

3.6.3 Leak-Before-Break Evaluation Procedures

This section describes the analyses used to eliminate from the design basis the dynamic effects of certain pipe ruptures for high-energy piping systems and demonstrate that the probability of pipe rupture is extremely low under conditions consistent with the design basis for the piping.

GDC 4 requires structures, systems, and components important to safety to be designed to accommodate the effects from loss-of-coolant accidents. However, dynamic effects associated with postulated pipe ruptures may be excluded from the design basis when analyses reviewed and approved by the NRC demonstrate that the probability of fluid system piping rupture is extremely low under conditions consistent with the design basis for the piping. Accordingly, this section addresses the piping systems that are qualified to be considered for the leak-before-break (LBB) application, the potential for piping failure mechanisms, the fracture mechanics analyses of postulated pipe cracks, and the leak detection system capability, which collectively demonstrate that the probability of pipe rupture is extremely low. This section also provides a description of the applicable piping and the analysis techniques used to eliminate from the structural design basis for the identified piping systems the dynamic effects of double-ended guillotine and equivalent longitudinal breaks.

A design report will confirm that the design LBB analysis remains bounding for each piping system and provide a summary of the results of the actual as-built, plant-specific LBB analysis, including material properties of piping and welds, stress analyses, leakage detection capability, and degradation mechanisms. The results of the bounding analyses are provided in the form of LBB allowable range of loadings or “LBB allowable load window.”

3.6.3.1 Application of Leak-Before-Break to the U.S. EPR

The application of LBB is limited to the following high energy piping systems:

- Main coolant loop (MCL) piping, (hot legs, crossover legs, and cold legs).
- Pressurizer surge line (SL).
- Main steam line (MSL) piping inside the containment (i.e., from the steam generators to the first anchor point location at the Containment Building penetration).

3.6.3.2 Methods and Criteria

The methods and criteria to evaluate LBB are consistent with the guidance in NUREG-1061, Volume 3 (Reference 1), and the Standard Review Plan (SRP) 3.6.3 (Reference 2) and are described in the following sections. The following steps are used to perform the LBB analyses:

- Evaluate potential failure mechanisms (Section 3.6.3.3).
- Perform bounding analyses (Sections 3.6.3.4 and 3.6.3.5).

The results of the analyses are provided in Section 3.6.3.6. A description of the leakage detection capability is provided in Section 3.6.3.6.1.

3.6.3.3 Potential Piping Failure Mechanisms

3.6.3.3.1 Water Hammer

Water hammer is a generic term that includes various unanticipated high-frequency hydrodynamic events, such as steam hammer and water slugging.

3.6.3.3.1.1 Main Coolant Loop Piping and Surge Line Piping

Operating experience with existing plants has demonstrated that water hammer is not an issue with the MCL or SL piping for pressurized water reactors (PWR), as addressed in NUREG-0582 (Reference 3), NUREG-0927, Revision 1 (Reference 4), and NRC Information Notices 91-50 and Supplement 1. Water/steam events, as described in these documents, resulted in only support damage. There were no events in the MCL or SL piping systems that resulted in loss of pressure boundary integrity. NUREG-0927 evaluated 67 events, five of which were in the primary system and were caused by relief valve discharge. Relief valve actuation and the associated transients following valve opening have been considered in the U.S EPR design.

The MCL and SL pipes and supports are designed to ASME Class 1 requirements and are designed for Level A, B, C, and D service conditions. These portions of the reactor coolant system (RCS) are also designed to preclude void formation during normal operation. Because safety valve discharge loads associated with the pressurizer have been identified and included in the component design basis, MCL and SL piping have a very low level of susceptibility to failure from water hammer.

3.6.3.3.1.2 Main Steam Line

The U.S. EPR main steam supply system, including MSL pipe support system components, is designed to accommodate dynamic loads resulting from inadvertent closure of the main steam isolation valve (MSIV). To reduce the effects of steam and water hammer, the numbers of elbows and miters in the MSL piping layout are minimized. Valves in the main steam supply system are designed to withstand loads developed from the various operating and design basis events and transients described in Section 3.9.1. Steam-propelled water slug transients are prevented by design features in the system design and layout.

Based on the low severity of the water hammer events described in NUREG/CR-2781 (Reference 5) and the design considerations of the main steam supply system, the LBB

portion of the MSL piping has a very low level of susceptibility to failure from water hammer.

3.6.3.3.2 Creep

Creep and creep fatigue are not a concern for ferritic steel piping when operated below 700°F and for austenitic steel piping below 800°F. Because operating temperatures of the U.S. EPR piping systems are below these limits, creep and creep fatigue are not a concern.

3.6.3.3.3 Corrosion and Erosion/Corrosion

The MCL and SL piping are fabricated from austenitic stainless steel materials that are resistant to corrosion. Because water chemistry for the main coolant system is closely controlled and monitored, these pipes have a very low level of susceptibility to failure from these failure mechanisms.

Flow-accelerated corrosion (FAC) (also referred to as flow-assisted corrosion, flow-induced corrosion or erosion-corrosion), has been observed in the secondary side of PWR water-steam systems. Operating conditions such as steam quality, intended operating temperatures, various secondary chemistry regimes, and materials of construction are evaluated in order to minimize the potential for FAC in the main steam piping. Programs in operating plants that manage aging effects due to FAC consider operating experience (e.g., NRC Bulletin 87-01, Information Notice 91-18) and the guidelines for an effective FAC program presented in EPRI Report 1011838 (Reference 6). Additional details regarding FAC in the main steam supply system are provided in Section 10.3.6.3

3.6.3.3.4 Stress Corrosion Cracking

This section demonstrates that the piping and weld materials for the LBB piping are not susceptible to stress corrosion cracking (SCC) and that primary water stress corrosion cracking (PWSCC), intergranular stress corrosion cracking (IGSCC), and transgranular stress corrosion cracking (TGSCC) are also unlikely to occur in these piping systems.

3.6.3.3.4.1 Main Coolant Loop and Surge Line Piping

The following conditions are required for SCC to occur: material susceptibility, a corrosive environment, and tensile stress. These conditions are addressed below.

Material Susceptibility

In some stainless steels and high nickel alloys, slow cooling through the 800°F–1500°F temperature range allows the precipitation of chromium carbides at grain boundaries, depleting the area adjacent to grain boundaries of chromium. This process is termed

“sensitization” and renders materials susceptible to SCC. To reduce the susceptibility to SCC, the MCL and SL piping conform to ASME Boiler and Pressure Vessel Code, Section III (Reference 7) requirements supplemented by the guidelines of RG 1.44 and ASME NQA-1-1994 (Reference 8). The stainless steel piping has a carbon content that does not exceed 0.03 wt% and welds are either “L” grade or limited by a maximum carbon content that does not exceed 0.03 wt%, which reduces the potential for sensitization. The welds between the stainless steel safe ends and the low alloy steel nozzles are Alloy 52, which has a higher resistance to SCC than Alloy 600/82/182.

Corrosive Environment

Reactor coolant chemistry controls prevent the occurrence of SCC. Dissolved oxygen, halides, and other impurities are monitored by plant surveillance testing. Controlling oxygen is a key to avoiding a corrosive environment. Dissolved oxygen concentrations are maintained at very low levels during normal plant operation by applying hydrogen injection to the coolant system. The design of non-metallic insulation for the RCS conforms to the guidelines in RG 1.36, which restricts the use of chlorides and fluorides in the thermal insulation to prevent SCC.

Tensile Stress

As the imposed tensile stress increases, the likelihood of initiation and propagation of SCC increases. Stresses close to the material yield strength are required in a light water reactor environment to initiate SCC. The MCL and SL piping conform to ASME Code, Section III requirements, which provide the code-specified margin to yield stress during normal operation. Weld residual stresses can exceed yield; however, because of the U.S. operational experience for controlling material susceptibility and the environment described above, the potential for SCC is minimized.

As noted in SRP 3.6.3, “Primary water stress corrosion cracking (PWSCC) is considered to be an active degradation mechanism in Alloy 600/82/182 materials in pressurized water reactor plants. Alloy 690/52/152 material is not currently considered susceptible to PWSCC for the purposes of LBB application.” As noted above, Alloy 52 weld material is used for the U.S. EPR. To further demonstrate that PWSCC is not a concern for LBB candidate piping, the U.S. EPR inservice inspection (ISI) program will consider the operating experience of the materials used in the U.S. EPR piping systems qualified for LBB. The U.S. EPR inspection program will be consistent with the inspection program adopted for operating PWRs that use Alloy 690, 52, and 152 in approved LBB applications. A COL applicant that references the U.S. EPR design certification will implement the ISI program as augmented with NRC approved ASME Code cases that are developed and approved for augmented inspections of Alloy 690/152/52 material to address PWSCC concerns.

Avoiding intergranular attack and IGSCC in austenitic stainless steels is accomplished by the following methods:

- Use of low carbon (less than 0.03 wt% carbon) unstabilized austenitic stainless steels.
- Measuring for correct ferrite content.
- Utilizing materials in the solution annealed plus rapidly cooled condition and the prohibition of subsequent heat treatments in the 800°F to 1500°F temperature range.
- Control of primary water chemistry to maintain an environment that does not promote intergranular attack.
- Control of welding processes and procedures to avoid heat affected zone sensitization, as addressed in RG 1.44.

Additional details regarding the above methods are presented in Section 5.2.3.

The prerequisite for TGSCC in 300-series austenitic stainless steels is an aggressive species, such as chloride, in association with oxygen. If high levels of dissolved oxygen are present in stagnant conditions, a higher susceptibility to SCC exists. When the stainless steel material is sensitized, IGSCC or mixed modes of cracking can occur and the material is more susceptible to SCC, as described by Gordon (Reference 9). Chloride and oxygen are typically associated as corrosive agents, although fluoride and sulfate can also be associated with SCC. Oxygen has a dominant role in the SCC susceptibility of austenitic stainless steels, with a small increase in oxygen resulting in a dramatic response in SCC. Very low levels of oxygen prevent TGSCC in these materials. TGSCC is unlikely at dissolved oxygen concentrations of less than 100 ppb and chloride levels of less than 150 ppb for various austenitic stainless steel alloys in both the annealed and sensitized heat treated condition when exposed to 480°F– 660°F water (Reference 9). The likelihood of both IGSCC and TGSCC for susceptible alloys exposed to dissolved oxygen of less than 100 ppb and chloride of less than 150 ppb at lower temperatures is significantly reduced. These limits are the historical basis for PWR RCS chemistry limits to prevent SCC.

Proper control of RCS water chemistry prevents the impurity intrusion that provides the necessary environment for TGSCC. The water chemistry limits verify that dissolved oxygen, sulfates, and halogens are minimized. Additionally, the MCL and SL piping are not subject to stagnant conditions during normal operation. Due to controls on RCS water chemistry and non-stagnant conditions in the main coolant loop and surge line piping, TGSCC is not expected in these piping systems.

3.6.3.3.4.2 Main Steam Line Piping

The U.S. EPR uses an all volatile chemistry treatment on the secondary system to increase cycle pH and provide a reducing environment. This produces the lowest possible general corrosion rate of the different materials present in the secondary system, thus minimizing flow-assisted corrosion and corrosion transport.

Additionally, there has been no evidence of stress corrosion cracking in the carbon steel piping of the main steam lines of operating plants. The secondary side water chemistry program is addressed in Section 10.3.5.

3.6.3.3.5 Fatigue

3.6.3.3.5.1 Main Coolant Loop and Surge Line Piping

An evaluation of fatigue for Class 1 piping is provided in U.S. EPR Piping Analysis and Pipe Support Design (Reference 10). Additionally, Section 3.12 addresses the effects of the reactor coolant environment on fatigue. Normal and upset thermal and seismic loadings are evaluated as part of the piping stress analysis.

The potential for high cycle fatigue is primarily due to excessive pump vibrations. The reactor coolant pumps (RCP) have instrumentation that alarms in the Main Control Room, to identify excessive pump shaft vibrations and preclude damage. Additionally, the RCS is monitored to provide an accurate assessment of fatigue over the lifetime of the plant. SL thermal stratification is not a concern due to the layout of the SL geometry and the continuous bypass spray flow. This is addressed further in Section 3.6.3.3.7.

3.6.3.3.5.2 Main Steam Line Piping

As noted in Reference 10, Class 2 and 3 piping is evaluated for fatigue due to thermal cycles by following the requirements in the ASME Code, Section III, Subsection NC on fatigue criteria.

The applicable design basis transients identified in Section 3.9.1 are considered in establishing the allowable stress limits, in accordance with Subsection NC, Subparagraph 3611.2. The allowable stress for thermal expansion is reduced for cyclic conditions based on the number of equivalent full temperature cycles.

The MSL piping is not subjected to severe Level A or B thermal or pressure transients when compared against the RCS primary piping. The impact of gross bending on the fatigue life of the piping is considered in the Class 2 design. The range of expected equivalent full temperature cycles in the steam line is less than 7000 cycles. Additionally, there are no normal or upset temperature or pressure variations that would result in significant local or through-wall stresses. Accordingly, a low usage factor is expected if the MSL is evaluated as Class 1 piping.

3.6.3.3.6 Thermal Aging

Forged austenitic stainless steel is used for the MCL and SL piping. Austenitic stainless steel forgings have a low susceptibility to thermal aging. The welds in the MCL stainless steel piping are fabricated using the gas tungsten arc welding (GTAW) process and meet the requirements of the ASME Code, Section III and the guidance of RG 1.31, which minimizes the effects of thermal aging. Lower bound toughness properties used in flaw stability analysis conservatively considers reduction because of thermal aging in the stainless steel weld metal and the component nozzles.

The component in the RCS loop that is predicted to experience the greatest reduction in toughness due to thermal aging is the RCP casing, which is made of cast austenitic stainless steel, type CF-3. The accepted screening limit for aging considerations states that static cast low-molybdenum steels with <20 percent ferrite are not susceptible to thermal aging embrittlement at the RCP operating temperature to an extent that would be of concern. Delta ferrite (δ_c) is limited to <20 percent and silicon to <1.5 percent. Lower bound curves were developed using a predictive model. The material properties used in the LBB analysis are based on the results predicted for the saturated condition. Therefore, thermal aging is not a concern for the RCP case.

Ferrite limitations for CASS RCPB materials are described in Section 5.2.3.4.6.

The MSL piping is carbon steel and contains no cast materials. Therefore, thermal aging of the MSL piping is not a concern.

