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 COL applicant that references the U.S. EPR design certification 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).

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 and welds are "L" grade, 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; therefore, PWSCC is not a concern.

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.

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 over-pressurization 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 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—Plan 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 Figure 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 F304LN or SA-182 F304LN austenitic stainless steel. 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 F316LN or SA-336 F316LN. 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 wells 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:

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

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 for the Main Coolant Loop Piping. The material parameters for the J-R equation (C and N) are determined using the $J_{Deformation}$ 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 = $J_{Deformation}$ 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 304LN and 316LN 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.

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 Class1 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.

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. The tensile properties and the Ramberg-Osgood parameters for SA-106 Grade C material are conservatively used in the analysis since these properties are not readily available for the pressurizer surge nozzle material. 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 and 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:

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

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

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

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. The leakage rate calculations are determined at the following locations in the MCL piping:

- Reactor pressure vessel (RPV) outlet nozzle region at the hot leg.
- SG inlet nozzle region at the hot leg.
- SG outlet nozzle region.
- Crossover leg, RCP outlet nozzle region, cold leg pipe, and RPV inlet.
- RCP inlet nozzle region.

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

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

The leakage crack lengths versus minimum moment at each of the above five 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 two locations are shown in Table 3.6.3-10—Minimum Moment versus Circumferential Crack Leakage

Sizes for 5 gpm at Two Surge Line Piping Locations and are illustrated in Figure 3.6.3-6—Minimum Moment versus Circumferential Leakage Crack Sizes for 5 gpm at Two Surge Line Locations. 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 Two 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, 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 Crack Leakage 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 Coolant Loop and 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:

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

where:

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

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

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

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

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

where:

Limit Load

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

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_o and ε_o= 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)

Since the parameter (h_1) of the plastic portion of the EPRI J-integral combined tension and bending solution is provided only for R/t = 10 and R/t =20 in Reference 23, the h_1 values for R/t = 10 are conservatively used in the analysis of MCL piping with R/t < 6. 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.

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 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):

$$K_1 = \sigma_b (\pi R \gamma)^{0.5} \bullet F_b = \sigma_t (\pi R \gamma)^{0.5} \bullet F_t$$

where:

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

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

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

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

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

therefore:

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

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 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:

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

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

where:

Limit Moment

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

Un-Cracked Ligament

2c = 2R(π - γ)

Plastic Zone Correction

$$a_e = a + \frac{1}{1 + \left(\frac{M}{M_0} \right)^2} \frac{1}{6\pi} \left[\frac{n-1}{n+1} \right] \frac{EJ_{elastic}}{\sigma_o^2}$$

Correction

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

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_o 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 Extrados 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 extrados 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:

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

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_0 = the limit axial load

M_0 = 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:

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

where:

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

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

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 Rm/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 Rm/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:

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

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 ($T_{material} = T_{applied}$ when $J_{material} = J_{applied}$), $J_{applied}$ 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:

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

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:

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

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 ($T_{material} \geq T_{applied}$) where $J_{applied} \leq J_{material}$. 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 $J_{applied} = J_{material}$ when $T_{applied} = T_{material}$) and the corresponding J value is $J_{instability}$.

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 flaw 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 Sections 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 Line 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 3.6.3.5.6 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 3.6.3.1.1 and 3.6.3.6.2.1, respectively. For the circumferential through-wall extrados crack in an elbow, the results are presented in Section 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 at Alloy 52 Weld. Similarly, the results for other components are shown in the figures as listed below:

- The steam generator inlet nozzle at the Alloy 52 weld: Figure 3.6.3-13—ALL for Steam Generator Inlet Nozzle at Alloy 52 Weld.
- The steam generator outlet nozzle at the Alloy 52 weld: Figure 3.6.3-14—ALL for Steam Generator Outlet Nozzle at Alloy 52 Weld.
- The RCP outlet nozzle region (includes cold leg pipe and RV inlet nozzle): Figure 3.6.3-15—ALL for CASS RC Pump Outlet Nozzle, Cold Leg Pipe, and RPV Inlet Nozzle.
- The RCP inlet nozzle region: Figure 3.6.3-16—ALL for CASS RC Pump Inlet Nozzle.
- The hot leg/crossover leg piping region: Figure 3.6.3-17—ALL for Hot Leg and Crossover Leg Piping.

