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Materials Reliability Program: Alloy 82/182 Pipe Butt Weld Safety Assessment for US PWR Plant Designs: Babcock & Wilcox Design Plants (MRP-112NP)

1009805

Final Report, July 2004

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PRODUCT DESCRIPTION

Background

In early October 2000 the V. C. Summer Plant shut down for a normal refueling outage, and conducted a walk-down to search for boron deposits. During the walk-down, significant boron deposits were discovered in the vicinity of the reactor vessel Loop A outlet nozzle to pipe weld. Leakage records showed that leakage from all sources was well below the plant Technical Specification limit of 1.0 gpm. Ultrasonic tests performed on the pipe from the outside surface were inconclusive, but ultrasonic tests performed from the inside surface revealed a single axial flaw in the weld near the top of the pipe. Supplemental eddy current testing revealed several other indications, some of which were later confirmed to be flaws. Since that time, flaws have been discovered in a number of other Alloy 182 butt welds, and it may be anticipated that others will be found in the future.

Objective

The purpose of this report is to evaluate the safety of Alloy 82/182 butt welds in the primary coolant system of B&W-design plants as it relates to primary water stress corrosion cracking (PWSCC).

Approach

This report has been prepared to address the safety significance of any postulated flaws that may be present in the butt welds in operating B&WOG plants. This report identifies all of the Alloy 82/182 butt weld locations in the B&WOG plants, the bounding locations from a PWSCC susceptibility, size, and location standpoint are selected for further evaluation. The evaluation relies on fracture mechanics methodology. A summary of the fracture evaluations is provided, followed by an assessment of leakage through the Alloy 82/182 butt welds.

Results

Analyses were performed for five different bounding/representative plant butt weld locations. The analysis started with of a determination of critical flaw size using the net section collapse approach for both axial and circumferential flaws. Once the critical flaw sizes were determined, crack growth analyses were performed to estimate the time required for a postulated small circumferential flaw to grow to a through-wall flaw. Another analysis provided an estimate for the time required for a detectable size flaw to propagate to a critical size flaw. In addition, a flaw size versus leakage relationship under normal sustained plant loads was developed. The results of these analysis show that the margin between a flaw that gives detectable leakage and the critical flaw size is very large for the larger diameter welds and decreases as the weld diameter decreases. One exception to this finding was the pressurizer relief nozzle where the predicted leakage rate is less than 1 gpm; for this location it is predicted that the part through-wall flaw will arrest at 37% of the wall thickness and there will be no leaking flaw in this nozzle. For the case of axial through-wall flaws, the calculated critical flaw length is greater than or equal to 11.4 inches. Since the maximum length of any axial flaw is limited to the width of the weld metal (~2 - 2½ inches), there is no safety concern relative to rupture from an axial flaw. A plant's leakage detection system will be capable of identifying a through-wall axial flaw. It is concluded that axial and circumferential PWSCC flaws that propagate through-wall in Alloy 82/182 butt welds in operating B&W-design nuclear power plants will produce leakage that can be detected in service before exceeding available structural margins, with the exception of the pressurizer relief nozzle.

EPRI Perspective
Over the last four years there have been several incidences involving PWSCC of Alloy 82/182 butt welds in PWR plants in the US and abroad. As a consequence of these events, the industry, acting through the EPRI Materials Reliability Program, developed an interim safety assessment report and continued work to produce a final safety assessment to assure continued safe operation of these plants. This report quantifies the relationships between flaw size, leakage, and component failure at dissimilar metal butt weld locations in B&W design plants. This work will be used as input to the final safety assessment for Alloy 82/182 pipe butt welds. The safety assessment will form the basis for recommended visual and nondestructive examinations that will ensure a low probability of leaks and extremely low probability of failure in the future.

Keywords
Alloy 82/182
Bimetallic Butt Welds
PWSCC
Safety Assessment
Boric Acid Leakage
Safe-end Welds

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INTRODUCTION

1.1 Purpose

The purpose of this report is to evaluate the safety of Alloy 82/182 butt welds in the primary coolant system of B&W-design plants as it relates to primary water stress corrosion cracking (PWSCC). This evaluation applies to the B&W-design nuclear power plants listed in Table 1-1.

Table 1-1
List of B&W Design Plants Evaluated in Safety Assessment

Plant*	Owner
Davis-Besse (D-B)	First Energy Nuclear Operating Company
Oconee Nuclear Station Units 1, 2, and 3 (ONS-1, -2, and -3)	Duke Energy Corporation
Arkansas Nuclear One Unit 1 (ANO-1)	Entergy Operations, Incorporated
Crystal River Unit 3 (CR-3)	Florida Power Corporation
Three Mile Island Unit 1 (TMI-1)	Exelon Corporation

* This group will subsequently be identified as the "B&WOG plants".

1.2 Background

Leakage was identified at the reactor vessel outlet nozzle-to-pipe weld in the “A” hot leg loop of the V.C. Summer Nuclear Station in October 2000. This weld is in a 29-inch inside diameter pipe and is located approximately 36 inches from the reactor vessel wall. The pipe wall and weld thickness are 2.33 inches minimum.

An axial flaw, approximately 2.7 inches long and located approximately 7° clockwise from the top of the pipe (as viewed from inside the reactor vessel), was identified on the inside surface of the pipe at V.C. Summer. Further examinations also identified a short circumferential flaw, approximately 1.5 inches long, intersecting the axial flaw as shown in Figure 1-1.

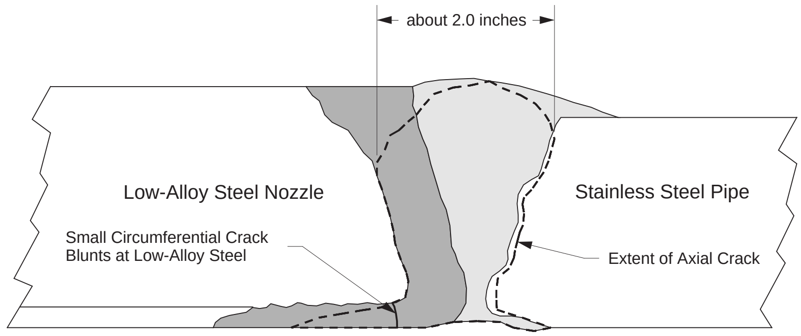


Figure 1-1
Location of Inside Surface Cracking at V.C. Summer "A" Hot Leg Nozzle

1.3 Technical Approach

The root cause analysis at V.C. Summer did not indicate that this problem was a plant-specific condition. Thus, the likelihood of similar flaws in other plants and their impact on safe operation must be addressed. This report has been prepared to address the safety significance of any postulated flaws that may be present in the butt welds of a similar configuration in operating B&WOG plants.

In Section 2 of this report, all of the Alloy 82/182 butt weld locations in the B&WOG plants are identified and the bounding locations from a PWSCC susceptibility, size, and location standpoint are selected for further evaluation. A description of the fracture mechanics methodology follows in Section 3. A summary of the fracture evaluations is then provided in Section 4 of the report, and is followed in Section 5 by an assessment of leakage through the Alloy 82/182 butt welds. Section 6 contains a summary of the conclusions followed by a listing of the reference documents in Section 7.

1.4 Technical Limitations

The following list describes technical limitations of this MRP butt weld safety assessment.

- No changes, modifications, or repairs following initial plant startup were included; tracing the records to the details of specific weld repairs was not feasible for various reasons including the fact that the field welds were completed by various Architect Engineers. Changes in residual stress due to weld repairs can significantly increase residual stresses and crack growth rates

- Small diameter (< 1.5 inch) butt welds are not evaluated in this report.

- The secondary discontinuity stress (Q-stress) has been shown to be compressive on the inner wall of some dissimilar metal butt welds. The Q-stress effects are not included herein, thereby making the results conservative.

- Consideration of these limitations may significantly change the crack growth results provided in Table 4-2.

2
LOCATIONS OF ALLOY 82/182 BUTT WELDS IN B&WOG PLANTS

This section summarizes the configurations and materials that are used for the reactor coolant system (RCS) butt welds containing Alloy 82/182 material in the B&WOG plants. The more susceptible locations to PWSCC are determined based on manufacturing, plant-specific operating, and structural parameters. Based on this information, several Alloy 82/182 butt weld locations are selected for subsequent analysis.

