3F U.S. EPR Piping Analysis and Pipe Support Design

3F.1 Introduction

This appendix presents the U.S. EPR Design Certification code requirements, acceptance criteria, analysis methods, and modeling techniques for the American Society of Mechanical Engineers (ASME) Code Class 1, 2, and 3 piping and pipe supports. These structures and components are designed and analyzed as required to meet the U.S. Nuclear Regulatory Commission's (NRC) regulations provided in Title 10 of the Code of Federal Regulations (10 CFR). To meet these requirements, the design and analysis utilizes the additional guidance provided by Sections 3.7 and 3.9 of the NRC's Standard Review Plan (SRP), documented in NUREG-0800, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants (Reference 1), and the requirements established in the ASME Boiler and Pressure Vessel Code, Section III, Division 1, 2004 (ASME Code (Reference 2)) for ASME Code Class 1, 2, and 3 pressure retaining components and their supports. Quality Group D piping is designed to ASME B31.1 (Reference 29). Appendix 3F focuses on Seismic Category I and Category II systems, but also addresses the interaction of non-seismic piping with Seismic Category I piping. The Reactor Coolant Loop (RCL) and Pressurizer Surge Line modeling techniques and loading analyses are addressed in Appendix 3C. Load combinations and stress limits are discussed in this Appendix.

3F.2 Codes and Standards

10 CFR Part 50, Appendix A, General Design Criterion (GDC) 1 requires that structures, systems, and components (SSC) important to safety must be designed to quality standards "commensurate with the importance of the safety functions to be performed." GDC 2 requires that SSC important to safety be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, and floods without the loss of their safety function. Codes and standards used to show that safety-related piping and pipe supports for the U.S. EPR design meet these GDCs are identified below.

3F.2.1 ASME Boiler and Pressure Vessel Code

[Piping analysis and pipe supports used for the U.S. EPR design addressed in this appendix use the ASME Code (Reference 2) as the base code with limitations identified in 10 CFR 50.55a(b)(1). Accordingly, the ASME Code (Reference 2) will be the design code for Class 1, 2, and 3 piping with the restriction that the treatment of dynamic loads, including seismic loads, in the pipe stress analyses will be according to Paragraphs NB-3650, NC-3650, and ND-3650 of the ASME Code 1993 Addenda (Reference 3). Class 1 piping greater than one inch Nominal Pipe Size (NPS) will be analyzed to Subarticle NB-3600. Class 1 piping one inch NPS and smaller and Class 1 piping meeting the requirements of Paragraph NB-3630(d)(2) may be analyzed to Subarticle NC-3600. Class 2 piping will be analyzed to Subarticle NC-3600. Class 3

*piping will be analyzed to Subarticle ND-3600. Quality Group D piping will be analyzed to ASME B31.1 (*Reference 29)*. Pipe supports will be designed to Subsection NF of the ASME Code (Reference 2).]**

3F.2.2 ASME Code Cases

ASME Code Cases applicable to the U.S. EPR Design Certification for piping and pipe supports are as follows:

- ASME Code Case N-122-2, "Procedure for Evaluation of the Design of Rectangular Cross Section Attachments on Class 1 Piping, Section III, Division 1." (This Code Case has been incorporated into the ASME Code (Reference 2).)
- ASME Code Case N-318-5, "Procedure for Evaluation of the Design of Rectangular Cross Section Attachments on Class 2 or 3 Piping, Section III, Division 1." (This Code Case has been incorporated into the ASME Code (Reference 2).)
- ASME Code Case N-319-3, "Alternate Procedure for Evaluation of Stresses in Butt Welding Elbows in Class 1 Piping, Section III, Division 1."
- ASME Code Case N-391-2, "Procedure for Evaluation of the Design of Hollow Circular Cross Section Welded Attachments on Class 1 Piping, Section III, Division 1." (This Code Case has been incorporated into the ASME Code (Reference 2).)
- ASME Code Case N-392-3, "Procedure for Evaluation of the Design of Hollow Circular Cross Section Welded Attachments on Class 2 and 3 Piping, Section III, Division 1." (This Code Case has been incorporated into the ASME Code (Reference 2).)

Other ASME Code Cases may be used if they are either conditionally or unconditionally approved in RG 1.84, Rev. 33 (Reference 4).

3F.2.3 Design Specification

A design specification is required by the ASME Code (Reference 2) for ASME Code Class 1, 2, and 3 piping. In addition, the ASME Code (Reference 2) requires design reports for all Class 1, 2, and 3 piping demonstrating and documenting that as-designed piping and support configurations adhere to the requirements of the design specification.

3F.3 Piping Stress Analysis Criteria

3F.3.1 Piping Seismic Classifications

The U.S. EPR design follows the guidance in RG 1.29, "Seismic Design Classification" (Reference 5), in classifying SSC as Seismic Category I, Seismic Category II, or non-seismic. The following definitions apply to these categories for piping:

- Seismic Category I piping is required to be designed to withstand the effects of a Safe Shutdown Earthquake (SSE) and remain functional during and after the event. These components must meet the requirements of 10 CFR Part 50, Appendix B.

- Piping that is not required to function during or after an SSE event, but whose structural failure could reduce the functioning of Seismic Category I SSC, is classified as Seismic Category II piping. To prevent adverse impact to Seismic Category I SSC, Seismic Category II piping will be designed to the same requirements as Seismic Category I piping.

- Piping that does not meet the criteria for Seismic Category I or II is considered non-seismic. Non-seismic pipe is routed away from safety equipment to prevent any interaction with Seismic Category I and II piping, where applicable. When it is not practical to route non-seismic pipe away from Seismic Category I and II piping, the non-seismic piping will be upgraded to Seismic Category II as defined above.

3F.3.2 Service Levels

The U.S. EPR design will utilize the four Service Levels used in the ASME Code (Reference 2), Levels A, B, C, and D, and testing conditions, in its design of piping and pipe supports. These four service level designations also have the alternate naming convention of Normal, Upset, Emergency, and Faulted, respectively. Based on the guidance in SRP 3.9.3 (Reference 1), loading combinations of the various potential analysis load cases will be developed for the four defined levels. The general definitions of each of the four levels are as follows:

3F.3.2.1 Level A (Normal)

Level A refers to sustained loadings encountered during normal plant/system start-up, operation, refueling, and shutdown.

3F.3.2.2 Level B (Upset)

Level B refers to occasional, infrequent loadings deviating from normal plant conditions but having a high probability of occurrence. Piping and pipe supports will be designed to withstand these loading conditions without sustaining any damage or reduction in function.

3F.3.2.3 Level C (Emergency)

Level C refers to infrequent loadings with a low probability of occurrence that are considered as design basis loadings causing no significant loss of integrity. Such an occurrence requires the unit to be shut down for inspection and repair to any damaged components prior to restart.

3F.3.2.4 Level D (Faulted)

Level D refers to infrequent loadings with an extremely low probability of occurrence, associated with design basis accidents, such as SSE, Design Basis Pipe Break (DBPB), and Loss of Coolant Accident (LOCA). Per RG 1.29 (Reference 5), SSC important to safety must retain their ability where required to "ensure

(1) the integrity of the reactor coolant pressure boundary,

(2) the capability to shut down the reactor and maintain it in a safe shutdown condition, or

(3) the capability to prevent or mitigate the consequences of accidents that could result in potential offsite exposures comparable to the guideline exposures of 10 CFR Part 100."

3F.3.2.5 Testing

Pressure overload tests such as primary and secondary hydrotests and other leak rate tests are included in the piping analysis for primary membrane stresses and fatigue evaluation.

3F.3.3 Loadings and Load Combinations

3F.3.3.1 Loadings

3F.3.3.1.1 Pressure

Internal design pressure, P, is used in the design and analysis of ASME Code Class 1, 2, and 3 piping. Minimum pipe wall thickness calculations are performed per ASME Code (Reference 2), Paragraphs NB-3640, NC-3640, and ND-3640, utilizing design pressure. Design pressures and maximum service pressures are used in load combinations as noted in Table 3F-1 and Table 3F-2 for calculating stresses for Design Conditions, Service Levels A, B, C, and D, and Testing.

3F.3.3.1.2 Deadweight

Deadweight loads will be calculated by applying a 1g negative vertical acceleration to the pipe, contents, insulation, and in-line components. The weight of water during hydrostatic testing shall be considered for piping systems carrying air, steam, or gas.

3F.3.3.1.3 Thermal Expansion

The effects on piping and supports from restrained thermal expansion and contraction shall be considered in the design. Various operating modes shall be considered in order to determine the most severe thermal loading conditions. Thermal anchor movements (TAMs) of equipment, support/restraints, and run piping for decoupled branch lines shall also be considered. The zero thermal load temperature is taken as 70°F.

No thermal analysis is required for piping systems with an operating temperature equal to or less than 150°F. Additionally, TAMs less than or equal to one-sixteenth inch may be excluded from the analysis since this represents the industry practice for acceptable gaps in pipe supports (refer to WRC Bulletin 353, Position Paper on Nuclear Plant Pipe Supports (Reference 6)).

3F.3.3.1.4 Seismic

The effects of seismic inertial loads and anchor movements shall be included in the design analysis.

The ground motion of the Operating Basis Earthquake (OBE) for the U.S. EPR design is equal to one-third of the ground motion of the SSE. Per 10 CFR Part 50, Appendix S, the OBE load case does not require explicit design analysis. In the event of an earthquake that meets or exceeds the OBE ground motion, plant shutdown is required and Seismic Category I piping and supports are required to be inspected to ensure no functional damage has occurred. The design of the U.S. EPR Seismic Category I piping and supports includes analysis of the inertial and anchor movement (greater than one-sixteenth inch) effects of the SSE event. These loads are Service Level D loads.

The consideration of fatigue effects due to seismic events is addressed in Section 3F.3.4.

3F.3.3.1.5 Fluid Transient Loadings

Relief Valve Thrust

Relief valve thrust loads for open and closed systems are functions of valve opening time, flow rate, fluid properties, and flow area. The analysis of these loads is usually accomplished using static loads as input to the piping analysis with appropriate dynamic load factors (DLFs). Dynamic analysis of relief valve thrusts will be used when static analysis produces undesirably conservative results. These loads are considered in Service Level B, C, or D load combinations.

Water and Steam Hammer

Water and steam hammer loads can be Service Level B, C, or D loads and are dynamic in nature. Hammers usually involve the rapid change in fluid flow creating a shock-wave effect in the piping system. They are usually set in motion by rapid actuation of control valves, relief valves, and check valves. Rapid start or trip of a pump or turbine can also initiate such a phenomenon.

3F.3.3.1.6 Wind, Hurricane, Tornado Loads

ASME Code Class 1, 2, and 3 piping for the U.S. EPR Design Certification is not exposed to wind, hurricane, or tornado loads. Should a COL applicant that references the U.S. EPR design certification find it necessary to route Class 1, 2, and 3 piping not included in the U.S. EPR design certification so that it is exposed to wind, hurricanes, or tornadoes, it must be designed to the plant design basis loads for these events.

3F.3.3.1.7 Design Basis Pipe Break Loads

Loads due to high energy pipe breaks can take the form of pipe whip, jet impingement, elevated room temperatures, and dynamic effects in the system due to the break. These loads must be evaluated for the appropriate service condition. Breaks in the RCL, Main Steam, and Pressurizer Surge lines that meet the Leak-Before-Break (LBB) criteria of SRP 3.6.3 are eliminated from consideration. However, DBPB loads do include the impact of small break LOCA, Main Steam, and Feedwater line breaks outside the LBB analyzed zone.

3F.3.3.1.8 Thermal and Pressure Transient Loads

Thermal and pressure transients are evaluated in the analysis of ASME Code Class 1 piping by calculating the range of primary plus secondary stress intensities. For ASME Code Class 2 and 3 piping, these transients are included as load cases in the appropriate ASME Code (Reference 2) equations (8, 9, or 10).

3F.3.3.1.9 Hydrotests

Piping systems are tested for leaks by filling the system with the test fluid and pressurizing to test pressures. Systems that are normally used for steam and gas services must have stops placed in spring hangers and temporary supports added as needed. Analysis of testing conditions for these lines must consider the temporary support configurations.

3F.3.3.2 Load Combinations

Using the methodology and equations from the ASME Code (Reference 2), pipe stresses shall be calculated for various load combinations. The ASME Code (Reference 2) includes design limits for Design Conditions, Service Levels A, B, C, and D, and testing. Load combinations for ASME Code Class 1 piping are given in Table 3F-1. Class 2 and 3 load combinations are given in Table 3F-2.

3F.3.4 Fatigue Evaluation

3F.3.4.1 ASME Code Class 1 Piping

ASME Code Class 1 piping shall be evaluated for the effects of fatigue as a result of pressure and thermal transients and other cyclic events including earthquakes. The fatigue analysis of Class 1 piping greater than 1 inch NPS is performed using the ASME Code (Reference 2), Paragraph NB-3653.

Per the guidance of SRP 3.7.3 (Reference 1), ASME Code Class 1 piping should be designed for a minimum of one SSE and five OBE events with ten maximum stress cycles per event. As described in Section 3F.3.3.1.4, a detailed design analysis of the OBE load case is not performed for the U.S. EPR design. Therefore, to meet this requirement, earthquake cycles included in the fatigue analysis are composed of two SSE events with 10 maximum stress cycles each for a total of 20 full cycles of SSE stress range. Alternatively, as allowed by NRC memo SECY-93-087, Policy, Technical, and Licensing Issues pertaining to Evolutionary and Advanced Light-Water (ALWR) Designs (Reference 7), the methods of IEEE Std 344-1987 (Reference 8), Appendix D, may be used to determine a number of fractional vibratory cycles equivalent to 20 full SSE cycles. When this method is used, the amplitude of the vibration is taken as one-third of the amplitude of the SSE, resulting in 300 fractional SSE cycles to be considered.

The effects of the reactor coolant environment on fatigue will be accounted for in the ASME Code Class 1 piping fatigue analyses using methods acceptable to the NRC at the time of performance.

3F.3.4.2 ASME Code Class 2 and 3 Piping

ASME Code Class 2 and 3 piping is evaluated for fatigue due to thermal cycles by following the requirements in Reference 2, Paragraph NC-3611.2 or ND-3611.2. This involves the reduction of ASME Code allowables for the thermal expansion stresses calculated to the requirements in Reference 2, Paragraphs NC-3653.2(a) and ND-3653.2(a) by a factor, *f*, as determined in Reference 2, Tables NC-3611.2(e)-1 and ND-3611.2(e)-1, “Stress Range Reduction Factors.” In addition, the stress intensification factors (SIFs) and stress indices used in ASME Code (Reference 2) equations for calculating stresses at components are based on fatigue testing and, therefore, indirectly account for fatigue in Class 2 and 3 piping components. No cumulative usage factor is calculated for Class 2 and 3 piping.

