3.6.2 Determination of Rupture Locations and Dynamic Effects Associated with the Postulated Rupture of Piping

This section describes the criteria used to determine the locations of breaks and cracks in high- and moderate-energy piping systems. It also describes the criteria for guard pipe assembly design, as well as analysis methods for calculating the jet forces on essential structures, systems, and components (SSCs), the analysis methods for calculating jet reaction forces at the pipe break locations, and the analysis methods for designing pipe whip restraints. As noted in Section 3.6.3, the U.S. EPR design applies the leak-before-break (LBB) methodology to eliminate the dynamic effects of certain pipe ruptures from the design basis. Jet forces and pipe whip are not evaluated for the piping for which the LBB methodology is applied.

GDC 4 requires that SSCs important to safety both accommodate the effects of, and are compatible with, the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents, including loss-of-coolant accidents. In the event of a high- or moderate-energy pipe failure within the plant, GDC 4 requires that adequate protection is provided so that essential SSCs are not impacted by the adverse effects of postulated piping failure, including pipe-whipping and discharging fluids. Non-safety-related systems are not required to be protected from the dynamic and environmental effects associated with the postulated rupture of piping. Compliance with GDC 4 is also demonstrated through conformance with the criteria of BTP 3-4 (Reference 1) described in Section 3.6.2.1.

3.6.2.1 Criteria Used to Define Break and Crack Location and Configuration

BTP 3-4 defines the criteria used for postulating the locations of breaks and leakage cracks in high-energy lines and leakage cracks in moderate-energy lines. The types of breaks postulated in the high-energy lines include gross failure around the circumference of the pipe (circumferential breaks) and gross failure of the pipe along its axis (longitudinal breaks). Leakage cracks are also postulated in high- and moderate-energy lines. Section 3.6.1 describes the criteria and methods applied when evaluating the effects of these breaks and cracks on essential equipment. Conformance with BTP 3-4 is described further in the following sections.

As described in Section 3.6.3, LBB is applied to:

- The main coolant loop piping (hot, cold, and crossover legs).
- The pressurizer surge line.
- The main steam line piping from the steam generators to the first anchor point location (i.e., the Containment Building penetration).

A controlled leakage crack replaces circumferential and longitudinal breaks and leakage cracks when the LBB criteria of Section 3.6.3 are satisfied.

For ASME Class 1, 2, and 3 piping, breaks are postulated at terminal end locations which are determined according to the applicable piping isometrics. Intermediate breaks and cracks in ASME Class 1, 2, and 3 piping are postulated per the guidance described in the sections that follow. A COL applicant that references the U.S. EPR design certification will perform the pipe break hazards analysis and reconcile deviations in the as-built configuration to this analysis.

3.6.2.1.1 Locations of High-Energy Line Breaks and Leakage Cracks

3.6.2.1.1.1 Break Locations in Containment Penetration Areas

For the portions of fluid systems in containment penetration areas, breaks and cracks are not postulated from the containment wall up to and including the inboard and outboard containment isolation valves, when the systems meet the requirements of Subarticle NE-1120 in Section III of the ASME Boiler and Pressure Vessel Code (Reference 2), and where the additional requirements listed in Items 1 through 3 below are met.

1. ASME Code, Section III, Division 1 – Class 1 Piping in Containment Penetration Areas.
    - The U.S. EPR has no ASME Code, Section III, Class 1 piping in containment penetration areas.
2. ASME Code, Section III, – Class 2 Piping in Containment Penetration Areas.
    - The maximum stress range, calculated by the sum of Equation 9 and Equation 10 of Paragraph NC-3653 in Section III of the ASME Code, considering loads and conditions for which Level A and Level B stress limits have been specified in the design specification (i.e. sustained loads, occasional loads, and thermal expansion loads), do not exceed $0.8(1.8S_h+S_A)$. S_h is the allowable stress at maximum temperature and S_A is the allowable stress range for thermal expansion, as defined in Subarticle NC-3600 in Section III of the ASME Code.
    - The maximum stress, calculated from Equation 9 of Paragraph NC-3653 in Section III of the ASME Code under the loadings resulting from a postulated piping failure of fluid system piping beyond these portions of piping, does not exceed $2.25S_h$ and $1.8S_Y$.
    - Primary loads used in Equation 9 include those which result from pipe whip, even if pipe deflection is limited by whip restraints. Following a failure outside containment, the pipe between the outboard isolation valve and the first restraint is permitted higher stress where:
        - A plastic hinge is not formed.

- The operability of the isolation valve with such stress is demonstrated in accordance with Section 3.9.3.
- The piping is constructed in accordance with the Power Piping Code ANSI B31.1 (Reference 3).
- The piping is of seamless construction with a full radiography of circumferential welds, or longitudinal and circumferential welds are fully radiographed.

3. Special Considerations for Piping in Containment Penetration Areas.

   – Welded attachments to the piping have been avoided in containment penetration areas, except where a detailed stress analysis or test verifies compliance with the stress limits in Item 2 above.

   – The number of circumferential and longitudinal welds and branches are minimized. Where guard pipes are used, the fluid system piping is seamless and without circumferential welds, or access is provided to permit inservice volumetric inspections where the piping is circumferentially or longitudinally welded.

   – The length of the portions of pipe in containment penetration areas are kept to a minimum practical length.