2.1 Summary of Factors that Contribute to PWSCC Susceptibility

In 1996, the B&WOG performed a detailed records search to determine the locations where Alloy 82/182 weld materials were utilized. The records search included a review of available B&WOG plant fabrication and construction data from the B&W Mt. Vernon Works and B&W Barberton facilities. Only the original construction and fabrication records were reviewed; no changes, modifications, or repairs following initial plant startup were included. Information obtained from the records search consists of the type of weld, weld metal heat number, and the component information. In addition, material test reports for the Alloy 82 and Alloy 182 weld consumables were obtained, when available.

The materials used at V.C. Summer for the reactor vessel nozzle-to-pipe design include a low alloy steel nozzle with Alloy 182 buttering welded to a stainless steel pipe with an Alloy 82/182 full penetration field weld. At B&WOG plants there are several full penetration welds that utilize a similar combination of materials. However, there are no Alloy 82/182 butt weld reactor vessel nozzle-to-pipe connections in the B&W-design plants since the primary piping is made of ferritic steels. An exception is the smaller (14-inch diameter) core flood line nozzle, which is directly connected to the reactor vessel [1].

Table 2-1 lists Alloy 82/182 butt weld locations in the B&WOG plants. There are multiple entries in the table which indicate that not all seven plants have identical nozzle connections. However, pipe diameters < 1.5 inches were excluded from this compilation, except for the resistance temperature element (RTE) connection mounting bosses. The excluded small diameter piping locations have relatively low stresses.

This review also focused on factors that could contribute directly to evaluating the potential for PWSCC in each butt weld or other structural factors that might be important in evaluating the overall integrity of a particular RCS location. It is well established that PWSCC is caused by the unfavorable interaction of three (3) factors: material, stress and environment. The PWSCC possible or potential contributors within each of these “factor” categories were sorted and tabulated as follows:

Material: The materials used for each of the individual weld types are provided in Table 2-1. In addition, an attempt was made to determine whether the weld location had been subjected to either ID machining or grinding. No specific judgment was made with respect to the potential increase in

PWSCC susceptibility, since either method could result in varying degrees of residual surface stresses and cold work. Both techniques were employed to reduce the geometrical discontinuities, which is a potentially positive effect.

Stress: The single most important element in this category is the residual stress produced in welding. Unfortunately, calculating residual stress is very time consuming and has not been calculated for B&WOG plant Alloy 82/182 butt welds except in isolated instances. However, weld junctions involving highly varying coefficients of expansion were noted, i.e., an Alloy 82/182 butt weld between Type 300 series stainless steel and low alloy steel. Also, as noted for “Material” above, the possible effects of manufacturing processes that could lead to surface tensile residual stresses are provided. A note was also made as to whether the welding was performed in the “shop” or “field”. This was thought to be important, since field welds might be more difficult to complete than those made in either of the two B&W manufacturing facilities. Operational stresses that could exacerbate the effects of PWSCC were also considered. Specifically, a thorough review of B&W Owners Group documents was performed to establish a uniform basis for fatigue usage. Since the level of detail for the various analyses of individual plant RCS butt weld locations was different, for various reasons, it was decided to assign fatigue usage at three (3) levels; high, medium and low. In addition, configurations were considered as well in ranking the potential effects of rapid temperature fluctuations, e.g., stratification. The notable example of this situation is the location of thermal sleeves with respect to the nozzle-to-pipe butt welds. Their function is protecting the component from severe temperature changes.

Environment: It was assumed that each utility controls their water chemistry to specific industry and internal standards and therefore, no attempt was made to collect water quality parameters. Operating temperature and time at temperature are considered to be very important in judging susceptibility.

The designation "unknown" means that the material for the field weld was not available to Framatome ANP.

Table 2-1
Alloy 82/182 Butt Welds in B&W Design Plants [×]

LOCATION	SIZE		TYPE OF WELD			TEMP[+](°F)	Cum. Usage	MATERIAL
	nominal	sched.	material	type	Machine /Grind ***	Max. normal Operating		
Reactor Vessel								
Core Flood Nozzles	14	140	Alloy 82/182	shop	yes	577	High	A-508 Cl 2 to SA-336 F8M
CRDM Adapters	[#]		Alloy 82	shop	yes	607.5	N/A	SB-167 to SA-182 TP F304
Steam Generator								
does not meet criteria of 1-1/2" or greater								
Pressurizer								
Pressure Relief Nozzle	[#]		Alloy 82/182	shop	yes	* 650	Low	A-508 Cl 1 to SA-182 TP F316
Spray Head Pipe	4	80	Alloy 82 or 182 [++]	shop	-----	** 650	High	A-403 TP WP-304 to SB-166
Spray Nozzle Pin	4	120	Alloy 82	shop	yes	** 650	Low	SB-166 to A-508 Cl 1
Spray Nozzle Safe End	4	120	Alloy 82	shop	yes	** 650	Low	A-508 Cl 1 to SB-166
Spray Nozzle Pipe	4	120	Unknown	field	no	** 650	High	SB-166 to SS
Surge Nozzle	10	140	Alloy 82/182	shop	yes	650	High	A-508 Cl 1 to A-336 Cl F8M
RC Piping - HL								
Decay Heat Nozzle	12	140	Alloy 182	field	no	607.5	High	A-105 Gr 2 to Alloy 182 (butter) to SS
Decay Heat Nozzle	12	140	Alloy 182	shop	yes	604	High	A-105 Gr 2 to A-336 Cl F8M
Decay Heat Nozzle	12	160	unknown	field	no	604	High	A-105 Gr 2 to butter to SS
Surge Nozzle	10	140	Alloy 182	field	no	607.5	High	A-105 Gr 2 to Alloy 182 (butter) to SA-376 TP 316
Surge Nozzle	10	140	Alloy 182	shop	yes	604	High	A-105 Gr 2 to A-336 Cl F8M
RTE Mounting Bosses	[#]		Alloy 82 or 182 [++]	shop	yes	607.5	High	A-106 Gr C to SB-166
RC Piping - LCL								
1-1/2" Drain Nozzles	1.5	160	Alloy 82	shop	yes	575	High	A-105 Gr 2 to SB-166-63
Drain Nozzle Pipe	1.5	160	unknown	field	no	575	High	SB-166-63 to SS
1-1/2" Drain Nozzles	1.5	160	Alloy 182	shop	yes	575	High	A-106 Gr C to SB-166
Drain Nozzle Pipe	1.5	160	unknown	field	no	575	High	SB-166 to SS
1-1/2" Drain Nozzles	1.5	160	Alloy 182	shop	yes	575	High	A-106 Gr C to SB-166
Drain Nozzle Pipe	1.5	160	unknown	field	no	575	High	SB-166 to SS
2-1/2" Drain Nozzles	2.5	160	Alloy 182	field	no	577	High	A-105 Gr 2 to Alloy 182 (butter) to SS
Drain/Letdown Nozzle	2.5	160	Alloy 82 or 182 [++]	shop	yes	575	High	A-105 Gr 2 to SB-166
Drain/Letdown Nozzle Pipe	2.5	160	unknown	field	no	575	High	SB-166 to SS
Drain/Letdown Nozzle	2.5	160	Alloy 182	field	no	577	High	A-105 Gr 2 to Alloy 182 (butter) to SS
RTE Mounting Bosses	[#]		Alloy 182	shop	yes	575	High	A-106 Gr C to SB-166

Table 2-1
Alloy 82/182 Butt Welds in B&W Design Plants (continued) ˣ

LOCATION	SIZE		TYPE OF WELD			TEMP⁺(°F)	Cum. Usage	MATERIAL
	nominal	sched.	material	type	Machine /Grind ***	Max. normal Operating		
28" Pump Inlet Pipe Transition	#		Alloy 82 or 182 ++	shop	yes	575	High	A-106 Gr C to SA-182 TP 316
28" Pump Inlet Pipe Safe End	#		Alloy 182	shop	yes	575	High	A-106 Gr C to SA-376 TP 316
28" Pump Inlet Pipe Safe End	#		Alloy 182	field	yes	577	High	SA-516 Gr 70 to SS
RC Piping - UCL								
HPI/MU Nozzles	2.5	160	Alloy 182	shop	yes	577	Low	A-105 Gr 2 to A-336 Cl F8M
HPI/MU Nozzles	2.5	160	Alloy 182	shop	yes	575	Low	A-105 Gr 2 to SB-166
HPI/MU Nozzle Pipe	2.5	160	unknown	field	no	575	High	SB-166 to SS
RTE Mounting Bosses	#		Alloy 182	shop	yes	577		A-106 Gr C to SB-166
28" Pump Outlet Pipe Safe End - Mod	#		Alloy 182	shop	yes	575	High	SA-516 Gr 70 to SA-182 TP 316
28" Pump Outlet Pipe Safe End	#		Alloy 182	shop	yes	577	High	SA-516 Gr 70 to SA-376 TP 316
Core Flood Tank								
Outlet Nozzle	14	40S	Alloy 82/182	shop	yes	Room	N/A	A-106 Gr C to SA-376 TP 316
Outlet Nozzle	14	140	Alloy 82 or 182 ++	shop	yes	Room	N/A	A-106 Gr C to SA-376 TP 316
Outlet Nozzle	14	140	Alloy 82 or 182 ++	shop	yes	Room	N/A	A-105 Gr 2 to SA-182 TP F316
2" Pressure Relief Nozzle	2	80	Alloy 82	shop	yes	Room	N/A	SA-105 Gr 2 to SB-166
2" Pressure Relief Nozzle	#		Alloy 82 or 182 ++	shop	yes	Room	N/A	SA-516 Gr 70 to SB-166