Environmental impact on fatigue of ASME Code Class 2 and 3 piping will follow guidelines established by the NRC at the time of analysis.

3F.3.5 Functional Capability

10 CFR Part 50, GDC 2 requires that all ASME Code Class 1, 2, and 3 piping systems essential for safe shutdown of the plant remain capable of performing their safety function for all Service Level D loading conditions. This criterion is met by meeting the recommendations in NUREG-1367, Functional Capability of Piping Systems (Reference 9).

The NUREG-1367 (Reference 9) provision that the dynamic moments be "calculated using an elastic response spectrum analysis with ±15 percent peak broadening and with not more than 5 percent damping" will be considered met for piping analyzed by elastic time history methods as long as uncertainties in the applied time histories are accounted for and pipe damping used is not more than five percent.

Table 3F-3 summarizes the criteria to be used to ensure that the functional capability requirement of GDC 2 is met.

3F.3.6 Welded Attachments

Support and restraint designs that require welded attachments to the pipe for transfer of the pipe loads to the supporting structure will adhere to industry practices and ASME Code Cases identified in Section 3F.2.2.

3F.3.7 Thermal Stratification (Thermal Stratification, Cycling, and Striping)

3F.3.7.1 NRC Bulletin 79-13 (Feedwater Lines)

NRC Bulletin 79-13, Cracking in Feedwater System Piping (Reference 10), was issued as a result of a feedwater line cracking incident at D.C. Cook Nuclear Plant Unit 2that led to the discovery of cracks in numerous other plants. The primary cause of the cracking was determined to be thermal fatigue loading due to thermal stratification and high-cycle thermal striping during low flow emergency feedwater injection.

For the U.S. EPR design, the steam generators and main feedwater lines are designed to minimize thermal stratification. There are separate nozzles on the steam generator for the main feedwater and emergency feedwater connections. The main feedwater nozzle is located in the conical section of the steam generator, which aids in reducing thermal stratification.

The effects of thermal stratification and striping will be evaluated during the evaluation of the main feedwater system and the evaluation will confirm that all load cases meet the ASME Code (Reference 2) requirements.

3F.3.7.2 NRC Bulletin 88-11 (Surge Line)

NRC Bulletin 88-11, Pressurizer Surge Line Thermal Stratification (Reference 11), requires consideration of the effects of thermal stratification on the pressurizer surge line. The surge line in the U.S. EPR design will be analyzed with the RCL piping and supports. The effects of thermal stratification and striping will be evaluated as part of this analysis or it will be demonstrated that the surge line is not subjected to significant stratification or striping effects due to design features that mitigate these effects.

3F.3.7.3 NRC Bulletin 88-08 (Unisolable Piping due to Leaking Valves)

Unisolable sections of piping connected to the RCL will be evaluated to determine if thermal stratification and striping caused by a leaking valve are plausible, as described in NRC Bulletin 88-08, Thermal Stresses in Piping Connected to Reactor Coolant System (Reference 12). Contributions to fatigue from thermal stratification and striping will be considered where it is determined that these phenomena are plausible.

3F.3.8 Design and Installation of Pressure Relief Devices

3F.3.8.1 Design and Installation Criteria

The design and installation of safety valves and relief valves for overpressure protection are performed to the criteria specified in the ASME Code (Reference 2), Appendix O, “Rules for the Design of Safety Valve Installations. In addition, the following additional requirements must be met:

- Where more than one relief device is placed on the same header, instantaneous stresses in the pipe and support loads are calculated using the most adverse sequence of valve openings.
- Stresses are evaluated for all components (pipes, valves, supports, welds, and connecting systems) for the most adverse valve sequence.
- Stresses calculated as a result of valve reaction forces utilize dynamic or static calculation methods. If static methods are utilized, a DLF of 2.0 will be used.
- Stress and load combination requirements are specified in Table 3F-1 for ASME Code Class 1 and Table 3F-2 for ASME Code Class 2 and 3 piping.

3F.3.8.2 Analysis Requirements for Pressure Relieving Devices

3F.3.8.2.1 Open Discharge

Safety or Relief Valves that discharge directly to the atmosphere are considered open discharge configurations. Discharge forces are usually calculated using static methods with a DLF of 2.0. These static loads are then applied to the valve discharge in the piping analysis to evaluate stresses and support designs. Snubbers are considered engaged for this analysis.

3F.3.8.2.2 Closed Discharge

Relief or safety valves with discharges piped to headers or tanks are analyzed with no steady state thrust forces but must be analyzed for intermediate forces acting on elbows and tees during the initial phase of the release. These forces are similar to water hammer and steam hammer due to the instantaneous opening of the valves and shall be evaluated with other load cases impacting the piping systems.

3F.3.9 Intersystem LOCA

Low pressure piping systems that interface with the RCL and are thus subjected to the full RCL pressure will be designed for the maximum operating pressure of the RCL. The appropriate minimum wall thickness of the piping will then be calculated for each system using Equation 1 of Paragraph NB-3640 of the ASME Code (Reference 2) for Class 1 piping or Equation 3 of Paragraphs NC-3640 and ND-3640 for Class 2 and 3 piping. The piping will be analyzed to the requirements in Paragraphs NB-3650, NC-3650, and ND-3650.

3F.3.10 Seismic Category I Buried Pipe

ASME Code Class 2 and 3 Seismic Category I buried piping systems in the U.S. EPR design will be analyzed for pressure, weight, thermal expansion, and seismic loads using dynamic or equivalent static load methods. The acceptance criteria for buried piping systems are described in Table 3F-4.

3F.3.10.1 Static Loads and Load Combinations for Buried Pipe

Loads and Loading Conditions are similar to those outlined in Section 3F.3.3 but are modified for additional considerations of strains and stresses induced by the motion of the pipe in the surrounding soil mass. Thermal loads are impacted by the friction between the pipe and soil due to expansion and contraction of the pipe per the guidance in Guideline for the Design of Buried Steel Pipe (Reference 13).

3F.3.10.1.1 Pressure

Internal design pressure, P, is calculated as described in Section 3F.3.3.1.1. However, there is an external pressure, P_V for buried pipe associated with the overburden of soil and P_P for loads from surface loads. The allowable external pressure is calculated using the methods and formula in the ASME Code (Reference 2), Paragraphs NC-3133 and ND-3133.

3F.3.10.1.2 Deadweight

For buried pipe, deadweight loads must include the weight of the soil overburden. It must also include live loads from surface traffic such as trucks, rail, and construction equipment.

3F.3.10.1.3 Soil Overburden

Soil overburden pressure is dependent on the diameter of buried pipe as well as the burial depth relative to the groundwater table. Buried pipes are designed for soil load corresponding to weight of the overlying soil prism.

$$P_v = \gamma H$$

This equation applies to pipes buried above the groundwater table.

Where

P_v = overburden pressure on pipe due to soil, psi.

γ = dry unit weight of backfill material, lbs/in^3.

H = burial depth to top of pipe, inches.

In the case where the pipe is located below groundwater table or where seasonal change in groundwater table is significant, the effect of buoyancy and increased weight of water is considered. For such condition, soil pressure is computed as follows:

$$P_v = \gamma H - 0.33\gamma h + \gamma_w h$$

Where

h = depth of groundwater above pipe, inches.

γ_w = unit weight of water, lbs/in^3.

3F.3.10.1.4 Surface Loads

Live loads such as those imposed by trucks, rail, and construction equipment or other construction conditions are considered in the analysis and design. The pressure transmitted to the buried pipe under these loads is computed as follows:

$$P_p = 0.48 \frac{P_s}{H^2 \left[1 + \left(\frac{d}{H} \right)^2 \right]^{2.5}}$$

Where

P_p = surface load transmitted to the buried pipe, psi.

d = offset distance from the surface load to buried pipe, inches.

H = thickness of soil cover above the pipe, inches.

P_s = concentrated surface load, lbs.

The magnitude of P_p above is multiplied by an impact factor that is dependent on the soil cover and type of surface load. Reference 13 provides impact factors for highways and railways based on cover thickness. These factors vary between 1.0 for deep piping under highways to 1.75 for shallow piping under railways.

The magnitude of P_p is taken from Reference 13, considering AASHTO HS-20 Truck and Cooper E-80 railroad loads.

3F.3.10.1.5 Buoyancy Force

For utilities buried below groundwater table, vertical force due to buoyancy is considered and is evaluated as follows:

$$F_b = W_w - W_p - P_v D + \gamma_w h D$$

The above equation conservatively assumes that the pipe is empty.

Where

F_b = buoyancy force per unit length of pipe, lb/in.

D = outside diameter of the pipe, inches.

P_v = γH = overburden pressure due to soil, psi.

W_w = weight of water displaced by pipe per unit length, lb/in.

W_p = self weight of pipe per unit length, lb/in.

The corresponding buoyancy stress on the utility is computed as follows:

$$\sigma_b = \frac{F_b L^2}{10Z}$$

Where

L = length of the utility in the buoyancy zone, inches.

Z = section modulus of the utility, in^3.

3F.3.10.1.6 Pipe Ovalization

Under combined dead and live loads, buried pipes tend to ovalize, thereby causing through-wall bending stresses. The allowable ovalization (Reference 13) of the pipe diameter is evaluated using the following equation:

$$\text{Pipe ovality} = \frac{\Delta}{D} = \frac{D'KP}{\left[\frac{(E_{sct}I)_{eq}}{R^3} + 0.061E'\right]}$$

$$\sigma_b = 4E_{sct}\frac{\Delta}{D}\frac{t}{D}$$

Where

E' = modulus of soil reaction, psi.

K = bedding constant (typically taken to be 0.1).

R = outside radius of pipe, inches.

Δ = vertical deflection of the utility/pipe, inches.

P = pressure due to soil overburden, surface loads, flooding, and snow load, psi.

$(E_{sct} I)_{eq}$ = equivalent pipe wall stiffness per unit length of pipe, lb-in^2/in.

σ_b = through-wall bending stress, psi.

t = thickness of the pipe, inches.

E_{sct} = secant Modulus of the pipe material, psi (Note: E_{sct} = E if pipe is fabricated from steel).

D' = deflection lag factor (typically taken to be between 1.0 and 1.5).

I = $t^3/12$ = moment of inertia, in^4/in.

Pipe must be buried deep enough that crushing of the side wall of the pipe is eliminated. Soil, surface, and other credible event loads must not be excessive and cause buckling of the pipe. To avert ring buckling, the magnitude of the total vertical pressure is limited to equation below.

$$P(\textit{as defined for ovality}) \leq \frac{1}{\mathrm{FS}}\sqrt{32\mathrm{R}_{\mathrm{w}}\mathrm{B}'\mathrm{E}'\frac{(\mathrm{E}_{\mathrm{sct}}\mathrm{I})_{\mathrm{eq}}}{\mathrm{D}^3}}$$

FS = factor of safety with value dependent on relative magnitude of thickness of cover soil, H, and external pipe diameter, D. For $\mathrm{H/D} < 2.0$, FS = 3.0 and for $\mathrm{H/D} \geq 2$, FS = 2.5.

R_{w} = water buoyancy factor with magnitude 1 - 0.33h/H (0<h<H).

h = height of groundwater table above the top of the buried utility, inches.

B' = dimensionless empirical coefficient of elastic support.

$$\mathrm{B}' = \frac{1}{1 + 4\mathrm{e}^{\left(-0.065\frac{\mathrm{H}}{\mathrm{D}}\right)}}$$

All other parameters in above equation have been defined previously.

The effects of pressure (P, P_P, P_V), dead, and live loads from the effects of ovality must meet the requirements of Table 3F-4 as follows for Equation 8:

$$S_{SL} = \frac{B_1 PD}{2t_n} + \frac{B_2 M_A}{Z} + \frac{F_b L^2}{10Z} + 4E_{sct}\frac{\Delta}{D}\frac{t}{D} \leq 1.5S_h$$

Where

S_{SL} = Stress from sustained loads, psi.

P = Internal pressure + ABS Sum (P_P + P_V), psi.

B_1, B_2 = Stress indices.

t_n = Pipe nominal wall thickness, inches.

M_A = Moment due to weight, in-ibs.

S_h = Allowable stress (hot), psi.

3F.3.10.2 Thermal Expansion and Contraction

Depending on the relative temperature of the soil in which the pipe is buried and the temperature of the fluid contained in the pipe, a pipe that is fully restrained by the surrounding soil may experience contraction or expansion. This thermal-induced stress (due to friction between the pipe and soil) is considered and is evaluated as follows:

$$\sigma_A = E_{sct}\alpha(T_2 - T_1)$$

Where

σ_A = axial compressive stress, psi, in fully restrained pipe due to difference in temperature between soil and pipe content.

α = coefficient of thermal expansion of the pipe, in/in/°F.

T_2 = maximum operating temperature of fluid in the pipe, °F.

T_1 = burial installation temperature, °F.

The effects of restrained thermal expansion and contraction forces in buried pipe are evaluated against the requirements of the ASME Code (Reference 2), Paragraph NC-3653.2(a) or ND-3653.2(a) by using a modified Equation 10M; or Paragraph NC-3653.2(c) or ND-3653.2(c) by using a modified Equation 11M. The equations are as follows:

$$S_E = \frac{iM_C}{Z} + E_{sct}\alpha(T_2 - T_1) \le S_a$$

(Reference 2, Equation 10M)

Where

S_a = Allowable stress range for thermal expansion, psi.

M_C = range of resultant bending moment due to restrained thermal expansion, in-lb.

or

$$S_{TE} = \frac{PD}{4t_n} + 0.75i\frac{M_A}{Z} + i\frac{M_C}{Z} + E_{sct}\alpha(T_2 - T_1) \le (S_h + S_a)$$

(Reference 2, Equation 11M)

Where

S_E = Stress from restrained thermal expansion, psi.

S_{TE} = Stress from pressure, weight, and thermal expansion, psi.