These regions are identified in Table 3.6.3-13. The Alloy 52 weld locations (see Figures 3.6.3-12 through Figure 3.6.3-14) that use the fusion line toughness values were evaluated using the stainless steel base metal tensile properties. The locations in Figure 3.6.3-15 and Figure 3.6.3-16 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 location in Figure 3.6.3-17 was 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. 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 (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 2000 kips to 3000 kips. The corresponding tabulated values for the ALL diagrams in Figure 3.6.3-12 through Figure 3.6.3-17 are provided in the following tables:

- Table 3.6.3-14—ALL for Reactor Vessel Outlet Nozzle at Alloy 52 Weld.

- Table 3.6.3-15—ALL for Steam Generator Inlet Nozzle at Alloy 52 Weld.
- Table 3.6.3-16—ALL for Steam Generator Outlet Nozzle at Alloy 52 Weld.
- Table 3.6.3-17—ALL for CASS RC Pump Outlet Nozzle, Cold Leg Pipe, and RPV Inlet Nozzle.
- Table 3.6.3-18—ALL for CASS RC Pump Inlet Nozzle.
- Table 3.6.3-19—ALL for Hot Leg and Crossover Leg Piping.

3.6.3.6.1.2 Circumferential Through-Wall Extrados 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 10.35 in is 95,367 in-kips. This evaluation accounts for the wall thinning at the extrados 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 $\leq$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 87,000 in-kips considering the base metal properties. This corresponds to almost a 10 percent increase in allowable moment obtained for the circumferential extrados 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 extrados 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 17 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 6.25 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 Extrados 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 extrados of the elbow where the wall thickness is 1.4 in. The adjoining straight pipe at the SL piping has a wall thickness $\leq$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).

In the event that the final applied loading data for the MSL piping are not within the “ALL LBB Zone” region, an additional ALL diagram is provided considering a safety factor of 1.7 on flaw size. That ALL diagram is shown in Figure 3.6.3-23—ALL for Main Steam Line Piping with Safety Factor of 1.7 on Flaw Size (Base Metal) with the corresponding tabulated values given in Table 3.6.3-26—ALL for the Main Steam Line Piping with Safety Factor of 1.7 on Flaw Size (Base Metal). In previous LBB evaluations, the NRC has concluded that margins of slightly less than two on the critical-leakage flaw size are acceptable provided that a full margin of 10 is maintained on the leakage uncertainty (Reference 27). As noted in Section 3.6.3.6.1, a margin of 10 on the predicted leakage rate is applied to the MSL.

3.6.3.6.3.2 Circumferential Through-Wall Extrados 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 extrados 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 extrados 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.” RG 1.45, Revision 0 recommends that the leakage detection system for the reactor coolant pressure boundary (RCPB) be composed of three separate detection methods that can detect a leakage rate, or its equivalent, of one gpm in less than one hour. RG 1.45, Revision 0 does not address the applicability of RCPB leakage detection systems for LBB.

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 0. Additionally, at least one of the RCPB leakage detections systems is capable of detecting a leakage rate of 0.5 gpm for the MCL and SL. This is consistent with the guidance in a proposed revision to RG 1.45 (DG-1173 dated June 2007). DG-1173 was intended, in part, to recognize improvements in leakage monitoring and locating techniques. DG-1173 also addresses monitoring for LBB analyses. Specifically, DG-1173 states: “The overall response time of at least one leakage monitoring system is sufficient to support LBB monitoring (if LBB is approved for the plant), such that sufficient time will be available for operators to place the facility in a safe condition prior to any potential gross structural failure of the leaking component. Under certain circumstances (e.g., to support LBB for smaller-diameter pipes), leakage monitoring system specifications may need to exceed the quantitative criteria in this regulatory guide."

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 0 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)	ID[1] (in)	Pipe Wall[2] 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	12.81	1.59
2	Surge Line Piping near Pressurizer	653	2250	12.81	1.59
3	Hot Leg Nozzle	624	2250	12.81	1.59

Notes:

1. ID of the pipe. At the weld prep location, the ID of the pipe is 12.91 in.
2. For detailed J-T analysis the weld prep thickness is conservatively used. For leak rate analysis the pipe wall thickness is conservatively used.

