Pipe Rupture External Loading Effects on U.S. EPR™ Essential Structures, Systems, and Components

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Nomenclature

(If applicable)

Acronym	Definition
ACI	American Concrete Institute
AISC	American Institute of Steel Construction
ASME	American Society of Mechanical Engineers
DLF	Dynamic Load Factor
HELBA	High Energy Line Break Accident
HEM	Homogeneous Equilibrium Model
NPR	Nozzle Pressure Ratio
SDOF	Single Degree of Freedom
SSC	Structures, Systems, and Components

Abstract

External loading effects on essential structures, systems, and components (SSC) of nuclear power plants are considered in accordance with the requirements of Reference 1. In the past, methods provided by Reference 2 have been used to determine the magnitude of the jet impingement loadings and the effects due to the unsteady nature of the fluid jet and the possible blast effects were ignored. As indicated in References 1, 3, and 4, the NRC has determined that some assumptions related to jet expansion modeling in the ANSI/ANS 58.2 standard may lead to nonconservative assessments of the jet impingement loads of postulated pipe breaks on neighboring SSCs. The NRC noted in Reference 1 that they are assessing the technical adequacy of the information pertaining to dynamic analyses models for jet thrust force and jet impingement load that are included in References 1 and 2. Pending completion of this effort, the NRC staff will review analyses of the jet impingement forces on a case by case basis. Therefore, analyses should show that jet impingement loadings on nearby safety-related SSCs will not impair or preclude their essential functions.

This report describes the AREVA NP methodology used to conservatively calculate the external loading effects on essential SSC due to jet impingement, including unsteadiness, and potential blast effects. In jet impingement loading, incompressible fluid jets, subcooled flashing jets, and single phase steam jets are considered and the potential for resonance is evaluated. In blast loading, methods are provided to determine the loading on essential SSC depending on the type and size of rupture and the distance to the SSC.

The conservative nature of the methods discussed in this report provide a robust design and, per Reference 1, provide methods to demonstrate that external loading effects on nearby safety related SSC will not impair or preclude their essential functions.

1.0 INTRODUCTION

This report describes the methods used to define the loading, to determine the response and to perform structural evaluations for essential SSC because of the external effects of ruptures in high-energy fluid system piping in the U.S. EPR™. The external effects of piping ruptures discussed in this report include jet impingement and blast effects. Simplified approaches are used to define the loadings and are intended to bound the actual external loadings that would be experienced in the unlikely event of a guillotine rupture in a high-energy fluid system piping line.

In defining the loading, determining the response, and performing the structural evaluations, the following areas are investigated specifically, with appropriate methods being provided for their inclusion in the analysis effort:

1. Jet Impingement, considering:
    a. Plume Effective Length.
    b. Thrust Coefficient.
    c. Jet Resonance.
    d. Jet Deflections.
2. Blast Effects, considering:
    a. Energy Release.
    b. Target Distance.
    c. Overpressure and Impulse.
    d. Secondary Shock Effects.
3. Loading Analysis, considering:
    a. Dynamic Analyses using Finite Element Analysis.

   b. Static Analyses using Dynamic Load Factors.

4. Structural Evaluation, considering:
   a. ASME Code for Piping and Components.
   b. AISC for Steel Structures.
   c. ACI for Concrete Structures.

This report represents a departure from past pipe rupture effects design methods in two areas: the jet impingement from subcooled flashing jets and single phase steam jets and blast waves from ruptured steam lines. The simplified methods provided in this report represent conservative approaches to define these loading constituents without the use of Computational Fluid Dynamics analyses.

2.0 CONCLUSIONS

Based on the calculations and evaluations provided in this report, the following conclusions are obtained:

1. Break Locations and Types – Break locations and types are discussed in Section 3.1 and are determined in accordance with Reference 5.

2. Jet Impingement

   a. Source Conditions – Source conditions used to perform jet impingement calculations as they vary with time after the rupture, and their determination, are discussed in Section 3.2.1.

   b. Jet Plume Effective Length and Thrust Coefficient – [

      ]

   c. Compressible Jet Properties – Section 3.2.4 demonstrates that the exit plane conditions may be calculated using the [

      ]

d. Jet Resonance – As documented in Section 3.2.5, resonance in compressible jets can cause significant increases in the structural response of targets when the jet frequency is within 40% of the target structure frequency. [

]

e. Jet Deflections – As discussed in Section 3.2.6, jet deflections are possible for compressible and incompressible jets and should be considered in certain cases. A conservative method for consideration of jet deflection is to consider the secondary target as a primary target.

f. Protection of Target Essential SSC – As discussed in Section 3.2.7, essential SSC that cannot be demonstrated to meet code requirements under jet impingement loading must be protected by a jet shield. The jet shield is designed in accordance with applicable codes and standards.

3. Blast Effects – As demonstrated in Section 3.3, blast effects can be important for SSC that lie within close proximity of the break. The overpressure and impulse forces that occur due to blast effects reduce quickly with respect to distance.

4. Structural Analysis – Methods used to perform loading analyses through the use of dynamic finite element analyses or static analyses are discussed in Section 3.4.

5. Code Compliance – Methods used to perform structural evaluations in accordance with applicable codes and standards are discussed in Section 3.5.

3.0 PIPE RUPTURE EXTERNAL LOADING EFFECTS

This section provides the basis for the determination of break locations and types, jet impingement loading and blast loading of target essential SSC.

3.1 Break Locations and Types

Piping failures are postulated to occur in high-energy fluid system piping in accordance with Reference 8. Per U.S. EPR FSAR, Tier 2, Tables 3.9.3-1 and 3.9.3-2, pipe break loading, including jet impingement loading, on ASME Class 1, 2 and 3 components is considered a Service Level D event. Tables 3-1 and 3-2 of Reference 9 categorize high-energy line break and secondary side pipe rupture loads as Level D events. As discussed in Reference 8, high-energy fluid system piping is defined as piping in which the normal operating conditions exceed 200°F or 275 psig. Failure locations in Class 1 and Class 2/3 piping are postulated in accordance with Reference 5, as follows:

- Class 1 Piping:
  - Terminal Ends (Circumferential Breaks only).
  - Locations where the ASME Eqns. 10 and 12 or 10 and 13 stress ranges exceed 2.4 S_m (i.e., 80% of the ASME Code allowable).
  - Locations where the cumulative usage factor exceeds 0.1 (10% of the ASME Code allowable).
- Class 2/3 Piping
  - Terminal Ends (Circumferential Breaks only).
  - Locations where the sum of the ASME Eqns. 9 and 10 stress range exceeds 0.8(1.8S_h + S_A) (i.e., 80% of the ASME Code allowable).