   – The design of pipe anchors and restraints do not require welding to the surface of the fluid system piping (e.g., flued integrally forged pipe fittings may be used), except where such welds can be 100 percent volumetrically examined in service and compliance with Items 1 and 2 above is demonstrated (see Section 3.8.2 for figures depicting containment penetrations for high-energy piping).

   – Guard pipe design is addressed in Section 3.6.2.2.

   – A 100 percent volumetric inservice examination of pipe welds is performed during each ASME Code, Section XI (Reference 4) inspection interval defined in Subarticle IWA-2400 of the code.

3.6.2.1.1.2 Break Locations in Areas other Than Containment Penetration Areas

1. ASME Code, Section III, Division 1 – Class 1 Piping in Areas other than Containment Penetration Areas.

   Breaks in Class 1 piping are postulated at the following locations:

   A. At terminal ends for the extremities of piping runs where they connect to vessels, pumps, valves, structures, and pipe anchors that act as rigid constraints. A branch connection to a main piping run is a terminal end of the branch run, except where the branch is part of the main run in the stress analysis, and is shown to have a significant effect on the behavior of the main run. For piping runs that remain pressurized during normal plant conditions for only a portion of the run up to the first normally closed valve, the terminal end is located at the connection of the normally pressurized portion of pipe to this closed valve.

B. At intermediate locations where the maximum Level A or Level B stress range, as calculated by Equation 10 of Paragraph NB-3653 in Section III of the ASME Code and either Equation 12 or 13 of NB-3653, exceeds $2.4S_m$, where S_m is the design stress intensity at temperature.

C. At intermediate locations where the cumulative usage factor exceeds 0.1.

These intermediate break locations do not need to be changed as a result of reanalysis unless a major change is required in pipe parameters (e.g., pipe size, schedule, wall thickness, or routing) or the dynamic effects of the as-built intermediate break locations are not mitigated by the original jet shields or pipe whip restraints.

2. ASME Code, Section III, Division 1 – Class 2 and 3 Piping in Areas other than Containment Penetration Areas.

   Breaks in Class 2 and 3 piping are postulated at the following locations:

   A. Terminal ends as defined in Item 1.A above.

   B. At intermediate locations chosen by one of the following criteria:

   - At each pipe fitting, such as an elbow, tee, cross, flange, or nonstandard fitting, and at each welded attachment and valve. Where the pipe contains no fittings, welded attachments, or valves, a location is chosen at each extreme of the piping run adjacent to the protective structures.

   - At intermediate locations, where stresses calculated by the sum of Equation 9 and Equation 10, from Paragraph NC/ND-3653 in Section III of the ASME Code, exceed 0.8 times the sum of the stress limits given in NC/ND-3653.

These intermediate break locations do not need to be changed as a result of reanalysis unless a change is required in pipe parameters (e.g., pipe size, schedule, wall thickness, or routing), or the dynamic effects of the as-built intermediate break locations are not mitigated by the original jet shields or pipe whip restraints.

3. Seismically Analyzed Non-ASME Code Piping in Areas other than Containment Penetration Areas.

   Breaks in seismically analyzed, non-ASME Code Class piping are postulated according to the rules for ASME Code, Class 2 and 3 piping as stated in Item 2 above.

4. High-Energy Piping in Areas other than Containment Penetration Areas.

   If a structure separates a high-energy line from essential equipment, the structure is designed to withstand the consequences of a break in that line that yields the greatest effect at the structure, even if the criteria described in Section 3.6.2.1.1.2 may not require the break location to be postulated.

5. Environmental Qualification of Safety-Related Mechanical and Electrical Equipment.

   Safety-related equipment is environmentally qualified according to Section 3.11. The environmental qualification of electrical equipment, inside and outside containment, includes postulated breaks and cracks in the design bases. Section 3.11 also addresses the qualification of mechanical equipment.

3.6.2.1.1.3 Leakage Crack Locations in High-Energy Piping Systems

1. ASME Code, III, Division 1 – Class 1 Piping in Areas other than Containment Penetration Areas.

   Leakage cracks in Class 1 piping are postulated at axial locations where the stress range calculated by Equation 10 from Paragraph NB-3653 in Section III of the ASME Code, exceeds $1.2S_m$.

2. ASME Code, III, Division 1 – Class 2, 3, and non-ASME Code Class Piping in Areas other than Containment Penetration Areas.

   With the exception of the portions of piping identified in Item 2 in Section 3.6.2.1.1.1 above, leakage cracks in ASME Code Class 2, 3, and non-ASME Code piping are postulated at axial locations where the stress calculated by the sum of Equations 9 and 10 from Paragraph NC/ND-3653 in Section III of the ASME Code, exceeds 0.4 times the sum of the stress limits given in NC/ND-3653.

3. Unanalyzed Non-Safety Class Piping.

   Non-safety-class piping that does not have detailed stress information has a through-wall crack postulated at axial locations that yield the most severe environmental consequences.

