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Materials Reliability Program: Alloy 82/182 Pipe Butt Weld Safety Assessment for US PWR Plant Designs: Westinghouse and CE Design Plants (MRP-109NP)

1009804

Final Report, July 2004

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REPORT SUMMARY

Background

In early October 2000 the V. C. Summer Plant shut down for a normal refueling outage, and conducted a walkdown to search for boron deposits. During the walkdown, 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.

Objectives

Evaluation of the condition at V. C. Summer did not indicate that this was a plant specific condition. This led to questions regarding the likelihood of similar flaws in other plants, and their impact on safe operation on those plants. The objective of this report is to address the safety significance of postulated flaws in bimetallic butt welds in Westinghouse and Combustion Engineering Plants.

Approach

The report identifies the Alloy 82 and 182 butt weld locations in plants designed by Westinghouse and Combustion Engineering. Then it establishes the expected flaw orientation if flaws were to occur. The fracture and leak-before-break evaluations are performed to demonstrate and provide confidence that large flaws are required to cause a failure, and that detectable leakage would be expected in all the geometries well before failure would occur.

Results

For each location, the limiting cases were evaluated to determine the size of the flaw which could lead to piping failure, and the corresponding leak rate as a function of through-wall flaw size. The result showed that there is a substantial margin between the size flaw that would lead to detectable leak (one gallon per minute (GPM)) and the size of flaw that could lead to failure.

EPRI Perspective

Over the last four years there have been several incidences involving PWSCC of Alloy 82/132/182 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 Westinghouse and CE 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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1
INTRODUCTION

1.1 Background

In early October 2000 the V. C. Summer Plant shut down for a normal refueling outage, and conducted a walkdown to search for boron deposits, as is done to begin each outage. During the walkdown, significant boron deposits were discovered in the vicinity of the reactor vessel Loop A outlet nozzle to pipe weld. Insulation was removed, and leakage monitoring records were searched.

Leakage records showed a nearly constant 0.3 gpm unidentified leakage from all sources, well below the plant Technical Specification limit of 1.0 gpm. The geometry of the V. C. Summer nozzle to pipe weld is shown in Figure 1-1. 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.

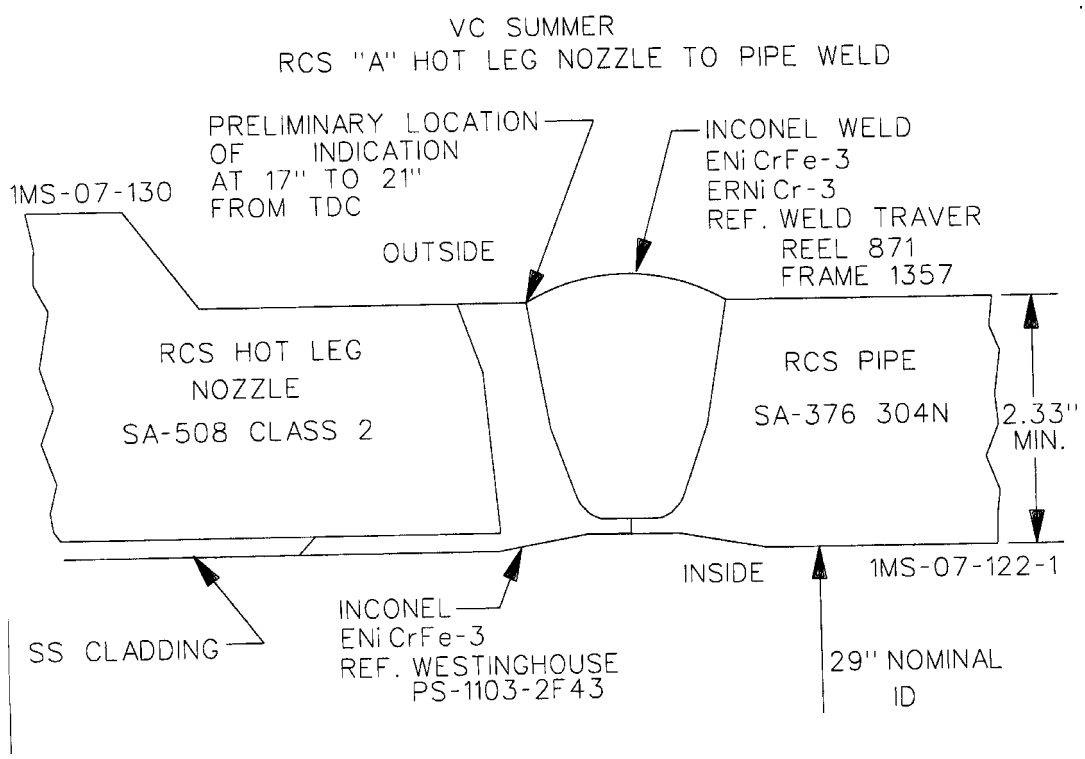

Figure 1-1
Geometry of V. C. Summer Nozzle to Pipe Weld Region

Supplemental eddy current testing revealed several other indications, some of which were later confirmed to be flaws.

Flaws have also been discovered in Alloy 182 butt welds in a number of other plants. Flaws were found in the outlet nozzle safe end region at Ringhals Units 3 and 4, and in a number of locations associated with the pressuirzer in other plants. The root cause of all these flaws has been determined to be stress corrosion cracking (PWSCC).

1.2 Safety Assessment Technical Approach

Evaluation of the condition at V. C. Summer did not indicate that this problem was a plant specific condition. This has led to questions regarding the likelihood of similar flaws in other plants, and their impact on safe operation on those plants. This report has been prepared to address the safety significance of any postulated flaws which could be present in bimetallic butt welds.

The report begins with an identification of the Alloy 82 and 182 butt weld locations in plants designed by Westinghouse and Combustion Engineering (CE). This is followed by a chapter, which describes the expected flaw orientation if flaws were to occur. The fracture evaluation and leak-before-break chapters are designed to demonstrate and provide confidence that large flaws are required to cause a failure, and that detectable leakage would be expected in all the geometries well before failure would occur. Stress corrosion crack growth calculations were carried out to quantify the time period between leakage and failure, for the full range of butt weld geometries which involve Alloy 182 safe ends.

2
ALLOY 182/82 PIPING BUTT WELD LOCATIONS IN WESTINGHOUSE PLANTS

The reactor coolant piping and fittings in Westinghouse designed reactors are austenitic stainless steel. Smaller diameter piping, such as the pressurizer surge line, spray line, safety and relief lines, and connecting lines to other systems are also austenitic stainless steel. All of the joints and connections are welded.

The major components of the system are carbon steel. These include the reactor vessel, steam generator and pressurizer. The reactor coolant pump, and loop isolating valves are austenitic stainless steel. Stainless steel safe-ends were applied to the nozzles of carbon steel components to simplify attachment of the austenitic pipe to the vessels. Both stainless steel and Alloy 82/182 welds were used in the nozzle-to-pipe weld regions. This section provides safe-end and nozzle-to-pipe weld information for the pressurizer, reactor vessel, and steam generators, with emphasis on those which contain Alloy 82/182 welds. These welds are generally used as a transition between carbon steel vessels and stainless steel piping. Nearly all of these welds are shop welds in the Westinghouse design.

There are 48 Westinghouse designed reactors currently in operation in the United States. This report provides information on the nozzle safe-end geometries for these 48 units, along with one unit designed by CE with stainless steel main loop piping. Domestic reactors that have ceased commercial operation and domestic units that have never reached commercial operation are not included. The reactor vessel safe-end configuration for two international units has been included for comparison purposes only.

2.1 Reactor Vessel

There are five reactor vessel nozzle safe end configurations on domestic Westinghouse plants. In addition to the 48 Westinghouse designed reactor vessels, this report includes one CE designed reactor vessel which has Alloy 82/182 in the reactor vessel safe-end welds. Note that the weld connecting the reactor vessel head penetration tubes to the stainless steel CRDM tubing above the vessel is also Alloy 182/82, but the operating temperature is estimated to be about 200°F to 300°F, too low for PWSCC to be a concern, and so it has not been treated. A similar weld exists below the head, for the BMI penetrations, on some plants, and was not treated here for the same reason. The nozzle safe-end configurations for these 49 reactor vessels are defined as follows:

Type 1: Consists of a weld deposited stainless steel safe end applied to the reactor vessel nozzle. The field weld to attach the reactor coolant pipe to this safe-end is performed using stainless steel filler material. Therefore, there is no Alloy 82/182 in the geometry.

Type 1A: This is a sub-group of the Type 1 safe-end. There is a band of Alloy 82/182 material on the OD and ID of the safe-end at the interface between the stainless steel weld build-up and the carbon steel nozzle. The field weld to attach the reactor coolant pipe to this safe-end is performed using stainless steel filler material. The amount of Alloy 82/182 found in this configuration is judged to be too thin to be an integrity concern. Even if a flaw were to initiate here, it would be stopped when it reached the nozzle base metal or the stainless weld, and would therefore remain very shallow.