Circumferential Break – These breaks are postulated at locations where the ratio of longitudinal stress to circumferential stress exceeds 1.5, in accordance with Reference 5.

Longitudinal Break – These breaks are postulated at locations where the ratio of longitudinal stress to circumferential stress is less than 1.5, in accordance with Reference 5.

Note that postulated longitudinal breaks are rare because the circumferential stress, caused by pressure, is maintained below approximately S_m in Class 1 piping. In order for a location to be considered a failure site in Class 1 piping, the stress must exceed 2.4 S_m, which indicates that the ratio of longitudinal stress to circumferential stress exceeds 2.4. This is greater than the maximum value of 1.5 that requires postulation of a longitudinal break. The ratio of longitudinal stress to circumferential stress in Class 2/3 piping is similar to that of Class 1 piping.

3.2 Jet Impingement

This section discusses source conditions, the plume effective length, the compressible jet velocity, jet resonance, and jet deflection.

3.2.1 Source Conditions

Source conditions at the break are typically determined using a thermal-hydraulics code (e.g., RELAP or CRAFT2) that is capable of providing pressure and enthalpy as a function of time after the postulated rupture. Using the time dependent source conditions of the blowdown event, from initial rupture through attainment of steady state, jet impingement calculations are performed to define the loading on target essential SSC. The following sections provide the methods used to define the loading.

3.2.2 Plume Effective Length and Maximum Thrust Coefficient

The behavior of a fluid jet from a ruptured pipe depends on the source conditions of the fluid in the pipe. Various reports and tests have been performed to characterize the jet plume geometries and to determine the distances at which the different types of jets can apply significant loading on targets. This section provides an evaluation to determine the appropriate effective lengths for use in U.S. EPR design.

3.2.2.1 Incompressible Liquid Jets

Incompressible liquid jets occur when the source temperature is below the fluid boiling point under ambient conditions, typically 212°F. In this case, the velocity of the jet is significantly below the fluid's speed of sound; therefore, shock waves are not present. In this type of jet, there is no limit to the plume effective length, except that gravity will cause the jet to accelerate downward based on projectile motion calculations.

3.2.2.1.1 Incompressible Liquid Jet Maximum Thrust Coefficient

The jet thrust coefficient for an incompressible water jet may be calculated directly from Bernoulli's equation as follows:

Bernoulli's Equation (ignoring effects due to gravity):

$$P_0 + \rho_0 V_0^2 / 2 = P_1 + \rho_1 V_1^2 / 2$$

Where:

V_0 = Initial System Fluid Velocity

P_0 = Initial System Pressure

ρ_0 = Initial System Density

V_1 = Jet Fluid Velocity at Exit Plane

P_1 = Jet Pressure at Exit Plane

ρ_1 = Jet Fluid Density at Exit Plane

If P_0 is set to the system stagnation pressure, the dynamic pressure associated with fluid velocity prior to the rupture may be neglected. In addition, the exit plane pressure (P_1) approaches the ambient pressure for low temperature applications. This provides the following equation with appropriate reduction of terms:

$$P_0 = \rho_1 V_1^2 / 2 \Rightarrow 2P_0 = \rho_1 V_1^2$$

The impulse force at the exit plane of a fluid jet is calculated as follows, based on conservation of momentum principles:

$$F_1 = (P_1 + \rho_1 V_1^2) A_e \Rightarrow F_1 = \rho_1 V_1^2 A_e$$

Where:

A_e = Exit Plane Flow Area

F_1 = Exit Plane Impulse Force

Combining these two equations provides:

$$2P_0 A_e = \rho_1 V_1^2 A_e$$

The thrust coefficient is defined by the following formula:

$$C_T = F_1 / P_0 A_e = \rho_1 V_1^2 A_e / P_0 A_e = 2$$

Therefore, based on basic fluid mechanics principles, the maximum force of a jet at the pipe exit plane is defined as $2P_0A_e$, which indicates that the maximum jet thrust coefficient for an incompressible water jet is 2.0.

3.2.2.2 Single Phase Steam Jets

Reference 10 documents test data used to determine the impact of jet impingement on various types of piping and component insulation used in nuclear power plants. Part of this test data focuses on single phase steam jets. As discussed in that report (Reference 10, Section 1.1.3), single phase steam jets with source pressures of 80 bars (≈1200 psia) can cause damage to insulation at a target distance of up to 25 times the pipe exit diameter (i.e., L/D = 25). The target essential SSC in a nuclear power plant that are evaluated for loadings due to jet impingement are of a construction that is significantly heavier than that of insulation. Therefore, these SSC would not experience similar damage from the relatively low jet momentum flux at this distance. Since some loading is to be expected, it is reasonable and conservative to assume that the jet is capable of applying full loading at this distance. [

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3.2.2.2.1 Steam Jet Maximum Thrust Coefficient

From Reference 7 (Part 4.4), the dimensionless impulse function (Eqn 4.23), which corresponds to the thrust coefficient, when considering the exit plane, as the control surface is as follows:

$$\frac{F}{P_0 A^*} = \frac{P}{P_0}\frac{A}{A^*}(1 + kM^2)$$

Where:

- F = Exit Plane Force
- P_0 = Stagnation Pressure
- A^* = Throat Area = Exit Plane Area
- P = Exit Plane Static Pressure
- A = Exit Plane Area
- k = Ratio of Specific Heats
- M = Mach Number at Exit Plane

Considering that the throat is the location where M = 1, which is equivalent to the exit plane in this case, the term P/P_0 may be calculated from Eqn. 4.15b of Reference 7, as follows:

$$\frac{P^*}{P_0} = \frac{P}{P_0} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$$

Where:

P^* = Throat Pressure = Exit Plane Static Pressure (P)

Combining these equations provides the following expression for thrust coefficient:

$$C_T = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}(1+k)$$

The specific heat ratio for steam can vary with quality and pressure. However, for exit plane pressures between 14.7 psi and 750 psi and qualities between 1.0 and 0.9, the specific heat ratio lies between 1.3 and 1.7 . Solving for C_T using this range of values provides a minimum of 1.26 and a maximum of 1.30 .

3.2.2.3 Subcooled Flashing Jets (Two Phase Jets)

Reference 6 performs numerical analyses for subcooled flashing jets and compares the calculated data to various sources of test data. The report provides plots of target pressures and target forces versus distance from the break for two phase jets at various upstream initial conditions.

Section 3.2.2.3.1 provides a tabulation of the thrust coefficients found on the plots from Reference 6 for use in defining a simplified method of determining jet impingement forces.

