AmericanLifelinesAlliance

A public-private partnership to reduce risk to utility and transportation systems from natural hazards

Seismic Design and Retrofit of Piping Systems

July 2002

American Society of Civil Engineers

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1.0 INTRODUCTION

The American Lifelines Alliance (ALA) was formed in 1998 under a cooperative agreement between the American Society of Civil Engineers (ASCE) and the Federal Emergency Management Agency (FEMA). In 2001, ALA requested George A. Antaki, P.E., to prepare a guide for the seismic design of new piping systems, and the seismic retrofit of existing, operating systems in critical facilities.

1.1 Project Objective

The purpose of this guide is to

- Provide comprehensive, yet easy to follow guidance for the seismic design of piping systems in essential facilities such as power plants, chemical process facilities, oil and gas pipelines and terminals, and post-earthquake critical institutions such as hospitals.
- Compile and describe in a single document the steps and techniques necessary for the seismic qualification of new or existing above ground piping systems, based on current analytical and dynamic testing technology, as well as experience from the behavior of piping systems in actual earthquakes.
- Propose a seismic qualification standard, to be submitted to the American Society of Mechanical Engineers, ASME, for consideration as the basis for a B31 standard.

1.2 Project Scope

The guide addresses the seismic design of piping systems or the retrofit of existing piping systems. The purpose of seismic design or retrofit is to assure that in case of earthquake, the piping system will perform its intended function: position retention (the pipe would not fall), leak tightness (the pipe would not leak), or operability (the piping system would deliver and regulate flow).

This Guide applies to above ground piping systems, which - except for seismic design – otherwise comply with the provisions of the ASME B31 pressure piping codes for materials, design, fabrication, examination and testing. For buried piping and pipelines, the reader is referred to an earlier ALA report “Guidelines for the Design of Buried Steel Pipe”, July 2001.

Piping systems may be seismically designed or retrofitted for any one of several reasons:

(1) Public and worker safety; for example, assuring the leak tightness of process piping containing toxic materials, or cooling water supply to a heat exchanger controlling the temperature of an exothermic or explosive mixture.

(2) Environmental protection; for example, assuring the integrity of a hazardous liquid pipeline or oil terminal in an environmentally sensitive area.

(3) Protection of capital assets; for example, assuring the integrity of costly systems at a chemical or power plant.

(4) Vital post-earthquake function; for example, assuring the supply and distribution of critical gases in a hospital, or the fuel supply to an emergency diesel-generator.

(5) Compliance with regulatory requirements.

This guide does not address the seismic design and retrofit of nuclear power plant piping systems, which are explicitly prescribed by the US Nuclear Regulatory Commission, and codified in ASME Boiler & Pressure Vessel Code, Section III, Division1, Nuclear Components.

1.3 Notations

A_C = area of base of 45^o concrete cone emanating from anchor bolt tip, in^2
a = lateral uniform acceleration, g's dL= change in length, in
a_P = component amplification factor (1.0 to 2.5)
dT = temperature change, ^{o}F
E = weld joint efficiency factor
c = corrosion allowance, in
D = pipe outer diameter, in
d = maximum displacement at impact, in
d = swing amplitude, in
d_s = static displacement of elastic member due to its own weight, in
d_{st} = static displacement due to weight plus the weight of the falling body, lb
E = Young's modulus, psi
F = maximum permitted load applied to the system, lb
F_{LAC} = limit analysis collapse load, lb
F_P = horizontal load, lb
F_{PAC} = plastic analysis collapse load, lb
F_{PI} = plastic instability load, lb
f = natural frequency, Hz
f_a = swing frequency, Hz
f_C' = concrete strength, psi
g = gravity, 386 in/sec^2
H = height of falling interaction, in
H = height from support-vessel attachment to vessel's center of gravity, in
h = height of structure
h = height of free fall, in
I = importance factor (1.0 or 1.5)
I = moment of inertia, in^4
K = total global stiffness of vessel assembly, lb/in
K_V = vessel stiffness, lb/in
K_L = total stiffness of support legs, lb/in
k = anchor bolt factor

k = stiffness of elastic member, referenced to point of impact, lb/in
L = length, in
L_T = span length from ASME B31.1 Table 121.5
N = number of cycles to fatigue failure
n = actual number of fatigue cycles
NEP = non-exceedance probability
P = design pressure, psi
P = impact force, lb
P_b = primary bending stress, psi
P_C = tensile capacity of anchor bolt, lb
P_N = nominal tensile capacity of anchor bolt, lb
P_L = primary general or local membrane stress, psi
P_m = primary membrane stress, psi
P_{max} = maximum primary stress intensity at any location, psi
P_N = nominal pullout strength, lb
P_U = mean measured strength of concrete anchor bolt, lb
R = resultant response
R = radius of the zone of influence, in
R_{EW} = east-west response
R_{NS} = north-south response
R_V = vertical response
R_i = response in mode i
r = exceedance probability = 1 – NEP
R_P = component response modification factor (1.0 to 5.0)
RP = return period, years
S = allowable stress defined in B31.1 or B31.3 for the material and design temperature, psi
S_a = spectral acceleration at frequency f_a, in/sec^2
S_S = short period acceleration (IBC), g
S_1 = 1 sec acceleration (IBC), g
S_{DS} = design spectral response acceleration at short period (IBC), g
S_{D1} = design spectral response acceleration at 1 second (IBC), g
S_U = minimum ultimate strength of the material, psi
T = minimum wall thickness required by code, in
T = exposure period, years
T = average primary shear across a section loaded in pure sheer, psi
V_C = shear capacity of anchor bolt, lb
V_N = nominal shear capacity of anchor bolt, lb
V_H = horizontal spectral velocity, in/sec
V_V = vertical spectral velocity, in/sec
W = weight, lb
W = weight of falling body, lb
W_b = weight of elastic member, lb
X_{ij} = concrete anchor penalty factor for tension
$x(t)$ = displacement as a function of time t, in
Y_{ij} = concrete anchor penalty factor for shear
y = temperature correction factor, 0.4 below 900^{o}F.

z = height of attachment to structure

α = coefficient of thermal expansion, $1/^oF$
σ = maximum bending stress, psi
σ = standard deviation of measured strength of anchor bolts, lb
Δ = deflection at mid-span, in
Φ = strength reducton factor [ACI 349]
ω = circular frequency, rad/sec
ω_D = damped circular frequency, rad/sec
ζ = damping, %

2.0 ASSEMBLING PIPING SYSTEM DATA

2.1 New System

In order to seismically design and qualify a piping system, the following data will have to be assembled up-front:

System isometric: The isometric is a three-dimensional pipe routing, showing segment lengths and directions, and the location and orientation of components, equipment, pipe supports and restraints.

Pipe size and schedule.

Linear weight of pipe contents and insulation.

Pipe material specification and grade.

Non-welded joints (flange joints, threaded fittings, other mechanical joints): Type, size or rating, make and model, limits on loads or displacements if available.

Component weight, approximate location of center of gravity.

Equipment flexibility: Local flexibility (equipment nozzle details), and global flexibility (equipment support details).

Design and operating parameters:

(a) Maximum and minimum operating pressure and temperature.
(b) Design pressure and temperature.
(c) Operating modes of pressure and temperature.
(d) Live loads such as snow, where applicable.
(e) Wind loads, where applicable.
(f) Other loads, as applicable.
(g) Seismic input (refer to Chapter 4).

2.2 Retrofit

2.2.1 System Design Parameters

For the seismic retrofit of an existing, operating, piping system, the data listed in section 2.1 should also be compiled. For older systems, some of this data may not be retrievable, in which case the Designer should gather the information from operating and maintenance records, and from field walk-down. Materials, pressure ratings, make and model, should be recorded from markings, and suppliers may be contacted to obtain information that can not be verified in the field.

2.2.2 Field Walk-Down

In addition to the system design parameters, the Designer should initiate the seismic retrofit of an existing system with a system walk-down to record the following information (with field notes and photographs):

The isometric layout (three dimensional sketch of pipe routing and dimensions).
Support types and locations.
Anchorage details.
Pipe material and size.
Components and equipment, with name tag information.
Type, thickness and linear weight of insulation.
Material condition of piping, equipment, components and supports.
Potential spatial interactions.
Estimated weights and center of gravity of heavy components.
Any notes and concerns of significance.

2.2.3 Material Condition

A review of material condition should include the following attributes:

Pipe fittings should be standard (ANSI/ASME B16), and have the right pressure rating (for example, a 150 lb flange should not be used on a 500 psi system).

The fabrication, welding, joining, erection of pipe, pipe supports and attachments to building structure should be sound and of good quality.

The review of maintenance records is important to determine the history of leakage, repairs, and operability. While minimal or mediocre maintenance may have been sufficient for normal operation of a system, the following conditions may pose a problem in case of earthquake:

Distortion of pipe supports.
Visibly poor welds (rough, incomplete, uneven) or brazed joints (no visible brazing).
Unusual temporary repairs.
Significant bearing, scratch marks of pipe surface.
Pipe dislodged from supports.
Deformed thin vessel shell.
Shifted base plate, loose anchor bolts, cracked foundation.
Missing nuts and bolts on pipe or support components.
Signs of leakage (discoloration, dripping, wet surface).
Deterioration of protective coating.
Restricted operation of pipe rollers or slide plates.
Insecure attachment between pipe and support, or between support and building.

The walk-down should also assess the internal corrosion condition of the pipe. This can be done by the following methods:

(1) Direct external and internal visual examination if the system can be opened at flanges.

(2) Volumetric examination of the pipe wall at points where corrosion would be expected (by ultrasonic, radiographic or magnetic techniques).

(3) Assessment of corrosion history in similar systems together with a review of the maintenance history of the system.

3.0 PRELIMINARY DESIGN

3.1 Design for Pressure and Temperature

Note that this section applies to new designs, not to the retrofit of installed systems. In practice, the design pressure and temperature of a system are the highest pressure and concurrent temperature that can be achieved in the system. If the system has a relief valve, it is the set pressure of the relief valve or rupture disc (the pressure at which the valve or disc will discharge). In a liquid system, if the valve is at a higher elevation than some of the pipe, the hydrostatic pressure (weight of the column of liquid between the valve and the lower pipe elevation) must be added to the relief valve set pressure to obtain the design pressure. For water, every 34 ft in elevation correspond to an additional pressure of 1 atmosphere or 14.7 psi. For systems that do not have a relief valve, the design pressure is the highest credible pressure that can be achieved. For example, in a system containing a centrifugal pump it could be the pump dead head pressure (the pressure reached in the piping system if the pump is running against a closed downstream valve).

The design pressure and temperature are used to size the pipe wall thickness and select the pipe schedule and the pressure rating for the fittings.

For ASME B31.1 (power plant) and B31.3 (process plant), the minimum wall thickness is given by

$$t = \frac{PD}{2(SE + Py)}$$

t = minimum wall thickness required by code, in
P = design pressure, psi
D = pipe outer diameter, in
S = allowable stress defined in B31.1 or B31.3 for the material and design temperature, psi
E = weld joint efficiency factor for longitudinal or spiral seam welded pipe, given in ASME B31.1 or B31.3
y = temperature correction factor, 0.4 below 900^{o}F.

A corrosion allowance "c" is added to the calculated minimum wall thickness required by code. A fabrication allowance is then added to t + c to reflect the under-thickness tolerance in material specifications. For example, ASTM A 106, a common carbon steel pipe material, permits a 12.5% pipe mill under-thickness. The specified wall thickness will therefore be (t + c) x 1.125, rounded up to the closest commercial size (or "schedule").

For gas and oil pipelines, the ASME B31.4 and B31.8 stress allowable is based on 72% of the minimum specified yield stress (SMYS) and, for gas pipelines, the population density.

3.2 Preliminary Weight Design

Note that this section applies to new designs, not to retrofit. This design step consists in selecting the location and type of pipe supports (supporting the pipe weight from underneath) or hangers (supporting the pipe weight from above). The objectives of a good support system are to:

(a) Maintain the pipe in its design position.
(b) Minimize pipe sag.
(c) Maintain pipe slope, if required.
(d) Keep longitudinal pipe stresses below the code allowable stress.
(e) Keep pipe weight reactions on equipment nozzles within vendor limits.
(f) Support the pipe during maintenance activities, such as the disassembly of flanges.

A good starting point is to evenly space pipe supports or hangers along the pipe. For horizontal metallic pipe, the spacing table of ASME B31.1, Table 121.5, may be followed, as shown in Table 3.2-1. A simple rule of thumb for liquid filled steel pipe is to support the pipe evenly, at a distance (in feet) equal to the pipe size (in inches) plus ten. For example, a 4" pipe would be supported every 4 + 10 = 14 ft. For non-metallic pipe (plastic, fiberglass, etc.), support spacing would follow the pipe vendor's recommendations.

NPS	Water	Gas
1	7	9
2	10	13
3	12	15
4	14	17
6	17	21
8	19	24
12	23	30
16	27	35
20	30	39
24	32	42

Table 3.2-1 Spacing of Weight Supports

The even spacing of Table 3.2-1 is based on a bending stress of 2300 psi and a mid-span deflection of 0.1". Longer spans can be used if a larger bending stress and sag can be accommodated. Further, the spans must be modified in the following cases:

(a) Place a support next to heavy in-line components (such as heavy valves).
(b) Place a support near equipment nozzles to permit their disassembly for maintenance.
(c) Supports should be placed at logical building structural attachment points.
(d) New supports should take advantage of existing structural steel or concrete attachments.
(e) Supports should not impede personnel access or egress.
(f) Support vertical risers for weight and lateral stability.

3.3 Preliminary Flexibility Design

Note that this section applies to new designs, not to retrofit. This design step consists in judging the adequacy of the piping flexibility, before modeling the line and performing the flexibility stress analysis. Until the mid-1970's piping stress analysis software was not widely available, and what was available was not user friendly. Flexibility analysis was achieved by dividing the system into short subsystems of several legs each, and checking their individual flexibility by hand calculations or flexibility charts. [Spielvogel, Kellog]. Today, flexibility is verified by computer stress analysis. A useful preliminary step, prior to stress analysis, consists in verifying that there are no obvious layout problems. By referring to the coefficients of thermal expansion given in Table 3.3-1, the Designer can estimate the expansion dL of pipe runs of length L (or the contraction dL for systems operating below ambient installation temperature)

$$dL = \alpha \, L \, dT$$

dL = change in length, in
α = coefficient of thermal expansion, $1/^{o}F$
L = initial length at $70^{o}F$, in
dT = temperature change, ^{o}F

For example, a 10 ft long carbon steel pipe operating at $400^{o}F$ will have expanded by an amount $dL = 7.1 \times 10^{-6} (10 \times 12")(400^{o}F - 70^{o}F) = 0.28"$. Bends and U-shaped expansion loops are then added to absorb the expansion of pipe runs.

Where congestion does not permit to add elbows or expansion loops, the Designer should consider installing expansion joints, following the layout guidance from the expansion joint manufacturer and the practice described in the "Standards of the Expansion Joints Manufacturers Association (EJMA)" published by the EJMA, White Plains, NY.

T ^{o}F	Carbon Steel ($10^{-6}\ 1/^{o}F$)	Low Alloy Stl. ($10^{-6}\ 1/^{o}F$)	Austenitic SS ($10^{-6}\ 1/^{o}F$)	70Cu – 30Ni ($10^{-6}\ 1/^{o}F$)	Aluminum ($10^{-6}\ 1/^{o}F$)
70	6.4	7.0	8.5	8.1	12.1
100	6.5	7.1	8.6	8.2	12.4
200	6.7	7.3	9.9	8.5	13.0
300	6.9	7.4	9.2	8.7	13.3
400	7.1	7.6	9.5	8.9	13.6
500	7.3	7.7	9.7	9.1	13.9

Table 3.3-1 Mean Coefficients of Thermal Expansion

3.4 Preliminary Seismic Design

3.4.1 Equipment Anchorage

Many piping failures in earthquakes have resulted from the sliding, rocking or overturning of large equipment to which the pipe is attached. Figure 3.4.1-1 illustrates the rupture of a pipe connected to two storage tanks. During the earthquake, the tanks slid and twisted in the concrete saddles, resulting in rupture of the pipe. Figure 3.4.1-2 illustrates the classic case of seismic induced sliding or rocking of an unanchored flat bottom storage tank, causing the rupture of the short pipe connection at the base of the tank, and loss of contents. It is therefore important to verify the seismic adequacy of equipment anchorage and tie-downs as part of the seismic design or retrofit of piping systems.

3.4.2 Mechanical Joints

By "mechanical joints" we refer to pipe joints other than welded and flanged joints. This includes flared, friction, grooved, and threaded joints. Dynamic testing as well as earthquake experience has shown that some mechanical joints can leak during earthquakes. Figure 3.4.2-1 illustrates leakage from a grooved joint as a result of excessive bending during the earthquake, well above the vendor's permitted angular misalignment for joint installation. Mechanical joints need to be evaluated where leak tightness or operability is required. Threaded joints can be evaluated by applying the ASME B31 stress intensification factor $i = 2.3$ for threaded joints to the longitudinal stress. Specialty fittings can be evaluated using vendor supplied limit loads or stress intensification factors.

3.4.3 Seismic Restraints

The seismic load will force the pipe to sway sideways and, for large earthquakes, to uplift off its deadweight supports. Figure 3.4.3-1 illustrates the case of a pipeline that uplifted from its shallow saddle and fell sideways. Figure 3.4.3-2 illustrates a sprinkler pipe, which sways and uplifts causing failure by impact against the suspended ceiling. It is necessary to brace piping systems against large side-way swaying and, for large earthquakes, to provide vertical seismic restraints. A preliminary bracing scheme, prior to proceeding with computer analysis for final design, would consist in placing lateral horizontal supports evenly spaced along the line [MSS-SP-127, NFPA-13]. The spacing between lateral restraints can be calculated taking into consideration the pipe size, material, and seismic input. For example, for a given span of pipe (given linear weight, Young's modulus and moment of inertia of the cross section)

$$\Delta / (a\, L^4) = \text{constant}$$

$$\sigma / (a\, L^2) = \text{constant}$$

Δ = deflection at mid-span, in
a = lateral uniform acceleration, g's
L = length of pipe span, in
σ = maximum bending stress, psi

The B31.1 spacing between weight supports is based on

$$\Delta = 0.1''$$

$$\sigma = 2300 \text{ psi}$$

$$a = 1 \text{ (gravity = 1g)}$$

To limit the mid-span deflection to 2" under a uniform seismic acceleration "a" applied concurrently to the pipe in two lateral directions (resultant 1.414a) the span length must be

$$2" / (1.414a \times L_2^4) = 0.1" / (1 \times L_T^4)$$

L_2 = span length that will deflect 2" under resultant acceleration 1.414a, in
L_T = span length from Table 3.2-1.

or

$$L_2 \leq 1.94\ L_T / a^{0.25}$$

To limit the maximum bending stress to 0.5 S_Y under a uniform seismic acceleration "a" applied concurrently to the pipe in two lateral directions (resultant 1.414a) the span length must be

$$L_{0.5Sy} \leq 0.0175\ L_T\ (S_Y / a)^{0.5}$$

S_Y = material yield stress at operating temperature, psi (ref. ASME B&PV Section II Part D, Table Y-1).

Therefore, to limit the mid-span deflection to 2" and the maximum bending stress to 0.5 S_Y, it is necessary limit the span length to

$$L_{max} = \min\{1.94\ L_T / a^{0.25}\ ;\ 0.0175\ L_T\ (S_Y / a)^{0.5}\}$$

For example, for a 4" NPS steel pipe in 70^{o}F water service, S_Y = 35,000 psi and L_T = 14 ft. For a seismic input acceleration a = 1g, we obtain

$$L_{max} = \min\ \{1.94 \text{ x } 14\text{ft} / 1^{0.25}\ ;\ 0.0175 \text{ x } 14 \text{ ft } (35{,}000 / 1)^{0.5}\}$$

$$L_{max} = \min\ \{27.16 \text{ ft}\ ;\ 45.84 \text{ ft}\} = 27 \text{ ft}$$

For long horizontal pipe spans, such as encountered in straight pipe racks, an axial support should be added to restrain the longitudinal movement of the pipe. Where the pipe is required to stay leak tight or to function (deliver and control flow), it is advisable, at the preliminary design stage, to restrain the pipe close to equipment nozzles to limit the load applied by the pipe on the equipment. Next to load sensitive equipment it may be necessary to design and install an anchor (a support that constrains the pipe in all six degrees of freedom).

Long and heavy vents and drains or valve operators may have to be braced either back to the pipe or to the building structure. In the latter case, the pipe itself must also be braced to the same structure to avoid large shear and bending if the pipe sways while the vent, drain or operator are restrained to the building structure.

3.4.4 Anchor Motion

In some cases, stiff pipe branches have failed from the seismic sway of flexible headers to which they are connected, as illustrated in Figure 3.4.4-1. The branch-header connection acts as an anchor point, and the branch is too stiff to accommodate the movement of this anchor point. A similar rupture is illustrated in Figure 3.4.4-2, where a suspended HVAC heater unit sways and ruptures the heater connection to a stiff water copper tube.

The same type of failure can take place when a pipe is attached (anchored) to two separate structures. The differential seismic movement of the two structures (called "seismic anchor motion") is transmitted to the pipe and, if the pipe is too stiff, this seismic anchor motion may cause the pipe to fail. Some building codes advocate the use of "flexible assemblies" to absorb differential building motion, for example placing a flexible assembly in the pipe where it crosses building joints. However, often times, the inherent flexibility of pipe spans is sufficient to absorb this differential movement. In these cases, and unless otherwise required by a building code, it is advisable to avoid placing "flexible assemblies" at the preliminary design stage, using them instead if the detailed stress analysis shows that there is no alternative.

3.4.5 Support Adequacy

As part of the seismic retrofit of an existing system, it is important to verify the adequacy of existing supports to sustain the seismic load, a load that was not part of the original design. At this preliminary stage, obvious shortcomings should be identified. Supports that rely on friction, such as illustrated in Figure 3.4.5-1 may slide during an earthquake, and should be modified. Undersized or stitch welds to structures may shear as illustrated in Figures 3.4.5-2 and 3.4.5-3. Unanchored weight supports may slide from under the pipe as illustrated in Figure 3.4.5-4.

