0.420	0.000	30%	0%	0.00%
SONGS 2	2006	Safety	0.000	0.000	0%	0%	0.00%
SONGS 2	2006	Spray	0.000	0.000	0%	0%	0.00%
Davis Besse	2006	CL Drain	0.056	0.000	7%	0%	0.00%
Calvert 1	2006	Relief	0.100	0.000	8%	0%	0.00%
SONGS 3	2006	Safety	0.000	0.000	0%	0%	0.00%
SONGS 3	2006	Safety	0.000	0.000	0%	0%	0.00%
SONGS 3	2006	Relief	0.000	0.000	0%	0%	0.00%
SONGS 3	2006	Spray	0.000	0.000	0%	0%	0.00%
SONGS 3	2006	Surge	0.000	0.000	0%	0%	0.00%
D-B	2006	Safety	0.000	0.000	0%	0%	0.00%
D-B	2006	Safety	0.000	0.000	0%	0%	0.00%
D-B	2006	Relief	0.000	0.000	0%	0%	0.00%
D-B	2006	Spray	0.000	0.000	0%	0%	0.00%
D-B	2006	Surge	0.000	0.000	0%	0%	0.00%
Watts Bar	2006	Surge	0.000	0.000	0%	0%	0.00%
Watts Bar	2006	Relief	0.000	0.000	0%	0%	0.00%
Watts Bar	2006	Safety	0.000	0.000	0%	0%	0.00%
Watts Bar	2006	Safety	0.000	0.000	0%	0%	0.00%
Watts Bar	2006	Safety	0.000	0.000	0%	0%	0.00%
Watts Bar	2006	Spray	0.000	0.000	0%	0%	0.00%
Prairie Is.	2006	Surge	0.000	0.000	0%	0%	0.00%

Table 9-2
Predicted Rupture Probability (per nozzle, per six months)
vs. Time from Monte Carlo Analyses

Time Period	P(rupture) Cumulative	p(rupture) Incremental
Current	3.27E-06	
6 Mo	6.78E-06	3.51E-06
12 Mo	1.65E-05	9.76E-06
18 Mo	6.24E-05	4.59E-05

Table 9-3
Summary of Key Results

	Fall 2006	Spring 2007	Fall 2007	Spring 2008
Number of Uninspected Welds Through Indicated Date	279	195	121	53
Number of Plants with uninspected nozzles	50	34	21	9
Planned Nozzle Inspections/ Mitigations at Indicated Date	84	74	68	53
Number of Plants with Planned Nozzle Inspections/Mitigations	16	13	12	9
Probability of Weld Rupture (per nozzle-cumulative)	3.27E-06	6.78E-06	1.65E-05	6.24E-05
Incremental Rupture Probability (per 6 months)	N/A	3.51E-06	9.76E-06	4.59E-05
Nozzle Rupture Frequency - all plants in category, per 6 months	N/A	6.84E-04	1.18E-03	2.43E-03
Nozzle Rupture Frequency (per plant year)	N/A	3.26E-05	8.09E-05	2.70E-04
Core Damage Frequency (per plant year)[1]	N/A	3.26E-08	8.09E-08	2.70E-07
Number of Plants with Accelerated Inspections if all Must be Inspected by Date	N/A	21	9	N/A
Reduction in Nozzle Rupture Frequency if all Must be Inspected by Date	N/A	-4.82E-05	-3.23E-05	N/A
Reduction in Core Damage Frequency if all Must be Inspected by Date[1]	N/A	-4.82E-09	-3.23E-08	N/A

Notes:
1. Assumes probability of CDF given rupture = 1E-3

Table 9-4
Effect of Accelerated Inspection Schedule on Predicted Rupture and Core Damage Frequencies

	Average Failure Freq. (per plant year)	Core Damage Frequency	Target Core Damage Frequency
MRP-139 Inspection Program	5.73E-05	5.73E-08	<1.00E-6
Accelerated Inspections (Spring-08 inspections pushed up to Fall-07)	2.50E-05	2.50E-08	<1.00E-6
Accelerated Inspections (All inspections pushed up to Spring-07)	9.13E-06	9.13E-09	<1.00E-6

Figure 9-1
Plot Showing Normalized Indication Lengths and Depths in Comparison to Critical Flaw Loci. Clean Inspections are Shown within Approximate 10% NDE Detectability Threshold