3.2.2.3.1 Subcooled Flashing Jet Maximum Thrust Coefficient

Table 3-1 tabulates the thrust coefficient (C_T) as a function of pressure and target distance, as calculated from Figures A.1 – A.125 of Reference 6. As shown in the table, in most cases, the plots do not provide this information beyond L/D=10 because C_T is trending towards a negligible value prior to L/D = 10. The only case where C_T values are provided for L/D ratios greater than 10 is for a source pressure of 2200 psia and subcooling of 63°F. Even in this case, the maximum C_T value is 0.1 at an L/D = 12.5, which is considered negligible.

Table 3-1: Thrust Coefficient (C_T)

Notes:

1. C_T is defined as the Target Force divided by P_0A_e and is taken as the maximum value for a given L/D and upstream pressure from the target load distributions plots from Figures A.1 – A.125 of Reference 6. The Max C_T is the maximum for any L/D for a given upstream pressure.

2. Plots of C_T at an L/D of 12.5 are not provided for any upstream pressures except for 2200 psia. In most cases, as shown in the table, the value of C_T reaches a negligible value prior to this distance. Also as shown in the table, although a value of C_T is plotted at L/D = 12.5 for a pressure of 2200 psia, the value of 0.1 may be considered negligible, particularly with respect to the conservatism in the "Max C_T" values plotted, which are significantly greater than the theoretical maximum of 2.0.

3.2.3 Jet Impingement Partial Intersection

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Figure 3-1: Partial Intersection

[ ]

Figure 3-2: Partial Intersection

[ ]

Figure 3-3: Partial Intersection

[ ]

3.2.4 Compressible Jet Properties

[ ] is used to determine the pipe rupture mass flow rate and exit plane conditions. [ ] Note that the static pressure in the jet can reach values lower than the ambient pressure; however, this requires the jet to go through normal or oblique shocks to regain equilibrium with the atmosphere. The shocks result in conversion of kinetic energy to thermal energy and an increase in entropy. This process results in a loss of jet dynamic pressure and momentum flux. The following sections provide more detail on the analysis.

3.2.4.1 Exit Plane Conditions

The properties at the exit plane (e.g., pressure, enthalpy, velocity) are determined using the [

] The velocity may then be determined from the following equations:

$$h_0 = h_1 + V_1^2 / 2$$

Where:

h_0	= Enthalpy at Upstream Conditions
h_1	= Enthalpy at Assumed Exit Plane Conditions
V_1	= Velocity at Exit Plane Conditions

Rearranging provides:

$$V_1 = \sqrt{2(h_o - h_1)}$$

The exit plane mass flux is then calculated as follows:

$$G_1 = \rho_1 V_1$$

Where:

G_1	= Mass Flux at Exit Plane
ρ_1	= Density at Assumed Exit Plane Conditions
V_1	= Velocity at Assumed Exit Plane Conditions

3.2.4.2 Compressible Jet Velocity

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$$h_0 = h_2 + V_2^{\ 2} / 2$$

Where:

- h_0 = Stagnation Enthalpy at Upstream Conditions
- h_2 = Enthalpy at Expanded Conditions
- V_2 = Jet Velocity at Expanded Conditions

Since the flow is assumed to be isentropic, the downstream enthalpy can be calculated by determining the quality from the following relation:

$$x_2 = \frac{s_0 - s_f}{s_g - s_f}$$

Where:

- x_2 = Quality at Fully Expanded Conditions
- s_0 = Entropy at Initial Conditions (BTU/lbm-R)
- s_f = Saturated Water Entropy at Atmospheric Pressure = 0.312 BTU/lbm-R
- s_g = Saturated Steam Entropy at Atmospheric Pressure = 1.757 BTU/lbm-R

Assuming that the static pressure at expanded conditions is equal to the atmospheric pressure, the enthalpy at expanded conditions can be calculated. From this, the velocity can be determined, as follows:

$$V_2 = \sqrt{2(h_0 - h_2)}$$

Using this formulation, along with that of Section 3.2.4.1, the exit plane conditions, as well as the expanded jet conditions, are calculated in Table 3-2.

Table 3-2: Exit Plane and Jet Conditions

Initial Press. (P_0) (psia)	Initial Temp. (T_0)	Initial Enthalpy (h_0) (Btu/lbm)	Initial Entropy (s_0) (Btu/lbm-R)	Exit Plane Density (ρ_1) (lbm/ft^3)	Exit Plane Velocity (V_1) (ft/sec)	Jet Quality (x_2)	Jet Enthalpy (h_2) (Btu/lbm)	Jet Velocity (V_2) (ft/sec)
Two Phase Jets								
2250	650	695.20	0.88	20.2	448	0.395	563	2572
2250	565	566.02	0.76	45.0	478	0.311	482	2051
2250	350	325.13	0.50	55.7	590	0.129	306	992
2250	250	223.26	0.36	58.9	587	0.036	215	630
1500	575	581.36	0.78	42.9	231	0.324	494	2092
1500	565	567.90	0.77	43.3	269	0.314	485	2035
1500	350	323.93	0.50	55.7	473	0.130	307	933
1500	250	221.69	0.37	58.9	477	0.037	216	531
1000	540	536.63	0.74	26.6	212	0.294	466	1883
1000	500	487.73	0.69	49.0	248	0.260	432	1666
1000	350	323.13	0.50	55.7	376	0.131	307	892
1000	250	220.64	0.37	58.9	386	0.038	217	453
500	450	430.22	0.63	51.5	116	0.219	392	1378
500	350	322.35	0.50	55.6	241	0.132	308	848
500	250	219.60	0.37	58.8	266	0.038	217	358
250	375	348.34	0.54	54.7	92	0.154	330	961
250	250	219.08	0.37	58.8	177	0.038	217	299
Steam Jets (x_0=1.0)								
1250	572.5	1182	1.362	1.7	1468	0.727	885	3854
1000	544.7	1193	1.391	1.3	1499	0.747	905	3799
500	467.0	1205	1.464	0.7	1463	0.798	954	3547

3.2.5 Jet Resonance

In this section, the ability for jet resonance to adversely impact the loadings on essential SSC is evaluated. The calculation of minimum jet resonance frequencies for impinging jets, and the conditions in which resonance is unlikely, are based on the following papers:

1. References 11 and 12 provide test data and analysis used in determining the resonant frequencies of high speed subsonic jets (0.7<M<1.0) at target distances (L/D) less than 7.5 (Section 1 of Reference 12). Jets at these velocities with targets at these ranges are subject to traveling waves that cause localized variations in the pressure time histories applied to the target. These localized pressure time histories can behave like a sine wave with narrow banded frequency content.