3F.3.10.3 Seismic Loads

Seismic-induced damage to buried piping is largely due to wave propagation or permanent ground deformation resulting from fault movement, landslide, and liquefaction-induced lateral spread. Where buried piping enters a structure, the seismic anchor movements of the structure must be accounted for in the design of the piping. Other forms of damage related to ground movement such as elastic and consolidation settlement (total and differential), freeze-thaw induced settlement, and seismic-induced settlement due to soil compaction and rearrangement should be considered on a case-by-case basis. For the case of piping anchored to an adjacent building, strain development in the utility due to settlement of the building should be evaluated. The seismic effects on buried piping are self limiting in that strains are limited by the surrounding soil. Therefore the stresses due to these strains are secondary in nature.

A site investigation to assess the best route for the underground piping will need to be performed. During this field investigation, sites that are vulnerable to fault movement and liquefaction-induced landslide and lateral spread should be avoided. If a pipe must be buried in loose saturated cohesionless soil susceptible to liquefaction, rigorous linear and non-linear pipe-soil interaction analysis is carried out to evaluate the integrity of the pipe under settlement and lateral spread conditions that may be caused by the liquefiable soil. If the result of the soil-pipe interaction is not acceptable, options recommended in Reference 14 shall be considered:

3F.3.10.3.1 Axial and Bending Strains Due to Propagation of Seismic Waves

Typically, the magnitude of axial and bending strains on buried piping due to propagation of seismic wave is dependent on several factors, such as the buried material and soil properties and pipe-soil interfacial properties. Conservatively, axial and bending strains on the buried piping are taken to be the same as those of the seismic wave if there is no site specific field instrumentation to measure the strain level experienced by the buried piping. Based on the axial and bending strains developed in the buried piping, assuming long, linear runs remote from anchors or bends, the corresponding axial load and bending stress can be computed as follows:

$$F_a = \varepsilon_a A E_{sct}$$

$$M_b = \sigma_b Z$$

Where

$$\sigma_b = \varepsilon_b E_{sct}$$

In above equations,

E_{sct} = Secant modulus of the buried piping, psi.

ε_a = Axial strain in the buried piping due to wave propagation.

ε_b = Bending strain in the buried piping due to wave propagation.

Z = Section modulus of the buried piping, in^3.

A = Cross-sectional area of the pipe, in^2.

For the computation of loads developed at elbows, the simplified procedures outlined in Reference 14 are recommended for flexible and rigid conditions. At site locations where the differential settlement is significant, flexible anchors may be used in lieu of rigid anchors. All support structures (anchors) are designed to resist the resulting axial loads and bending stresses.

The general axial and bending strains due to seismic wave propagation are found as follows:

$$\varepsilon_a = \pm \frac{v}{\alpha_\varepsilon c}$$

$$\varepsilon_b = \pm \frac{Ra}{(\alpha_k c)^2}$$

Where

v = maximum velocity of the soil layer (particle) in which the piping is embedded, ft/sec.

a = maximum acceleration of the soil layer (particle) in which the piping is embedded, ft/sec^2.

c = apparent velocity relative to ground surface, ft/sec.

R = radius of the pipe, ft.

ε_b = bending strain.

ε_a = axial strain.

α_ε = wave velocity axial coefficient (compression = 1.0, shear = 2.0, Rayleigh = 1.0).

α_k = wave velocity bending coefficient (compression = 1.6, shear and Rayleigh = 1.0).

In Reference 15, it is noted that axial and bending strains are a result of three types of seismic waves: compression, shear, and surface or Rayleigh. The strain for each wave is calculated using the general form for axial and bending noted above.

As noted in Table 3F-2 for above ground piping, the effects of seismic loads on above ground piping must meet the requirements of Reference 2, Paragraph NC-3655 or ND-3655. As further indicated in Table 3F-2 and in compliance with the guidance in SECY-93-087 (Reference 7), page 23, the effect of SSE seismic anchor movements (which produce secondary stresses) together with normal loads are evaluated to a Service Level D limit. This has been done for above ground piping in the secondary stress equation shown in Table 3F-2 for Level D. Since the seismic effects in buried pipe produce secondary stresses, to be consistent with Table 3F-2 and the guidance provided, the two equations shown below for buried pipe must be evaluated. The use of the two equations allows for two possible cases: thermal expansion plus the amplitude of the buried pipe SSE effects or the range (equal to twice the amplitude) of the buried pipe SSE effects, whichever is larger. The use of the larger of the two results is consistent with the methodology in the example provided in Reference 14, Appendix 3, pages 45 and 46.

$$S_{NSSE} = \frac{iM_C}{Z} + \frac{iM_{SSE}}{Z} + \varepsilon_b E_{sct} + \varepsilon_a E_{sct} + E\alpha(T_2 - T_1) \le 3.0S_h \text{ but not greater than } 2.0S_y$$

$$S_{SSE} = \frac{2iM_{SSE}}{Z} + 2\varepsilon_a E_{sct} + 2\varepsilon_b E_{sct} \le 3S_h \text{ but not greater than } 2.0S_y$$

Where

S_{NSSE} = buried pipe stress due to normal plus the amplitude of SSE loads.

S_{SSE} = buried pipe stress due to the range of SSE loads.

M_{SSE} = amplitude of moments due to earthquake moment loading and anchor movements; earthquake moment loading is induced in the pipe near bends, intersections, and anchor points as described in Reference 15, Section 3.5.2.2(b).

S_Y = yield stress, psi.

The allowable stress, $3.0S_h$ or $2.0S_Y$, is based on Service Level D limits due to the fact that only SSE load case is evaluated in the piping design for the U.S. EPR design.

The value of M_{SSE}, ε_b, and ε_a represent the amplitude of the seismic moment and seismic strains.

3F.4 Piping Analysis Methods

3F.4.1 Experimental Stress Analysis

Experimental Stress Analysis will not be used to qualify piping for the U.S. EPR Design Certification.

3F.4.2 Seismic Analysis Methods

Seismic Category I piping systems shall be designed to withstand the effects of an SSE and maintain the capability of performing their safety functions. This design will be accomplished by performing a seismic analysis for all Seismic Category I subsystems using methods in accordance with SRP 3.7.3 (Reference 1).

The seismic response of a piping system is determined by developing a mathematical model of the system suitable for calculating the response of the system to the seismic input. Dynamic equilibrium equations are formulated for the system using the direct stiffness method. In this method, the element stiffness matrices are formed according to virtual work principles and assembled to form a global stiffness matrix for the system relating external forces and moments to nodal displacements and rotations.

Once the mathematical model has been established, dynamic equilibrium equations are solved to determine the seismic response of the system by performing a modal analysis by either the Response Spectrum Method or Time History Method. Alternatively, the Direct Integration Time History Method and, where applicable, the Equivalent Static Load Method may be used. These methods of seismic analysis are described below.

Non-seismic piping that interacts with Seismic Category I or II SSC will be analyzed by response spectra or equivalent static methods.

3F.4.2.1 Seismic Input

The response spectra curves for the U.S. EPR design are being developed to cover an appropriate range of possible soil conditions with the vertical and horizontal ground motion anchored to a peak ground acceleration of 0.3g.

3F.4.2.2 Response Spectrum Method

The effects of the ground motion during an SSE event are transmitted through structures to the piping systems at support and equipment anchorage locations. In the response spectrum method of analysis, peak values of response are determined for each mode of the piping system by application of floor response spectra, which represent the maximum acceleration response of an idealized single-degree-of-freedom damped oscillator as a function of natural frequency to the vibratory input motion of the structure.

The floor response spectra are applied to the piping system at locations of structural attachment, such as support or equipment locations. The response spectra analysis is performed using either enveloped uniform response spectra or independent support motion (ISM) using multiple spectra.

Response spectrum analysis of piping systems subjected to dynamic seismic loads is performed using a linear method of analysis based on normal mode – modal superposition techniques. In this approach, seismic analysis of linear systems is based on the solution of simultaneous differential equations subject to a set of initial conditions and forces.

The response of a multi degree-of-freedom linear system subjected to seismic excitation is represented by the following differential equation of motion:

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=-[M]\{\ddot{u}\}$$

Where:

$[M]$ = mass matrix (n x n).

$[C]$ = damping matrix (n x n).

$[K]$ = stiffness matrix (n x n).

$\{X\}$ = column vector of relative displacements (n x 1).

$\{\dot{X}\}$ = column vector of relative velocities (n x 1).

$\{\ddot{X}\}$ = column vector of relative accelerations (n x 1).

$\{\ddot{u}\}$ = input acceleration vector.

n = number of degrees of freedom.

The response spectrum method of analysis uses modal-superposition methods where the mode shapes are used to transform X in the equations of motion into a generalized coordinate system by substitution of the following:

$$\{X\}=[\phi]\{Y\}$$

Where:

$[\phi]$ = mass normalized mode shape matrix, $[\phi]^T[M][\phi] = [1]$.

$\{Y\}$ = vector of normal or generalized coordinates.

This transformation decouples the equation of motion above when each term is multiplied by the transposition of the mode shape matrix. This solution assumes that the mode shapes are normal (orthogonal) and also assumes orthogonality of the damping matrix.

The decoupled equation of motion for a system subjected to input acceleration due to seismic motion, $\ddot{u}$, for the nth mode is:

$$\ddot{Y}_n + 2\lambda_n\omega_n\dot{Y}_n + \omega_n{}^2Y_n = -\Gamma_n\ddot{u}$$

Where:

Y_n = generalized coordinate of nth mode.

λ_n = damping ratio for the nth mode expressed as fraction of critical damping.

ω_n = circular frequency of nth mode of the system (radians/second).

Γ_n = modal participation factor of the nth mode

= $\{\phi_n\}^T[M]\{r\}/(\{\phi_n\}^T[M]\{\phi_n\})$

where $\{r\}$ = influence coefficient vector due to a unit input displacement.

If all support points in a piping system move in phase (i.e., uniform excitation), then $\{r\}$ consists of ones and zeros to reflect the direction of input excitation. If all support points do not move in phase (i.e., multiple excitation), $\{r\}$ is calculated to reflect the attenuation of the effect of motion of one support group through the other support groups and a unique influence coefficient matrix is developed for each support group. The magnitude of the influence coefficient at a given point in the system is equivalent to the motion at the point of interest due to a statically applied unit displacement of the support group subjected to the excitation.

For the response spectrum method, the generalized response of each mode is determined from the expression below.

$$Y_n(\max) = \Gamma_n\left(\frac{S_{an}}{\omega_n{}^2}\right)$$

Where:

S_{an} = Spectral acceleration corresponding to frequency ω_n.

The maximum displacement of node *j* relative to the base due to mode *n* is then:

$$X_{jn}(\max) = \phi_{jn}Y_n(\max)$$

This expression gives the maximum displacement from which other modal response quantities, such as forces, can be calculated. In performing these calculations for response quantities of interest, the signs of the participation factor, Γ, the maximum generalized coordinate, $Y_{jn}(\max)$, the maximum displacement of node *j* relative to the base due to mode *j*, $X_{jn}(\max)$, and other response quantities are retained.

The acceleration of a mass point and the associated inertia force are calculated in a similar manner as follows:

$$\ddot{Y}_n = \omega_n^2 Y_n = \Gamma_n S_{an}$$

and the acceleration of node *j* due to mode *n*, a_{jn}, equals:

$$a_{jn} = \ddot{Y}_n \phi_{jn}$$

and the inertia force at node *j* due to mode *n*, F_{jn}, equals:

$$F_{jn} = M_j a_{jn} = M_j \ddot{Y}_n \phi_{jn}$$

The floor response spectra are applied to the piping system in each of three orthogonal directions. Each of the directional components of earthquake motion input will in turn produce responses in the piping system in all three directions at each natural frequency of the piping system. The total seismic response of the system is determined by combining the modal and spatial results using the methods below.

3F.4.2.2.1 Development of Floor Response Spectrum

In the response spectrum method of analysis, the design floor response spectra for the structures shall be generated according to RG 1.122, Rev. 1 (Reference 17). The development of the floor response spectra will consider simultaneous earthquake accelerations acting in three orthogonal directions, two horizontal and one vertical.

The uncertainties in the structural frequencies due to uncertainties and approximations in the material and structural properties and modeling methods used in the development of the floor response spectrum shall be considered in the response spectrum analysis in one of two ways. Either the raw floor spectra will be smooth and then peak broadened or, where a reduction in unnecessary conservatism is desired, the peak shifting method of analysis will be used.

Peak Broadening Method

Peak broadened response spectra shall be generated using the methods of RG 1.122 (Reference 17). In order to account for uncertainties in the structural response, response spectra will be peak broadened by a minimum of ±15 percent.

Peak Shifting Method

Peak shifting analysis may be used in place of peak broadening in order to reduce unnecessary conservatism in the design. Similar to broadening, peak shifting will consider a minimum of ±15 percent uncertainty in the peak structural frequencies. However, spectral shifting reduces the amount of conservatism by considering that the structural natural frequency is defined by a single value, not a range of values. Therefore, only one mode of the piping system can respond at the peak acceleration (Reference 18).

In the peak shifting method, the natural frequencies of the piping system within the maximum peak acceleration broadened spectral frequency range defined above are determined. If no piping system natural frequencies exist within this frequency range, successively lower acceleration peaks are broadened until the first range containing at least one natural frequency of the piping is found.

Considering that the peak structural frequency may lie at any one frequency within the broadened range, N + 3 separate response spectra analyses are then performed, where N is the number of piping modes within the broadened frequency range. The first analysis uses the unbroadened response spectrum. The second and third analyses use the unbroadened spectrum modified by shifting the frequencies associated with each spectral value by $-\Delta fj$ and $+\Delta fj$, where Δfj is the amount of peak shifting required to account for the uncertainties of the structural response. The remaining N analyses also use the unbroadened spectrum modified by shifting the frequencies associated with each spectral value by a factor of:

$$1+\frac{(f_e)_n - f_j}{f_j}$$

Where

$(f_e)_n$ = Piping system natural frequency occurring within the broadened range, for n = 1 to N.

f_j = frequency at which the peak acceleration occurs (for the peak under consideration).

The modal results of each of these analyses are then combined separately using the combination procedures below. The final results are obtained by enveloping the results of the separate analyses.

Where three different floor spectrum curves are used to define the response of the structure, the peak shifting method is applied in each direction.

3F.4.2.2.2 Multiply Supported Systems

Uniform Support Motion

Piping systems supported by multiple elevations within one or more buildings may be analyzed using Uniform Support Motion (USM). This analysis method applies a single set of spectra at all support locations that envelops all of the individual response spectra for these locations. An enveloped response spectrum is developed and applied for each of the three orthogonal directions of input motion.