3.6.2.1.1.4 High-Energy Fluid Systems Separated From Essential Systems and Components

For high-energy lines that are separated from essential systems and components, break and crack locations based on the criteria in Sections 3.6.2.1.1.2 and 3.6.2.1.1.3 are only postulated if the consequences of the rupture can be shown to have an environmental effect on the essential equipment, such as an increased temperature in a room containing essential equipment that results from a high-energy line break in a nearby, separate room. Similarly, rupture and target interactions need not be evaluated in cases where the essential system targets are in systems with complete train separation and redundancy. The U.S. EPR design has many essential systems with redundant safety trains located in each of four separate Safeguard Buildings. This four train separation and redundancy allows for one train to be lost due to the rupture, while a second train is lost due to single active failure and a third is down due to normal maintenance. With the fourth train still capable of operating the system, the effects of ruptures need not be specifically evaluated or protection provided.

3.6.2.1.2 Locations of Leakage Cracks in Moderate Energy Lines

3.6.2.1.2.1 Leakage Crack Locations in Fluid Systems in Containment Penetration Areas

Leakage cracks are not postulated in those portions of moderate-energy lines that extend from the containment wall up to and including the inboard and outboard containment isolation valves where they meet the requirements of Subarticle NE-1120 in Section III of the ASME Code, and where the Level A or Level B stress calculated by the sum of Equations 9 and 10 from Paragraph NC-3653 does not exceed 0.4 times the sum of the stress limits given in NC-3653.

3.6.2.1.2.2 Leakage Crack Locations in Fluid Systems in Areas other than Containment Penetration Areas

With the exception of the portions of piping identified in Section 3.6.2.1.2.1, leakage cracks are postulated at the following locations:

1. Through-wall cracks are postulated in piping located adjacent to safety-related SSCs except:
    A. When the piping is exempted by the criteria in Section 3.6.2.1.2.1 or Section 3.6.2.1.2.3.
    B. Where the ASME Code Class 1 piping stress range is calculated by Equation 10 from Paragraph NB-3653 in Section III of the ASME Code is less than 1.2 S_m.
    C. Where ASME Code Class 2, 3, and non-safety piping stresses are calculated by the sum of Equations 9 and 10 from Paragraph NC/ND-3653 in Section III of the ASME Code are less than 0.4 times the sum of the stress limits in NC/ND-3653.
2. Leakage cracks, unless exempted by Item 1 above, are postulated at circumferential and axial locations that yield the most severe environmental consequences.
3. Leakage cracks are postulated in piping designed to non-seismic standards at locations where the resultant leakage impacts the functional capability of affected essential equipment.

3.6.2.1.2.3 Moderate-Energy Fluid Systems in Close Proximity to High-Energy Fluid Systems

Leakage cracks are not postulated in moderate-energy lines where the crack is in close proximity to a high-energy line break, as long as the crack does not result in more limiting environmental conditions than the high-energy line break. When a leakage crack in a moderate-energy line causes more limiting environmental conditions than a proximate high-energy line break, the provisions from Section 3.6.2.1.2.2 are used.

3.6.2.1.2.4 Moderate-Energy Fluid Systems Separated from Essential Systems and Components

For moderate-energy lines that are separated from essential systems and components, leakage crack locations based on the criteria in Section 3.6.2.1.2.2 are postulated if the consequences of the crack can be shown to have an effect on the essential equipment, such as an increased temperature in a room containing essential equipment that results from a moderate-energy line leakage crack in a nearby, separate room. Similarly, rupture and target interactions need not be evaluated in cases where the essential system targets are in systems with complete train separation and redundancy. The U.S. EPR design has many essential systems with redundant safety trains located in each of four separate Safeguard Buildings. This four train separation and redundancy allows for one train to be lost due to the rupture, while a second train is lost due to single active failure and a third is down due to normal maintenance. With the fourth train still capable of operating the system, the effects of ruptures need not be specifically evaluated, or protection provided.

3.6.2.1.2.5 Fluid Systems that Qualify As Moderate-Energy Systems Based on Short Operational Periods as High-Energy

Leakage cracks, instead of breaks, are postulated in systems that are high-energy for only a short operational period of time and moderate-energy for most of the time. The operational period is defined as “short” if the time that the system operates under high-energy system conditions is two percent or less of the time that the system operates under moderate-energy system conditions, or is less than or equal to one percent of the plant operating time.

3.6.2.1.3 Types of Breaks and Leakage Cracks

3.6.2.1.3.1 Circumferential Pipe Breaks

The following circumferential breaks are considered individually in high-energy fluid systems at the locations specified in Section 3.6.2.1.1:

- Circumferential breaks are postulated in piping greater than a one inch nominal pipe size (NPS), except where the maximum Level A or Level B stress range exceeds the limits specified in Items 1 and 2 of Section 3.6.2.1.1.2, but the circumferential stress range is at least 1.5 times the axial stress range. Instrument lines, including one inch and less nominal pipe or tubing size, meet the guidance of RG 1.11.

- In the absence of stress calculations, circumferential break locations are selected at piping welds to each fitting, valve, or welded attachment.

- In the event of a circumferential break, it is assumed that the ends of the break move laterally a distance of one pipe diameter (perpendicular to the pipe axis) away from each other, unless physically limited by restraints, structural members, or pipe stiffness.

- When circumferential breaks have two ends that are not restrained, the ends are assumed to move clear of each other so that the jets do not interfere with each other. For circumferential breaks that are restrained from significant separation (e.g., axial pipe movement is less than or equal to one-half of the pipe diameter and lateral movement is less than the wall thickness), the jet centerline is assumed to be normal to the pipe centerline and extend 360° around the pipe.