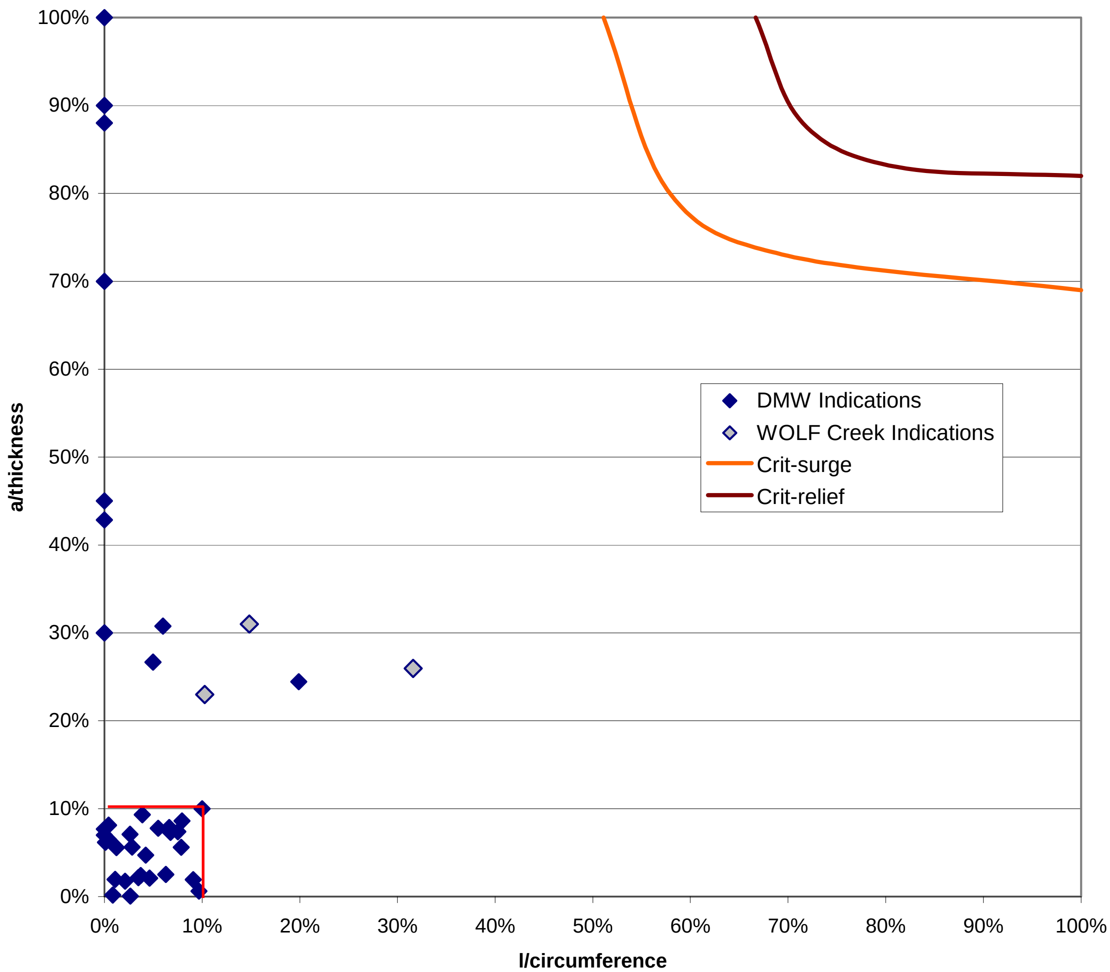


Figure 9-2
Observed Flaw Distribution at End of Current (Fall 2006) Outage Season.
(Weibull and Exponential Curvefits Shown, as well as Critical Flaw Size Distribution)