The combinations of modal responses and spatial components for systems analyzed using USM are performed consistent with the guidance provided in RG 1.92, Rev. 2 (Reference 21). The modal and directional responses are combined as described in Sections 3F.4.2.2.3 and 3F.4.2.2.4, respectively. See Section 3F.4.2.2.5 for consideration of relative displacements at support locations.

Independent Support Motion

ISM may be used when piping systems are supported by multiple support structures or at multiple levels within a structure. In this method of analysis, supports are divided into support groups with different seismic excitation applied to each group. A support group is made up of supports that have the same time-history input. Typically, a support group is made up of supports attached to the same structure, floor, or portion of a floor.

The combinations of modal responses and spatial components for systems analyzed using ISM are performed consistent with the recommendations in NUREG-1061, Volume 4 (Reference 19). Additionally, when using ISM, the seismic response of each mode is calculated by combining the responses of all support groups into one by using absolute summation method per the recommendations of NUREG-1061, Volume 4 (Reference 19). The modal and directional responses are then combined as described in Sections 3F.4.2.2.3 and 3F.4.2.2.4, respectively. See Section 3F.4.2.2.5 for consideration of relative displacements at support locations.

Analyses performed using ISM shall use the RG 1.61, Rev. 1 (Reference 20), damping values (See Section 3F.4.2.5).

3F.4.2.2.3 Modal Combination

The inertial response of a piping system in a seismic response spectrum analysis is considered in two parts. The modal analysis calculates the peak response of the piping system for all natural frequencies of the system below a defined cutoff frequency. This analysis consists of all modes with seismic excitation frequencies up to the frequency at which spectral accelerations return to the zero period acceleration (ZPA). This frequency is referred to as the ZPA cutoff frequency. For the U.S. EPR design, the ZPA cutoff frequency is 70 Hz for high frequency (HF) cases and 40 Hz for generic cases for seismic analysis or as defined by Figures 2 and 3 in RG 1.92, Rev. 2 (Reference 21). Higher ZPA cutoff frequencies may be required for other dynamic load cases.

At modal frequencies above that corresponding to the ZPA, pipe members are considered rigid. The acceleration associated with these rigid modes is usually small. However, in certain situations the response to high frequency modes can significantly affect support loads, particularly axial restraints on long piping runs. To account for the effects of the residual rigid response, a missing mass correction is applied.

When performing response spectrum analyses using USM, the inertial response from the modal analysis is also divided into two types of response, periodic or rigid. At low frequencies, in the amplified regions of the response spectrum, the total inertial response is considered as a periodic response. Beyond this region but below the ZPA cutoff frequency (intermediate frequencies), the modal response consists of both periodic and rigid components. The total inertial solution is then determined by combining the individual modal responses, both periodic and rigid, and the residual rigid response per the guidance of RG 1.92 (Reference 21) as described in Section 3F.4.2.2.3.

For analyses performed using ISM, all modal response at frequencies below the ZPA cutoff frequency is treated as periodic while the response above this frequency is rigid. The treatment and combination methods of these responses to obtain the total inertial solution will be performed per NUREG-1061 (Reference 19) as described in Section 3F.4.2.2.3.

3F.4.2.2.3.1 USM Periodic Modal Responses

RG 1.92 (Reference 21) provides guidance on combining the individual periodic modal results due to each response spectrum in a dynamic analysis performed using USM.

For piping systems with no closely spaced modes, the square root of the sum of the squares (SRSS) method is applied to obtain the representative maximum response of each element, as shown in the following equation:

$$R = \left[\sum_{k=1}^{N} R_k^2 \right]^{\frac{1}{2}}$$

Where

R = the representative maximum response due to the input component of the earthquake.

R_k = the peak response due to the kth mode.

N = the number of significant modes.

This method may produce unconservative results for piping systems with closely spaced modes. Therefore, the double sum method for combining the periodic modal responses considering either the Rosenblueth or Der Kiureghian correlation coefficients provided in RG 1.92 (Reference 21) will be used to obtain a more accurate modal response for frequencies below the rigid range.

3F.4.2.2.3.2 USM Rigid Components of Modal Response

In the intermediate frequency region where modal responses consist of both periodic and rigid components, these components are separated using either the Gupta Method or Lindley-Yow method as presented in RG 1.92 (Reference 21).

These rigid individual modal responses will then be combined by algebraic summation.

3F.4.2.2.3.3 Residual Rigid Response

Piping system modes with frequencies greater than the ZPA cutoff frequency are considered as high frequency or rigid range modes. For flexible piping systems, the high frequency response may not be significant since a significant portion of the system mass is excited at frequencies below the ZPA. However, for piping systems, or portions of piping systems, that are more rigidly restrained or have lumped masses near rigid restraints, a significant portion of the system mass may not be accounted for in the low frequency modal analysis. This mass that is not excited at the lower frequencies is termed the “missing mass” of the system. While high frequency modes usually involve small displacement amplitudes and small pipe stresses, they can have a significant impact on support loads.

The response from high frequency modes must be included in the response of the piping system. Guidance for including the missing mass effects for USM is provided in RG 1.92 (Reference 21).

The peak modal responses of the system at frequencies above the ZPA are considered to be in phase. Thus, the responses of all high frequency modes are combined by algebraic summation.

The U.S. EPR design will use the method presented in RG 1.92 (Reference 21) or the left-out-force method described below for calculating and applying the response of the high frequency modes based on applying a missing mass correction. Although this method uses a different computational procedure than described in RG 1.92 (Reference 21), Appendix A, the two methods produce the same result. The left-out-force method is used by SUPERPIPE and BWSPAN uses the method in RG 1.92 (Reference 21), Appendix A.

The total inertia forces in a system, considering a piping system under simple excitation in a steady-state condition with a unit acceleration applied in a specified direction, is mathematically represented by:

$$\{F_t\} = [M]\{r\}$$

Where

$\{F_t\}$ = Total inertia forces in the specified direction.

$[M]$ = Mass matrix.

$\{r\}$ = Mass point displacement vector produced by a statically applied unit ground displacement.

The sum of the inertia forces for all modes included in the modal analysis is calculated as:

$$\{F_s\} = \sum_{n=1}^{N}\{F_n\} = \sum_{n=1}^{N}[M]\{\phi_n\}\{\phi_n\}^T[M]\{r\}$$

Where

$\{F_s\}$ = total inertia force seen by the system in the low frequency modal analysis.

$\{F_n\}$ = inertia force of mode n.

$\{\phi_n\}$ = mode shape.

N = number of modes calculated in the modal analysis.

Therefore, the missing or left out forces, considering a unit ground acceleration in a specified direction, are calculated as:

$$\{F_m\} = \{F_t\} - \{F_s\} = [M]\{r\} - \sum_{n=1}^{N}[M]\{\phi_n\}\{\phi_n\}^T[M]\{r\}$$

Or:

$$\{F_m\} = [M]\{r\}\left[1 - \sum_{n=1}^{N}[M]\{\phi_n\}\{\phi_n\}^T\right]$$

The missing inertia forces are calculated independently for all input components of earthquake motion (i.e., in each direction for each support group). The mode displacements, member end action, and support force corresponding to each missing force vector is determined with a modal acceleration equal to the ZPA.

As an alternative, when using the Lindley-Yow method, the Static ZPA method for calculating a total mass rigid response presented in RG 1.92 (Reference 21), Section C.1.4.2, may be used.

3F.4.2.2.3.4 USM Complete Inertial Response

For USM response spectra analyses, the complete inertial response is calculated using the methodology provided in RG 1.92 (Reference 21), Section C.1.5. In using these methods, the total rigid response will be calculated by algebraic summation of the applicable rigid response components and then combined with the total periodic response using the SRSS method.

3F.4.2.2.3.5 ISM Combination of Modal Responses

For piping systems analyzed using ISM methods, modal results are combined without the consideration of closely spaced modes, per NUREG-1061 (Reference 19). Therefore, for these systems, modal results are combined by the SRSS method presented in Section 3F.4.2.2.3. Additionally, the entire modal response for modes below the ZPA cutoff frequency is treated as a periodic response.

The residual rigid response will be calculated using the missing mass method as that presented in Section 3F.4.2.2.3. This missing mass response will then be combined with the low frequency modal results by the SRSS method, per NUREG-1061 (Reference 19).

3F.4.2.2.4 Directional Combination

Following the modal combination of results, the responses of the piping system due to each of the three orthogonal earthquake motion inputs are combined. The collinear responses due to each of the input components of motion are combined using the SRSS method (Reference 21).

3F.4.2.2.5 Seismic Anchor Movements

In addition to the dynamic inertia loads, the effects of differential displacements of equipment or structures to which the piping system attaches during a safe shutdown earthquake shall also be considered. The maximum relative displacement for each support location may be obtained from the results of the structural dynamic analysis for the supporting structure or calculated from the applicable floor response.

If the support locations are within a single structure, the seismic displacements are considered to be in-phase and the relative displacement between locations is generally small and may be neglected from the analysis. However, where supports are located within different structures or at flexible equipment connections, the displacements of these locations are conservatively assumed to move 180 degrees out-of-phase and the relative displacements between supported locations must be considered. The analysis of seismic movements at decoupled branch line locations is described in Section 3F.5.4.2.

The analysis of these seismic anchor movements will be performed as a static analysis with all dynamic supports active. The results of this analysis shall be combined with the piping system seismic inertia analysis results by absolute summation when an enveloped USM is used for the dynamic analysis, per SRP 3.7.3 (Reference 1). When ISM is used in the inertial analysis, the responses due to the relative displacements and those due to inertia are combined by the SRSS method, per NUREG-1061 (Reference 19).

3F.4.2.3 Time History Method

Seismic analyses may be performed using time history analysis methods in lieu of response spectrum analysis. Time history analysis may also be used for the dynamic analysis of water hammer or steam hammer effects, relief valve or safety valve thrust loads, jet force loads, or other hydraulic transient loads. The time history analyses of piping systems for the U.S. EPR design may be performed using BWSPAN or SUPERPIPE (See Section 3F.5.1 for description of computer codes).

The modal superposition method of time history analysis is used for seismic piping analyses with acceleration time history seismic input. This method is based on decoupling of the differential equations of motion, considering a linear elastic system, using the same method as that described in Section 3F.4.2.2. The total response of the system is determined by integrating the decoupled equations for each mode and combining the results of the modes at each time step using algebraic addition.

The mode shapes and frequencies are determined as in the response spectrum analysis. The cutoff frequency for the determination of modal properties is 40 Hz for generic cases and 70 Hz for HF cases, or as defined in Figures 2 and 3 of RG 1.92, Rev. 2 (Reference 21), as this is expected to encompass all of the important response frequencies of the system. Missing mass effects of the high frequency modes beyond the cutoff frequency are included via the Missing Mass Method described in Regulatory Position C.1.4.1 and RG 1.92, Rev. 2 (Reference 21), Appendix A.

Time step studies will be performed for three of the ASME Code Class 1 attached piping problems that are slated to be analyzed during the detailed design effort for the U.S. EPR design. The smallest integration time step required for convergence in these sample analyses will be used for all of the Class 1 piping analyses. Convergence will be determined by halving the integration time step until it can be shown that halving it further will not increase the response of the system by more than 10 percent. If time history analysis of Class 2 and 3 piping problems is performed, the integration time step will be established in a similar manner, that is, through time step studies on a representative sample of Class 2 and 3 piping problems.

To account for uncertainties in the structural analysis for seismic loading, a peak shifting approach similar to that described in Section 3F.4.2.2.1 for response spectrum analysis is used. This is accomplished by first converting the seismic time history excitations into response spectra, and then proceeding through the methodology outlined in Section 3F.4.2.2.1. Note that shifting of the input excitation peaks is accomplished by adjusting the time step of the time histories that represent the excitations.

Damping values are described in Section 3F.4.2.5.

The direct integration time history analysis method may be used as an alternative to the modal superposition time history analysis. In this method, the differential equation of motion, as provided in Section 3F.4.2.2, is solved directly on the uncoupled equations without transformation. Rayleigh damping, or mass and stiffness damping, is used when direct integration time history analysis is performed.

Input time histories are analyzed for each of the three mutually orthogonal directions of input motion. The three directional time history inputs are statistically independent and they are applied simultaneously in one analysis. The total response at each time step is calculated as the algebraic sum of the three directional results. Alternatively, the three time histories may be applied individually and the responses combined by the SRSS method.

3F.4.2.4 Equivalent Static Load Method

An alternate method of analyzing the effects of the SSE on a piping system is to use an equivalent static load method. This simplified analysis considers the mass of piping and components as lumped masses at their center of gravity locations. The seismic response forces due to these masses are then statically determined by multiplication of the contributing mass by an appropriate seismic acceleration coefficient at each location. The seismic acceleration coefficient is determined based on the dynamic properties of the system. When the equivalent static load method is used, justification will be provided that the use of a simplified model is realistic and the results are conservative.

In general, piping systems are multiple degree of freedom systems and have a number of significant modal frequencies in the amplified region of the response spectrum curve (below the ZPA). For multiple degree of freedom systems, the peak acceleration of the appropriate floor response spectra will be multiplied by 1.5. For cases where a piping configuration can be demonstrated to respond as a single degree of freedom system with a known fundamental frequency or rigid system with fundamental frequency beyond the cutoff frequency, a factor of 1.0 may be used with the highest spectral accelerations at that frequency or any higher frequency (as may be the case for multiple peak input spectra).

Mathematically, the seismic force, F_1, on a mass point in one direction is represented as:

$$F_1 = kmS_a$$

where:

k = 1.0 for single degree of freedom or rigid system.

1.5 for multiple degree of freedom system.

m = mass in direction one.

S_a = value of acceleration from response spectrum.

The forces from each of the three orthogonal directions of earthquake are applied to calculate seismic stresses and then combined by the SRSS method to calculate overall seismic stresses.

This analysis is performed for all three directions of seismic input motion. The results of these three analyses are then combined using the SRSS method, as in the response spectrum analyses. The relative motion of support locations (seismic anchor movements) are considered as in Section 3F.4.2.2.5.

All seismic supports are considered active in this analysis.

3F.4.2.5 Damping Values

RG 1.61, Rev. 1 (Reference 20), damping values will be used for ISM response spectra and Time-History analysis. RG 1.61, Rev. 1 (Reference 20), will also be used for piping systems analyzed using USM response spectra. Frequency dependent damping, as defined in RG 1.61, Rev. 1 (Reference 20), Regulatory Position C.2, Figure 1, may be used for a piping analysis provided the five conditions defined in Regulatory Position C.2 are met.