- The dynamic force of the jet discharge at the break location is based on the effective cross-sectional pipe area and on a pressure as modified by an analytically or experimentally determined thrust coefficient. Limited pipe displacements at break locations, line restrictions, flow limiters, positive pump-controlled flow, and the absence of energy reservoirs are taken into account, as applicable, in reducing the jet discharge.

- Pipe whipping is assumed to occur in the plane defined by the geometric configuration of the pipe, and the movement of the whip initiates in the direction of the jet reaction.

3.6.2.1.3.2 Longitudinal Pipe Breaks

The following longitudinal breaks are considered individually in high-energy fluid systems at the locations specified in Section 3.6.2.1.3.1:

- Longitudinal breaks in fluid system piping are postulated in pipes four inches NPS and larger, except where the maximum stress range exceeds the limits specified in Items 1 and 2 in Section 3.6.2.1.1.2 above, but the axial stress range is at least 1.5 times the circumferential range.

- Longitudinal breaks are not postulated at terminal ends.

- Longitudinal breaks are assumed to result in an axial split without pipe severance. Splits are oriented (not concurrently) at two diametrically opposed points on the piping circumference such that the jet reactions cause out-of-plane bending in the pipe configuration. Alternatively, in the case where detailed stress analysis is used to establish the section of highest tensile stress, a single split is assumed.

- The dynamic force of the longitudinal pipe break is based on a circular or elliptical break area (2D x ½ D) equal to the effective cross-sectional flow area of the pipe at the break location, and on the calculated fluid pressure modified by an analytically or experimentally determined thrust coefficient as determined for a circumferential break at the same location. Line restrictions, flow limiters, positive pump-controlled flow, and the absence of energy reservoirs are taken into account, as applicable, in reducing the jet discharge.

- The pipe movement is assumed to occur in the direction of the jet reaction, unless it is physically limited by means of whip restraint, structural members, or pipe stiffness as established by inelastic limit analysis.

3.6.2.1.3.3 Leakage Cracks

Leakage cracks are postulated at axial locations specified in Section 3.6.2.1.1.3 for high-energy piping and in those moderate-energy piping systems that are not exempted in Item 1 of Section 3.6.2.1.2.2.

- Leakage cracks are not postulated in piping one inch NPS or smaller.
- For high-energy piping, leakage cracks are postulated in the circumferential locations that yield the most severe environmental consequences, and for moderate-energy piping leakage cracks are postulated at circumferential and axial locations that yield the most severe environmental consequences.
- Leakage cracks are postulated to be circular openings with an area equal to a rectangle with dimensions ½ d_p x ½ t_n, where d_p is the inside pipe diameter and t_n is the nominal wall thickness.
- The flow from a leakage crack is assumed to result in an environment that wets unprotected components within the compartment, with consequent flooding in the compartment and communicating compartments. Flooding effects are determined on the basis of a conservatively estimated time period required to take corrective actions. Section 3.4 provides additional information on flooding effects.

3.6.2.2 Guard Pipe Assembly Design Criteria

Guard pipes in containment penetration areas meet the requirements of Class MC, Subsection NE of Section III of the ASME Code where the guard pipe is part of the containment boundary. In addition, the guard pipe assemblies are designed to also meet the following requirements:

- Guard pipe assemblies are tested to a pressure not less than their design pressure.
- Design pressure and temperature are not less than the maximum operating pressure and temperature of the enclosed pipe during normal plant conditions.
- Containment design pressure and temperature, combined with safe shutdown earthquake loading, does not cause stress in the guard pipe assemblies to exceed Level C service limits from Subarticle NE-3220 in Section III of the ASME Code.
- Guard pipes do not prevent access for performing inservice inspections of piping welds, as required by Item 3 in Section 3.6.2.1.1.1. Additional information on inservice inspection and testing of the reactor coolant pressure boundary is provided in Sections 5.2.4 and 6.6.8.

A COL applicant that references the U.S EPR design certification will provide information regarding the implementation of the design criteria relating to protective assemblies or guard pipes, including their final design and arrangement of the access openings used to examine the process pipe welds within such protective assemblies to meet the requirements of the inservice inspection program for the plant.

3.6.2.3 Analytical Methods to Define Forcing Functions and Response Models

Movement of pipe, due to pipe breaks and cracks, is analyzed to show that the motion does not result in overstress of any structure, system, or component important to safety. This section will address the criteria for dynamic or pseudo-dynamic analysis of piping systems, targets, and protection devices. Criteria for the dynamic analysis that will be followed are:

- For each postulated pipe break an analysis of the dynamic response of the broken pipe is performed.
- In the case of circumferential pipe breaks, the need for a pipe whip dynamic analysis is determined based on the driving energy of the fluid.
- Mass inertia and stiffness properties of the systems, elastic and inelastic deformation of piping systems, impact and rebound, and support boundary conditions are adequately accounted for when calculating the dynamic response of piping and restraints.
- Loading condition (pressure, temperature, and inertial effects) prior to rupture is used in the evaluation of postulated breaks. For piping pressurized during normal power operation, the initial conditions are the greater of system energy at hot standby or at 102 percent of rated power.
- Crushable material used to dissipate the energy of a moving pipe is limited to 80 percent of its rated energy dissipating capacity. A 10 percent increase of the design yield strength (S_Y) is used to account for strain rate effects.
- Unrestrained whipping pipe is considered to be capable of causing circumferential and longitudinal breaks, individually, in smaller NPS piping and leakage cracks in piping that is of equal or larger NPS with thinner wall thickness, except where analytical or experimental justification is provided that demonstrates that the impact does not cause rupture.