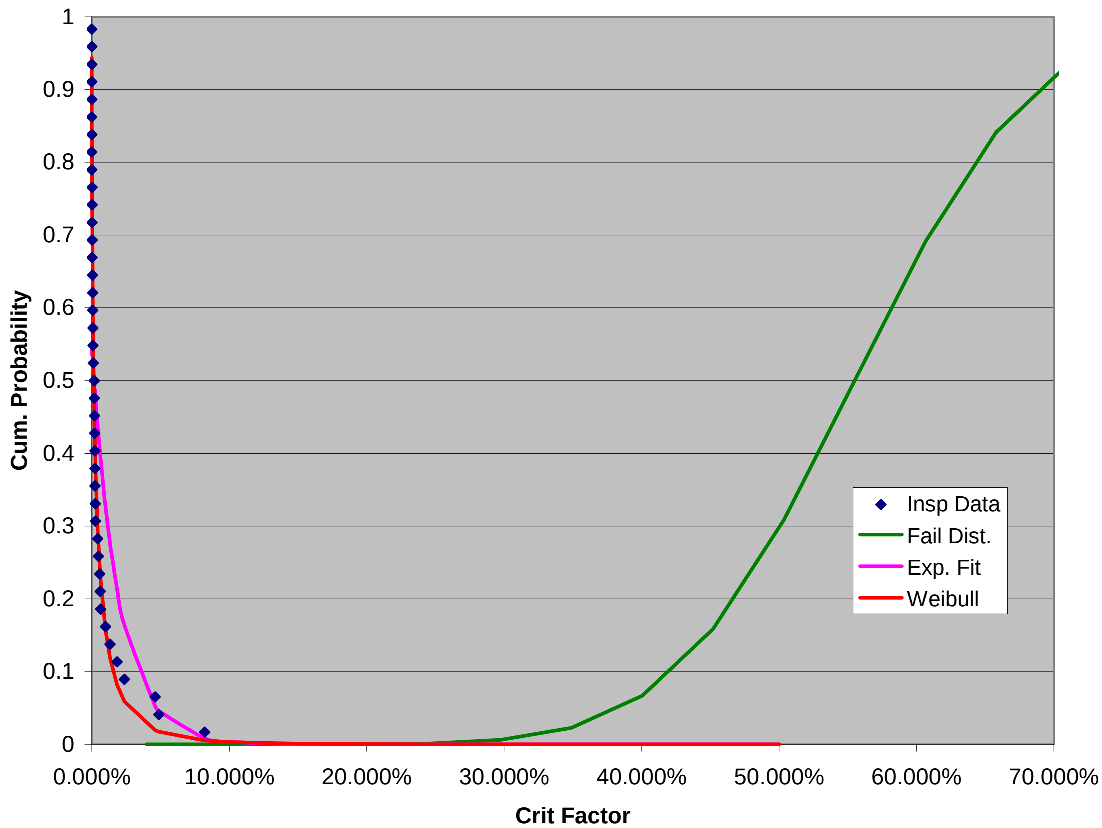
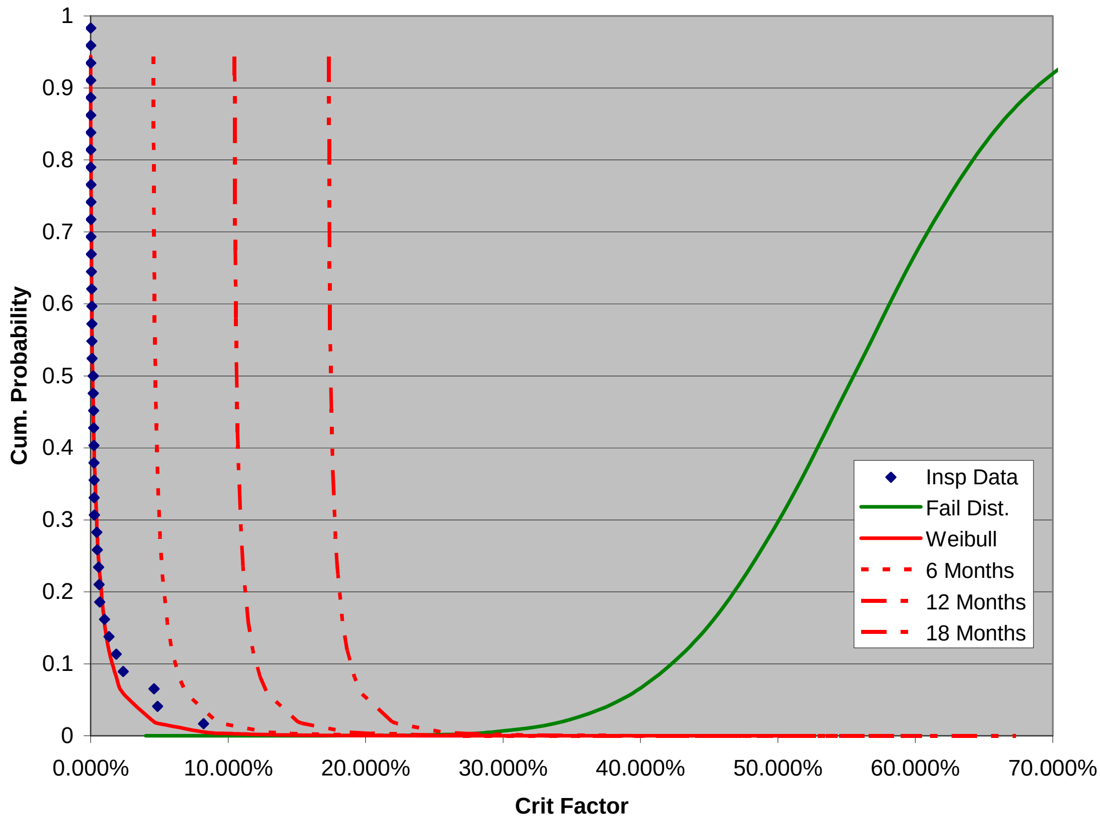


Figure 9-3
Projected Growth of Observed Flaw Size Distribution in Figure 8-2 with Time, Based on NRC Conservative PWSCC Crack Growth Computations for Wolf Creek Indications



10. Leakage Detection

Leakage detection provides a major defense-in-depth for PWR plants and has detected three through-wall cracks at Alloy 82/132/182 butt weld locations in PWR plants. These are:

- Leaking pressurizer relief nozzle butt weld at Palisades in 1993
- Leaking reactor vessel outlet nozzle butt weld at VC Summer in 2000
- Leaking pressurizer relief nozzle butt weld at Tsuruga 2 in 2003

Based on this experience, leakage detection has been a major commitment to provide defense-in-depth until all butt weld have been inspected per PDI qualified methods or mitigated to preclude PWSCC. Major milestones are described below.

Recommendations from MRP-44 Part 1, Interim Butt Weld Safety Assessment
Four recommendations to utilities were provided by MRP letter dated March 1, 2001 [36] regarding inspections and leakage detection. These recommendations were:

- Enhance the sensitivity of personnel performing inspections for boric acid per the requirements of generic Letter 88-05
- Enhance the sensitivity of NDE inspection personnel to inspection capabilities, limitations and results
- Enhance the sensitivity of operations personnel to small changes in containment leak rates, and possible leak sources
- Encourage the use of mockup demonstrations of NDE capabilities for any planned inspections

MRP Letter 2004-05, Visual Inspection of Alloy 82/182 Butt Welds
In April 2004, prior to issue of the MRP-113 butt weld safety assessment in July 2004, the MRP issued requirements to perform bare metal visual inspections of primary coolant system butt welds containing Alloy 82 and 182 weld metal within the next two RFO's after November 20, 2003 [37]. For normal 18 month outage cycles, the bare metal visual inspections were to have been completed by November 2006.