3.6.3.3.7 Thermal Stratification

Thermal stratification is a potential issue in horizontal pipe segments when fluid at a significantly different temperature than the fluid in the piping is introduced at low flow velocities. The U.S. EPR is designed to preclude those conditions (refer to Section 3.7 of Reference 10 and FSAR Section 3.12). Each of the piping systems is addressed below.

3.6.3.3.7.1 Main Coolant Loop Piping

The MCL piping is not susceptible to thermal stratification since it does not experience stagnant flow conditions.

3.6.3.3.7.2 Surge Line Piping

Section 3.7.2 of Reference 10 and FSAR Section 3.12 describe the design features that minimize the potential for thermal stratification in the SL. The SL geometry is also described in Section 5.4.10.

3.6.3.3.7.3 Main Steam Line Piping

Because the MSL operates in a saturated steam environment, thermal stratification is not a concern for the MSL piping.

3.6.3.3.8 Other Mechanisms

3.6.3.3.8.1 Failure from Indirect Causes

Pipe degradation or failure by indirect causes (e.g., fires, missiles, or component support failures) is precluded by design, fabrication, and inspection. Additionally, piping design considers separation of potential hazards in the vicinity of the safety-related piping. The structures, larger pipe, and components in the vicinity of pipe evaluated for LBB are safety-related and seismically designed, or are seismically supported if they are non-safety-related. Further information is provided below:

- Missiles: Missile prevention and protection are described in Section 3.5.
- Flooding: Flood protection and analysis are provided in Section 3.4.
- Fires: Fire prevention and protection are described in Section 9.5.1.
- System overpressurization: The reactor coolant system is protected from overpressurization by ASME Code safety relief valves (refer to Section 5.2.2). Overpressure protection for the MSL is described in Section 10.1.
- Damages from moving equipment: Load drops are highly improbable due to the design of handling devices and administrative controls. Additionally heavy loads are not handled inside containment while at power. Chapter 15 describes accident analyses due to load drops.
- Seismic: The RCS and the MSL are designed to maintain their integrity during a safe shutdown earthquake (see Section 3.2).

3.6.3.3.8.2 Cleavage Type Failures

Cleavage type failures are not a concern for the system operating temperatures and materials present in the MCL, SL, and MSL. Material tests for these components show the materials to be highly ductile and resistant to cleavage type failures at operating temperatures.

3.6.3.3.9 Failure Prevention and Detection

3.6.3.3.9.1 Snubber Reliability

Snubber use and locations are determined during detailed design in accordance with Reference 10 and tested as described in Section 3.9.6.

3.6.3.3.9.2 Inservice Inspection

For ASME Code Class 1 and Class 2 systems for which LBB is demonstrated, the ASME Code, Section III (Reference 7) and ASME Code, Section XI (Reference 11) preservice and inservice inspection requirements provide for the integrity of each system. Pressure-retaining components are designed to permit preservice and inservice inspections. The design provides accessibility for inspection in accordance with ASME Code Section XI, Division 1, Subarticle IWA-1500 and the requirements of 10 CFR 50.55a(g)(3)(i). Welds in Class 2 high-energy piping are subject to augmented inservice inspection, in accordance with the requirements of Article IWC-2000 for Examination Category C–F welds.

3.6.3.4 Inputs for Leak-Before-Break Analysis

3.6.3.4.1 Geometry and Operating Condition

The dimensional information and operating conditions for each MCL piping assembly are summarized in Table 3.6.3-1—Main Coolant System Piping Dimensions and Operating Condition. The U.S. EPR design minimizes the number of butt welds in the RCS primary piping. The butt welds are a narrow-groove design. The locations and number of narrow-groove butt welds are illustrated for loop 4 of the MCL piping by the plan and elevation views in Figure 3.6.3-1—Plain View of U.S. EPR RCS Primary Piping and Figure 3.6.3-2—Elevation View of U.S. EPR RCS Primary Piping, respectively.

The dimensional information and operating conditions for each SL piping assembly are summarized in Table 3.6.3-2—Surge Line Piping Dimensions and Operating Condition. The locations and number of narrow-groove butt welds in the SL piping are shown in Table 3.6.3-3—Plan, Elevation, and Isometric View of the U.S. EPR Surge Line.

The dimensional information and operating conditions for each MSL piping assembly are shown in Table 3.6.3-3—Main Steam Line Dimensions and Operating Condition. The location and number of butt welds for the LBB portion of a typical MSL piping are depicted in Figure 3.6.3-4—Isometric View of the Main Steam Line.

*[For the LBB evaluation, the plant is assumed to be operating under normal full power conditions with a postulated flaw size that produces ten times the overall leak detection capability of a given piping system.]**

3.6.3.4.2 Materials

3.6.3.4.2.1 Main Coolant Loop and Surge Line Piping Materials

The MCL and SL piping consist of SA-336 F304 or SA-182 F304 austenitic stainless steel. The MCL and SL piping is solution annealed and rapidly cooled, and has carbon

content that does not exceed 0.03 wt%. The RCP casings are the only cast stainless product form within the MCL, and are made of SA-351 CF-3 with additional restrictions described in Section 3.6.3.4.3.3 The stainless steel pipe welds are fabricated with dual-certified ER308/308L using the narrow-groove GTAW welding process. The safe end forging material is SA-182 F316 or SA-336 F316. The dissimilar metal weld joints between the safe ends and the respective component nozzles of the pressurizer surge nozzle, the steam generator (SG) nozzles, and RPV nozzles are fabricated using NiCrFe alloy filler metal Alloy 52/52M (ERNiCrFe-7/ ERNiCrFe-7A respectively). The pressurizer surge nozzle (forging) material and the steam generator inlet and outlet nozzle (forging) material are SA-508 Grade 3 Class 2 and the RPV inlet and outlet nozzle material is SA-508 Grade 3 Class 1.

3.6.3.4.2.2 Main Steam Line Piping Materials

The MSL piping is made of SA 106 Grade C carbon steel material.

3.6.3.4.3 Material Properties

3.6.3.4.3.1 Main Coolant Loop Piping Weld and Base Metal Properties

A test program based on Reference 1 was conducted on three ER308/308L narrow groove GTAW welds with different wire heats to provide for lower bound J-R fracture toughness and tensile data. The testing was conducted using compact tension specimens cut from the full thickness of the pipe welds, as well as 1T size compact tension specimens. The lower bounding J-R curve, with projected reduction of toughness because of thermal aging, was derived from the test results for the welds. The J-R properties for low alloy steel nozzles and the J-R properties for cast austenitic stainless steel (CASS) pump casing nozzles that account for thermal aging are determined from applicable industry data.

The engineering stress-strain curves for the base metal and weld metal are obtained from the test program and converted to true-stress true-strain curves. The following Ramberg-Osgood equation is used to fit the stress-strain curve data:

$$\frac{\epsilon}{\epsilon_o} = \frac{\sigma}{\sigma_o} + \alpha \left(\frac{\sigma}{\sigma_o} \right)^n$$

where:

σ, ϵ = true-stress, true-strain

σ_o, ϵ_o = yield stress, yield strain

α, n = Ramberg-Osgood material parameters

The tensile properties and the Ramberg-Osgood parameters for the hot and cold leg piping are presented in Table 3.6.3-4—Tensile Properties of Materials at Various Locations of Main Coolant Loop Piping. The material parameters for the J-R equation (C and N) are determined using the $J_{\text{Deformation}}$ and Δa experimental data of the applicable compact tension specimens. The power law formula for the J-R data is obtained using a linear regression analysis and is given below:

$$J_D = C(\Delta a)^N$$

where:

$J_D = J_{\text{Deformation}}$ in units of lbs/in

Δa is in inches

C = the material constant

N = the exponent

The J-R curve for the base metal of the MCL piping material is determined from the test results, as well as from similar materials in the industry as summarized in NUREG/CR-6446 (Reference 12), NUREG/CR-4082, Vol. 8 (Reference 13), and NUREG/CR-4599 (Reference 14). The lower bound J-R curve power law parameters for the MCL base metal are determined for the LBB analysis. Thermal aging of wrought 304 and 316 is expected to be negligible, therefore it is not considered in this evaluation.

3.6.3.4.3.2 Dissimilar Metal Weld between Component Nozzle and MCL Piping

Alloy 52/52M is the dissimilar metal weld that is used between the MCL piping and both the primary component nozzles of the reactor vessel and the primary nozzles of the steam generators. The J-R curve for the Alloy 52 weld metal is determined using specimens that are fatigue pre-cracked on the fusion line. The J-R curve parameters, using ASTM Standard E1820 (Reference 15), were used in this assessment considering the case without a limit on crack extension. The J-R curve for Alloy 52 weld metal, developed at the fusion line, is lower than the J-R curve for the base metal and the stainless steel weld metal of the MCL piping. For the Alloy 52 weld metal, the J-R parameters considering the fusion line toughness are used in the LBB analysis. The equivalent material tensile properties for the dissimilar metal weld (DMW) at the fusion line location are determined using finite element based elastic-plastic fracture mechanics analysis and provided in Table 3.6.3-4. These material properties at the DMW fusion line region are determined considering the adjoining base metal materials which are F304LN and SA-508 Grade 3 Class 2. The material properties for SA-508 Grade 3 Class 2 are approximated by the material properties for SA-508 Class 3 which are obtained from NUREG/CR-6837, Volume 2 (Reference 25).

3.6.3.4.3.3 Primary Component Nozzles of the MCL

The effects of thermal aging for the primary component nozzles of the reactor vessel and the steam generator nozzles, fabricated from SA-508 Grade 3 Class 1, and SA-508 Grade 3 Class 2, respectively, are considered in determining the lower bound J-R curves for the nozzles. The J-R curves for these materials are determined from published literature. Adjustments to the J-R curves for the reactor vessel nozzle materials are made to account for operating conditions and anticipated aging effects. The J-R curves for SA-508 Grade 3, Class 2 material are determined using the correlation between upper shelf energy and upper shelf J-R properties for SA-508 Grade 3 Class 1 material. Based on the correlation, the SA-508 Grade 3 Class 1 curves are reduced by 30 percent to approximate the J-R curves for SA-508 Grade 3 Class 2 material.

3.6.3.4.3.4 RCP Casing Nozzles

The RCP casings (including the nozzles) are fabricated from static CASS. The RCP casings are fabricated using SA-351 CF-3 material specification with additional restrictions on silicon (1.5 percent maximum) and niobium (restricted to trace amounts). In addition, the ferrite number is restricted to <20 percent. The lower bound J-R curves for the saturated condition are determined based on a predictive model developed in NUREG/CR-6177 (Reference 16).

3.6.3.4.3.5 Surge Line Weld and Base Metal Properties

The SL weld and base metal properties are determined from the same test program described in Section 3.6.3.4.3. The testing was conducted using compact tension specimens cut from the full thickness of the SL pipe weld geometry. The lower bound SL weld and base metal J-R curves are developed using the same approach as provided in Section 3.6.3.4.3 for the MCL. Therefore, the thermal aging effects of the SL weld metal are considered. The tensile properties with associated Ramberg-Osgood parameters of the various SL piping materials are shown in Table 3.6.3-5—Tensile Properties for the Surge Line Piping.

3.6.3.4.3.6 Dissimilar Metal Weld between Pressurizer Surge Nozzle and Surge Line Piping

The Alloy 52 fusion line toughness J-R properties, determined in Section 3.6.3.4.3.2, are used in the analysis. The equivalent material tensile properties for the dissimilar metal weld (DMW) at the fusion line location are determined using finite element based elastic-plastic fracture mechanics analysis and provided in Table 3.6.3-5. These material properties at the DMW fusion line region are determined considering the adjoining base metal materials which are F304LN and SA-508 Grade 3 Class 2. The material properties for SA-508 Grade 3 Class 2 are approximated by the material properties for SA-508 Class 3 which are obtained from NUREG/CR-6837, Volume 2

(Reference 25).

3.6.3.4.3.7 Pressurizer Surge Nozzle

The pressurizer surge nozzle is fabricated from SA-508 Grade 3 Class 2 material. The lower bound J-R properties, considering the effects of thermal aging, for SA-508 Grade 3 Class 2, addressed in Section 3.6.3.4.3.3 are also applicable to the pressurizer surge nozzle. In the region of the pressurizer nozzle it is the dissimilar metal weld location that is limiting for LBB application, as shown in Table 3.6.3-6—Surge Line Piping Locations Based on Key Geometry, Operating Conditions & Lower Bound Material Toughness.

3.6.3.4.3.8 Main Steam Line Weld and Base Metal Properties

The tensile and fracture material properties for ASME SA-106 Grade C carbon steel material and associate weld material used in this analysis are based on a piping material test program that examined six heats of weld metals. Three heats were manual weld metals (one E7015 SMAW and two E8015 SMAW), and the other three heats were automatic submerged weld metals (High Mn-Mo SAW). The properties used in the analysis are the lower bound properties obtained from the test program. The tensile properties are provided in terms of the yield stress, ultimate strength, flow stress, and Young's modulus and are shown in Table 3.6.3-7—Tensile Properties for the Main Steam Line Piping. The Ramberg-Osgood material model parameters are also summarized in Table 3.6.3-7. The fracture toughness properties are provided in terms of the J-R curve. The lower bound material J-R curves for the SA106, Grade C and the weld metals are determined and used in the flaw stability analysis of Section 3.6.3.5.4.1.

3.6.3.5 General Methodology

The load combination methods described in Section 3.6.3.5.1 are applicable to the LBB analyses. For the MCL and the SL piping, the leak rate calculations, performed considering fatigue crack morphology, are determined using AREVA NP computer code KRAKFLO (see Section 3.6.3.5.2). For the MSL LBB analysis, computer code SQUIRT Version 1.1 (see Section 3.6.3.5.3) is used. Since the MCL and SL piping materials are highly ductile austenitic stainless steels, both the limit load analysis and the flaw stability analysis methodology are considered appropriate. For the MCL and SL piping, the flaw stability analysis methodology is used. Since the MSL is made of ferritic steel, the flaw stability methodology is also used in that analysis.