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 for the Main Coolant Loop Piping

Tensile Properties (ksi)		
	Cold Leg Piping	Hot Leg Piping
Yield Stress ($\sigma_{y)}$	18.8[1]	18.2[1]
Ultimate Strength ($\sigma_{ult)}$	59.2	89.5
Flow Stress ($\sigma_{f)}$	39.0	38.7
Young's Modulus (E)	25,500	25,200
Ramberg-Osgood Parameters ($\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + \alpha\left(\frac{\sigma}{\sigma_o}\right)^n$)		
	Cold Leg Piping	Hot Leg Piping
α	19.0	19.0
n	5.5	5.5
Reference Stress (σ_o)	18.8 ksi[1]	18.2 ksi[1]
Reference Strain (ε)	0.00017	0.00017

Note:

1. Conservatively considered 18.0 ksi in the analysis.

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

Tensile Properties (ksi)			
	SL Piping near Pressurizer	Pressurizer Nozzle	Hot Leg Nozzle
Yield Stress (σ_y)	18.0	39.0	18.2
Ultimate Strength (σ_{ult})	59.2	81.0	59.2
Flow Stress (σ_f)	38.6	60.0	38.7
Young's Modulus (E)	25,050	26,500	25,180
Ramberg-Osgood Parameters ($\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + \alpha\left(\frac{\sigma}{\sigma_o}\right)^n$)			
	SL Piping near Pressurizer	Pressurizer Nozzle	Hot Leg Nozzle
α	16.0	1.48	16.0
n	7.0	5.08	7.0
Reference Stress (σ_o)	19.4 ksi	39.0 ksi	19.4 ksi
Reference Strain (ε)	0.00017	0.0147	0.00017

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	1.545	4.68	Alloy 52
2	Surge Line Piping near Pressurizer	653	1.545	4.68	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 ($\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + \alpha\left(\frac{\sigma}{\sigma_o}\right)^n$)		
	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)	0.0147	0.0287

Table 3.6.3-8—Minimum Moment versus Circumferential Crack Leakage Sizes for 5 gpm at Various Main Coolant Loop Piping Locations
Sheet 1 of 2

RV Outlet Nozzle		SG Inlet Nozzle		SG Outlet Nozzle		RCP Outlet Nozzle		RCP Inlet Nozzle	
Leakage Size (in)	Minimum Moment (in-kips)	Leakage Size (in)	Minimum Moment (in-kips)	Leakage Size (in)	Minimum Moment (in-kips)	Leakage Size (in)	Minimum Moment (in-kips)	Leakage Size (in)	Minimum Moment (in-kips)
8.71	0	10.35	0	9.08	0	7.67	0	8.62	0
8.21	2500	9.85	2500	8.73	2500	7.29	2500	8.26	2500
7.58	5000	9.11	5000	8.07	5000	6.72	5000	7.63	5000
7.06	7500	8.5	7500	7.53	7500	6.26	7500	7.11	7500
6.63	10,000	7.99	10,000	7.07	10,000	5.88	10,000	6.68	10,000
6.27	12,500	7.56	12,500	6.69	12,500	5.55	12,500	6.31	12,500
5.95	15,000	7.18	15,000	6.35	15,000	5.27	15,000	6	15,000
5.67	17,500	6.85	17,500	6.06	17,500	5.02	17,500	5.72	17,500
5.43	20,000	6.56	20,000	5.8	20,000	4.8	20,000	5.47	20,000
5.01	25,000	6.07	25,000	5.36	25,000	4.44	25,000	5.06	25,000
4.68	30,000	5.66	30,000	5	30,000	4.14	30,000	4.72	30,000
4.39	35,000	5.32	35,000	4.7	35,000	3.88	35,000	4.43	35,000
4.15	40,000	5.03	40,000	4.45	40,000	3.67	40,000	4.19	40,000
3.95	45,000	4.77	45,000	4.21	45,000	3.45	45,000	3.98	45,000
3.77	50,000	4.56	50,000	4.03	50,000	3.32	50,000	3.8	50,000
3.46	60,000	4.19	60,000	3.71	60,000	3.05	60,000	3.49	60,000
3.22	70,000	3.9	70,000	3.44	70,000	2.84	70,000	3.24	70,000
3.02	80,000	3.65	80,000	3.22	80,000	2.66	80,000	3.04	80,000
2.84	90,000	3.45	90,000	3.04	90,000	2.5	90,000	2.86	90,000