ˣ This table does not include butt welds with diameter less than 1.5 inch
* Always steam
** Potentially steam
*** Does not include nozzle repairs
⁺ Bounding plant temperatures
++ Although no documentation was found, the material for these shop welds is strongly believed to be Alloy 82 or 182
\# Non-standard pipe size

The information provided in Table 2-1 represents all that is readily available about the configuration, materials and structural details of B&W-designed 177-FA RCS Alloy 82/182 butt welds. The work on the VC Summer reactor vessel nozzle-to-pipe weld cracking incident showed the importance of weld repairs on the effect on residual stresses. Unfortunately, tracing the records to the details of specific weld repairs was not feasible for various reasons including the fact that the field welds were completed by various Architect Engineers. Moreover, the industry's understanding of PWSCC in weld joints containing Alloy 82/182 weld metal is not complete since the focus over the last ten (10) years has been on wrought materials and the evidence of weld metal vulnerability is fairly recent in terms of plant experience. While the information provided might ultimately assist in future model development, the selection of the "most susceptible locations" is based on six (6) simple considerations. These are the following:

- Temperature-Arrhenius relationships developed to describe the time to flaw initiation show the importance of temperature, e.g., an operating temperature of 650°F results in flaw initiation times of ~5X shorter than an operating temperature of 600^{o}F assuming an activation energy of 50 Kcal/mole. A similar effect occurs on crack propagation.

- Operating Time - The range of effective full power years (EFPY) for each plant is from 14 to 20.
- The complexity of the weld joint - This is meant to include the joint with the largest thermal expansivity differences, e.g., carbon or low alloy steel nozzle coupled to a stainless steel safe end or pipe. In addition, discontinuities in or adjacent to the weld are believed to contribute adversely to residual stress.
- "High" cumulative usage - For example, the surge line nozzles are known to be subject to stratification and a corresponding increase in fatigue loading.
- The use of Alloy 182, which is used in manual processes and has lower chromium content than Alloy 82.
- Pipe Diameter - The reasoning here is that the larger the pipe diameter, the greater the pipe thickness which requires more weld passes to complete. It is assumed that the greater the weld volume, the greater the probability of having to perform weld repairs.

2.2 Selected Alloy 82/182 Piping Butt Weld Locations

Based on the above evaluation, five larger diameter Alloy 82/182 butt welds in the B&WOG plants have been selected for further analysis and these are provided below:

- Core flood nozzle-to-safe end weld at Plant A
- Decay heat nozzle-to-reactor coolant piping weld at Plant B
- Pressurizer surge nozzle-to-safe end weld at Plant C
- Pressurizer spray nozzle-to-safe end weld at Plant A
- Pressurizer pressure relief nozzle-to-flange weld at Plant A

These plants are selected based on the availability of the most recent stress analysis information.

In the B&W design nuclear steam supply system (NSSS), the primary RCS piping is made of carbon steel with cladding on the inside surface; therefore, there are no Alloy 82/182 welds in the primary loop except the pump housing connections. These lines are excluded due to the limited scope of this evaluation and the consideration of the low service temperature of these lines. The core flood line in the B&W design is directly connected to the reactor vessel instead of being connected to a RCS pipe.

To simplify discussion of these welds in the remainder of the report, each weld location has been given an abbreviated identification, as provided in Table 2-2. These weld location identities will hereafter be used in the remaining portions of the report.

Table 2-2
Selected Alloy 82/182 Welds for Evaluation

PLANT	LOCATION	SIZE	TYPE OF WELD	TEMP[++] (°F)
A	Core Flood Nozzle	14	Alloy 82/182	577
B	Decay Heat Nozzle	12	Alloy 182	604
C	Pressurizer Surge Nozzle	10	Alloy 82/182	650
A	Pressurizer Spray Nozzle	4	Alloy 82	650
A	Pressurizer Relief Nozzle	2 ½	Alloy 82/182	650

[++]Bounding plant temperatures

2.3 Weld Geometries of Five Selected Lines

Figures 2-1 through 2-3 depict the generalized configurations of the selected Alloy 82/182 butt welds used in the B&WOG plants. All welds are manufactured with a clad carbon (or low alloy) steel nozzle with Alloy 600 buttering and a full penetration Alloy 82/182 weld connected to a stainless steel or Alloy 600 safe end as shown in Figure 2-1. The decay heat nozzle is of a similar design but has a shorter length (Fig. 2-2). The pressurizer relief nozzle is a much smaller 2½ inch line as shown in Figure 2-3.

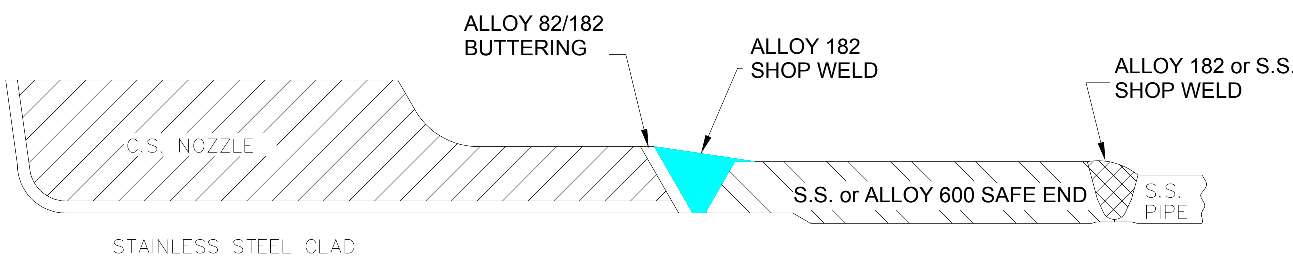


Figure 2-1
Typical Configuration of Alloy 82/182 Full Penetration Welds in Core Flood Nozzle, Pressurizer Surge Nozzle, and Pressurizer Spray Nozzle

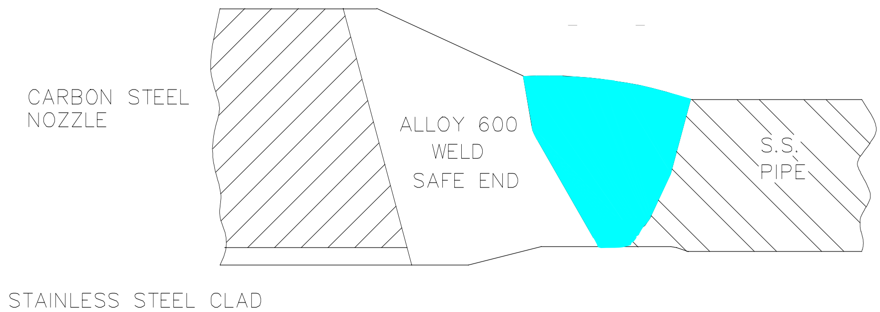


Figure 2-2
Typical Configuration of Alloy 182 Full Penetration Weld in Decay Heat Nozzle