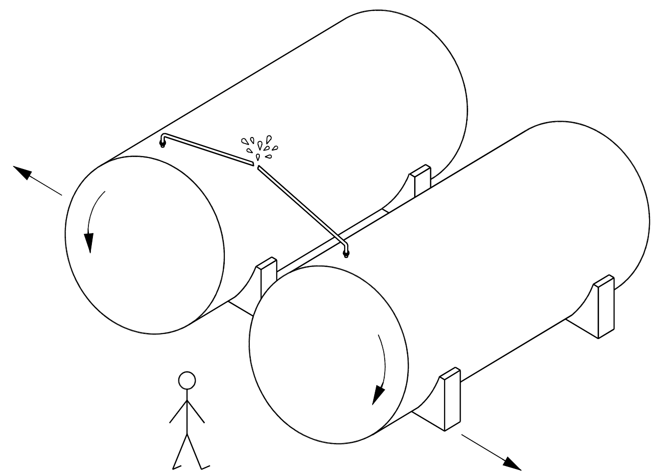


Figure 3.4.1-1 Unanchored Tanks Slide and Twist on Saddles

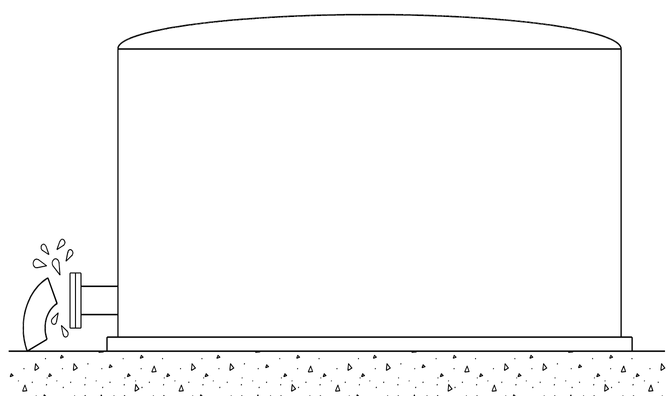


Figure 3.4.1-2 Unanchored Flat Bottom tank Slides and Rocks

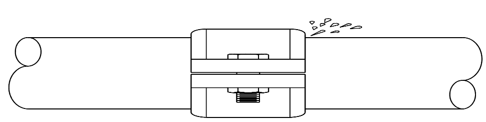


Figure 3.4.2-1 Grooved Coupling Leak from Excessive Bending

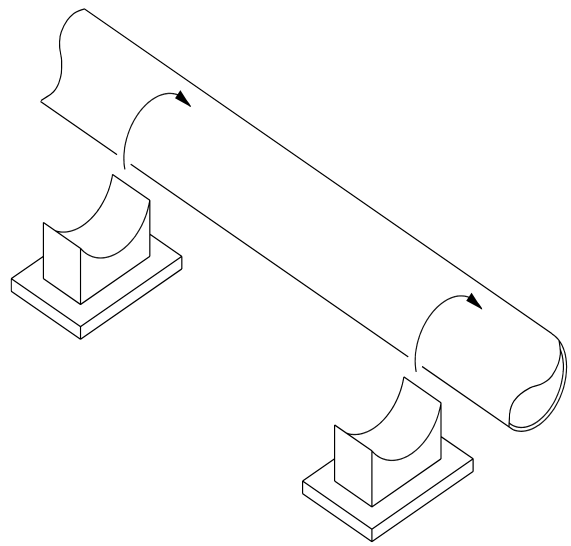


Figure 3.4.3-1 Pipeline Lifts Off Shallow Saddles

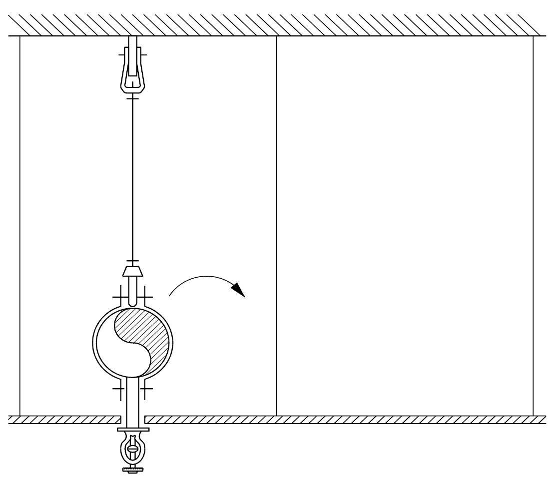


Figure 3.4.3-2 Sprinkler Pipe Sways and Impacts Suspended Ceiling

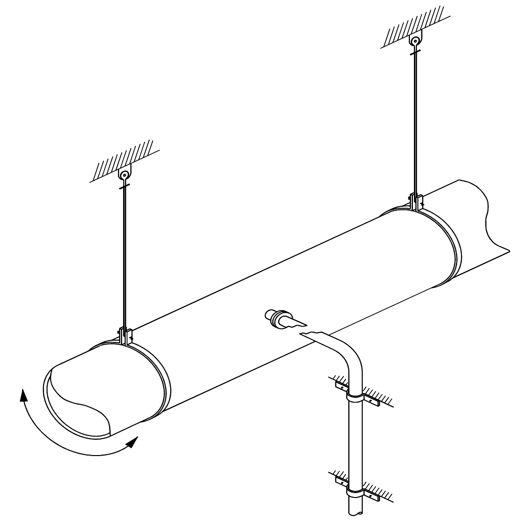


Figure 3.4.4-1 Suspended Header and Stiff Branch

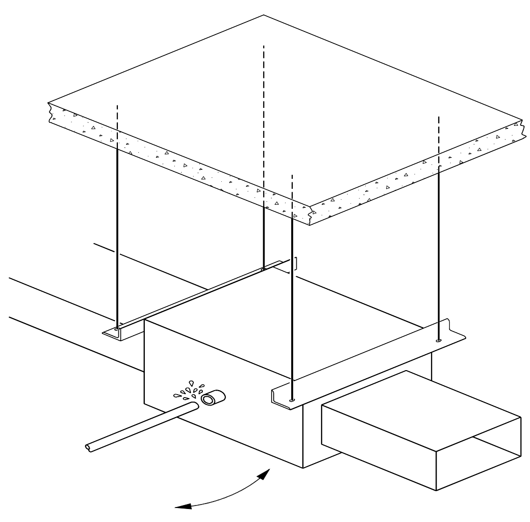


Figure 3.4.4-2 HVAC Heater Sways and Ruptures Brazed Copper Tube

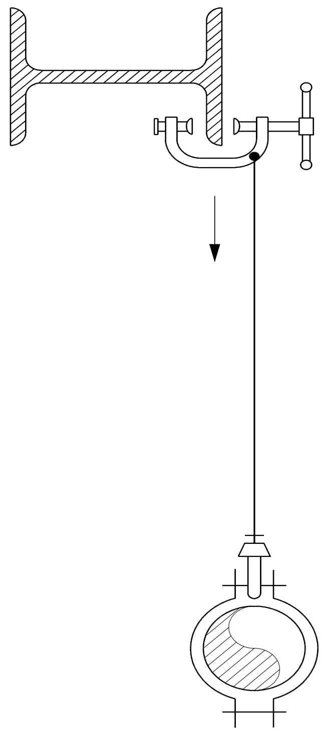


Figure 3.4.5-1 C-Clamp Relies on Friction, May Slide

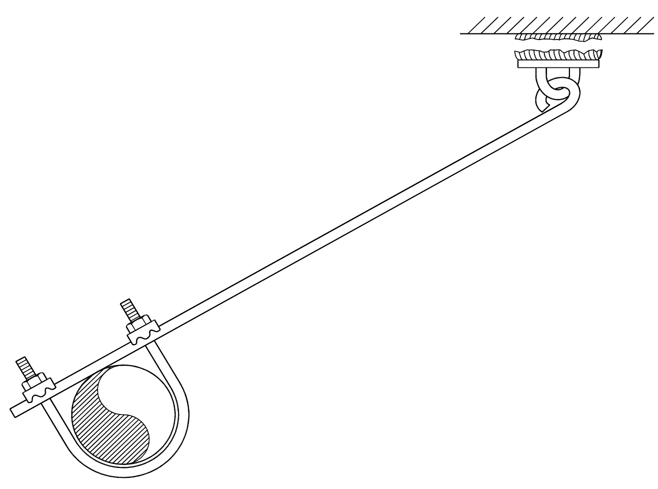


Figure 3.4.5-2 Undersize Weld May Shear

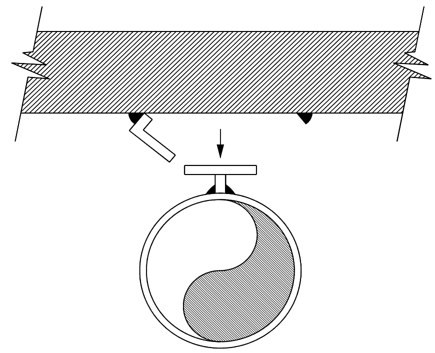


Figure 3.4.5-3 Undersize Angle Weld, May Shear

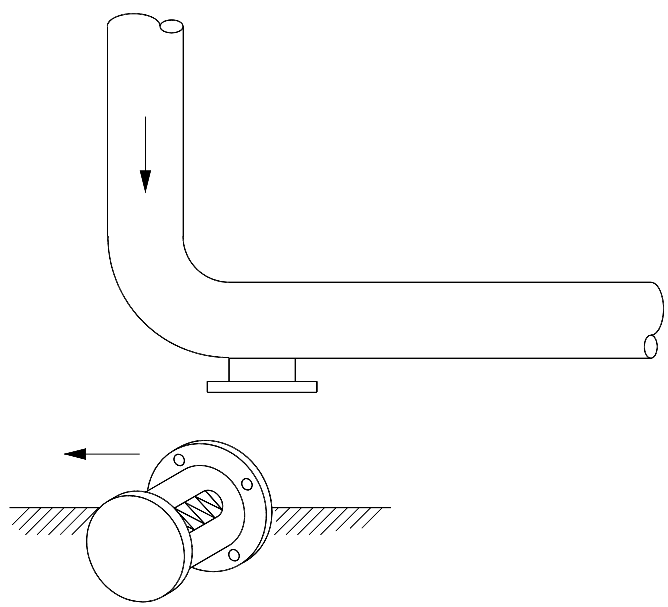


Figure 3.4.5-4 Unanchored Spring Support Slides From Under Pipe

4.0 SESIMIC ANALYSIS TECHNIQUES

4.1 Seismic Input

The input to the seismic analysis of a piping system may be either dynamic (time history or response spectra) or static (static coefficient). In either case, the seismic input is obtained, as described later in this section, from building code seismic maps or from a detailed geotechnical and seismological investigation of the site (referred to as "site specific" seismic input).

4.1.1 Time History

The time history input consists in one or a series of seismic motions (displacement, velocity or accelerations) as a function of time, that last for the full extent of ground shaking (typically in the order of 20 to 60 seconds), as illustrated in Figure 4.1.1-1. The maximum ground acceleration reached during the earthquake (approximately 0.25g in Figure 4.1.1-1) is the peak ground acceleration. The seismic time history ground motion (displacement, velocity or acceleration vs. time) is established for each of three directions, typically east-west, north-south and vertical up-down. These three time histories are then applied to a finite element model of a building structure to obtain, as output, the time history excitations at each floor in the structure. The excitation typically increases with elevation in the structure. Time history seismic input is rarely used for design or retrofit of equipment or piping systems. It is used to generate facility specific response spectra analyses, or as a research tool, to study in detail the behavior of a component or system as a function of time.

4.1.2 Response Spectra

Seismic response spectra are plots of acceleration or velocity or displacement vs. frequency or period (typically, acceleration vs. frequency is the most common form of seismic response spectrum used in piping and equipment analysis). Figure 4.1.2-1 illustrates a set of acceleration vs. frequency in-structure response spectra (spectra at a certain elevation within a structure) at 2%, 5% and 10% damping. For a given frequency "f_N", the seismic response spectrum at damping ζ gives the maximum acceleration reached by a single degree of freedom (a "lollipop" of natural frequency f_N with dash pot of damping ζ) subject to the input excitation represented by the response spectrum.

The higher the damping of the single degree of freedom, the lower its acceleration, as can be intuitively expected. This is illustrated in Figure 4.1.2-1. The constant acceleration at high frequency (the right hand side horizontal tail in Figure 4.1.2-1) is the peak ground acceleration. A rigid single degree of freedom oscillator (an oscillator with a natural frequency in the order of 30 Hz or more) will follow the ground motion, without amplification, its maximum acceleration will therefore be the maximum ground acceleration, or "peak ground acceleration".

Other terms commonly used in seismic analysis are listed at the end of the report, in section "Terms and Definitions".

4.1.3 Static Coefficient

The static coefficient is typically a single horizontal acceleration value and a single vertical acceleration value, specified as a fraction or multiple of "g". For example a horizontal static coefficient $a_H = 0.3g$ and a vertical static coefficient $a_V = 0.2g$.

Static coefficients are usually obtained from seismic contour maps in building codes. Until recently, the building codes defined seismic "zones" from 0 to 4, each zone corresponding to a level of seismic acceleration. The concept of seismic zones was however abandoned by the United States Geological Survey (USGS) in 1969, in favor of probabilistic based seismic contour maps. The building codes continued using seismic zones until recently. In its 2000 issue, the International Building Code followed the USGS lead and abandoned the seismic zones in favor of seismic contour maps. These maps provide horizontal ground accelerations with a 98% non-exceedance probability (NEP) in an exposure period (T) of 50 years. In other words, there is a 98% chance that a particular site will not see a seismic acceleration larger than the acceleration shown on the contour map, in 50 years. This probability can also be expressed as a return period

$$RP = T / r^*$$

$$r^* = - \log_e (NEP) \sim r (1 + 0.5r)$$

RP = return period
r = exceedance probability = 1 – NEP
NEP = non-exceedance probability
T = exposure period, years

For example, for the IBC-2000 maps, NEP = 0.98 and T = 50 years, which leads to a return period RP = 2475 years ~ 2500 years. In other words, the seismic accelerations in the IBC 2000 maps may be experienced once every 2500 years. The longer the return period, the larger the projected seismic acceleration.

4.1.4 Seismic Anchor Motion

Seismic anchor motion (or "SAM") is the differential motion between pipe support attachment points (for example, supports attached to an upper floor would sway with the building, with a larger amplitude than supports attached at a lower elevation), or the differential motion between equipment nozzles and pipe supports. Seismic anchor movements are input as displacements (translations and rotations) at the support attachments or at equipment nozzles. The resulting stresses and loads in the piping system are then combined by square root sum of the squares (SRSS) to the stress and loads due to inertia (seismic induced sway or vibration of the pipe).

4.2 Choosing the Type of Seismic Analysis

The type of seismic analysis may be (a) a “cook-book” approach, (b) a static hand calculation technique, (c) a static analysis of a piping model, or (d) a computerized response spectrum analysis of a piping model.

4.2.1 Cook Book

In a “cook-book” approach, the designer selects seismic restraint locations at fixed intervals, following a “recipe”, for example: a lateral “sway brace” (seismic restraint) is placed every 40 ft along the pipe and a longitudinal restraint every 80 ft. The braces may be pre-designed based on the specified spacing. The technique has the advantage of simplicity, but has two important drawbacks:

(1) In order to cover all practical configurations, the cook-book methods tend to be “conservative”, in other words they will over-predict the number and size of seismic supports.

(2) Cook books can be so simple that they may have been developed and may be used by engineers who have little, if any, understanding of piping systems and seismic design.

4.2.2 Static Hand Calculations

For a static hand calculation approach, the pipe is divided into individual spans or into a series of simple U, T or Z configurations. The peak acceleration from the response spectrum is applied as a lateral force distributed along the span, and bending stresses and support reactions are calculated using beam formulas. This technique was useful throughout the 1960’s and 1970’s; however, with the advent of user-friendly PC-based piping design software, computerized system analysis is now preferred, as more accurate and faster than the hand calculations. The hand calculation techniques are still useful as a tool to intuitively interpret the output of a computer analysis.

As a refinement in hand calculation techniques, the span natural frequency can be calculated. In this case, the spectral acceleration at the calculated span natural frequency may be applied to predict the load and displacement distribution along the span [Pickey, Blevins].

4.2.3 Static System Analysis

Another analysis technique consists in preparing a piping model of the system, using PC-based piping analysis software. The use of general finite element analysis software is not recommended in piping design, except in the very rare case where an elastic-plastic analysis is needed, or in the case of research to calculate detailed stress distributions in particular pipe fittings.

The seismic static coefficient is applied statically and uniformly in each of three directions (typically east-west, north-south and vertical) to the computer model of the whole system, providing the full distribution of stresses and support loads in the system.

4.2.4 Response Spectra Analysis

To perform a seismic response spectra analysis of a piping system, a computer model representing the piping system is first created. As in 4.2.3, the model should be created with a special purpose piping analysis software, rather than a general purpose finite element software. The model needs to be sufficiently accurate to properly reflect the dynamic characteristics of the system since the analysis results will depend on the accuracy of the computed natural frequencies of the system.

Three seismic response spectra are input into the program: east-west, north-south and vertical spectra, typically in the form of accelerations vs. frequency, from very low frequencies up to the ZPA. The computer program will calculate displacements and loads separately for each natural frequency (mode) of the system and for each of three directions (north-south, east-west, vertical). The modal results and directional results are then combined to obtain a total, resultant response of the system. The engineer has a choice of modal and directional combination techniques. In the early days of modal analysis, the resultant response the square root sum of squares of the individual modal responses ("response" here means loads or displacements at the various points along the piping system) [Newmark]:

$$R = \sqrt{\sum_{1}^{N} R_i^{\,2}}$$

R = resultant response
R_i = response in mode i

Studies by Singh et. al. concluded that the SRSS combination could underestimate the total response if some modal frequencies of the equipment were "closely spaced"; as a result, more elaborate modal combination techniques have been developed and applied [Singh, R.G. 1.92].

The resulting loads and displacements of the piping system are typically obtained by taking the square root sum of squares of the response (loads and displacements) in each of the three directions

$$R = [(R_{EW})^2 + (R_{NS})^2 + (R_V)^2]^{0.5}$$

R = resultant response
R_{EW} = east-west response
R_{NS} = north-south response
R_V = vertical response

As a less common alternative, the response in each direction may be combined by the "100-40-40" technique:

$$R_{100,40,40} = 100\%\ R_{EW} + 40\%\ R_{NS} + 40\%\ R_V$$

$$R = \max\ \{R_{100\text{-}40\text{-}40}\ ;\ R_{40\text{-}100\text{-}40}\ ;\ R_{40\text{-}40\text{-}100}\}$$

4.3 IBC Seismic Input

The International Building Code provides a procedure to determine seismic input applicable to a facility. Two types of input can be obtained: A static coefficient for static analysis, or a seismic response spectrum for dynamic analysis.

The IBC technique for developing the seismic input to equipment and piping systems consists of three parts:

(1) The input acceleration at ground level, based on seismic maps and soil characteristics.
(2) The amplified seismic load for equipment and piping located inside a structure.
(3) The seismic load for tall equipment located at grade, for example in the plant yard.

These three parts will be described step by step in the following sections.

4.3.1 Site Ground Motion

The first step in the International Building Code procedure [IBC-2000] is to determine the site ground motion at the facility, given its geographic location and soil characteristic, as illustrated by the nine steps in the logic diagram of Figure 4.3.1-1. It will be applied, as an example, to a facility.

Step-1: The site ground motion will be selected from the IBC seismic maps, and not from a site-specific seismicity study.

Step-2: To obtain the IBC site ground motion, the facility location is first placed on the IBC map (IBC-2000, Figures F1615(1) to (10)), and the mapped maximum considered earthquake spectral acceleration (MCESRA) is read from the contour intervals as

$$S_S$$
$$S_1$$

S_S = MCESRA at short period, 5% damping in a site class B.
S_1 = MCESRA at 1 sec, 5% damping in a site class B.

Step-3: The soil is characterized as hard rock, dense clay, sand, etc; and the shear wave velocity v_S is estimated.

Step-4: According to IBC Table 1615.1.1 the soil is classified as class A to E.

Step-5: The site coefficients F_A and F_V are determined from IBC Tables 1615.1.2(1) and (2), given the site class and the MCESRA S_S and S_1

Step-6: The mapped spectral acceleration for short period S_{MS} and the mapped spectral acceleration for 1-second period S_{M1} are calculated as

$$S_{MS} = F_a \, S_S$$
$$S_{M1} = F_V \, S_1$$

Step-7: The design spectral response accelerations (DSRA) for short period and 1-second are calculated as

$$S_{DS} = (2/3) \, S_{MS}$$
$$S_{D1} = (2/3) \, S_{M1}$$

To understand this multiplication by 2/3 we refer to "NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures", Part 2 Commentary, Chapter 4 Ground Motion, 1997 Edition, Building Seismic Safety Council, Washington, DC., which states "The design ground motions are based on a lower bound estimate of margin against collapse inherent in structures designed to the Provisions. This lower bound was judged, based on experience, to be about a factor of 1.5 in ground motion. Consequently, the design earthquake ground motion was selected at a ground shaking level that is 1/1.5 (2/3) of the maximum considered earthquake ground motion".

Step-8: Two reference spectral periods are defined as

$$T_o = 0.2 \, S_{D1}/S_{DS}$$
$$T_S = S_{D1}/S_{DS}$$

Step-9: The design response spectrum (DRS) of the facility, at 5% damping, can now be traced. It consists of three regions:

Period Range T(sec)	Spectral Acceleration S(g)
0 to T_o	$0.6 \, (S_{DS}/T_o) \, T + 0.4 \, S_{DS}$
T_o to T_S	S_{DS}
T_S to infinite	S_{D1} / T

Table 4.3.1-1 IBC-2000 Response Spectrum

4.3.2 Seismic Load In-Structure

The seismic load applied to equipment and piping inside a building or structure, above ground level, is larger than the load at ground level. The steps followed to calculate the seismic load applied to a piping system contained inside a structure (building or steel frame structure), referred to as "in-structure" seismic load, are illustrated in the logic diagram of Figure 4.3.2-1.

Step – 1: Based on the consequence of failure of the system (failure effect), the system is assigned a Seismic Use Group I, II or III (IBC 1616.2), and an importance factor I = 1.0 or 1.5 (IBC 1621.1.6).

Step – 2: Given the Seismic Use Group (SUG I, II or III) and the values of S_{DS}, $S_{D1}$and S_1, the system is assigned a Seismic Design Category (SDC) A to F (IBC 1616.3). The extent of detail in seismic design and qualification will increase from SDC A to SDC F.

Step – 3: At this point, several types of systems or components can be exempted from seismic design, according to IBC (IBC 1621.1.1), as summarized in table 4.3.2-1.

SDC	I	W	FC	H
A, B	any	any	any	any
C	1.0	any	any	any
D,E,F	1.0	20 lb	Yes	any
All	1.0	400 lb	Yes	4 ft

Table 4.3.2-1 Exemption from Seismic Design

I =importance factor (1.0 or 1.5)
W = maximum weight, component below this weight can be exempted.
FC = only distributed systems (piping, duct, etc.) with flexible connections exempted if "Yes".
H = maximum height above floor, component below this height can be exempted.

Step – 4: The horizontal seismic load applies separately in the longitudinal and lateral directions, it is given by F_P where (IBC 1621.1.4)

$$0.3\ S_{DS}\ I\ W \leq F_P = [0.4\ a_P\ S_{DS}\ W\ I\ /\ R_P]\ (1 + 2\ z/h) \leq 1.6\ S_{DS}\ I\ W$$

S_{DS} = Project Spectral acceleration for short period
I = importance factor (1.0 or 1.5)
W = weight
F_P = horizontal load
a_P = component amplification factor (1.0 to 2.5)
a_P = 1.0 for any piping system
R_P = component response modification factor (1.0 to 5.0)
R_P = 1.25 for low deformability piping systems, 2.5 for limited deformability piping system, 3.5 for high deformability piping systems
z = height of attachment to structure
h = height of structure

It is useful, at this stage, to dissect the above F_P equation.

The term 0.4 S_{DS} is the zero period acceleration input to the piping system. It is the acceleration that would be applied to a very rigid system.

The term a_P amplifies the ZPA acceleration from 1.0 x $0.4S_{DS}$, which would logically apply to a rigid piping system, up to 2.5 x $0.4S_{DS} = S_{DS}$, which is the peak spectral acceleration. A value a_P = 2.5 would therefore logically apply to a system that would have a natural frequency that falls within the range of frequencies where the seismic excitation is at its maximum value S_{DS}.

The term R_P accounts for the "ductility" of the system, its ability to absorb and redistribute the imparted seismic excitation, without failure [WRC 379]. This term is closely related to the ability to of the system to yield locally, without breaking.

The term (1 + 2z/h) amplifies the ground acceleration as a function of elevation. For example, a pipe atop a 20-ft tall rack will see an acceleration that is (1 + 2(20' / 20')) = 3 times larger than a pipe at ground. On the other hand, a pipe that is half-way up a 40-ft tall rack, i.e. still 20-ft above ground, will experience an acceleration that is (1 + 2(20' / 40')) = 2 times larger than a pipe at ground.

Step – 5: The effect of the horizontal seismic load F_P (applied separately in the lateral and longitudinal direction) is added to the effect of the vertical seismic load F_V given by (IBC 1617.1.1, 1621.1.4)

$$F_V = 0.2\ S_{DS}\ W$$

F_P = vertical component of seismic load

The total seismic load is therefore the horizontal load F_P plus the vertical load F_V. This is a vectorial addition, in other words, the effects of the horizontal load are added to the effects of the vertical load to obtain the total seismic effect on the system (IBC 1617.1.1, 1621.1.4)

$$E = F_P + F_V$$

Step – 6: The total load is the sum of the seismic load E and the weight W. If the allowable stress design method (also called working stress design method) is used to qualify the piping system, as is the common practice, then the seismic load E should be divided by 1.4 (IBC 1605.3.2), the total load is therefore.

$$F_T = W + E/1.4$$

4.3.3 Seismic Load At-Grade

The seismic lateral load on equipment at grade is given by a different method than used for in-structure equipment. In fact, the at-grade procedure follows very closely the method for calculating shear forces and base shear in buildings. It is to be applied to tall towers and vessels but is not readily applicable to piping systems or equipment with a low center of gravity (such as pumps, compressors, horizontal tanks and heat exchangers).