For piping systems analyzed using a uniform enveloped response spectra analysis, RG 1.61, Rev. 1 (Reference 20), damping will be used in conjunction with RG 1.92, Rev. 2 (Reference 21).

When composite modal damping is applied in a dynamic analysis, each model subgroup (piping, supports, equipment, etc.) is assigned an appropriate damping value per RG 1.61, Rev. 1 (Reference 20). The equivalent modal damping matrix or composite modal damping matrix is calculated for each mode by one of the two methods shown below:

$$\overline{\beta_j} = \{\phi\}^T[\overline{M}]\{\phi\}$$

or

$$\beta_j = \frac{\{\phi\}^T[\overline{K}]\{\phi\}}{K^*}$$

Where:

$$K^* = \{\varphi\}^T[K]\{\varphi\}$$

$[K]$ = assembled stiffness matrix.

$\overline{\beta_j}$ = equivalent modal damping ratio of the j^{th} mode.

$[\overline{K}],[\overline{M}]$ = the modified stiffness or mass matrix constructed from element matrices formed by the product of the damping ratio for the element and its stiffness or mass matrix.

$\{\varphi\}$ = j^{th} normalized modal vector.

Note: Damping beyond 20 percent will not be used.

3F.4.3 Inelastic Analysis Methods

Inelastic analysis will not be used to qualify piping for the U.S. EPR Design Certification.

3F.4.4 Non-Seismic/Seismic Interaction

The U.S. EPR design utilizes state-of-the-art computer modeling tools for design and location of structures, equipment, and piping. These same tools are used to minimize the interactions of seismic and non-seismic components, making it possible to protect Seismic Category I piping systems from adverse interactions with non-seismic piping and components. In the U.S. EPR design, the primary method of protection for seismic piping is isolation from all non-seismically analyzed piping. In cases where it is not possible or practical to isolate the seismic piping, adjacent non-seismic piping is classified as Seismic Category II and analyzed and supported such that an SSE event will not cause an unacceptable interaction with the Seismic Category I piping. Alternatively, an interaction evaluation may be performed to demonstrate that the interaction will not prevent the Seismic Category I piping system from performing its safety related function.

For non-seismic piping attached to seismic piping, the dynamic effects of the non-seismic piping are accounted for in the modeling of the seismic piping. The non-seismic piping attached to the analysis boundary is designed to preclude causing failure of the seismic piping during a seismic event.

3F.4.4.1 Isolation of Seismic and Non-Seismic Systems

Isolation of seismic and non-seismic systems is provided by either geographical separation or by the use of physical barriers. Isolation minimizes the interaction effects that must be considered for the seismic systems and minimizes the number of non-seismic systems requiring more rigorous analysis.

Several routing considerations are used to isolate seismic and non-seismic systems. When possible, non-seismic piping is not routed in rooms containing safety-related piping or equipment. Non-seismic piping that cannot be completely separated from seismic systems must be shown to have no interaction with the seismic systems based on separation distance or an intermediate barrier, or it must be classified as Seismic Category II piping.

3F.4.4.2 Interaction Evaluation

Non-seismic piping and components may be located in the vicinity of safety-related piping without being qualified as Seismic Category II provided an impact evaluation is performed to verify that no possible adverse impacts will occur. In this evaluation, the non-seismic components are assumed to fall or overturn as a result of a seismic event. Any safety-related piping system or component that may be impacted by the non-seismic component is identified as an interaction target and evaluated to ensure that there is no loss of ability to perform its safety-related function.

The following assumptions and guidelines are used to evaluate non-seismic/seismic interactions:

- All non-seismic hangers on the non-seismic piping system are assumed to fail instantaneously.
- All flanges on bolted connections on the non-seismic piping system are assumed to fail, thus allowing each section of piping to fall independently.
- Welded non-seismic piping supported by a seismic structure or component is assumed to fail at all rigidly constrained locations.

3F.4.5 Small Bore Piping

Small bore piping (including instrumentation lines) for the U.S. EPR design is defined as ASME Code Class 1 piping that is one inch NPS and smaller, and Class 2, 3, and Quality Group D piping that is two inch NPS and smaller. This piping may be analyzed using response spectrum methods described in Section 3F.4.2.2 or the equivalent static method described in Section 3F.4.2.4.

3F.5 Piping Modeling Techniques

3F.5.1 Computer Codes

The following computer programs are used in the analysis of safety-related piping systems.

3F.5.1.1 SUPERPIPE

SUPERPIPE is a comprehensive computer program for the structural design and analysis of piping systems. This program is used to analyze piping for both static and dynamic loads and performs design checks for ASME Code Class 1, 2, and 3 and ASME B31.1 piping.

Static analyses performed by SUPERPIPE include deadweight, distributed loads, thermal, internal pressure, and applied forces moments or displacements. Dynamic analysis methods include both response spectrum analysis and time-history analysis using either modal superposition or direct integration methods.

SUPERPIPE is developed and maintained by AREVA and has been verified and validated to NRC standards.

3F.5.1.2 BWSPAN

BWSPAN is an AREVA developed code that performs structural analysis of piping and structural systems. Deadweight, thermal expansion, response spectrum, time history, and thermal stratification loading can be analyzed. Output includes displacements, loads, accelerations, and displacement time histories, as appropriate. BWSPAN also performs pipe stress and fatigue calculations to a variety of design codes including ASME B31.1 (Reference 29) and the ASME Code (Reference 2). BWSPAN also calculates stresses for linear type supports according to Subsection NF of the ASME Code (Reference 2).

3F.5.1.3 GT STRUDL

GT STRUDL is a general purpose structural analysis program used for the design and analysis of pipe support structures. The program has the capability to perform both static and dynamic analyses using simple beam elements found in most pipe support structures. GT STRUDL is being used to determine member stresses, weld stresses, forces, and moments applied to the building structures, and deflections used to validate the rigid support assumptions used in design of the piping. The program is being used for ASME Code Class 1, 2, and 3 supports, as well as supports meeting ANSI/AISC N690, Specification for the Design, Fabrication and Erection of Steel Safety-Related

Structures for Nuclear Facilities (Reference 24), and the AISC Manual of Steel Construction (Reference 25).

GT STRUDL is owned and maintained by Georgia Tech. Verification of the GT STRUDL computer program is accomplished by executing verification cases and comparing the results to those provided by Georgia Tech. Each document that describes a GT STRUDL analysis includes information regarding the verification analysis and its results. Error notices from Georgia Tech are processed and records pertaining to error notification, tracking, and disposition are available for NRC inspection.

3F.5.2 Dynamic Piping Model

For dynamic analysis, the piping system is idealized as a three dimensional framework using specialized finite element analysis programs. The analysis model consists of a sequence of nodes connected by beam elements with stiffness properties representing the piping and other in-line components. Nodes are typically modeled at points required to define the piping system geometry as well as lumped mass locations, support locations, locations of structural or load discontinuities, and at other locations of interest along the piping. System supports are idealized as springs with appropriate stiffness values for the restrained degrees of freedom.

In the dynamic mathematical model, the distributed mass of the system, including pipe, contents, and insulation weight, is represented either as a consistent (distributed) mass or as lumped masses placed at each node. For the latter case, in order to adequately determine the dynamic response of the system, elements may be subdivided and additional mass points added. The minimum number of degrees of freedom in the model is to be equal to twice the number of modes with frequencies below the ZPA frequency. Maximum mass point spacing may be no greater than one half of the span length of a simply supported beam with stiffness properties and distributed mass equal to that of the piping cross-section and a fundamental frequency equal to the cutoff frequency. This maximum span between mass locations is mathematically represented as:

$$S_m = \frac{1}{2}\left(\frac{\pi}{2f_m}\right)^{0.5}\left(\frac{EIg}{w}\right)^{0.25}$$

Where,

S_m = Maximum mass point spacing span.

f_m = Dynamic properties analysis cut-off frequency.

E = Young's Modulus.

I = Moment of Inertia of the pipe.

g = Gravitational Acceleration.

w = Weight of the pipe per unit length.

Concentrated weights of in-line components, such as valves, flanges, and instrumentation, are also modeled as lumped masses. Torsional effects of eccentric masses are included in the analysis. For rigid components (those with natural frequencies greater than the ZPA cutoff frequency), the lumped mass is modeled at the center of gravity of the component with a rigid link to the pipe centerline. Flexible components (those with natural frequencies less than the ZPA cutoff frequency) are included in the model using beam elements and lumped mass locations to represent the dynamic response of the component.

A portion of the weight of component type supports (such as snubbers, struts, spring hangers, etc.) is supported by the pipe and must be considered in the piping analysis model. The mass contributed by the support is included in the analysis when it is greater than 10 percent of the total mass of the adjacent pipe span (including pipe, contents, insulation, and concentrated masses). The adjacent span is defined as the piping including the applicable support and bounded by the adjacent restraint on each side of this support in each direction. Because the mass of a given support will not typically contribute to the piping response in the direction of the support, only the support mass in the unsupported directions need to be considered, unless the support is flexible in the supported direction.

3F.5.3 Piping Benchmark Program

Pipe stress and support analysis will be performed by the COL applicant(s) as discussed in Section 3.9.1.2.

3F.5.4 Model Boundaries

Piping system analysis models are typically terminated by one of three techniques. These include termination at structural boundaries, termination based on decoupling criteria, or termination by model isolation methods. Structural boundaries and the use of decoupling criteria are the preferred methods. However, after applying these first two methods, further division of the piping system may be desired to create more manageable models for analysis. This may be accomplished using the model isolation method.

3F.5.4.1 Structural Boundaries

The most preferable model boundary is a rigid structural attachment restraining all six degrees of freedom for the piping, such as an equipment nozzle or penetration. Structural model boundaries provide isolation of the effects of the piping on one side of the boundary to the piping on the opposite side. For large piping systems, the following types of intermediate structural boundaries may be added to the system during design to allow for further division of the analysis model.

3F.5.4.1.1 In-line Anchors

An in-line anchor is a pipe support that restrains the piping in all six degrees of freedom, thereby isolating the piping effects on each side of the support from the other. While an in-line anchor provides a clean model boundary for analysis purposes, it may not be practical in many situations. The addition of in-line anchors generally creates stiffer piping systems and may cause significant increases in stress and support loads on lines with high thermal movements. Additionally, the use of in-line anchors on high energy lines adds additional postulated terminal end pipe rupture locations. Therefore, additional in-line anchors are only added if they are determined to be practical.

When in-line pipe anchors are used, anchor load results from seismically analyzed piping on both sides of an anchor are combined to obtain the design loads for the anchor.

3F.5.4.2 Decoupling Criteria

Piping analysis models may be divided by the use of decoupling criteria. Unlike the isolation of effects at the termination point provided by the structural boundary methods, the decoupling criteria provide a model termination point where the effects from one side to the other are limited and can be accounted for using defined methods.

A branch line may be excluded from the analysis model of the run pipe if it is sufficiently small compared to the run pipe, so that the branch has little effect on the results of the run pipe analysis. Generally, branch lines and instrument connections may be decoupled from the analysis model of larger run piping provided that either the ratio of the branch pipe diameter to the run pipe diameter (D_b:D_r) is less than or equal to 1:3 or the ratio of the moment of inertia of the two lines (I_b:I_r) is less than or equal to 1:25.

The decoupling criteria may also be applied for in-line pipe size changes, such as at a reducer or reducing insert. In this case, the smaller diameter pipe would be treated as the branch line and the larger pipe would be treated as the run.

In addition to the size requirements, a decoupled branch line must be designed to accommodate the thermal and seismic movements of the run pipe without restraint.

Because the decoupling criteria ensure that the branch line has little effect on the run pipe, only two additional items need to be included in the run pipe analysis. The run pipe analysis must include an appropriate SIF or stress indices at the point where the piping is decoupled. Additionally, mass effects of the branch line shall also be considered. The mass to be considered is the mass of one-half of the first span of the branch pipe, including concentrated weights and eccentric masses, in each direction.

Large concentrated masses should not be located within the first span of the branch pipe. If a large valve or other large concentrated mass is located within the first span of the branch piping, the torsional effects of the eccentric mass must be considered. In these cases, the branch piping will be modeled and analyzed with the run pipe, or a portion of the branch line shall be included in the run pipe analysis to adequately include the torsional effects of the eccentric mass.

The branch pipe analysis must include more consideration for the effects of the run piping. The branch point is considered as an anchor in the analysis of the branch pipe with the appropriate SIF or stress indices for the branch connection. The movements (displacements and rotations) of the run pipe at the branch intersection due to statically applied loads in the run pipe analysis, such as thermal and seismic anchor movements, shall be applied as anchor movements with their respective load cases in the branch line analysis. Additionally, in the branch analysis, the applied SAMs at the decoupled location shall include the run pipe movements from both the run pipe SAM analysis and the run pipe SSE inertia analysis. The inertial effects of the run pipe on the branch line are considered in one of the following methods:

For branch lines decoupled from the RCL, the inertial input to the branch line is generated from the analysis of the RCL. The analysis of the RCL yields time history responses at the branch connections and equipment nozzles. This time history response of the RCL, or a response spectrum generated from the time history response, is then applied as the input inertial excitation at the branch-to-RCL intersection. This method may also be used for decoupling pipe from flexible equipment if the response of the equipment is known.

For other decoupled lines, branch piping analysis will include one of the following:

The fundamental frequency of the run pipe at the branch location will be determined. If this frequency is at or above the ZPA cutoff frequency, the run pipe is considered as rigid and there will be no amplification of the building response spectra. Therefore, the applied inertial excitation at the branch-to-run pipe anchor shall include the envelope of building excitations for the nearest supports on both the branch and run pipes.

If the fundamental frequency of the run pipe at the branch location is below the ZPA cutoff frequency, the run pipe at this location is considered to be flexible and therefore may amplify the input inertial effects. Where practical in these cases, amplified response spectra will be developed from the run pipe analysis and applied at the branch-to-run pipe anchor in the branch pipe analysis.

As an alternative to a decoupled analysis for branch lines connected to flexible run piping where amplified response spectra are not generated, the branch line analysis may include a portion of the run pipe defined using the model isolation method described in Section 3F.5.4.3 in order to capture the possible amplification of inertial input from the run pipe. Therefore, the applied inertial excitation shall include the envelope of building excitations for the nearest supports on both the branch and run pipes. In these cases, the run pipe analysis remains qualified by the decoupled analysis.

3F.5.4.3 Model Isolation Method

The Overlap Region model isolation method is used to divide large seismic piping systems that cannot be separated by structural methods or decoupling criteria.