Type 2: Consists of Weld Deposited Alloy 82 applied to the reactor vessel nozzle. The field weld to attach the reactor coolant pipe to this safe-end is performed using Alloy 82/182 filler material. This is the only geometry that requires an Alloy 82/182 field weld.

Type 3A: Consists of a Forged stainless steel Safe End welded to the reactor vessel nozzle. Prior to attachment of the safe-end, the nozzle was buttered with Alloy 82, and stress relieved. The field weld to attach the reactor coolant piping to all of the Type 3 variations is performed using stainless steel filler material.

Type 3B: This type also consists of a Forged stainless steel Safe End welded to the reactor vessel nozzle. This geometry differs from Type 3A in that the safe end is welded directly to the nozzle without the buttering.

Type 3C: This configuration consists of a Forged stainless steel Safe End welded to the reactor vessel nozzle without butter. In addition, a layer of stainless steel cladding is applied to the inside and outside surfaces of the safe-end.

Two European plants have the safe-end configuration as defined below. There are no US plants, either Westinghouse or CE, with this Safe End configuration.

Type 3D: Consists of a Forged stainless steel Safe End welded to the reactor vessel nozzle with a double V-groove weld. Prior to attachment of the safe-end, the nozzle was buttered with Alloy 82/182, and stress relieved.

Graphical representations of the seven reactor vessel nozzle safe end configurations discussed above are contained in Figures 2.1 through 2.7. The cladding is stainless steel.

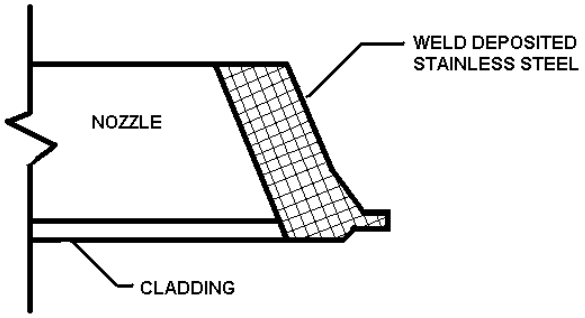

Figure 2-1
Type 1 Reactor Vessel Safe End Weld Deposited Stainless Steel

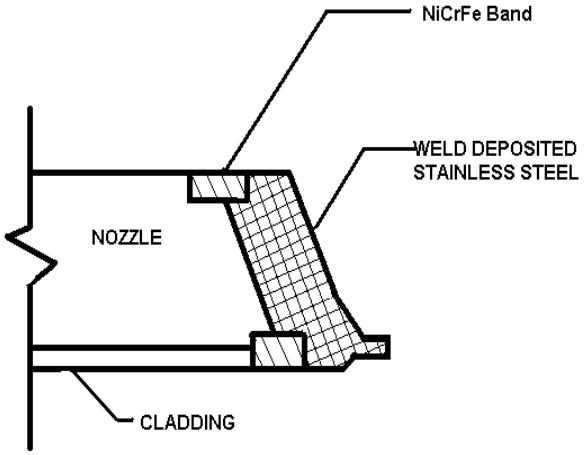

Figure 2-2
Type 1A Reactor Vessel Safe End Weld Deposited Stainless Steel with Alloy 82/182 Bands

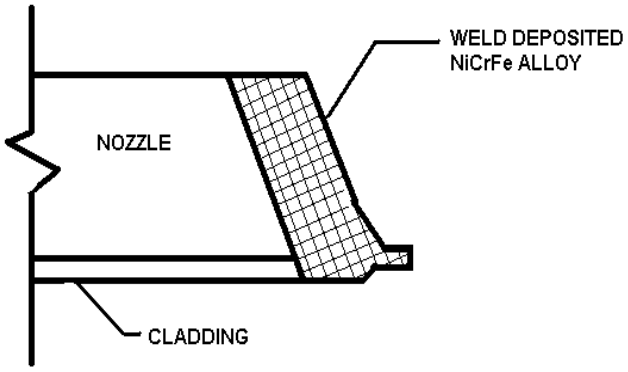

Figure 2-3
Type 2 Reactor Vessel Safe End Weld Deposited NiCrFe Alloy (82/182)

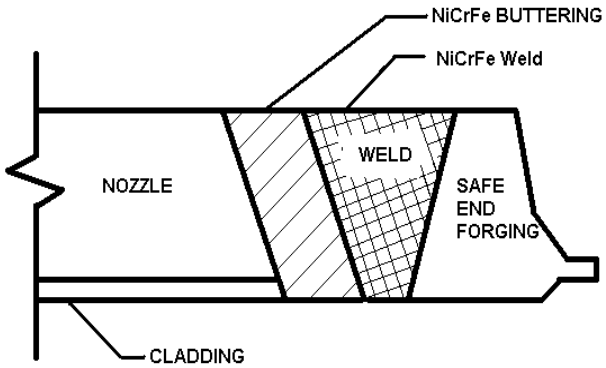

Figure 2-4
Type 3A Reactor Vessel Safe End Forged Stainless Steel Safe End with NiCrFe Butter and Single V-Weld

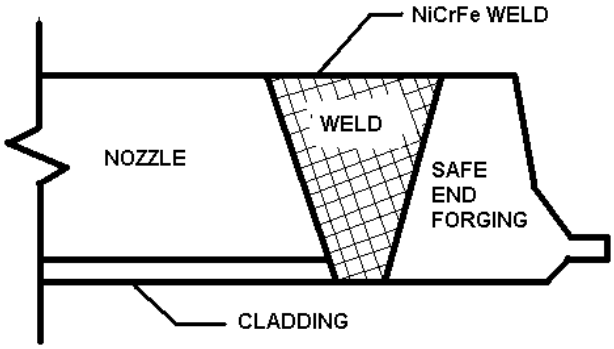

Figure 2-5
Type 3B Reactor Vessel Safe End Forged Stainless Steel Safe End with NiCrFe Single V-Weld

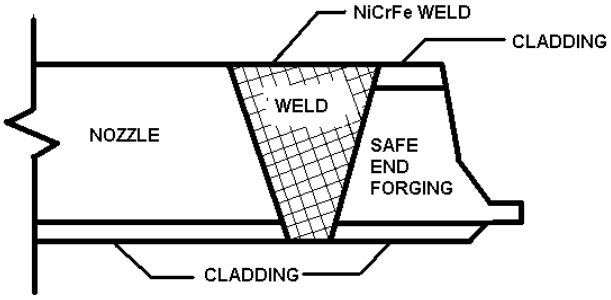

Figure 2-6
Type 3C Reactor Vessel Safe End Forged Stainless Steel Safe End with Cladding with NiCrFe Single-V Weld

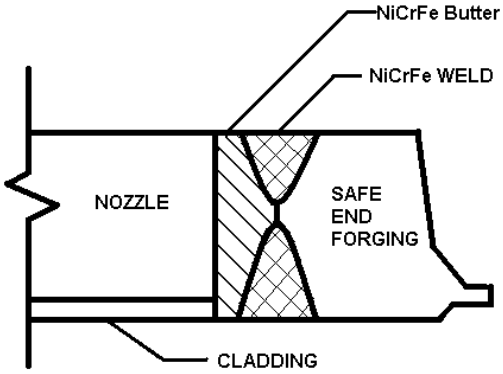

Figure 2-7
Type 3D Reactor Vessel Safe End Forged Stainless Steel Safe End NiCrFe Buttering and Double J-Groove Full Penetration Weld

2.2 Steam Generators

There are three classes of steam generators covered in this report:

- Original Equipment steam generators supplied by Westinghouse
- Replacement steam generators supplied by Westinghouse
- Replacement steam generators supplied by others.

The majority of the replacement steam generators supplied by "Others" were supplied by Babcock and Wilcox Canada, Ltd. B&W Canada replacement steam generators are included in this report.

Five nozzle safe end configurations used on steam generators in domestic Westinghouse plants have been identified. These configurations are defined as follows:

Type 1: Consists of a Forged stainless steel Safe End welded to the steam generator nozzle with stainless steel weld material.

Type 2: Consists of a Forged stainless steel Safe End welded to the steam generator nozzle with Alloy 82/182 weld material. Most replacement steam generators have a layer of Alloy 52/152 cladding on the pipe ID to act as a barrier to water contact, as shown in Figure 2-12.

Type 3A: Consists of a Forged stainless steel Safe End welded to the steam generator nozzle with Alloy 52 buttering and an Alloy 152 single-V weld.

Type 3B: Consists of a Forged stainless steel Safe End welded to the steam generator nozzle with an Alloy 152 single-V narrow groove weld.

Graphical representations of the five steam generator nozzle safe end configurations discussed above are contained in Figures 2.8 through 2.12.