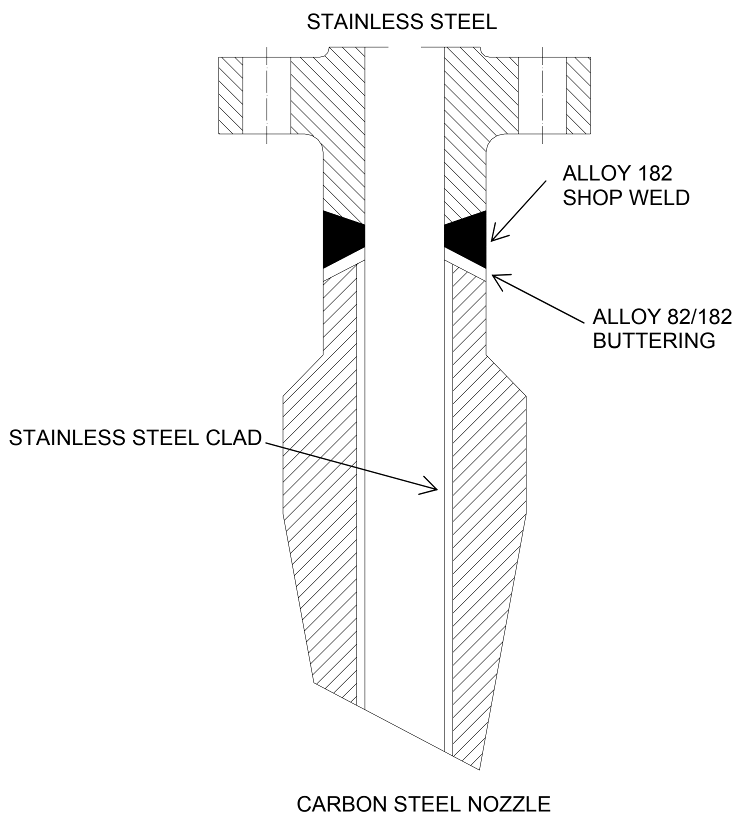


Figure 2-3
Typical Configuration of Alloy 182 Full Penetration Weld in Pressurizer Relief Nozzle

3
FRACTURE MECHANICS METHODOLOGY

3.1 Pipe Flaw Evaluation Procedure

The Alloy 82/182 butt welds are austenitic material and their failure is controlled by net section failure instead of the linear elastic fracture mechanics criteria. The ASME Code piping flaw evaluation procedure [2] is used here to calculate critical flaw sizes by the net section failure approach. The critical flaw sizes for both axial and circumferential through-wall flaws are calculated. In addition, the stress intensity factor K_I is calculated because both PWSCC crack growth rate and fatigue crack growth rate are indexed to either K_I or ΔK_I and it is desired to estimate the time-to-failure following initiation.

3.2 Flaw Types and Orientations

Service experience to date has primarily identified axially-oriented flaws in Alloy 82/182 weld regions in PWR plants. At V.C. Summer, the discovery of several axial weld flaws is well documented, including one through-wall flaw that resulted in leakage. Other examples of identified axial flaws are at Ringhals Units 3 and 4, Tsuruga 2 and TMI-1.

Two circumferential flaw indications have also been reported, both at V.C. Summer. One was found to be an artifact, and the second was confirmed to be a shallow flaw with depth limited to the cladding, about 0.20 inches. In addition, a flaw was identified at the Duane Arnold BWR that was nearly a full circumferential flaw, which had a crevice geometry to serve as an initiation site. An actual leaking flaw in an Alloy 82/182 weld was also detected at the Palisades' relief nozzle area. This was a circumferential flaw that went through the wall thickness. Therefore, both axial and circumferential flaws are considered possible and must be evaluated.

As noted above, critical flaw sizes for axial and circumferential through-wall flaws are determined based on a net section failure approach. However, crack growth analyses are performed only for circumferential flaws since Alloy 82/182 weld designs have a narrow band on the inside surface of the nozzle, not exceeding 2 or 2½ inches in width. Any potential axial flaws that initiate will be restricted to a finite size due to the physical limit in the width of the Alloy 82/182 weld material. An exception to this is the pressurizer spray nozzle where the connected safe end is made of Alloy 600. However, the PWSCC crack growth rate for Alloy 600 is on the order of 20% of the CGR for Alloy 82/182; axial crack growth may still occur, but it is somewhat restricted. On the other hand, any potential circumferential weld flaws that initiate may grow further in the circumferential direction at the faster CGR.

3.3 Stress Intensity Factor (K_I) Equations

The applied stresses are membrane and bending stresses across the cross-section of the pipe. For residual stresses, also from the ASME Section XI pipe flaw evaluation procedure, a third order polynomial stress profile form is given. To accommodate this profile, the K_I solution in Appendix A of

ASME Section XI is used in this analysis and is superimposed with the K_I from other stresses. For convenience of the analyses, the K_I solution in the ASME Code piping analysis is also selected.

3.3.1 Part Through-Wall Circumferential Flaw

A realistic flaw type expected in pipes is a part through-wall circumferential surface flaw. This type of flaw is shown in Fig. 3-1 and the K_I expression for this type of flaw can be found in ASME Code Case 494-3 [3]. This K_I equation is given as function of membrane, bending and expansion stresses.

$$K_I = (SF)P_m\sqrt{\pi a'}\ F_m + [(SF)\ P_b + P_e]\ \sqrt{\pi a'}F_b + K_{Ir}$$

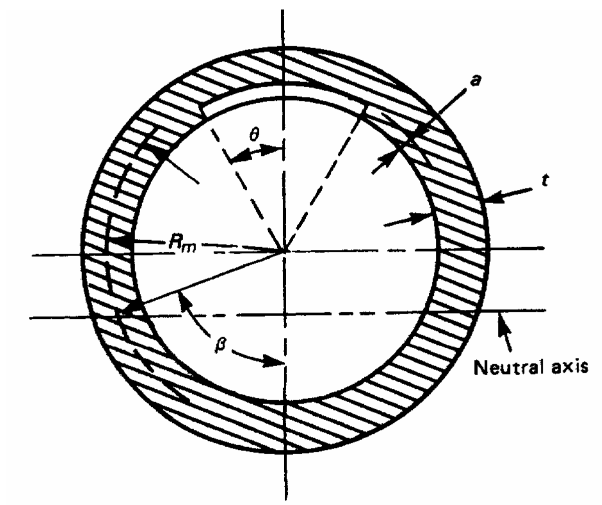


Figure 3-1
Part Through-Wall Flaw

where

P_m = primary membrane stress in the pipe at the flaw, ksi
P_b = primary bending stress in the pipe at the flaw, ksi
P_e = expansion stress in the pipe at the flaw, ksi
a' = updated flaw depth, in
= $a + \Delta a$
K_{Ir} = K_I due to residual stress, ksi$\sqrt{in}$
F_m = 1.1+ a'/t [0.15241+16.722*(a'/t*θ/π)^0.855-14.944*(a'/t*θ/π)]
F_b = 1.1 + a'/t [-0.09967+5.0057*(a'/t *θ/π)^0.565-2.8329*(a'/t*θ/π)]
θ = one half of flaw angle, radian

3.3.2 Stress Intensity Factors (SIF) from Appendix A, Section XI

Although the nozzle is a cylindrical tube, surface flaws may be conservatively analyzed as flaws in a flat plate. A convenient influence function solution for stress intensity factors is available in Appendix A to Section XI of ASME Boiler & Pressure Vessel Code [2] and is used here to calculate K_I due to residual stress and steady state stresses. The semi-elliptical surface flaw model used to simulate surface flaws is shown in Figure 3-2.