A representative mathematical model of a piping system and its restraints is shown in Figure 3.6.2-1—Representative Mathematical Model of a Piping System and its Restraints. The analytical methods used to predict the response of the piping and restraint system are presented in the sections below.

3.6.2.3.1 Rupture Response Models and Forcing Functions for LBB-Analyzed Piping

Since the LBB evaluation eliminates dynamic effects, there are no response models or forcing functions for the piping for which the LBB methodology is applied (see Sections 3.6.2.1 and 3.6.3).

3.6.2.3.2 Rupture Response Models and Forcing Functions for Piping Not Analyzed for LBB

In evaluating pipe thrust and jet loads, the types of breaks, the wave forces, the dynamic force of the fluid jet, potential pipe whipping, and the evaluation of jet impingement effects, are considered. Jet impingement forces and pipe whip impacts are calculated only if they can potentially cause damage to an essential system.

3.6.2.3.2.1 Development of Jet Discharge Forces

The fluid jet discharge forces acting on the ruptured pipe are dependent on the state of the fluid in the pipe at the time and the location of the rupture, the pipe flow area at the break, the system fluid inventory between the source and the break, the piping system frictional losses, and the piping system geometry. The development of these dynamic jet forces is described in Section 6.2 of ANSI/ANS 58.2-1988 (Reference 5). In addition to the dynamic analysis methodology given in Section 6.2 of this standard, there is also a simplified pseudo-dynamic methodology provided in Appendix B of the standard, that is based on empirical data.

The jet forces consist of an initial transient jet force, followed by a steady state thrust force condition, which continues until the fluid inventory is exhausted. This thermal-hydraulics problem is solved using standard computer programs, or the analysis is simplified using the methodology from Appendix B of Reference 5.

High-energy line breaks are assumed to occur almost instantaneously. For analysis purposes, the break opening time for the full break plane area to develop for both circumferential and longitudinal breaks is assumed to be one millisecond, unless experimental data or a detailed analysis can be shown to vary this assumed time.

In addition, the geometry of the piping system from the source of the fluid energy to the break location can have a significant effect on the calculated jet forces. The system flow characteristics of the piping can be determined by accounting for flow restricting devices such as orifices, as well as friction losses due to piping fittings and direction changes. Other geometry conditions, such as the limited broken pipe separation conditions mentioned earlier, are also utilized to develop the appropriate jet forces at the break. An appropriately detailed thermal-hydraulics computer model accounts for these effects, or the effects are determined separately and applied to the simplified approach of Appendix B of Reference 5.

The general jet force determination considers an initial transient thrust force and a steady state thrust force. The initial thrust force is unaffected by friction flow losses and is assumed to occur in one millisecond. The steady state thrust force is affected by friction in the piping system; however, these effects may or may not be significant, depending on the piping geometry in question. Appendix B of Reference 5 shows two curves for the total thrust force transients, one utilizing a frictionless flow model and the second showing the friction flow case model. In addition, these curves also include the assumed simplified transient shapes for these two cases, using the following simple equations for the two forces:

- Initial Thrust Force:

  $T_{INT} = P_o A_e$

  Where:

  P_o = initial total stagnation pressure in the pipe

  A_e = pipe internal cross-sectional area.

- Steady State Thrust Force:

  $T_{SS} = C_T P_o A_e$

  Where:

  C_T = the steady state thrust coefficient.

The steady state thrust coefficient, C_T, depends on the fluid state and any friction loss terms being considered. The fluid states considered in the Reference 5, Appendix B methodology are:

- Saturated and superheated steam.
- Saturated steam and water mixtures.
- Subcooled water.
- Incompressible liquid.

Reference 5 provides equations and curves to determine C_T values for these states, for both frictionless flow and flow considering friction losses. The following is a summary of the C_T calculations for these states.

Saturated and Superheated Steam

For saturated and superheated steam conditions, assuming an ideal gas and isentropic flow, the frictionless flow equation for C_T is:

$C_T = 1.26 - P_a / P_o$

Where:

P_a = ambient pressure around the pipe.

For typical high-energy piping systems where $P_a << P_o$, a C_T value of 1.26 is obtained.

Figure B-3 or Figure B-4 in Appendix B of Reference 5 is used to determine C_T when either significant friction losses (fL / D terms) or an upstream flow restriction are present.

Saturated Steam/Water Mixtures

For saturated steam and water mixtures, or two-phase mixed flow, C_T values for frictionless flow are determined in Appendix B of Reference 5 using a set of curves (Figure B-5) and knowing the stagnation enthalpy of the fluid.

Figure B-3 or Figure B-4 in Appendix B of Reference 5 is used to determine C_T when either significant friction losses (fL / D terms) or an upstream flow restriction are present.