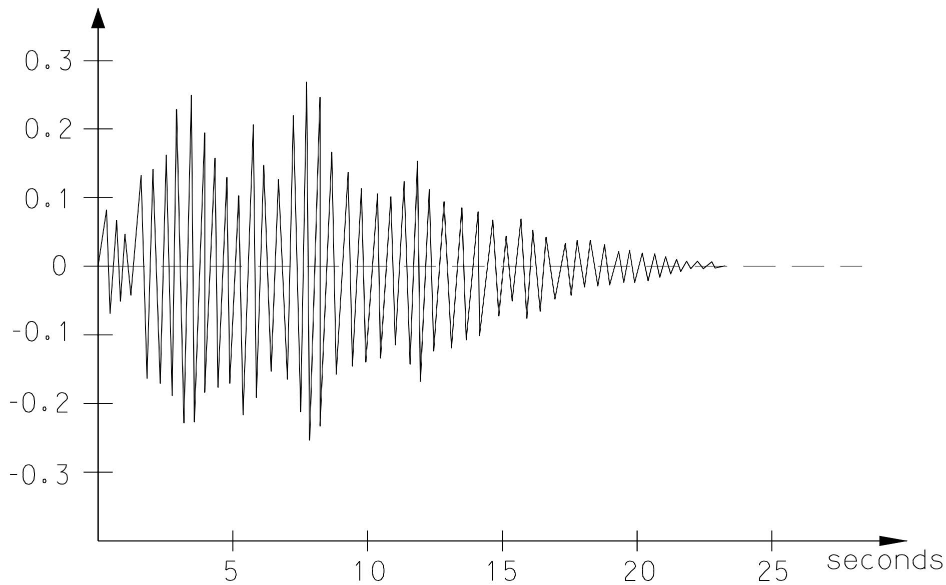


Figure 4.1.1-1 Illustration of a Seismic Time History Acceleration

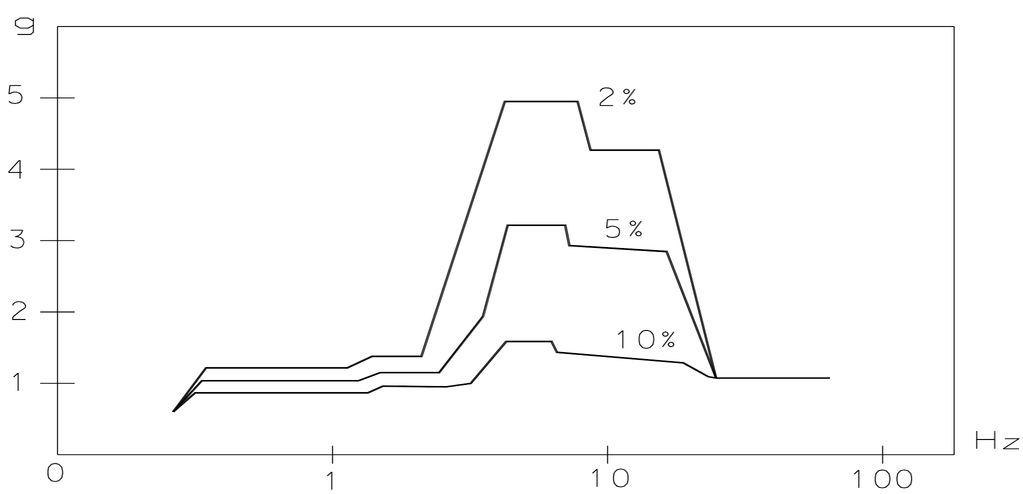


Figure 4.1.2-1 In-Structure Seismic Response Spectra

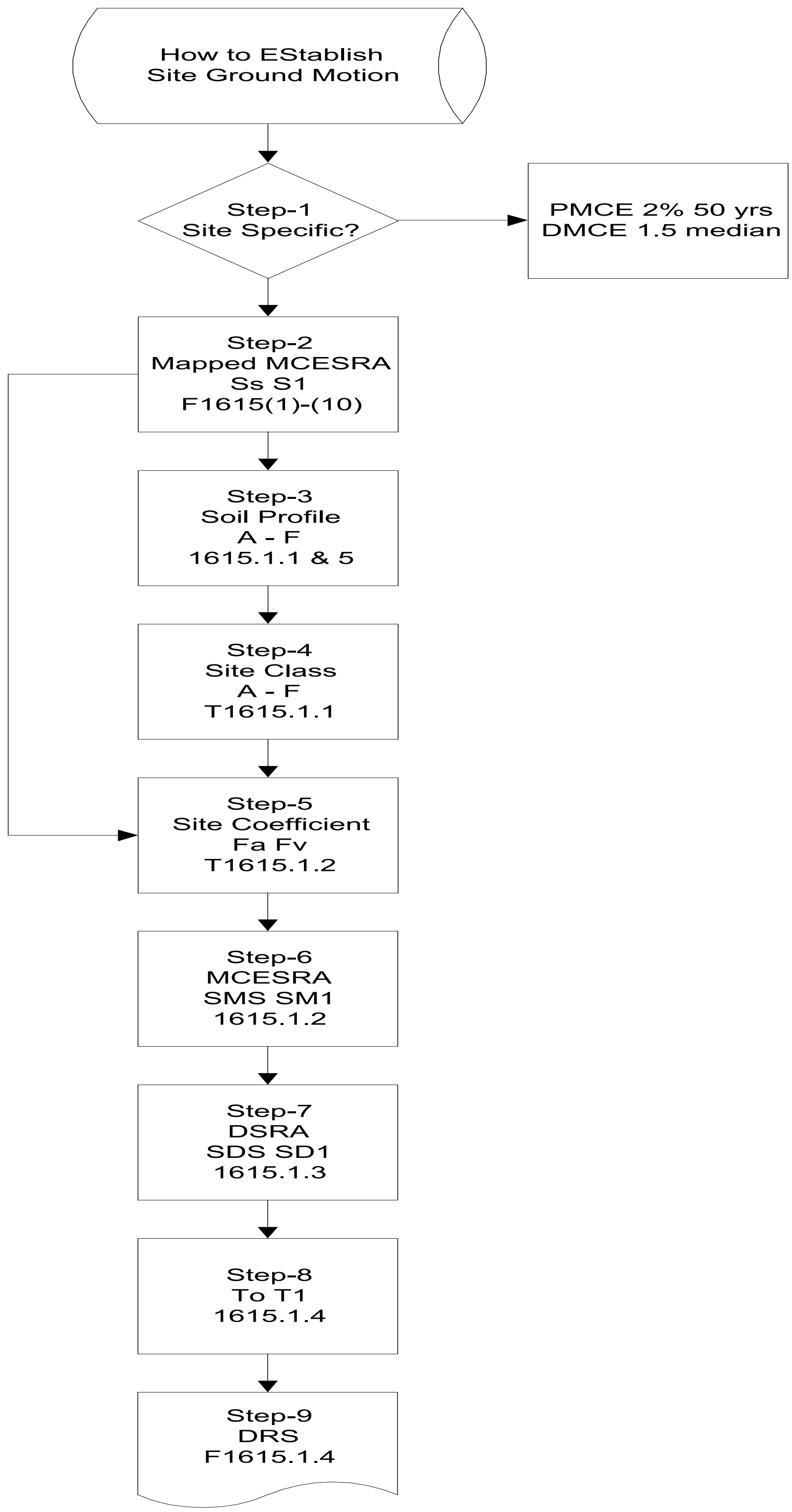


Figure 4.3.1-1 Determination of Site Ground Motion per IBC
(Numbers 1600's refer to IBC-2000 section number)

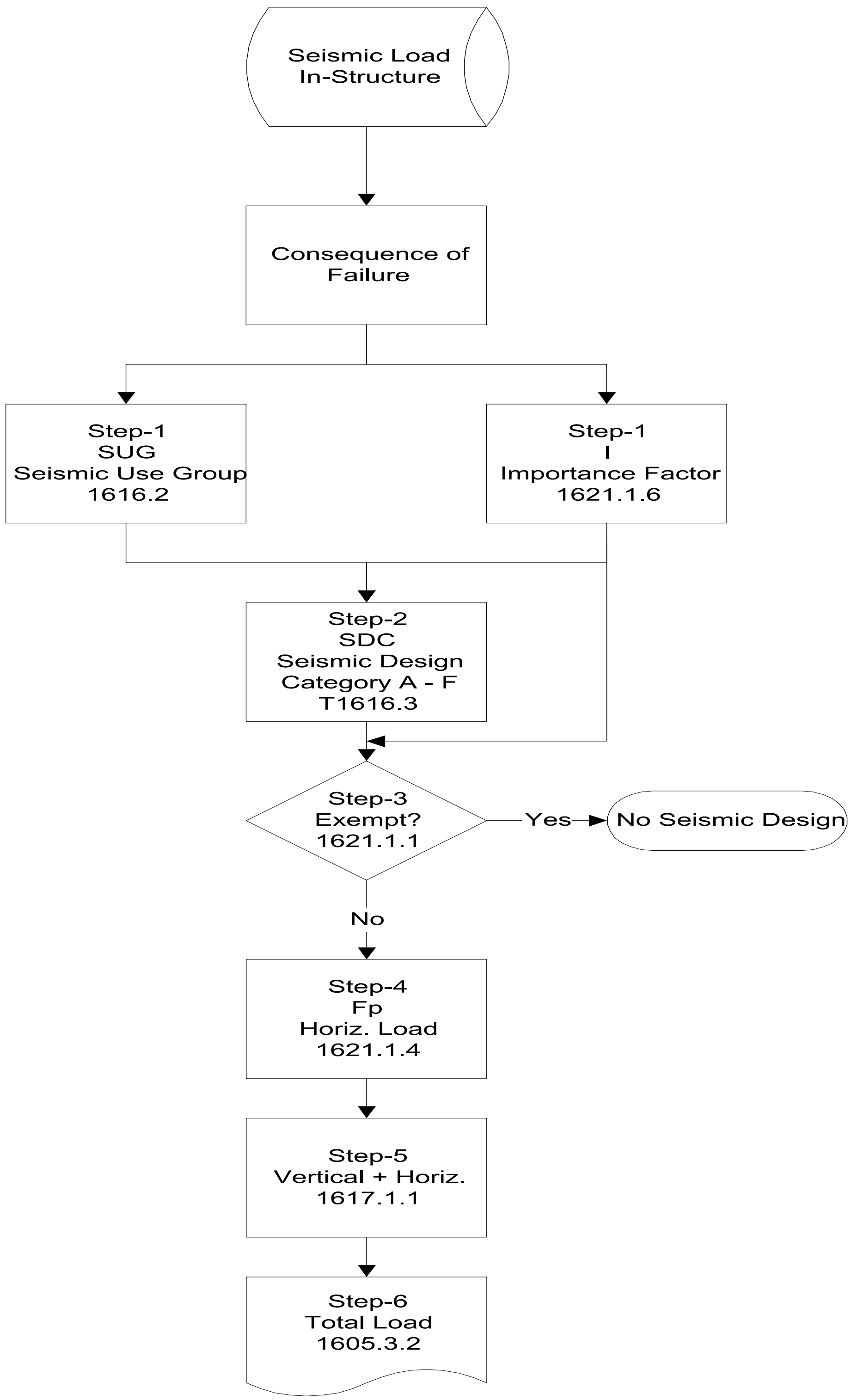


Figure 4.3.2-1 Determination of Seismic Load per IBC
(Numbers 1600's refer to IBC-2000 section number)

5.0 MODELING FOR ANALYSIS

5.1 Structural Boundaries

The model of a piping system typically begins and ends at anchor points, such as stiff equipment nozzles or fully constrained wall penetrations. These are points that effectively restrain all six degrees of freedom. If there are no anchors, the model could become very large and difficult to analyze. One solution would be to “decouple” and “overlap” the model.

“Decoupling” means that branch lines are excluded from the model of the main line. This can be done reasonably well if the branch line is small compared to the run pipe, for example

$$I_{run} > 25\ I_{branch}$$

Then, in the model of the branch line, it will be necessary to apply the run displacements at the decoupled point. In the run pipe analysis and the branch pipe analysis, it is necessary to include the branch stress intensification factor.

Also, the response spectrum for the branch analysis should consider the elevation of support attachments on the run pipe, close to the branch.

“Overlap” means that the model is terminated at a support point A and the next continuing model starts at a point B within the first model, goes through point A and continues on. The pipe section AB is common to both models. It is an overlap region that should contain at least two bi-lateral supports.

5.2 Model Accuracy

The accuracy of the piping model must be commensurate with the analysis technique and the seismic qualification margins. With static calculations, the precision on span lengths and weights is not as important as with seismic response spectra analysis, which relies on the prediction of system and component frequency. Also, if the seismic loads are well below the allowable limits, the accuracy of the model and predictions is less important than for systems stressed close to the allowed limit. Therefore, only general guidelines are provided here [ASME III, NCIG-05, WRC 316]. The precision of the model must be decided on a case basis.

(1) In no case should the tolerance affect the order of fittings and components along the line

(2) The direction of the pipe centerline should be within 10^o, and models of valve operators should be oriented within 15^o of the field installed condition.

(3) Restraint locations should be within 6” for NPS 2 and smaller (small bore piping), and the greater of 12” or one pipe diameter for pipe larger than NPS 2. These tolerances should be reduced by half close to active equipment. For stress analysis and load predictions, the direction of action of restraints should be within 10^o.

(4) The tolerance on pipe segment length is indicated in Table 5.2-1.

Pipe Segment length	Tolerance
Up to 5’	3”
5’ to 10’	6”
10’ to 15’	9”
15’ to 20’	12”
20’ to 25’	15”
25’ to 30’	18”
30’ to 35’	21”
Over 35’	24”

Table 5.2-1 Tolerance on Pipe Segment Length

5.3 Equipment Flexibility

Piping system models often originate or terminate at equipment nozzles (pump, heat exchanger, vessel or tank nozzle). These nozzle connections are not infinitely rigid; they are not “perfect anchors” for two reasons:

(1) The “local” flexibility of the nozzle itself and the equipment shell.

(2) The “global” flexibility of the equipment supports (legs, skirt, concrete anchor bolts, etc.).

5.3.1 Local Shell Flexibility

To illustrate the effect of vessel or tank shell flexibility consider the following simple example: A 12 ft long, 6” sch.40 gas pipe is connected at one end to a vessel nozzle, and at the other end the pipe is simply supported vertically. The vessel is 10 ft diameter and 10 ft high, with the radial nozzle at mid-height.

Four cases are analyzed: In the first case, the vessel is infinitely stiff; in the second, third and fourth cases the vessel has a wall thickness of 0.5”, 0.4” and 0.3” respectively, which makes the vessel shell more and more flexible (able to bend when subject to piping loads). A 6” displacement is imposed at the simply supported end. Table 5.3.1-1 summarizes the results of the analysis for this “simple” configuration.

Table 5.3.1-1 illustrates two important facts, which complicate modeling and design by analysis of piping systems:

(1) Including the equipment shell flexibility in the analysis reduced the reaction loads at the nozzle. However, under the same applied load, the pipe displacement is larger if the equipment flexibility is included in the analysis. Because of this contradictory effect (an increase in displacement and a decrease in nozzle loads), it is difficult to predict whether simplifying the

model by excluding the vessel shell flexibility will be over-predict or under-predict the loads in the system.

(d) Including the equipment shell flexibility in the analysis will reduce the system's natural frequency. This could result in either larger or smaller seismic loads, depending on the relative position of the response spectral peak frequency compared to the piping natural frequency. Therefore, it is again difficult to predict whether excluding the vessel shell flexibility will be conservative in design.

	Anchor	0.5" Wall	0.4" Wall	0.3" Wall
Radial k (kips/in) (1,4)	infinite	136	86	47
Circumf. k (ft-kip/deg) (1,4)	infinite	5	3	1
Longit. k (ft-kip/deg) (1,4)	infinite	8	5	3
Shear at nozzle (kips) (2)	5	1	0.8	0.5
Moment at nozzle (ft-kip) (2)	57	14	10	6
First mode freq. (Hz) (3)	12	4	3	2

Notes:
(1) "Radial k" is the linear stiffness of the vessel shell against a radial push or pull. "Circumferential k" is the bending stiffness of the vessel shell against bending along the circumference. "Longitudinal k" is the bending stiffness of the vessel shell against bending along the length of the vessel.
(2) "Shear and moment at nozzle" is the load at the vessel-pipe nozzle due to the 6" displacement imposed at the simply supported end of the pipe.
(3) "First mode frequency" is the natural vibration frequency of the pipe connected to the vessel at one end and vertically simply supported at the other end. This first mode (natural) frequency corresponds to a lateral "fixed (vessel end) – free (vertical support end)" vibration of the 12 ft long 6" pipe span.
(4) The vessel shell stiffness is calculated following the method of Welding Research Council (WRC) Bulletin 297. This stiffness calculation is part of most modern piping analysis software.

Table 5.3.1-1 Static and Dynamic Effects of Vessel Shell Flexibility

In summary, equipment flexibility will affect the displacements and loads in a piping system. The significance of this effect is difficult to predict, it is therefore advisable to include the equipment's flexibility in the analytical model of the piping system.

5.3.2 Global Equipment Flexibility

The global flexibility of equipment is due to (a) the equipment's bending flexibility, and (b) the equipment's support flexibility. In the simple case of a cylindrical vessel mounted on four legs made of steel angles, the global flexibility of the vessel is

$$1/K = 1/K_V + 1/K_L$$

K = total global stiffness of vessel assembly, lb/in
K_V = vessel stiffness, lb/in
K_L = total stiffness of support legs, lb/in

$$K_V = 12\ EI / H^3$$

E = Young's modulus, psi
I = moment of inertia of cylindrical vessel shell, in^4
H = height from support-vessel attachment to vessel's center of gravity, in

$$K_L = 4\ K_I$$

K_I = bending stiffness of individual leg in the direction of seismic input, lb/in

Other equipment stiffness and frequencies can be obtained from structural dynamics handbooks and publications [ASCE Petrochem, Pickey, Blevins].

5.4 Seismic Restraint Stiffness and Gap

5.4.1 Restraint Stiffness

New seismic restraints should be designed to be "stiff", which in practice means that they should not deform more than 1/8" under seismic load. In these cases, the supports can be modeled as rigid in the direction of action. For restraints that are not as rigid, the exact seismic analysis solution would require the support stiffness to be included in the analysis model. This could however cause unnecessary iterations when the installed support (and therefore its stiffness) does not exactly match the design. To avoid the complications and costs of an iterative reconciliation process, restraint stiffness should be modeled with approximate, rounded values. For example, supports may be grouped into three categories: Very stiff (K > 1E6 lb/in), stiff (K = 1E5 to 1E6 lb/in), and soft (K < 1E5 lb/in). Restraints within each category would then be assigned a nominal stiffness, with the very stiff supports modeled as rigid.

At the same time, all supports should be designed to a minimum seismic load, for example 100 times the pipe size. For example, a seismic restraint on a 6" line would be sized for the calculated seismic load, but no less than 600 lb. This would avoid future iterations on lightly loaded supports if the support stiffness or location changed, causing a change in seismic load.

5.4.2 Restraint Gap

It is common practice to provide a small gap between pipe and structural support steel to avoid binding during normal operation. Such a gap represents a rattle point during a seismic event. As a result there will be a local impact between the pipe and the support during the earthquake. The exact solution to this impact problem depends on several factors: the gap size, the pipe and support local and global stiffness, the pipe velocity at impact, the pipe and support mass, the elasticity of pipe and support [Kumar]. The study of earthquake damage indicates that this type of local impact through support gaps is mostly of little consequence, but needs to be considered in the following cases:

(a) The pipe span contains impact sensitive components (instruments, valve actuator controllers, etc.).

(b) A gas pipeline operating at high pressure (hoop stress close to 72% of yield), where a surface dent or gouge could cause the pipe to fail.
(c) For large gaps, in the order of the pipe radius for 2" NPS and smaller pipe, and 2" gap for larger pipe, the restraint load calculated on the basis of zero gap may be amplified by an impact factor of 2 to account for impact.

5.5 Flexibility of Fittings

The response of a piping system to a dynamic excitation, such as an earthquake, depends on the system's natural frequencies, which – in turn – depend on the flexibility of its fittings (tees, elbows, bends, etc.). The flexibility of fittings must therefore be correctly modeled. The flexibility of a pipe fitting is defined by a flexibility factor "k" provided in the applicable ASME B31 code, and is automatically calculated in piping analysis computer codes. The difficulty arises when using non-standard fittings, for which a flexibility factor is not provided in the ASME B31 code. This is for example the case for grooved or flared pipe joints. If the fitting is "stiff" relative to the pipe span, the seismic load will tend to deflect the pipe as a uniformly loaded beam, in a U shape. If the fitting is "flexible" relative to the pipe span, the same seismic load will tend to deflect the span in a V shape, with hinge rotation around the joint. This difference in behavior can not be ignored, particularly if excessive rotation of the pipe at the joint can cause the joint to leak or rupture.

5.6 Stress Intensification Factors

The bending stress in a pipe fitting is obtained by multiplying the nominal bending stress in a straight pipe M/Z (M = moment, Z = section modulus) by a stress intensification factor "i" (SIF) specific to the fitting. This approach, and the first SIF's, were developed in the 1940's and 1950's by Markl, George and Rodabaugh [Markl, et. al., Rodabaugh]. Stress intensification factors for standard (ASME B16) fittings are listed in the applicable ASME B31 Code. The SIF for fittings not listed in ASME B31 may be obtained by fatigue testing, similar to Markl's tests.

6.0 QUALIFICATION

6.1 Operating Conditions

The qualification of the piping system for operating conditions such as pressure, expansion, weight, must comply with the requirements of the applicable ASME B31 code.

6.2 Seismic Qualification

6.2.1 System Qualification

The seismic analysis output typically consists of:

(a) Loads (forces and moments) at model points along the piping systems.
(b) Total longitudinal stress at the same points.
(c) Displacements and rotations at the same points.

The piping is qualified for seismic loads if:

(a) The stresses in the pipe are within allowable limits.
(b) The loads at equipment nozzles are within vendor allowable limits.
(c) Pipe supports and restraints have been qualified.
(d) The loads or deflections at specialty mechanical joints are within the vendor limits.
(e) The acceleration and loads on valve operators or other acceleration sensitive components or instruments are within vendor limits, or limits established by test or analysis.
(f) Where required, the operability of active components (components that have to change state or have moving parts, such as valve actuators or pumps) is established, by testing, analysis or based on earthquake experience.
(g) Seismic interactions have been evaluated and credible and significant interactions have been eliminated.

6.2.2 IBC Qualification Options

The International Building Code (IBC) exempts certain systems from seismic qualification, as follows:

If I = 1, only pipe supports need to be seismically designed (IBC 1621.3.10). If I > 1 then the piping systems “themselves” must be seismically designed, but IBC provides no explicit requirements to qualify the “pipe itself”.

For fire sprinkler systems, the seismic design techniques of NFPA 13 are acceptable provided 1.4 times the NFPA “seismic design force and displacement” are not less than those prescribed by IBC.

For pressure piping, the seismic design techniques of the applicable ASME B31 code, except ASME B31.9, are acceptable.

For piping other than sprinkler systems (NFPA-13) and pressure piping (ASME B31), IBC provides design rules for strength design of concrete anchorage (1621.1.7, 1913), but no explicit rules apply for pipe supports or the pipe itself.

6.2.3 Allowable Stress

The ASME B31.1 code provides an explicit equation for stresses due to occasional loads [B31.1-2001]

$$\frac{PD}{4t} + 0.75i\frac{M_A + M_B}{Z} \le kS_h$$

P = internal design pressure, psi
D = outside diameter of pipe, in
i = stress intensification factor
M_A = resultant moment due to sustained loads (such as weight), in-lb
M_B = resultant moment due to occasional loads (in our case, seismic), in-lb
Z = pipe section modulus, in^3
k = 1.15 for occasional loads acting for no more than 8 hrs at any one time and no more than 800 hr/year, or 1.2 for occasional loads acting for no more than 1 hr at any one time and no more than 80 hr/year. Therefore, in the case of an earthquake, k = 1.2.
S_h = code allowable stress, psi

ASME B31.3 does not provide an explicit equation for calculating the longitudinal stress, but specifies that it should be limited to 1.33 times the code allowable stress S for earthquake design. The pipeline codes [B31.4, B31.8] do not explicitly address seismic design.