MRP-139, Butt Weld Inspection and Evaluation Guidelines
Table 6-2 of the butt weld inspection and evaluation guidelines states that bare metal visual examinations are required of each pressurizer and hot leg butt weld 4 inch NPS and greater, and the B&W plant pressurizer safety relief nozzle welds, every refueling outage that volumetric examinations are not being performed until the butt welds are mitigated or replaced. Since volumetric examination involves removal of insulation, this requirement effectively requires a bare metal visual examination every refueling outage until the butt weld material is mitigated or replaced.

MRP Letter 2005-014, Primary System Butt Weld Inspection and Evaluation Guideline
This letter transmits the butt weld inspection and evaluation guidelines (MRP-139) and reiterates that the requirements are "Mandatory" [38].

INPO Activities Related to Leakage Detection
INPO completed reviews at all 41 PWR plant sites by the end of 2005 that in part evaluated leakage detection/monitoring and has visited nine sites a second time. Key findings regarding "Beneficial Practices" are as follows:

- Continuous monitoring of parameters associated with potential primary system leakage by Control Room Operator provides a high level of awareness and sensitivity with regard to primary system structural integrity.
- Licensed Operators have a high degree of awareness with regard to the current reactor coolant system leakage rates and immediate indications that would be evident in the case of a small reactor coolant system leak.
- The program and processes used to monitor reactor coolant system (RCS) leakage are comprehensive and were improved to reduce uncertainties and to provide management with accurate information to assess RCS leakage.

The following recommendations for improvement were identified:

- Establish a lower limit of reactor coolant system (RCS) leakage that would initiate investigation by operation personnel.
- Establish a protocol for reviewing all parameters associated with RCS leakage to determine if an adverse trend exists that requires further investigation.
- Benchmark the reactor coolant system unidentified leak rates against industry peers with regard to the test methodology used and the values being measured.
- Determine the appropriate threshold for requiring operators to investigate indication of containment leakage, and revise operation procedures to reflect this new threshold. Consider benchmarking plants and other units of similar design in assessing the appropriate action threshold.

PWROG Activities Related to Leakage Detection
In response to regulator concerns related to leakage detection and monitoring at PWRs (RIS-2003-13) [39], the PWROG issued two new guidelines in September of 2006. The first is standard process and methods for calculating RCS leak rate at PWRs [40]. The second, is standard action levels and response guidance for PWRs [41].

The purpose of the first document is to provide standard guidelines for RCS leak rate calculational methods, assumptions, and leak rate reporting conditions.

The guideline recommends the use of a two snapshot mass balance method to calculate RCS leak rate. Where relevant, RCS and connected system conditions are taken at Time-1 and Time-2. The difference in water mass is computed between Time-1 and Time-2. And the difference is expressed as a volumetric leak rate in gallons per minute. This guideline also recommends that all plants report the RCS leak rate in gallons per minute, where the reported gallon is normalized to 70°F.

In addition to providing a standard guideline for calculating and reporting RCS leak rate, this report also includes a statistical analysis to quantitatively determine the "minimum level of detectability" (the smallest unidentified leak rate that can be detected in a given period of time using a given “alarm” function such as a leak rate Action Level).

The purpose of the second document is to provide standard action levels and response guidelines consistent with the intent of NRC Inspection Manual, IMC 2215, Appendix D [42].
The PWROG guidelines take a statistical approach similar to NRC IMC 2215, Appendix D [42] by establishing a quarterly baseline dataset of valid unidentified RCS leak rate results. Statistical values for the baseline mean (μ) and standard deviation (σ) are computed and used to determine nominal limits and progressive action levels.

As time moves forward each new RCS leak rate result is compared to the plant specific nominal limits and the appropriate action is taken. The standard action levels are a combination of the following:

1. Absolute Unidentified Leak Rate in gpm.
2. Deviation from the baseline mean in gpm.
3. Total integrated unidentified Leakage in gallons.

The action levels are constructed to complement each other. One type of Action Level is a check of the other. Within each type of Action Level, the triggers get progressively larger, so as to focus attention on detection of very small leaks since larger leaks will be more apparent and therefore easier to detect. The action levels are arranged into three tiers. Each tier contains at least one action level for each type so as to corroborate each other. Tier one, two and three Action Levels are designed to address progressively larger leaks.

Tier One Action levels:

IF ANY of the following Action Levels are exceeded:

1. One seven (7) day rolling average of daily Unidentified RCS leak rates > 0.1 gpm.
2. Nine (9) consecutive daily Unidentified RCS leak rates > baseline mean [μ].