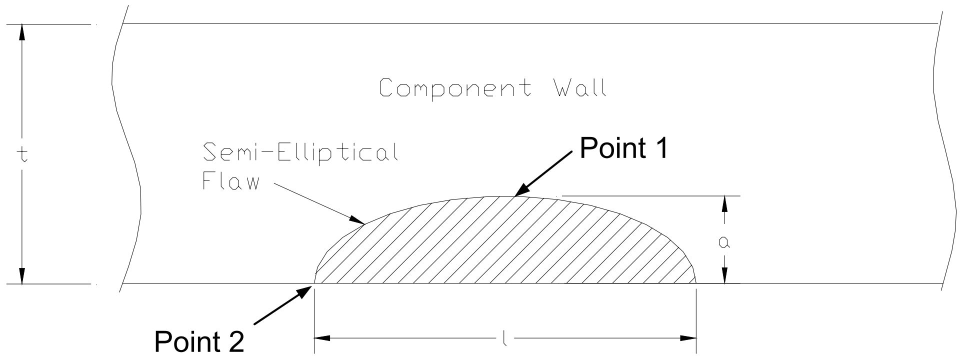


Figure 3-2
Semi-Elliptical Surface Flaw in a Plate

where, a = flaw depth
$l = 2c$ = flaw length
t = wall thickness

Stress intensity factors are determined at two points along the semi-elliptical crack front, using cubic polynomials to characterize through-wall stress profiles and geometry-dependent influence functions for the two points. Point 1 is at the maximum flaw depth, and Point 2 is on the surface. The 1995 Section XI, Appendix A solution [2] for flat plate surface flaws is described below:

Applicability: $0.0 \le a/t \le 0.80$

The ASME Code solution characterizes the distribution of stress through the wall as a third-order polynomial up to the depth of the flaw,

$$\sigma = A_0 + A_1\left(\frac{x}{a}\right) + A_2\left(\frac{x}{a}\right)^2 + A_3\left(\frac{x}{a}\right)^3$$

where, a = flaw depth
x = distance from inside surface $\le a$
A_j = stress coefficients

The stress intensity factor is then described by the product of stress coefficients, A_j, and influence coefficients, G_j, defined by

$$K_I = \left[(A_0 + A_p)G_0 + A_1G_1 + A_2G_2 + A_3G_3\right]\sqrt{\pi a / Q}$$

where, A_p = crack face pressure
$Q = 1 + 4.593(a/l)^{1.65} - q_y$
$q_y = [\,(A_0 G_0 + A_1 G_1 + A_2 G_2 + A_3 G_3) / \sigma_y\,]^2 / 6$
σ_y = yield strength

The influence coefficients G_j are tabulated in Reference 2 for a/t ratios of 0.0, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.40, 0.50, 0.60, 0.70, and 0.80, and flaw depth-to-length ratios (a/l) of 0.0, 0.1, 0.2, 0.3, 0.4, and 0.5. Interpolation is used for ratios of a/t and a/l between these tabulated values.

3.3.3 Through-Wall Circumferential Flaw

A flaw that initiates at the inside surface of a circumferential weld can grow radially to become a through-wall flaw. Further growth of this through-wall flaw in the circumferential direction can be modeled as a through-thickness flaw in a finite-width plate (center cracked panel model) [4].

The stress intensity factor for such a flaw is given below.

$$K_I = \sigma\sqrt{\pi a}\left(\frac{2b}{\pi a}\tan\frac{\pi a}{2b}\right)^{1/2}$$

where, σ = average axial stress around the circumference, ksi
$2a$ = flaw depth, in.
$2b$ = panel width (mean circumference), in.

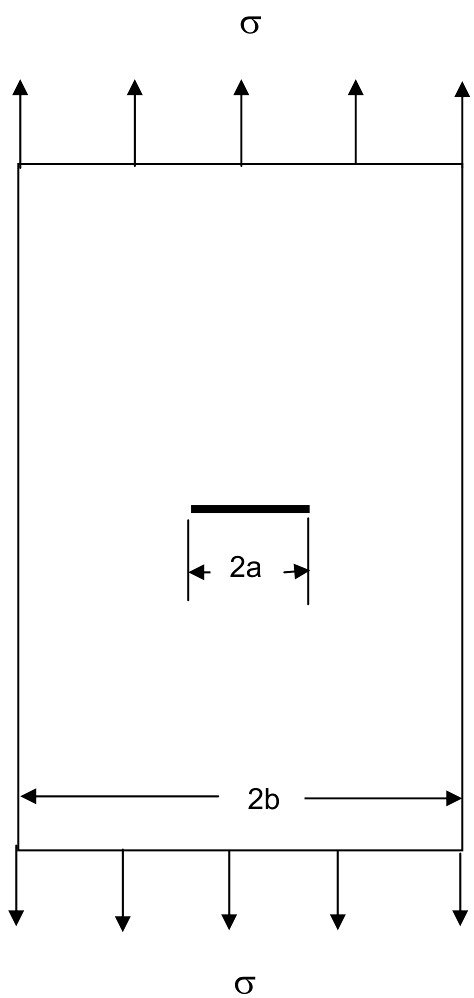
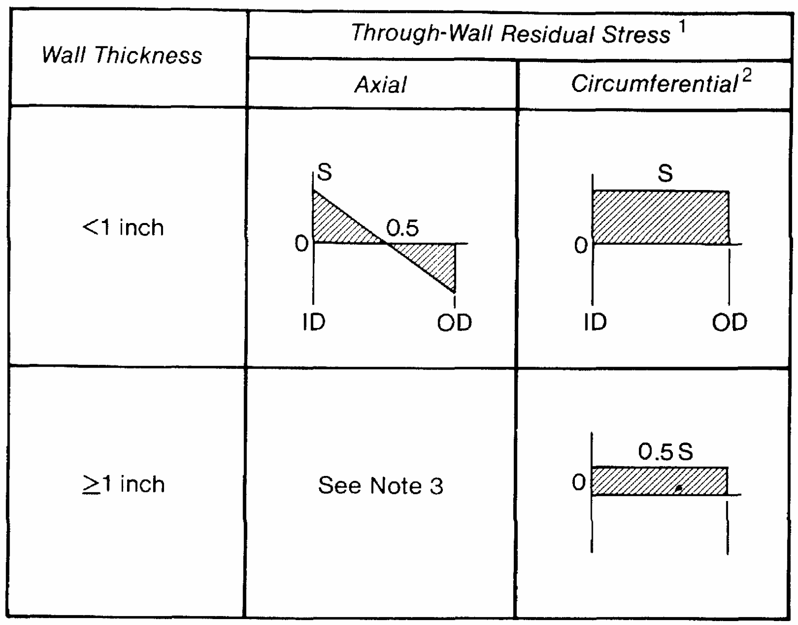


Figure 3-3
Center Crack Panel Geometry

3.4 Residual Stresses in Pipe Welds

The technical basis document for austenitic pipe flaw evaluations [5] provides a residual stress profile based on a large number of measured data (see Fig. 3-4 and 3-5a). For pipes with wall thickness greater than 1 inch, a polynomial equation is provided for the axial residual stress profile across the thickness of the pipe, which is plotted in Fig. 3-5b.

$$\sigma_{res} = 30[1 - 6.91(a/t) + 8.69(a/t)^2 - 0.48(a/t)^3 - 2.03(a/t)^4] \text{ ksi}$$



Wall Thickness	*Through-Wall Residual Stress* [1]	
	Axial	*Circumferential* [2]
<1 inch	S, 0, 0.5, ID, OD	S, 0, ID, OD
≥1 inch	See Note 3	0.5 S, 0

[1] S = 30 ksi

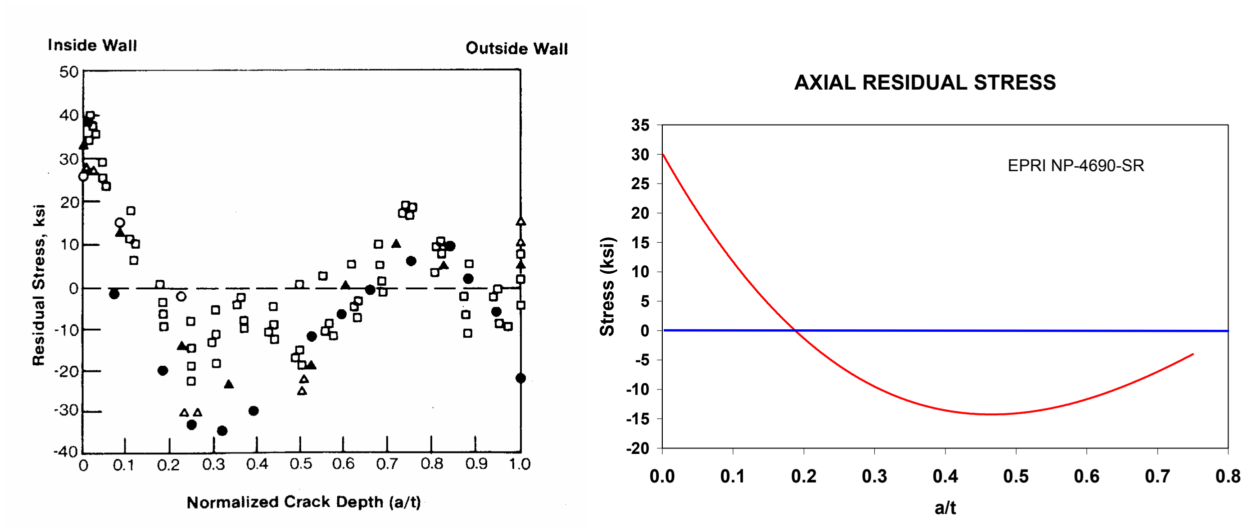
[2] Considerable variation with weld heat input.