The ASME Boiler & Pressure Vessel Code, Section III, Div.1, Subsection NC-3600, specifies the following stress equation for “reverse dynamic loads” (which includes earthquake loads) if the system is to remain functional (deliver and regulate flow)

$$i\frac{M_R}{Z} \le 2S_A$$

M_R = range of resultant moment due to inertia and anchor motion effects, in-lb
S_A = allowable stress = $f(1.25\ S_C + 0.25\ S_h)$, psi
f = cycle dependent factor, 1 for less than 7000 cycles
S_C = code allowable stress at ambient temperature, psi
S_h = code allowable stress at operating temperature, psi

If functionality is not required, but leak tightness and position retention are required, then the “level D” rules of NC-3600 would apply

$$B_1 \frac{P_D D}{2t} + B_2' \frac{M_E}{Z} \leq 3S_m$$

B_1 = primary stress index from Table NC-3673.2(b)-1 of ASME III Div.1, NC-3600
P_D = system pressure during the earthquake, psi
B_2' = primary stress index from Table NC-3673.2(b)-1 of ASME III Div.1, NC-3600 and section NC-3655.
M_E = amplitude of resultant inertial seismic and weight moment, in-lb
S_m = ASME B&PV Code Section III Div.1 allowable stress for class 1 materials, at operating temperature, psi

In addition, seismic anchor motion shall satisfy the following stress equation

$$C_2 \frac{M_{AM}}{Z} < 6S_m$$

$$\frac{F_{AM}}{A_{AM}} < S_m$$

C_2 = secondary stress index from ASME III Div.1, NB-3681(a)-1
M_{AM} = range of resultant seismic anchor motion moment, in-lb
F_{AM} = amplitude of longitudinal force due to seismic anchor motion, lb
A_M = cross-sectional area of metal, in^2

For a piping system operating at nearly steady state conditions (no significant temperature gradients), the alternating stress intensity is

$$S_{alt} = K_e \frac{S_P}{2}$$

$$S_P = K_1 C_1 \frac{P_o D}{2t} + K_2 C_2 \frac{M_i}{Z}$$

S_{alt} = alternating stress intensity, psi
K_e = factor, from ASME III Div.1, NB-3653.6
S_P = peak stress intensity, psi
K_i = local stress indices, from ASME III Div.1 Table NB-3681(a)-1
C_i = secondary stress index from ASME III Div.1, NB-3681(a)-1
P_o = operating pressure, psi
M_i = resultant range of (1) all load ranges plus the seismic amplitude or (2) seismic range alone, in-lb

The alternating stress intensity is then used with the fatigue curves of ASME III Appendix I, Figures I-9.0 to obtain the number of allowable cycles N, which is compared to the number of actual cycles n (n = 100 cycles of full amplitude response may be used for earthquake). The usage factor from earthquake is n/N, which should be less than 1. If there are other cyclic loads (such as heat-up and cool-down) their usage factor should also be added so that

$$\sum \frac{n_i}{N_i} \leq 1$$

The fatigue curves (S_a vs. N) in ASME III Appendix I are based on smooth bar specimen tested in air (no corrosion effects), they reflect crack initiation and propagation to a certain point in the smooth bar specimen, with a safety factor of two on stress and 20 on cycles.

Tests on actual carbon steel pipe (as opposed to smooth bar specimen) indicate that failure (crack initiation and propagation through-wall) follows the law [Markl]

$$iS_{ampl} = 245{,}000 / N^{0.2}$$

S_{ampl} = amplitude of the elastically calculated applied cyclic stress, psi

6.3 Seismic Qualification by Testing

6.3.1 Seismic Testing

The most direct method to seismically qualify an active component that must perform a function during or after an earthquake is through shake table testing.

The Designer specifies the 5% damped “required response spectrum” (RRS) for which the equipment must be qualified. The test laboratory develops then the artificial seismic input motion x(t) which envelopes the RRS. This time history x(t) is programmed into the servo-mechanism of a shake table. The designer also prepares drawing details of how the equipment will be installed and anchored in the field. The equipment is mounted on the shake table accordingly, and then subject to the seismic excitation. The equipment integrity and operation may be verified during and after the test. Seismic testing is particularly well suited to qualify electrical equipment and “active” mechanical equipment, which must operate during or following the earthquake.

A seismic test must be well planned and entrusted to a test facility experienced in applying seismic testing and test standards [ICBO AC156, IEEE-344, IEEE-382].

6.3.2 Planning the Seismic Test

Step 1 – Select testing method: Equipment is seismically tested and qualified by one of three methods: Proof testing (test the equipment to a test response spectrum (TRS) equal to or slightly larger than the RRS). Generic testing (test the equipment to a larger RRS than required by the DBE). Fragility testing (test with steadily increasing input excitation, until failure of the equipment or until the table capacity is reached).

Step 2 – Decide whether to test the assembly or a device. When testing an assembly such as a pump skid, the test arrangement must accurately simulate the equipment mounting and its attachments. When testing a device, such as a valve actuator alone without the valve, the test arrangement must accurately simulate the amplification of seismic input that will take place through the pipe span and the valve stem.

Step 3 – Specify the test input. The applicable test standard, such as ICBO AC156, will normally specify the type of test: single frequency, sine sweep or response spectrum test. The single frequency test is suitable for equipment with single dominant frequency and excitation with a narrow range of frequencies, typical of input to in-line mounted components. The test should be sufficiently long, in the order of 30 seconds (10 seconds to ramp up, 10 seconds at full capacity, and 10 seconds to ramp down). The sine-sweep test consists of a sinusoidal input with varying frequency, sweeping the frequency range of the spectrum. The table dwells on certain frequencies, for example 4 dwell points between 2-4-8-16-32 Hertz. The test is valuable in identifying the equipment natural frequencies. The response spectrum test is a test at the specified 5% damped Required Response Spectra (RRS) in each direction. The test facility will have to provide a plot of the measured Test Response Spectra (TRS) at 5% damping, showing that they equal or exceed the RRS.

Step 4 – Choose whether the test will be single-axis or multi-axis. In a single-axis test, the equipment is shaken in a single direction. It is a useful test for detailed studies and research on fundamental seismic behavior, because the response is not complicated by multi-directional input. The bi-axial test consists of a horizontal direction run simultaneously with the vertical direction then rotated 90^o horizontally and repeated. The tri-axial test consists of statistically independent input in all three directions, and in practice it is used for most qualification tests.

Step 5 – Specify interface requirements. These include mounting and hold-down details, wiring, piping loads at equipment nozzles.

Step 6 - Specify Inspections. The designer should specify the desired function during and/or after testing, and what to inspect at the test facility, prior to, during and following the test.

For example, for manual valves, pre-test inspections may include: Visual inspection for damage; mounting and pipe spools conformance to drawings; free movement when opening and closing; no body leakage at pressure; no through-leakage across the seat (or leak-through within certain limits) when closed, under a specified pressure differential. During test, the inspections may include flow through when tested open; seat tightness when tested closed. Post-test inspections would repeat the pre-test inspections plus a detailed inspection for damage.

For motor or air operated valves, pre-test inspections may include visual inspection for damage; mounting and pipe spools conformance to drawings; verify movement when opening and closing on signal; verify current and resistance (motor operated) and trip pressure to open or close (air operated); verify actuator torque; no body leakage at pressure; no through-leakage (or leak-through within certain limits) when closed, under a specified pressure differential. During test, the inspections may include flow through when tested open; seat tightness when tested closed;

opening and closing during test. Post-test inspections would repeat the pre-test inspections plus a detailed inspection for damage.

For pumps, pre-test inspections may include visual inspection for damage; mounting and pipe spools conformance to drawings; verify voltage, current, RPM; measure operating vibration. During test, the inspection may include testing the pump running and de-energized; starting the pump during test if required; recording voltage during test. Post-test inspections would repeat the pre-test inspections plus a detailed inspection for damage.

Step 7 – Specify instrumentation and records. Typically, the test instrumentation includes accelerometers on the table, to record the table input and confirm that the required input (RRS) is enveloped by the test response spectra (TRS), over a certain frequency range (such as 1 Hz to 100 Hz).

Step 8 – Specify the contents of the test report. The applicable standard will normally specify the contents of the test report. The results must be "readable" and easy to interpret, accompanied by photographs (or, better yet, video footage) of the test. The test report will normally include pre-, during and post-test inspections. Results of the functional test. Photos, drawings of test setup. Plots of RRS vs. TRS at same damping (typically 5%). Report of anomalies. Certification.

6.4 Seismic Interaction Review

6.4.1 Types of Seismic Interactions

Seismic interactions are an important part of seismic qualification for two reasons:

(1) Earthquake experience indicates that many failures are caused by the failure of overhead or adjacent components tha, in turn, fail the piping system by interaction.

(2) It is not uncommon for the costs of upgrades resulting from interaction reviews to exceed the cost of seismic qualification of the piping system itself.

There are two types of seismic interactions: spatial interactions and system interactions. Spatial interactions can in turn be divided into falling interactions, swing interactions, and spray interactions.

(1) Spatial Interactions

(1.1) Falling interaction: A falling interaction is an impact on a critical component due to the fall of overhead or adjacent equipment or structure.

(1.2) Swing interactions: A swing interaction is an impact due to the swing or rocking of adjacent component or suspended system.

(1.3) Spray interactions: A spray interaction is due to the leakage of overhead or adjacent piping or vessels.

(2) System interactions: System interactions are spurious or erroneous signals resulting in unanticipated operating conditions, such as the spurious start-up of a pump or closure of a valve.

6.4.2 Interaction Source and Target

Interaction source: An interaction source is the component or structure that could fail and interact with a target.

Interaction target: An interaction target is a component that is being impacted, sprayed or spuriously activated.

6.4.3 Credible and Significant Interactions

Credible interaction: A credible interaction is one that can take place.

Significant interaction: A significant interaction is one that can result in damage to the target.

6.4.4 Interaction Review

Having clearly identified the interaction targets, an interaction review consists of a walk-down, photographic record, and supporting calculations to document credible and significant sources of interactions.

In practice, it is only necessary to document credible and significant sources of interaction. It is not necessary to list and evaluate every single overhead or adjacent component in the area around the target, only those that could interact and whose interaction could damage the target. In all cases, a photographic record of the interaction walk-down should be maintained.

Because only credible and significant sources of interaction are documented, an important aspect of the interaction review is engineering judgement. As a minimum, a team of two reviewers, each with at least 5 years experience in seismic design, must reach consensus on credible and significant interactions. The review team must be familiar with all three aspects of seismic engineering: analysis, testing and earthquake experience. Where system interactions are of concern, the written input of a system engineer is in order. An owner may also perform an independent third party review to verify the conclusions of the interaction review.

6.4.5 Falling Interactions

In most cases, judgment is sufficient to establish whether a falling object can reach a target and be a credible interaction. Alternatively, one can calculate the radius R of the zone in which a falling object can strike. This zone is called the zone of influence

$$R = V_H \{[(V_V/g)^2 + 2H/g]^{0.5} - V_V/g\}$$

R = radius of the zone of influence, in
V_H = horizontal spectral velocity, in/sec
V_V = vertical spectral velocity, in/sec
g = gravity = 386 in/sec^2
H = height of fall, in

The safety factors in a seismic interaction review differ from those used in the seismic design process. When judging whether a source component will rupture and fall, it is not necessary to establish that it has a typical design safety factor of 3 to 5 against rupture. Instead, a safety factor of 1.5 of the interaction source against ductile failure and 2 against non-ductile failure may be sufficient.

Earthquake experience indicates that suspended ceilings and block walls are often a credible and significant source of interaction. They must be explicitly addressed in the interaction review process.

When a falling body of weight W falls from a height h and impacts a target of weight W_b and stiffness k, the impact force and deflection can be calculated based on energy conservation [Pickey]:

$$P = W + W_b + \sqrt{W_b^{\,2} + 2W(W_b + kh)}$$
$$d = d_{st} + \sqrt{d_{st}^{\,2} + 2h(d_{st} - d_s) - d_s^{\,2}}$$

P = impact force, lb
W = weight of falling body, lb
W_b = weight of elastic member, lb
k = stiffness of elastic member, at point of impact, lb/in
h = height of free fall, in
d = maximum displacement at impact, in
d_s = static displacement of elastic member due to its own weight, in
d_{st} = static displacement due to weight plus the weight of the falling body, lb

P is an overestimate of of the impact force because it does not account for rebound, deformation of the source and friction and heat loss at impact. When the target being hit is a section of pipe, its stiffness k can be calculated by a beam approximation. The stiffness of a cantilevered beam of moment of inertia I, Young's modulus E, and length L, loaded at free end is $3EI/L^3$. The stiffness of a fixed-fixed beam loaded at a distance a and b from each end is $3EIL^3/(a^3b^3)$, and the stiffness of a simply supported beam loaded at a distance a and b from each end is $3EIL/(a^2b^2)$.

6.4.6 Rocking or Swing Impact

Studies of seismic induced rocking and sliding of unanchored equipment indicate that the potential for sliding, rocking or overturning of free standing, unanchored equipment depends on its slenderness ratio (the height of the equipment's center of gravity relative to the width of its base), the coefficient of friction between the equipment and floor, and the horizontal and vertical acceleration [Shao, Aslam, Zhu, Gates].

The swing displacement of a suspended system (suspended piping, HVAC, cable trays, etc.) can be estimated by

$$d = 1.3\ S_a / \omega^2$$

d = swing amplitude, in
S_a = spectral acceleration at frequency f_a, in/sec^2
ω = natural circular of swing motion = $2\pi f_a$ 1/sec
f_a = swing frequency, Hz

The natural frequency f_a of a pendulum of length L is $(g/L)^{0.5} / (2\pi)$.

Credible impacts that are significant must be documented. This includes, as a minimum, any one of the following conditions:

They affect an active component such as a pump or valve.
They affect instruments and impact sensitive components.
The source is a pipe larger than a target pipe.
The source is a portion of a wall or structure.
The source is a heavy component.
The source is an overhead architectural feature or ceiling.
The source is an overhead grating.

6.4.7 Spray Interactions

During an earthquake overhead or adjacent piping can break (severance of the pipe in two, also called “guillotine” break) or leak through a crack. The consequence of such failures can be a liquid, gas or steam spray or jet on critical equipment, loss of contents, and flooding of certain areas in the facility. Non-seismically qualified piping should be assumed to leak or break as a result of the earthquake [SRP].

7.0 ADVANCED ANALYSIS TECHNIQUES

7.1 Objective

When the seismic analysis of a piping system shows that certain piping components are overstressed, it is best to modify the design and support arrangement to reduce stresses to within the allowable limits. This may not be feasible in a few cases, such as seismic retrofit when the cost of modifications would be prohibitive. In this case, the designer may consider a more advanced, less conservative, analytical technique to try to solve the overstress. Several advanced techniques are presented in this chapter.

7.2 More Accurate SIF's

When the overstress is at a fitting, it may be due to the use of an overly conservative stress intensification factor (SIF) "i". Significant testing and analyses have been conducted in the 1980's and 1990's to obtain a better estimate of SIF's. In many cases this work has shown that the SIF values used in ASME B31 are conservative (larger than they should be). To take advantage of more precise SIF's, the Designer should refer to ASME Boiler & Pressure Vessel Code Section III Code Cases, and research bulletins published by the Pressure Vessel Research Council (PVRC, New York).

7.3 Analysis Technique for Faulted Loads

The rules of ASME B&PV Code Section III, Div.1 (Rules for Construction of Nuclear Facility Components), Appendix F (Rules for Evaluation of Service Loading with Level D Service Limit) may be followed to evaluate the seismic adequacy of piping system and components of good construction (per ASME B31 Pressure Piping Codes). The stress limits of ASME III Appendix F apply to one-time faulted events, as is the case for a Design Basis Earthquake. Some distortion of the piping may occur, but would not significantly affect flow area. Components and equipment have to be qualified separately for operability.

7.3.1 Elastic Analysis

Where the piping system is elastically analyzed, the stress-strain relationship is linear $\sigma = E\varepsilon$ and above yield the calculated stress is fictitious (Figure 7.3-1 (a)). The stress limits are

$$T < 42\%\ S_U$$
$$P_m < 70\%\ S_U$$
$$P_L + P_b < 105\%\ S_U$$

T = average primary shear across a section loaded in pure sheer, psi
S_U = minimum ultimate strength of the material, psi
P_m = primary membrane stress, psi
P_L = primary general or local membrane stress, psi

P_b = primary bending stress, psi

7.3.2 Plastic Analysis

The component model includes the actual stress-strain curve, including strain hardening in the plastic range (Figure 7.3-1 (b)). The stress limits using plastic analysis are

$$T < 42\% \, S_U$$
$$P_m < 70\% \, S_U$$
$$P_{max} < 90\% \, S_U$$

P_{max} = maximum primary stress intensity at any location, psi

7.3.3 Limit Analysis Collapse Load

The piping system elements are modeled as elastic-perfectly plastic ("limit analysis" assumes zero rigidity – or hinge mechanism - beyond yield. Because a piping system is redundant, several hinges may have to form before a span of the piping system collapses, as illustrated in Figure 7.3-1(c)). The load limit using static collapse analysis is

$$F < 90\% \, F_{LAC}$$

F = maximum permitted load applied to the system, lb
F_{LAC} = limit analysis collapse load, load that would cause a failure mechanism of an elastic-perfectly plastic model, lb

7.3.4 Plastic Analysis Collapse Load

The system is analyzed by plastic analysis (Figure 7.3-1(d)). The load limit using plastic instability analysis is

$$F < F_{PAC}$$

F_{PAC} = plastic analysis collapse load obtained by intersection of line Φ_2 with the stress-strain curve of the material, where [ASME BPV III Div.1 NB-3213]

$$\Phi_2 = \tan^{-1} (2 \tan\Phi_1)$$

7.3.5 Plastic Instability Load

The system is analyzed by plastic analysis (Figure 7.3-1(e)). The load limit using plastic instability analysis is

$$F < 70\% \, F_{PI}$$

F_{PI} = plastic instability load, where unbound plastic deformation can occur, lb

7.4 Alternative Methods

Several alternative methods for seismic analysis and qualification of piping systems have been compiled and published [WRC 379]. Alternative analysis techniques include: (1) Limit load, (2) Stress-strain correlation, (3) Synthetic average, (4) Time history analysis, (5) Energy balance, (6) Load coefficient, (7) Volumetric strain energy, (8) Secondary stress, (9) Inelastic response spectrum, (10) Dynamic / static margin, (11) fatigue – ratcheting, and (12) Incremental hinge methods. These methods could be investigated for the resolution of seismic overstress conditions.

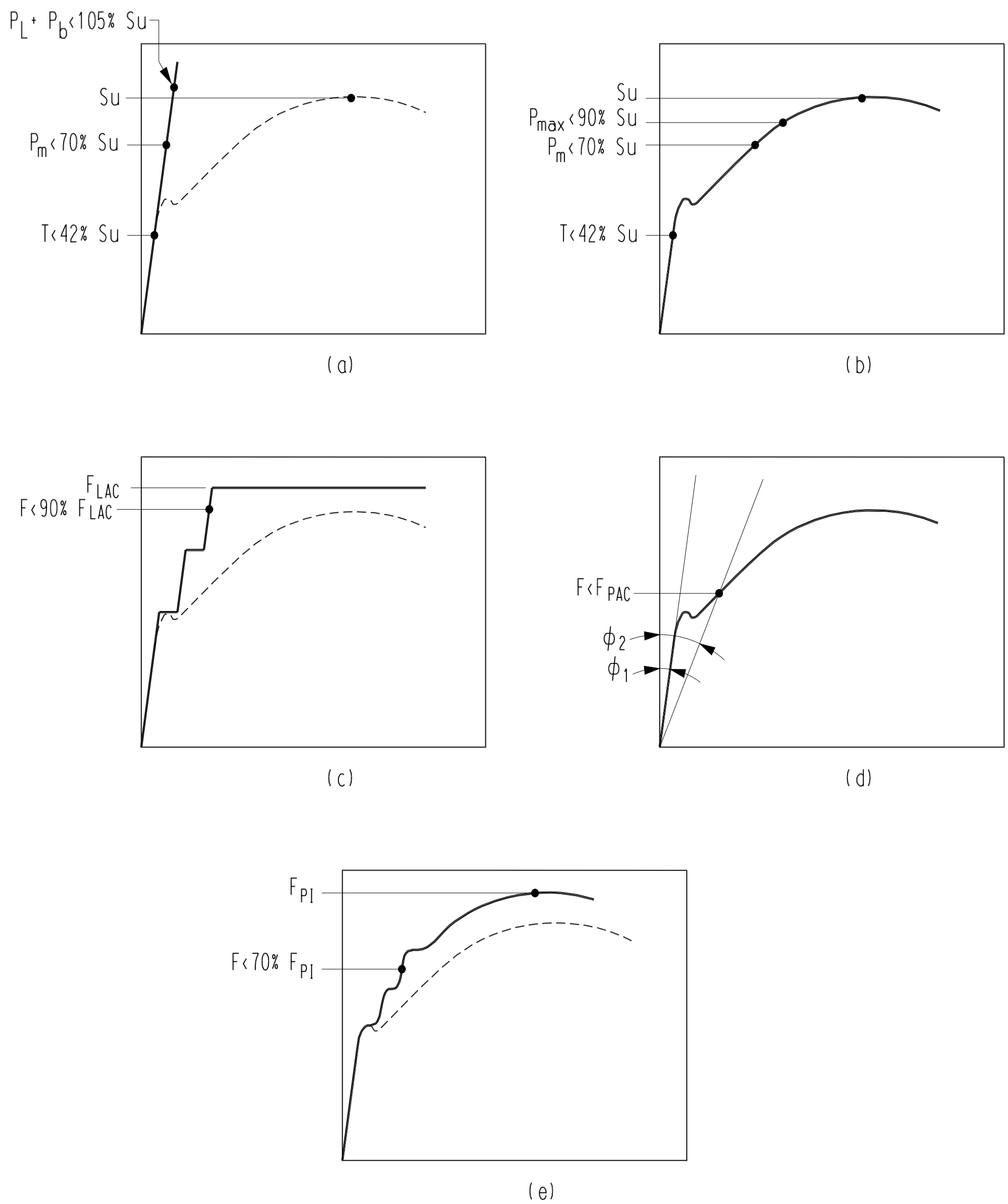


Figure 7.3-1 Analysis Techniques for Faulted Loads

8.0 SEISMIC RESTRAINTS

8.1 Standard Catalog Restraints

Standard catalog restraints are load rated components, listed in vendor catalogs, that can be readily procured and used "off the shelf". They can be divided into three categories of hardware:

(1) Attachment of restraint to pipe: pipe clamps, clevis, pipe rings, U-bolt, U-hook, riser clamps, etc.

(2) Restraint member: strut, rod, snubber, sway brace, spring, saddle, roller, vibration spring, etc.

(3) Restraint attachment to the building or structural steel: ceiling flange, beam attachment, beam clamps, concrete inserts, etc.

Figure 8.1-1 illustrates a standard catalog spring hanger assembly, with pipe clamp, spring can and rods, and beam clamp. Figure 8.1-2 illustrates a pair of standard catalog sway braces. Figure 8.1-3 illustrates a wall-mounted strut with pipe clamp or fingers, standard catalog items commonly used in supporting small bore piping and tubing. Figure 8.1-4 illustrates a U-bolt arrangement, where the U-bolt is a standard catalog item with commonly listed tensile capacity (upward resistance in Figure 8.1-4) and side resistance (lateral horizontal in Figure 8.1-4) usually available from manufacurer tests.

Standard supports are illustrated in MSS-SP standards [MSS-SP-69, MSS-SP-90, MSS-SP-127]. For fire protection sprinkler systems, standard supports are listed in NFPA [NFPA-13], with qualification or rating requirements specified in reference documents, such as those issued by Factory Mutual or UL.

Seismic wire rope (cable bracing) is also available as catalog items for use in bracing piping systems, suspended ceilings, HVAC ducts and components. They are generally manufactured from steel wires braided into cables.

For the seismic restraint of equipment and piping used for heating, refrigeration and air conditionning, ASHRAE recommends the use of seismic "snubbers" (side bumpers at floor level) and restrained spring isolators which are available as standard catalog items [ASHRAE].

8.2 Steel Frames

Steel frames and racks are often used as pipe supports or intervening members between standard catalog pipe supports and the building structure. Such steel frames are typically made from welded steel shapes (I-beams, channels, structural tubing, etc.). They can provide uni-directional or bi-directional restraint (Figure 8.2-1), or can be used as full anchors restraining the pipe against translation and rotation (Figure 8.2-2).

Steel frame members and welds are designed and sized in accordance with structural design standards [AISC, AISI] and reference design manuals [Blodgett]. Steel frames can be sized by hand calculations or modeled and analyzed by computer. Often times the piping analysis codes do include support frame analysis modules. The steel frame can also be modeled as part of the piping system, but this complicates the piping system model, and is seldom necessary.

The seismic design should not take credit for the friction force between pipe and support, which tends to reduce seismic motion of the pipe. However, pipe-support friction caused by thermal expansion or contraction should be accounted for as an applied load in designing the support.

8.3 Concrete Anchor Bolts

8.3.1 Types of Concrete Anchor Bolts

Concrete anchor bolts are commonly used to secure pipe support and restraint base plates to the building. They can be grouped into two categories: shell and non-shell anchor bolts (Figure 8.3.1-1).

(1) Shell Anchors

Shell anchors are concrete anchor bolts in which the bolt penetrates a shell that is expanded tightly against the concrete. There are three categories of shell anchors:

(1.1) Self-Drilling: The shell is the drill bit. Once the hole is drilled, it is cleaned and a plug is placed into the hole. The shell is reinserted, expanding over the plug.

(1.2) Non-Drill: Same as self-drill, but the shell is hammered over the plug.

(1.3) Drop-In: The hole is drilled and the shell hammered into place. A setting tool expands the shell against the concrete.