Table 3.6.3-8—Minimum Moment versus Circumferential Crack Leakage Sizes for 5 gpm at Various Main Coolant Loop Piping Locations
Sheet 2 of 2

RV Outlet Nozzle		SG Inlet Nozzle		SG Outlet Nozzle		RCP Outlet Nozzle		RCP Inlet Nozzle	
Leakage Size (in)	Minimum Moment (in-kips)	Leakage Size (in)	Minimum Moment (in-kips)	Leakage Size (in)	Minimum Moment (in-kips)	Leakage Size (in)	Minimum Moment (in-kips)	Leakage Size (in)	Minimum Moment (in-kips)
2.7	100,000	3.27	100,000	2.88	100,000	2.37	100,000	2.71	100,000
2.57	110,000	3.11	110,000	2.74	110,000	2.26	110,000	2.58	110,000
2.46	120,000	2.98	120,000	2.62	120,000	2.16	120,000	2.47	120,000
2.36	130,000	2.85	130,000	2.51	130,000	2.07	130,000	2.37	130,000
2.27	140,000	2.75	140,000	2.42	140,000	1.99	140,000	2.28	140,000

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

MCL Location	Leakage Crack Size (in)
RV Outlet Nozzle	5.60
SG Inlet Nozzle	6.62
SG Outlet Nozzle	5.86
RCP Outlet Nozzle	4.97
RCP Inlet Nozzle	5.57

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

Surge Nozzle		Hot Leg Nozzle	
Leakage Size (in)	Minimum Moment (in-kips)	Leakage Size (in)	Minimum Moment (in-kips)
8.760	0	8.261	0
7.850	200	7.435	200
7.310	400	6.920	400
6.867	600	6.490	600
6.495	800	6.130	800
6.170	1000	5.822	1000
5.891	1200	5.553	1200
5.644	1400	5.320	1400
5.425	1600	5.110	1600
5.230	1800	4.920	1800
5.051	2000	4.750	2000
4.890	2200	4.596	2200
4.741	2400	4.455	2400
4.606	2600	4.325	2600
4.481	2800	4.206	2800
4.370	3000	4.095	3000
4.257	3200	3.994	3200
4.157	3400	3.900	3400
4.065	3600	3.810	3600
3.974	3800	3.725	3800
3.891	4000	3.645	4000
3.703	4500	3.467	4500
3.540	5000	3.311	5000
3.394	5500	3.174	5500
3.265	6000	3.051	6000
3.149	6500	2.941	6500
3.042	7000	2.842	7000
2.948	7500	2.751	7500
2.852	8000	2.668	8000
2.778	8500	2.591	8500
2.702	9000	2.519	9000

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

SL Location	Leakage Crack Size (in)
Surge Nozzle End	5.429
Hot Leg Nozzle End	5.140

Table 3.6.3-12—Minimum Moment versus Circumferential Crack Leakage 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 Thickness[1], 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.

Table 3.6.3-14—ALL for Reactor Vessel Outlet Nozzle at Alloy 52 Weld

With Axial Load of:			2000 kips	2500 kips	3000 kips
Set No.	**Flaw Size (in)**	**Minimum Moment (in-kips)**	**Maximum Moment (in-kips)**	**Maximum Moment (in-kips)**	**Maximum Moment (in-kips)**
1	8.71	0	58,300	53,800	48,500
2	8.21	2500	60,450	56,050	50,800
3	7.58	5000	63,200	59,000	53,950
4	7.06	7500	65,600	61,500	56,600
5	6.63	10,000	67,600	63,650	58,900
6	6.27	12,500	69,350	65,450	60,800
7	5.95	15,000	70,900	67,100	62,550
8	5.67	17,500	72,300	68,550	64,100
9	5.43	20,000	73,550	69,850	65,400
10	5.01	25,000	75,750	72,150	67,850
11	4.68	30,000	77,550	74,000	69,800
12	4.39	35,000	79,200	75,700	71,550
13	4.15	40,000	80,600	77,150	73,100
14	3.95	45,000	81,800	78,400	74,400
15	3.77	50,000	82,900	79,550	75,600
16	3.46	60,000	84,900	81,600	77,700
17	3.22	70,000	86,500	83,250	79,450
18	3.02	80,000	87,900	84,700	80,950
19	2.84	90,000	89,250	86,050	82,350
20	2.70	100,000	90,300	87,150	83,450
21	2.57	110,000	91,300	88,200	84,500
22	2.46	120,000	92,200	89,100	85,500
23	2.36	130,000	93,000	89,950	86,350
24	2.27	140,000	93,800	90,750	87,200