Subcooled Water

For subcooled water, the steady state thrust coefficient varies between 1.26 for steam and 2.0 for water. The thrust coefficient increases toward the value of 2.0 as the amount of subcooling increases. Appendix B of Reference 5 provides a set of curves (Figure B-6) to determine C_T values for frictionless flow, using known stagnation enthalpy and stagnation pressure values. This document also provides equations that can be used to determine the thrust coefficient values, in lieu of the curves supplied.

For friction flow, Reference 5 provides two sets of curves (Figures B-7 and B-8) for determining thrust coefficients from fL / D friction loss terms at specific fluid pressures, and the stagnation enthalpy.

Incompressible Liquid

For the break of a cold water pipe, for which the water is less than 212°F and above atmospheric pressure, the flow is considered to be that of an incompressible liquid. The equation for the thrust coefficient for this condition is:

$C_T = 2 / (1 + fL / D)$

Where:

f = piping system friction factor

L/D = pipe length-to-diameter ratio

Figure B-3 of Reference 5 also provides a curve, for non-flashing water, for determining C_T values when friction losses are significant.

Another factor needed to develop the simplified thrust force transient curves of Appendix B in Reference 5 is the time to reach steady state conditions, t_{ss}. As for the thrust coefficient determination, the time to reach steady state flow is based on the fluid state prior to rupture and the piping system geometry. In general, this time is estimated to be when the initial pipe contents have been expelled, which is a function of the discharge velocity, discharge density, and length of pipe. In general, the time required to discharge the initial pipe contents, t_D, is:

$$t_D = \rho_o L / \rho_D U_D$$

Where:

ρ_o = initial fluid density

L = length of pipe

ρ_D = discharge density

U_D = discharge velocity.

Time to steady state, $t_{ss,}$ is assumed to be equal to t_D. Manipulating this equation, the actual t_{ss} values are determined based on whether the discharged fluid is compressible or non-compressible.

For non-flashing fluids,

$$t_{ss} = 2L [\rho_o / 2 g_c P_o]^{1/2}$$

Where:

g_c = Newton's constant.

For compressible fluids:

$$t_{ss} = (\rho_o / \rho) (c_o / U) (L / c_o)$$

Where:

c_o = sonic speed in the fluid.

ρ_o / ρ and c_o / U are dimensionless ratios determined from Figure B-9 in Appendix B of Reference 5, knowing the initial pressure and the saturation pressure.

The sonic speed in the fluid is determined from Figure B-10 in Reference 5.

Utilizing detailed thermal-hydraulic modeling, the simplified thrust force transients outlined above, or conservatively utilizing only the highest of the initial or steady state thrust forces as constant forces, the jet discharge forces from the broken piping are established.

3.6.2.4 Dynamic Analysis Methods to Verify Integrity and Operability

3.6.2.4.1 Evaluation for Jet Impingement

With a high-energy line break event and the ensuing jet forces as calculated in the previous section, there is a potential for jet impingement on an essential component or structure, or on a designated barrier between the jet and an essential target. Such jet impingements depend on the placement of the target relative to the break, the jet energy discharged, the jet shape, and also the target characteristics (shape, structural, and dynamic characteristics). In addition to dynamic effects, there is also the probability of increased temperature and wetting of the target as a result of direct impingement from the jet. Although these last two effects are also considered environmental effects for the general area, there may be a more significant effect on the target from direct impingement than occurs in the area in general.

The jet shape of the discharged fluid tends to follow two shape patterns based on whether the fluid has flashed to steam (or is already steam) or is a water jet. For the latter, the jet shape will generally have a jet diameter equal to the pipe diameter. For steam jets, the shape will be an expanding one from the break point outward. As noted in Section 3.6.1.1.1, this expanding jet shape can be assumed to be damaging out to a distance of ten pipe diameters from the break location. Beyond this distance, the energy of the jet is assumed to be negligible. In addition, the jet is assumed, at least initially, to come from both ends of the broken pipe, and can also be traveling with a whipping pipe, if such a whip is shown to occur. The shape or path of the jet cannot be determined exactly, so allowances are made for targets close to the assumed jet shape to be included within that shape for analysis purposes.

Appendix C of ANSI/ANS 58.2 (Reference 5) provides simplified jet shapes for expanding jets. The assumed jet shape is broken down into three separate regions. Region 1 extends from the break to the end of the jet core region, where a target within this region will experience full recovery of the jet stagnation pressure upstream of the break. Region 2 extends from the end of Region 1 out to the asymptotic plane. Between the break and this plane, the jet is assumed to undergo free expansion to the pressure at the asymptotic plane. Beyond the asymptotic plane, the jet is assumed to begin interacting with the surrounding environment, and is postulated to expand at a half angle of 10°. This region beyond the asymptotic plane is called Region 3, and continues until the jet energy has dissipated. These shape conditions are assumed for circumferential breaks with limited separation and for longitudinal breaks. Appendix C of Reference 5 provides the equations and curves necessary to calculate the parameters needed to define the jet shape based on the fluid conditions.

With the jet discharge forces and the jet shapes defined, the jet impingement load on a target is the force exerted on the target by the jet. This dynamic problem is not only dependent on the jet forcing function, but also on the dynamic characteristics of the target in question. It can be solved dynamically with a model of the target, and utilizing the jet forcing function, however, it can also be solved using an equivalent static approach. The equation for this equivalent static approach is:

$F_s = (DLF)\ (F_{imp})$

Where:

F_s = equivalent static impingement force.