(2) Non-Shell Anchors

Non-shell anchors are concrete anchors that penetrate directly the concrete, without a shell surrounding the bolt. There are two categories of non-shell anchors:

(2.1) Wedge: As the nut is torqued, the bolt pulls up, expanding the clip.
Sleeve: Same as a wedge anchor, but the expanding clip is replaced by an expanding sleeve.

(2.2) Cast-in-place concrete anchor bolts are bolts that are placed in position and the concrete is then poured around the bolt, as the concrete cures the bolt is cast into position. There are two categories of cast-in-place concrete anchor bolts:

(2.2.1) Headed Stud: A straight bolt with head (typically at least 1.5D) embedded in concrete or grout.

(2.2.2) L- or J-Bolt: A steel bar L or J shaped embedded in concrete. 3/8” to 1” bolts have typically a 3D radius, while larger bolts have a 4D radius.

8.3.2 Bolt Materials

Anchor bolts are typically made of high strength carbon steel, with a yield stress of 75 to 115 ksi and an ultimate strength of 90 to 150 ksi. Material specifications for anchor bolts include ASTM A 193, A 307, A 325, A 354, A 449, A 490 and A 687. Cast-in-place rods may be high strength steel or carbon steel with a yield stress of 36 to 46 ksi and an ultimate strength of 58 to 70 ksi. Material specifications include ASTM A 36, A 572, A588, A 1554. High strength rods can be made with a yield stress of 105 ksi and an ultimate strength of 125 ksi (ASTM A 193 and A 1554 Gr.105). Concrete anchor bolts can be protected against corrosion by galvanizing (zinc coating) or by epoxy coating.

8.3.3 Qualification of Anchor Bolts

The seismic qualification of concrete anchor bolts is accomplished in three steps: First, the calculation of seismic demand (applied load) on each anchor; second, the calculation of the tensile and shear capacity of the anchor bolt; and third, the comparison of demand to capacity.

The codes and standards applicable to the design and qualification of concrete anchor bolts include: International Building Code [IBC]; American Concrete Institute [ACI].

(1) Calculation of Seismic Demand

The calculation of seismic demand (applied load) on individual anchor bolts consists of two steps: (1) distribution of load applied by the pipe to individual base plates, and (2) distribution of the base plate load to each individual bolt, as tension and shear.

The first step, distribution of load on individual base plates is a classic statics problem, and can be resolved by hand calculations and, for more complex or statically indeterminate configurations by a model of the support structure.

The second step typically involves a lateral load F applied at a certain height above the base plate (Figure 8.3.3-1). The applied load F is reacted by the base plate anchors as a shear (simply equal to F/N where N is the number of anchor bolts), and a tension T given by T X = F L where L is the eccentricity (height) of F above the base plate. The distance X depends on the assumed mode of compressive reaction at the base plate. If the base plate is stiff (for example, a base plate with a thickness at least equal to the bolt size) X can be taken as the distance between the two bolts (case (a) in Figure 8.3.3-1), or X may be based on a triangular compression of the concrete, with a resultant compressive reaction at 2/3 the distance from the centerline of the plate to its edge. If the plate is thinner, it could bend and pry the bolts in tension, and the moment arm would be based on a compressive reaction as indicated in (c) (this is the shortest moment arm and therefore would lead to the largest tension) or (d).

(2) Calculation of Capacity

The total capacity of an anchor bolt in tension and in shear is equal to a nominal value multiplied by penalty factors, where applicable, to account for embedment length, anchor spacing, edge distance, concrete strength and concrete cracks.

$$P = P_N\ (X_{EM}\ X_{AS}\ X_{ED}\ X_{CS}\ X_{CC})$$
$$V_C = V_N\ (Y_{EM}\ Y_{AS}\ Y_{ED}\ Y_{CS}\ Y_{CC})$$

P_C = tensile capacity, lb
P_N = nominal tensile capacity, lb
V_C = shear capacity, lb
V_N = nominal shear capacity, lb
X_{EM} , Y_{EM} = embedment length penalty factors for tension and shear
X_{AS} , Y_{AS} = anchor spacing penalty factors for tension and shear
X_{ED} , Y_{ED} = edge distance penalty factors for tension and shear
X_{CS} , Y_{CS} = concrete strength penalty factors for tension and shear
X_{CC} , Y_{CC} = concrete cracking penalty factors for tension and shear

The penalty factors are often specified in anchor bolt vendor catalogs.

Anchor bolts are tested to failure under tensile (pullout) and shear loads. The bolt manufacturer may gain approval of bolt capacities from ICBO, UL, FM and city or state jurisdictions.

(2.1) Nominal Capacity: The nominal capacities are then set at a fraction of the ultimate load

$$P_N = P_U / SF$$
$$V_N = V_U / SF$$

The safety factor may be established by regulations, contract or by the design agency. It is typically in the order of 4 to 5.

NEHRP-97, Section 9.2 recommends a nominal capacity established based on 10 specimen tests, as

$$P_N = k(P_U - \sigma)$$

P_N = nominal pullout strength, lb
k = 0.80 for ductile (bolt steel) failure and 0.65 for brittle (concrete) failure
P_U = mean measured strength, lb
σ = standard deviation of measured strengths, lb

(2.2) Embedment Depth: When a concrete expansion anchor is subject to a pullout load, two things happen: (1) the bolt steel itself is placed in tension and (2) the concrete around the bolt is also placed in tension. Failure can occur from either excessive tensile elongation, necking than rupture of the steel bolt (ductile failure) or from sudden concrete fracture (brittle failure).

The tensile ductile failure of the bolt steel occurs when

$$P_U = A_b \, S_U$$

P_U = tensile load at failure, lb
A_b = minimum cross section of the bolt, in^2
S_u = ultimate strength of the bolt material, psi

The tensile brittle failure of the concrete occurs when the tensile load reaches a limit equal to

$$P_U = 4 \, \Phi \, A_C \, (f'_C)^{0.5}$$

Φ = strength reducton factor [ACI 349]
P_U = tensile load at failure, lb
A_C = area of base of 45^o cone emanating at bolt tip, in^2
f_C' = concrete strength, psi

with

Φ = 0.65, except that Φ = 0.85 if:
(a) Embedments anchored beyond the member far face reinforcement, or
(b) Embedments anchored in a compression zone of a member, or
(c) Embedment anchored in a tension zone of a member where the uncracked concrete tension stress at the surface is less than 5 $(f_C')^{0.5}$.

Ductile steel failure by tensile rupture will happen before brittle concrete failure, if the concrete strength exceeds the steel bolt strength

$$4 \, \Phi \, A_C \, (f'_C)^{0.5} > A_b \, S_U$$

Since the area A_C at the base of a 45^o cone of height L_E is $A_C = \pi L_E^2$

$$L_E > \{A_b S_U / [\Phi \pi (f'_C)^{0.5}]\}^{0.5} / 2$$

Vendor catalogs will typically provide minimum embedment length for each anchor bolt. The vendor information may have the format of Table 8.3.3-1.

Head Style	Catalog No.	Bit Dia.	Bolt Dia.	Bolt Length	Thick. Mat'l	Emb. depth	P_U Kips	V_U Kips
Hex	ABC	¾"	5/8"	2.5"	0.25"	2.25"	6470	13071
Nut		¾"	5/8"	4"	1.75"	2.25"	6470	13071
		¾"	5/8"	6.25"	4"	2.25"	6470	13071

Table 8.3.3-1 Example of Anchor Bolt Capacity Table

Note that, in this case, the minimum embedment depth is approximately 4 times the bolt diameter.

(2.3) Anchor Spacing: If the spacing between adjacent anchors is more than 10D (where D is the anchor bolt diameter) then X_{AS} = 1.0 (no penalty). If the spacing is 10D down to 5D then X_{AS} must be reduced from 1.0 to 0.5. Y_{AS} is 1.0 if the anchor bolt spacing is larger than 2D.

(2.4) Edge Distance: If the distance from anchor bolt to the free edge of concrete, with no concrete reinforcement, is over 10D than $X_{ED} = Y_{ED} = 1.0$. From 10D down to 5D, X_{ED} must be reduced from 1.0 to0.5, and Y_{ED} varies as $(d/10)^{1.5}$ where d is the edge distance.

(2.5) Concrete Strength: For concrete strength above 4000 psi X_{CS} = 1.0, from 4000 down to 2000 X_{CS} varies as f_C'/4000 where f_C' is the concrete strength. For concrete strength above 3500 psi Y_{CS} = 1.0, from 3500 down to 2000 Y_{CS} varies as 0.65 + (f_C'/10,000).

(2.6) Concrete Crack: Cracks in concrete: If there are no cracks passing through the anchor bolt, X_{CC} = 1.0. For cracks not wider than approximately 10 mils, X_{CC} = 0.75, between 10 and 20 mils, X_{CC} = 0.5. Unless the crack is a gross rupture of concrete, Y_{CC} = 1.0.

(2.7) Cast-In-Place: An example of approximate pullout and shear capacities of headed studs is shown in table 8.3.3-2 [LANL].

Bolt Dia. (in)	Pullout (Kips)	Shear (Kips)	Min. Embed't. (in)	Min. Spacing (in)	Min. Edge Dist (in)
3/8	3	1	3-3/4	4-3/4	3-3/8
1/2	6	3	5	6-1/4	4-3/8
5/8	10	5	6-1/4	7-7/8	5-1/2
3/4	15	7	7-1/2	9-1/2	6-5/8
1	26	13	10	12=5/8	8-3/4

Table 8.3.3-2 Example of Load capacity of Headed Studs

(3) Comparing Demand and Capacity

Having established the demand (applied pullout *P* and shear *V*) and the capacity P_C *and* V_C , including penalty factors, we must now compare demand to capacity. The general form of the acceptance criterion can be written as

$$(P / P_C)^n + (V / V_C)^n < 1$$

P = applied pullout, lb
V = applied shear, lb
P_C = pullout capacity of bolt, lb
V_C = shear capacity of bolt, lb
n = exponent

The value of the exponent *n* depends on the applicable reference, for example in ACI 318 Appendix D "Anchoring to Concrete" n = 5/3.

8.3.4 Quality of Installation

An essential aspect of the seismic adequacy of concrete anchor bolts is the quality of their installation. The following is of particular importance:

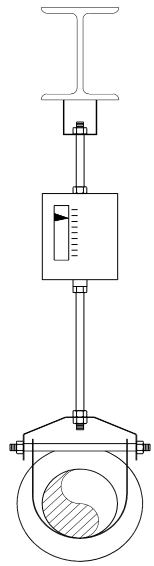
(a) Concrete anchor bolts should be installed by personnel trained in accordance with the anchor vendor's recommendations.
(b) The installation should follow the vendor's instructions.
(c) Concrete anchor bolts should be installed in cured concrete.
(d) The drilled hole should be of the right depth, diameter and should be cleaned.
(e) The anchor should not be welded, unless it is of a weldable steel grade.
(f) The installer should follow the Designer's torque requirement.
(g) Avoid conditions leading to capacity penalties (spacing, edge distance, concrete strength, cracks) unless the penalties have been accounted for in design.
(h) Rebar cutting should be pre-approved by civil engineering.

Newly installed expansion anchors may be checked for tightness at 80% to 100% unless specified otherwise by the manufacturer.

Verification of seismic adequacy of existing expansion anchors should include a tightness check at ~ 20% of the installation torque, such as indicated by the torque check values of Table 8.3.4-1.

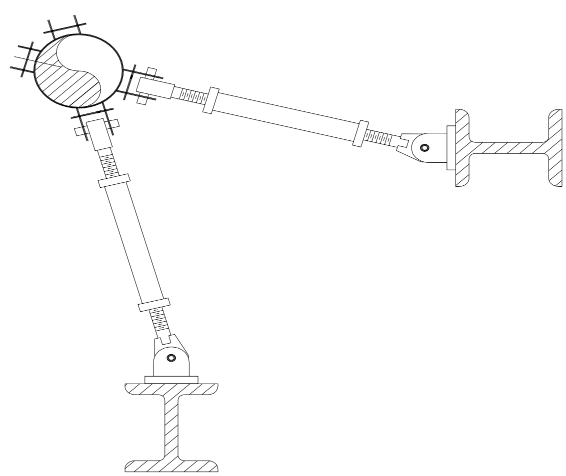
Bolt size	Installation torque ft-lb	20% torque ft-lb
3/8"	25 – 35	5 – 7
½"	45 – 65	9 – 13
5/8"	80 – 90	16 – 18
¾"	125 – 175	25 – 35

Table 8.3.4-1 Example of Torque Check Values



(a)

Figure 8.1-1 Spring Hanger



(f)

Figure 8.1-2 Rigid Struts Sway Braces

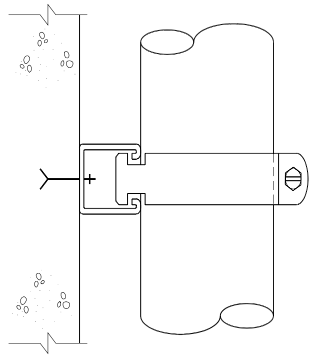


Figure 8.1-3 Wall Mounted Strut with Pipe Clamp

Figure 8.1-4 U-Bolt Arrangement

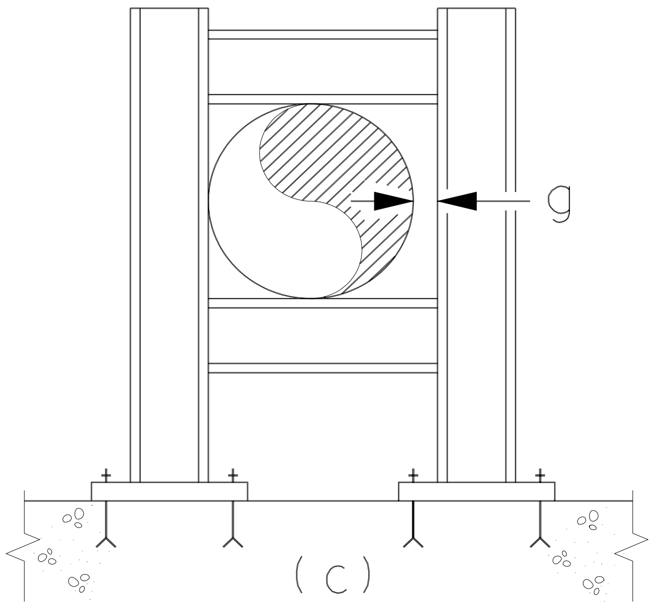


Figure 8.2-1 Rigid Frame as a Lateral Seismic Support

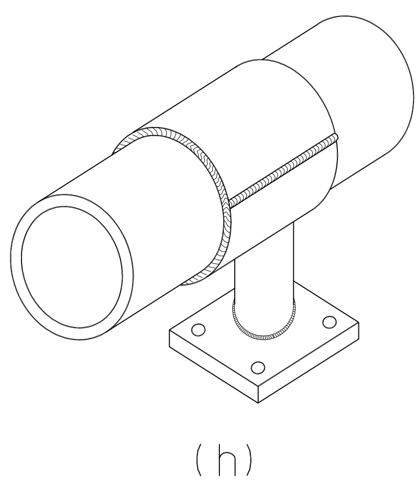


Figure 8.2-2 Steel Pipe Anchor

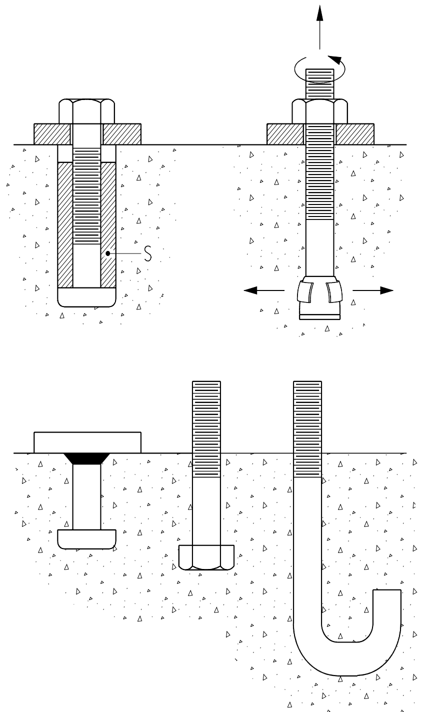


Figure 8.3.1-1 Shell Anchor (top right), Non-Shell Anchor (top left), Cast-in-Place (bottom)

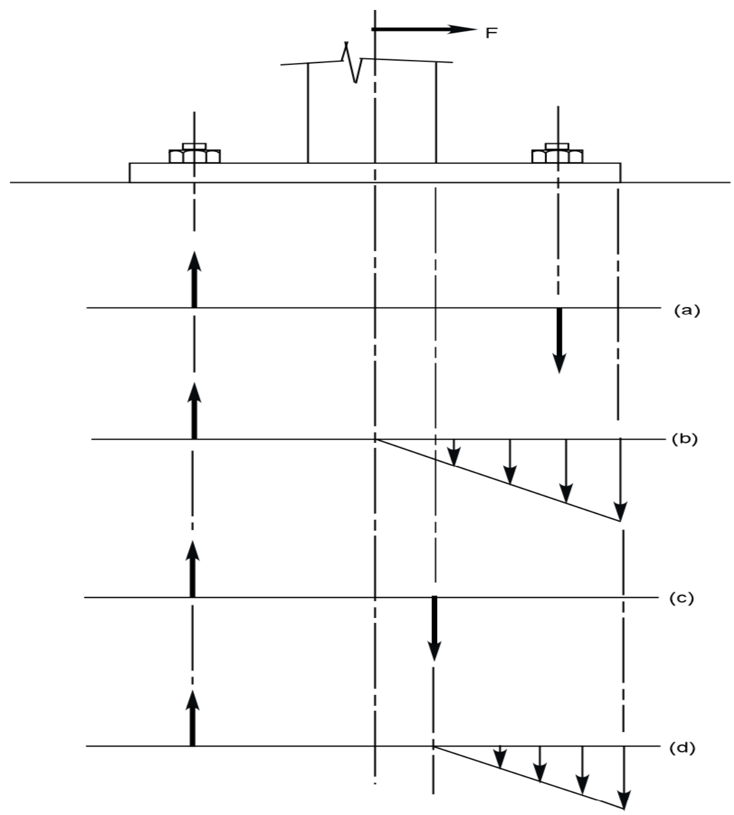


Figure 8.3.3-1 Base Plate reaction to Overturning Moment

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ACRONYM LIST

ACI	American Concrete Institute
AISC	American Institute of Steel Construction
AISI	American Iron and Steel Institute
ALA	American Lifeline Alliance
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating and Refrigerating, and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
EJMA	Expansion Joints Manufacturers Association
IBC	International Building Code
IEEE	Institute of Electrical and Electronics Engineers
NFPA	National Fire Protection Association
PGA	Peak Ground Acceleration
RRS	Required Response Spectrum
SIF	Stress Intensity Factor
TRS	Test Response Spectrum
ZPA	Zero Period Acceleration

Terms and Definitions

Spectral Displacement - The maximum value of the displacement x(t) of the SDOF oscillator of frequency of natural frequency ω_D and damping ζ subject to an earthquake P(t) is the spectral displacement at frequency $f = \omega_D / 2\pi$ and damping ζ.

Spectral Velocity and Acceleration – The maxima of the first and second derivatives of x(t) are the spectral velocity and acceleration respectively. The spectral acceleration will be noted $a(f,\zeta)$.

Peak Spectral Acceleration – Is the maximum spectral acceleration for a given damping ζ: $a(\zeta) = \max a(f, \zeta)$. In Figure 4.1.2-1 the peak spectral acceleration at 5% damping is approximately 3.2g.

Peak Ground Acceleration (PGA) – Is the maximum seismic acceleration of a SDOF oscillator with infinite frequency $a(f=\infty,\zeta)$ placed on the ground. Note that in the "rigid range" (large frequencies f) the acceleration does not depend much on damping. The maximum acceleration of a rigid SDOF $a(f=\infty,\zeta)$ is the maximum acceleration of the ground since the rigid SDOF does nothing more than follow the ground motion, hence the name "peak ground acceleration". In earthquakes, the "rigid range" typically starts between 20 Hz and 33 Hz. In Figure 4.1.2-1 the peak ground acceleration is approximately 1.0g (the right hand tail of the response spectra curves).

Zero Period Acceleration (ZPA) – Is the spectral acceleration at zero period, i.e. at infinite frequency. At ground level, the ZPA is the PGA. In the case of Figure 4.1.2-1, the ZPA is approximately 1.0g.

Seismic Design Spectra - For a given Design, the plot of SDOF frequency f (or period $T = 1/f$) and damping ζ vs. acceleration $a(f,\zeta)$ is the earthquake's acceleration response spectrum at damping ζ. Over the years, engineers have used a few classical (typical) shapes of the bell shaped spectrum curve (a, f) as seismic response spectra. These classical shapes are then scaled up or down to match the site's peak ground acceleration (PGA) [Housner, Newmark, R.G. 1.60].

Falling interaction: A falling interaction is an impact on a critical component due to the fall of overhead or adjacent equipment or structure.

Swing interactions: A swing interaction is an impact due to the swing or rocking of adjacent component or suspended system.

Spray interactions: A spray interaction is due to the leakage of overhead or adjacent piping or vessels.

System interactions: System interactions are spurious or erroneous signals resulting in unanticipated operating conditions, such as the spurious start-up of a pump or closure of a valve.

Interaction source: An interaction source is the component or structure that could fail and interact with a target.

Interaction target: An interaction target is a component that is being impacted, sprayed or spuriously activated.

Credible interaction: A credible interaction is one that can take place.

Significant interaction: A significant interaction is one that can result in damage to the target.

APPENDIX A - PROPOSED SEISMIC STANDARD

PROPOSED STANDARD
FOR THE SEISMIC DESIGN AND RETROFIT OF PIPING SYSTEMS
(DRAFT)

S100 – PURPOSE

This standard establishes alternate requirements for the seismic design of piping systems in the scope of the ASME B31 pressure piping codes. The standard applies to the seismic design of new piping systems as well as the seismic retrofit of existing piping systems.

S101 – SCOPE

This standard applies to above ground, metallic and non-metallic piping systems in the scope of the ASME B31 pressure piping codes (B31.1, B31.3, B31.4, B31.5, B31.8, B31.9, B31.11). Except for seismic design, the piping system in the scope of this standard must comply with the materials, design, fabrication, examination and testing requirements of the applicable ASME B31 code.

S102 – DEFINITIONS

Active components: Components that must perform an active function, involving moving parts or controls during or following the earthquake (e.g. valve actuators, pumps, compressors that must operate during or following the design earthquake).

Critical piping: Piping system that must remain leak tight or operable (deliver, control or shut-off flow) during or following the earthquake. A piping system may be classified by the owner or designee as critical, if it contains toxic or flammable materials, operates at high pressure (above 6000 psi), high temperature (above 750^{o}F), or must operate (deliver, control or shut-off flow) during or after the design earthquake.

Design earthquake: The level of earthquake for which the system must be designed.

Free field seismic input: The seismic input (typically static acceleration coefficients or seismic response spectra) in the free field, at the facility location. It may be obtained from the applicable standard (such as ASCE-7), or may be developed specifically for the site.

In-structure seismic response spectra: The seismic excitation (typically static acceleration coefficients or seismic response spectra) within a building or structure, at the elevation of the equipment attachments to the building or structure. The in-structure response spectra may be obtained (a) by amplification of the free field seismic input as described in the applicable standard (such as ASCE-7), or (b) by dynamic analysis of a specific building, structure or equipment.

Lateral restraint: A brace that restrains a pipe horizontally, in a direction lateral to its axis.

Leak tightness: The ability of a piping system to remain leak tight, typically defined as (a) no visible leak in liquid service and (b) bubble solution tight in gas service.

Longitudinal restraint: A brace that restrains the pipe along the pipe axis.

Operability: The ability of a piping system to deliver, control or shut-off flow during or after the design earthquake.

Peak ground acceleration: The maximum ground acceleration at the facility.

Peak spectral acceleration: The 5% damped maximum acceleration value input to the pipe, including in-structure amplification. It is the peak of the response spectrum.

Position retention: The ability of a piping system not to fall or collapse in case of design earthquake.

Seismic design: The activities necessary to demonstrate that the system can perform its seismic function in case of design earthquake. Seismic design may be achieved by rules, static or dynamic analysis, testing, or comparison to the documented performance of similar components in earthquakes.

Seismic function: A function to be specified by the owner or designee either as position retention, leak tightness, or operability.

Seismic interactions: Spatial interactions or system that could affect the seismic function of the piping system. An example of spatial interaction is the fall of overhead components, ceilings or structures on the piping system. Examples of system interactions include seismically induced spurious signals that would cause a valve actuator to close unintentionally, or loss of contents through the rupture of an un-isolable branch line. Credible interactions are interactions likely to take place, such as the collapse of an unreinforced masonry wall. Significant interactions are interactions that, should they occur, would affect the seismic function of the piping system, for example the fall of a small instrument on a large pipe may be credible but not significant, while the fall of a block wall on the same pipe would be significant. The impact of insulated adjacent pipe runs may be credible but not significant.