3F.5.4.3.1 Overlap Region Methodology

An overlap region consists of a section of the piping system that is modeled in two or more analyses. This region is defined to be large enough to prevent the transmission of motion due to seismic excitation from one end of the region to the other and must meet the following criteria, which are consistent with the recommendations of NUREG/CR-1980, Dynamic Analysis of Piping Using the Structural Overlap Method (Reference 22).

As a minimum, an overlap region must contain at least four seismic restraints in each of three perpendicular directions and at least one change in direction. If a branch is encountered, the balance of restraints required beyond that point shall be included on all lines joining at the branch. An axial restraint on a straight run of pipe may be counted effective at each point of lateral restraint on that same run.

The overlap region should be selected in a rigid area of the piping system. A dynamic analysis of the overlap region shall be made with pinned boundaries extended beyond the overlap region either to the next actual support or to a span length equal to the largest span length within the region. The fundamental frequency determined from this analysis shall be greater than the frequency corresponding to the ZPA.

When using the overlap methodology, pipe stresses in the overlap region must be qualified separately in each piping model. Supports located in the overlap region, including the ends, are qualified for the enveloped loads and movements resulting from all models covering the overlap region.

3F.5.5 Seismic/Non-Seismic Interface Boundaries

The effects of non-seismic piping connected to Seismic Category I piping must either be isolated from the Seismic Category I piping or included in the analysis model. The model boundary at a non-seismic/seismic piping interface may consist of structural isolation, decoupling, or model isolation methods similar to those described in

Section 3F.5.4. However, additional considerations are required to ensure that the dynamic effects of the non-seismic piping are considered.

Seismic Category I design requirements extend to the first seismic restraint beyond the seismic system boundary. The non-seismic piping and supports beyond this location that impact the dynamic analysis of the Seismic Category I piping are reclassified as Seismic Category II and included in the model. The extent of piping classified as Seismic Category II may be bounded by the following methods:

- Any of the structural boundaries in Section 3F.5.4.1 may be used to terminate the Seismic Category II region. In these cases, all piping and supports between the Seismic Category I design boundary and the structural anchor, or the final restraint of a restrained elbow or tee, are classified as Seismic Category II.
- Locations in the seismic/non-seismic interface region that meet the decoupling criteria in Section 3F.5.4.2 are acceptable model boundaries. When this method is applied, all piping and restraints beyond the Seismic Category I boundary up to the decoupled location are classified as Seismic Category II.
- Alternatively, a series of piping restraints may be utilized to isolate the seismic response of non-seismically designed piping from seismically designed piping, similar to the model isolation methods described in Section 3F.5.4.3. In this case, isolation of dynamic effects is provided by four seismic restraints in each of the three orthogonal directions beyond the Seismic Category I system boundary.

In all cases, the Seismic Category II portion of the system is analyzed with the Seismic Category I piping for the SSE load case as well as loads resulting from the potential failure of the non-seismic piping and pipe supports. This is accomplished by the application of a plastic moment in each of three orthogonal directions at the termination of the model. The plastic moment is calculated as:

$$M_P = S_Y Z_P \text{ and } Z_P = \left(D^3 - d^3\right)/6$$

Where,

M_P = Plastic moment to be applied.

S_Y = Material Yield Strength at 70°F.

Z_P = Plastic section modulus of the pipe.

D = Outside diameter of the pipe.

d = Inside diameter of the pipe.

Each moment is applied and evaluated in a separate analysis and the results of each analysis are individually combined with the seismic inertia results by absolute summation methods. The results of these three analyses are then enveloped to obtain the design loads for the piping and supports.

Each moment is applied and evaluated in a separate analysis and the results of the three analyses are enveloped.

3F.6 Pipe Support Design Criteria

Pipe supports are designed for the loading, deflections, and directionality of support required by the piping analysis in order to provide for the proper functionality requirements of the piping itself. In addition, the pipe support elements must be designed to meet the requirements of the appropriate design codes in order to again be consistent with the code requirements of the overall piping system. Pipe supports typically include structural elements, at times also coupled with standard manufactured catalog items developed specifically for pipe support usage.

The piping analysis usually makes idealized supporting assumptions as required by the specific analysis conditions. In turn, the supports are typically designed separately from the piping analysis, with design methods to match the assumed analysis constraints. As such, the supports are designed to minimize their effects on the piping analysis and must not invalidate the piping analysis assumptions.

3F.6.1 Applicable Codes

The design codes for U.S. EPR piping supports are designated based on the seismic category of the support in question. Seismic Category I pipe supports shall be designed in accordance with Subsection NF of the ASME Code (Reference 2) for Service Levels A, B, C, and D while using the acceptance limits of Subsection NF for Levels A, B, and C and the acceptance limits of Appendix F for Level D. Subsection NF will be used for the manufacturing, installation, and testing of all Seismic Category I pipe supports. Subsection NF details varying requirements for ASME Code Class 1, 2, and 3 support structures, and is further delineated into plate and shell type supports, linear type supports, and standard piping supports. *[In addition, the welding requirements for A500, Grade B tube steel from AWS D1.1, Structural Welding Code – Steel (Reference 23), are utilized.]**

Plate and shell type supports, as defined in the ASME Code (Reference 2), are supports such as skirts or saddles fabricated from plate elements and loaded to create a biaxial stress field. Linear type supports are essentially subjected to a single component of direct stress, but may also be subjected to shear stresses. Examples of linear type support elements would be beams, columns, frames, and rings. Standard supports are made from typical support catalog items such as springs, rigid struts, and snubbers. Standard support items are typically load rated items, but also may be qualified by plate and shell or linear analysis methods.

[For all Seismic Category II pipe supports other than standard component supports, the design, manufacturing, installation, and testing meet the requirements of ANSI/AISC N690 (Reference 24). Standard component supports are designed, manufactured, installed, and tested to Subsection NF of the ASME Code (Reference 2). Any structural members used as part of a pipe support also containing standard components are designed, manufactured, installed, and tested to ANSI/AISC N690 (Reference 24).

For non-seismic category pipe supports supporting piping analyzed to ASME B31.1 (Reference 29)*, the requirements of ASME B31.1* (Reference 29) *for supports (Sections 120 and 121) are met, where applicable. In addition, the structural elements are designed using guidance from the ANSI/AISC N690 (Reference 24). For standard components used in these supports, vendor's catalog requirements, which also meet ASME B31.1* (Reference 29) *requirements, are utilized.*

For non-seismic category pipe supports supporting unanalyzed piping, the structural elements are designed using guidance from the AISC Manual of Steel Construction (Reference 25), and standard components meet the vendor's catalog requirements.

*In addition to the pipe support design codes mentioned above, expansion anchors and other steel embedments in concrete shall be designed for concrete strength in accordance with ACI-349, Code Requirements for Nuclear Safety Related Concrete Structures (Reference 26).]**

3F.6.2 Jurisdictional Boundaries

The jurisdictional boundaries for pipe supports fall into two categories. The first boundary is between the pipe and the support structure. The second boundary is between the support structure and the associated building structure. For the U.S. EPR design, the pipe support jurisdictional boundaries will be as defined in the ASME Code (Reference 2).

The jurisdictional boundary between the pipe and its support structure will follow the guidance of Paragraphs NB-1132, NC-1132, and ND-1132, as appropriate for the ASME Code Class of piping involved. For piping analyzed to ASME B31.1 (Reference 29), the jurisdictional boundary guidance of Paragraph ND-1132 will be utilized. In general, for attachments to the pipe that are not directly welded to the pipe, the jurisdictional boundary is at the outer surface of the pipe. For attachments that are welded directly to the pipe, the boundary will vary in accordance with the configuration of the attachment. For such welded attachments, the guidance in Paragraphs NB-1132, NC-1132, and ND-1132 will be utilized. In addition, local pipe stresses due to the welded attachments will be evaluated in accordance with the appropriate ASME Code Cases given in Section 3F.2.2.

The jurisdictional boundary between the pipe support and the building structure will follow the guidance of Paragraph NF-1130 of the ASME Code (Reference 2). In general, for attachments to building steel, the boundary is taken at the interface with the building steel, with the weld being designed to the rules of Subsection NF. For attachments to concrete building structures, the boundary is generally at the weld of the support member to a baseplate or embedded plate, with the weld again being designed to the rules of Subsection NF.

3F.6.3 Loads and Load Combinations

Load combinations for the U.S. EPR design will be defined based on the four Service Levels used in the ASME Code (Reference 2); Levels A, B, C, and D. These four level designations are defined in Section 3F.3.2. Based on the guidance given in SRP 3.9.3 (Reference 1), loading combinations of the various potential analysis load cases will be developed for the four defined levels.

Note that the load combinations used for all four levels will always include the normal plant operating loadings in effect for all conditions (i.e., deadweight and thermal). However, since signed thermal loadings may cancel other signed loadings, the cold condition must also always be considered for support loads.

Sections 3F.6.3.1 through 3F.6.3.10 provide an explanation of the various analysis load cases used in the load combinations, and Table 3F-5 provides the specific load combinations for pipe supports. The acceptance criteria associated with the Service Levels will be per ASME Code (Reference 2), Subsection NF, or ANSI/AISC N690 (Reference 24), as appropriate. Section 3F.6.3.11 provides minimum design loads for pipe support design when the actual calculated design loads are very small. The symbol designations in parentheses in the section titles are used in the table to represent the corresponding loadings.

3F.6.3.1 Deadweight (D) Loads

Deadweight loads for a pipe support are usually based on the deadweight load case of the associated piping analysis and include the weight of the pipe and fittings, contents, insulation, and pipe support components directly supported by the pipe, such as clamps for spring supports (See Section 3F.5.2 for specific details). In addition to gravity loads from the piping analysis, the deadweight of the support itself should be considered in the support qualification, if considered significant.

Note that gravity supports are either designed to be rigid or flexible supports based on the piping analysis thermal movements of the pipe. High thermal movements often require a flexible spring support to allow thermal growth while still supporting the pipe under the deadweight condition.

3F.6.3.2 Thermal (T_N, T_U, T_E, T_F) Loads

Thermal loads for a pipe support will usually be calculated in one or more load cases in the associated piping analysis based on the thermal operating parameters of the piping system. Since there may be differing temperatures of the piping fluid for the various service levels, the subscripts of the symbol designations above represent the four service levels; normal, upset, emergency, and faulted. The various temperatures in the piping system will cause the overall system to expand or contract, thereby applying loads to the pipe supports that are restricting the free expansion or contraction. In addition, anchor points for the piping system, such as equipment nozzles or branch connections, may also be moving thermally so that they apply thermal movements to the piping analysis. These are typically referred to as thermal anchor movements, which must also be considered in the overall piping analysis.

Along with the overall system effects mentioned above, consideration for local, radial thermal expansion of the pipe cross section must be made. This effect is often addressed by having small gaps around the pipe for such thermal growth, while still maintaining relatively tight constraints for seismic loadings (See Section 3F.6.11).

One further consideration for the pipe support design is the environmental condition around the pipe support, including the pipe temperature. The air temperature around the support may cause expansion of the support structure itself, as well as affect the material properties of the support structure. In addition, an elevated pipe temperature may cause the support structure to undergo local expansion, or be subject to reduced material allowables near the vicinity of the pipe.

3F.6.3.3 Friction (F) Loads

Friction loads to be applied to the pipe support are typically not calculated in the piping analysis, but instead are hand calculated during the support design. Such loads are developed when sliding of the pipe across the surface of a support member in the unrestrained direction(s) occurs under thermal expansion conditions. See Section 3F.6.10 for further description of the development of these loads.

3F.6.3.4 System Operating Transient (R_{SOT}) Loads

System operating transients (SOTs) are defined in SRP 3.9.3 (Reference 1) as “the transients and their resulting mechanical responses due to dynamic occurrences caused by plant or system operation.” These dynamic loads will typically come from load cases analyzed in the computerized piping analysis, and are the result of transients such as safety or relief valve thrust, fast valve closure, water hammer, and steam hammer.

3F.6.3.5 Wind (W) Loads

If applicable (See Section 3F.3.3.1.6), exposed piping and support structures will be analyzed for the design basis wind forces. This will typically be the result of a load case in the piping analysis performed for the piping system. Depending on the speed of application of the wind loading, snubber supports may or may not activate. Conservatively, both a static support (snubbers unlocked) and dynamic support (snubbers locked) configuration will be analyzed and the results enveloped.

3F.6.3.6 Tornado (W_T) Loads

If applicable (See Section 3F.3.3.1.6), exposed piping will also be analyzed for the design basis tornado. The tornado loads will consist of loads due to tornado wind speeds, differential pressures, and tornado generated missiles, as appropriate. The tornado wind speeds are calculated from the translational velocity of the tornado added to the rotational velocity. As for the wind loadings, the support loads will typically be the result of a load case in the piping analysis and both a static support (snubbers unlocked) and dynamic support (snubbers locked) configuration will be analyzed and the results enveloped for the tornado wind loads. Missile loadings will be considered as a dynamic load case for support activation purposes.

3F.6.3.7 Design Basis Pipe Break (R_{DBPB}) Loads

DBPBs are defined in SRP 3.9.3 (Reference 1) as “those postulated pipe breaks other than a LOCA or MS/FWPB. This includes postulated pipe breaks in ASME Code Class 1 branch lines that result in the loss of reactor coolant at a rate less than or equal to the capability of the reactor coolant makeup system”. These include loads applied to the piping from another nearby broken pipe (jet impingement or pipe whip), or loads in a pipe from a break in the same pipe (dynamic effects in the system due to the break).

3F.6.3.8 Main Steam or Feedwater Pipe Break ($R_{MS/FWPB}$) Loads

These pipe break loads are the same type of loadings, determined in the same fashion as for the DBPB, except that they are specifically for the two subject systems.

3F.6.3.9 Loss of Coolant Accident (LOCA) Loads

LOCAs are defined in Appendix A to 10 CFR Part 50 as “those postulated accidents that result from the loss of reactor coolant, at a rate in excess of the capability of the reactor coolant makeup system, from breaks in the reactor coolant pressure boundary, up to and including a break equivalent in size to the double-ended rupture of the largest pipe of the Reactor Coolant System.” LBB methodology will be used to eliminate double ended guillotine breaks in the RCL and Pressurizer Surge Line piping, but breaks in the smaller attached lines will be considered. Again, these loads would be determined in the same fashion as for the other pipe break scenarios.