Table 3.6.3-15—ALL for Steam Generator Inlet Nozzle at Alloy 52 Weld

With Axial Load of:			2000 kips	2500 kips	3000 kips
Set No.	Flaw Size (in)	Minimum Moment (in-kips)	Maximum Moment (in-kips)	Maximum Moment (in-kips)	Maximum Moment (in-kips)
1	10.35	0	73,250	69,250	64,450
2	9.85	2500	75,750	71,850	67,200
3	9.11	5000	79,500	75,800	71,300
4	8.50	7500	82,700	79,100	74,800
5	7.99	10,000	85,500	81,900	77,750
6	7.56	12,500	87,850	84,400	80,300
7	7.18	15,000	90,000	86,600	82,600
8	6.85	17,500	91,900	88,600	84,650
9	6.56	20,000	93,700	90,400	86,550
10	6.07	25,000	96,600	93,400	89,650
11	5.66	30,000	99,200	96,000	92,350
12	5.32	35,000	101,400	98,300	94,700
13	5.03	40,000	103,300	100,250	96,700
14	4.77	45,000	105,100	102,100	98,550
15	4.56	50,000	106,500	103,600	100,100
16	4.19	60,000	109,250	106,300	102,950
17	3.90	70,000	111,500	108,600	105,250
18	3.65	80,000	113,500	110,600	107,350
19	3.45	90,000	115,100	112,250	109,050
20	3.27	100,000	116,600	113,800	110,650
21	3.11	110,000	118,000	115,250	112,100
22	2.98	120,000	119,300	116,500	113,340
23	2.85	130,000	120,500	117,700	114,600
24	2.75	140,000	121,500	118,675	115,550

Table 3.6.3-16—ALL for Steam Generator Outlet Nozzle at Alloy 52 Weld

With Axial Load of:			2000 kips	2500 kips	3000 kips
Set No.	**Flaw Size (in)**	**Minimum Moment (in-kips)**	**Maximum Moment (in-kips)**	**Maximum Moment (in-kips)**	**Maximum Moment (in-kips)**
1	9.08	0	79,750	76,000	71,550
2	8.73	2500	81,600	77,900	73,550
3	8.07	5000	85,100	81,580	77,350
4	7.53	7500	88,100	84,650	80,575
5	7.07	10,000	90,700	87,350	83,350
6	6.69	12,500	93,000	89,700	85,800
7	6.35	15,000	95,000	91,750	87,900
8	6.06	17,500	96,750	93,550	89,800
9	5.80	20,000	98,350	95,200	91,500
10	5.36	25,000	101,200	98,100	94,500
11	5.00	30,000	103,600	100,500	97,000
12	4.70	35,000	105,700	102,650	99,200
13	4.45	40,000	107,490	104,450	101,000
14	4.21	45,000	109,250	106,250	102,900
15	4.03	50,000	110,600	107,600	104,300
16	3.71	60,000	113,100	110,200	106,900
17	3.44	70,000	115,300	112,400	109,200
18	3.22	80,000	117,200	114,400	111,100
19	3.04	90,000	118,850	116,000	112,800
20	2.88	100,000	120,300	117,500	114,350
21	2.74	110,000	121,700	118,900	115,750
22	2.62	120,000	122,850	120,100	116,950
23	2.51	130,000	124,000	121,200	118,100
24	2.42	140,000	124,990	122,200	119,100

Table 3.6.3-17—ALL for CASS RC Pump Outlet Nozzle, Cold Leg Pipe, and RPV Inlet Nozzle