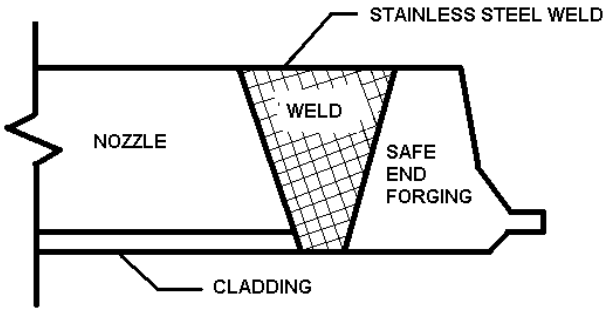

Figure 2-8
Type 1 Steam Generator Primary Nozzle Forged Stainless Steel Safe End Stainless Steel Attachment Weld

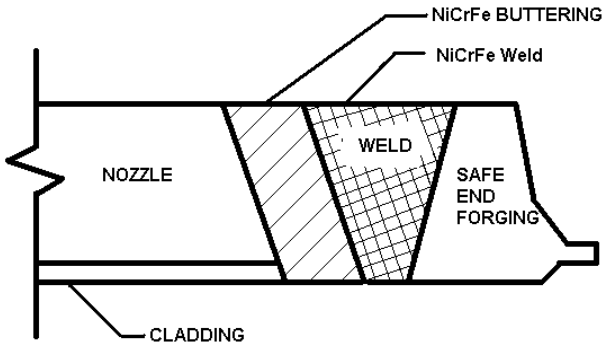

Figure 2-9
Type 2 Steam Generator Primary Nozzle Forged Stainless Steel Safe End Alloy 82/182 Attachment Weld

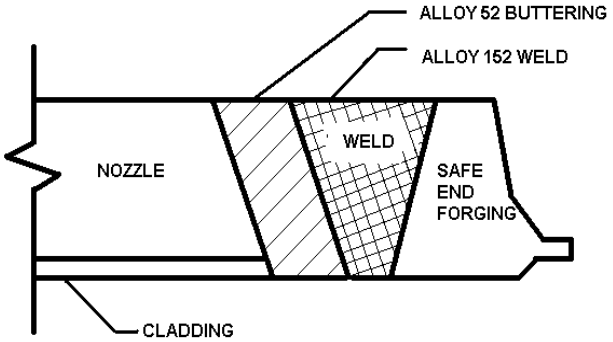

Figure 2-10
Type 3A Steam Generator Primary Nozzle Forged Stainless Steel Safe End Alloy 52 Butter with Alloy 152 Attachment Weld

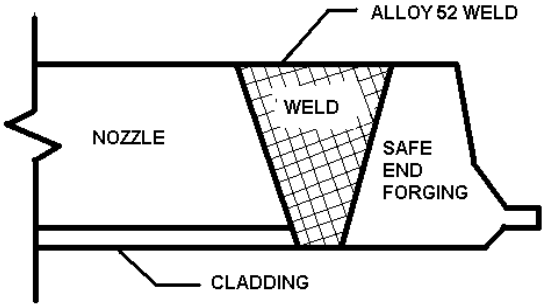

Figure 2-11
Type 3B Steam Generator Primary Nozzle Forged Stainless Steel Safe End Alloy 52 Attachment Weld

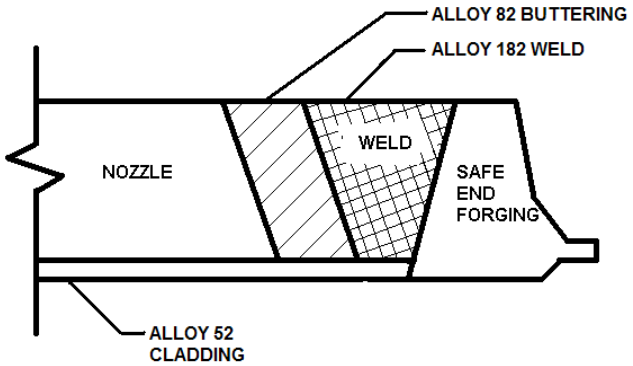

Figure 2-12
Steam Generator Primary Nozzle, Forged Stainless Steel Safe End Stainless Steel Safe End, Alloy 82 Butter and Alloy 182 Attachment Weld

2.3 Pressurizers

There are four nozzles on Westinghouse supplied pressurizers which potentially contain Alloy 82/182 weld material:

- Surge Nozzle
- Spray Nozzle
- Safety Nozzles (2 on 2-loop plants, 3 on 3-loop and 4-loop plants)
- Relief Nozzles

Two nozzle safe end configurations used on pressurizers in domestic Westinghouse plants have been confirmed. These configurations are defined as follows:

Type 1: Consists of a Forged stainless steel Safe End welded to the pressurizer nozzle with stainless steel weld material.

Type 2: Consists of a Forged stainless steel Safe End welded to the pressurizer nozzle with Alloy 82/182 weld material.

Graphical representations of the two pressurizer nozzle safe end configurations discussed above are contained in Figures 2-13 through 2-14. Most pressurizers have a thermal sleeve welded on the ID of the surge nozzle. An example of such a geometry is shown in Figure 2-15.

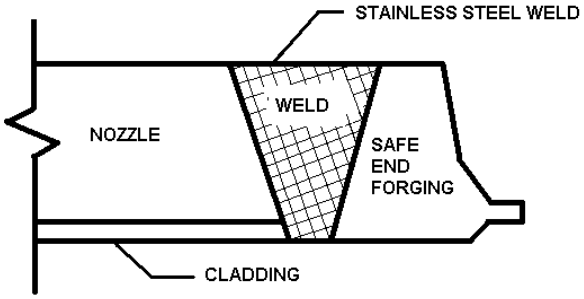

Figure 2-13
Type 1 Pressurizer Safe End Forged Stainless Steel Safe End Stainless Steel Attachment Weld

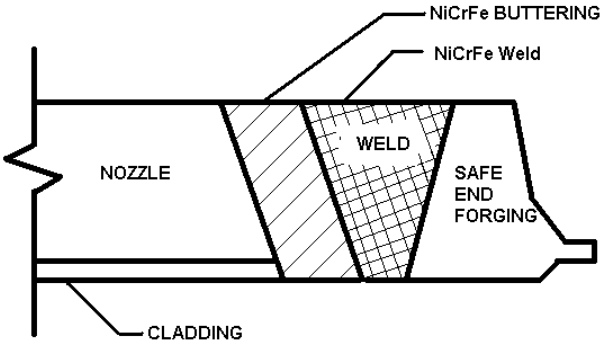

Figure 2-14
Type 2 Pressurizer Safe End Forged Stainless Steel Safe End Alloy 82/182 Attachment Weld

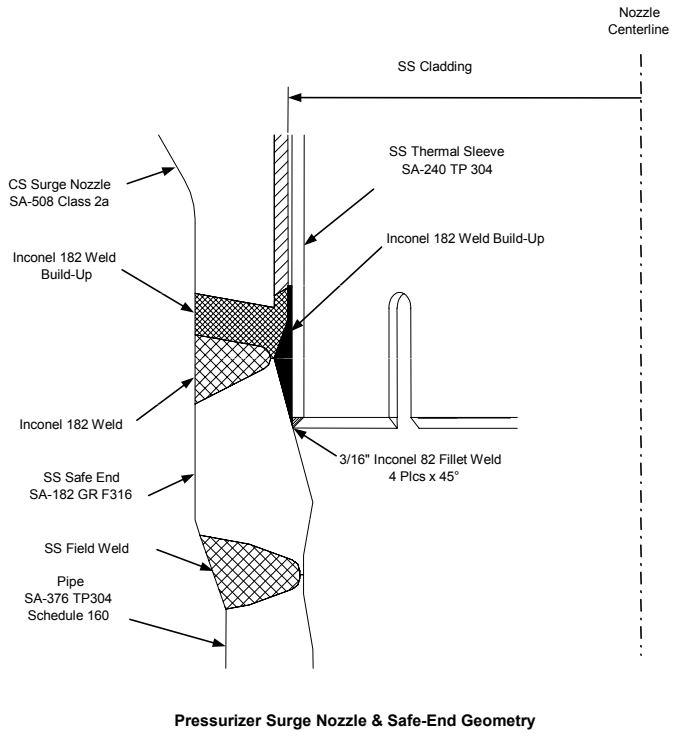

Figure 2-15
Example of a Welded Thermal Sleeve in a Pressurizer Nozzle

2.4 Choice of Key Plants

The evaluations completed for this final report concentrated on Westinghouse and CE plants with high pipe loads on the nozzle safe-end region. The results of the plants with high pipe loads on the nozzle safe-end region envelope the results of all other plants, since the operating pressures are nominally the same for all the plants. Note that thermal stratification loadings have been included where appropriate, such as for the pressurizer surge nozzles. Fatigue and PWSCC were evaluated in the assessments reported here, but not used as a basis for choosing a governing plant.

2.5 Repair Welds

It is recognized that repair welds may have been a contributing factor to the cracking which occurred at V. C. Summer plant, and also at Ringhals Unit 4. No such repairs were identified at Ringhals Unit 3, which also had cracks. This report has not compiled repair weld information, as it was beyond the scope of this project.