Tier Two Action Levels:

IF ANY of the following Action Levels are exceeded:

1. Two consecutive daily Unidentified RCS leak rates > 0.15 gpm.
2. Two (2) of three (3) consecutive daily Unidentified RCS leak rates > [μ + 2σ].
3. Short Term (30 Day) Total Integrated Unidentified Leakage > 5,000 gallons.

Tier Three Action Levels:

IF ANY of the following Action Levels are exceeded:

1. One daily Unidentified RCS leak rate > 0.3 gpm.
2. One (1) daily Unidentified RCS leak rate > [μ +3σ].
3. Long Term (Operating Cycle) Total Integrated Unidentified RCS Leakage > 50,000 gallons.

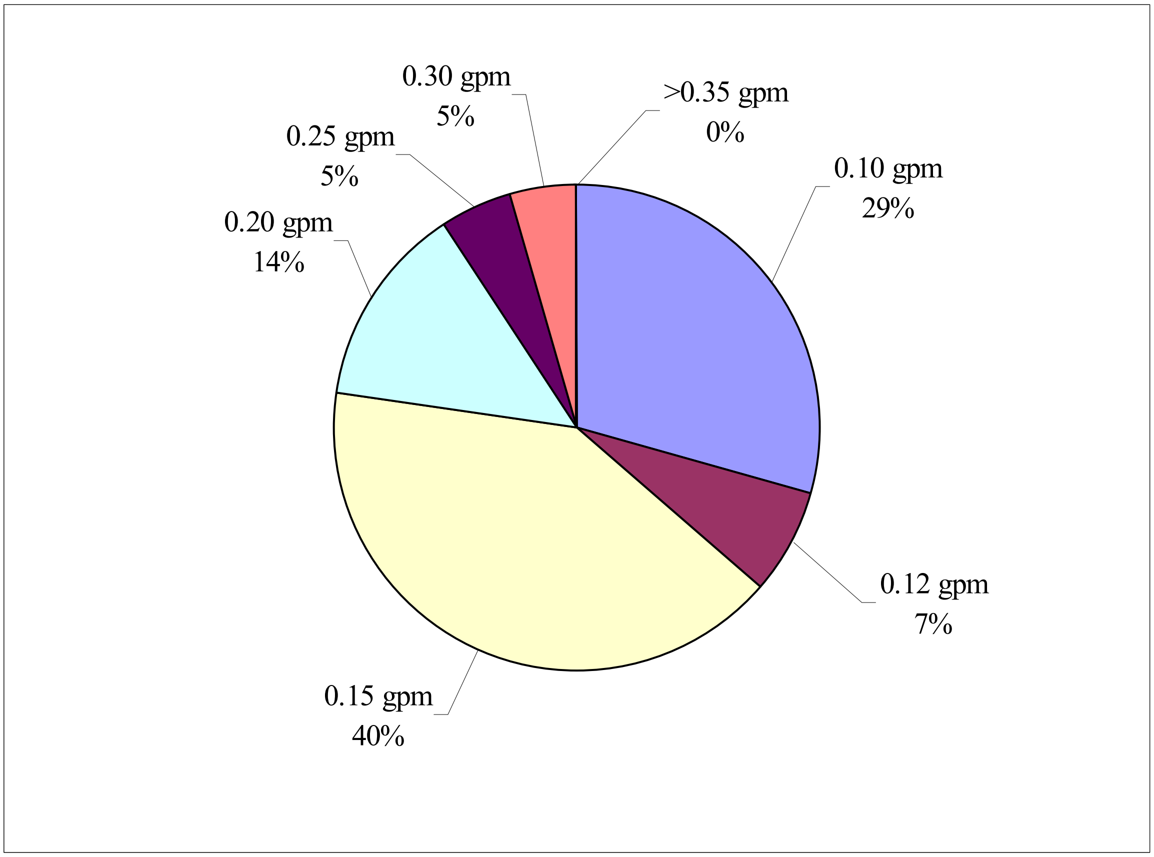
These action levels are considerably lower than current Technical Specification limits of 1 gpm.

Plant Survey
A survey of current procedural requirements at plants was conducted to assess typical plant response to changes in unidentified leakage. Although the details regarding how the criteria are applied vary from utility to utility, the action levels are generally similar to those proposed by the Owners Group report. Some plant procedures require action at an absolute value of unidentified leakage while others establish trigger levels relative to a rolling baseline value. Some are described more in terms of a change from a defined baseline while others apply a combination of these triggers as is suggested by the OG report.

Notwithstanding these important programmatic details, all plants that reported have procedural requirements to take action in response to an adverse trend in unidentified leakage at levels well below the rate that is required under Technical Specifications. The survey results are graphically presented in Figure 10-1. [The survey did not ask the frequency at which unidentified leakage is currently assessed (e.g., 24, 48, 72 hrs.)]

Conclusion Regarding Leakage Detection
It is concluded that PWR plants are capable of reliably detecting leaks from pressurizer butt welds at an early enough stage to prevent rupture and most if not all currently have such requirements in place. Implementation of the Owners Group guidelines will improve consistency and accuracy of the measurements and action levels across the fleet.