2. Reference 13 provides theoretical background and test data to determine the minimum resonant frequencies for axisymmetric and helical mode shapes for supersonic jets (M>1.0). It is also demonstrated that the results for subsonic jets match well with those of References 11 and 12. Therefore, the calculation of minimum resonance frequency is based on Reference 13.

3. Reference 14 provides an overview of many tests that have been performed on impinging jets. In this paper it is shown that, for cases in which the NPR exceeds 3.8 and the target distance (L/D) exceeds 5, there is no experimental evidence indicating the existence of impingement tones. This is likely due to the existence of a strong normal shock near the nozzle exit in a converging nozzle. This indicates that resonance is unlikely in these cases.

4. **[**

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3.2.5.1 Jet Resonance Minimum Frequency

Reference 13 provides the theory behind jet mode shapes and compares the theoretical data to experimental data. As demonstrated in Reference 13, the theoretical data and experimental data correlate very well. It is indicated that subsonic jets with Mach numbers between 0.7 and 1.0 are capable of supporting axisymmetric mode shapes while supersonic jets with Mach numbers greater than 1.0 are capable of supporting axisymmetric as well as helical mode shapes.

Based on review of the reference material discussed above (References 11, 12, 13 and 14), the following conclusions are drawn:

1. Supersonic and high speed subsonic (M>0.7) flows can generate significant pressure oscillations. The amplitude of the oscillations is discussed in Section 3.2.5.2.

2. Reference 14 demonstrates that tonal production is limited with NPR greater than 3.8 and L/D greater than 5. This indicates that resonance is unlikely in these conditions.

Reference 13 is used to determine the frequencies for axisymmetric modes in supersonic jet flows. In that paper, the following equation (Eqn 22), after rearrangement, is provided:

$$f = \frac{\sigma_i U_{jet}}{\pi D_{jet} M_{jet} (a_{jet} / a_{\infty})(((a_{\infty} / a_{jet}) + M_{jet})^2 - 1)^{0.5}}$$

Where:

f = Minimum Axisymmetric Mode Resonance Frequency for Supersonic Jet

σ_i = First Positive Zero of the Order 1 Bessel Function ($J_1(x)$) = 3.83

U_{jet} = Jet Velocity

D_{jet} = Jet Diameter

M_{jet} = Jet Mach Number

a_{jet} = Jet Speed of Sound

a_{∞} = Ambient Speed of Sound

As demonstrated in Reference 13, the frequencies of the subsonic axisymmetric modes and supersonic helical modes can be calculated using the Strouhal number for the jet. The Strouhal number is a dimensionless parameter that provides a measure of oscillating flow mechanisms and is calculated as follows:

$$St = \frac{fL}{V}$$

Where:

St = Strouhal Number

f = Frequency

L = Characteristic Length = Nozzle Diameter

V = Velocity

Reference 13 provides a plot of Strouhal number versus Mach number for axisymmetric modes in subsonic jets, which is provided herein as Figure 3-4. Reference 13 also provides a plot of Strouhal number versus Mach number for helical modes in supersonic jets, which is provided as Figure 3-5. The Strouhal number for the jet is taken from these plots based on the Mach number of the expanded jet conditions, calculated as explained in Section 3.2.2. Based on this information, the minimum resonance frequency can be determined for a given set of fluid conditions. Table 3-3 provides a tabulation of frequencies and speed of sound for various conditions and nozzle sizes calculated using the formula in Section 3.2.5.1, Figure 3-4, and Figure 3-5.

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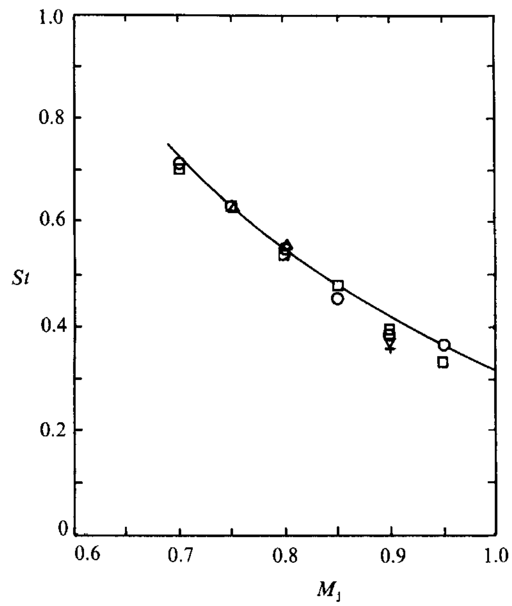
Table 3-3: Jet Minimum Resonance Frequencies

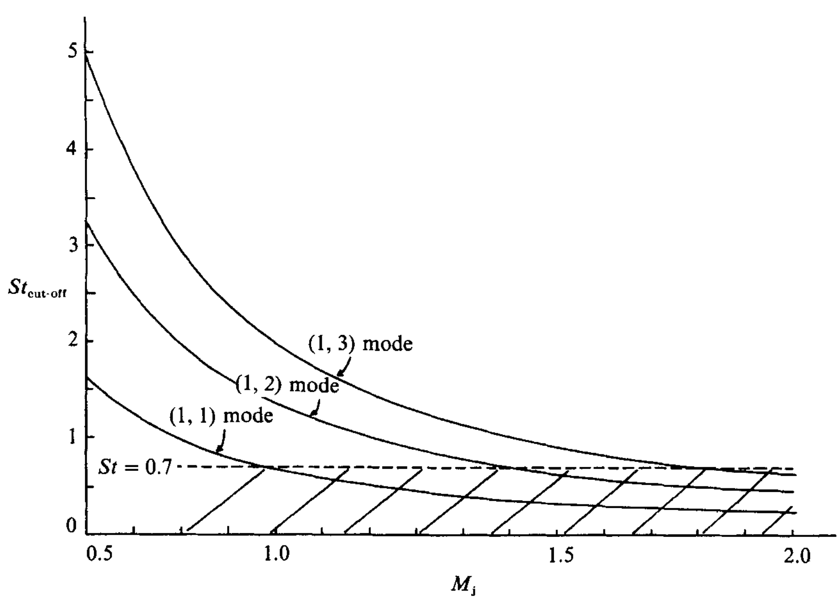
Pipe Diameter (in)	Jet Sound Speed (ft/sec)	Subsonic Jet Freq (M=0.7) (Hz)	Subsonic Jet Freq (M=0.9) (Hz)	Supersonic Jet Axisym. Freq (M=2) (Hz)	Supersonic Jet Helical Freq (M=2) (Hz)
4	1500	2205	1620	1130	1286
6	1500	1470	1080	753	857
10	1500	882	648	452	514
14	1500	630	463	323	367
18	1500	490	360	251	286
24	1500	368	270	188	214

Figure 3-4: Strouhal Number for Subsonic Axisymmetric Modes



(Reference 12)

Figure 3-5: Strouhal Number for Supersonic Helical Modes



(Reference 12)

3.2.5.2 Jet Force Amplitude

Reference 15 provides a numerical analysis of supersonic impinging jet flow. As shown in Figures 7 and 12 of Reference 15, the amplitude of the pressure oscillation is shown to be as great as 45% of the stagnation pressure upstream of the exit plane.