Seismic response spectra: A plot or table of accelerations, velocities or displacements versus frequencies or periods, for each of three orthogonal directions (typically east-west, north-south, vertical).

Seismic restraint: A brace that constrains the pipe against movement in case of earthquake. Seismic restraints. It includes rigid struts, mechanical or hydraulic snubbers, and steel frames.

Seismic retrofit: The activities involved in evaluating the seismic adequacy of an existing piping system and identifying the changes or upgrades required to seismically qualify the system.

Seismic static coefficient: Acceleration values to be applied to the piping system in each of three directions (typically two horizontal directions, east-west and north-south, and the vertical direction).

Static component: Mechanical component that does not perform an active function (involving moving parts) during or following the design earthquake. For example pressure vessels, tanks, strainers, manual valves that do not need to change position.

Vertical restraint: A brace that restrains the pipe in the vertical direction.

S103 – OWNER'S RESPONSIBILITY

The owner or designee shall specify:

(a) The scope and boundaries of piping systems to be seismically designed or retrofitted.
(b) The applicable ASME B31 code.
(c) The classification of piping as critical or non-critical, and the corresponding seismic function (position retention for non-critical systems; leak tightness or operability for critical systems).
(d) The free field seismic input for the design earthquake.
(e) The responsibility for developing the in-structure seismic response spectra, where required.
(f) The operating conditions concurrent with the seismic load.
(g) The responsibility for qualification of static and active components, including the operability of active components where required
(h) The responsibility for the evaluation of seismic interactions.
(i) The responsibility for as-built reconciliation of construction deviations from the design drawings.

S200 – MATERIALS

S201 – APPLICABILITY

The standard applies to piping with metallic or non-metallic materials that conform to the applicable ASME B31 code, with an elongation at rupture of at least 10% at the operating temperature.

S202 – RETROFIT

The seismic retrofit of existing piping systems shall take into account the material condition of the system. The Designer shall evaluate the condition of the piping system to identify and account for material or component degradation or lack of quality that could prevent the piping system from performing its seismic function.

S300 – DESIGN

S301 - SEISMIC INPUT

The seismic input excitation may be defined as horizontal and vertical seismic static coefficients, or as horizontal and vertical seismic response spectra. The seismic input is to be specified by the owner or designee by reference to the applicable standard (e.g. ASCE-7) or to site-specific input.

The seismic input shall be specified for each of three orthogonal directions: east-west, north-south and vertical. The seismic design may be based on either
(a) The resultant (square root sum of the squares) of the east-west plus vertical or north-south plus vertical loads, whichever is larger, or
(b) The resultant (square root sum of the squares) of the east-west plus north-south plus vertical loads concurrently.

The seismic input to piping systems inside buildings or structures shall account for the in-structure amplification of the free field accelerations by the structure. The in-structure amplification may be determined based on existing consensus standards, (such as the in-structure seismic coefficient in ASCE-7), or by a facility specific dynamic evaluation.

The damping for the seismic static coefficient or response spectra to be used as input for static or dynamic analysis of the piping system shall be 5%.

S302 – DESIGN METHOD

The method of seismic design and the applicable sections are given in Table S302-1. The method of seismic design depends on (a) the classification of the piping system (critical or non-critical), (b) the magnitude of the seismic input, and (c) the pipe size.

In all cases, the designer may select to seismically design the pipe by analysis, in accordance with S304 or S305.

a	Non-Critical Piping			Critical Piping	
	NPS ≤ 2”	2” < NPS < 6”	NPS ≥ 6”	NPS ≤ 2”	NPS > 2”
< 0.2 g	NR S400	NR S400	NR S400	NR S400	NR S400
0.2 g to 0.3 g	NR S400	NR S400	NR S307 S308 S400	DR S303 S306 S307 S308 S400	DR S303 S306 S307 S308 S400
> 0.3 g	NR S400	DR S303 S306 S307 S308 S400	DR S303 S306 S307 S308 S400	DR S303 S306 S307 S308 S400	DA S304/305 S306 S307 S308 S400

Nomenclature:
a = Maximum value of the peak spectral acceleration or seismic coefficient, g
NPS = Nominal pipe size, inches
NR = Not required. Explicit seismic design is not required, provided the piping system complies with the provisions of the applicable ASME B31 code, including design for loading other than seismic.
DR = Design by rule.
DA = Design by analysis.

Table S302-1 Seismic Design Requirements, Applicable Sections

S303 – DESIGN BY RULE

Where design by rule permitted in Table S302-1, the seismic qualification of piping systems may be established by providing lateral and vertical seismic restraints at a maximum spacing given by

$$L_{max} = \min\{1.94\ L_T / a^{0.25}\ ;\ 0.0175\ L_T\ (S_Y / a)^{0.5}\}$$

L_{max} = maximum permitted pipe span between lateral and vertical seismic restraints, ft
L_T = recommended span between weight supports, from ASME B31.1 (reproduced in Table S303-1), ft
a = maximum acceleration input to the pipe, g
S_Y = material yield stress at normal operating temperature, psi

Pipe Size NPS (in)	Water Service (ft)	Steam, Gas or Air Service (ft)
1	7	9
2	10	13
3	12	15
4	14	17
6	17	21
8	19	24
12	23	30
16	27	35
20	30	39
24	32	42

Table S301-1 ASME B31.1 Suggested Pipe Support Spacing (L_T) [ASME B31.1 Table 121.5]

In addition, straight pipe runs longer than three times the span of Table S303-1 should be restrained longitudinally.

The distance between lateral and vertical restraints should be reduced for pipe spans that contain heavy in-line components (with a total component weight in excess of 10% of the weight of the tabulated pipe span).

Unrestrained cantilevered pipe must be evaluated case-by-case.

The effect of seismic restraints on the flexibility (expansion or contraction) of the piping system must be verified in accordance with the design rules of the applicable ASME B31 code.

S304 - DESIGN BY ANALYSIS

Where design by analysis is required in Table S302-1, or where it is used as an alternative to the rules of section S303, the elastically calculated longitudinal stresses due to the design earthquake (calculated by static or dynamic analysis) shall comply with equation S304-1

$$i\,(M_i^2 + M_a^2)^{0.5} / Z < S_S \qquad \text{(S304-1)}$$

S_S = 16 ksi carbon and low alloy steel
S_S = 19 ksi austenitic stainless steel

i = stress intensification factor (from the applicable ASME B31 Code)
M_i = resultant moment amplitude due to inertia, in-lb (1)
M_a = resultant moment amplitude due to relative anchor motion, in-lb (1)
Z = pipe section modulus, in^3
S_S = allowable seismic stress at –20°F to 100°F , psi

Note:

(1) The resultant moment at a point may be the square root sum of the square of the three moment components at that point. Alternatively, the in-plane, out-of-plane and torsional moments may be multiplied by their respective stress intensification factor, then combined to obtain a resultant moment, where permitted in the applicable ASME B31 code.

S305 – ALTERNATIVE DESIGN METHODS

Where equation S304-1 cannot be met, the piping system may be qualified by more detailed analysis techniques, including fatigue, plastic or limit load analysis.

S306 – MECHANICAL JOINTS

For critical piping systems, the movements (rotations, displacements) and loads (forces, moments) at mechanical joints (non-welded joints unlisted in an ASME B16 standard) must remain within the limits specified by the joint manufacturer.

S307 – SEISMIC RESTRAINTS

The seismic load on seismic restraints and their attachment to building structures and anchorage to concrete, shall be calculated by static or dynamic analysis. The seismic adequacy of seismic restraints and their attachments must be determined in accordance with the applicable design code, such as MSS-SP-69 for standard support components, AISC or AISI for steel members, and ACI for concrete anchor bolts. A total gap equal to the pipe radius for 2” nominal pipe size (NPS) and smaller pipe, and 2” for pipe larger than 2” NPS, is permitted in the restrained direction, provided the seismic load, calculated on the basis of zero gap, is multiplied by an impact factor of 2.

S308 - COMPONENTS

The seismic and concurrent loads applied by the pipe at component nozzles must be determined as part of the seismic design of the piping system. The owner or designee is to determine the responsibility for qualification of the components, including the operability of active components where required.

S400 - INTERACTIONS

Piping systems shall be evaluated for seismic interactions. Credible and significant interactions shall be identified and resolved by analysis, testing or hardware modification.

S500 - DOCUMENTATION

The designer shall submit to the owner documentation of the seismic design, to include, as a minimum:

(a) Drawing showing the scope of work.
(b) Arrangement of pipe supports and restraints.

(c) Calculations showing design input and calculation results to show compliance with this standard and the owner's requirements.
(d) Drawings for new or modified supports, with dimensions, weld and anchor bolt details, bill of materials, and sufficient information for procurement and construction.

S600 – MAINTENANCE

The Owner is responsible for maintaining the configuration of the seismically qualified piping system. In particular, changes to layout, supports, components or function, as well as material degradation in service must be evaluated to verify the continued seismic adequacy of the system.

S700 - REFERENCES

ACI 318 Building Code Requirements for Reinforced Concrete, American Concrete Institute.

AISC, Manual of Steel Construction, American Institute of Steel Construction.

AISI, Specification for the Design of Cold-Formed Steel Structural Members, American Iron and Steel Institute, Washington D.C..

ASCE-7, Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers.

ASME B31.1, Power Piping, American Society of Mechanical Engineers, New York, NY.

ASME B31.3, Process Piping, American Society of Mechanical Engineers, New York, NY.

ASME B31.4, Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids, American Society of Mechanical Engineers, New York, NY.

ASME B31.5, Refrigerant Piping and Heat Transfer Components, American Society of Mechanical Engineers, New York, NY.

ASME B31.8, Gas Transmission and Distribution Piping Systems, American Society of Mechanical Engineers, New York, NY.

ASME B31.9, Building Services Piping, American Society of Mechanical Engineers, New York, NY.

ASME B31.11, Slurry Transportation Piping, American Society of Mechanical Engineers, New York, NY.

ICBO AC156, Acceptance Criteria for the Seismic Qualification Testing of Nonstructural Components, International Conference of Building Officials, Whittier, CA.

MSS-SP-69, Pipe Hangers and Supports – Selection and Application.

APPENDIX B – COMMENTARY TO PROPOSED STANDARD

S100C – PURPOSE

Currently, the ASME B31 codes require consideration of all design loads, including earthquakes where applicable. The B31 codes treat earthquake as an occasional load, the longitudinal seismic stress being added to the longitudinal stresses due to pressure and sustained loads. ASME B31.1 provides an explicit equation for computing the longitudinal stress. The code allowable stress for seismic plus sustained stresses is 1.2S for ASME B31.1 and 1.33S for ASME B31.3, where S is the code allowable stress. This standard provides an alternate approach for the seismic design of pressure piping systems, and is applicable to all the ASME B31 codes.

S101C – SCOPE

The standard applies to piping systems and pipelines designed and constructed to one of the ASME B31 codes. Code compliance provides a level of design and construction quality necessary for the application of the rules in this standard. The ASME B31 Pressure Piping codes are:

ASME B31.1, Power Piping
ASME B31.3, Process Piping
ASME B31.4, Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids
ASME B31.5, Refrigerant Piping and Heat Transfer Components
ASME B31.8, Gas Transmission and Distribution Piping Systems
ASME B31.9, Building Services Piping
ASME B31.11, Slurry Transportation Piping

S102C – DEFINITIONS

Active components: Note that a manual or actuated valve that does not need to change its position during or following the earthquake is not considered to be an "active" component.

Critical piping: The definition of high pressure is based on B31.3, which defines high pressure as a B16.5 pressure rating of 2500, which corresponds to approximately 6000 psi for steel at ambient temperature.

The limit of 750^{o}F provides an upper limit for steel, beyond which the mechanical properties are significantly affected by temperature.

The definition of material content in critical piping can also be based on OSHA regulation 19 CFR 1910 or rules of the National Fire Protection Association (NFPA).

The piping must be classified "critical" if its function or leak tightness is required by regulation.

An owner may also classify a piping system as critical for economic reasons, if loss of system function or leaks would be too costly.

Design earthquake: A design earthquake may be specified by regulation or building codes.

Free field seismic input: Free field seismic input is ground motion, unaffected by the proximity of structures. Seismic maps provide free field seismic input. The free field input may also be obtained from seismic maps, United States Geological Survey (USGS) regional data, or they may be developed based on explicit geotechnical and seismological studies of a given site, in which case it is referred to as “site specific”.

In-structure seismic response spectra: The seismic excitation at ground level is amplified with elevation in a structure. For example, the acceleration atop a pipe rack will be larger than at ground level. If the piping system is supported within a structure, its input excitation is therefore larger than if it was supported at ground level. There are two common methods to obtain the amplified spectra in a structure: (a) A finite element analysis of the structure, in which the ground excitation is the input and the accelerations at various floor elevations are obtained as output. (b) An approximate multiplier applied to the ground acceleration, for example $1 + 2z/h$, where z is the elevation of the floor in the structure and h is the total height of the structure. In this case, the largest in-structure amplification of ground accelerations will therefore be 3 at roof level ($z = h$). For a piping system, the elevation to consider (z) is the highest elevation of pipe restraint attachment points to the building structure.

Lateral restraint: For example, an east-west brace provides lateral restrain to a north-south run of pipe. A horizontal brace provides lateral restrain to a vertical pipe riser.

Leak tightness: Leak tightness, as used here, is the ability of the piping system to prevent its contents from leaking out of the system, within a level of tightness specified by the owner. In most industrial applications, leak tightness will correspond to a lack of visible leakage for liquids and bubble-solution tightness for gases. Leak tightness does not apply to valve through-seat leakage, which falls under the definition of operability (delivery, control and shutoff of flow). For example, as defined here, a leak tight valve may not leak out through flange or packing, but may leak through its seat.

Longitudinal restraint: For example, an east-west brace provides longitudinal restrain to an east-west run of pipe. A vertical brace provides longitudinal restrain to a vertical pipe riser. A restraint placed within 12” of a bend may be considered to act as a longitudinal restraint to the run of pipe upstream of the bend, in the direction of the restraint. For example, an east-west brace on a north-south run, 12” from the east-west / north-south bend, acts as a longitudinal restraint to the east-west run.

Operability: Where operability is required, it will be necessary to specify what components need to operate and the required function. For example, an air operated valve actuator may have to open or close a gate valve or throttle flow through a globe valve. A manual valve may have to be closed by an operator following the earthquake to isolate a potential spill, a pump may have to start-up or shutdown. The owner, or designee, needs to consider the failure mode of active components, such as valve actuators on loss of power or loss of air (common in large earthquakes unless the power supply or plant air systems have been seismically qualified). In defining what component needs to remain operable, keep in mind the following post-earthquake conditions:

(a) Normal offsite and non-qualified emergency power may be lost for several days (for example 3 days).
(b) If operators are required to take actions, they must have access to the equipment and the equipment needs to be qualified.
(c) Non-qualified piping systems may leak or rupture causing loss of function, flooding, etc.
(d) The earthquake may cause fires.

Peak ground acceleration: It is the highest value of the seismic response spectrum at ground level. It is typically the value of the ground-level seismic static coefficient calculated following a building code practice, not including in-structure amplification (e.g. not including the term 1 + 2 z/h).

Peak spectral acceleration: It is the peak of the response spectrum, or the maximum value of the static coefficient including in-structure amplification (i.e.. including the term 1 + 2 z/h).

Position retention: A piping system may leak and not operate (control, shut-off or maintain flow) yet maintain its position, by not falling.

Seismic function: No seismic design should proceed without an understanding of the desired system function. For piping systems and pipelines, there are three possible functions:
(a) Position retention means that the pipe will not fall (collapse), and injure workers or the public.
(b) Leak tightness means that the pipe should not leak to the environment (a typical requirement for toxic or flammable fluids). Through-leakage of valve seats should be considered an operability requirement.
(c) Operability means that the system must deliver, shut-off or throttle flow.

Seismic response spectra: Typically, for piping design, response spectra are specified as acceleration (in g's) versus frequency (in Hz). They can be obtained from building codes or from site-specific analyses. The maximum value (or "peak") of the in-structure response spectra is the value "a" used in Table S302-1

Seismic restraint: Note that a seismic restraint may also be provided by a wall penetration or a hard interference with the pipe. The restraint should have sufficient stiffness and strength to restrict the pipe movement. Spring hangers are not seismic restraints, rod hangers that can only act in tension (they would buckle under compressive loads) may be considered seismic restraints only if the vertical acceleration is smaller than the pipe weight (i.e. the pipe will not tend to uplift and compress the rod hanger).

Seismic interactions: The evaluation of seismic interactions starts in the field. The designer should use judgment and calculations, as necessary, to determine which nearby or overhead structures, systems or components could adversely affect the pipe function. The pipe being seismically designed is the "target" of interactions. The structures, systems and components that can affect the pipe are the "sources" of interaction. Credible sources of interactions include the building itself, block walls, suspended ceilings, large unanchored equipment that could slide or overturn, or poorly anchored overhead ducts or cable trays. Significant interactions include impact of valve actuators against adjacent walls where operability is required, fall of ceiling panels on top of pipes, overturning of tall equipment onto pipes.

Seismic static coefficient: The value of the seismic static coefficient is typically obtained from building codes (such as the International Building Code) or standards (such as ASCE-7).

S103C – OWNER'S RESPONSIBILITY

The success of a seismic design or retrofit effort depends on the clarity and completeness of the purpose, scope and input. To that end, the owner may rely on an expert individual (consultant) or engineering firm (the designee).

S200C – MATERIALS

S201C – APPLICABILITY

For process and power plant applications, at least 10% elongation at rupture is a reasonable measure of ductility of the material. For pipelines, operating at pressure induced hoop stresses close to 72% yield, a ductility is better measured by a minimum shear area in a drop weight tear test (DWTT) or Charpy V-notch test (CVN). This ductility permits the material to yield if overloaded and redistribute the seismic load, prior to rupture. The rules of this standard are based on analyses, tests and earthquake experience with ductile materials.

S202C – RETROFIT

The seismic retrofit of an existing piping system is similar to the seismic design of a new piping system, with one added advantage and one added difficulty. The advantage is that the system has been in operation and its weaknesses, if any, are known through its performance and maintenance records (for example, a persistently leaking joint would require particular attention in seismic design). The difficulty is that components may be corroded or otherwise degraded, which would be the source of leaks or ruptures in case of earthquake. A visual inspection, supplemented with internal or volumetric inspections (such as ultrasonic examination) may be in order where degradation is suspected.

S300C – DESIGN

Where design by rule is permitted in Table S302-1, the seismic qualification of piping systems may be established by providing lateral and vertical seismic restraints at a maximum spacing (distance between supports) given by

$$L_{max} = \min\{1.94\ L_T / a^{0.25}\ ;\ 0.0175\ L_T\ (S_Y / a)^{0.5}\}$$

L_{max} = maximum permitted pipe span between lateral and vertical seismic restraints, ft
L_T = recommended span between weight supports, from ASME B31.1 (reproduced in Table S303-1), ft
a = maximum acceleration input to the pipe, g
S_Y = material yield stress at operating temperature, psi

This equation for L_{max} stems from the following considerations. For a given span of pipe (given linear weight, Young's modulus and moment of inertia of the cross section)

$$\Delta / (a\, L^4) = \text{constant}$$

$$\sigma / (a\, L^2) = \text{constant}$$

Δ = deflection at mid-span, in
a = lateral uniform acceleration, g's
L = length of pipe span, in
σ = maximum bending stress, psi

The span lengths in Table S301-1 are based on

$$\Delta = 0.1''$$

$$\sigma = 2300 \text{ psi}$$

$$a = 1 \text{ (gravity = 1g)}$$

To limit the mid-span deflection to 2" under a uniform seismic acceleration "a" applied concurrently to the pipe in two lateral directions (resultant 1.414a) it is necessary that

$$2'' / (1.414a \times L^4) = 0.1'' / (1 \times L_T^4)$$

L = span length that will deflect 2" under resultant acceleration 1.414a, in
L_T = span length from ASME B31.1 Table 121.5

or

$$L \leq 1.94\, L_T / a^{0.25}$$

To limit the maximum bending stress to 0.5 S_Y under a uniform seismic acceleration "a" applied concurrently to the pipe in two lateral directions (resultant 1.414a) it is necessary that

$$L \leq 0.0175\, L_T\, (S_Y / a)^{0.5}$$

S_Y = material yield stress at operating temperature, psi (ref. ASME B&PV Section II Part D, Table Y-1).

Therefore, to limit the mid-span deflection to 2" and the maximum bending stress to 0.5 S_Y, it is necessary limit the span length to

$$L_{max} = \min\{1.94\, L_T / a^{0.25}\ ;\ 0.0175\, L_T\, (S_Y / a)^{0.5}\}$$

Repeating this calculation for a series of pipe sizes and accelerations, we obtain the maximum spacing of lateral and vertical seismic restraints in 70°F service shown in the following table

NPS	ASME-B31.1 Table 121.5	0.1g	1.0g	2.0g	3.0g
1	7	24	13	11	9
2	10	34	19	16	13
3	12	41	23	19	15
4	14	48	27	22	18
6	17	58	32	27	22
8	19	65	36	30	25
12	23	79	44	37	30
16	27	93	52	44	35
20	30	103	58	48	39
24	32	110	62	52	42

In design by analysis, equation S304-1 is based on the relationship between applied reversing stress amplitude S and fatigue cycles to failure N

$$i\,S = C / N^{0.2}$$

i = stress intensification factor
S = applied stress amplitude, psi
N = cycles to failure
C = material coefficient = 122,000 for carbon steel (245,000 stress range / 2)
= 140,000 for austenitic stainless steel (281,000 stress range / 2)

Allowing the seismic load to cause an incremental stress of 1/3 (=0.33) in 100 cycles of maximum applied seismic load, the stress equation becomes

$$iS = 0.33\ C / 100^{0.2} = 0.13\ C = 16.2 \text{ ksi carbon steel} \sim 16 \text{ ksi and } 18.6 \text{ ksi SS} \sim 19 \text{ ksi}$$

S305C – ALTERNATIVE DESIGN METHODS

Where equation S304-1 cannot be met, the piping system may be qualified by more detailed analysis techniques, including fatigue, plastic or limit load analysis. Welding Research Council Bulletin WRC 379, Alternative Methods for the Seismic Analysis of Piping Systems, February 1993, provides an overview of various alternate seismic design methods [ASME, New York].

For passive equipment (vessel and heat exchanger) the forces and moments at equipment nozzles are evaluated by comparison to vendor allowable limits. For pressure vessels, if vendor allowable nozzle loads are not available, the nozzle loads may be evaluated by calculations. Applicable references for nozzle load evaluation include:

(a) ASME Boiler and Pressure Vessel Code section VIII Pressure Vessels [ASME New York.
(b) The Standard of the Tubular Heat Exchangers manufacturers Association [TEMA, Tarrytown, NY].
(c) WRC 107 [Welding Research Council Bulletin 107, Local Stresses in Spherical and Cylindrical Shells Due to External Loadings, March 1979, ASME, New York].
(d) WRC 297 [Welding Research Council Bulletin 297, Local Stress in Cylindrical Shells Due to External Loadings and Nozzles, September 1987, ASME, New York].

S400C - INTERACTIONS

Piping systems shall be evaluated for seismic interactions. Credible and significant interactions shall be identified and resolved by analysis, testing or hardware modification.

S500C - DOCUMENTATION

The designer shall submit to the owner documentation of the seismic design. The documentation shall include, as a minimum:

(a) Drawing showing the scope of work.
(b) Arrangement of pipe supports and restraints.
(c) Calculations showing design input and calculation results to show compliance with this standard and the owner's requirements.

(d) Drawings for new or modified supports, with dimensions, weld and anchor bolt details, bill of materials, and sufficient information for procurement and construction.

S600 – MAINTENANCE

The Owner is responsible for maintaining the configuration of the seismically qualified piping system. In particular, changes to layout, supports, components or function, as well as material degradation in service must be evaluated to verify the continued seismic adequacy of the system.

APPENDIX C - SEISMIC DESIGN EXAMPLE

S100 – PURPOSE

To illustrate the application of ASME B31S to a new process steam line, from a vertical vessel to a heat exchanger (Figure C-1).

S101 – SCOPE

The scope of work includes the steam piping from the vertical vessel to the heat exchanger, including the 2" branch line to the isolation valve and excluding the vessel and heat exchanger, Figure C-1 and C-2.