With Axial Load of:			2000 kips	2500 kips	3000 kips
Set No.	**Flaw Size (in)**	**Minimum Moment (in-kips)**	**Maximum Moment (in-kips)**	**Maximum Moment (in-kips)**	**Maximum Moment (in-kips)**
1	7.67	0	59,750	55,400	50,150
2	7.29	2500	61,400	57,150	52,000
3	6.72	5000	63,950	59,850	54,850
4	6.26	7500	66,100	62,100	57,300
5	5.88	10,000	67,900	64,000	59,300
6	5.55	12,500	69,500	65,650	61,050
7	5.27	15,000	70,900	67,100	62,600
8	5.02	17,500	72,150	68,400	64,000
9	4.80	20,000	73,300	69,600	65,200
10	4.44	25,000	75,200	71,600	67,350
11	4.14	30,000	76,900	73,350	69,150
12	3.88	35,000	78,400	74,900	70,750
13	3.67	40,000	79,600	76,200	72,100
14	3.45	45,000	81,000	77,600	73,550
15	3.32	50,000	81,800	78,450	74,450
16	3.05	60,000	83,550	80,250	76,350
17	2.84	70,000	85,000	81,700	77,900
18	2.66	80,000	86,300	83,050	79,250
19	2.50	90,000	87,500	84,300	80,550
20	2.37	100,000	88,500	85,300	81,600
21	2.26	110,000	89,400	86,200	82,550
22	2.16	120,000	90,200	87,050	83,450
23	2.07	130,000	90,950	87,850	84,250
24	1.99	140,000	91,650	88,550	85,000

Table 3.6.3-18—ALL for CASS RC Pump Inlet Nozzle

With Axial Load of:			2000 kips	2500 kips	3000 kips
Set No.	Flaw Size (in)	Minimum Moment (in-kips)	Maximum Moment (in-kips)	Maximum Moment (in-kips)	Maximum Moment (in-kips)
1	8.62	0	72,750	68,800	64,100
2	8.26	2500	74,500	70,650	66,000
3	7.63	5000	77,650	73,900	69,500
4	7.11	7500	80,350	76,750	72,450
5	6.68	10,000	82,700	79,150	75,000
6	6.31	12,500	84,700	81,200	77,100
7	6.00	15,000	86,450	83,000	79,000
8	5.72	17,500	88,000	84,650	80,700
9	5.47	20,000	89,450	86,150	82,200
10	5.06	25,000	91,950	88,650	84,850
11	4.72	30,000	94,000	90,800	87,100
12	4.43	35,000	95,900	92,750	89,050
13	4.19	40,000	97,500	94,350	90,750
14	3.98	45,000	98,900	95,850	92,250
15	3.80	50,000	100,200	97,100	93,600
16	3.49	60,000	102,400	99,400	95,900
17	3.24	70,000	104,350	101,350	97,900
18	3.04	80,000	105,900	103,000	99,600
19	2.86	90,000	107,400	104,500	101,100
20	2.71	100,000	108,700	105,800	102,500
21	2.58	110,000	109,850	106,950	103,700
22	2.47	120,000	110,850	108,000	104,700
23	2.37	130,000	111,800	108,950	105,700
24	2.28	140,000	112,700	109,850	106,600

Table 3.6.3-19—ALL for Hot Leg and Crossover Leg Piping

With Axial Load of:			2000 kips	2500 kips	3000 kips
Set No.	Flaw Size (in)	Minimum Moment (in-kips)	Maximum Moment (in-kips)	Maximum Moment (in-kips)	Maximum Moment (in-kips)
1	8.71	0	67,300	63,175	58,250
2	8.21	2500	69,640	65,650	60,850
3	7.58	5000	72,670	68,825	64,225
4	7.06	7500	75,250	71,500	67,050
5	6.63	10,000	77,450	73,800	69,475
6	6.27	12,500	79,350	75,775	71,550
7	5.95	15,000	81,075	77,550	73,400
8	5.67	17,500	82,600	79,150	75,050
9	5.43	20,000	83,950	80,525	76,500
10	5.01	25,000	86,375	83,025	79,100
11	4.68	30,000	88,350	85,075	81,225
12	4.39	35,000	90,150	86,925	83,150
13	4.15	40,000	91,700	88,525	84,800
14	3.95	45,000	93,025	89,875	86,200
15	3.77	50,000	94,250	91,125	87,500
16	3.46	60,000	96,450	93,350	89,800
17	3.22	70,000	98,225	95,200	91,675
18	3.02	80,000	99,800	96,775	93,300
19	2.84	90,000	101,250	98,250	94,850
20	2.70	100,000	102,400	99,450	96,050
21	2.57	110,000	103,550	100,600	97,250
22	2.46	120,000	104,525	101,600	98,275
23	2.36	130,000	105,450	102,550	99,250
24	2.27	140,000	106,300	103,400	100,125