Reference 16 provides a plot of the pressure time history at a location on the target as well as a plot of the target response time history, measured as forces in the target supports. As shown in Figure 7 of Reference 16, the measured pressure oscillates with an amplitude of approximately 13% of the average target pressure.

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3.2.5.3 Total Response

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3.2.5.3.1 Idealized Single Degree of Freedom Structures

Certain simple structures, such as pipe supports, whip restraints and jet shields, may be idealized as single degree of freedom (SDOF) structures. The response of these structures to static and dynamic loading may often be determined through hand calculations, using methods described in Reference 17, for example.

The initial pulse force provides a dynamic load factor of 2.0 for a target structure that can be considered as a SDOF structure, which leads to a maximum response load of $2C_TP_0A_e$.

Based on Figure 3-6 of Reference 17, the Dynamic Load Factor (DLF) for an SDOF structure with a sinusoidal varying load and a damping value of less than 10% percent of critical, is less than 1.0 when the ratio of the frequency of the load (Ω) to the frequency of the structure (ω) is greater than 1.4. In other words, if the forcing function frequency is 40% greater than the target structure frequency, the DLF is a maximum of 1.0. As stated above, the range of the sinusoidal load (i.e., 2 x the amplitude) is equal to twice the jet force. Therefore, in cases where the frequency of the resonant jet is at least 40% greater than the frequency of the target structure, the response of an SDOF structure to a resonant jet is no greater than the steady jet pulse response.

This indicates that resonant jets do not require evaluation in cases where the minimum jet frequency is at least 40% greater than the target structure frequency.

3.2.5.3.2 Multi-Degree of Freedom Structures

Many target structures, such as large pressure vessels, have multiple degrees of freedom and are not conducive to analysis through hand calculations. In those cases, computer analyses are performed using force time histories with the appropriate frequency and amplitude. Structural evaluation of target structures using computer analysis techniques is discussed in greater detail in Section 3.4.

Figure 3-6: Dynamic Load Factor – Sinusoidally Varying Load

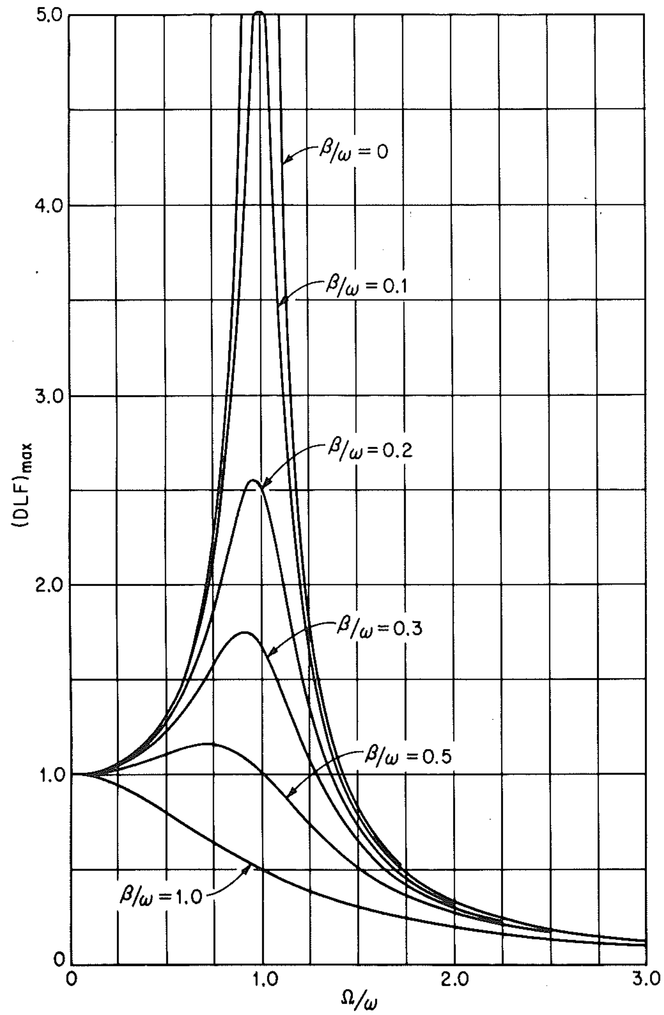

FIGURE 2.18 Maximum dynamic load factor for sinusoidal load, $F_1 \sin \Omega t$, damped systems.

(Reference 17)

3.2.5.4 Random Unsteadiness

Unlike jet resonance, random unsteadiness in a fluid jet is a broadband phenomenon, much like turbulence. Because it is a broadband phenomenon, the amplitude of the forcing function at a given frequency is limited. Therefore, stresses in robust SSC (e.g., pressure vessels) are not a concern under these loadings.

Figure 3 from Reference 12 provides a comparison of the surface pressure fluctuation signal power spectra for a resonant (i.e., narrow-banded) jet at a Mach number of 0.8 and a non-resonant (i.e., broad-banded) jet at a Mach number of 0.5. The figure is comparing normalized power spectra, which indicates that the total area under each curve is equivalent. As shown in the figure, the maximum power in the resonant jet at its resonant Strouhal number (~0.5) is approximately 10 times the maximum power in the non-resonant jet. As power is proportional to the square of signal amplitude, this indicates that the amplitude of the pressure variations in the resonant jet are approximately 100 times the amplitude of the pressure variations in the non-resonant jet. The initial pulse loading from the jet is equivalent to that of a resonant jet and, therefore, bounds the response from non-resonant jet loading. Based on this evaluation, consideration of broad-banded sources for loading of rugged structures is not required.

However, random unsteadiness can cause fatigue failures in lightly constructed SSC over time. Therefore, failure in lightly constructed SSC (e.g., valve operators, instrumentation) under jet impingement loading is assumed to occur unless protected by a jet shield, as discussed in Section 3.2.7.

3.2.6 Jet Deflection

Jet impingement loads on secondary targets due to jet deflection may occur in certain situations and are considered in this section. It is typically considered that a jet, whether it is incompressible or compressible, loses a significant amount of energy after striking the primary target. This section provides a method for consideration of the loading on a secondary target.