DLF = a dynamic load factor.

F_{imp} = maximum value of the applied jet impingement force (see below).

The dynamic load factor may be determined using a dynamic analysis of the target, or may be assumed to be 2.0 for cases where the target can be treated as a single degree of freedom system (refer to Section 7 of Reference 5).

The jet impingement force (F_{imp}) is essentially the jet discharge force (F_{jet}), factored as necessary to account for the amount of the jet cross-sectional area intercepted by the target. This force is also a function of a correction factor for the target, known as a shape factor (K_φ). Thus,

$F_{imp} = K_\varphi\ F_{jet}$

The shape factor is a measure of the potential of the target to change the momentum of the jet flow, and is therefore a factor of the shape of the target and its orientation with respect to the jet. Section D2 of Appendix D of Reference 5 provides a means of determining this factor for various target shapes.

With this equivalent static jet impingement force, or a force transient, the target structure can be analyzed for jet impingement effects using standard structural analysis techniques.

3.6.2.4.2 Analysis of Essential System Piping Due to a Break in Attached Piping

In addition to the dynamic aspects of the jet discharge from a broken high-energy line, there may also be significant dynamic loads and displacements in essential system piping attached to the broken pipe. An example of this would be wave forces arising from rapidly traveling waves due to the depressurization of the broken pipe in attached essential system piping. Similarly, there might be dynamic displacements of in-line components due to such dynamic events caused by the line break, which might be significant enough to be considered as terminal end (anchor) motions.

As such, the location of the break relative to other essential system attached piping, as well as the potential isolation characteristics of the break effects, is considered during the evaluations subsequent to a high-energy line break. A factor in the definition of such a dynamic problem is the existence and location of check valves in the remaining unbroken piping. With closing check valves, the faster the closing time for the valve the higher the dynamic loading in the remaining piping.

3.6.2.4.3 Development of Pipe Whip Hinges

The criteria described in Sections 3.6.2.3.2 and 3.6.2.4 concern the fluid discharge of a broken pipe, neglecting the potential of a plastic hinge to develop in the pipe, and thus allowing whipping of the broken pipe. For protection purposes, the following are considered:

- The broken pipe is shown to have insufficient energy to develop a plastic hinge.
- A whip restraint is located and designed to preclude the whip from taking place.
- The whipping pipe is shown to not contact an essential system target, or to cause a jet to impact an essential system target.
- The essential system target impacted by the whipping pipe, or a jet due to the whipping motion, is shown to be structurally adequate to withstand the effects of the impact.

If a pipe whip from a high-energy line break can be postulated to occur and to have an adverse effect on an essential system target, the location of a plastic hinge, or hinges, is established. These hinge locations will determine the potential whipping motion and travel of the broken pipe. In addition, if a whip restraint is to be designed, but cannot be placed close to the first elbow upstream of the postulated circumferential break point (or close to the longitudinal break point), a hinge may be shown to develop downstream of the whip restraint.

The following methods are used to analyze the broken piping for potential whip effects:

- Dynamic analysis using lumped mass or continuous mass methodologies.
- Energy balance methodology.
- Equivalent static methodology.

The dynamic analysis method utilizes a lumped mass or continuous mass computer model, accounting for the stiffness and inertia effects of the piping and whip restraint system, along with the clearances built into the whip restraint designs. The time history forcing functions of the ruptured pipe are applied to this model at the break location, and the responses of the pipe whip restraints and pipe deformations are determined utilizing elastic-plastic analysis techniques.

The energy balance method is based on the conservation of energy principle. This method is not time dependent, and as such the maximum jet discharge force is utilized as a constant thrust force. This method is performed for the first quarter cycle of pipe movement (where the initial and final pipe velocities are zero). For this method, the kinetic energy developed during the pipe movement is equated into equivalent strain energy at the time of impact with the restraints or the target. This kinetic energy can be reduced by accounting for the energy required to develop the plastic hinge. The energy used to crush the pipe at impact may also be considered. If a pipe rebound can occur at impact, an amplification factor of 1.1 is applied to the forcing function. Amplification factors other than 1.1 may be used if they can be justified by a more detailed analysis.

The equivalent static method simplifies the dynamic analysis method above by utilizing a static analysis with amplification factors to conservatively represent the neglected dynamic effects. The calculated design force is the jet discharge force multiplied by 1.1 for rebound effects, and a dynamic load factor, conservatively taken as 2.0. This design force can be used to design a whip restraint to place in the vicinity of the break, and can also be used to determine the location of the plastic hinge. To determine the length of pipe from the first elbow upstream of the circumferential break reacting the jet force (or the length from a longitudinal break point), the following equation is used:

$$L = M_p / F_D$$

Where:

L = length described above.

M_p = plastic moment of the pipe.

F_D = design force due to the jet, as described above.

For the above equation to calculate the length of pipe to the hinge, the plastic moment is calculated using the following:

$$M_p = 1.1\ Z_p\ S_y$$

Where:

1.1 = a factor to account for 10 percent strain hardening of the pipe.

Z_p = plastic section modulus of the pipe.

S_y = yield stress of the pipe.

Using one of the above methods, the whipping pipe problem is characterized to determine the appropriate pipe movements, pipe impact loads, and pipe whip restraint design forces.