The piping has been designed for normal operating loads (pressure, temperature, weight) in accordance with the ASME B31.3 Process Piping Code. The pipe is ASTM A 106 Grade B, size 6" schedule 40, with a 2" schedule 40 branch line.

The piping is to be constructed (materials, welding, NDE and hydrostatic testing) in accordance with ASME B31.3 Process Piping.

S103 – SPECIFIED REQUIREMENTS

(a) The scope and boundaries of piping system to be seismically qualified is shown in Figure C-2, it consists of the 6" piping from the vertical vessel to the heat exchanger, and the 2" branch to the first anchor point past the isolation valve. The scope of work does not include the design of the heat exchanger, or the design of the pressure vessel.
(b) The applicable code is ASME B31.3.
(c) The pipe is considered "critical". The system is required to operate following the earthquake.
(d) The free field seismic input is to be obtained from IBC-2000. The system is Seismic Use Group III, with an importance factor I = 1.5. The soil is very dense with soft rock, and has a shear wave velocity v_S estimated at 2,000 ft/sec.
(e) The in-structure seismic response spectra is to be obtained from IBC-2000 (1 + 2z/h amplification factor for elevation).
(f) The operating and design conditions concurrent with the seismic load are:
Design Pressure: 450 psi.
Design Temperature: 460^{o}F
Ambient temperature: 100^{o}F max, 40^{o}F min.
Operating Pressure: 350 psi
Operating Temperature: 435^{o}F max., 70^{o}F min.
Design Life: 52 cycles per year for 30 years
Dead Load: Fluid density = 0.
Live loads: None.
Wind: None (indoor).
(g) Seismic interactions review is excluded from this scope of work.
(h) As-built reconciliation of the installed system is excluded from this review.

S200 - MATERIALS

Piping: ASTM A 106 Grade B.
Valves: cast steel body.
Pressure vessel and heat exchanger shell: ASME BPV II, SA XXX.
Insulation: 1" thick, 1.83 lb/ft.
Fluid: steam
Corrosion Allowance: 1/16" =0.06".
Joints: Welded in all places.

S201 – APPLICABILITY

The pipe and joints are metallic, ductile at operating conditions.

S202 – RETROFIT

This section is not applicable.

S300 – DESIGN

S301 – SEISMIC INPUT

S301.1 – SEISMIC INPUT AT GRADE

Step-1: The site ground motion will be selected from the IBC seismic maps, and not from a site-specific seismicity study.

Step-2: To obtain the IBC site ground motion, the facility location is first placed on the IBC map (IBC Figures F1615(1) to (10)), and the mapped maximum considered earthquake spectral response acceleration (MCESRA) is read from the contour intervals as, for example:

$$S_S = 50\%\ g = 0.50\ g$$
$$S_1 = 25\%\ g = 0.25\ g$$

S_S = MCESRA at short period, and 5% damping in a site class B.
S_1 = MCESRA at 1 sec, and 5% damping in a site class B.
$g = 32.2\ ft/sec^2 = 386\ in/sec^2$ = gravity

Step-3: At the facility, the soil is very dense with soft rock, and has a shear wave velocity v_S estimated at 2,000 ft/sec.

Step-4: According to IBC Table 1615.1.1 this soil is classified as class C. Since the soil is "softer" than a class B (rock) soil, we can expect that the spectral accelerations will be larger than the IBC map values, which apply to a class B soil. This adjustment of accelerations with soil is achieved through the "site coefficients" F_a and F_V in step 5.

Step-5: From IBC Tables 1615.1.2(1) and (2), given the site class C and the MCESRA values S_S = 0.5g, S_1 = 0.25g we read:

$$F_a = 1.20$$
$$F_V = 1.55$$

F_A and F_V = site coefficients

Step-6: Following the IBC procedure, we calculate the maximum considered earthquake spectral response acceleration (MCESRA)

$$S_{MS} = F_a\, S_S = 1.20 \text{ x } 0.50g = 0.60 \text{ g}$$
$$S_{M1} = F_V\, S_1 = 1.55 \text{ x } 0.25g = 0.39 \text{ g}$$

S_{MS} = mapped spectral acceleration for short period
S_{M1} = mapped spectral acceleration for 1-second period

Step-7: The design seismic response accelerations (DSRA) are

$$S_{DS} = (2/3)\, S_{MS} = 2/3 \text{ x } 0.60g = 0.40 \text{ g}$$
$$S_{D1} = (2/3)\, S_{M1} = 2/3 \text{ x } 0.39g = 0.26 \text{ g}$$

S_{DS} = Design spectral acceleration for short period
S_{D1} = Design spectral acceleration for 1-second period

Step-8: Two reference spectral periods are defined as

$$T_o = 0.2\, S_{D1}/S_{DS} = 0.2\ (0.26/0.40) = 0.13 \text{ sec } (7.7 \text{ Hz})$$
$$T_S = S_{D1}/S_{DS} = 0.26/0.40 = 0.65 \text{ sec } (1.5 \text{ Hz})$$

Step-9: The design response spectrum (DRS) of the facility, at 5% damping, can now be traced. It consists of three regions:

Period Range T(sec)	Spectral Acceleration S(g)
0 to T_o	$0.6\ (S_{DS}/T_o)\ T + 0.4\ S_{DS}$
T_o to T_S	S_{DS}
T_S to infinite	S_{D1} / T

Period Range T(sec)	Frequency Range f(Hz)	Spectral Acceleration S(g)
0 to 0.13 sec	infinite to 7.7 Hz	S = 1.85 T + 0.16 S = 0.16 + 1.85 / f
0.13 to 0.65 sec	7.7 to 1.5 Hz	S = 0.40
0.65 to infinite	1.5 to 0 Hz	S = 0.26 / T S = 0.26 f

S301.2 – SEISMIC EXCITATION IN-STRUCTURE

Step – 1: Based on the consequence of failure of the system (failure effect), the system is assigned a Seismic Use Group I, II or III (IBC 1616.2), and an importance factor I = 1.0 or 1.5 (IBC 1621.1.6). The example facility is Seismic Use Group III, with an importance factor I = 1.5.

Step – 2: Given the Seismic Use Group (SUG I, II or III) and the values of S_{DS}, $S_{D1}$and S_1, the system is assigned a Seismic Design Category (SDC) A to F (IBC 1616.3). The extent of seismic design and qualification will increase from SDC A to SDC F. Since S_{DS} = 0.40g, S_{D1} = 0.26g and I = 1.5, the assigned SDC is D.

Step – 3: The system is not to be exempted from seismic qualification.

Step – 4: The horizontal seismic load applies separately in the longitudinal and lateral directions, it is given by F_P where (IBC 1621.1.4)

$$0.3\ S_{DS}\ I\ W \leq F_P = [0.4\ a_P\ S_{DS}\ W\ I\ /\ R_P]\ (1 + 2\ z/h) \leq 1.6\ S_{DS}\ I\ W$$

S_{DS} = Project Specificationtral acceleration for short period
I = importance factor (1.0 or 1.5)
W = weight
F_P = horizontal load
a_P = component amplification factor (1.0 to 2.5)
a_P = 1.0 for any piping system
R_P = component response modification factor (1.0 to 5.0)
R_P = 1.25 for low deformability piping systems, 2.5 for limited deformability piping system, 3.5 for high deformability piping systems
z = height of attachment to structure
h = height of structure

With,
S_{DS} = 0.40 g
I = 1.5
W = distributed weight of piping system
a_P = 1.0
R_P = 2.5 because the piping is welded steel (high deformability) but the 2" line is joined by swage mechanical fittings (medium deformability)
z /h = 1 because the pipe may be supported from the building roof (z = h).

$$F_P = (0.4 \times 1.0 \times 0.40 \times W \times 1.5 / 2.5)(1 + 2 \times 1) = 0.3\ W$$

The horizontal load is verified to be larger than 0.3 S_{Ds} I W = 0.3 x 0.40 x 1.5 x W = 0.18 W
And it need not be larger than 1.6 S_{DS} I W = 1.6 x 0.40 x 1.5 x W = 0.96 W

Step – 5: The effect of the horizontal seismic load F_P (applied separately in the lateral and longitudinal direction) is added to the effect of the vertical seismic load F_V given by (IBC 1617.1.1, 1621.1.4)

$$F_V = 0.2\ S_{DS}\ W$$

F_P = vertical component of seismic load

In this case,

$$F_V = 0.2 \times 0.40 \times W = 0.08\ W = 8\%$$

The total seismic load is therefore the horizontal load F_P plus the vertical load F_V. This is a vectorial addition, in other words, the effects of the horizontal load are added to the effects of the vertical load to obtain the total seismic effect on the system (IBC 1617.1.1, 1621.1.4)

$$E = F_P + F_V = 0.30\ W\ \text{(lateral)} + 0.08\ W\ \text{(vertical)}$$

In summary, the system will have to be seismically designed to resist a horizontal force equal to 30% of its weight ($F_P = 0.3$ W), applied separately in the lateral direction (for example east-west), and the longitudinal direction (for example north-south). In addition, and concurrent with either the lateral or the longitudinal force, the system will have to sustain a vertical force (upward or downward) equal to 8% of its weight ($F_V = 0.08$ W).

Step – 6: The total load is the sum of the seismic load E and the weight W. If the allowable stress design method (also called working stress design method) is used to qualify the piping system, as is common practice, then the seismic load E should be divided by 1.4 (IBC 1605.3.2). The total load is therefore

$$F_T = W + E/1.4$$

In this case, this leads to

$$F_T = [W]_{\text{vertical down weight}} + [0.3/1.4\ W]_{\text{horizontal EW or NS}} + [0.08/1.4\ W]_{\text{vertical up or down}}$$

$$F_T = [1\ (\text{+or-})\ 0.06]\ W_{\text{vertical down}} + 0.21\ W_{\text{EW or NS}}$$

S302 – DESIGN METHOD

Given that (a) the piping is 6” and 2”, (b) the lateral acceleration is 0.21g, and (c) the piping system is critical, then – according to table S302-1 – the piping system may be qualified by design rules. However, for the purpose of illustration, the system will be qualified by analysis, with notes (2) and (3) from Table S302-1:

Note (2) Detailed seismic design of braces is required for critical piping systems, and will be addressed in section S306.
Note (3) Operability is required, and will be addressed in section S308.

S303 – DESIGN BY RULE

This section is not applicable.

S304 - DESIGN BY ANALYSIS

S304.1 – PIPING MODEL INPUT

P&ID: Figure C-2,enclosed.

Isometric: Figure C-3.

Piping:
Pipe size and schedule: 6" NPS, with a 2" NPS, schedule 40.
Pipe material specification and grade: ASTM A 106 Grade B carbon steel.
Joints: Welded.
Linear weight of pipe contents and insulation:
Contents = steam = 0 lb/ft.
Insulation = 1" calcium silicate.
Valves:
Two 6" manual gate valves. Make ABC,model ABC, Class 300.
Weight: 320 lb each, center of gravity approximately at pipe centerline.
One 2" manual gate valve. Make DEF, model DEF, Class 300.
Weight: 74 lb, center of gravity approximately at pipe centerline.

Equipment flexibility: Local flexibility (nozzle, shell), and global flexibility (equipment support): to be included in the piping system model.

S304.2 – PRELIMINARY SEISMIC DESIGN

We would first place a seismic lateral support (sway brace) every forty feet. In this case, since the pipe span between vessel and heat exchanger is only 45 ft long, the preliminary design does not dictate lateral bracing. Yet, because of the heavy weight of valves V1 and V2, and because it is straightforward to make A02 a vertical (active two-way: up and down) and lateral support, we will preliminarily specify a vertical two-way (up and down) plus lateral support at A02. This will also preclude the 6" header from swaying excessively and causing an overstress in the 2" branch line, which is fixed at a floor penetration at point B04.

We may need a lateral support close to valve V2, but because of its elevation, such a support would be more difficult and costly to erect. We will therefore postpone the decision for seismic bracing valve V2 until the detailed analysis stage.

There are no large valve operators, and therefore no eccentric weights to support. The manual valves have a center of gravity close to the pipe centerline.

S304.3 - ANALYSIS MODEL

The piping system is modeled as shown in Figure C-3.
Nozzle flexibility, developed in accordance with WRC-297 (common subroutine in piping analysis software) is included at the equipment nozzle connections A00 and A13.
A02 is modeled as a rigid support.
A06 is modeled as a variable spring.
Wall penetration B04 is modeled as a full anchor.

Thermal and radial growth of the vertical vessel are applied at node A13.
The thermal growth at the heat exchanger (A00) and wall penetration (B04) are negligible.
The seismic movement at the vertical vessel (A13), the heat exchanger (A00) and the wall penetration (B04) are calculated to be negligible.

The system is analyzed for weight (W), pressure (P), thermal expansion (T) and three dimensional (X, Y and Z) seismic response spectra (S).

S304.4 – ANALYSIS OUTPUT

The analysis output consists of loads (forces and moments), displacements (translations and rotations), accelerations and ASME B31 stresses at each node point. Following is a summary of key output values, where P = pressure, W = weight, T = thermal expansion, S = seismic.

Forces (lb) and Moments (in-lb) at Nozzles and Supports

Point	Load	FX	FY	FZ	MX	MY	MZ
A00	W	-31	-87	-10	-144	4	-6
	T	-288	7	429	-145	-125	0
	S	97	31	10	280	3	5
A02	W	0	-590	64			
	T	-157	450	477			
	S	67	93	114			
A06	W	0	-646	0			
	T	0	108	0			
	S	0	3	0			
A13	W	31	-280	-18	-919	-201	-322
	T	238	172	68	390	-467	-53
	S	117	35	92	241	435	90
B04	W	0	-48	-36	-35	0	1
	T	50	-130	-946	-1422	98	-86
	S	5	7	10	13	3	8

Accelerations (g) at Valve Nozzles

Point	a_X	a_Y	a_Z
A02	0.2	0	0
A11	0.2	0.1	0
A07	4.8	1.1	4.7
A12	4.8	1.2	3.5

Points of Maximum Stress (psi)

Point	Load Case	Stress
B05	P + W	4,372
B04	T	30,568
B05	P + W + S	5,121
A03	P	4,592

S304.5 - EVALUATION

Movements: All displacements are reviewed and found to be reasonable (weight and thermal as predicted, seismic not too large) and not to lead to interference.

Support Loads: The loads at supports (A02 and A06) will be used to design and size the supports (S306).

Equipment Nozzle Loads: The forces and moments at equipment nozzles (A00 and A13) are evaluated by comparison to vendor allowable limits. For vessels, if vendor allowables are not available, the nozzle loads may be evaluated following the rules of ASME Boiler and Pressure Vessel Code section VIII Pressure Vessels, TEMA (for heat exchangers), or WRC 107, or WRC 297.

Accelerations: In many cases, valve actuators (AOV or MOV) will have acceleration limits for structural integrity or operability. These acceleration limits are usually in the order of 3g to 5g resultant (SRSS of X, Y and Z acceleration at the center of gravity of the actuator). In the case of this example, the specification imposes no acceleration limits because the valves have manual actuators (hand wheel) that are not sensitive to seismic acceleration.

Pipe Stress: The computer program automatically calculates the ASME B31 code stress, in this case the maximum stresses are

$$PD/(4t) + 0.75i\,(M_A + M_B)/Z = 5{,}121 \text{ psi}$$

P = operating pressure, psi
D = pipe outside diameter, in
t = pipe wall thickness, in
M_A = resultant moment from deadweight, in-lb
M_B = resultant moment from seismic loads, in-lb
Z = pipe section modulus, in^3

The maximum seismic stress is

$$i\,(M_i^2 + M_a^2)\,/\,Z = 749 \text{ psi} << 1.5\,S_Y = 52{,}500 \text{ psi}$$

S305 – MECHANICAL JOINTS

The system is welded, there are no mechanical joints in the system.

S306 – SEISMIC BRACING AND ANCHORAGE

Pipe and equipment supports are sized, analyzed and qualified in accordance with the following codes and standards:

Standard catalog supports: In accordance with supplier load rating.
Steel members and welds: AISC manual of Steel Construction.
Concrete anchor bolts: ACI 318 Appendix D.

S307 – STATIC EQUIPMENT

The vertical vessel and the horizontal heat exchangers are static equipment (no moving parts). Their seismic qualification is excluded from the scope of this application. Their supports have been qualified in section S306. Loads at nozzles have been developed in S304.4 and will be reported to the vessel and heat exchanger designer for approval.

S308 – ACTIVE EQUIPMENT

There is no active equipment in this application. The manual valves are cast steel, and verified to be stronger than the pipe.

S400 – INTERACTIONS

This section is excluded from the scope of work.

S500 – DOCUMENTATION

(a) Drawing showing the scope of work: Figures C-1, C-2, C-3.
(b) Final pipe support arrangement: Figure C-3.
(c) Calculations showing design input and compliance with the requirements of the Project Specification for piping, equipment, and supports: (computer analysis input-output would be enclosed).

(d) Documentation of qualification of equipment operability where applicable: Not applicable.

(e) Drawings for new or modified supports, with dimensions, weld and anchor bolt details, bill of materials, and sufficient information for material procurement and construction: (would be enclosed).

S600 – MAINTENANCE

This section does not apply.

S700 – REFERENCES

ASME B31.3 Process Piping, for design, materials, fabrication, examination and testing, latest edition.
International Building Code, latest edition.
AISC Manual of Steel Construction.
ACI 318 Appendix D Anchoring to Concrete.
ASTM A 106 Seamless Carbon Steel Pipe for High Temperature Service.
Vendor catalogs (would be listed).

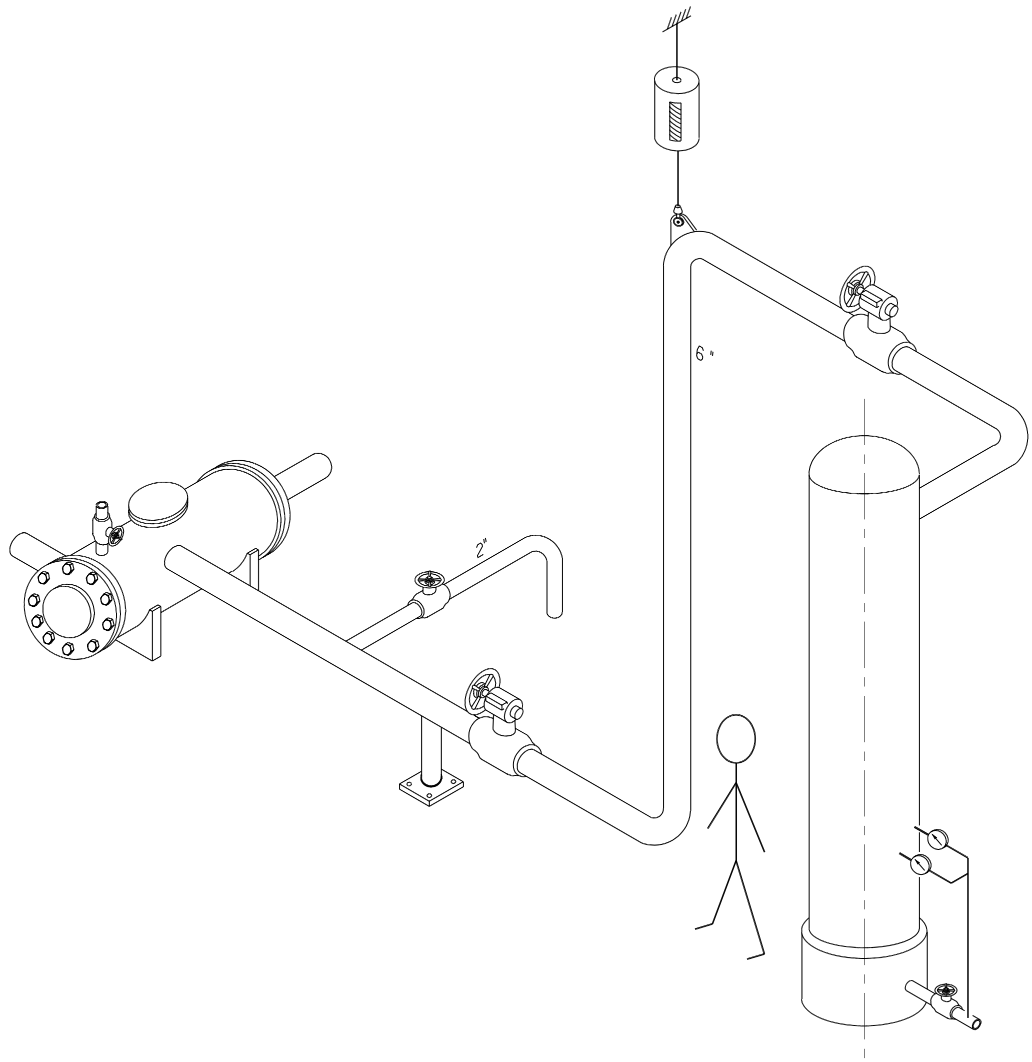


Figure C-1 Illustration of Example 1 Piping System

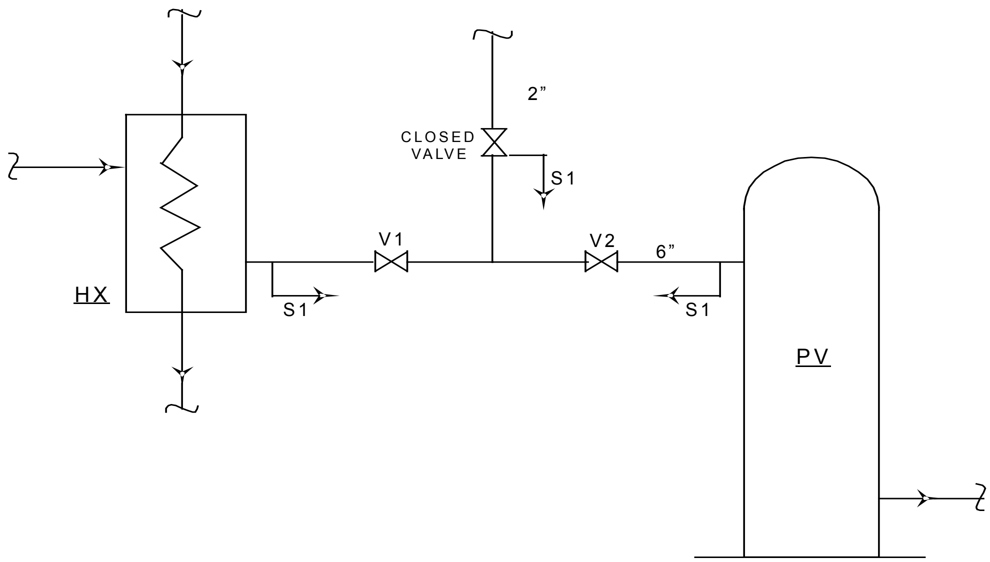


Figure C-2 P&ID Diagram pf Example 1 System

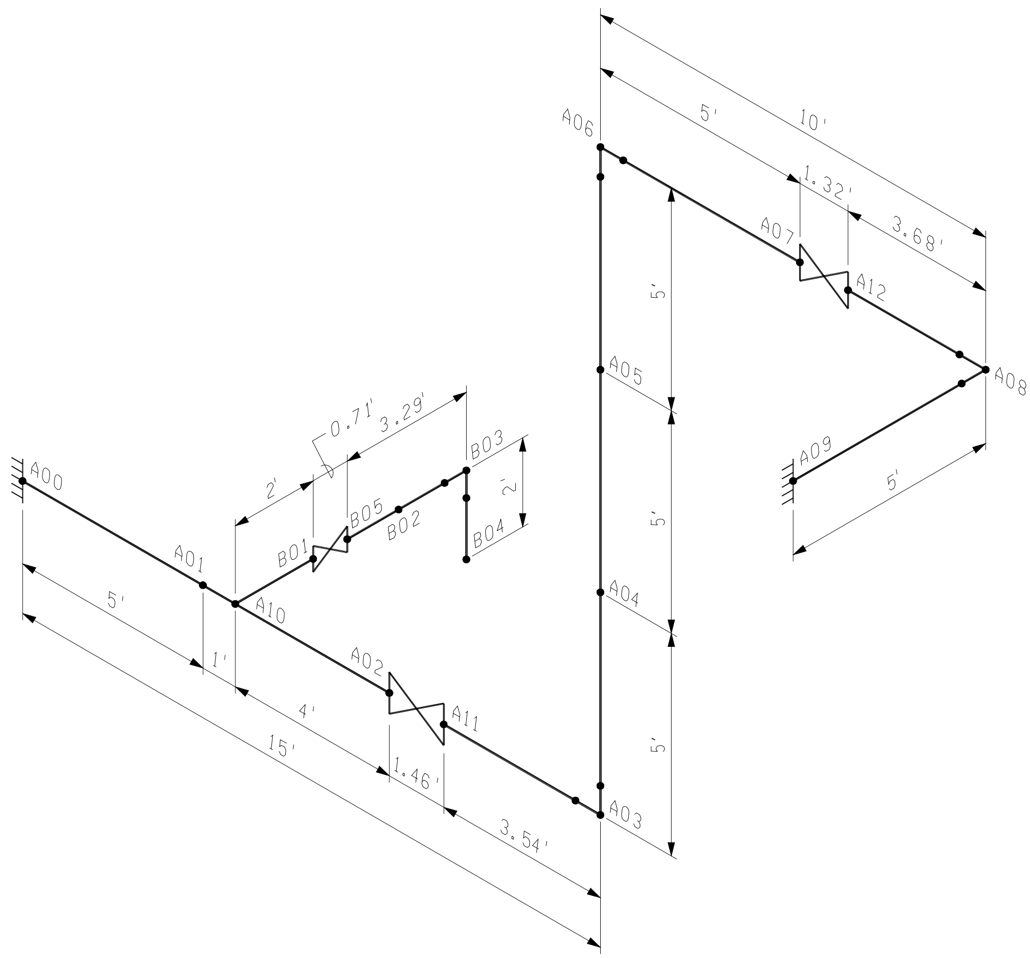


Figure C-3 Isometric of Example 1 Piping System

APPENDIX D - SESIMIC RETROFIT EXAMPLE

S100 - PURPOSE

To illustrate the application of ASME B31S to a nitrogen gas supply system. The system consists of

(1) The cryogenic, liquid nitrogen vessel.
(2) Liquid nitrogen stainless steel pipe to the vaporizer.
(3) Gas nitrogen carbon steel pipe to the building penetration.