3.2.6.1 Jet Deflection – Incompressible Jet

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Figure 3-7: Jet Deflection Schematic

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3.2.6.2 Jet Deflection – Compressible Jet

The deflection of a supersonic compressible jet occurs through normal and oblique shocks that represent discontinuities in the flow stream. The two types of shocks and the associated loss of energy are discussed in the following subsections.

3.2.6.2.1 Normal Shock

In supersonic compressible jets, which are typical of most jets originating from high-energy piping systems, a normal shock exists upstream of the target SSC, as demonstrated by Reference 6. A normal shock is an irreversible process that causes the jet to lose kinetic energy and transforms the supersonic jet into a subsonic jet. The jet may then re-expand to become supersonic again; however, the momentum flux of the jet is reduced by the shock.

As shown in Reference 7, the entropy increases across the shock. When considered at equilibrium conditions, an increase in entropy corresponds to an increase in enthalpy. This indicates that some of the kinetic energy is transferred to thermal energy, reducing the velocity and density of the jet; therefore, the momentum flux is reduced.

The conclusion is that loading of a secondary target, one that is struck by the jet after passing through a shock and re-expanding to form a supersonic jet, is not as severe as loading of a primary target.

3.2.6.2.2 Oblique Shock

In the case of a supersonic compressible jet striking a target structure at a shallow deflection angle (i.e., large angle of incidence), the flow can change direction through an oblique shock and maintain supersonic velocity downstream of the shock. The maximum deflection angle that will allow downstream supersonic flow is dependent upon the jet's Mach number and specific heat ratio. As discussed in Reference 7 (Figures 16.4 – 16.6), flows with greater upstream Mach numbers can be deflected through greater angles, while maintaining supersonic conditions. For example, considering air with a specific heat ratio of 1.4, flow with a Mach number of 2.5 has a maximum possible deflection angle of 30° while flow with a Mach number of 1.5 has a maximum possible deflection angle of about 12°.

However, as demonstrated in Reference 7 (Part 16.3), oblique shocks, just like normal shocks, cause an increase in entropy. This has the effect of reducing the density and the velocity, which reduces the forces.

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3.2.6.2.3 Secondary Target Loading

3.2.7 Protection of Target Essential SSC

Target essential SSC that cannot be demonstrated to meet code requirements under the loading caused by jet impingement must be protected by a jet shield. The jet shield may be designed as any type of structure (e.g., concrete, steel) that is capable of deflecting the jet and withstanding the external loading effects due to pipe rupture, including the effects due to resonance and random unsteadiness. Jet shields are considered safety-related structures and must meet the same code requirements as other target essential SSC, typically those of AISC (Reference 18) or ACI (Reference 19).

3.3 Blast Effects

The blast effects of an explosion are in the form of a high-intensity front shock wave. The shock expands radially outward from the surface of the explosive into the surrounding air. The pressure time history of a typical blast wave, as observed at a location removed from the center of the explosion, is shown in Figure 3-9 from Reference 20. At an arrival time of t_a seconds after the explosion, the pressure at this removed location suddenly increases to a peak value of overpressure. An object located in the positive phase is then subjected to an instantaneous lateral force. The overpressure decays to ambient after the positive phase duration and then the negative phase duration occurs with pressures below ambient. In general, the positive pressure phase is far more intense that the negative phase. But this is not a stable condition as the shock wave rapidly decays in strength, lengthens in duration, and decreases in velocity. As the wave expands, the front wave impinges on structures located within its path. The magnitude of the blast load on the structure arising from these pressures is a function of the energy available to drive the blast wave and distance to the structure.

In order to describe the blast wave, the initial shock intensity, the arrival time and impulse per unit area are quantified. [

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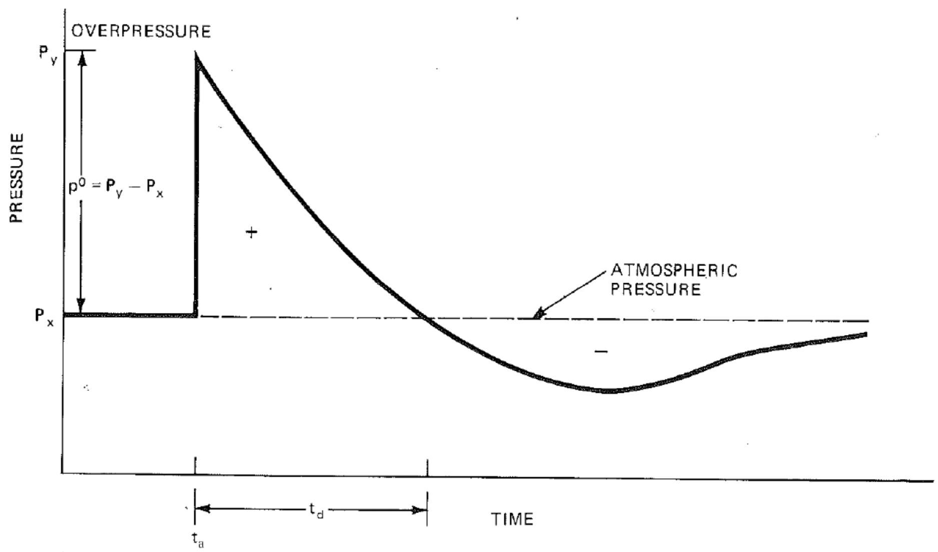
Figure 3-9: Typical Blast Wave Pressure-Time Curve



3.3.1 Energy Release

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3.3.2 TNT Equivalency Method

3.3.3 Scaling Law

3.3.4 Blast Overpressure

[ ]

3.3.5 Arrival Time

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3.3.6 Impulse

3.3.7 Blast Parameters

Table 3-4: Blast Parameters

Initial Press. (P_0) (psia)	Initial Temp. (T_0)	Initial Internal Energy (u_0 (Btu/lbm)	Initial Entropy (s_0) (Btu/lbm-R)	Expanded Internal Energy (u_2) (Btu/lbm)	Heat of Detonation (h_{exp})	
					(Btu/lbm)	(ft-lbf/lbm)
1250	572.5	1102	1.362	832	270	210E5
1000	544.7	1110	1.391	850	260	202E5
500	467.0	1119	1.464	896	223	173E5

3.3.8 Example Problems

The following sections provide evaluations of the blast effects due to ruptures in subcooled water lines and steam lines.

3.3.8.1 Subcooled Water

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In addition, Reference 22 indicates that ruptures in fluid system piping containing subcooled water are not likely to develop blast waves, and if blast waves do develop, they would be insignificant compared to the forces exhibited by the jet blowdown.