3
ALLOY 182/82 PIPING BUTT WELD LOCATIONS IN CE PLANTS

Locations of Alloy 182/82 butt weld joints in the primary system components have been identified for each CE plant. In general, these welds are limited to the Reactor Coolant (RC) primary piping and the larger nozzles in the pressurizer. Transitions from carbon or low allow steel components to stainless steel piping lines are accomplished by shop-welding stainless steel safe ends to the ferritic components. Nozzles and piping components are either carbon or low alloy steel. Safe ends are fabricated from either wrought or cast stainless steel. Welds are typically configured with nickel base alloy weld deposits (i.e., buttering) on the carbon or low alloy steel components which is then joined to the stainless steel safe end with a full penetration weld deposit of similar filler material. Figure 3-1 shows a typical CE Alloy 182/82 weld configuration. This geometry represents over 95 percent of the welds in service. Fabrication drawing notes clearly indicate that the weld between the safe end and the buttered nozzle was only to be made after final post-weld heat treatment of the ferritic component. Small bore nozzles (diameter less than two inches) are typically made with J-type welds and are excluded from this assessment.

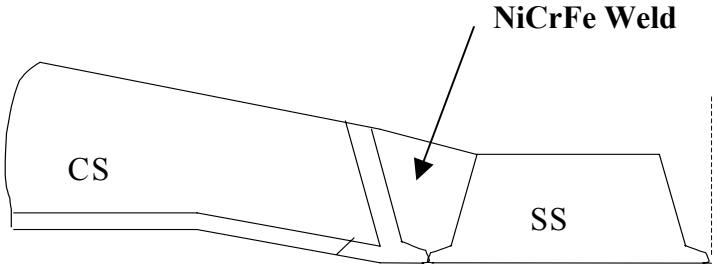

Figure 3-1
Typical CE Nozzle Bi-metallic Weld Geometry

3.1 Pressurizers

- Surge Line Nozzle (1 per Unit)
- Spray Nozzle (1 per Unit)
- Relief and Safety Valve Nozzles (3 per Unit)

3.2 Main Loop Piping

One Plant with Stainless Steel Piping has Alloy 182/82 RV and SG Nozzle Welds. Because of the similarities with the Westinghouse Fleet, this plant is grouped and evaluated with the Westinghouse plants, as noted in Section 2.0.

The only remaining Alloy 182/82 welds are at the reactor coolant pump (RCP) suction and discharge nozzle to cold leg safe end locations.

3.3 Auxiliary Line Welds

With exception of one plant, all CE branch line connections have Alloy 182/82 nozzle to safe end welds.

- RCP Surge Line Nozzle (1 per plant)
- Charging Inlet Nozzles (2 per plant)
- Safety Injection and SDC Inlet Nozzles (4 per plant)
- Shut Down Cooling (SDC) Outlet Nozzle (1 per plant)
- Spray Nozzles (2 per plant)
- Let-Down and Drain Nozzles (5 per plant)

3.4 Reactor Vessel and CEDMs

Each CEDM pressure housing of all later CE plants has two Alloy 182/82 butt welds. Because of the relatively low temperature at these locations (~200°F) they are not considered to be of interest to this study, because PWSCC does not occur at such a low temperature.

3.5 Choice of Key Location

In order to rank the CE plant Alloy 182/82 weld locations with respect to criticality of plant safety, the following criteria were applied:

- Operating Temperature (PZR higher than Hot Leg which is higher than Cold Leg)
- Nozzle Size and Location (Larger Diameter more critical to Plant Safety)

- Duty (Applicable Combinations of Large Normal Operating Loads, Thermal Stratification Loads, High Fatigue Usage Factors and High Seismic Loads)

While different lines have differing impacts on plant safety significance, the margins between leakage flaw size and critical flaw size will be shown to be smaller for the smaller diameter pipes, so all the butt welds with Alloy 82/182 welds in CE plants were included in this assessment. As with the Westinghouse designs, the plants with the largest piping loads were the governing cases, and are reported here.

4
PREFERRED FLAW ORIENTATIONS

The orientation of potential flaws in Alloy 82/182 welds is of great significance from the standpoint of structural integrity, leakage rate, and safety. The service experience thus far in PWR plant piping butt welds has been that nearly all the flaws have been oriented axially, and this section details that experience and discusses some engineering reasons why that behavior is expected.

4.1 Service Experience

The significant flaws found in Alloy 82/182 weld regions in PWR plants to date have all been oriented axially.

At V. C. Summer, six axial flaws were discovered in the loop A hot-leg weld that was removed and replaced. At the Ringhals Unit 4 plant in Sweden, four flaws have been discovered and removed, all of which are oriented axially. At Ringhals Unit 3, two axial flaws have been removed.

Axial flaws have also been discovered in the pressurizer surge nozzle at Tihange in Belgium, and in the safety and relief nozzles of Tsuruga Unit 2 in Japan. Axial flaws were also discovered in the surge line to hot leg safe-end weld at Three Mile Island, in 2003.

Only two circumferential indications have been reported to date in weld metal, 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 Alloy 182 cladding, terminating at the low alloy steel, about 0.20 inches deep. Two early circumferental flaws have also been reported in Alloy 600 base metal near welds. One was in the pressurizer relief line at Palisades in 1993 and the other was in a 1.5” Alloy 600 elbow attached to an Alloy 600 nozzle in a test reactor pressurizer at Bettis Atomic Power Laboratory.

4.2 Stress and Crack Driving Force

A number of nozzle safe-end regions have been evaluated, and in all cases the hoop stress exceeded the axial stress. This would lead to the conclusion that axial flaws would be more likely than circumferential flaws. It is obvious that the pressure stresses in the hoop direction will be double those in the axial direction, but piping loads and residual stress need to also be considered.

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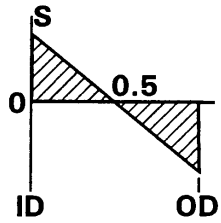
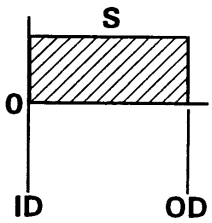
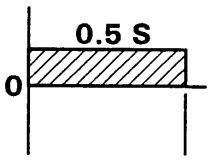
Figure 4-1
Example Comparison of Crack Driving Force from Hoop vs. Axial Stresses, Aspect Ratio 6:1, Showing a Higher Driving Force for Axial Flaws

Wall Thickness	Through-Wall Residual Stress[1]	
	Axial	Circumferential[2]
< 1 inch		
≥ 1 inch	See Note 3	

[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 4-2
Recommended Axial and Circumferential Residual Stress Distributions for Austenitic Pipe Welds [2]

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Figure 4-3
Example Comparison of Crack Driving Force from Hoop vs. Axial Stresses, Aspect Ratio 2:1, Showing a Higher Driving Force for Axial Flaws

4.3 References

1. Raju, I. S. and Newman, J. C., "Stress Intensity Factor Influence Coefficients for Internal and External Surface Cracks in Cylindrical Vessels," in Aspects of Fracture Mechanics in Pressure Vessels and Piping, ASME publication PVP Vol. 58, 1982.

2. "Evaluation of Flaws in Austenitic Steel Piping," Trans ASME, Journal of Pressure Vessel Technology, Vol. 108, August 1986, pp. 352-366.

5
FRACTURE EVALUATION

5.1 Methodology

The calculations discussed here have considered all the appropriate loadings, including dead weight, thermal expansion, thermal stratification, welding residual stress, and pressure. For critical flaw size calculations, the seismic loads are included. For the leak rate calculations, the normal loads are used.

The loadings for both the governing normal/upset condition and the governing emergency/faulted condition 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 forces and moments for each condition were obtained from calculations previously performed by Westinghouse, or by others who have been involved with system changes as described above. The stress values were calculated using the following equations:

$$\sigma_m = \frac{F_x}{A}$$

$$\sigma_b = \frac{1}{Z}[M_y^2 + M_z^2]^{0.5}$$

where

F_x = axial force component (membrane)
M_y, M_z = moment components (bending)
A = cross-section area
Z = section modulus

The section properties A and Z at the weld location were determined based on the nominal pipe dimensions. The following load combinations were considered.

For circumferential flaws:

- Thermal normal–100 percent power
- Dead weight

- Steady state pressure
- Safe shutdown earthquake (SSE)
- Thermal stratification, as appropriate

For axial flaws: Steady state pressure

It should be noted that other piping loadings have no impact on axial flaws.

The fracture assessment was carried out for Alloy 182 materials. The Alloy 82/182 weldments are known to have very high fracture toughness, and there are no known mechanisms which could degrade the toughness of the 82/182 welds during service. Thermal aging is known to have an impact on cast stainless steel, and also has a second order effect on stainless steel welds, but has no effect on Alloy 82/182 welds. The calculations carried out here are intended to produce a best estimate of the critical flaw size, which will be compared to a similar best estimate of the leak rate. There are conservatisms in the Section XI critical flaw size calculation methodology, in that conversative values of ductile limit load are calculated, but no other overt conservatisms were applied. Such conservatisms are not used in the leak rate calculations.