Figure 10-1
Unidentified Leakage Rate Monitoring Trigger Levels
Unidentified Leak Rate or Δ above Baseline (44 Plants Reporting)



11. Boric Acid Corrosion

The subject of boric acid corrosion from pipe butt welds was addressed in Section 6.8 of MRP-113. The conclusion from this work was that, while the potential for boric acid corrosion cannot be ruled out, the potential for significant boric acid corrosion is considered to be very low. This conclusion was supported by six main technical points that are not repeated herein.

Over the two years since MRP-113 was published, significant additional work has been accomplished regarding leakage detection and boric acid corrosion testing and modeling. The following additional support can be offered to the previous conclusion:

- Leakage from one of the pressurizer steam space nozzles (those other than surge and spray) is unlikely to create a significant liquid environment, making significant boric acid corrosion extremely unlikely for such locations. The steam in the pressurizer steam space is saturated steam, so the potential for a small amount of liquid to be created by a leak cannot be ruled out.
- MRP testing completed so far (MRP-163; MRP-165) and ANL testing (NUREG/CR-6875) has shown that galvanic effects are generally not expected to significantly increase the potential for significant boric acid corrosion. A galvanic mechanism is a potential concern for pressurizer nozzle butt welds because of the use of stainless steel, low alloy steel, and Alloy 82/182.
- Since MRP-113 was issued in July 2004, there have been no new reported cases of leakage due to Alloy 82/132/182 pipe butt weld cracking, and therefore no boric acid corrosion from this source.
- Utilities are more sensitive to the potential consequences of small leaks as discussed in the previous section, and therefore the risk of significant boric acid corrosion has been reduced.

12. Conclusions

The following is a summary of recently completed work related to Wolf Creek pressurizer nozzle butt weld indications and the conclusions regarding butt weld inspection requirements.

Wolf Creek Indications

In addition to the previously reported indications, new information has been received regarding repairs during fabrication. This new information suggests that some of the indications may be related to weld repairs. The circumferential arc length and similar maximum depths of most of the indications are unique relative to previous indications in PWR butt welds and may be related to the weld repairs and related repair residual stresses. However, given the fact that no metallurgical samples were taken, it has been conservatively assumed that the reported Wolf Creek indications are PWSCC.

Impact of Wolf Creek Indications on Butt Weld Safety Assessment (MRP-113)

The existence of the indications reported at Wolf Creek is generally consistent with the work performed in preparation of the final butt weld safety assessment (MRP-113). Specifically:

- While axial flaws are typically expected, circumferential cracks have been seen in other welds and were addressed in MRP-113.
- Large circumferential flaws have occurred in Alloy 600 materials at pressurizer butt welds (Palisades and Bettis test reactor): these flaws resulted in a greater loss of cross section area than at Wolf Creek, and these conditions were addressed in MRP-113.
- The potential for weld repairs to create large circumferential flaws in Alloy 82/182 butt welds was anticipated and is addressed in MRP-113 and MRP-114.
- The presence of multiple circumferential flaws in the Wolf Creek surge nozzle butt weld is consistent with findings and analyses in MRP-113 and MRP-114.
- It is not surprising that previous volumetric inspections in 1993 and 2000 did not detect the indications. It is widely accepted that the UT "state of the art" in the 1993-2000 time frame could have resulted in indications the size of those currently reported not being detected.

Additional Analysis Work since Discovery of Wolf Creek Indications

As documented in this summary report, the industry has performed considerable additional work since discovery of the Wolf Creek indications to ensure that the inspection requirements of MRP-139 are still valid. This work has involved several main areas as follows:

- <u>Reassessment of Crack Growth Rates</u>
  Results of calculations performed by the MRP are consistent with findings of the NRC that cracks could grow through wall rapidly assuming the conditions used by the NRC. However, such calculations lead to the improbable result that four of five rapidly growing cracks have been detected at similar depths after about 18 full power years of operation. This condition is statistically unlikely. Unfortunately, given the lack of a physical specimen, the reason for the difference between modeling assumptions and behavior of indications in the Wolf Creek welds cannot be conclusively determined. Possible factors

could include the indications being some type of fabrication flaw not detected during earlier inspections, or the fact that the indications represent PWSCC cracks that have grown into a zone of low stress where crack growth has slowed or arrested.

- Reassessment of Critical Flaw Sizes and Leakage Before Risk of Rupture
  Calculations in Section 5 show that the critical flaw sizes in the ductile Alloy 82/182 weld metal are larger than previously reported. The potential for large crack opening areas occurring before rupture is supported by analysis and NRC sponsored tests on precracked Alloy 600 pipes. Additional fracture mechanics calculations were performed to demonstrate that shallow cracks which initiate over the full 360º circumference are likely to grow in a manner that result in leakage before rupture under the presence of applied pipe bending moments.

- Confirmation of Extremely Low Probability of Rupture
  A probabilistic analysis performed using butt weld inspection results to date and calculations of critical flaw size confirm that the probability of rupture is extremely low and that the reduction of risk by accelerating planned pressurizer inspections is not significant.