3.6.3.5.1 Load Combination Methods

SRP 3.6.3 addresses two load combination methods: the absolute sum load combination method and the algebraic sum load combination method. The absolute

sum load combination method is provided in SRP 3.6.3. The algebraic sum load combination method is shown below:

$$M_{XMAX} = |M_{Xdw} + M_{Xth} + M_{Xpress}| + |M_{Xsse}| + |M_{Xsam}|$$

$$M_{YMAX} = |M_{Ydw} + M_{Yth} + M_{Ypress}| + |M_{Ysse}| + |M_{Ysam}|$$

$$M_{ZMAX} = |M_{Zdw} + M_{Zth} + M_{Zpress}| + |M_{Zsse}| + |M_{Zsam}|$$

where:

M_{idw} = the moment due to deadweight, for I = X, Y, and Z

M_{ith} = the moment due thermal expansion, for I = X, Y, and Z

M_{ipress} = the moment due to pressure, for I = X, Y, and Z

M_{isse} = the moment due seismic, for I = X, Y, and Z

M_{isam} = the moment due seismic anchor motion moment, for I = X, Y, and Z

and

$$M_{MAX} = 1.4\sqrt{M_{XMAX}^2 + M_{YMAX}^2 + M_{ZMAX}^2}$$

For the calculations of the minimum moment, only the algebraic sum load combination method is applicable. However, for the calculations of the maximum moment, the algebraic sum load combination method or the absolute sum load combination method may be used. The LBB flaw stability analyses summarized in Section 3.6.3.5.4 are performed using the absolute sum load combination method.

The premise of the LBB concept in piping is that a flaw will be detected via loss of fluid prior to the failure of the pipe. This requires two types of analyses: one in which the minimum load that leads to a detectable leak rate is calculated, and another which calculates the maximum allowable load in the flawed pipe. The minimum and maximum moment loads are defined below. The maximum allowable load must exceed the minimum load evaluated for leakage crack size, with applicable margins of safety on both flaw size and load.

Minimum Moment

The minimum moment corresponds to deadweight, steady state pressure and thermal expansion moment for normal operation. The minimum moment is obtained by

algebraically summing the individual components of moments due to deadweight, steady state pressure, and thermal expansion, and then determining its square root of the sum of the squares value. The minimum moment, including axial load due to operating pressure, is present during steady state conditions; if a leaking crack exists it tends to open the crack and allow flow through the crack. For a higher operating pressure and minimum moment at a constant leak rate (gallons per minute), the crack length necessary to produce the same leak rate is actually smaller, since higher stress enlarges the crack width.

Maximum Moment

The maximum moment to be evaluated combines the minimum moment with the moments due to seismic and seismic anchor motions. The SSE loadings include the seismic anchor motion loads. As previously noted, the maximum moment is determined using the absolute sum load combination method.

Loadings on Main Coolant Loop, Surge Line, and Main Steam Line

A bounding analysis in the form of LBB allowable load window approach is used in this analysis. Once the allowable load window for a given piping system is generated, the loads for the piping system can then be plotted on the allowable load window. If the applied loading points lie within the allowable load window, LBB is justified for the pipe with appropriate safety margins already included in the window.

3.6.3.5.2 Leak Rate Determination Method for Main Coolant Loop and Surge Line

Leak rate calculations for MCL and SL piping are performed using AREVA NP computer code KRAKFLO, which is similar to the NRC code LKRATE. The leak flow calculations used in KRAKFLO are benchmarked against the Battelle Columbus Laboratories data as presented in EPRI Report NP-3395 (Reference 17). KRAKFLO is based on the LEAK-01 program documented in Reference 17 but has improved ability to determine pressure drops for initially subcooled, non-flashing liquid. KRAKFLO's crack geometry methodology is based on NUREG/CR-3464 (Reference 18); and its flow rate calculation is based on NUREG/CR-1319 (Reference 19). This code has been benchmarked and is in agreement with experimental data.

*[Leakage crack sizes associated with a leak rate of 5 gpm are determined in the analysis. This leak rate provides a factor of ten to the leak detection system (LDS) capability.]** The leakage rate calculations are performed for straight pipe with both axial and circumferential through-wall cracks. For the axial through-wall crack orientations, pressure-only loading is considered, while external bending and pressure loadings are considered for the circumferential through-wall cracks.

Main Coolant Loop

The leakage rate calculations are determined at the following locations (Location 1 through Location 9) in the MCL piping:

1. RV Outlet Nozzle Region at Hot Leg.
2. Hot Leg Pipe.
3. SG Inlet Nozzle Region at Hot Leg.
4. SG Outlet Nozzle Region.
5. Crossover Leg.
6. RCP Inlet Nozzle Region.
7. RCP Outlet Nozzle Region.
8. Cold Leg Pipe.
9. RV Inlet Nozzle Region.

Surge Line

For the SL piping, the leakage rate calculations are determined at the following locations:

- Pressurizer surge nozzle end of the SL.
- Pressurizer SL
- Hot leg nozzle end of the SL.

The leak rate analysis considers fatigue (air) crack morphology with applicable number of turns and roughness values reported in NUREG/CR-6004 (Reference 29) and shown in Table 3.6.3-26. The leakage crack lengths versus minimum moment at each of the above nine locations for the MCL are shown in Table 3.6.3-8—Minimum Moment versus Circumferential Crack Leakage Sizes for 5 gpm at Various Main Coolant Loop Piping Locations and are illustrated in Figure 3.6.3-5—Minimum Moment versus Circumferential Leakage Crack Sizes for 5 gpm at Various Main Coolant Loop Locations. For the through-wall axial cracks, the leakage crack sizes are shown in Table 3.6.3-9—Axial Through-Wall Leakage Crack Sizes for 5 gpm at Various Main Coolant Loop Piping Locations. For SL piping, the leakage crack lengths versus moment at each of the above three locations are shown in Table 3.6.3-10—Minimum Moment versus Circumferential Leakage Crack Sizes for 5 gpm at Two Surge Line Piping Locations and are illustrated in Table 3.6.3-6—Surge Line Piping Locations Based on Key Geometry, Operating Conditions & Lower Bound Material Toughness.

For the through-wall axial cracks, the leakage crack sizes are shown in Table 3.6.3-11—Axial Through-Wall Leakage Crack Sizes for 5 gpm at Three Surge Line Piping Locations.

3.6.3.5.3 Leak Rate Determination Method for Main Steam Line

The leak rate calculations for the MSL piping are performed using SQUIRT Code Version 1.1. The SQUIRT Code is described in NUREG/CR-5128 (Reference 20) and the SQUIRT User's Manual (Reference 21) and has been benchmarked to the experimental steam data developed in Japan, as described in NUREG/CR-6861 (Reference 22). The SQUIRT code has been updated with technical enhancements as part of the NRC large break LOCA program. The SQUIRT Code is used to calculate the leakage rate through the cracked pipe for single phase steam conditions.

*[Leakage crack sizes associated with a leak rate of one gpm are determined in the analysis. This leak rate provides a factor of ten to the LDS capability.]** The leakage rate calculations are performed for straight pipe with both axial and circumferential through-wall cracks. Similar to MCL, for the axial through-wall crack orientation, pressure-only loading is considered while external bending and pressure loading is considered for the circumferential through-wall crack. The results of the pressure-only case, as depicted in Figure 3.6.3-7—Pressure Only Leakage Rate versus Crack Length for Both Axial and Circumferential Crack Morphologies in Main Steam Line, show that for a given crack size the axial through-wall cracks produced a higher leakage rate. As a result, the circumferential leakage crack sizes are conservatively used when analyzing axial leakage cracks. The results of the leak rate calculations provided in Table 3.6.3-12—Minimum Moment versus Circumferential Leakage Crack Sizes for 1 gpm in the Main Steam Line Piping. The results are also shown in Figure 3.6.3-8—Minimum Moment versus Circumferential Crack Leakage Sizes for 1 gpm in Main Steam Line Piping, in terms of the minimum moment diagrams for a leakage rate of one gpm. The external axial load is set equal to zero in the leak rate calculations. This is considered conservative, since the crack size required to produce a given leakage rate will actually be smaller in the presence of external axial tensile loads. The leakage crack sizes calculated from the circumferential through-wall crack in straight pipe are also used for analyzing circumferential through-wall extrados crack in an elbow.

3.6.3.5.4 Flaw Stability Analysis Method

The method employed for the flaw stability analysis is the tearing instability analysis method, using a J versus T diagram. The inputs for the flaw stability analysis include the applied J and the material J-R curves. The applied J (J_{applied}) depends on the geometry, material, and the applied loads. The material properties are described in terms of the J-R fracture resistance curves which are obtained from tests in accordance with Reference 15 as well as industry data of comparable materials.

To estimate the J_{applied} , a J-integral solution is needed. The J-integral solution is a function of geometry, material, and crack size and orientation. Each J-integral solution is usually tabulated in terms of influence coefficients that are calculated based on finite element analyses. The stability analysis covers the following crack geometries:

- Circumferential through-wall crack in a straight pipe.
- Axial through-wall crack in straight pipe.
- Circumferential through-wall extrados crack in an elbow.

A J-integral solution is used for each of the above crack orientations. The following sections address the J-integral solution for each of the crack geometries. For the circumferential through-wall cracks in a straight pipe, the EPRI/GE method reported in EPRI NP-5596 (Reference 23) is used to calculate the J-integral. For the MCL and SL piping, the alpha term in the J_{Plastic} part of the equation given in Section 3.6.3.5.4.1 is modified based on the recommendation provided in Analysis of Experiments on Stainless Steel Flux Welds (Reference 24). This modification of the alpha term is provided as the last set of J-integral equations for SL piping in Section 3.6.3.5.4.1. For a circumferential through-wall extrados crack in an elbow, the criteria of NUREG/CR-6837 (Reference 25) are used to evaluate the J-integral.

3.6.3.5.4.1 Circumferential Through-Wall Crack in Straight Pipe Solution

Main Steam Line Piping

The J-integral solution for a circumferentially through-wall cracked cylinder for a combined tension and bending loading condition is used for this analysis. A schematic of this cracked pipe geometry is illustrated in Figure 3.6.3-9—Schematics of Analyzed Crack Geometries Considered for Straight Pipe Section. The solution procedure is summarized as follows:

$$J = J_{\text{Bending-Elastic}} + J_{\text{Axial-Elastic}} + J_{\text{Plastic}}$$

where:

$$J_{\text{Bending-Elastic}} = \frac{M^2}{E} \pi a \left(\frac{R}{I} \right)^2 F_B^2 \left(\frac{ae}{b}, \frac{R}{T} \right)$$

$$J_{\text{Axial-Elastic}} = \frac{P^2}{E} \frac{a F_T^2 \left(\frac{ae}{b}, \frac{R}{t} \right)}{4\pi R^2 t^2}$$

$$J_{Plastic} = \alpha \sigma_o \varepsilon_o c \frac{a}{b} h_1 \left(\frac{a}{b}, n, \lambda, \frac{R}{t} \right) \left[\frac{P}{P_o'} \right]^{n+1}$$

The P_o' in the $J_{Plastic}$ equation is the reference load for the combined tension and bending loads given as:

$$P_o' = \frac{1}{2} \left[\frac{-\lambda P_o'^2 R}{M_o} + \sqrt{\left(\frac{\lambda P_o'^2 R}{M_o} \right)^2 + 4 P_o'^2} \right]$$

where:

Limit Load

$$P_o = 2 \sigma_o R t \left(\pi - \gamma - 2 \arcsin \left(\frac{1}{2} \sin \gamma \right) \right)$$

Limit Moment

$$M_o = 4 \sigma_o R^2 t \left(\cos \left(\frac{\gamma}{2} \right) - \frac{1}{2} \sin \gamma \right)$$

Un-Cracked Ligament

$$2c = 2R(\pi - \gamma)$$

Non-Dimensional Parameter

$$\lambda = \frac{M}{PR}$$

Plastic Zone Correction

$$a_e = a + \frac{1}{1 + \left(\frac{P}{P_o} \right)^2} \frac{1}{6\pi} \left[\frac{n-1}{n+1} \right] \frac{EJ_{Elastic}}{\sigma_o^2}$$

where:

R = the pipe mean radius

t = the pipe thickness

I = area moment of inertia of the pipe section

a = the flaw size or one-half the leakage crack size

b = one-half the pipe circumference

c = uncracked ligament ($b - a$)

E = Young's modulus

M = the bending moment

P = the tensile load

σ_0 and ϵ_0 = the reference stress and reference strain in the Ramberg-Osgood material model

γ = the crack half-angle

F_B and F_T = the tabulated elastic solution coefficients for bending and axial loading (functions of geometry only – a/b and R/t) as provided in Reference 23

h_1 = the tabulated fully plastic solution parameter, function of (material strain hardening exponent, n and geometry, a/b and R/t)

For the MSL piping, the elastic solution coefficients (F_B and F_T) from the EPRI reports are linearly interpolated where applicable to generate the solution for the specific R/t geometry that is being evaluated.

Main Coolant Loop and Surge Line Piping

A J-integral solution for a circumferentially through-wall cracked cylinder subjected to bending loads is used in the analysis for the SL piping. This EPRI/GE solution is provided in Reference 23. The alpha term in the solution is corrected based on Reference 24. This particular J-integral solution is chosen since the SL geometry has an R_m/t ratio of approximately five (with Ramberg-Osgood material constant $n=7$) and the h-function for $R_m/t = 5$ is available for through-wall cracks in bending. For the SL piping, the J-integral solution for combined tension and bending provided above (main coolant loop and main steam line piping) is not used, since the coefficients for this solution are only developed for R_m/t of 10 or greater.

In order to use the J-integral solution for bending loads only, the axial forces due to end cap pressure or external loads are converted into an equivalent moment. The equivalent bending is then combined with the applied moment to obtain the total moment to which the pipe is subjected. The general approach of calculating an equivalent moment is outlined below.

The moment M_{eq} is considered to be equivalent to axial load P when the Mode I stress intensity factor, K_I due to bending moment M_{eq} is the same as K_I due to axial tensile load P .

From the Ductile Fracture Handbook (Reference 26):

$$K_I = \sigma_b (\pi R \gamma)^{0.5} \cdot F_b = \sigma_t (\pi R \gamma)^{0.5} \cdot F_t$$

where:

$$\sigma_b = \frac{M_{eq}}{\pi R_m^2 t}$$

$$\sigma_t = \frac{P}{2\pi R_m t}$$

$$F_b = 1 + A [4.5967(\gamma/\pi)^{1.5} + 2.6422(\gamma/\pi)^{4.24}]$$

$$F_t = 1 + A [5.3303(\gamma/\pi)^{1.5} + 18.773(\gamma/\pi)^{4.24}]$$

$$A = [0.125(R_m/t) - 0.25]^{0.25}$$

therefore:

$$M_{eq} = 0.5 R_m (F_t / F_b) \cdot P$$

In the above equations, R_m is the pipe mean radius, t is the pipe thickness, M_{eq} is the equivalent bending moment, P is the axial tensile load, and γ is the crack half-angle. The F_t and F_b formulas listed above are used for calculating M_{eq} only.