3.3.8.2 Steam

convert the available energy into an equivalent charge weight of TNT, W_E using the following relationship from References 20 and 21.

$$W_E = \frac{h_{EXP}}{h_{TNT}} W_{EXP} = \frac{2.1E5 ft - lbf / lbm}{1.97E6 ft - lbf / lbm}(10.3 lbm) = 1.1 lbm$$

Where:

W_E = Effective Charge Weight (lbf)

W_{EXP} = Weight of the Explosive in Question = 10.3 lbm

h_{EXP} = Heat of Detonation of Explosive in Question = 2.1E5ft-lbf/lbm

h_{TNT} = Heat of Detonation of TNT = 1.97E6 ft-lbf/lbm

Table 3-5: Blast Wave Static Loads

3.4 Structural Evaluation of Typical Target Essential SSC

Structural evaluations of target essential SSC are performed considering the dynamic nature of the jet impingement loading and blast pressure wave loading associated with ruptures in high-energy fluid system piping systems. Depending on the type of SSC, the structural evaluation may be performed using either of the following methods:

- Dynamic Modal Integration Finite Element Analysis.

  This method is typically used for complex multiple degree of freedom systems with natural frequencies in the range of interest for impinging jets with possible resonance.

- Static Analysis using Dynamic Load Factors.

  This method is typically used for structures that may be idealized as single degree of freedom systems with natural frequencies in the range of interest for impinging jets with possible resonance.

The applied loading for the target SSC is defined as discussed in Section 3.2 for jet impingement and in Section 3.3 for blast effects.

3.4.1 Dynamic Finite Element Analysis

The response of essential SSC that may only be considered as multi-degree of freedom structures is typically determined through finite element analysis, using beam models, plate and shell models, or a combination of the two. Figure 3-11 illustrates a typical plate and shell finite element model of a steam generator from the U.S. EPR. This model is used to perform stress analyses and to determine the dynamic response to a jet impingement load on the steam drum region.

The general analytical methodology for determining the dynamic response of a structure to jet impingement loads is as follows:

- Develop a finite element model of the structure using codes such as BWSPAN (beam element models) or ANSYS (plate and shell element models).
- Perform modal analyses to identify the structural frequencies and mode shapes of the target structure.
- Develop forcing functions representing jet impingement loads. These forcing functions are expressed as sinusoidal time histories with the magnitudes representative of the jet force amplitude (as derived in Section 3.2.5). The frequencies of oscillation are developed to match the structural frequencies of interest.
- Perform transient dynamic analyses using the Direct Integration or Modal Superposition method of solution.
- Perform a frequency sweep analysis to identify the modes with the largest dynamic response to the applied forcing function. The displacement response will generally peak within the first few structural modes and then reduce significantly for higher modes.
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3.4.1.1 Modeling

There are two types of structural response that must be considered for any target SSC, local and global.

- Local response can be significant in plate and shell structures (e.g., pressure vessels) and involves out of plane bending modes. Figure 3-10 illustrates typical mode shapes for an edge supported rectangular plate. In plate and shell element models, the mass is distributed evenly; therefore, mass point spacing is not considered critical. Sensitivity studies are typically performed to determine proper meshing schemes for accurate calculation of frequencies in excess of the jet resonant frequency and the frequency of maximum response. Note that the frequency of maximum response is typically one of the first few shell modes because the response of higher order modes gives smaller displacements.

- Global response can be significant in any structure and is often modeled with beam elements. To properly define the modes of vibration for a beam, enough node points and mass points must be included in the model. Mass point spacing for beam element dynamic models is critical in determining frequencies of higher order modes. The maximum mass point spacing for a lumped mass model is determined as discussed in Reference 9.

3.4.1.2 Damping

Damping is selected based on the type of analysis and response being calculated. When finite element analyses are performed to determine the high frequency (i.e., > 33 Hz) local and global response in plate and shell structures due to jet impingement, 1% damping is used because the strain in high frequency modes is lower than would be expected from lower frequency modes.

3.4.1.3 Loading Method

The method used for applying jet impingement loading depends on the type of analysis being performed, local or global, as follows:

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Figure 3-10: Rectangular Plate Mode Shapes