Rapid, non-ductile failure is possible for ferritic materials at low temperatures, but is not applicable to austenitic steels. In these materials, the higher ductility leads to two possible modes of failure, plastic collapse or unstable ductile tearing. The second mechanism can occur when the applied J integral exceeds the J_{Ic} fracture toughness, and some stable tearing occurs prior to failure. If this mode of failure is dominant, the load carrying capacity is less than that predicted by the plastic collapse mechanism.

The limit load solution for a pipe section containing a circumferential through-wall flaw subjected to a combined loading was used to determine the critical circumferential through-wall flaw length. The combined loading consists of a bending moment, an axial load, internal pressure and a torsional moment. The determination of the critical longitudinal through-wall flaw length was done using pipe burst pressure theory. The methodologies of the limit load solution and pipe burst theory are similar to the methodology of Section XI, Appendix C [1].

The loads necessary for determining the critical crack size include pressure, dead-weight and thermal loads plus the most limiting thermal stratification transient or the SSE event. In order to obtain a bounding crack size, the loadings for all plants were compiled. The bending moment in combination with the pressure is the dominant loading for a circumferential crack. The torsion and mechanical axial force do not significantly affect the limit load results.

Circumferential cracks are assumed to be located in the weld material or along the fusion line. Axial cracks, longer than the width of the weld, were assumed to be in the safe end/pipe material.

5.2 Results for Westinghouse Fleet

The critical flaw sizes were determined for three flaw types:

Critical length–Axial through-wall flaw
Critical length–Circumferential through-wall flaw
Critical depth–Continuous circumferential flaw

Note that attempts were made to define a critical depth for continuous axial part through flaws, but it was determined that a through-wall flaw would be required, to cause a failure.

Piping loads were compiled for all 48 operating Westinghouse plant designs, along with one CE plant design with stainless steel main coolant piping and 82/182 welds in the safe-end region, as described in Section 2.

Of these reactor vessels, those with Alloy 82/182 in the safe-end region and the highest applied piping loads were selected for presentation. The piping loads are affected by both geographical location and the plant piping layout. The range of piping outside diameters selected ranged from 33-38 inches, and the wall thickness ranged from 2.4 to 3.1 inches. These geometries include both three- and four-loop Westinghouse designs, as well as the CE design. There are no domestic two-loop Westinghouse designs with Alloy 82/182 in the reactor vessel safe-end region.

The CE design with stainless steel main coolant piping is one of only two plants with Alloy 82/182 welds in the steam generator nozzle safe end region, and was selected for evaluation. The second plant has Westinghouse replacement steam generators. The stainless steel 308L welds were used for all Westinghouse designed steam generator nozzle safe end regions.

For the pressurizer, all have 4 inch diameter spray nozzles except one with a 6 inch diameter. The 6 inch spray nozzle piping load is enveloped by the 4 inch spray nozzle piping loads. Therefore, the 4 inch spray nozzles with highest piping loads were selected for evaluation. The pressurizer surge nozzle is either 16 inches or 14 inches in diameter, and the safety and relief nozzles with Alloy 182 welds are all 6 inches in diameter. The surge nozzles with highest piping loads for both 16 inch and 14 inch were selected for evaluation, and the safety and relief nozzles with highest piping loads were selected for evaluation.

The results are presented for one of each of the chosen nozzles in Table 5-1. The selected plants have been identified as A through I. Examples of each of the calculations are shown in Figures 5-1 through 5-21, and the results are summarized in Table 5-1.

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Figure 5-1
Plant C Reactor Vessel Outlet Nozzle Longitudinal Through-Wall Crack Length vs. Limit Pressure

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Figure 5-2
Plant C Reactor Vessel Outlet Nozzle Circumferential Through-Wall Crack Length vs. Limit Moment

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Figure 5-3
Plant C Reactor Vessel Outlet Nozzle Continuous Circumferential Part-Through Flaw Depth/Wall Thickness vs. Limit Moment

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Figure 5-4
Plant C Reactor Vessel Inlet Nozzle Longitudinal Through-Wall Crack Length vs. Limit Pressure

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Figure 5-5
Plant C Reactor Vessel Inlet Nozzle Circumferential Through Wall Crack Length vs. Limit Moment

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Figure 5-6
Plant C Reactor Vessel Inlet Nozzle Continuous Circumferential Part-Through Flaw Depth/Wall Thickness vs. Limit Moment

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Figure 5-7
Plant D Steam Generator Outlet Nozzle Longitudinal Through Wall Crack Length vs. Limit Pressure

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Figure 5-8
Plant D Steam Generator Outlet Nozzle Circumferential Through Wall Crack Length vs. Limit Moment

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Figure 5-9
Plant D Steam Generator Outlet Nozzle Continuous Circumferential Part-Through Flaw Depth/Wall Thickness vs. Limit Moment

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Figure 5-10
Plant D Steam Generator Inlet Nozzle Longitudinal Through Wall Crack Length vs. Limit Pressure

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Figure 5-11
Plant D Steam Generator Inlet Nozzle Circumferential Through Wall Crack Length vs. Limit Moment

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Figure 5-12
Plant D Steam Generator Inlet Nozzle Continuous Circumferential Part-Through Flaw Depth/Wall Thickness vs. Limit Moment

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Figure 5-13
Plant F Pressurizer Surge Nozzle Longitudinal Through-Wall Crack Length vs. Limit Pressure

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Figure 5-14
Plant F Pressurizer Surge Nozzle Circumferential Through Wall Flaw Crack Length vs. Limit Moment

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Figure 5-15
Plant F Pressurizer Surge Nozzle Continuous Circumferential Part-Through Flaw Depth/Wall Thickness vs. Limit Moment

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Figure 5-16
Plant G Pressurizer Spray Nozzle Longitudinal Through Wall Flaw Crack Length vs. Limit Pressure

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Figure 5-17
Plant G Pressurizer Spray Nozzle Circumferential Through Wall Flaw vs. Limit Moment

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Figure 5-18
Plant G Pressurizer Spray Nozzle Continuous Circumferential Part-Through Flaw Depth/Wall Thickness vs. Limit Moment

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Figure 5-19
Plant I Pressurizer Safety & Relief Nozzle Longitudinal Through Wall Flaw Crack Length vs. Limit Pressure

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Figure 5-20
Plant I Pressurizer Safety & Relief Nozzle Circumferential Through Wall Flaw vs. Limit Moment

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Figure 5-21
Plant I Pressurizer Safety and Relief Nozzle Continuous Circumferential Part-Through Flaw Depth/Wall Thickness vs. Limit Moment

The results of the fracture assessment for those key plants nozzle safe end welds are shown in Table 5-1, for Alloy 182 materials. The results show very large critical flaw sizes for the nozzle safe end regions. The Alloy 182 materials have very high fracture toughness. Therefore, the failure mode is plastic limit load, which is governed by the material yield and ultimate tensile strengths.

The case of the longitudinal flaw is a safe situation because the length of the flaw is limited to the width of the weld. Therefore, for the maximum flaw length the burst pressures were calculated as shown in Table 5-1 and found to be 7.7 ksi or greater, which is much higher than the 2.25 ksi maximum operating pressure. Therefore, longitudinal bursting is not a concern.

Table 5-1
Critical Flaw Size & Weld Burst Pressure Results for Westinghouse Fleet

Weld Locations	Plant	Burst Pressure for Longitudinal Through-Wall Flaw Equal to Weld Width of 2.5 inch (ksi)	Critical Longitudinal Through-Wall Flaw Length (in.)	Critical Circumferential Through-Wall Flaw Length (1) (in.)	Critical Continuous Circumferential Flaw Depth (a/t)
Reactor Vessel Outlet Nozzle Safe-end Weld	A	8.0	28.4	31.5 (29%)	0.63
	B	8.9	34.1	30.0 (27%)	0.62
	C	7.8	27.4	25.5 (24%)	0.54
	D	8.6	38.5	44.0 (37%)	0.72
Reactor Vessel Inlet Nozzle Safe-end Weld	A	8.0	27.1	36.2 (35%)	0.68
	B	8.2	28.1	33.3 (32%)	0.66
	C	7.7	25.9	36.4 (36%)	0.67
	D	8.6	30.0	36.3 (40%)	0.75
Steam Generator Outlet Nozzle	D	8.8	30.0	39.3 (43%)	0.77
Steam Generator Inlet Nozzle	D	8.6	38.5	49.0 (41%)	0.76
Pressurizer Surge Nozzle	E	11.8	27.5	21.4 (39%)	0.76
	F	9.9	20.5	15.3 (32%)	0.69
Pressurizer Spray Nozzle	G	12.0	16.4	9.0 (48%)	0.87
	H	10.1	13.4	7.6 (40%)	0.82
Pressurizer Safety & Relief Nozzle	I	11.5	17.4	11.5 (46%)	0.85
	E	15.2	24.2	10.0 (40%)	0.82

Notes:

(1) Values in parentheses are expressed as a percentage of the circumference.