The J-integral solution from Reference 23 for bending load is summarized as follows:

$$J = J_{elastic} + J_{plastic}$$

where:

$$J_{elastic} = \frac{M^2}{E} \pi a \left(\frac{R_m}{I} \right)^2 F^2$$

$$J_{plastic} = \alpha \sigma_o \varepsilon_o c \frac{a}{b} h_1 \left[\frac{M}{M_o} \right]^{n+1}$$

where:

Limit Moment

$$M_o = 4\sigma_o R_m^2 t \left(\cos\left(\frac{\gamma}{2}\right) - \frac{1}{2} \sin \gamma \right)$$

Un-Cracked Ligament

$$2c = 2R(\pi - \gamma)$$

Plastic Zone Correction

$$a_e = a + \frac{1}{1 + \left(\frac{M}{M_o}\right)^2} \frac{1}{6\pi} \left[\frac{n-1}{n+1} \right] \frac{EJ_{elastic}}{\sigma_o^2}$$

α Correction

$$\alpha = \left[\alpha_o \left(\frac{\sigma_o}{\sigma_y} \right)^{[(n-1)n]} \right]^{\left(\frac{1}{n+1}\right)}$$

where:

R_m = the pipe mean radius

t = the pipe thickness

I = the pipe section moment of inertia

a = the flaw size or one-half the leakage crack size

b = the half-circumference

c = the uncracked ligament

E = Young's modulus

M = the total bending moment (applied moment + equivalent moment)

σ_o and ε_o = the reference stress and reference strain in the Ramberg-Osgood material model

α_0 and n = the Ramberg-Osgood material constants

γ = the crack half-angle.

The solution coefficient F (a function of the material strain hardening exponent, n and geometry, a/b and R_m/t) is the tabulated elastic solution parameter for remote bending for a circumferential crack in a straight pipe and is from Reference 23. The solution coefficient h_1 (a function of the material strain hardening exponent, n and geometry, a/b and R_m/t) is the tabulated fully plastic solution parameter for remote bending for a circumferential crack in a straight pipe per Reference 23.

The solution coefficients h_1 and F (for bending only) are provided for only limited a/b , R_m/t , and n values in Reference 23. Therefore, a polynomial curve approximately fitting these limited data points is developed and used to interpolate for the specific a/b or R_m/t geometry that is being evaluated.

3.6.3.5.4.2 Axial Through-Wall Crack in Straight Pipe

The Ductile Fracture Handbook (Reference 26) solution for an axial through wall crack in a straight pipe under internal pressure only was used to evaluate crack stability for the range of leakage crack sizes evaluated in this analysis.

The J-integral solution is provided in Reference 26 as:

$$J = \frac{8C\sigma_f^2}{\pi E} \ln \left(\sec \left(\frac{M \pi \sigma}{2\sigma_f} \right) \right)$$

where:

$$M = [1 + 1.12987 \lambda^2 - 0.026905 \lambda^4 + 5.3549 \times 10^{-4} \lambda^6]^{0.5}$$

$$\lambda = \frac{C}{\sqrt{Rt}}$$

$$\sigma = \frac{pR}{t}$$

where:

p = the internal pressure

σ = the hoop stress

R and t = the pipe mean radius and wall thickness, respectively

C = the crack half length

σ_f = the reference flow stress.

3.6.3.5.4.3 Circumferential Through-Wall Extradados Crack in an Elbow

Main Coolant Loop and Main Steam Line Piping

The J-integral solution in Reference 25 is used to address the stability of circumferential through-wall extradados crack in an elbow. Reference 25 provides J solutions for crack sizes with crack half angles of 45° and 90°. Thus, the reference does not provide a solution for interpolating a J solution for an arbitrary crack size. However, the J-integral solution in Reference 25 provides some bases to determine whether the straight pipe solution is sufficiently conservative to lower-bound the window of stable loads for cracked elbows. Thus, the goal of the evaluation of a circumferential through-wall crack in an elbow is to demonstrate whether the straight pipe solution conservatively estimates the stable load limit in the cracked elbow for the MCL piping. The J-integral solution for a through-wall circumferential crack in an elbow is given by:

$$J = J^e + J^p$$

where:

$$J^e = J_T^e + J_B^e = \frac{[F_T \sigma_T \sqrt{\pi a}]^2}{E} + \frac{[F_B \sigma_B \sqrt{\pi a}]^2}{E}$$

For Circumferential Cracks:

$$\sigma_T = \frac{p(\pi R_i^2)}{\pi(R_o^2 - R_i^2)}$$

and

$$\sigma_B = \frac{M(R_m)}{\frac{\pi}{4}(R_o^4 - R_i^4)}$$

Plastic Component

$$J^p = \alpha \sigma_o \varepsilon_o a \left(1 - \frac{\theta}{\pi}\right) h_1 \left(\frac{P}{P_o}\right)^{n+1}$$

$$P_o' = \frac{1}{2} \left[\frac{-\lambda P_o^2 R_m}{M_o} + \sqrt{\left(\frac{\lambda P_o^2 R_m}{M_o}\right)^2 + 4P_o^2} \right]$$

$$\lambda = \frac{M}{PR_m}$$

$$P = \sigma_T \pi (R_o^2 - R_i^2)$$

$$M_o = 4 \sigma_o R_m^2 t \left[\cos\left(\frac{\theta}{2}\right) - 0.5 \sin \theta \right]$$

$$P_o = 2 \sigma_o R_m t \left[\pi - \theta - 2 \sin^{-1}(0.5 \sin \theta) \right]$$

where:

R_i and R_o = the inner and outer radii of the pipe

R_m = the mean radius

t = pipe wall thickness

a and θ = flaw size (half leakage crack size) and half angle

σ_T and σ_B = the axial and bending stresses

E = Young's modulus

P = the end cap pressure load

p = the operating pressure

M = the external applied moment

P_o = the limit axial load

M_o = the limit moment

The F_T , F_B , and h solution coefficients for the through-wall circumferential crack in an elbow are determined for the applicable R/t pipe geometry.

Surge Line Piping

The J-integral solution for the SL is similar to that of the MCL and the MSL. However, the equivalent bending moment approach is followed to consider the axial loads P , thus slightly modifying the evaluation of the J-integral.

The J-integral solution from Reference 25 for bending is:

$$J_{\text{applied}} = J_{\text{elastic}} + J_{\text{plastic}}$$

where:

$$J_{\text{elastic}} = \frac{M^2}{E} \pi a \left(\frac{R_m}{I} \right)^2 F^2$$

$$J_{\text{plastic}} = \alpha \sigma_o \epsilon_o a \left(1 - \frac{\gamma}{\pi} \right) h_1 \left[\frac{M}{M_o} \right]^{n+1}$$

where:

Limit Moment

$$M_o = 4 \sigma_o R_m^2 t \left(\cos\left(\frac{\gamma}{2}\right) - \frac{1}{2} \sin \gamma \right)$$

In the above equations, the solutions coefficient F (a function of the material strain hardening exponent n and geometry R_m/t and γ) is the tabulated elastic solution parameter for remote bending for a circumferential crack in an elastic elbow from Reference 25. The solution coefficient h_1 (a function of the material strain hardening exponent n and geometry R_m/t and γ) is the tabulated fully plastic solution parameter for remote bending for a circumferential crack in an elbow from Reference 25. All other terms of the equations are as previously defined for the J-integral solution in a straight pipe for the surge line piping reported in Section 3.6.3.5.4.1.

3.6.3.5.5 J-T Stability Analysis Procedure

The purpose of J-Tearing (J-T) stability analysis is to determine at what applied load the crack becomes unstable. After the J-integral solutions are identified, it is possible to evaluate J_{applied} for a given crack geometry and loading condition. The next step is to compare the J_{applied} to J_{material} . The material resistance to fracture (J_{material}) is defined by the J-R curve in the form of a power law equation fit as:

$$J_{\text{material}} = C\Delta a^N$$

If the applied J (J_{applied}) is equal to the material J (J_{material}), any crack growth may be stable as long as the applied tearing modulus (T_{applied}) is less than the material tearing modulus (T_{material}). To achieve the condition of instability, the applied tearing modulus must be greater than or equal to the material tearing modulus. To evaluate the tearing modulus at the instability point ($T_{\text{material}} = T_{\text{applied}}$ when $J_{\text{material}} = J_{\text{applied}}$), J_{applied} may be differentiated with respect to the crack length, a , and the slope of the J_{applied} , (dJ/da) can be obtained, using the following equation:

$$\frac{dJ}{da} = \frac{J(a + \zeta) - J(a - \zeta)}{2\zeta}$$

where ζ is a small increment in crack size. The tearing modulus, T , for J_{applied} can then be determined as follows:

$$T = \left(\frac{E}{\sigma_f^2} \right) \frac{dJ}{da}$$

where E is Young's modulus and σ_f is the flow stress. The tearing modulus, T , is dimensionless. For a given tearing modulus (T), the material J -integral (J_{material}) is determined according to the following equation:

$$J_{\text{material}} = \left(\frac{T \sigma_f^2}{N E} C^{\frac{-1}{N}} \right)^{\frac{N}{N-1}}$$

where C and N are the coefficient and exponent in the J - R fracture resistance power law curve, respectively. For a stable crack growth, the material's tearing modulus must be greater than or equal to the tearing modulus obtained from the applied load ($T_{\text{material}} \geq T_{\text{applied}}$) where $J_{\text{applied}} \leq J_{\text{material}}$. The instability point may be found by plotting J_{applied} against T_{applied} and J_{material} versus T_{material} on a single graph called a J - T diagram, as shown in Figure 3.6.3-10—Schematic of J -Tearing Instability Diagram. The intersection of the two curves depicts the instability point (the point where $J_{\text{applied}} = J_{\text{material}}$ when $T_{\text{applied}} = T_{\text{material}}$) and the corresponding J value is $J_{\text{instability}}$.

To solve for the instability point, the material J -integral (J_{material}) is set equal to the applied J -integral (J_{applied}) in the J - T diagram. The applied load that achieves this equality is determined through an iterative process. This load represents the maximum allowable load.

For the SL piping that uses the J-integral solution due to bending moment only, the applied load that achieves the equality is the total moment (i.e., the applied bending moment and the equivalent moment due to end cap pressure loading). This total moment minus the equivalent moment is the maximum allowable load that may be applied. Since the J-integral solution used for the MCL and MSL piping is the tension and bending solution, the maximum load that can be applied is the maximum allowable bending moment for a given total tension loading.

3.6.3.5.6 Determination of Maximum Allowable Piping Moment

Leakage crack sizes (twice the flaw size) with corresponding minimum moments that produced the desired leak rate were determined in the leak rate analysis. Since flow stability has to be demonstrated considering a safety factor of two on the leakage crack size per SRP 3.6.3, these leakage crack sizes are assumed as the flaw sizes in the J-T stability analysis described in Section 3.6.3.5.5. For a given flaw size, the maximum allowable moment associated with a given minimum moment loading is subsequently determined. The maximum moment calculations were determined using the solutions provided in Section 3.6.3.5.4. Since the absolute load combination method is considered for the analyses, a safety factor of one is appropriate per SRP 3.6.3. For each pipe size, LBB analysis requires identifying locations that have the least favorable combination of stress and material properties for base metal, weldments, nozzles, and safe ends. The lower bounding material properties associated with a given location, as described in Section 3.6.3.5.7, are used in the analysis to determine the lower bound maximum allowable piping moments.

3.6.3.5.7 Identification of Locations for Flaw Stability Analysis

LBB analysis normally considers the applied loadings for the piping system. Therefore, the least favorable combination of stress and material properties of the base metal (piping), weldments, nozzles, and safe ends can be identified. Since the applied loadings are not available, the “LBB allowable load windows” approach is used in this analysis. Using this approach, the identification of the locations is based on consideration of the pipe geometry, operating condition, and consideration of the lower bound material toughness at the given location.

3.6.3.5.7.1 Locations in Main Coolant Loop Piping

Based on the above approach, the locations in the MCL, shown in Table 3.6.3-1 are revised to the locations with associated lower bounding materials shown in Table 3.6.3-13—Main Coolant Loop Piping Locations based on Key Geometry, Operating Conditions and Lower Bound Material Toughness. The geometry and operating conditions helped establish the number of locations for leakage calculations. The lower bounding material properties associated with the location is subsequently used in the flaw stability analysis.

3.6.3.5.7.2 Locations in the Surge Line Piping

Using a similar approach as above, the locations in Table 3.6.3-2 are identified with the associated lower bounding materials as shown in Table 3.6.3-6.

3.6.3.5.7.3 Locations in the Main Steam Line Piping

Since the pipe geometry and operating condition throughout the LBB portion of the MSL piping are the same, as reflected in Table 3.6.3-3, the flaw stability analysis is performed considering both the base and the weld metal properties.

3.6.3.5.8 Development of Allowable Load Limit Diagrams

The lower bound maximum moment curve developed by the approach provided in Section 3.6.3.5.3 is plotted against the minimum moment loadings addressed in Section 3.6.3.5.1. This is referred to as an Allowable Load Limit (ALL) diagram, which is illustrated in Figure 3.6.3-11—Typical Allowable Load Limit (ALL) Diagram Considering Various Axial Loadings. In this plot, the minimum moment is plotted against the maximum moment. The presence of the 45 degree minimum moment line is due to the fact that the maximum moment cannot be lower than the minimum moment. The region between the maximum and the minimum curve is the “ALL LBB Zone,” as depicted in Figure 3.6.3-11. It is also referred to as the “LBB Window.” Maximum moment curves can also be developed for various assumed axial loadings as illustrated in Figure 3.6.3-11.

3.6.3.6 Results

The results for each of the three LBB piping systems addressed in Section 3.6.3.5.4, and for each of the cracked pipe geometries, are shown in this section. The results in the form of ALL diagrams are provided only for the limiting cracked pipe geometry, which is the geometry for the circumferential through-wall crack in a straight pipe. For the MCL and SL piping, the results for the circumferential through-wall crack in a straight pipe are given in Sections 3.6.3.6.1.1 and 3.6.3.6.2.1, respectively. For the circumferential through-wall extrados crack in an elbow, the results are presented in Sections 3.6.3.6.1.2 and 3.6.3.6.2.2 for the MCL and SL piping, respectively. The results for the MCL and SL piping, involving the axial through-wall crack in straight pipe geometry, are described in Sections 3.6.3.6.1.3 and 3.6.3.6.2.3, respectively. Similarly, the results for the MSL piping for each of the cracked pipe geometries are addressed in Section 3.6.3.6.3.