[3] $\sigma = \sigma_i [1.0 - 6.91 (a/t) + 8.69 (a/t)^2 - 0.48 (a/t)^3 - 2.03 (a/t)^4]$

σ_i = stress at inner surface (a = 0)

Figure 3-4
Residual Stresses in Pipe Welds [5]

Recent finite element analysis of a pipe weld simulation [11] confirmed a similar residual stress distribution. The above ASME Code model is slightly conservative. A similar simulation of a pipe weld with a weld repair shows a different distribution. Since only the original construction and fabrication records were reviewed in this report; no changes, modifications, or repairs following initial plant startup were included. So it is assumed that there are no weld repairs on the selected butt weld locations in this evaluation



(a) (b)

Figure 3-5
Measured Residual Stress Data and Residual Stress Model [5]

3.5 PWSCC Crack Growth Rate

Stress corrosion crack growth is calculated using the MRP Alloy 82/182 crack growth rate from MRP-21 [6] with an activation energy of 33,000 calories/mole. This crack growth rate model is based on industry data for stress corrosion cracking of Alloy 82/182 material. The activation energy is utilized to adjust crack growth rates for temperatures other than the test temperature of 325°C or 617°F.

The crack growth rate equation in MRP-21 has the same form as the Peter Scott model [7] for crack growth rate of Alloy 600 wrought material. Since the equation is for the temperature at 325°C (617°C), the equation is modified for the applied temperature by a temperature correction term that reduces to unity at 325°C.

The crack growth rate equation is:

Metric units: $$da/dt = C_o(1.4\times10^{-11})(K_I-9)^{1.16} \text{ m/sec}$$

where K_I is the applied stress intensity factor in MPa√m, or

English units: $$da/dt = C_o(6.15\times10^{-10})(K_I-8.19)^{1.16} \text{ in/sec}$$

where K_I is the applied stress intensity factor in ksi√in.

The temperature correction coefficient, C_o, is defined as

$$C_o = e^{-\frac{Q}{R}\left(\frac{1}{T_2}-\frac{1}{T_1}\right)}$$

where $Q =$ 33,000 calories/mole
$R =$ 1.987 calories/mole-K

and $T_1 =$ Test temperature (325°C) in degrees Kelvin
$T_2 =$ Operating temperature in degrees Kelvin (from Table 2-1)

The crack growth equation given above includes an explicit threshold for a stress intensity factor of 9 MPa√m (8.19 ksi√in).

3.6 Fatigue Crack Growth Rate

Crack growth due to cyclic loading is calculated using the following fatigue crack growth model [8]:

$$\frac{da}{dN} = CGR_{air} + 4.4x10^{-7} (CGR_{air})^{0.33}$$

where

$CGR_{air} = 2 \text{ x } C_{A600} \text{ x } (1\text{-}0.82R)^{-2.2} (\Delta K)^{4.1}$

$C_{A600} = 4.835 \text{ x } 10^{-14} + (1.622\text{x}10^{-16})T - (1.490 \text{ x } 10^{-18})T^2 + (4.355 \text{ x } 10^{-21})T^3$

where

T = component temperature (°C)
ΔK = stress intensity factor range (MPa√m)
da/dN = crack growth rate for Alloy 600 in LWR environment (m/cycle).

For calculation convenience, ΔK is converted into units of ksi√in and da/dN is converted to inches/cycle.

4

FRACTURE EVALUATION

4.1 Applied Loads and Stresses

There are three different sets of stresses used in this evaluation:

1. Long-term sustained stresses required to calculate crack growth by PWSCC. For this, dead weight, thermal load, Q-stresses, residual stress and internal pressure were considered. The thermal loads include thermal load due to 100% power and thermal stratification as applicable.
2. For the critical flaw size calculation, all the loads in 1 above plus SSE and Seismic Anchor Motion (SAM) load were considered.
3. Cyclic stresses for fatigue crack growth analysis.

The forces and moments for each condition were obtained from calculations performed by Framatome ANP. The stress values were calculated using the following equations:

$$\sigma_m = F_x/A$$

$$M_R = \sqrt{[(M_x)^2 + (M_y)^2 + (M_z)^2]}$$

$$\sigma_b = M_R/Z$$

where
A = cross sectional area
Z = section modulus
F_x = axial force
M_R = resultant moment

The critical circumferential flaw sizes are determined by a limit load approach using the Appendix C procedure in Section XI of the ASME Code [2]. For circumferential flaw evaluations, all the Alloy 82/182 welds considered join a carbon steel nozzle and stainless steel or Alloy 600 safe end. Therefore, in addition to the normal piping stresses and thermal expansion stresses, axial stresses due to differential thermal expansion and internal pressure (Q-stresses) acting on three different materials with three different Young's Moduli need to be considered. The Q-stresses are secondary stresses; however, they are treated as primary stresses since there is no provision to treat them otherwise. In addition to these stresses, the residual stress (which is also a secondary stress) needs to be superimposed. This creates very conservative stresses because any flaw initiated on the inside surface will immediately relax part of the secondary stresses through redistribution. Thus, the resulting crack growth analyses are conservative.

4.2 Results of Analyses

4.2.1 Critical Flaw Sizes

The critical flaw length for a through-wall flaw was determined using the methodology of Section XI, Appendix C [2]. This methodology has been extended to through-wall flaws in ASME Code Case N513 [9] which is entitled: "Evaluation Criteria for Temporary Acceptance of Flaws in Class 3 Piping." This Code Case has been accepted for use by the NRC via Reg. Guide 1.147, as issued in November of 1999. Although this Code Case is used for the justification for operation on moderate energy systems with through-wall flaws, it provides a useful tool for evaluating through-wall flaws in any piping system.

The critical flaw sizes were determined for three flaw types:

- Axial through-wall flaw - Critical flaw length
- Circumferential through-wall flaw - Critical flaw length
- Continuous part through-wall circumferential flaw - Critical flaw depth or 75% of the thickness

There are two major outputs from this evaluation: the first is determination of critical flaw sizes for both axial and circumferential flaws, which provide the failure point predictions, and the second is the amount of crack growth due to PWSCC and fatigue crack growth for circumferential flaws such that the time periods to reach critical flaw sizes can be estimated. The latter is a function of initial flaw size, temperature, and stresses and is evaluated using sustained stresses only. The results for critical flaw sizes are provided here in Table 4-1. Three plots for each nozzle weld showing pressure versus axial flaw length, moment versus circumferential flaw length and moment versus circumferential part through-wall flaw depth to thickness ratio are presented in Figures 4-1 through 4-15. The time-to-failure under PWSCC conditions is shown in subsection 4.2.2.

Figure 4-1 illustrates the relationship between flaw length versus pressure for an axial flaw in the core flood nozzle weld. This evaluation conservatively assumed that the entire region is made of Alloy 82/182 weld material, even though there is only a finite narrow band of Alloy 82/182 weld on the inside surface. Figure 4-2 shows the relationship between flaw lengths versus moment for a circumferential through-wall surface flaw. The flaw length between the 10 gpm leakage rate crack size and the failure point is assessed as additional margin. The failure point is defined as the intersection point of the limit moment and applied moment or 75% through-wall length whichever is limiting. The flaw length corresponding to the failure point becomes the critical flaw size. Figure 4-3 illustrates 360 degree part through-wall flaw depth versus limit moment. In this case, the 75% through-wall flaw is treated as failure point. This set of three figures is shown for each nozzle analyzed consecutively.