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

LBB Piping Location	Description of Pipe Geometry	Leakage Crack Size (in)	Critical Crack Size (in)	Safety Margin
1	RV Outlet at Hot Leg	5.60	17.5	6.25
2	SG Inlet at Hot Leg	6.62	27.0	8.16
3	SG Outlet	5.86	27.3	9.32
4	Crossover Leg	4.97	17.6	7.08
5	RCP Inlet	5.57	23.3	8.37
6	RCP Outlet and Cold Leg	4.97	17.3	6.97

Table 3.6.3-21—ALL for Pressurizer Surge Nozzle at Alloy 52 Weld

With Axial Load of:			1.5 kips	15 kips	30 kips	40 kips	50 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)
1	8.760	0	2720	2660	2590	2550	2510
2	7.850	200	3420	3370	3300	3260	3220
3	7.310	400	3870	3810	3750	3710	3670
4	6.867	600	4250	4190	4130	4090	4050
5	6.495	800	4570	4520	4460	4420	4380
6	6.170	1000	4860	4810	4750	4710	4670
7	5.891	1200	5110	5060	5000	4960	4920
8	5.644	1400	5340	5290	5230	5190	5150
9	5.425	1600	5540	5490	5430	5390	5350
10	5.230	1800	5720	5670	5610	5570	5530
11	5.051	2000	5890	5840	5780	5740	5700
12	4.890	2200	6040	5990	5930	5890	5860
13	4.741	2400	6180	6130	6070	6040	6000
14	4.606	2600	6310	6260	6200	6160	6130
15	4.481	2800	6430	6380	6320	6280	6250
16	4.370	3000	6540	6490	6430	6390	6350
17	4.257	3200	6650	6590	6540	6500	6460
18	4.157	3400	6740	6690	6630	6600	6560
19	4.065	3600	6830	6780	6720	6690	6650
20	3.974	3800	6920	6870	6810	6770	6740
21	3.891	4000	7000	6950	6890	6860	6820
22	3.703	4500	7190	7130	7080	7040	7000
23	3.540	5000	7350	7300	7240	7200	7160
24	3.394	5500	7490	7440	7390	7350	7310
25	3.265	6000	7620	7570	7510	7480	7440
26	3.149	6500	7740	7690	7630	7590	7560
27	3.042	7000	7850	7800	7740	7700	7670
28	2.948	7500	7940	7890	7840	7800	7760
29	2.852	8000	8040	7990	7940	7900	7860
30	2.778	8500	8120	8070	8010	7980	7940
31	2.702	9000	8200	8150	8090	8060	8020

Table 3.6.3-22—ALL for Surge Line Piping
Sheet 1 of 2

With Axial Load of:			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)
1	8.760	0	2870	2810	2750	2700	2660	2620	2570
2	7.850	200	3640	3580	3520	3480	3440	3390	3350
3	7.310	400	4120	4070	4010	3960	3920	3880	3840
4	6.867	600	4530	4480	4410	4370	4330	4290	4250
5	6.495	800	4880	4820	4760	4720	4680	4640	4600
6	6.170	1000	5190	5130	5070	5030	4990	4950	4920
7	5.891	1200	5450	5400	5340	5300	5260	5220	5180
8	5.644	1400	5690	5640	5580	5540	5500	5460	5420
9	5.425	1600	5900	5850	5790	5750	5710	5670	5630
10	5.230	1800	6090	6030	5970	5940	5900	5860	5820
11	5.051	2000	6260	6200	6150	6110	6070	6030	5990
12	4.890	2200	6410	6360	6300	6260	6220	6180	6150
13	4.741	2400	6550	6500	6440	6400	6370	6330	6290
14	4.606	2600	6680	6630	6570	6530	6490	6460	6420
15	4.481	2800	6800	6750	6690	6650	6610	6580	6540
16	4.370	3000	6900	6850	6800	6760	6720	6680	6640
17	4.257	3200	7010	6960	6900	6860	6830	6790	6750
18	4.157	3400	7110	7050	7000	6960	6920	6880	6850
19	4.065	3600	7190	7140	7080	7050	7010	6970	6930
20	3.974	3800	7280	7230	7170	7130	7090	7060	7020