3.6.3.6.1 Main Coolant Loop Piping

3.6.3.6.1.1 Circumferential Through-Wall Crack in a Straight Pipe (ALL Diagrams)

The results of the flaw stability analysis are shown in terms of ALL diagrams for circumferential through-wall cracks in a straight pipe. The results for the reactor

vessel outlet nozzle at the Alloy 52 weld fusion line region are depicted in Figure 3.6.3-12—ALL for Reactor Vessel Outlet Nozzle Region at Hot Leg (Location 1). Similarly, the results for other components are shown in the figures as listed below:

- Figure 3.6.3-13—ALL for Hot Leg Pipe (Location 2).
- Figure 3.6.3-14—ALL for Steam Generator Inlet Nozzle at Hot Leg (Location 3).
- Figure 3.6.3-15—ALL for Steam Generator Outlet Nozzle (Location 4).
- Figure 3.6.3-16—ALL for Crossover & Cold Leg Pipe (Locations 5 & 8).
- Figure 3.6.3-17—ALL for RCP Inlet Nozzle (Location 6).
- Figure 3.6.3-24—ALL for RCP Outlet Nozzle (Location 7)
- Figure 3.6.3-25—ALL for RV Inlet Nozzle (Location 9)

These regions are identified in Table 3.6.3-13. The Alloy 52 weld locations (see Figure 3.6.3-12, Figure 3.6.3-14, Figure 3.6.3-15, and Figure 3.6.3-25) that use the fusion line toughness values were evaluated using the equivalent material tensile properties. The locations in Figure 3.6.3-17 and Figure 3.6.3-24 were evaluated using the lower bound toughness properties for the CASS RCP casing so that the cold leg pipe and RPV inlet nozzles are conservatively evaluated. The locations in Figure 3.6.3-13 and Figure 3.6.3-16 were evaluated considering the tensile and toughness properties of the base metal of the piping.

The explanations for the interpretation of the ALL diagrams are provided in Figure 3.6.3-12 through Figure 3.6.3-17, Figure 3.6.3-24, and Figure 3.6.3-25. As long as the maximum applicable moment (normal operating plus SSE loading) load for the applicable location is within the “ALL LBB Zone,” LBB is justified for that location. The maximum moment loads are derived considering various coincident axial loading conditions (1000 kilo lbs (kips), 1500 kilo lbs (kips), 2000 kilo lbs (kips), 2500 kips, and 3000 kips). The maximum axial loading (i.e., external applied loading plus 100 percent normal operating pressure end-cap load) that is applicable for the location is used as the maximum moment curve for the location. The “ALL LBB Zone” region is reduced as the axial loading is increased from 1000 kips to 3000 kips. The corresponding tabulated values for the ALL diagrams in Figure 3.6.3-12 through Figure 3.6.3-17, Figure 3.6.3-24 and Figure 3.6.3-25 are provided in the following tables:

- Table 3.6.3-14—ALL for RV Outlet Nozzle Region at the Hot Leg (Location 1)
- Table 3.6.3-15—ALL for Hot Leg Pipe (Location 2)
- Table 3.6.3-16—ALL for SG Inlet Nozzle at Hot Leg (Location 3).

- Table 3.6.3-17—ALL for SG Outlet Nozzle (Location 4).
- Table 3.6.3-18—ALL for Crossover & Cold Leg Pipe (Locations 5 & 8).
- Table 3.6.3-19—ALL for RCP Inlet Nozzle (Location 6).
- Table 3.6.3-27—ALL for RCP Outlet Nozzle (Location 7)
- Table 3.6.3-28—ALL for RV Inlet Nozzle (Location 9)

3.6.3.6.1.2 Circumferential Through-Wall Extradados Crack in an Elbow

A sample problem was evaluated to demonstrate that this cracked geometry is bounded by the results of the circumferential through-wall crack in the adjoining straight pipe at a given location. That analysis showed that the maximum allowable moment in the steam generator inlet elbow with a flaw size of 12.4 in is 54,067 in-kips. This evaluation accounts for the wall thinning at the extradados of the elbow where the wall thickness is 2.91 in. The adjoining straight pipe at the steam generator inlet has a wall thickness of <3.66 in. Even with consideration of the greater wall thickness, the maximum allowable moment for a circumferential crack of the same size in a straight pipe is only 52,133 in-kips considering the base metal properties. This corresponds to a 3.7 percent increase in allowable moment obtained for the circumferential extradados crack in the elbow compared to the circumferential crack in the straight pipe. The ALL diagram results provided in Section 3.6.3.6.1.1 are also applicable for the circumferential extradados crack in an elbow.

3.6.3.6.1.3 Axial Through-Wall Crack in a Straight Pipe

The axial through-wall cracks in a straight pipe were evaluated at each of the regions identified for the circumferential through-wall crack in a straight pipe. The critical crack sizes for each of the regions are shown in Table 3.6.3-20—Critical Axial Crack Size at Main Coolant Loop Piping Locations. The minimum critical crack size was greater than 33 in. The appropriate lower bound material properties for each of the regions are also considered for the axial through-wall cracks. The minimum safety margin (ratio of critical crack size to leakage crack size) was determined to be 4.89 and occurs in the RPV outlet nozzle region. *[This is greater than the required safety factor of two for LBB analysis.]** Therefore, the LBB required safety margins are met for this cracked pipe geometry.

3.6.3.6.2 Surge Line Piping

3.6.3.6.2.1 Circumferential Through-Wall Crack in a Straight Pipe (ALL Diagrams)

The results of the flaw stability analysis are shown in terms of ALL diagrams for circumferential through-wall cracks in a straight pipe. The results for the pressurizer surge nozzle at the Alloy 52 weld fusion line region are depicted in Figure 3.6.3-18—

ALL for Pressurizer Surge Nozzle at Alloy 52 Weld. Similarly, the results for the SL piping and hot leg nozzle are illustrated in Figure 3.6.3-19—ALL for Surge Line Piping and Figure 3.6.3-20—ALL for Hot Leg Nozzle, respectively. These three regions are identified in Table 3.6.3-6.

As long as the maximum applicable moment (normal operating plus SSE loading) load for the applicable location is within the “ALL LBB Zone,” LBB is considered to be justified for that location. The maximum moment loads are derived considering various coincident axial loading conditions due to normal operating pressure, as well as external loads whose magnitudes are noted on the curves. The maximum axial loading (external applied) that is applicable for the location is used as the maximum moment curve for the location. The “ALL LBB Zone” region is reduced as the axial loading is increased. The corresponding tabulated values for the ALL diagrams in Figure 3.6.3-18 through Figure 3.6.3-20 are provided in Table 3.6.3-21—ALL for Pressurizer Surge Nozzle at Alloy 52 Weld, Table 3.6.3-22—ALL for Surge Line Piping, and Table 3.6.3-23—ALL for Hot Leg Nozzle.

3.6.3.6.2.2 Circumferential Through-Wall Extradados Crack in an Elbow

A sample problem was evaluated to demonstrate that this cracked geometry is bounded by the results of the circumferential through-wall crack in the adjoining straight pipe at a given location. The results from that analysis showed that the maximum allowable moment in the SL piping elbow with a flaw size of 5.6 in is 5421 in-kips. This evaluation accounts for the wall thinning at the extradados of the elbow where the wall thickness is 1.4 in. The adjoining straight pipe at the SL piping has a wall thickness <1.55 in. The maximum allowable moment for a circumferential crack of the same size in a straight pipe is also about 5421 in-kips considering the base metal properties.

3.6.3.6.2.3 Axial Through-Wall Crack in a Straight Pipe

The axial through-wall cracks in a straight pipe are evaluated at each of the regions identified in Table 3.6.3-11. The critical crack sizes for each of the three regions are shown in Table 3.6.3-24—Critical Axial Crack Size at Surge Line Piping Locations. The appropriate lower bound material properties for each of the three regions are considered for the axial through-wall cracks. The minimum safety margin (ratio of critical crack size to leakage crack size) is determined to be 4.2 and occurs in the SL piping region. *[This is greater than the safety factor of two required for LBB analysis.]** Therefore, the LBB required safety margins are met for this cracked pipe geometry.

3.6.3.6.3 Main Steam Line Piping

3.6.3.6.3.1 Circumferential Through-Wall Crack in a Straight Pipe (ALL Diagrams)

The results of the flaw stability analysis are shown in terms of ALL diagrams for circumferential through-wall cracks in a straight pipe. The results considering the flaws in the base metal as well as the weld metal are shown in Figure 3.6.3-21—Comparison of Base and Weld Metal ALL in Main Steam Line Piping. These results demonstrate that the base metal is the most limiting material for the MSL piping. The results of the flaw stability analysis, considering the limiting base metal properties and all the required safety margins for LBB, are shown in Figure 3.6.3-22—ALL for Main Steam Line Piping with Safety Factor of 2 on Flaw Size (Base Metal).

The explanations for the interpretation of the ALL diagram are provided in Figure 3.6.3-22. As long as the maximum applicable moment (normal operating plus SSE loading) load for the applicable location is within the “ALL LBB Zone,” LBB is justified for that location. The maximum moment loads are derived considering various coincident axial loading conditions (100 kips, 200 kips, 300 kips, 451 kips, and 600 kips). The maximum axial loading (external applied) that is applicable for the location, is used as the maximum moment curve for the location. These maximum moment curves already include the end cap load due to pressure at 100 percent power operating condition. The “ALL LBB Zone” region is reduced as the axial loading is increased from 100 kips to 600 kips. The corresponding tabulated values for the ALL diagrams in Figure 3.6.3-22 are provided in Table 3.6.3-25—ALL for the Main Steam Line Piping with Safety Factor of 2 on Flaw Size (Base Metal).

3.6.3.6.3.2 Circumferential Through-Wall Extradados Crack in an Elbow

A sample problem is evaluated to demonstrate that this cracked geometry is bounded by the results of the circumferential through-wall crack in the adjoining straight pipe at a given location. As previously noted in Section 3.6.3.5.4.3, the J-solutions for this cracked geometry are only available for crack half-angles of 45° and 90°. The results of the evaluation of the circumferential crack at the extradados of the elbow are illustrated in Figure 3.6.3-22 which also depicts the results of the circumferential through-wall crack in a straight pipe. As shown in this figure, the results for the circumferential crack at the extradados of the elbow are comparable to the results of the circumferential through-wall crack in a straight pipe.

3.6.3.6.3.3 Axial Through-Wall Crack in a Straight Pipe

The hoop stresses due to operating pressure are the main crack driving force on the axial through-wall crack in a straight pipe, while the effect of external loads are not considered significant for this crack orientation. Therefore, no allowable load limit diagram is generated for the axial through-wall crack in a straight pipe. Instead the critical crack size in the lower bounding base metal material is determined and

compared against the leakage crack size corresponding to a leak rate of one gpm. The critical crack size is 43.6 in, whereas the leakage crack size is only 15.75 in. This provides a safety factor of 2.8 on crack size, which is greater than the required safety factor of two. Therefore, the LBB required safety margins are met for this cracked geometry.

3.6.3.7 Leak Detection

*[As noted in Sections 3.6.3.5.2 and 3.6.3.5.3, in order to provide a factor of ten to the actual plant leakage detection system capabilities, leak rates of 5.0 gpm for the MCL and SL and 1.0 gpm for MSL were used for determining the leakage flaw sizes.]**

Section 5.2.5 describes the leak detection systems for the primary coolant inside containment. SRP 3.6.3 states “The specifications for plant-specific leakage detection systems inside the containment are equivalent to those in Regulatory Guide 1.45.”

As noted in Section 5.2.5, the RCPB leakage detections systems for the U.S. EPR conform to the sensitivity and response times recommended in RG 1.45, Revision 1. Additionally, at least two of the RCPB leakage detections systems are capable of detecting a leakage rate of 0.5 gpm for the MCL and SL.

The primary method used to detect leakage from the MSL is the local humidity detection system, which has the capability of detecting a leakage of 0.1 gpm within four hours. RG 1.45, Revision 1 specifies a time frame of one hour for leakage detection. However, as noted in NUREG-1793 (Reference 28) leakage detection for LBB purposes does not require the same degree of timeliness. The local humidity detection system measures the moisture penetrating a sensor tube. A secondary method of detecting a leakage of 0.1 gpm within four hours for the MSL is the containment sump level, as described in Section 5.2.5. Containment air cooler condensate flow and containment atmosphere pressure, temperature, and humidity also provide an indication of possible leakage.

3.6.3.8 References

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Table 3.6.3-1—Main Coolant System Piping Dimensions and Operating Condition

| Location | Description of Pipe Geometry | Temperature (°F) | Pressure (psia) | ID¹ (in) | Pipe Wall² Thickness (in) |
|-----------------|-------------------------------------|-------------------------|------------------------|----------------------------|---|
| 1 | RV Outlet at Hot Leg | 625 | 2250 | 30.71 | 2.99 |
| 2 | Hot Leg Pipe | 625 | 2250 | 30.71 | 2.99 |
| 3 | SG Inlet at Hot Leg | 625 | 2250 | 30.71 | 3.82 |
| 4 | SG Outlet | 563 | 2250 | 30.71 | 3.82 |
| 5 | Crossover Leg | 563 | 2250 | 30.71 | 2.99 |
| 6 | RCP Inlet | 563 | 2250 | 30.71 | 3.54 |
| 7 | RCP Outlet | 563 | 2250 | 30.71 | 2.99 |
| 8 | Cold Leg Pipe | 563 | 2250 | 30.71 | 2.99 |
| 9 | RPV Inlet | 563 | 2250 | 30.71 | 2.99 |

Notes:

1. ID of the pipe. At the weld prep location the ID of pipe is 30.87 in.
2. For detailed J-T analysis the weld prep thickness is conservatively used. For leak rate analysis, the pipe wall thickness given in the table is used.

Table 3.6.3-2—Surge Line Piping Dimensions and Operating Condition

| Location | Description of Pipe Geometry | Temperature (°F) | Pressure (psia) | ID ¹ (in) | Pipe Wall ² Thickness (in) |
|----------|------------------------------------|------------------|-----------------|----------------------|---------------------------------------|
| 1 | Pressurizer Surge Nozzle | 653 | 2250 | 13.61 | 2.055 |
| 2 | Surge Line Piping near Pressurizer | 653 | 2250 | 12.81 | 1.595 |
| 3 | Hot Leg Nozzle | 624 | 2250 | 12.91 | 1.545 |

Notes:

1. ID of the pipe. At the weld prep location, the ID of the pipe is 12.91 in.
2. For consistency, the pipe wall thickness is used in both the leak rate and flaw stability analysis.