3.6.2.5 Implementation of Criteria Dealing with Special Features

3.6.2.5.1 Pipe Whip Restraints

The pipe whip restraints are a gapped, crushable, bumper-type support near an elbow and provide clearance to access welds. Additional information on the crushable material is described in Section 3.6.2.3. The restraint consists of a structural member and a bracket mounted to the structural member, with clearance around the subject piping to allow for thermal movement and the installation of pipe insulation. A COL applicant that references the U.S. design certification will provide diagrams showing the final as-designed configurations, locations, and orientations of the pipe whip restraints in relation to break locations in each piping system.

3.6.2.5.1.1 Location of Whip Restraints

The ideal location for a pipe whip restraint is near the first elbow upstream of the circumferential break location (or near the longitudinal break location), as close to the first elbow (or longitudinal break) as practical. This location prevents the whipping motion, while preventing a plastic hinge from developing in the pipe between the elbow and the restraint. If the placement cannot be close to the elbow (or longitudinal break) due to physical constraints, a potential hinge location is calculated using a simplified static analysis approach so that the whip restraint is properly placed. Pipe whip restraints are located so that they do not cover piping welds that require inservice inspections.

With the pipe break jets and whips characterized per the sections above, there is still a need to design pipe whip restraints which have been assumed in the rupture analysis, or to design structural barriers between the break and potential essential system targets. Both of these types of structural designs are for essential system protection purposes.

3.6.2.5.1.2 Pipe Whip Support Design

Pipe whip supports are typically only designed for the restraint of a whipping pipe following a postulated high-energy line break, and are typically separate from the other system pipe supports which are designed for other design basis loadings. Whip restraints are typically designed for a one-time accident event; so they are designed to undergo deformation as long as the whipping pipe is fully restrained for the entire time of the blowdown event. Similarly, the whip restraint has gaps to allow for the free thermal and seismic movements of the pipe at that location, so that the restraint does not affect the parameters of the design basis piping analysis. If a support is designed as both a standard pipe support and a pipe whip restraint, the design of the support meets the design criteria of a standard pipe support for loadings using the appropriate loading combinations.

The calculation of design loads to be utilized in the design of pipe whip supports is described in Section 3.6.2.4.3. For a whip restraint near the first elbow upstream of a circumferential break, or near a longitudinal break, a static analysis calculation can be performed using the maximum jet discharge force multiplied by a factor of 1.1 for rebound effects, and a factor of 2.0 for a dynamic load factor. With this design load, a typical whip restraint usually consists of crushable, energy-absorbing material. The allowable capacity of such a crushable material is limited to 80 percent of its rated energy dissipating capacity, as determined by dynamic testing, at loading rates within plus or minus 50 percent of the specified design loading rate. The rated energy dissipating capacity is not greater than the area under the load-deflection curve from Figure 3.6.2-1 of SRP 3.6.2.

3.6.2.5.2 Structural Barrier Design

Structural barriers are used for high-energy line break protection purposes in order to provide separation between safety trains of essential systems, and to provide shields between rupture effects and an essential system component. The dynamic effects of a rupture are jet impingement and pipe whip impacts. Jet impingement analysis loads on a structural barrier are described in Section 3.6.2.4.1. The methodology to determine pipe whip analysis loads on a structural barrier is provided in Section 3.6.2.4.3. The barrier structural analysis methodology utilizing these pipe rupture design loads is based on the criteria in Section 3.8.

3.6.2.5.3 Evaluation of Pipe Rupture Environmental Effects

In addition to the dynamic effects from the pipe rupture, environmental effects from both breaks and cracks are considered. These environmental effects include increased temperature, increased pressure, increased humidity, spray wetting, and flooding. Temperature, pressure, and humidity are considered in the essential system environmental equipment qualification (see Section 3.11). Additionally, the effects of increased pressure in a compartment are described further in Section 3.8.

Spray wetting is assumed to affect electrical components in the compartment where the rupture occurs. Spray wetting is not assumed to affect mechanical components, subcomponents, or other passive, non-electrical components, such as piping in the compartment. Essential system electrical components are protected against the effects of spray wetting by using spray shields or housing the equipment in NEMA 4 or NEMA 12 rated enclosures.

Pipe ruptures, both breaks and cracks, can also cause water buildup in a compartment, which may lead to flooding of essential system components in the same, or a connecting, compartment. Flooding effects are described further in Section 3.4.

3.6.2.6 References

1. Branch Technical Position 3-4, Revision 2, "Postulated Rupture Locations in Fluid System Piping Inside and Outside Containment," Nuclear Regulatory Commission, March 2007.
2. ASME Boiler and Pressure Vessel Code, Section III, "Rules for Construction of Nuclear Facility Components," The American Society of Mechanical Engineers, 2004.
3. ASME Piping and Pipelines Code, B31.1, "Power Piping," The American Society of Mechanical Engineers, 2004.
4. ASME Boiler and Pressure Vessel Code, Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components," The American Society of Mechanical Engineers, 2004.
5. ANSI/ANS-58.2-1988, "Design Basis for Protection of Light Water Nuclear Power Plants Against the Effects of Postulated Pipe Rupture," American Nuclear Society, 1988.

Figure 3.6.2-1—Representative Mathematical Model of a Piping System and its Restraints