Table 4-1
Critical Flaw Sizes

Plant	Weld Location	Critical Flaw Length of Axial Through-Wall Flaw (in.)	Critical Flaw Length of Circumferential Through-Wall Flaw * (in.)	Critical Flaw Depth to Thickness Ratio of 360° Part Through-Wall Circumferential Flaw
A	Core Flood Nozzle	22.3	20.7	0.75
B	Decay Heat Nozzle	12.3	12.4	0.72
C	Pressurizer Surge Nozzle	16.7	7.1	0.57
A	Pressurizer Spray Nozzle	11.4	6.7	0.75
A	Pressurizer Relief Nozzle	18.0	4.1	0.75

* Based on inside wall of nozzle

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Figure 4-1
Plant A Core Flood Nozzle Limit Pressure vs. Axial Through-Wall Flaw Length

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Figure 4-2
Plant A Core Flood Nozzle Limit Moment vs. Circumferential Through-Wall Flaw Length

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Figure 4-3
Plant A Core Flood Nozzle Limit Moment vs. Circumferential Part Through-Wall Flaw Depth to Thickness Ratio

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Figure 4-4
Plant B Decay Heat Nozzle Limit Pressure vs. Axial Through-Wall Flaw Length

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Figure 4-5
Plant B Decay Heat Nozzle Limit Moment vs. Circumferential Through-Wall Flaw Length

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Figure 4-6
Plant B Decay Heat Nozzle Limit Moment vs. Circumferential Part Through-Wall Flaw Depth to Thickness Ratio

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Figure 4-7
Plant C Pressurizer Surge Nozzle Limit Pressure vs. Axial Through-Wall Flaw Length

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Figure 4-8
Plant C Pressurizer Surge Nozzle Limit Moment vs. Circumferential Through-Wall Flaw Length

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Figure 4-9
Plant C Pressurizer Surge Nozzle Limit Moment vs. Circumferential Part Through-Wall Flaw Depth to Thickness Ratio

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Figure 4-10
Plant A Pressurizer Spray Nozzle Limit Pressure vs. Axial Through-Wall Flaw Length

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Figure 4-11
Plant A Pressurizer Spray Nozzle Limit Moment vs. Circumferential Through-Wall Flaw Length

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Figure 4-12
Plant A Pressurizer Spray Nozzle Limit Moment vs. Circumferential Part Through-Wall Flaw Depth to Thickness Ratio

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Figure 4-13
Plant A Pressurizer Relief Nozzle Limit Pressure vs. Axial Through-Wall Flaw Length

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Figure 4-14
Plant A Pressurizer Relief Nozzle Limit Moment vs. Circumferential Through-Wall Flaw Length

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Figure 4-15
Plant A Pressurizer Relief Nozzle Limit Moment vs. Circumferential Part Through-Wall Flaw Depth to Thickness Ratio

In Fig. 4-14, it is noted that the critical circumferential flaw length of the pressurizer relief nozzle weld is only 4 inches, because of the small diameter and relatively thick wall design. This critical flaw length is less than a 1 gpm leakage size crack, therefore, the leak-before-break argument can not be applied to this nozzle. However, in Figure 4-20, it is shown that the part through-wall flaw (with 6 to 1 aspect ratio), when considering residual stresses, will arrest at 37% of the wall thickness and there will be no leaking flaw in this case.

4.2.2 Crack Growth Analyses of Part Through-Wall Circumferential Cracks

In the preceding subsection, the critical size of each postulated flaw was determined. Based on postulated flaw sizes that correspond to the threshold K_I values in each circumferential flaw configuration, crack growth analyses were performed under both PWSCC conditions and fatigue crack growth. The amount of crack growth from fatigue is very small compared with PWSCC. The crack growth rate equations described in Section 3 were used for the evaluation, and the results are presented in Table 4-2.

Since the time for flaw initiation is not determined in this evaluation, the starting point was assumed to be the flaw size that causes the applied K_I to be equal to the PWSCC threshold level K_I of 8.19 ksi$\sqrt{\text{in}}$. For each nozzle, the predicted time to reach the critical flaw size or to exceed the ASME Code acceptance criterion can be obtained from the following figures (Fig. 4-16 through Fig. 4-20), and is listed in Table 4-2.

Finite element analyses of the Alloy 82/182 weld locations at the pressurizer relief nozzle and the pressurizer spray nozzle have shown that the Q-stress is initially compressive on the inner wall of the weld, and does not becomes tensile until about 30% through-wall. This may be due to the effect of the stainless steel cladding at the inside surface of the carbon steel nozzle located just below the weld. The applied stress intensity factor due to the Q-stress is negative on the inside surface, and remains negative over the inside half of the weld. When combined with the other stress intensity factors, a larger initial flaw depth is required to attain the threshold K_I level than when compared to the case without considering the effect of the Q-stress. It is therefore conservative not to include the effect of Q-stress in this work.

Core Flood Nozzle-to-Safe End Weld
The core flood nozzle will take more than 40 years for a circumferential flaw to reach a 75% through-wall depth under very conservative load combinations including the residual stress.

Decay Heat Nozzle-to-Reactor Coolant Piping Weld
The decay heat nozzle shows similar behavior to the core flood nozzle, and also shows more than 40 years to reach a 75% through-wall flaw depth.

Pressurizer Surge Nozzle-to-Safe End Weld
The pressurizer surge nozzle is predicted to take approximately 3.5 years to exceed 75% through-wall flaw depth.

Pressurizer Spray Nozzle-to-Safe End Weld
The spray nozzle will also take more than 40 years to become a through-wall flaw.

Pressurizer Pressure Relief Nozzle-to-Flange Weld
The pressurizer relief nozzle diameter is only 2½ inch. It is predicted that the flaw will not exceed 75% through-wall in 40 years.

The pressurizer surge nozzle appears to be the worst case becoming a through-wall flaw within 3.5 years (Fig. 4-18). All these predicted times for part through-wall flaws are without consideration of flaw initiation phase and using conservative applied stresses.

Table 4-2
Combined Crack Growth Results – Circumferential Through-Wall Flaws

Plant	Weld Location	Period from Initiation to Critical Flaw Depth PWSCC+FCG (Years)	Period from 1 GPM Flaw to Critical Flaw (Years)	Critical Flaw Length of Circumferential Through-Wall Flaw from Table 4-1 (in.)
A	**Core Flood Nozzle**	>40	>70	20.7
B	**Decay Heat Nozzle**	>40	7.1	12.4
C	**Pressurizer Surge Nozzle**	3.5	0.9	7.1
A	**Pressurizer Spray Nozzle**	>40	1.8	6.7
A	**Pressurizer Relief Nozzle**	>40	*	4.1

* Not applicable. It is noted that the critical flaw length of the pressurizer relief nozzle weld is only 4 inches because of the small diameter and relatively thick wall design. The leak rate prediction according to Figure 5-5 is only a fraction of the 1 gpm rate. Subsequently no additional margin can be claimed; however, it is predicted that the part through-wall flaw will arrest at 37% of the wall thickness and there will be no leaking flaw in this case as shown in Figure 4-20.

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Figure 4-16
Predicted Crack Growth under PWSCC and FCG - Core Flood Nozzle

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Figure 4-17
Predicted Crack Growth under PWSCC and FCG - Decay Heat Nozzle

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Figure 4-18
Predicted Crack Growth under PWSCC and FCG - Pressurizer Surge Nozzle

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Figure 4-19
Predicted Crack Growth under PWSCC and FCG - Pressurizer Spray Nozzle

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Figure 4-20
Predicted Crack Growth under PWSCC and FCG - Pressurizer Relief Nozzle

4.2.3 Crack Growth Analysis of Through-Wall Circumferential Flaws

The part through-wall crack growth analyses in the preceding section indicate that only the pressurizer surge nozzle may develop through-wall flaws and the remaining four nozzles are shown unlikely to become through-wall flaws. In Fig. 4-21 through Fig. 4-24, additional crack growth time is shown starting from a 1 gpm leakage size crack growing to the critical circumferential flaw size, for all the nozzles except the relief nozzle.

Since the critical flaw size for the relief nozzle corresponds to a fraction of the 1 gpm leakage crack size, no additional margin analysis is performed. However, as there is virtually no growth after the flaw reaches 37% through-wall, development into a through-wall flaw is highly unlikely.

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Figure 4-21
Plant A Core Flood Nozzle – Circumferential Through-Wall Crack Growth

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Figure 4-22
Plant B Decay Heat Nozzle - Circumferential Through-Wall Crack Growth

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Figure 4-23
Plant C Pressurizer Surge Nozzle - Circumferential Through-Wall Crack Growth

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Figure 4-24
Plant A Pressurizer Spray Nozzle - Circumferential Through-Wall Crack Growth

5
LEAKAGE ASSESSMENT

The purpose of this section is to assess leakage through the Alloy 82/82 welds and to show that safety is maintained.

Parametric leak rate calculations were performed using an in-house computer code "KRAKFLO." This computer code has been used for the LBB applications of the RCS primary piping for the B&W Owners Group plants, which have been reviewed and approved by the NRC. For this application, the leak rates were determined assuming an IGSCC-type crack. Leak rates through IGSCC-type cracks are considered representative of leakages through PWSCC-type cracks that are likely to occur in Alloy 82/182 welds in a PWR. "KRAKFLO" has been benchmarked to Battelle Columbus Laboratory's (BCL) Phase II experiments involving 82 IGSCC type crack experiments [10].