Table 3.6.3-3—Main Steam Line Dimensions and Operating Condition

| Location | Description of Pipe Geometry | Temperature (°F) | Pressure (psia) | ID (in) | Pipe Wall ¹ Thickness (in) |
|----------|------------------------------|------------------|-----------------|---------|---------------------------------------|
| 1 | Main Steam Line Piping | 556 | 1111 | 27.5 | 1.86 |

Note:

1. Pipe wall thickness is used for both the J-T analysis and the leak rate analysis.

Table 3.6.3-4—Tensile Properties of Materials at Various Locations of Main Coolant Loop Piping

| Locations | Temp., °F | E (ksi) | $\sigma_o (= \sigma_y, \text{ksi})$ | ϵ_o | a | n | $\sigma_u (\text{ksi})$ |
|-----------|-----------|---------|-------------------------------------|--------------|-------|-------|-------------------------|
| 1* | 625 | 25252 | 21.545 | 0.000853 | 5.570 | 4.090 | 61.356 |
| 2 | 625 | 25000 | 19.200 | 0.000768 | 5.850 | 3.878 | 59.200 |
| 3* | 625 | 25396 | 22.885 | 0.000901 | 5.420 | 4.210 | 62.588 |
| 4* | 563 | 25879 | 23.523 | 0.000909 | 4.930 | 4.290 | 62.588 |
| 5 | 563 | 25500 | 19.790 | 0.000776 | 5.280 | 3.997 | 59.200 |
| 6 | 563 | 25500 | 19.790 | 0.000776 | 5.280 | 3.997 | 59.200 |
| 7 | 563 | 25500 | 19.790 | 0.000776 | 5.280 | 3.997 | 59.200 |
| 8 | 563 | 25500 | 19.790 | 0.000776 | 5.280 | 3.997 | 59.200 |
| 9* | 563 | 25741 | 22.167 | 0.000861 | 5.060 | 4.180 | 61.356 |

Note:

1. *Note: Dissimilar metal weld (DMW) at fusion line determined using elastic-plastic fracture mechanics (EPFM) and finite element method.

Table 3.6.3-5—Tensile Properties for the Surge Line Piping

| Tensile Properties (ksi) | | | |
|---|-------------------------------|--|-------------------|
| | SL Piping near Pressurizer | Pressurizer Nozzle DMW ¹ | Hot Leg Nozzle |
| Yield Stress (σ_y) | 18.0 | 22.9 | 18.21 |
| Ultimate Strength (σ_{ult}) | 59.2 | 62.6 | 59.2 |
| Flow Stress (σ_f) | 38.6 | 42.8 | 38.7 |
| Young's Modulus (E) | 25,000 | 25,400 | 25,180 |
| Ramberg-Osgood Parameters ($\frac{\epsilon}{\epsilon_o} = \frac{\sigma}{\sigma_o} + \alpha \left(\frac{\sigma}{\sigma_o} \right)^n$) | | | |
| | SL Piping near Pressurizer | Pressurizer Nozzle | Hot Leg Nozzle |
| α | 5.90 | 5.38 | 6.13 |
| n | 3.50 | 4.28 | 3.50 |
| Reference Stress (σ_o) | 18.0 ksi | 22.9 ksi | 18.21 ksi |
| Reference Strain (ϵ) | 0.00072 | 0.000901 | 0.000723 |

Note:

1. Dissimilar metal weld (DMW) at fusion line determined using elastic-plastic fracture mechanics (EPFM) and finite element method.

Table 3.6.3-6—Surge Line Piping Locations Based on Key Geometry, Operating Conditions & Lower Bound Material Toughness

| LBB Piping Location | Description of Pipe Geometry | Temperature (°F) | Thickness (in) | R _m /t | Lower Bounding Material |
|---------------------|------------------------------------|------------------|----------------|-------------------|-------------------------|
| 1 | Pressurizer Surge Nozzle | 653 | 2.005 | 3.81 | Alloy 52 |
| 2 | Surge Line Piping near Pressurizer | 653 | 1.595 | 4.52 | SS Base Metal |
| 3 | Hot leg Nozzle | 624 | 1.545 | 4.68 | SS Base Metal |

Table 3.6.3-7—Tensile Properties for the Main Steam Line Piping

| Tensile Properties (ksi) | | |
|---|------------|------------|
| | Base Metal | Weld Metal |
| Yield Stress (σ _y) | 39.0 | 76.0 |
| Ultimate Strength (σ _{ult}) | 81.0 | 89.5 |
| Flow Stress (σ _f) | 60.0 | 82.75 |
| Young's Modulus (E) | 26,750 | 26,750 |
| Ramberg-Osgood Parameters ($\frac{\epsilon}{\epsilon_o} = \frac{\sigma}{\sigma_o} + \alpha \left(\frac{\sigma}{\sigma_o} \right)^n$) | | |
| | Base Metal | Weld Metal |
| α | 1.12 | 0.897 |
| n | 9.54 | 14.8 |
| Reference Stress (σ _o) | 39.0 ksi | 76.0 ksi |
| Reference Strain (ε) | 0.00146 | 0.00284 |

Table 3.6.3-8—Minimum Moment versus Circumferential Crack Leakage Sizes for 5 gpm at Various Main Coolant Loop Piping Locations

| Min Moment In-kips | Circumferential Leakage Flaw Size at 5.0 GPM, inch | | | | | | |
|-----------------------|--|--------|--------|--------|---------|--------|-------|
| | 1 | 2 | 3 | 4 | 5, 7, 8 | 6 | 9 |
| 0 | 11.322 | 10.314 | 14.683 | 12.824 | 9.592 | 11.549 | 9.985 |
| 10000 | 8.630 | 8.378 | 11.153 | 9.547 | 7.328 | 8.759 | 7.466 |
| 20000 | 6.764 | 6.442 | 9.035 | 7.709 | 5.688 | 6.948 | 5.889 |
| 30000 | 5.140 | 4.616 | 7.372 | 6.361 | 4.191 | 5.400 | 4.617 |
| 40000 | 3.662 | 3.214 | 5.927 | 5.205 | 2.975 | 4.074 | 3.344 |
| 50000 | 2.625 | 2.265 | 4.672 | 4.187 | 2.115 | 3.179 | 2.433 |
| 60000 | 1.912 | 1.645 | 3.653 | 3.358 | 1.536 | 2.283 | 1.784 |
| 70000 | 1.455 | 1.234 | 2.861 | 2.635 | 1.149 | 1.746 | 1.403 |
| 80000 | 1.095 | 0.954 | 2.262 | 2.097 | 0.884 | 1.361 | 1.021 |
| 90000 | 0.861 | 0.757 | 1.865 | 1.683 | 0.698 | 1.083 | 0.801 |
| 100000 | 0.691 | 0.614 | 1.468 | 1.366 | 0.563 | 0.879 | 0.641 |
| 110000 | 0.568 | 0.507 | 1.207 | 1.124 | 0.462 | 0.725 | 0.522 |
| 120000 | 0.472 | 0.427 | 1.028 | 0.956 | 0.386 | 0.606 | 0.434 |
| 130000 | 0.398 | 0.363 | 0.849 | 0.787 | 0.328 | 0.515 | 0.365 |
| 140000 | 0.340 | 0.318 | 0.723 | 0.670 | 0.282 | 0.442 | 0.310 |
| 150000 | 0.294 | 0.273 | 0.623 | 0.576 | 0.244 | 0.383 | 0.268 |
| 160000 | 0.258 | 0.251 | 0.542 | 0.500 | 0.214 | 0.335 | 0.234 |

Table 3.6.3-9—Axial Through-Wall Leakage Crack Sizes for 5 gpm at Various Main Coolant Loop Piping Locations

| MCL Locations | Description | Leakage Crack Size (in) |
|---------------|----------------------|-------------------------|
| 1 | RV Outlet at Hot Leg | 7.189 |
| 2 | Hot Leg Pipe | 7.311 |
| 3 | SG Inlet at Hot Leg | 8.529 |
| 4 | SG Outlet | 7.395 |
| 5 | Crossover Leg | 6.342 |
| 6 | RCP Inlet | 7.124 |
| 7 | RCP Outlet | 6.342 |
| 8 | Cold Leg Pipe | 6.342 |
| 9 | RV Inlet | 6.254 |

Table 3.6.3-10—Minimum Moment versus Circumferential Leakage Crack Sizes for 5 gpm at Two Surge Line Piping Locations

| With Axial Load of: | | 1,000 kips | 1,500 kips | 2,000 kips | 2,500 kips | 3,000 kips |
|---------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| Flaw Size (in) | Min Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) |
| 11.322 | 0 | 37,974 | 33,471 | 28,969 | 24,552 | 19,965 |
| 8.630 | 10,000 | 48,654 | 44,249 | 39,843 | 35,449 | 31,032 |
| 6.764 | 20,000 | 56,679 | 52,327 | 47,975 | 43,622 | 39,271 |
| 5.140 | 30,000 | 64,380 | 60,068 | 55,757 | 51,445 | 47,134 |
| 3.662 | 40,000 | 72,497 | 68,219 | 63,942 | 59,663 | 55,386 |
| 2.625 | 50,000 | 79,479 | 75,224 | 70,968 | 66,712 | 62,456 |
| 1.912 | 60,000 | 85,560 | 81,319 | 77,077 | 72,836 | 68,594 |
| 1.455 | 70,000 | 90,534 | 86,301 | 82,068 | 77,836 | 73,603 |
| 1.095 | 80,000 | 95,564 | 91,337 | 87,111 | 82,885 | 78,659 |
| 0.861 | 90,000 | 99,763 | 95,541 | 91,319 | 87,096 | 82,874 |
| 0.691 | 100,000 | 103,596 | 99,377 | 95,157 | 90,937 | 86,718 |
| 0.568 | 110,000 | 107,024 | 102,806 | 98,588 | 94,370 | 90,152 |
| 0.472 | 120,000 | 110,284 | 106,067 | 101,851 | 97,634 | 93,417 |
| 0.398 | 130,000 | 113,313 | 109,098 | 104,882 | 100,666 | 96,450 |
| 0.340 | 140,000 | 116,140 | 111,924 | 107,709 | 103,494 | 99,279 |
| 0.294 | 150,000 | 118,776 | 114,561 | 110,346 | 106,132 | 101,917 |
| 0.258 | 160,000 | 121,169 | 116,955 | 112,741 | 108,526 | 104,312 |

Table 3.6.3-11—Axial Through-Wall Leakage Crack Sizes for 5 gpm at Three Surge Line Piping Locations

| SL Location | Leakage Crack Size (in) |
|---|-------------------------|
| Pressurizer Surge Nozzle at Alloy 52 weld | 7.635 |
| Surge Line Piping | 6.665 |
| Hot Leg Nozzle | 6.526 |

Table 3.6.3-12—Minimum Moment versus Circumferential Leakage Crack Sizes for 1 gpm in the Main Steam Line Piping

| Leakage Size (in) | Minimum Moment (in-kips) |
|------------------------------|-------------------------------------|
| 13.85 | 2400 |
| 12.05 | 4820 |
| 10.73 | 7270 |
| 9.75 | 9620 |
| 8.93 | 12,100 |
| 8.25 | 14,700 |
| 7.70 | 17,200 |
| 7.20 | 19,800 |
| 6.76 | 22,500 |
| 6.33 | 25,600 |
| 5.94 | 28,800 |

Table 3.6.3-13—Main Coolant Loop Piping Locations based on Key Geometry, Operating Conditions and Lower Bound Material Toughness

| LBB Piping Location | Description of Pipe Geometry | Temperature (°F) | Pipe Wall Thickness¹, t (in) | Rm/t | Lower Bounding Material |
|----------------------------|-------------------------------------|-------------------------|--|-------------|--------------------------------|
| 1 | RV Outlet at Hot Leg | 625 | 2.913 | 5.80 | Alloy 52 |
| 2 | Hot Leg Pipe | 625 | 2.835 | 5.94 | Base Metal |
| 3 | SG Inlet at Hot Leg | 625 | 3.661 | 4.72 | Alloy 52 |
| 4 | SG Outlet | 563 | 3.661 | 4.72 | Alloy 52 |
| 5 | Crossover Leg | 563 | 2.835 | 5.94 | Base Metal |
| 6 | RCP Inlet | 563 | 3.386 | 5.06 | CASS |
| 7 | RCP Outlet | 563 | 2.913 | 5.80 | CASS |
| 8 | Cold Leg Pipe | 563 | 2.913 | 5.80 | Base Metal |
| 9 | RPV Inlet | 563 | 2.913 | 5.80 | Alloy 52 |

Note:

1. Corresponds to the minimum thickness at the weld prep location. However, for consistency with leak rate analysis, the thickness from Table 3.6.3-1 are used.