5.3 Results for CE Fleet

The limit moments as a function of circumferential through-wall crack length were calculated for all critical weld locations for each CE plant. It was opted here to tabulate the results for the two most limiting plants but to graph only the most limiting results per location. The results presented herein are always those that reflect the more conservative loading situation. Graphical results for the critical circumferential through-wall crack length computations are included for the two RCP nozzle locations, the two Surge line nozzle locations, the Shut Down Cooling nozzle location, the Pressurizer Spray and Safety Injection/Relief Valve nozzle locations.

Each graph includes a horizontal line that represents either the operating pressure or the bending moment that is applied to the pipe; where the operating pressure is the important loading for axial or longitudinal flaws and the bending moment is the important loading for circumferential flaws. As the longitudinal or circumferential crack grows, the respective limit pressure and limit moment curves drop until they intersect with the horizontal line. This point of intersection constitutes the critical flaw length. Typically two vertical lines are also superimposed on each graph and represent the flaw lengths that correspond to a leak rate of 1 and 10 GPM.

The limit moment as a function of crack depth for a uniform 360 degree crack extending from the inside of the pipe was determined for all weld locations for each of the CE plants. The maximum normal operation + SSE moment and the dead weight + thermal + maximum thermal stratification transient moment were applied and these loads are shown superimposed on the various figures as appropriate, so that the critical crack depth for these loadings can be determined. The bounding load case for the critical crack depth was selected for inclusion in the summary table for each plant and each location. Referring to the various figures for the limit moment versus flaw depth, the pipe limit is shown as a horizontal line and is compared with a second, much lower line that represents the combined plant loading condition. As the crack depth continues to grow the permissible limit moment is seen to drop until it intersects with the applied moment line. This intersection represents the permissible flaw depth for that particular case.

Axial cracks are not significantly affected by the bending moment on the pipe. Therefore the loading condition of concern is internal pressure. The limit pressure as a function of length of a through-wall axial crack in the safe-end/pipe material was determined for each plant and each selected weld location. Each crack shows the limit (burst) pressure as a function of axial flaw length. The intersection of the limit pressure curve with the maximum design pressure curve of 2,250 psi represents the critical flaw length. Superimposed are two vertical lines, one representing 1 GPM, the second 10 GPM leakage flow.

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Figure 5-22
Plant J RCP Suction Nozzle Limit Pressure vs. Axial Crack Length

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Figure 5-23
Plant J RCP Suction Nozzle Limit Moment vs. Circumferential Through Wall Crack Length

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Figure 5-24
Plant J RCP Suction Nozzle Limit Moment vs. Circumferential Part Through Wall Crack Depth to Thickness Ratio

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Figure 5-25
Plant J RCP Discharge Nozzle Limit Pressure vs. Axial Crack Length

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Figure 5-26
Plant J RCP Discharge Nozzle Limit Moment vs. Circumferential Through Wall Crack Length

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Figure 5-27
Plant J Discharge Nozzle Limit Moment vs. Circumferential Part Through Wall Crack Depth to Thickness Ratio

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Figure 5-28
Plant L Shutdown Cooling Nozzle Limit Pressure vs. Circumferential Part Through Wall Crack Depth to Thickness Ratio

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Figure 5-29
Plant L Shutdown Cooling Nozzle Limit Moment vs. Circumferential Part Through Wall Crack Depth to Thickness Ratio

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Figure 5-30
Plant L Shutdown Cooling Nozzle Limit Moment vs. Circumferential Through Wall Crack Length

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Figure 5-31
Plant M Hot Leg Surge Nozzle Limit Pressure vs. Axial Through Wall Crack Length

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Figure 5-32
Plant M Hot Leg Surge Nozzle Limit Moment vs. Circumferential Through Wall Crack Length

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Figure 5-33
Plant M Hot Leg Surge Nozzle Limit Moment vs. Circumferential Part Through Wall Crack Depth to Thickness Ratio

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Figure 5-34
Plant N Pressurizer Surge Nozzle Limit Pressure vs. Axial Through Wall Crack Depth to Thickness Ratio

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Figure 5-35
Plant N Pressurizer Surge Nozzle Limit Moment vs. Circumferential Through Wall Crack Length

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Figure 5-36
Plant N Pressurizer Surge Nozzle Limit Moment vs. Circumferential Part Through Wall Crack Depth to Thickness Ratio

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Figure 5-37
Plant O Pressurizer Spray Nozzle Limit Pressure vs. Axial Through Wall Crack Depth to Thickness Ratio

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Figure 5-38
Plant O Pressurizer Spray Limit Moment vs. Circumferential Through Wall Crack Length

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Figure 5-39
Plant O Pressurizer Spray Nozzle Limit Moment vs. Circumferential Part Through Wall Crack Depth to Thickness Ratio

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Figure 5-40
Plant P Pressurizer Safety and Relief Nozzle Limit Pressure vs. Axial Through Wall Crack Depth to Thickness Ratio

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Figure 5-41
Plant P Pressurizer Safety and Relief Nozzle Limit Moment vs. Circumferential Through Wall Crack Length

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Figure 5-42
Plant P Pressurizer Safety and Relief Nozzle Limit Moment vs. Circumferential Part Through Wall Crack Depth to Thickness Ratio

Table 5-2
Critical Flaw Size and Weld Burst Pressure Results for CE Fleet

Weld Location	Limiting Plant	Burst Pressure for Longitudinal Through-Wall Flaw Length = 2.5 in. (Ksi)	Critical Longitudinal Through-Wall Flaw Length (in.)	Critical Circumferential Through-Wall Flaw Length (1) (in.)	Critical Continuous Circumferential Flaw Depth (a/t)
RCP Suction	J	9.4	38.2	36.5 (32%)	0.62
	L	9.4	38.2	38.2 (34%)	0.64
RCP Discharge	J	9.4	38.2	33.2 (29%)	0.56
	L	9.4	38.2	40.5 (36%)	0.67
SDC	L	10.3	21.4	18.7 (37%)	0.74
	M	10.3	23.0	18.0 (35%)	0.72
Surge Line (Hot Leg)	M	10.3	19.5	10.3 (25%)	0.56
	K	9.1	17.3	11.8 (29%)	0.63
Surge Line (Pressurizer)	N	12.2	23.8	14.2 (35%)	0.74
	K	11.8	23.0	14.4 (35%)	0.71
Pressurizer Spray	O	5.7	7.2	6.5 (44%)	0.81
	R	5.7	7.2	3.0 (20%)	0.44
Pressurizer Safety / Relief	P	6.7	8.1	5.2 (44%)	0.85
	N	18.1	24.0	6.9 (36%)	0.82

Notes:

(1) Values in parentheses are expressed as a percentage of the circumference.

5.4 Stress Corrosion and Fatigue Crack Growth Methodology

5.4.1 Stress Corrosion Crack Growth

Stress corrosion crack growth is presumed to occur only in the Alloy 82/182 weld material. Therefore, both circumferential and axial cracks will be considered to grow in the Alloy 82/182 material.

The crack growth rate for Alloy 182 at 325°C (617°F) is given in Reference 2.

$$D_{am} = C_o (K_{im}-9.0)^{1.16}$$

where

C_o = 1.4E-11 at 617°F

K_{im} = stress intensity factor in [MPa-m$^{0.5}$]

D_{am} = crack growth in meters per second

A temperature adjustment based on the Ahrreneous relationship is applied to the C_o coefficient.

$$C_o = 1.4E\text{-}11 \times \exp \{ (-Q/0.001103) \times [1/(Temp+459.7) - 1/(617.0 + 459.7)] \}$$

Where Q is found to be 32.4 based on the data of Reference 2.

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$^{0.5}$, thereby ensuring crack growth occurs.

5.5 Crack Growth Results for the Westinghouse Fleet

The stress corrosion crack (SCC) growth evaluation was performed with the equation appropriate for the temperature of the component. SCC growth for both part through and through-wall flaws was calculated, and the results were tabulated on Table 5-3. This was done to ensure that the governing result was presented. As will be seen in the figures, the limiting case is not always obvious until the two results are obtained. As shown in Table 5-3, the time required for flaws of various sizes to propagate has been calculated. The column titles indicate the initial flaw size assumed. For example, “1 GPM” means that the assumed initial flaw length was that for a through-wall flaw to give a leak rate of one gallon per minute.