- Improvement in Leakage Reduction Capability
  Work had been completed prior to discovery of the Wolf Creek indications to assess and improve plant leakage detection programs. Interim guidance has been distributed and formal requirements are anticipated early next year. This work will result in consistent reliable detection of leakage in the range of 0.1 to 0.3 gpm over periods of 1 to 7 days across the fleet. Further, of 44 plants responding to a recent survey request, all have existing procedural requirements that trigger corrective action at levels ≤0.3 GPM. Therefore, current practice and anticipated fleet wide improvements provide significantly better information regarding leaks than the current 1 gpm Technical Specification requirements.

Conclusions
The following conclusions have been reached from the work described herein:

- There is nothing regarding the Wolf Creek indications that would invalidate either the MRP-113 safety assessment or the MRP-139 butt weld inspection requirements. The risk of leaks is low and the risk of rupture is extremely low and constantly decreasing as inspections and mitigation are performed. .
- The industry does not intend to manage butt weld PWSCC by leakage as evidenced by the commitment to have all Alloy 82/182 butt welds inspected using PDI qualified equipment, procedures and operators and/or mitigated by the spring of 2010.
- The industry is currently on an aggressive schedule to inspect all pressurizer butt welds and mitigate about 95% of the pressurizer butt welds by the spring of 2008 (approximately 16 months from now).
- Requiring inspection of all pressurizer butt welds by the summer or fall of 2007 with little reduction in the risk of rupture is not warranted

- Analyses show that careful visual inspections and improved on-line leakage monitoring will ensure an extremely low risk of rupture over the four year period while the inspections and appropriate mitigation activities are completed.

13. References

[1] *Materials Handbook for Nuclear Plant Pressure Boundary Applications*, EPRI, Palo Alto, CA: 2002. 1002792.

[2] *PWSCC of Alloy 600 Materials in PWR Primary System Penetrations*, EPRI, Palo Alto, CA: 1994. TR-103696.

[3] *Materials Reliability Program – PWSCC of Alloy 600 Type Materials in Non-Steam Generator Tubing Applications – Survey Report Through June 2002: Part 1: PWSCC in Components Other Than CRDM/CEDM Penetrations (MRP-87)*, EPRI, Palo Alto, CA: 2003. 1007832.

[4] *Crack Growth of Alloy 182 weld Metal in PWR Environments (MRP-21)*, EPRI, Palo Alto, CA: 2000. 1000037.

[5] *PWR Materials Reliability Project – Interim Alloy 600 Safety Assessments for US PWR Plants (MRP-44): Part 1: Alloy 82/182 Butt Welds*, EPRI, Palo Alto, CA: 2001. TP-1001491.

[6] *Materials Reliability Program: GE Experience Report on Cracking in Alloy 182 (MRP-57)*, EPRI, Palo Alto, CA: 2001. 1006603.

[7] *Elastic-Plastic Finite Element Analysis: Single and Double-V Hot Leg Nozzle-to-Pipe Welds (MRP-33)*, EPRI, Palo Alto, CA: 2000. TR-1001501.

[8] *Materials Reliability Program: Welding Residual and Operating Stresses in PWR Plant Alloy 182 Butt welds (MRP-106)*, EPRI, Palo Alto, CA: 2003. 1009378.

[9] *Materials Reliability Program: Alloy 82/182 Pipe Butt Weld Safety Evaluation for US PWR Plant Designs: Westinghouse and CE Plant Designs (MRP-109)*, EPRI, Palo Alto, CA: 2004. 1003203.

[10] *Alloy 82/182 Pipe Butt Weld Safety Assessment for US PWR Plant Designs: Babcock & Wilcox Design Plants (MRP-112)*, EPRI, Palo Alto, CA: 2004. 1009805.

[11] *Fracture Mechanics Analysis for Selected Nozzles Including Weld Repairs (MRP-114)*, EPRI, Palo Alto, CA: 2004. 1009559.

[12] *Probabilistic Risk Assessment for Butt Weld PWSCC (MRP-116)*, EPRI, Palo Alto, CA: 2004. 1009806.

[13] *Materials Reliability Program: Crack Growth rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 82, 182 and 132 Welds (MRP-115)*, EPRI, Palo Alto, CA: 2004. 1006696.

[14] *Materials Reliability Program: Alloy 82/182 Butt Weld Safety Assessment for US PWR Plant Designs (MRP-113)*, EPRI, Palo Alto, CA: 2004. 1007029.

[15] *Materials Reliability Program: Primary System Piping Butt Weld Inspection and Evaluation Guidelines (MRP-139)*, EPRI, Palo Alto, CA: 2005. 1010087.

[16] G.J. Powell, S.W. Porembka and J.R. Politano, "Destructive Examination of an Alloy 600 Pressurizer Relief Line Elbow Removed from and Advanced Test Reactor Test Loop," *Proceedings; 1992 EPRI Workshop on PWSCC of Alloy 600 in PWRs*. EPRI, Palo Alto, CA: 1993. 103345.

[17] H. Kobayashi, et al., "PWSCC Experience of Pressurizer Dissimilar Metal Welds at Tsuruga Unit 2," *Proceedings of 12th International Conference on Nuclear Engineering*, ASME International, April 25-29, 2004, Arlington, Virginia.