3F.6.3.10 Safe Shutdown Earthquake (SSE) Loads

The seismic loads to be applied to the pipe supports from the piping, due to the maximum potential earthquake expected in the area of the plant, are the SSE loads. These loads will include inertial loads from the piping, as well as seismic movements at anchor points such as piping anchor supports, equipment nozzles, and branch line points.

In addition to the SSE loads from the piping, the seismic acceleration of the support structure itself must also be considered. This effect is called self-weight excitation, and is described further in Section 3F.6.8.

3F.6.3.11 Minimum Design Loads

Minimum design loads will be defined for all pipe supports so that uniformity is obtained in the load carrying capability of the supports. As such, all support components other than constant and variable spring hangers should be designed for the largest of the following three loads:

- 125 percent of the Level A condition load.
- The weight of a standard ASME B31.1 (Reference 29) span of water filled schedule 80 pipe.
- Minimum value of 150 pounds.

3F.6.4 Pipe Support Baseplate and Anchor Bolt Design

*[Although the use of baseplates with expansion anchors is expected to be minimized in the U.S. EPR design, there will likely be some instances where baseplate designs must be utilized. For such designs, the concrete will be evaluated using ACI-349 (Reference 26), Appendix B, subject to the conditions and limitations of RG 1.199, Anchoring Components and Structural Supports in Concrete (Reference 27).]** This guidance accounts for the proper consideration of anchor bolt spacing and distance to a free edge of concrete. In addition, all aspects of the anchor bolt design, including baseplate flexibility and factors of safety, will be utilized in the development of anchor bolt loads, as addressed in NRC Bulletin 79-02, Pipe Support Base Plate Designs Using Concrete Expansion Anchor Bolts (Reference 28).

3F.6.5 Analysis of Piping Systems with Non-Linear Supports

The use of gapped rigid supports (limit stops) is not anticipated in the U.S. EPR design. However, should the need for such supports arise, the non-linear piping analysis will be solved using direct integration time history methods. If non-linear piping analysis is performed, the modeling and analysis methods must be submitted to and approved by the NRC prior to its use.

3F.6.6 Use of Snubbers

Snubber supports for piping systems are utilized for situations requiring free thermal movements while restraining movements due to dynamic loadings. An example of such a situation would be the need to relieve dynamic stresses at a pipe fitting while allowing thermal growth of the pipe, thereby minimizing the thermal loads/stresses at the same fitting. Many times this approach is used for the first support on piping adjacent to an equipment nozzle. Due to the rigidity of an equipment nozzle (usually modeled as a rigid piping anchor), care should be taken in the support design to assure that the pipe will have the required dynamic acceleration/movement to properly activate the snubber. Typical snubber components are manufactured standard hardware, and may be either hydraulic or mechanical in operation.

The size and location of snubbers in a piping system will be a function of the thermal and dynamic analyses requirements. Snubbers, in general, should not be used where thermal movements are small. Also, use of snubbers should be minimized as much as reasonable due to the maintenance and testing requirements for these components. As such, accessibility of any snubbers utilized must also be a consideration in the design of the piping system.

Other design/analysis considerations for snubbers are related to the ability of the snubbers to properly activate for their design loadings. For snubbers that might experience high thermal growth rates, the analysis should verify that such growth rates do not exceed the snubber lock-up velocity. Also, for parallel snubbers utilized in the same support, care must be taken to make sure that total fitting clearances are not mismatched between the tandem snubbers so that one will activate before the other. Other load sharing considerations for tandem snubbers, such as significant stiffness differences, must also be a support design criterion.

The Design Specification(s) provided to the supplier(s) of snubbers should contain the following types of information:

- Applicable codes and standards.
- Functional requirements.
- Operating environment (both normal and post accident).
- Materials (construction and maintenance).
- Functional testing and certification.
- Requirement for construction to meet ASME Code (Reference 2), Subsection NF.

As discussed in Section 3.9.1.1, the COL applicant will describe essential elements of a program to confirm that thermal deflections do not create adverse conditions during hot functional testing.

3F.6.7 Pipe Support Stiffnesses

Supports in the piping analysis model may be modeled with either the actual stiffness of the support structure or an arbitrarily rigid stiffness. In general, rigid stiffnesses will be utilized for the piping supports, with a check on support deflection in the restrained direction(s) to verify the rigidity. The actual stiffness will be modeled for variable spring supports. If actual support stiffnesses are utilized for other than spring supports, the support should be designed so that the stiffness is approximately the same for both directions along a single axis. If the actual support stiffness is used for any support other than a variable spring support, all supports within the piping model shall use the actual support stiffnesses. Also, caution should be used in the support design to keep the unrestrained direction of the support from having a frequency that would tend to provide significant amplification of the support structure mass.

Two deflection checks will be performed for each support modeled as rigid in the piping analysis. The first check will compare the deflection in the restrained direction(s) to a maximum of one-sixteenth inch for SSE loadings or the minimum support design loadings of Section 3F.6.3.11. The second check will compare the deflection in the restrained direction(s) to a maximum of one-eighth inch for the worst case deflection for any load case combination. Note that in the development of the support deflections, dynamically flexible building elements beyond the support jurisdictional boundaries will also be considered.

3F.6.8 Support Self-Weight Excitation

3F.6.8.1 Seismic Loads

The response of the support structure itself to SSE loadings is to be included in the pipe support analysis. In general, the inertial response of the support mass will be evaluated using a response spectrum analysis similar to that performed for the piping. Damping values for welded and bolted structures are given in RG 1.61, Rev. 1 (Reference 20). This support self-weight SSE response, the piping inertial load SSE response, and the SSE loads from SAM are to be combined by absolute sum.

3F.6.8.2 Other Dynamic Loads

For ASME Code Class 1, 2, or 3 piping system analyses, the support structures are not expected to be explicitly modeled in the piping analysis. The analyses will assume rigid support points in the piping model using the default stiffnesses in the analysis code, with support rigidity confirmed as described in Section 3F.6.7. As also described in Section 3F.6.7, if supports do not meet the requirements in Section 3F.6.7, the actual support stiffnesses will be determined for all supports within that model and will be used in a reanalysis of the piping along with the mass of the support. Therefore, the dynamic characteristics of supports that are not rigid will be included in the piping analysis.

3F.6.9 Design of Supplemental Steel

As described in Section 3F.6.1, all Seismic Category I and II pipe supports for the U.S. EPR design will be designed to Subsection NF of the ASME Code (Reference 2) or to ANSI/AISC N690 (Reference 24), respectively. This will include any supplemental steel required to connect the main support structure to the building structure. As is also described in Section 3F.6.2, the jurisdictional boundaries of the support structures to the building structures will likewise follow the guidance of Subsection NF. This guidance would include any supplemental steel within the support boundary. Thus, the supplemental steel will be designed to Subsection NF of the ASME Code (Reference 2) or ANSI/AISC N690 (Reference 24) for Seismic Category I and II pipe supports, respectively. For non-seismic pipe supports, the AISC Manual of Steel Construction (Reference 25) will be utilized for the supplemental steel, as it will for the main support structure.

3F.6.10 Consideration of Friction Forces

As described in Section 3F.6.3.3, friction forces develop in the pipe support when sliding of the pipe across the surface of a support member in the unrestrained direction(s) occurs under thermal expansion conditions. Since friction is due to the gradual movement of the pipe, loads from friction will only be calculated using the deadweight and thermal loads normal to the applicable support member. Friction due to other piping loads will not be considered.

Specifically, to calculate the friction forces, a force will only need to be calculated if the thermal movement in the applicable unrestrained direction(s) is greater than one-sixteenth inch. The force will be calculated using the following equation:

$$F = CN$$

Where,

F = Friction Force.

C = The coefficient of friction (0.3 for steel/steel surfaces, 0.1 for low friction slide/bearing plates.

N = The force normal to the direction of movement.

Alternatively, if the piping analysis has used actual support stiffnesses and the calculated friction force is reduced, the following equation can be used:

$F = KX$

Where,

F = Friction Force.

K = The support stiffness in the restrained direction.

X = The displacement in restrained direction.

3F.6.11 Pipe Support Gaps and Clearances

For rigid guide pipe supports modeled as rigid restraints in the piping analysis, the typical industry design practice is to provide small gaps between the pipe and its surrounding structural members. These small gaps allow radial thermal expansion of the pipe, as well as allow rotation of the pipe at the support. The U.S. EPR design uses a nominal cold condition gap of one-sixteenth inch on each side of the pipe in the restrained direction. This will lead to a maximum total cold condition gap around the pipe for a particular direction of one-eighth inch.

For gaps around the pipe in an unrestrained direction, the gap magnitudes should be specified large enough to accommodate the maximum movement of the pipe.

3F.6.12 Instrumentation Line Support Criteria

The design and analysis loadings, load combinations, and acceptance criteria to be used for instrumentation line supports will be similar to those used for pipe supports. The applicable design loads will include deadweight, thermal expansion, and seismic loadings (where appropriate). The applicable loading combinations will follow those used for the ASME Levels in Table 3F-5, utilizing the design loadings mentioned above. The acceptance criteria will be from ASME Code (Reference 2), Subsection NF, for Seismic Category I instrumentation lines, ANSI/AISC N690 (Reference 24) for Seismic Category II instrumentation lines, and the AISC Manual of Steel Construction (Reference 25) for non-seismic instrumentation lines.

3F.6.13 Pipe Deflection Limits

For pipe supports utilizing standard manufactured hardware components, the manufacturer’s recommendations for limitations in its hardware will be followed. Examples of these limitations are travel limits for spring hangers; stroke limits for snubbers; swing angles for rods, struts, and snubbers; alignment angles between clamps or end brackets with their associated struts and snubbers; and the variability check for variable spring supports. In addition to the manufacturer’s recommended limits, allowances will be made in the initial designs for tolerances on such limits. This is especially important for snubber and spring design where the function of the support can be changed by an exceeded limit.

The check for travel range limitation for spring hangers will utilize the “working range” given in the standard Load Table for Selection of Hanger Size typically given in the vendor catalogs. This working range already provides a deflection tolerance beyond each end limit of the range (with the magnitude dependent on the spring type), provided the hot and cold loads fall within the working range.

The stroke limit checks for snubbers will allow at least one-half inch of stroke at each end for the initial design checks.

The check of swing angle for rods, struts, and snubbers applies a tolerance of 1 degree to the manufacturers limit for initial design.

The check for alignment angles of strut and snubber paddles and their associated clamps or end brackets applies a tolerance of 1 degree to the manufacturers limit for initial design.

The check for the spring variability applies a tolerance of 5 percent the manufacturers limit for initial design.

3F.7 References

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Table 3F-1—Load Combinations and Acceptance Criteria for ASME Code Class 1 Piping
Sheet 1 of 3

Service Condition	Service Level	Category	Loading or Stress Component	Acceptance Criteria[1]
Design	–	Primary Stress	Design Pressure, Deadweight, Steady State Flow Load, and Dynamic Fluid Load[2] specified as Level A	Equation 9N NB-3652
Normal	A	Primary plus Secondary Stress Intensity Range (S.I.R.)	Range of Level A: Service Pressure, Steady State Flow Load, Dynamic Fluid Load[2], Thermal Expansion Load[3], Thermal Expansion Anchor Movement Load[3], Cyclic Thermal Load[4], Material Discontinuity Stress	Equation 10N NB-3653.1
		Peak S.I.R.	Range of Level A: Service Pressure, Steady State Flow Load, Dynamic Fluid Load[2], Thermal Expansion Load[3], Thermal Expansion Anchor Movement Load[3], Cyclic Thermal Load[4], Material Discontinuity Stress, Thermal Radial Gradient Stress (linear and non-linear)	Equation 11N NB-3653.2
		Thermal S.I.R.[5]	Range of Level A: Thermal Expansion Load[3], Thermal Expansion Anchor Motion Load[3], Cyclic Thermal Load[4]	Equation 12N NB-3653.6(a)
		Primary plus Secondary Membrane plus Bending S.I.R.[5]	Range of Level A: Service Pressure, Steady State Flow Load, Dynamic Fluid Load[2], Material Discontinuity Stress	Equation 13N NB-3653.6(b)
		Alternating Stress Intensity (S.I.) (Fatigue Usage)[6]	Range of Level A: Service Pressure, Steady State Flow Load, Dynamic Fluid Load[2], Thermal Expansion Load[3], Thermal Expansion Anchor Movement Load[3], Cyclic Thermal Load[4], Material Discontinuity Stress, Thermal Radial Gradient Stress (linear and non-linear)	Equation 14N NB-3653.6(c)
		Thermal Stress Ratchet	Range of Level A Linear Thermal Radial Gradient	NB-3653.7

Table 3F-1—Load Combinations and Acceptance Criteria for ASME Code Class 1 Piping
Sheet 2 of 3

Service Condition	Service Level	Category	Loading or Stress Component	Acceptance Criteria[1]
Upset	B	Permissible Pressure	Maximum Level B Service Pressure	NB-3654.1
		Primary Stress	Coincident Level B Service Pressure, Deadweight, Steady State Flow Load, Dynamic Fluid Load[2]	Equation 9U NB-3654.2(a)
		Primary plus Secondary S.I.R.	Range of Level B: Service Pressure, Steady State Flow Load, Dynamic Fluid Load[2], Thermal Expansion Load[3], Thermal Expansion Anchor Motion Load[3], Cyclic Thermal Load[4], Material Discontinuity Stress, Earthquake Inertial Load[7]	Equation 10U NB-3654.2(b)
		Peak S.I.R.[8]	Range of Level B: Service Pressure, Steady State Flow Load, Dynamic Fluid Load[2], Thermal Expansion Load[3], Thermal Expansion Anchor Motion Load[3], Cyclic Thermal Load[4], Material Discontinuity Stress, Earthquake Inertial Load[7], Level B Thermal Radial Gradient Stress (linear and non-linear)	Equation 11U NB-3654.2(b)
		Thermal S.I.R.[5]	Range of Level B: Thermal Expansion Load[3], Thermal Expansion Anchor Motion Load[3], and Cyclic Thermal Load[4]	Equation 12U NB-3654.2(b)
		Primary plus Secondary Membrane plus Bending S.I.R.[5]	Range of Level B: Service Pressure, Steady State Flow Load, Dynamic Fluid Load[2], Material Discontinuity Stress, Earthquake Inertial Load[7]	Equation 13U NB-3654.2(b)
		Alternating S.I. (Fatigue Usage)[6]	Range of Level B: Service Pressure, Steady State Flow Load, Dynamic Fluid Load[2], Thermal Expansion Load[3], Thermal Expansion Anchor Movement Load[3], Cyclic Thermal Load[4], Material Discontinuity Stress, Earthquake Inertial Load[7], Level B Thermal Radial Gradient Stress (linear and non-linear)	Equation 14U NB-3654.2(b)
		Thermal Stress Ratchet	Range of Level B Linear Thermal Radial Gradient	NB-3654.2(b)
		Deformation Limits	As Set Forth in the Design Specification	NB-3654.2(b)