Table 5-3
SCC Growth Results and Comparison of Structural Failure Flaw Length and Detectable Flaw Length for Circumferential Flaws in Westinghouse Designs

Weld Location	Limiting Plant	Period from Assumed SCC Initiation to Through-Wall [years]		Period from a 1 or 10 GPM Through-Wall Crack to Critical Flaw Length [years]		Critical Circumferential Through-Wall Flaw Length [in.]
		Aspect Ratio 6:1	Aspect Ratio 2:1	1 GPM	10 GPM	
Reactor Vessel Outlet Nozzle Safe-end Weld	A	2.0	6.5	8.3	4.1	31.5
	B	2.6	7.7	10.7	4.6	30.0
	C	2.9	9.8	11.9	5.2	25.5
	D	6.9	23.5	19.2	12.6	44.0
Reactor Vessel Inlet Nozzle Safe-end Weld	A	23.5	>40	>40	>40	36.2
	B	22.3	>40	>40	>40	33.3
	C	>40	>40	>40	>40	36.4
	D	>40	>40	>40	>40	36.3
Steam Generator Outlet Nozzle	D	>40	>40	>40	>40	39.3
Steam Generator Inlet Nozzle	D	11.8	35.7	>40	18.3	49.0
Pressurizer Surge Nozzle	E	1.9	5.6	4.3	1.7	21.4
	F	1.4	3.9	2.6	1.1	15.3
Pressurizer Spray Nozzle	G	1.3	>40	11.8	<1	9.0
	H	1.1	2.6*	2.6	<1	7.6
Pressurizer Safety & Relief Nozzle	I	3.5**	4.2**	4.8	1.2	11.5
	E	4.1+	5.2+	5.6	<1	10.0

* SCC initiation a/t = 0.78
\+ SCC initiation a/t = 0.33 for AR=6:1, a/t=0.62 for AR=2:1
** SCC initiation a/t = 0.35 for AR=6:1, a/t=0.70 for AR=2:1.

Fatigue crack growth (FCG) was also performed for the nozzle safe end weld regions by using the Alloy 600 fatigue crack growth model described in Reference 3. An example of the effects of fatigue crack growth for the reactor vessel outlet nozzle safe end region is shown in Table 5-4.

Table 5-4
Example Fatigue Crack Growth Results for the Reactor Vessel Outlet Nozzle Safe End Weld Region for Plant C (Circumferential Flaw length: Flaw depth = 6:1, Wall thickness = 2.35 in.)

Initial Crack Depth (inch)	Crack Depth After			
	10 years	20 years	30 years	40 years
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Figure 5-43
Plant C Reactor Vessel Outlet Nozzle Safe End Weld Region SCC growth (Circumferential flaw)

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Figure 5-44
Plant C Reactor Vessel Inlet Nozzle Safe End Weld Region SCC growth (Circumferential flaw)

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Figure 5-45
Plant D Steam Generator Outlet Nozzle Weld SCC Growth (Circumferential Part-Through Flaw)

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Figure 5-46
Plant D Steam Generator Inlet Nozzle Weld SCC Growth (Circumferential Part-Through Flaw)

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Figure 5-47
Plant F Pressurizer Surge Nozzle Weld SCC Growth (Circumferential Part-Through Flaw)

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Figure 5-48
Plant G Pressurizer Spray Nozzle Weld SCC Growth (Circumferential Part-Through Flaw)

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Figure 5-49
Plant I Pressurizer Safety/Relief Nozzle Weld Growth (Circumferential Part-Through Flaw)

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Figure 5-50
Plant C Reactor Vessel Outlet Nozzle Weld SCC Growth (Circumferential Through-Wall Flaw)

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Figure 5-51
Plant C Reactor Vessel Inlet Nozzle Weld SCC Growth (Circumferential Through-Wall Flaw)

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Figure 5-52
Plant D Steam Generator Outlet Nozzle Weld SCC Growth (Circumferential Through-Wall Flaw)

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Figure 5-53
Plant D Steam Generator Inlet Nozzle Weld SCC Growth (Circumferential Through-Wall Flaw)

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Figure 5-54
Plant F Pressurizer Surge Nozzle Weld SCC Growth (Circumferential Through-Wall Flaw)

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Figure 5-55
Plant G Pressurizer Spray Nozzle Weld SCC Growth (Circumferential Through-Wall Flaw)

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Figure 5-56
Plant I Pressurizer Safety and Relief Nozzle Weld SCC Growth (Circumferential Through-Wall Flaw)

5.6 Crack Growth Results for the CE Fleet

The stress corrosion crack growth analysis results for the CE fleet are summarized for all locations under consideration both in graphical and in tabular form. Figures 5-57 to 5-63 represent the results for only the most-limiting plant locations. Both zero residual stress and 30 ksi residual stress curves are plotted due to the uncertainty of the actual residual stress level/profile. Aspect ratios of 2:1 and 6:1 were assumed for the crack shape.

In addition, a series of calculations were carried out for through-wall flaws, and sample results for each location are shown in Figures 5-64 through 5-70. The results from these analyses are plotted only for the most-limiting plant locations. Superimposed on the graphs are the crack lengths associated with both 1 and 10 GPM leakage flow.

The same calculations were performed for all plants. (Note that in some of the plots the plant designation is followed by a 1 or 2, to differentiate between Units.) The RCP suction and discharge nozzles appear to be the least susceptible locations, which may be explained by the relatively cooler temperature. For the remaining locations, the situation is highly influenced by the assumption made for the residual weld stress.

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Figure 5-57
Plant J Reactor Coolant Pump Suction Nozzle Inconel Weld PWSCC Growth (Circumferential Part-Through Wall Flaw)

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Figure 5-58
Plant J Reactor Coolant Pump Discharge Nozzle Inconel Weld PWSCC Growth (Circumferential Part-Through Wall Flaw)

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Figure 5-59
Plant L Shut Down Cooling Nozzle Inconel Weld PWSCC Growth (Circumferential Part-Through Wall Flaw)

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Figure 5-60
Plant M Hot Leg Surge Line Nozzle Inconel Weld PWSCC Growth (Circumferential Part-Through Wall Flaw)

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Figure 5-61
Plant N Pressurizer Surge Line Nozzle Inconel Weld PWSCC Growth (Circumferential Part-Through Wall Flaw)

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Figure 5-62
Plant O Pressurizer Spray Line Nozzle Inconel Weld PWSCC Growth (Circumferential Part-Through Wall Flaw)

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Figure 5-63
Plant P Pressurizer Safety and Relief Nozzle Inconel Weld PWSCC Growth (Circumferential Part-Through Wall Flaw)

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Figure 5-64
Plant J Reactor Coolant Pump Suction Nozzle Inconel Weld PWSCC Growth (Circumferential Through Wall Flaw)

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Figure 5-65
Plant J Reactor Coolant Pump Discharge Nozzle Inconel Weld PWSCC Growth (Circumferential Through Wall Flaw)

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Figure 5-66
Plant L Shut Down Coolant Nozzle Inconel Weld PWSCC Growth (Circumferential Through Wall Flaw)

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Figure 5-67
Plant M Hot Leg Surge Line Nozzle Inconel Weld PWSCC Growth (Circumferential Through Wall Flaw)

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Figure 5-68
Plant N Pressurizer Surge Line Nozzle Inconel Weld PWSCC Growth (Circumferential Through Wall Flaw)

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Figure 5-69
Plant O Pressurizer Spray Line Nozzle Inconel Weld PWSCC Growth (Circumferential Through Wall Flaw)

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Figure 5-70
Plant P Pressurizer Safety and Relief Nozzle Inconel Weld PWSCC Growth (Circumferential Through Wall Flaw)

Table 5-5
SCC Growth Results & Comparison of Structural Failure Flaw Length and Detectable Flaw

Weld Location	Limiting Plant	Period from SCC Initiation to Thru-Wall [years]		Period from a 1 or 10 GPM Thru-Wall Crack (2) to Critical Flaw Length [years]		Critical Circumferential Thru-Wall Flaw Length [in.]
		6:1 (1)	2:1 (1)	1 GPM	10 GPM	
RCP Suction	J	27.0	>40	>40	>40	36.5
	L	34.3	>40	>40	>40	38.2
RCP Discharge	J	19.7	>40	>40	38.5	33.2
	L	28.5	>40	>40	>40	40.5
SDC	L	3.3	10.5	8.3	3.7	18.7
	M	4.6	12.4	10.3	3.8	18.0
Surge Line (Hot Leg)	M	8.8	13.8	14.2	2.7	10.3
	K	11.0	16.8	22	4.4	11.8
Surge Line (Pressurizer)	N	3.9	6.5	5.3	1.6	14.2
	K	4.2	6.8	6.5	1.7	14.4
Pressurizer Spray	O	<1	>40	2.0	<1	6.5
	R	<1	>40	<1	(3)	3.0
Pressurizer Safety/Relief	P	1.1	>40	2.1	<1	5.2
	N	3.6	4.6	2.3	<1	6.9

Notes:

1. Aspect ratio defined as: Flaw length: Flaw depth.
2. Through-wall defined as producing either 1 GPM or 10 GPM leak.
3. Critical condition occurs prior to 10 GPM. Refer to time from 1 GPM to critical condition.

5.7 References

1. ASME Boiler and Pressure Vessel Code, Section XI, "Rules for In-service Inspection of Nuclear Power Plant Components," 1995 edition through 96 Addends.

2. EPRI Report, "Crack Growth of Alloy 182 Weld Metal in PWR Environments (PWRMRP-21)."

3. James, L. A., "Fatigue Crack Propagation Behavior of Inconel 600," in Hanford Engineering Labs Report, HEPL-TME-76-43, May 76.

6
LEAK-BEFORE-BREAK (LBB) ASSESSMENT

The purpose of this section is to make an assessment of LBB on the Alloy 82 and 182 Welds and to show that the safety is maintained.