[18] Letter ET 06-0049 from Terry J. Garrett (Wolf Creek) to the USNRC, *Response to Request for Additional Information Relating to Pre-Weld Overlay Examination of Pressurizer Nozzle to Safe-End Dissimilar Metal Welds*, dated November 29, 2006.

[19] Letter from G. A. Brassart (Westinghouse) to M.A. Dingler (Wolf Creek), *Wolf Creek – Pressurizer Surge, Safety, Relief and Spray Nozzle Alloy 82/182*, NSD-EPRI-06-43, December 15, 2006.

[20] US NRC, "NRC Wolf Creek Flaw Evaluation," presented at November 30, 2006, public meeting between US NRC and MRP, North Bethesda, Maryland.

[21] *SmartCrack: A General Purpose Fracture Mechanics Software*, Engineering Mechanics Technology, Inc., San Jose, California 1997

[22] *Fatigue Crack Growth Computer Program "NASA/FLAGRO"*, NASA Johnson Space Center, Houston, Texas, May 1994

[23] S.R. Mettu and R. G. Forman, "Analysis of Circumferential Cracks in Circular Cylinders Using the Weight-Function Method", *Fracture Mechanics: Twenty Third Symposium*, ASTM STP 1189, ASTM, Philadelphia, 1993, pp. 417-440

[24] R.A. Sire, D.O. Harris and E.D. Eason, "Automated Generation of Influence Functions for Planar Crack Problems", *Fracture Mechanics: Perspectives and Directions (Twentieth Symposium)*, ASTM STP 1020, Philadelphia, 1989, pp. 351-365

[25] Cheng, W. and Finnie I., *On the Prediction of Stress Intensity Factors for Axisymmetric Cracks in Thin-Walled Cylinders From Plane Strain Solutions*, Journal of Engineering materials and technology, Vol. 106, 227-231, 1985.

[26] BWRVIP-14-A: *BWR Vessel and Internals Project, Evaluation of Crack Growth in Stainless Steel RPV Internals*, EPRI, Palo Alto, CA: 2003.

[27] *Investigation and Evaluation of Stress Corrosion Cracking in Piping of Boiling Water Reactor Plants – Report of the U.S. Nuclear Regulatory Commission Piping Review Committee*, U.S. Nuclear Regulator Commission, NUREG-1061, Volume 1, August 1984.

[28] *Technical Report on Material Selection and Processing Guidelines for BWR Coolant Pressure Boundary Piping: Final Report*, U.S. Nuclear Regulatory Commission, NUREG-0313,

[29] "Evaluations of Flaws in Austenitic Piping," *Transactions of ASME, J. of Pressure Vessel Technology*, v. 108, Aug. 1986, pp. 352-366.

[30] T. L. Anderson, et al., *WRC SSS: Development of Stress Intensity Factor Solutions for Surface and Embedded Cracks in API 579*, Private Communication.

[31] Westinghouse Owners Group, Transmittal of Remaining Responses to NRC Request for Additional Information Concerning WCAP-16180-NP, Revision 0, "Operability Assessment for Combustion Engineering Plants with Hypothetical Circumferential Flaw Indications in Pressurizer Heater Sleeves," PA-MSC-0143, dated October 19, 2004. NRC ADAMS Accession No. ML042960451.

[32] *Ductile Fracture Handbook – Applications to: Power Plants, Offshore Structures, Petrochemical Plants, Transportation Systems*, EPRI, Palo Alto, CA: 1989. NP-6301-D.

[33] *An Assessment of Circumferentially Complex-Cracked Pipe Subjected to Bending*, U. S. Nuclear Regulatory Commission, NUREG/CR-4687, October 1986.

[34] Abernathy, R.B., *The New Weibull Handbook, Reliability & Statistical Analysis for Predicting Life, Safety, Survivability, Risk, Cost, and Warranty Claims*, Fourth Edition, September 2000.

[35] Aladar Csontos (NRC) and David Rudland (EMC^2), Private Communication to P. Riccardella, Dec. 1, 2006.

[36] Letter from Jack Bailey to MRP Senior Representatives, *MRP 82/182 Weld Integrity Inspection Committee – Short Term Inspection Guidance*, dated March 1, 2001.

[37] *Needed Action for Visual Inspection of Alloy 82/182 Butt Welds and Good Practice Recommendations for Weld Joint Configurations*, letter MRP 2004-05, April 2, 2004.

[38] Letter from Leslie Hartz to PMMP Executive Committee, *Primary System Piping Butt Weld Inspection and Evaluation Guideline (MRP-139)*, letter MRP2005-014 dated September 12, 2005.

[39] NRC Regulatory Issue Summary (RIS) 2003-13, *NRC Review of Responses to Bulletin 2002-01, Reactor Pressure Vessel Head Degradation and Reactor Coolant Pressure Boundary Integrity*.

[40] *PWROG Standard Process and Methods for Calculating RCS Leak Rate for Pressurized Water Reactors*, WCAP-16423-NP, Revision 0, September 2006.

[41] *PWROG Standard RCS Leakage Action Levels and Response Guidelines for Pressurized Water Reactors*. WCAP-16465-NP, Revision 0, September 2006.

[42] NRC Inspection Manual, IMC 2215, Appendix D.