Table 3.6.3-14—ALL for RV Outlet Nozzle Region at the Hot Leg (Location 1)

| With Axial Load of: | | 1,000 kips | 1,500 kips | 2,000 kips | 2,500 kips | 3,000 kips |
|----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Flaw Size (in) | Min Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) |
| 11.322 | 0 | 37,974 | 33,471 | 28,969 | 24,552 | 19,965 |
| 8.630 | 10,000 | 48,654 | 44,249 | 39,843 | 35,449 | 31,032 |
| 6.764 | 20,000 | 56,679 | 52,327 | 47,975 | 43,622 | 39,271 |
| 5.140 | 30,000 | 64,380 | 60,068 | 55,757 | 51,445 | 47,134 |
| 3.662 | 40,000 | 72,497 | 68,219 | 63,942 | 59,663 | 55,386 |
| 2.625 | 50,000 | 79,479 | 75,224 | 70,968 | 66,712 | 62,456 |
| 1.912 | 60,000 | 85,560 | 81,319 | 77,077 | 72,836 | 68,594 |
| 1.455 | 70,000 | 90,534 | 86,301 | 82,068 | 77,836 | 73,603 |
| 1.095 | 80,000 | 95,564 | 91,337 | 87,111 | 82,885 | 78,659 |
| 0.861 | 90,000 | 99,763 | 95,541 | 91,319 | 87,096 | 82,874 |
| 0.691 | 100,000 | 103,596 | 99,377 | 95,157 | 90,937 | 86,718 |
| 0.568 | 110,000 | 107,024 | 102,806 | 98,588 | 94,370 | 90,152 |
| 0.472 | 120,000 | 110,284 | 106,067 | 101,851 | 97,634 | 93,417 |
| 0.398 | 130,000 | 113,313 | 109,098 | 104,882 | 100,666 | 96,450 |
| 0.340 | 140,000 | 116,140 | 111,924 | 107,709 | 103,494 | 99,279 |
| 0.294 | 150,000 | 118,776 | 114,561 | 110,346 | 106,132 | 101,917 |
| 0.258 | 160,000 | 121,169 | 116,955 | 112,741 | 108,526 | 104,312 |

Table 3.6.3-15—ALL for Hot Leg Pipe (Location 2)

| With Axial Load of: | | 1,000 kips | 1,500 kips | 2,000 kips | 2,500 kips | 3,000 kips |
|----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Flaw Size (in) | Min Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) |
| 10.314 | 0 | 51,970 | 47,519 | 43,069 | 38,632 | 34,168 |
| 8.378 | 10,000 | 60,759 | 56,371 | 51,984 | 47,529 | 43,209 |
| 6.442 | 20,000 | 70,317 | 65,983 | 61,648 | 57,313 | 52,978 |
| 4.616 | 30,000 | 80,643 | 76,351 | 72,059 | 67,767 | 63,475 |
| 3.214 | 40,000 | 90,395 | 86,133 | 81,870 | 77,608 | 73,345 |
| 2.265 | 50,000 | 98,991 | 94,747 | 90,503 | 86,259 | 82,015 |
| 1.645 | 60,000 | 106,485 | 102,252 | 98,019 | 93,786 | 89,553 |
| 1.234 | 70,000 | 113,105 | 108,878 | 104,652 | 100,426 | 96,200 |
| 0.954 | 80,000 | 119,029 | 114,807 | 110,585 | 106,362 | 102,140 |
| 0.757 | 90,000 | 121,754 | 118,551 | 114,863 | 110,702 | 106,088 |
| 0.614 | 100,000 | 122,516 | 119,346 | 115,690 | 111,561 | 106,976 |
| 0.507 | 110,000 | 123,085 | 119,940 | 116,307 | 112,202 | 107,639 |
| 0.427 | 120,000 | 123,509 | 120,383 | 116,768 | 112,680 | 108,135 |
| 0.363 | 130,000 | 123,848 | 120,737 | 117,137 | 113,063 | 108,531 |
| 0.318 | 140,000 | 124,086 | 120,985 | 117,396 | 113,331 | 108,809 |
| 0.273 | 150,000 | 124,324 | 121,234 | 117,654 | 113,600 | 109,087 |
| 0.251 | 160,000 | 124,441 | 121,355 | 117,781 | 113,731 | 109,222 |

Table 3.6.3-16—ALL for SG Inlet Nozzle at Hot Leg (Location 3)

| With Axial Load of: | | 1,000 kips | 1,500 kips | 2,000 kips | 2,500 kips | 3,000 kips |
|---------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| Flaw Size (in) | Min Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) |
| 14.683 | 0 | 45,852 | 41,087 | 36,324 | 31,675 | 26,796 |
| 11.153 | 10,000 | 63,088 | 58,493 | 53,898 | 49,337 | 44,707 |
| 9.035 | 20,000 | 74,262 | 69,742 | 65,222 | 60,701 | 56,182 |
| 7.372 | 30,000 | 83,615 | 79,145 | 74,674 | 70,202 | 65,732 |
| 5.927 | 40,000 | 92,372 | 87,939 | 83,505 | 79,072 | 74,639 |
| 4.672 | 50,000 | 100,755 | 96,352 | 91,948 | 87,544 | 83,141 |
| 3.653 | 60,000 | 108,471 | 104,090 | 99,709 | 95,328 | 90,948 |
| 2.861 | 70,000 | 115,441 | 111,077 | 106,713 | 102,349 | 97,985 |
| 2.262 | 80,000 | 121,680 | 117,328 | 112,977 | 108,625 | 104,273 |
| 1.865 | 90,000 | 126,566 | 122,222 | 117,878 | 113,535 | 109,191 |
| 1.468 | 100,000 | 132,421 | 128,085 | 123,749 | 119,413 | 115,077 |
| 1.207 | 110,000 | 137,100 | 132,769 | 128,437 | 124,106 | 119,774 |
| 1.028 | 120,000 | 140,892 | 136,563 | 132,235 | 127,907 | 123,578 |
| 0.849 | 130,000 | 145,383 | 141,058 | 136,732 | 132,407 | 128,081 |
| 0.723 | 140,000 | 149,148 | 144,825 | 140,501 | 136,178 | 131,854 |
| 0.623 | 150,000 | 152,642 | 148,320 | 143,998 | 139,676 | 135,354 |
| 0.542 | 160,000 | 155,924 | 151,603 | 147,282 | 142,961 | 138,640 |

Table 3.6.3-17—ALL for SG Outlet Nozzle (Location 4)

| With Axial Load of: | | 1,000 kips | 1,500 kips | 2,000 kips | 2,500 kips | 3,000 kips |
|---------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| Flaw Size (in) | Min Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) |
| 12.824 | 0 | 56,353 | 51,686 | 47,019 | 42,485 | 37,685 |
| 9.547 | 10,000 | 73,420 | 68,884 | 64,347 | 59,849 | 55,274 |
| 7.709 | 20,000 | 83,753 | 79,273 | 74,793 | 70,312 | 65,832 |
| 6.361 | 30,000 | 91,860 | 87,416 | 82,972 | 78,527 | 74,084 |
| 5.205 | 40,000 | 99,371 | 94,956 | 90,540 | 86,124 | 81,709 |
| 4.187 | 50,000 | 106,671 | 102,278 | 97,886 | 93,493 | 89,101 |
| 3.358 | 60,000 | 113,384 | 109,009 | 104,635 | 100,261 | 95,886 |
| 2.635 | 70,000 | 120,176 | 115,817 | 111,458 | 107,099 | 102,740 |
| 2.097 | 80,000 | 126,173 | 121,825 | 117,477 | 113,128 | 108,780 |
| 1.683 | 90,000 | 131,693 | 127,353 | 123,013 | 118,673 | 114,333 |
| 1.366 | 100,000 | 136,774 | 132,440 | 128,106 | 123,772 | 119,438 |
| 1.124 | 110,000 | 141,434 | 137,104 | 132,774 | 128,444 | 124,114 |
| 0.956 | 120,000 | 145,275 | 140,948 | 136,621 | 132,294 | 127,966 |
| 0.787 | 130,000 | 149,841 | 145,517 | 141,192 | 136,868 | 132,543 |
| 0.670 | 140,000 | 153,627 | 149,304 | 144,981 | 140,659 | 136,336 |
| 0.576 | 150,000 | 157,190 | 152,869 | 148,548 | 144,226 | 139,905 |
| 0.500 | 160,000 | 160,540 | 156,220 | 151,899 | 147,579 | 143,259 |

Table 3.6.3-18—ALL for Crossover & Cold Leg Pipe (Locations 5 & 8)

| With Axial Load of: | | 1,000 kips | 1,500 kips | 2,000 kips | 2,500 kips | 3,000 kips |
|---------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| Flaw Size (in) | Min Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) |
| 9.592 | 0 | 56,384 | 51,959 | 47,535 | 43,126 | 38,685 |
| 7.328 | 10,000 | 67,088 | 62,731 | 58,374 | 53,951 | 49,659 |
| 5.688 | 20,000 | 75,660 | 71,344 | 67,028 | 62,711 | 58,395 |
| 4.191 | 30,000 | 84,645 | 80,362 | 76,079 | 71,796 | 67,514 |
| 2.975 | 40,000 | 93,589 | 89,332 | 85,074 | 80,816 | 76,559 |
| 2.115 | 50,000 | 101,800 | 97,558 | 93,317 | 89,076 | 84,834 |
| 1.536 | 60,000 | 109,177 | 104,946 | 100,715 | 96,484 | 92,253 |
| 1.149 | 70,000 | 115,773 | 111,548 | 107,323 | 103,098 | 98,873 |
| 0.884 | 80,000 | 121,736 | 117,515 | 113,294 | 109,073 | 104,852 |
| 0.698 | 90,000 | 123,105 | 119,937 | 116,286 | 112,165 | 107,592 |
| 0.563 | 100,000 | 123,827 | 120,691 | 117,070 | 112,979 | 108,435 |
| 0.462 | 110,000 | 124,367 | 121,254 | 117,656 | 113,587 | 109,064 |
| 0.386 | 120,000 | 124,772 | 121,677 | 118,096 | 114,044 | 109,537 |
| 0.328 | 130,000 | 125,081 | 121,999 | 118,431 | 114,392 | 109,897 |
| 0.282 | 140,000 | 125,325 | 122,254 | 118,697 | 114,668 | 110,183 |
| 0.244 | 150,000 | 125,527 | 122,465 | 118,917 | 114,896 | 110,418 |
| 0.214 | 160,000 | 125,687 | 122,631 | 119,090 | 115,075 | 110,604 |

Table 3.6.3-19—ALL for RCP Inlet Nozzle (Location 6)

| With Axial Load of: | | 1,000 kips | 1,500 kips | 2,000 kips | 2,500 kips | 3,000 kips |
|----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Flaw Size (in) | Min Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) |
| 11.549 | 0 | 46,509 | 41,933 | 37,357 | 32,873 | 28,206 |
| 8.759 | 10,000 | 58,946 | 54,470 | 49,995 | 45,525 | 41,043 |
| 6.948 | 20,000 | 67,733 | 63,309 | 58,886 | 54,462 | 50,038 |
| 5.400 | 30,000 | 75,995 | 71,610 | 67,225 | 62,840 | 58,456 |
| 4.074 | 40,000 | 84,053 | 79,698 | 75,344 | 70,990 | 66,635 |
| 3.179 | 50,000 | 90,422 | 86,087 | 81,752 | 77,417 | 73,082 |
| 2.283 | 60,000 | 98,210 | 93,893 | 89,577 | 85,260 | 80,943 |
| 1.746 | 70,000 | 104,147 | 99,840 | 95,534 | 91,228 | 86,922 |
| 1.361 | 80,000 | 109,488 | 105,189 | 100,890 | 96,591 | 92,292 |
| 1.083 | 90,000 | 114,311 | 110,016 | 105,722 | 101,428 | 97,133 |
| 0.879 | 100,000 | 118,692 | 114,401 | 110,109 | 105,818 | 101,527 |
| 0.725 | 110,000 | 122,739 | 118,450 | 114,162 | 109,873 | 105,584 |
| 0.606 | 120,000 | 126,527 | 122,239 | 117,952 | 113,665 | 109,378 |
| 0.515 | 130,000 | 129,990 | 125,704 | 121,418 | 117,132 | 112,846 |
| 0.442 | 140,000 | 133,273 | 128,988 | 124,703 | 120,418 | 116,133 |
| 0.383 | 150,000 | 136,382 | 132,097 | 127,813 | 123,528 | 119,244 |
| 0.335 | 160,000 | 139,317 | 135,033 | 130,749 | 126,465 | 122,182 |

Table 3.6.3-20—Critical Axial Crack Size at Main Coolant Loop Piping Locations

| Location | Component | Leakage Flaw Size at 5.0 GPM, inch | Critical Flaw Sizes, inch | Safety Margin |
|-----------------|-----------------------------|---|----------------------------------|----------------------|
| 1 | RV Outlet Nozzle at Hot Leg | 7.189 | 35.19 | 4.89 |
| 2 | Hot Leg Pipe | 7.311 | 37.68 | 5.15 |
| 3 | SG Inlet Nozzle at Hot Leg | 8.529 | 51.46 | 6.03 |
| 4 | SG Outlet Nozzle | 7.395 | 51.93 | 7.02 |
| 5 | Crossover Leg | 6.342 | 38.04 | 6.00 |
| 6 | RCP Inlet Nozzle | 7.124 | 42.84 | 6.01 |
| 7 | RCP Outlet Nozzle | 6.342 | 33.37 | 5.26 |
| 8 | Cold Leg Pipe | 6.342 | 38.04 | 6.00 |
| 9 | RV Inlet Nozzle | 6.254 | 35.52 | 5.68 |

**Table 3.6.3-21—ALL for Pressurizer Surge Nozzle at Alloy 52 Weld
Sheet 1 of 2**

| With Axial Load of: | | | 0 kips | 1.5 kips | 15 kips | 30 kips | 40 kips | 50 kips | 60 kips | 70 kips |
|---------------------|----------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| Set No. | Flaw Size (in) | Min Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) |
| 1 | 12.318 | 0 | 2,076 | 2,068 | 1,993 | 1,910 | 1,855 | 1,800 | 1,745 | 1,690 |
| 2 | 11.094 | 500 | 2,934 | 2,927 | 2,855 | 2,779 | 2,728 | 2,676 | 2,625 | 2,573 |
| 3 | 10.142 | 1000 | 3,710 | 3,702 | 3,636 | 3,562 | 3,513 | 3,464 | 3,415 | 3,366 |
| 4 | 9.353 | 1500 | 4,435 | 4,428 | 4,363 | 4,292 | 4,245 | 4,197 | 4,150 | 4,103 |
| 5 | 8.634 | 2000 | 5,152 | 5,145 | 5,083 | 5,014 | 4,968 | 4,921 | 4,875 | 4,829 |
| 6 | 8.006 | 2500 | 5,819 | 5,813 | 5,752 | 5,684 | 5,639 | 5,594 | 5,549 | 5,504 |
| 7 | 7.377 | 3000 | 6,524 | 6,517 | 6,458 | 6,392 | 6,347 | 6,303 | 6,259 | 6,215 |
| 8 | 6.758 | 3500 | 7,251 | 7,244 | 7,185 | 7,120 | 7,077 | 7,034 | 6,990 | 6,947 |
| 9 | 6.152 | 4000 | 7,992 | 7,986 | 7,928 | 7,864 | 7,821 | 7,779 | 7,736 | 7,693 |
| 10 | 5.565 | 4500 | 8,737 | 8,731 | 8,674 | 8,611 | 8,569 | 8,527 | 8,485 | 8,442 |
| 11 | 5.008 | 5000 | 9,469 | 9,463 | 9,407 | 9,344 | 9,303 | 9,261 | 9,219 | 9,178 |
| 12 | 4.493 | 5500 | 10,168 | 10,162 | 10,106 | 10,044 | 10,003 | 9,962 | 9,920 | 9,879 |
| 13 | 4.021 | 6000 | 10,830 | 10,824 | 10,768 | 10,707 | 10,666 | 10,625 | 10,584 | 10,543 |
| 14 | 3.597 | 6500 | 11,445 | 11,439 | 11,384 | 11,323 | 11,282 | 11,241 | 11,201 | 11,160 |
| 15 | 3.219 | 7000 | 12,014 | 12,008 | 11,953 | 11,892 | 11,852 | 11,811 | 11,771 | 11,730 |
| 16 | 2.883 | 7500 | 12,540 | 12,534 | 12,479 | 12,419 | 12,378 | 12,338 | 12,298 | 12,257 |
| 17 | 2.587 | 8000 | 13,024 | 13,018 | 12,963 | 12,903 | 12,863 | 12,823 | 12,783 | 12,743 |
| 18 | 2.326 | 8500 | 13,471 | 13,465 | 13,411 | 13,351 | 13,311 | 13,271 | 13,231 | 13,191 |
| 19 | 2.098 | 9000 | 13,882 | 13,876 | 13,822 | 13,762 | 13,722 | 13,682 | 13,642 | 13,602 |