6.1 Leak Rate Calculation Methodology

Parametric leak rate calculations were performed with the same methodology for all LBB applications, which have been reviewed and approved by the NRC. Three plants with the highest piping faulted loads were selected for evaluation. Geometries include both three and four loop Westinghouse design plants. In addition, one plant with high seismic loads was also evaluated.

Loadings from the plant piping stress analysis of record were used. Loadings included power upratings, steam generator snubber reductions and steam generator replacements as applicable. Leak rate in gpm was calculated for various circumferential through-wall flaws (inches) using the deadweight, thermal, normal 100% power, and steady state normal operating pressure. Loads were combined by algebraic sum method.

Leak rates were also calculated for various through-wall axial flaws using the steady state normal operating pressure. Note that these flaws were postulated to extend beyond the Alloy 182/82 weld material for the purpose of these calculations.

Steps involved in the leak rate predictions were to calculate the crack opening area and to determine leak rate using two-phase flow formulation taking into account the surface roughness. Using the results of the leak rate calculations, plots were generated providing the leak rate as a function of flaw sizes. Westinghouse fleet plots are shown in Figures 6-1 to 6-7. CE fleet plots are shown in Figures 6-8 to 6-14.

The RCS pressure boundary leak detection capability of the plants is required to be at least 1 gpm, but recent plant interactions with the NRC have revealed that the actual capability for a typical plant is about 0.1 gpm. By comparing the critical flaw sizes shown in Chapter 5 with the leak rate sizes, the margins between detectable leakage and break can be determined. Furthermore, the time required for a crack to progress from a detectable leak to a break can be quantified. These results have been presented in Table 5-3 for the Westinghouse designs and in Table 5-5 for the CE designs.

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Figure 6-1
Plant C Reactor Vessel Outlet Nozzle Leak Rate vs Flaw Size

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Figure 6-2
Plant C Reactor Vessel Inlet Nozzle Leak Rate vs Flaw Size

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Figure 6-3
Plant D Steam Generator Outlet Nozzle Leak Rate vs Flaw Size

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Figure 6-4
Plant D Steam Generator Inlet Nozzle Leak Rate vs Flaw Size

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Figure 6-5
Plant F Pressurizer Surge Nozzle Leak Rate vs Flaw Size

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Figure 6-6
Plant G Pressurizer Spray Nozzle Leak Rate vs Flaw Size

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Figure 6-7
Plant I Pressurizer Safety/Relief Nozzle Leak Rate vs Flaw Size

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Figure 6-8
Plant J, RCP Suction Nozzle, Leak Rate vs. Flaw Size

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Figure 6-9
Plant J, RCP Discharge Nozzle, Leak Rate vs. Flaw Size

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Figure 6-10
Plant L, Shut Down Cooling Line Nozzle, Leak Rate vs. Flaw Size

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Figure 6-11
Plant M, Hot Leg Surge Line Nozzle, Leak Rate vs. Flaw Size

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Figure 6-12
Plant N, Pressurizer Surge Line Nozzle, Leak Rate vs. Flaw Size

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Figure 6-13
Plant O, Pressurizer Spray Nozzle, Leak Rate vs. Flaw Size

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Figure 6-14
Plant P, Pressurizer Safety Valve/Relief Nozzle, Leak Rate vs. Flaw Size

7
SUMMARY AND CONCLUSIONS

The work presented in this report has dealt with the structural integrity of Alloy 82/182 butt weld locations in operating nuclear plants of Westinghouse and CE designs.

Alloy 82/182 piping butt welds are used in the safe end region of following locations:

Westinghouse Design:

- Reactor vessel primary outlet nozzle
- Reactor vessel primary inlet nozzle
- Steam generator primary outlet nozzle
- Steam generator primary inlet nozzle
- Pressurizer surge nozzle
- Pressurizer spray nozzle
- Pressurizer safety/relief nozzles

Combustion Engineering Design:

- Reactor coolant pump suction nozzle
- Reactor coolant pump discharge nozzle
- Shut-down coolant outlet nozzle
- Pressurizer surge nozzle
- Hot leg surge line nozzle
- Pressurizer spray nozzle
- Pressurizer safety & relief nozzles

For each location, the piping loads were compiled for all operating plants, and the limiting cases were evaluated to determine the size of the flaw which could lead to piping failure, and the leak rate as a function of through-wall flaw size. The results showed that the margin between the flaw which gives detectable leakage and the critical flaw size is very large for large diameter pipes and decreases as pipe diameter decreases.

The case of the longitudinal flaw is a safe situation, because the length of the flaw is limited to the width of the weld material. Therefore, for the maximum flaw length (~2.5 inches), the burst pressures were calculated (as shown in Tables 5-1 and 5-2) and found to be 5.7 ksi or greater, which is well

above the current maximum operating pressure of 2.25 ksi. Therefore, longitudinal flaw bursting is not a concern.

The circumferential crack growth result for each location is discussed below:

- Reactor Vessel Primary Outlet Nozzle

  The crack growth result summarized in Table 5-3 showed it will take at least 8 years to propagate to critical flaw length from a 1 GPM leak for the safe end region of the outlet nozzle. This provides enough time for detection of cracking from initial leakage before a failure could occur.

- Reactor Vessel Primary Inlet Nozzle and Steam Generator Primary Outlet Nozzle

  The crack growth results given Table 5-3 (see Figures 5-44 and 5-45) indicate it will take greater than 40 years, in most cases, to propagate a flaw to a through-wall flaw. The 10 year-inspection required by Section XI will provide detection of cracking long before the flaw depth reaches the wall thickness. Therefore, there is no integrity concern for these regions.

- Steam generator primary inlet nozzle

  The SCC crack growth for the safe end weld region of the steam generator primary inlet nozzle (shown in Figure 5-46) indicates it will take at least 11 years to propagate a flaw to a through-wall flaw, which provides enough time for detection of cracking. Therefore, the 10-year inspection required by Section XI will provide for detection of cracking before the flaw depth reaches the wall thickness.

- Pressurizer Surge Nozzle (Westinghouse Series 84 Pressurizer, 14 inch surge line)

  Figure 5-47 showed the stress intensity factors for the Pressurizer surge nozzle are small, in many cases below the stress intensity factor of 9 MPa $\sqrt{m}$. The initial flaws have to reach 40% of safe end weld thickness of the surge in order to cause the crack to propagate, if the threshold were assumed to be 9 MPa $\sqrt{m}$. There is no mechanism to cause the flaw to reach over 40% of the weld thickness. Therefore, the cracking of this region is very unlikely.

- Pressurizer Surge Nozzle (Westinghouse Series 100 Pressurizer, 16 inch surge line) and Pressurizer Spray Nozzle (Westinghouse design)

  The through-wall flaw results are plotted in Figures 5-54 to 5-56 and are summarized in Table 5-3. For the Pressurizer Surge Nozzle (Westinghouse Series 100 Pressurizer, 16 inch surge line) and Pressurizer spray nozzle (Westinghouse design), the crack growth results from these figures showed it will take at least 2.5 years to propagate the flaw to its critical flaw length from a 1 GPM leak for the safe end regions.

- Pressurizer Safety/Relief Nozzle (Westinghouse design)

  Figure 5-49 showed the results for the Pressurizer safety/relief nozzles. There are two sets of analyses provided, with and without residual stress. For the case with residual stress, the flaws stop propagating after reaching 37% of the wall thickness because the stress intentisy factor drops below 9 MPa $\sqrt{m}$. For the case without residual stress, the stress intensity factor is below the stress intensity factor (9 MPa $\sqrt{m}$) until the flaw depth grows to 36% of the wall thickness.

- Reactor Coolant Pump Suction/Discharge Nozzle (CE design)

  The limiting crack growth results indicate it will take at least 19 years to propagate the flaw to through-wall and greater than 40 years to reach the critical flaw length assuming a 1 GPM through-wall flaw. The 10 year-inspection required by Section XI will provide detection of cracking long before it reaches the wall thickness.

- Hot Leg Surge Line Nozzle (CE design)

  The limiting crack growth results indicate it will take at least 8 years to propagate the flaw to through-wall and another 14 years to reach the critical flaw length, assuming a 1 GPM through-wall flaw.

- Shut Down Cooling Nozzle (CE design) and Pressurizer Surge Nozzle (CE design)

  The limiting crack growth results indicate it will take at least 3 years to propagate the flaw to through-wall and at least 5 years to reach the critical flaw length assuming a 1 GPM through-wall flaw.

- Pressurizer Spray Nozzle (CE design)

  The limiting crack growth results indicate it will take less than 1 year to propagate the flaw to through-wall and less than 1 year to reach the critical flaw length, assuming a 1 GPM through-wall flaw.

- Pressurizer Safety/Relief Nozzles (CE design)

  The limiting crack growth results indicate it will take approximately 1 year to propagate the flaw to through-wall and approximately 2 years to reach the critical flaw length, assuming a 1 GPM through-wall flaw.