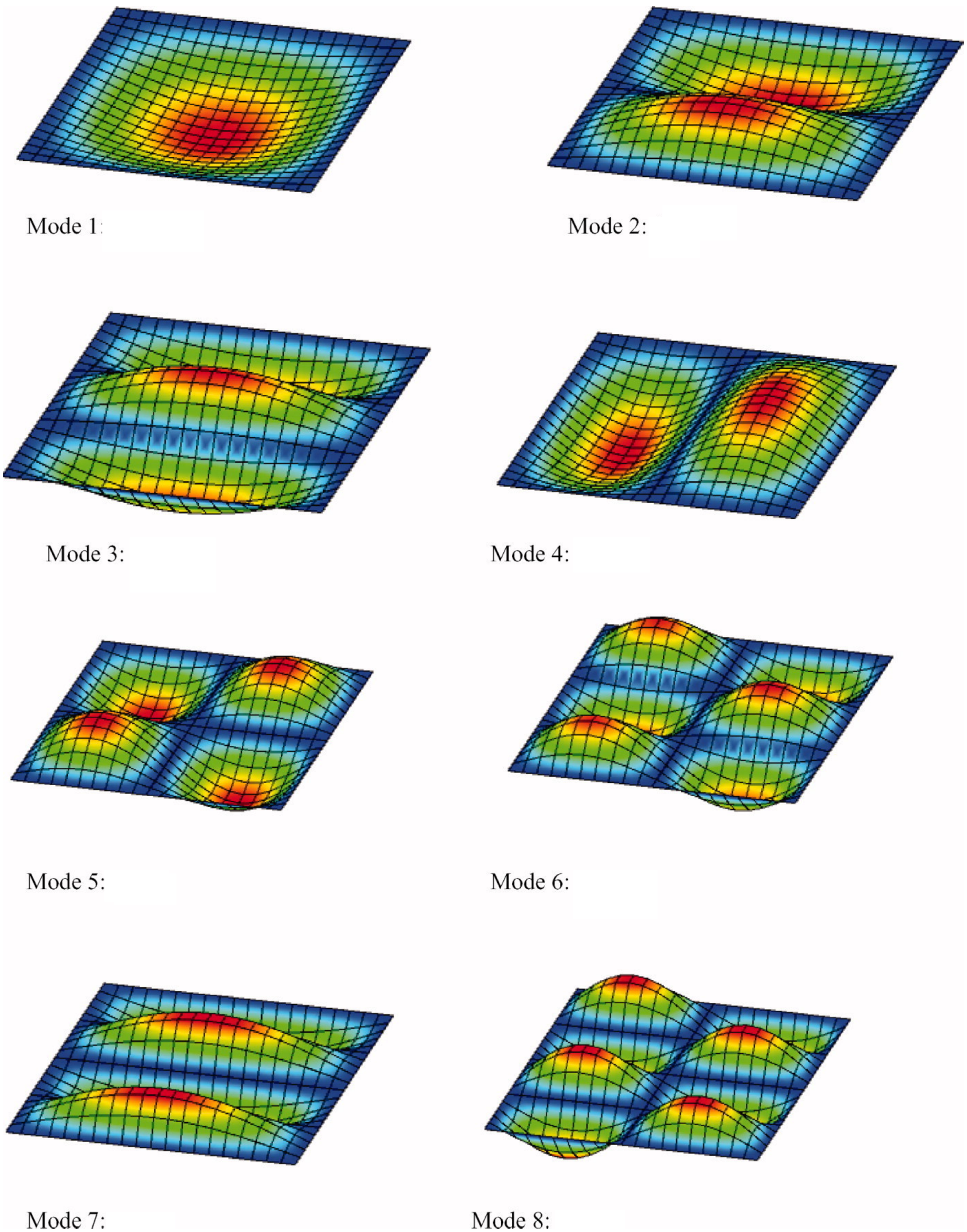
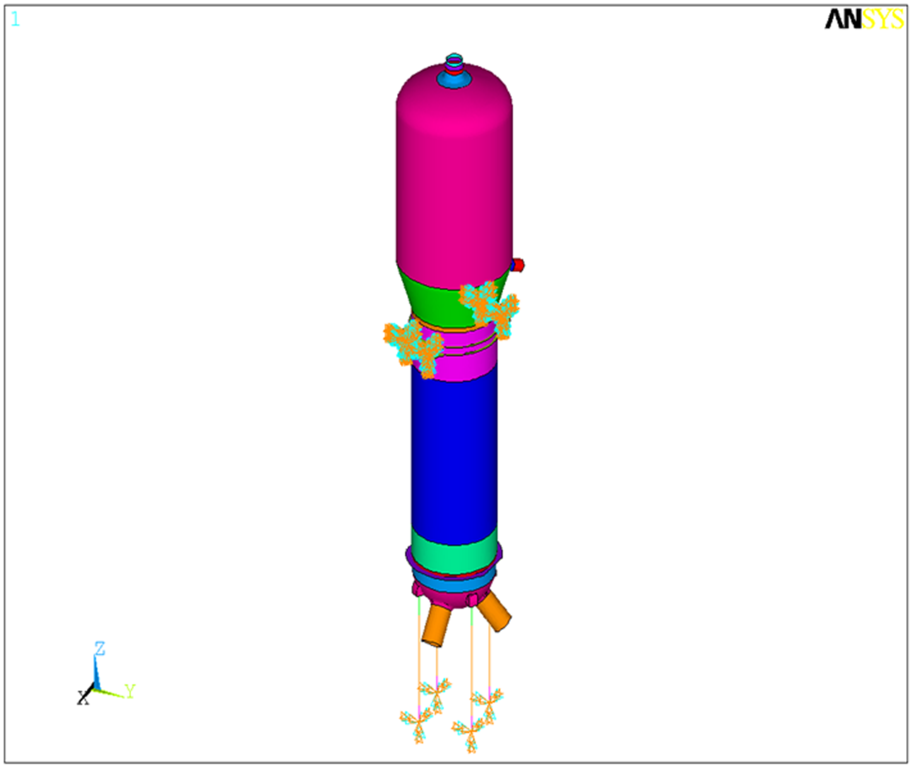


Figure 3-11: Typical Plate and Shell Finite Element Model



3.4.2 Static Analysis using Dynamic Load Factors

Hand calculations or finite element analyses using dynamic load factors may be used to accurately predict the response of essential SSC that may be idealized as single degree of freedom oscillators to a pulse or sinusoidal forcing function. Pulse forcing functions associated with pipe rupture would be caused by the initial stage of jet impingement or by blast waves. The procedure for performing structural evaluations of simple structures through hand calculations or finite element analysis is as follows:

- Determine structure's dominant natural frequency.
- Define blast and jet impingement pulse dynamic loading.
- Define jet impingement resonant dynamic loading.
- Determine dynamic load factor for each type of loading.
- Determine maximum response and member loads/stresses for comparison to applicable code allowables.

3.4.3 Analysis Methodology Steps

Figure 3-12 provides a flow chart illustrating the basic steps taken to determine jet impingement and blast loads and their application to target SSC.

Figure 3-12: Loading Analysis Methodology Flow Chart

3.5 Applicable Codes and Standards

Essential target SSC are evaluated in accordance with applicable codes and standards for the item in question. The following codes and standards provide the design requirements for typical SSC in the U.S. EPR:

- ASME Section III Boiler and Pressure Vessel Code, 2004 Edition (Reference 25).
- AISC N-690, 1994 Edition, including Supplement 2 (2004) (Reference 18).
- ACI 349, 2001 Edition (Reference 19).

The following sections briefly describe the basic design requirements for essential SSC in the U.S. EPR.

3.5.1 Pressure Vessel Code Requirements

Level D events (e.g., pipe rupture) are evaluated in accordance with Appendix F of the ASME Code, Section III (Reference 25). The basic requirement found in Appendix F, Paragraph F-1331.1, when using elastic analysis, is that primary membrane stresses shall not exceed 70% of the material tensile strength (Reference 25, F-1331). This implies a minimum margin in excess of 40% (1/0.7 – 1 = 0.43).

3.5.2 Steel Structure Code Requirements

Reference 18 provides design requirements for steel structures under abnormal loading, such as during a pipe rupture event. When performing linear elastic analysis, most tension allowable stresses are increased by 60% over the normal allowable stresses except that these stresses shall not exceed 70% of the material tensile strength (Reference 18, Table Q1.5.7.1). This implies a minimum margin in excess of 40%, which is the same as that of ASME piping and components required to maintain pressure boundary, as discussed in Section 3.5.1.

3.5.3 Concrete Structure Code Requirements

Reference 19 provides design requirements for concrete structures under abnormal loading (e.g., during a pipe rupture event). The strength design method is used for the structural analysis of concrete, which required the application of load factors (Section 9.2 of Reference 19) and design strength reduction factors (Section 9.3 of Reference 19). Appendix C of Reference 19 also provides special provisions for impulsive loading on concrete, which allows the use of ductility ratios. The provisions provide a minimum safety margin of 20% to the ultimate strength of concrete for impulsive loading per Section C.3.2 of Reference 19.

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