**Table 3.6.3-21—ALL for Pressurizer Surge Nozzle at Alloy 52 Weld
Sheet 2 of 2**

| With Axial Load of: | | | 0 kips | 1.5 kips | 15 kips | 30 kips | 40 kips | 50 kips | 60 kips | 70 kips |
|---------------------|----------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| Set No. | Flaw Size (in) | Min Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) |
| 20 | 1.897 | 9500 | 14,264 | 14,258 | 14,204 | 14,145 | 14,105 | 14,065 | 14,025 | 13,985 |
| 21 | 1.719 | 10000 | 14,622 | 14,616 | 14,562 | 14,503 | 14,463 | 14,423 | 14,383 | 14,344 |

Table 3.6.3-22—ALL for Surge Line Piping

| With Axial Load of: | | | 0 kips | 1.5 kips | 15 kips | 30 kips | 40 kips | 50 kips | 60 kips | 70 kips |
|---------------------|----------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| Set No. | Flaw Size (in) | Min Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) |
| 1 | 9.459 | 0 | 2,547 | 2,539 | 2,468 | 2,388 | 2,335 | 2,281 | 2,227 | 2,172 |
| 2 | 8.536 | 500 | 3,386 | 3,378 | 3,311 | 3,236 | 3,186 | 3,135 | 3,084 | 3,033 |
| 3 | 7.639 | 1000 | 4,257 | 4,250 | 4,187 | 4,117 | 4,070 | 4,023 | 3,975 | 3,927 |
| 4 | 6.652 | 1500 | 5,228 | 5,222 | 5,167 | 5,106 | 5,065 | 5,025 | 4,984 | 4,944 |
| 5 | 5.616 | 2000 | 6,287 | 6,281 | 6,227 | 6,169 | 6,129 | 6,090 | 6,051 | 6,011 |
| 6 | 4.650 | 2500 | 7,358 | 7,352 | 7,300 | 7,243 | 7,204 | 7,166 | 7,127 | 7,089 |
| 7 | 3.826 | 3000 | 8,343 | 8,337 | 8,286 | 8,229 | 8,192 | 8,154 | 8,116 | 8,078 |
| 8 | 3.158 | 3500 | 9,144 | 9,140 | 9,104 | 9,062 | 9,034 | 9,006 | 8,977 | 8,941 |
| 9 | 2.628 | 4000 | 9,744 | 9,740 | 9,707 | 9,669 | 9,643 | 9,617 | 9,591 | 9,564 |
| 10 | 2.210 | 4500 | 10,214 | 10,211 | 10,180 | 10,145 | 10,122 | 10,097 | 10,073 | 10,048 |
| 11 | 1.878 | 5000 | 10,585 | 10,582 | 10,553 | 10,521 | 10,499 | 10,476 | 10,453 | 10,430 |
| 12 | 1.612 | 5500 | 10,880 | 10,877 | 10,850 | 10,820 | 10,799 | 10,778 | 10,756 | 10,734 |
| 13 | 1.397 | 6000 | 11,117 | 11,114 | 11,089 | 11,060 | 11,040 | 11,020 | 10,999 | 10,978 |
| 14 | 1.221 | 6500 | 11,309 | 11,307 | 11,283 | 11,255 | 11,236 | 11,216 | 11,197 | 11,176 |
| 15 | 1.077 | 7000 | 11,466 | 11,464 | 11,440 | 11,414 | 11,395 | 11,377 | 11,358 | 11,338 |
| 16 | 0.956 | 7500 | 11,597 | 11,595 | 11,572 | 11,546 | 11,529 | 11,511 | 11,492 | 11,473 |
| 17 | 0.854 | 8000 | 11,707 | 11,705 | 11,683 | 11,658 | 11,641 | 11,623 | 11,605 | 11,587 |

Table 3.6.3-23—ALL for Hot Leg Nozzle

| With Axial Load of: | | | 0 kips | 1.5 kips | 15 kips | 30 kips | 40 kips | 50 kips | 60 kips | 70 kips |
|---------------------|---------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| Set No. | Flaw Size(in) | Min Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) |
| 1 | 8.776 | 0 | 3,060 | 3,052 | 2,984 | 2,907 | 2,855 | 2,803 | 2,751 | 2,698 |
| 2 | 7.897 | 500 | 3,883 | 3,876 | 3,812 | 3,740 | 3,691 | 3,642 | 3,593 | 3,544 |
| 3 | 7.039 | 1000 | 4,733 | 4,726 | 4,666 | 4,599 | 4,554 | 4,508 | 4,462 | 4,416 |
| 4 | 6.089 | 1500 | 5,657 | 5,651 | 5,597 | 5,538 | 5,498 | 5,458 | 5,418 | 5,378 |
| 5 | 5.102 | 2000 | 6,691 | 6,685 | 6,633 | 6,574 | 6,535 | 6,496 | 6,457 | 6,418 |
| 6 | 4.193 | 2500 | 7,719 | 7,713 | 7,661 | 7,604 | 7,566 | 7,528 | 7,489 | 7,451 |
| 7 | 3.429 | 3000 | 8,623 | 8,618 | 8,579 | 8,535 | 8,499 | 8,462 | 8,424 | 8,386 |
| 8 | 2.817 | 3500 | 9,302 | 9,298 | 9,263 | 9,223 | 9,196 | 9,168 | 9,140 | 9,112 |
| 9 | 2.336 | 4000 | 9,833 | 9,829 | 9,797 | 9,761 | 9,736 | 9,711 | 9,685 | 9,659 |
| 10 | 1.958 | 4500 | 10,247 | 10,244 | 10,214 | 10,181 | 10,158 | 10,134 | 10,110 | 10,086 |
| 11 | 1.660 | 5000 | 10,572 | 10,569 | 10,541 | 10,509 | 10,487 | 10,465 | 10,443 | 10,420 |
| 12 | 1.417 | 5500 | 10,834 | 10,831 | 10,805 | 10,775 | 10,755 | 10,734 | 10,712 | 10,691 |
| 13 | 1.228 | 6000 | 11,037 | 11,034 | 11,009 | 10,981 | 10,961 | 10,941 | 10,921 | 10,900 |
| 14 | 1.074 | 6500 | 11,201 | 11,199 | 11,175 | 11,147 | 11,128 | 11,109 | 11,089 | 11,069 |
| 15 | 0.945 | 7000 | 11,338 | 11,335 | 11,312 | 11,286 | 11,268 | 11,249 | 11,230 | 11,210 |
| 16 | 0.839 | 7500 | 11,450 | 11,447 | 11,425 | 11,399 | 11,381 | 11,363 | 11,345 | 11,326 |
| 17 | 0.749 | 8000 | 11,545 | 11,542 | 11,520 | 11,495 | 11,478 | 11,460 | 11,442 | 11,424 |

Table 3.6.3-24—Critical Axial Crack Size at Surge Line Piping Locations

| LBB Piping Location | Description of Pipe Geometry | Leakage Crack Size (in) | Critical Crack Size (in) | Safety Margin |
|---------------------|---|-------------------------|--------------------------|---------------|
| 1 | Pressurizer Surge Nozzle at Alloy 52 weld | 7.635 | 33.65 | 4.41 |
| 2 | Surge Line Piping | 6.665 | 23.83 | 3.58 |
| 3 | Hot Leg Nozzle | 6.526 | 22.55 | 3.46 |

Table 3.6.3-25—ALL for the Main Steam Line Piping with Safety Factor of 2 on Flaw Size (Base Metal)

| Minimum Moment (in-kips) | Maximum Allowable Moment with Moment Plus Axial Load | | | | | |
|--------------------------|--|--------------------|--------------------|--------------------|--------------------|--------------------|
| | 0 kip (in-kips) | 100 kips (in-kips) | 200 kips (in-kips) | 300 kips (in-kips) | 451 kips (in-kips) | 600 kips (in-kips) |
| 2402 | 25,153 | 24,495 | 23,892 | 23,214 | 22,047 | 20,720 |
| 4815 | 29,053 | 28,321 | 27,664 | 27,084 | 26,085 | 24,955 |
| 7270 | 32,379 | 31,626 | 30,859 | 30,241 | 29,339 | 28,320 |
| 9618 | 34,845 | 34,116 | 33,377 | 32,634 | 31,799 | 30,856 |
| 12,122 | 37,002 | 36,288 | 35,569 | 34,833 | 33,926 | 33,041 |
| 14,661 | 38,858 | 38,159 | 37,453 | 36,734 | 35,746 | 34,904 |
| 17,169 | 40,352 | 39,722 | 39,026 | 38,318 | 37,259 | 36,449 |
| 19,805 | 41,751 | 41,186 | 40,496 | 39,798 | 38,707 | 37,887 |
| 22,550 | 43,016 | 42,509 | 41,825 | 41,134 | 40,058 | 39,181 |
| 25,628 | 44,285 | 43,837 | 43,158 | 42,473 | 41,411 | 40,474 |
| 28,822 | 45,466 | 45,056 | 44,398 | 43,718 | 42,667 | 41,673 |

Table 3.6.3-26—Air Fatigue Crack Morphology Parameters

| Material | Roughness $\mu\text{G}, \mu\text{inch}$ | 90-degree Turns per inch n, inch-1 |
|-----------------|---|------------------------------------|
| Carbon Steel | 1325 | 51 |
| Stainless Steel | 1325 | 64 |

Table 3.6.3-27—ALL for RCP Outlet Nozzle (Location 7)

| With Axial Load of: | | 1,000 kips | 1,500 kips | 2,000 kips | 2,500 kips | 3,000 kips |
|---------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| Flaw Size (in) | Min Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) |
| 9.592 | 0 | 40,627 | 36,192 | 31,757 | 27,400 | 22,888 |
| 7.328 | 10,000 | 49,557 | 45,192 | 40,826 | 36,462 | 32,096 |
| 5.688 | 20,000 | 56,673 | 52,350 | 48,027 | 43,704 | 39,381 |
| 4.191 | 30,000 | 64,055 | 59,766 | 55,478 | 51,190 | 46,902 |
| 2.975 | 40,000 | 71,283 | 67,021 | 62,759 | 58,497 | 54,235 |
| 2.115 | 50,000 | 77,791 | 73,546 | 69,302 | 65,057 | 60,812 |
| 1.536 | 60,000 | 83,532 | 79,298 | 75,065 | 70,831 | 66,598 |
| 1.149 | 70,000 | 88,586 | 84,360 | 80,133 | 75,906 | 71,680 |
| 0.884 | 80,000 | 93,102 | 88,880 | 84,657 | 80,435 | 76,213 |
| 0.698 | 90,000 | 97,172 | 92,952 | 88,732 | 84,513 | 80,293 |
| 0.563 | 100,000 | 100,899 | 96,681 | 92,463 | 88,246 | 84,028 |
| 0.462 | 110,000 | 104,362 | 100,145 | 95,929 | 91,712 | 87,496 |
| 0.386 | 120,000 | 107,547 | 103,332 | 99,116 | 94,901 | 90,685 |
| 0.328 | 130,000 | 110,470 | 106,255 | 102,040 | 97,825 | 93,610 |
| 0.282 | 140,000 | 113,217 | 109,002 | 104,788 | 100,573 | 96,359 |
| 0.244 | 150,000 | 115,882 | 111,668 | 107,454 | 103,240 | 99,025 |
| 0.214 | 160,000 | 118,329 | 114,115 | 109,901 | 105,687 | 101,473 |

Table 3.6.3-28—ALL for RV Inlet Nozzle (Location 9)

| With Axial Load of: | | 1,000 kips | 1,500 kips | 2,000 kips | 2,500 kips | 3,000 kips |
|---------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| Flaw Size (in) | Min Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) | Max Moment (in-kips) |
| 9.985 | 0 | 44,523 | 40,072 | 35,622 | 31,264 | 26,720 |
| 7.466 | 10,000 | 55,084 | 50,713 | 46,342 | 41,984 | 37,601 |
| 5.889 | 20,000 | 62,307 | 57,978 | 53,648 | 49,319 | 44,990 |
| 4.617 | 30,000 | 68,749 | 64,450 | 60,150 | 55,851 | 51,552 |
| 3.344 | 40,000 | 76,201 | 71,930 | 67,659 | 63,388 | 59,117 |
| 2.433 | 50,000 | 82,740 | 78,488 | 74,236 | 69,984 | 65,733 |
| 1.784 | 60,000 | 88,632 | 84,393 | 80,154 | 75,915 | 71,676 |
| 1.403 | 70,000 | 92,997 | 88,765 | 84,534 | 80,302 | 76,070 |
| 1.021 | 80,000 | 98,607 | 94,382 | 90,157 | 85,932 | 81,708 |
| 0.801 | 90,000 | 102,844 | 98,622 | 94,401 | 90,180 | 85,958 |
| 0.641 | 100,000 | 106,729 | 102,510 | 98,291 | 94,072 | 89,853 |
| 0.522 | 110,000 | 110,326 | 106,108 | 101,891 | 97,673 | 93,456 |
| 0.434 | 120,000 | 113,583 | 109,367 | 105,151 | 100,934 | 96,718 |
| 0.365 | 130,000 | 116,667 | 112,452 | 108,236 | 104,021 | 99,805 |
| 0.310 | 140,000 | 119,607 | 115,392 | 111,177 | 106,963 | 102,748 |
| 0.268 | 150,000 | 122,256 | 118,042 | 113,827 | 109,613 | 105,399 |
| 0.234 | 160,000 | 124,752 | 120,538 | 116,323 | 112,109 | 107,895 |

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