Table 3.6.3-22—ALL for Surge Line Piping
Sheet 2 of 2

With Axial Load of:			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)
21	3.891	4000	7360	7310	7250	7210	7170	7140	7100
22	3.703	4500	7530	7480	7430	7390	7350	7310	7280
23	3.540	5000	7690	7640	7580	7540	7510	7470	7430
24	3.394	5500	7830	7780	7720	7680	7640	7610	7570
25	3.265	6000	7950	7900	7840	7800	7770	7730	7690
26	3.149	6500	8060	8010	7950	7910	7880	7840	7800
27	3.042	7000	8160	8110	8050	8020	7980	7940	7900
28	2.948	7500	8250	8200	8140	8110	8070	8030	7990
29	2.852	8000	8340	8290	8240	8200	8160	8120	8090
30	2.778	8500	8410	8360	8310	8270	8230	8200	8160
31	2.702	9000	8490	8440	8380	8340	8310	8270	8230

Table 3.6.3-23—ALL for Hot Leg Nozzle
Sheet 1 of 2

With Axial Load of:			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)
1	8.261	0	3320	3260	3200	3150	3110	3070	3030
2	7.435	200	4050	3990	3930	3890	3830	3810	3760
3	6.920	400	4520	4470	4410	4370	4310	4280	4240
4	6.490	600	4930	4870	4810	4770	4720	4690	4650
5	6.130	800	5270	5220	5160	5120	5060	5040	5000
6	5.822	1000	5570	5510	5450	5420	5360	5340	5300
7	5.553	1200	5830	5770	5710	5680	5620	5600	5560
8	5.320	1400	6050	6000	5940	5900	5850	5820	5780
9	5.110	1600	6250	6200	6140	6100	6050	6030	5990
10	4.920	1800	6440	6380	6330	6290	6240	6210	6170
11	4.750	2000	6600	6550	6490	6450	6400	6370	6340
12	4.596	2200	6750	6690	6640	6600	6550	6520	6480
13	4.455	2400	6880	6830	6770	6730	6680	6660	6620
14	4.325	2600	7000	6950	6900	6860	6810	6780	6740
15	4.206	2800	7120	7070	7010	6970	6920	6900	6860
16	4.095	3000	7220	7170	7120	7080	7030	7000	6960
17	3.994	3200	7320	7270	7210	7170	7130	7100	7060
18	3.900	3400	7410	7360	7300	7260	7220	7190	7150
19	3.810	3600	7490	7440	7390	7350	7300	7270	7240
20	3.725	3800	7580	7520	7470	7430	7390	7360	7320

Table 3.6.3-23—ALL for Hot Leg Nozzle
Sheet 2 of 2

With Axial Load of:			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)
21	3.645	4000	7650	7600	7540	7510	7460	7430	7390
22	3.467	4500	7820	7770	7710	7680	7630	7600	7560
23	3.311	5000	7970	7920	7860	7830	7780	7750	7710
24	3.174	5500	8100	8050	7990	7960	7910	7880	7840
25	3.051	6000	8220	8170	8110	8070	8030	8000	7960
26	2.941	6500	8320	8270	8220	8180	8140	8110	8070
27	2.842	7000	8420	8370	8310	8280	8240	8200	8160
28	2.751	7500	8510	8460	8400	8360	8330	8290	8250
29	2.668	8000	8590	8540	8480	8450	8410	8370	8330
30	2.591	8500	8660	8610	8560	8520	8480	8450	8410
31	2.519	9000	8730	8680	8630	8590	8550	8520	8480

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	5.429	31.30	5.76
2	Surge Line Piping	5.429	22.80	4.20
3	Hot Leg Nozzle	5.140	22.87	4.45

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—ALL for the MSL Piping with Safety Factor of 1.7 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	29,705	28,972	28,282	27,714	26,738	25,633
4815	33,591	32,851	32,099	31,420	30,552	29,572
7270	36,493	35,776	35,053	34,311	33,426	32,528
9618	38,758	38,054	37,348	36,627	35,644	34,800
12,122	40,655	40,039	39,344	38,639	37,564	36,761
14,661	42,286	41,745	41,058	40,363	39,279	38,435
17,169	43,646	43,169	42,487	41,799	40,730	39,824
19,805	44,917	44,499	43,822	43,140	42,083	41,116
22,550	46,454	46,069	45,382	44,627	43,490	42,399
25,628	47,395	47,006	46,406	45,696	44,617	43,522
28,822	48,284	47,891	47,353	46,683	45,656	44,605