Loads from the plant piping stress analysis of record were used. Additional supplemental loads/stress analyses were performed, as necessary, to obtain the loadings necessary for the leak rate analyses. Loadings used in the analysis are considered representative of B&WOG plants, and included the effects of power uprates, effects of thermal stratification and steam generator replacements, as applicable. The leak rate (in gpm) was calculated for various circumferential through-wall flaws using the deadweight, thermal load due to 100% power normal operating condition, and steady state normal operating pressure. Loads are combined using the algebraic sum method.

Leak rates were also calculated for various through-wall axial flaws (inches) using the steady state normal operating pressure.

The steps involved in the leak rate predictions were to calculate the crack opening areas for assumed leakage crack sizes and applied loadings and then to determine the leak rate using two-phase flow formulation, taking into account surface roughness and number of turns to account for tortuosity within a PWSCC/IGSCC-type crack. Using the results of the leak rate calculations, plots were generated for the leak rate vs. flaw sizes. Plots are shown in Figures 5-1 to 5-5 for plants A, B and C.

The reactor coolant system pressure boundary leak detection capability of the plants is less than 1 gpm. By comparing the critical flaw sizes shown in Section 4 with the 1 gpm leak rate sizes, the margins between detectable leakage and critical flaw size can be determined. Furthermore, the time required for a flaw to extend from a detectable leak size to a critical flaw size can be quantified. Significant margins involving leak rates greater than 10 gpm (at critical flaw size) have been demonstrated for:

(a) Core Flood Nozzle
(b) Decay Heat Nozzle
(c) Pressurizer Surge Nozzle (axial flaws only)
(d) Pressurizer Spray Nozzle (axial flaws only)
(e) Pressurizer Relief Nozzle (axial flaws only)

The flaw sizes corresponding to a 1 gpm leak rate through the circumferential flaws for the core flood, decay heat, and pressurizer surge and spray nozzles have been demonstrated to be less than the critical flaw length. Due to the small size of the pressurizer relief nozzle (2½”), the predicted leak rate through the critical circumferential flaw size is less than 1 gpm. The results for the circumferential flaws are summarized in the following table.

Table 5-1
Summary of Leakage Crack Sizes

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Figure 5-1
Leak Rate vs. Flaw Length for Core Flood Nozzle

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Figure 5-2
Leak Rate vs. Flaw Length for Decay Heat Nozzle

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Figure 5-3
Leak Rate vs. Flaw Length for Pressurizer Surge Nozzle

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Figure 5-4
Leak Rate vs. Flaw Length for Pressurizer Spray Nozzle

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Figure 5-5
Leak Rate vs. Flaw Length for Pressurizer Relief Nozzle

6
SUMMARY AND CONCLUSIONS

An evaluation of the structural integrity of Alloy 82/182 butt welds in operating B&W-design nuclear power plants, as it relates to primary water stress corrosion cracking, has been performed and summarized in this report. The conclusions of this work are applicable to the following nuclear power plants currently in the B&W Owners Group:

- Davis-Besse
- Oconee Nuclear Station Units 1, 2, and 3
- Arkansas Nuclear One Unit 1
- Crystal River Unit 3
- Three Mile Island Unit 1

A review of the plant fabrication and construction data records was first performed to identify all the butt weld locations and to identify those considered to be most susceptible to PWSCC based on manufacturing, operating, and structural parameters. The weld locations for the bounding and/or representative plant designs were concluded to be:

- Core flood nozzle-to-safe end weld at Plant A
- Decay heat nozzle-to-reactor coolant piping weld at Plant B
- Pressurizer surge nozzle-to-safe end weld at Plant C
- Pressurizer spray nozzle-to-safe-end weld at Plant A
- Pressurizer pressure relief nozzle-to-flange weld at Plant A

Three separate analyses were performed for each line: the first was a determination of critical flaw size using the net section collapse approach in Appendix C of ASME Code Section XI. This was done for both axial and circumferential flaws. This was based on the fact that this highly ductile material shows net section failure as the predominant failure mechanism. Once the critical flaw sizes were determined, crack growth analyses were performed to estimate the time required for a postulated small circumferential flaw to grow to a through-wall flaw, then an estimate for a detectable size flaw to propagate to a critical size flaw was determined from the first step of the evaluation. In addition, a flaw size versus leakage relationship under normal sustained plant loads was developed. The results show that the margin between a flaw that gives detectable leakage and the critical flaw size is very large for the larger diameter welds and decreases as the weld diameter decreases, except the pressurizer relief nozzle where the predicted leakage rate is less than 1 gpm. However, it is predicted that the part through-wall flaw will arrest at 37% of the wall thickness and there will be no leaking flaw in this nozzle.

The above analyses of these five selected weld locations were performed and the results are presented in this report. For the case of axial through-wall flaws, the calculated critical flaw length is greater than or equal to 11.4 inches. Since the maximum length of any axial flaw is limited to the width of the weld metal (~2 - 2½ inches), there is no safety concern relative to rupture from an axial flaw. A plant's leakage detection system will be capable of identifying a through-wall axial flaw.

For the case of circumferential flaws, the results for each location are discussed below:

- Core flood nozzle-to-safe end weld at Plant A

  The core flood nozzle will take more than 40 years for a circumferential flaw to reach a 75% through-wall depth under very conservative load combinations. Residual stress is treated as a primary stress without accounting for possible stress relaxation due to the onset of cracking. If a leaking circumferential flaw were to develop, an additional margin between a detectable leakage crack (1 gpm) and the failure flaw exists. Through-wall crack growth from a 1 gpm leakage crack size to a through-wall critical flaw would take additional time in excess of 70 years of operation.

- Decay heat nozzle-to-reactor coolant piping weld at Plant B

  The decay heat nozzle shows similar behavior to the core flood nozzle, and does not fail within 40 years. A through-wall flaw at a 1 gpm leakage crack size would take an additional 7.1 years to reach a critical size.

- Pressurizer surge nozzle-to-safe end weld at Plant C

  The pressurizer surge nozzle is predicted to take 42 months to reach a 75% through-wall flaw depth. The predicted time to failure is based on conservative stresses. Should a through-wall flaw develop, it would take a 1 gpm leakage size crack 0.9 year to reach a critical size. This is the most limiting case among the five selected welds.

- Pressurizer spray nozzle nozzle-to-safe end weld at Plant A

  A part through-wall crack in the pressurizer spray nozzle will arrest at a 31% through-wall flaw depth. In the unlikely event that a leaking circumferential through-wall flaw develops, an additional margin between a detectable leakage size crack (1 gpm) and the critical crack size can be assessed. This through-wall crack growth will take additional time in excess of 1.8 years of operation.

- Pressurizer pressure relief nozzle-to-flange weld at Plant A

  It is predicted that crack arrest occurs at a 37% through-wall depth, again based on very conservative stresses. Therefore, it is highly unlikely for a circumferential flaw to become a through-wall flaw.

It is concluded that axial and circumferential PWSCC flaws that propagate through-wall in Alloy 82/182 butt welds in operating B&W-design nuclear power plants will produce leakage that can be detected in service before exceeding available structural margins, with the exception of the pressurizer relief nozzle. This is the result of the high ductility of Alloy 82/182 materials coupled with the presence of significant external bending moments and high thermally-induced stresses at these dissimilar metal weld locations. Continued emphasis on non-destructive evaluation inspections of the most susceptible butt weld locations will provide the primary defense against leakage and rupture. Based on the results of the analyses performed in this report, appropriate inspection intervals, particularly for the pressurizer surge nozzle, should be defined by the industry (e.g., the MRP).

7 REFERENCES

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CERTIFICATION

This report is an accurate and true description of the evaluation of safety of Alloy 82/182 pipe butt weld in B&W design plants and the results are accurately reported. The conclusions described are based on the data analysis presented.

K. K. Yoon Date
Materials and Structural Analysis

A. D. Nana Date
Materials and Structural Analysis

This report was reviewed and was found to be an accurate description of the work reported.

S. Fyfitch Date
Materials and Structural Analysis

H. P. Gunawardane Date
Materials and Structural Analysis

Verification of independent review.

A. D. McKim Date
Manager, Materials and Structural Analysis Unit

This report has been approved for release.

W. R. Gray Date
Program Manager, EPRI Projects