Table 3F-1—Load Combinations and Acceptance Criteria for ASME Code Class 1 Piping
Sheet 3 of 3

Service Condition	Service Level	Category	Loading or Stress Component	Acceptance Criteria[1]
Emergency[9]	C	Permissible Pressure	Maximum Level C Service Pressure	NB-3655.1
		Primary Stress	Coincident Level C Service Pressure, Deadweight, Steady State Flow Load, Dynamic Fluid Load[2]	Equation 9E NB-3655.2(a)
		Deformation Limits	As Set Forth in the Design Specification	NB-3655.3
Faulted	D	Permissible Pressure	Maximum Level D Service Pressure	NB-3656(a)(1)
		Primary Stress[10]	Coincident Level D Service Pressure, Deadweight, Steady State Flow Load, Dynamic Fluid Load[2,11], Earthquake Inertial Load[11], High Energy Line Break Load[11] (Loss-of-Coolant Accident or Secondary Side Pipe Rupture)	Equation 9F NB-3656(a)(2)
		Secondary Stress[12]	MAX [Range of (Bending Moments due to Thermal Expansion Load[3] plus Thermal Expansion Anchor Movement Load[3] plus one-half Earthquake Anchor Motion Load) OR Range of Earthquake Anchor Movement Load]	$6S_m$[13]
Pressure Testing[14]	–	Primary Membrane S.I.	Test Pressure, Deadweight	NB-3657 NB-3226(b)
		Primary Membrane plus Bending S.I.	Test Pressure, Deadweight	NB-3657 NB-3226(c)

Notes:

1. Acceptance Criteria are taken from the referenced section in the ASME Code (Reference 2), or are as noted.
2. Dynamic Fluid Loads are occasional loads associated with hydraulic transients caused by events such as valve actuation (safety or relief valve discharge, rapid valve opening and closing), water hammer, or steam hammer.
3. Thermal Expansion and Thermal Expansion Anchor Movement Loads are not calculated for those operating conditions where the piping system does not exceed 150°F.

4. Cyclic Thermal Load includes loads due to thermal stratification, and stresses due to high cycle thermal striping and thermal penetration (i.e., thermal mixing).

5. The Thermal Bending and Primary plus Secondary Membrane plus Bending Stress Intensity Ranges (Equations 12 and 13) are only calculated for those load sets that do not meet the Primary plus Secondary Stress Intensity Range (Equation 10) allowable.

6. The cumulative fatigue usage factor is calculated by summing the Level A and Level B fatigue usage. If applicable, fatigue usage from Level C and Pressure Testing conditions is also included in the calculation of the cumulative usage factor (See Notes 9 and 14).

7. The Earthquake Inertial Load considered in the Level B Primary plus Secondary Stress Intensity Range, Peak Stress Intensity Range, and Alternating Stress Intensity calculations (Equations 10, 11, and 14) is taken as one-third of the peak SSE inertial load or as the peak SSE inertial load. If the earthquake inertial load is taken as the peak SSE inertial load, then 20 cycles of earthquake loading is considered. If the earthquake inertial load is taken as one-third of the peak SSE inertial load, then the number of cycles to be considered for earthquake loading is 300 (the equivalent number of 20 full SSE cycles as derived in accordance with Appendix D of IEEE Std 344-1987 (Reference 8)).

8. The resultant moment calculated is the maximum of the resultant moment due to the full range of Earthquake Inertial Load or the resultant moment due to the consideration of half of the range of Earthquake Inertial Load with all other applicable loads.

9. If a piping system is subjected to more than 25 Emergency Condition transient cycles that result in an alternating stress intensity (S_a) value greater than that for 106 cycles, as determined from the applicable fatigue design curves of Figure I-9.0 in the ASME Code (Reference 2), then those cycles in excess of 25 are included in the fatigue calculation that determines the cumulative usage factor. See Paragraph NB-3113(b) in the ASME Code (Reference 2).

10. The rules given in Appendix F of the ASME Code (Reference 2) may be used in lieu of those given in Paragraphs NB-3656(a) and NB-3656(b) when evaluating Level D primary stress.

11. Loads due to dynamic events other than High Energy Line Break (i.e., Loss-of-Coolant Accident and Secondary Side Pipe Rupture) and SSE are combined considering the time phasing of the events (i.e., whether the loads are coincident in time). When the time phasing relationship can be established, dynamic loads may be combined by the SRSS method, provided it is demonstrated that the non-exceedance criteria given in NUREG-0484 (Reference 16) is met. When the time phasing relationship cannot be established, or when the non-exceedance criteria in NUREG-0484 (Reference 16) are not met,

dynamic loads are combined by absolute sum. SSE and High Energy Line Break loads are always combined using the SRSS method.

12. This secondary stress check is only necessary if the stresses, including those due to Earthquake Inertial Load, exceed the Equation 10U (primary plus secondary stress intensity range for the Upset service condition) allowable stress. See Paragraph NB-3656(b)(4) in the ASME Code (Reference 2).

13. S_m = Allowable Design Stress Intensity value from Part D of Section II of the ASME Boiler and Pressure Vessel Code.

14. If a piping system is subjected to more than 10 Pressure Test cycles that result in an alternating stress intensity (S_a) value greater than that for 106 cycles, as determined from the applicable fatigue design curves of Figure I-9.0 in the ASME Code (Reference 2), then those cycles in excess of 10 are included in the fatigue calculation that determines the cumulative usage factor. See Paragraphs NB-3657 and NB-3226(e) in the ASME Code (Reference 2).

Table 3F-2—Design Conditions, Load Combination, and Stress Criteria for ASME Code Class 2 and 3 Piping

Loading Condition	Service Levels	Loads	Stress Criteria[4, 9]
Design	–	Primary Stress Loads: Pressure, Weight, Other Sustained Mechanical Loads	Equation 8 NC/ND-3652[3]
Normal/ Upset	A/B	Occasional: Pressure, Weight, Other Sustained Mechanical Loads, Dynamic Fluid Loads (DFL)[1], Wind[7]	Equation 9U NC/ND-3653.1 (Level B Only)[6]
		Secondary Stress: Thermal Expansion, TAM	Equation 10 NC/ND-3653.2(a)[2]
		Non-Repeated Anchor Movement	Equation 10a NC/ND-3653.2(b)
		Sustained Plus Secondary Stress: Pressure, Weight, Other Sustained Mechanical Loads, Thermal Expansion, TAM	Equation 11 NC/ND- 3653.2(c)[2]
Emergency	C	Occasional Stress: Pressure, Weight, DFL[1], Tornado[7]	Equation 9E NC/ND-3654.2(a)[5]
Faulted	D	Occasional Stress: Pressure, Weight, DFL[1], SSE Inertia, Design Basis Pipe Break	Equation 9F NC/ND-3655(a)[5]
		Secondary Stress: Thermal Expansion, TAM, Seismic Anchor Movement (SSE)	$\frac{iM_c}{Z} \leq MIN(3.0S_h, 2.0S_y)$[6, 8]

Notes:

1. Dynamic Fluid Loads are occasional loads such as safety/relief valve thrust, steam hammer, water hammer, or other loads associated with Plant Upset, Emergency, or Faulted Condition as applicable.

2. Stresses must meet the requirements of either Equation 10 or 11, not both.

3. If, during operation, the system normally carries a medium other than water (air, gas, steam), sustained loads should be checked for weight loads during hydrostatic testing as well as normal operation weight loads.

4. ASME Code (Reference 2).

5. When causal relationships can be established, dynamic loads may be combined by the SRSS method, provided it is demonstrated that the non-exceedance criteria given in NUREG-0484 (Reference 16) is met. When the causal relationship cannot be established, or when the non-exceedance criteria given in NUREG-0484 (Reference 16) are not met, dynamic loads must be combined by absolute sum. SSE and High Energy Line Break loads are always combined using the SRSS method.

6. OBE inertia and SAM loads are not included in the design of ASME Code Class 2 and 3 piping (Reference 7).

7. Wind and tornado loads are not combined with earthquake loading.

8. M_c = Range of resultant moments due to thermal moments due to expansion and TAMs (Level A and B only) and SSE Seismic Anchor Movements. M_c is equal to the maximum moment range of either the full range of thermal plus one-half the range of SAM, or the full range of SAM. S_h is equal to the pipe material allowable stress at the operating temperature. S_y is equal to the pipe material yield stress at the operating temperature.

9. ASME Code equations and paragraph numbers refer to the 2004 Edition (no addenda) of the ASME Code (Reference 2). However, dynamic loads are treated in accordance with the applicable subarticles of the ASME Code 1993 Addenda (Reference 3) per the limitations of 10 CFR 50.55a(b)(1).

Table 3F-3—Functional Capability of ASME Code Class 1, 2, and 3 Piping[1]

Criteria	Class 1		Class 2 and 3	
	Equation	**Allowable**	**Equation**	**Allowable**
Wall Thickness	$D_o/t < 50$	Meet	$D_o/t < 50$	Meet
Service Level D	Equation 9	Smaller of $2.0S_y$ or $3.0S_m$[2]	Equation 9	Smaller of $2.0S_y$ or $3.0S_h$[2]
External Pressure	$P_{external} < P_{internal}$	–	$P_{external} < P_{internal}$	–

Notes:

1. Applicable to Level D plant events for which the piping system must maintain an adequate fluid flow path.
2. Applicable to ASME Code Class 1, 2, and 3 when the following are met:
   - Dynamic loads are reversing.
   - Steady-state bending stress from deadweight loads does not exceed:

     $$\frac{B_2 M}{Z} \leq 0.25 S_y$$

   - When elastic response spectrum analysis is used, dynamic moments are calculated using a minimum of 15 percent peak broadening and pipe damping is not more than 5 percent. When elastic time history analysis is used, uncertainties in the applied time histories are accounted for and pipe damping is not more than 5 percent.

Table 3F-4—Design Conditions, Load Combination and Stress Criteria for ASME Code Class 2 and 3 Buried Piping

Loading Condition	Service Levels	Loads	Stress Criteria
Design	–	Primary Stress Loads: Pressure[1], Weight Loads, Other Sustained Mechanical Loads	Equation 8[5] NC-3652 or ND-3652
Normal/Upset	A/B	Occasional: Pressure[1], Weight Loads, Other Sustained Mechanical Loads, DFL	Equation 9U[5] NC-3653.1 or ND-3653.1 (Level B Only)
		Secondary Stress: Thermal Expansion, TAM, Thermal Friction Forces	Equation 10M[2, 4] NC-3653.2(a) or ND-3653.2(a)
		Non-Repeated Anchor Movement	Equation 10a NC-3653.2(b)or ND-3653.2(b)
		Sustained Plus Secondary Stress: Pressure[1], Weight Loads, Other Sustained Mechanical Loads, Thermal Expansion, TAM, Thermal Friction Forces	Equation 11M[3, 4, 5] NC-3653.2(c) or ND-3653.2(c)
Emergency	C	Occasional Stress: Pressure[1], Weight Loads, DFL	Equation 9E[5] NC-3654.2(a) or ND-3654.2(a)
Faulted	D	Secondary Stress: SSE effects and SAM (M_{SSE}), Thermal Expansion and TAM (M_C), Friction Axial Forces from Thermal Expansion	See note 6

Notes:

1. Pressure for buried pipe includes internal pressure and the soil overburden loads and loads due to motor vehicles and train cars.

2. Equation 10 modified to include stress due to axial friction forces caused by thermal expansion and soil interaction.

3. Equation 11 modified to include stress due to axial friction forces caused by thermal expansion and soil interaction.

4. Stresses must meet Equation 10M or 11M, not both.

5. Buried piping systems must be designed to meet the external pressure load criteria of Paragraph NC-3133 or ND-3133 of the ASME Code (Reference 2).

6. $\frac{i(M_{SSE}+M_C)}{Z}+\varepsilon_a E_{sct}+\varepsilon_b E_{sct}+E_{sct}\alpha(T_2-T_1)\leq$ lesser of $3S_h$ or $2S_y$

or

$$\frac{2i(M_{SSE})}{Z} + 2\varepsilon_a E_{sct} + 2\varepsilon_b E_{sct} \leq \text{ lesser of } 3S_h \text{ or } 2S_y$$

For definition of terms, see Section 3F.3.10.3.1.

Table 3F-5—Loading Combinations for Piping Supports

Condition	Load Combination[1, 2, 3]
Normal (Level A)	$D + T_N + F$
Upset (Level B)	$D + T_U + R_{SOT}$ $D + T_U + W$
Emergency (Level C)	$D + T_E + R_{SOT}$ $D + T_E + W_T$ $D + T_E + R_{SOT} + R_{DBPB}$[4]
Faulted (Level D)	$D + T_F + R_{SOT}$ $D + T_F + R_{SOT} + R_{DBPB}$[4] $D + T_F + R_{SOT} + R_{MS/FWPB}$[4] $D + T_F + R_{SOT} + LOCA$[4] $D + T_F + R_{SOT} + SRSS\ (R_{DBPB} + SSE)$[4] $D + T_F + R_{SOT} + SRSS\ (R_{MS/FWPB} + SSE)$[4] $D + T_F + R_{SOT} + SRSS\ (LOCA + SSE)$[4]

Notes:

1. OBE inertia and SAM loads are not included in the design of ASME Code Class 1, 2, and 3 piping (Reference 7).

2. The acceptance criteria for the load combinations are described in Section 3F.6.3.

3. SSE includes inertia and SAM loads combined by absolute sum.

4. Loads due to dynamic events are combined considering the time phasing of the events (i.e., whether the loads are coincident in time). When the time phasing relationship can be established, dynamic loads may be combined by the SRSS method, provided it is demonstrated that the non-exceedance criteria given in NUREG-0484 (Reference 16) are met. When the time phasing relationship cannot be established, or when the non-exceedance criteria in NUREG-0484 (Reference 16) are not met, dynamic loads are combined by absolute sum. SSE and High Energy Line Break (i.e., Loss of Coolant Accident and Secondary Side Pipe Rupture) loads are always combined using the SRSS method.

Figure 3F-1—Overlap Region Model Isolation Method