S101 - SCOPE

The piping has been designed for normal operating loads (pressure, temperature, weight) in accordance with the ASME B31.3 Process Piping code. The pipe size is 2" sch.40.

The piping has been constructed (materials, welding, NDE and hydrotesting) in accordance with ASME B31.3 Process Piping system.

S103 – OWNER'S REQUIREMENTS

(a) The scope and boundaries of piping systems to be seismically retrofitted is from the liquid nitrogen vessel, through the vaporizer J-L, to the building penetration AI, as shown in Figure 9.2-1.
(b) The applicable code is ASME B31.3.
(c) The pipe is considered "critical". The system is required to operate following the earthquake.
(d) The free field seismic input is to be obtained from IBC-2000.
(e) The in-structure seismic response spectra is to be obtained from IBC-2000 (1 + 2z/h amplification factor for elevation).
(f) The operating and design conditions concurrent with the seismic load:
The liquid pipe (vessel to vaporizer) operates at -250 ^{o}F and 250 psi.
The gas pipe (vaporizer to building penetration) operates at 80 ^{o}F and 250 psi.
(g) The seismic evaluation must address seismic interactions.
(h) The system is already installed, so there is no need for as-built reconciliation of procurement and construction deviations.

S200 – MATERIALS

S201 – APPLICABILITY

The pipe from the vessel to the vaporizer is ASTM A372 type 316, used above the minimum permitted temperature, per ASME B31.3 table A-1. The gas pipe (vaporizer to building) is carbon steel ASTM A 106 Grade B. All joints are welded, except for vaporizer inlet and outlet flanges.

S202 – RETROFIT

The piping system was walked-down and inspected for material condition. The inspection report is enclosed, in Appendix A.

S300 – DESIGN

S301 - SEISMIC INPUT

The horizontal load is developed based on IBC-2000

$F_P = (0.4\ a_P\ S_{DS}\ I\ /\ R_P)\ (1 + 2z/h)\ W$
$a_P = 1.0$
$S_{DS} = 0.8g$
$I = 1.5$
$R_P = 3.5$
$z = h/2$
Therefore, $F_P = 0.27\ W$
But F_P can not be less than $0.3\ S_{DS}\ I\ W = 0.36\ W$
The applied lateral acceleration is therefore 0.36 g.

Note that z = h/2 because part of the piping runs along mid-height of the building exterior wall.

The vertical acceleration is $0.2\ S_{DS} = 0.16$ g

S302 – DESIGN METHOD

Given that (a) the pipe is 2", (b) the lateral acceleration is 0.36g,and (c) the piping system is critical, then – according to table S302-1 – the piping can be seismically designed by rule, with notes (2) and (3) from table S302-1:

Note (2) Detailed seismic design of braces is required for critical piping systems, and will be addressed in section S306.
Note (3) Operability is required, and will be addressed in section S308.

S303 – DESIGN BY RULE

Upstream from the vaporizer (liquid side): The longest span of pipe is 11 ft (from tie-back support E to vaporizer inlet flange J). There are two extended stem manual valves (F and G) on this 11-ft section. They weigh 10 lb each, or the equivalent of 4 ft of 2" sch 40 liquid-filled pipe (5.15 lb/ft). The total length of pipe (11 ft) plus equivalent length of the two valves (4 ft) is within the 20-ft span, well within the 20-ft guideline for liquid filled pipe.

Downstream from the vaporizer (gas side): The longest span is 9 ft (from AB to AD). The pipe spans are within the 30-ft guideline for gas pipe.

The two relief valves at location C weigh 30 lb each. The maximum unintensified bending stress at the bottom of the 3-ft riser is

$$M/Z = 30 \text{ lb} \times 24\text{"} / 0.56 \text{ in}^3 = 1286 \text{ psi}$$

The seismic bending stress is well below the allowable seismic stress, acceptable.

Since we did not add seismic braces, we have not modified the flexibility of the liquid section which operates at – 250 ^{o}F.

S304 - DESIGN BY ANALYSIS

Stress analysis of the piping system is not required, in accordance with section S302.

S305 – MECHANICAL JOINTS

All piping joints are either welded or flanged with ASME B16.5 class 150 flanges. The pressure gage at Z is welded.

S306 – SEISMIC BRACING AND ANCHORAGE

Liquid side: The resultant load on the tie-back support at E is

$$\tfrac{1}{2} \{(11 \text{ ft} + 4 \text{ ft}) \times (5.15 \text{ lb/ft}) \times [(0.36 \text{ g})^2 + (0.16 \text{ g})^2]^{0.5}\} = 15 \text{ lb}$$

The load is well within the capacity of the brace and its weld to the tank structure.

Gas side: The resultant load on each strut in regulator station Q-to-X is

$$\tfrac{1}{2} \times \tfrac{1}{2} \times 30 \text{ ft} \times 5.15 \text{ lb/ft} \times [(0.36 \text{ g})^2 + (0.16 \text{ g})^2]^{0.5} = 15 \text{ lb}$$

The load is well within the capacity of the strut, its base plate and anchor bolts.

Gas side: The load on the finger clamps on the building wall (AB, AD, AE, AF, AH) is

$$\tfrac{1}{2} \times 9 \text{ ft} \times 5.15 \text{ lb/ft} \times [(0.36 \text{ g})^2 + (0.16 \text{ g})^2]^{0.5} = 9 \text{ lb}$$

The load is within the catalog 100 lb load capacity of the finger clamp.

S307 - STATIC EQUIPMENT

The seismic evaluation of the vessel and of the vaporizer would be conducted in accordance with ASME and IBC codes. Their anchorage would be analyzed per ACI 318 Appendix D.

S308 - ACTIVE EQUIPMENT

Per Owner Requirement (c) in section S103, the system is to remain functional, capable of delivering gas to the building during and following the earthquake.

Pressure Regulators: There are two self-actuated pressure regulators on the gas side (U and T) which are to remain in the normal operating condition during and following the earthquake. The regulators are to remain functional (should not fail close or open). They are qualified by comparison to similar valves shake table tested per ICBO ACI 156 at an input response spectrum larger than the facility ground spectrum.

Liquid Pressure Relief Valves: There are two liquid pressure relief valves (D). They may not fail open, which would deplete the vessel contents. They are qualified by comparison to similar valves shake table tested per ICBO ACI 156 at an input response spectrum larger than the facility ground spectrum.

Gas Pressure Relief Valve: There is one gas pressure relief valve at P. It may not fail open, which would deplete the vessel contents. It is qualified by comparison to similar valves shake table tested per ICBO ACI 156 at an input response spectrum larger than the facility ground spectrum.

Manual Valves: There are two extended stem manual valves (F and G) they are to remain as-is (open). The stem and hand wheel are light weight, and the open gate valve acts as a passive component, which – if it was to fail – would fail in-place (binding).

Plug and Check Valves: Considered passive components, would fail in place (acceptable).

S400 - INTERACTIONS

As indicated in the walkdown inspection report, in Appendix A, two potentially credible and significant spatial seismic interactions have been identified:
(1) The building block wall.
(2) The second vessel.

These potential interactions must be analyzed to determine whether they could collapse on the system.

S500 - DOCUMENTATION

(a) Drawings are enclosed (Figures 1 and 2).
(b) Final pipe support arrangement is shown in Figure 2. The installed configuration is acceptable as-is.
(c) Calculations are documented in this report.
(d) Operability (here, provide documentation of operability test or analysis of valves).
(e) The installed supports are acceptable as-is. No new support drawings are required.

S600 – MAINTENANCE

All supports have been tagged to read “seismic support – do not modify”. Plant drawings have been marked to indicate “seismic system – do not modify without engineering approval”.

S700 - REFERENCES

ACI 318 Building Code Requirements for Reinforced Concrete, American Concrete Institute.

AISC, Manual of Steel Construction, American Institute of Steel Construction.

ASME B31.3, Process Piping, American Society of Mechanical Engineers, New York, NY.

IBC, International Building Code, International Code Council, Falls Church,VA.

APPENDIX A
WALKDOWN INSPECTION REPORT

SYSTEM
NITROGEN SUPPLY TO BUILDING XYZ

The system maintenance history is satisfactory	Yes (1)
The fittings are standards (ASME B16)	Yes
There are no missing parts on components.	Yes
There is no visible damage, scratches, gouges, distortion, etc.	Yes
The welding is of good quality (visual)	Yes
The flange gaskets have a good record	Yes (1)
The pipe is not dislodged from its support	Yes
The pipe supports are in position	Yes
There are no missing parts on pipe supports	Yes
There is no damage to the building attachment	Yes
There is no visible material degradation	Yes
There is no evidence of leakage	Yes
The operating record indicates no degradation	Yes (1)
The metallurgical review indicates no cause of degradation	Yes (2)
There are no adverse anchor motions	Yes (4)
Equipment is well anchored	Yes (3)
There is no differential motion of support attachments	Yes (4)
There is no large motion of header against a stiff branch	Yes
There is no differential soil settlement	Yes (5)
There are no friction joints in the piping system	Yes
The flange joints have the right rating	Yes
There are no eccentric weights	No (6)
There are no credible or significant interactions	No (7)

Walkdown by: date:
Walkdown by: date:

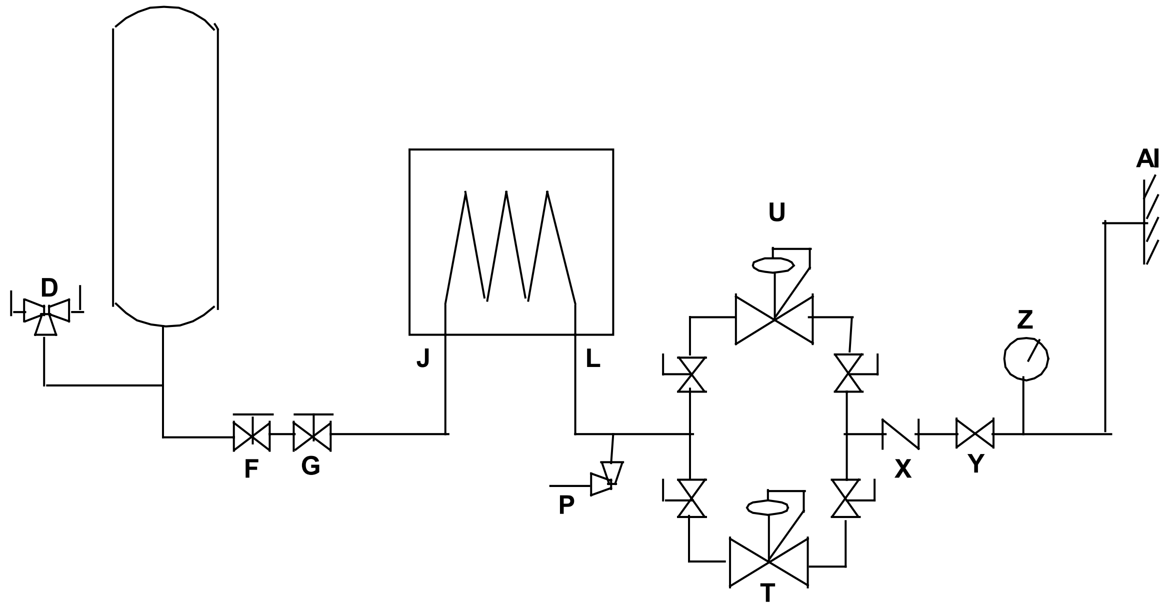
Field Notes:

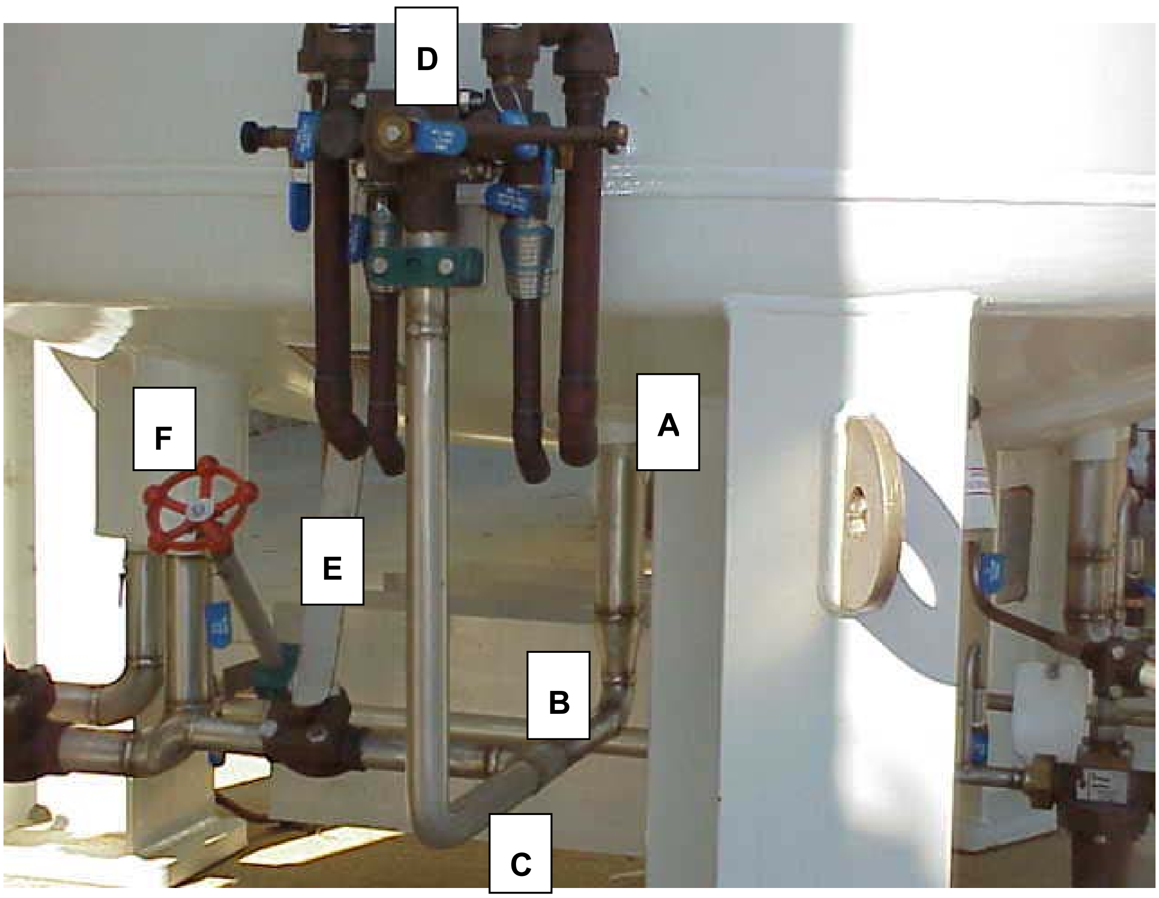
(1) Per input from XYZ, system maintenance mechanic, date X/Y/Z.
(2) Per input from ABC, system supplier from experience with same systems, date X/Y/Z.
(3) Vessel and vaporizer must be evaluated.
(4) Per input from building analysis, ref. DEF, date X/Y/Z.
(5) Per geotechnical evaluation ref. DEF, date X/Y/Z.
(6) The cantilevered pressure relief valves at location C weigh 30 lb each. To be evaluated.
(7) Two potentially credible and significant spatial seismic interactions have been identified: The building block wall, and the second vessel. They need to be evaluated.

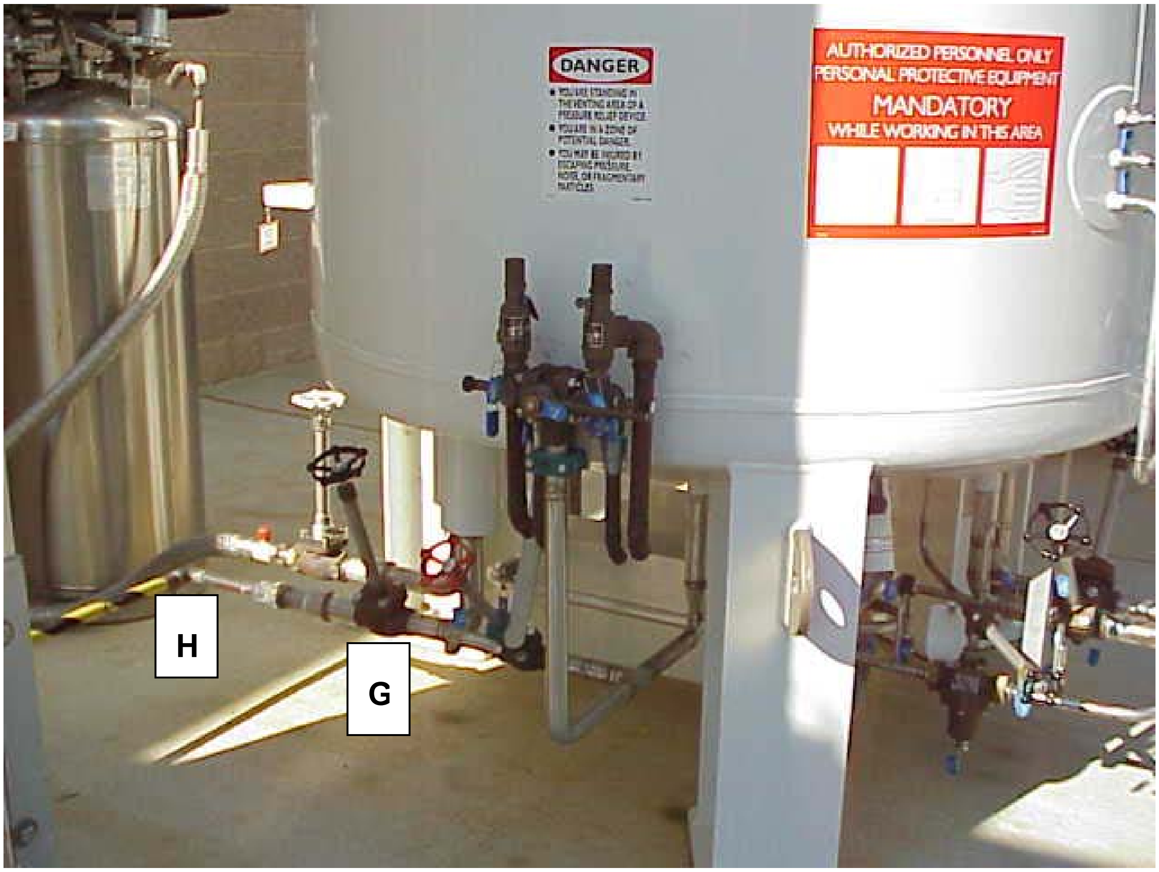
Photo Notes:

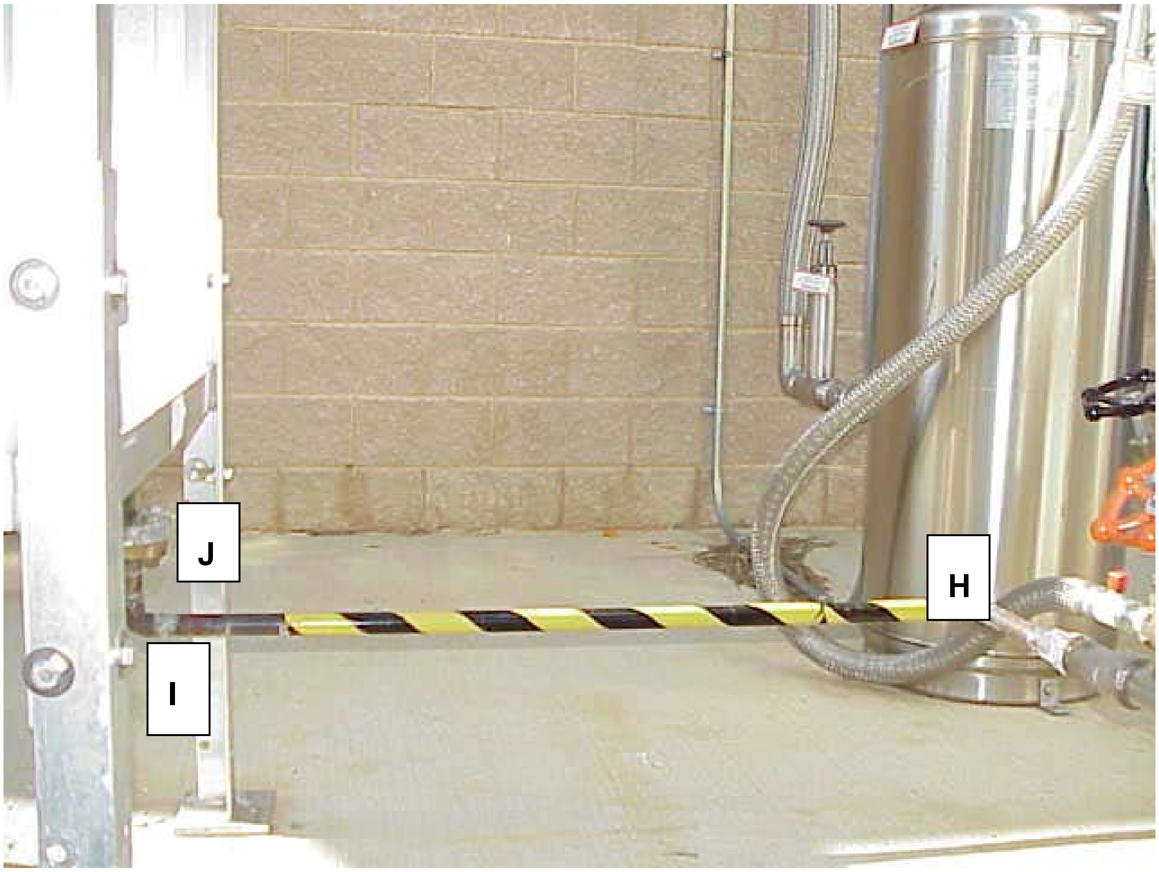
General view of liquid nitrogen vessel (forefront) and vaporizer (left of vessel).
Vessel nameplate data: U stamp, NB number XYZ, manufacturer XYZ, MAWP 350 psi.
A = liquid nitrogen vessel outlet
B = reducer and elbow on 3”x2” outlet pipe
C = elbow on 2” pipe (stainless steel ASTM A372 type 316)
D = dual liquid relief valves
E = tie-back support pipe-to-tank
F = first extended stem gate valve, make XYZ, model XYZ, size XYZ, rating XYZ
G = second extended stem gate valve, make XYZ, model WYZ, size XYZ, rating XYZ
H = elbow
I = elbow to vaporizer
K = vaporizer
J = vaporizer inlet flange class 150
L = vaporizer outlet flange class 150
M = gas pipe elbow (carbon steel ASTM A106 Grade B)
N,O = pipe elbow
P = gas relief valve
Q = tee
R,S = elbows, two plug valves, make XYZ, model XYZ, size XYZ
U,T = self-actuated regulators, make XYZ, model XYZ, size XYZ
V,W = elbows, two plug valves, make XYZ, model XYZ, size XYZ
X = check valv, make XYZ, model XYZ, size XYZ
Y = plug valve, make XYZ, model, XYZ, size XYZ
Z = pressure gage, make XYZ, model XYZ, reading XYZ psi, scale range XYZ psi
AA = elbow
AB, AD, AE, AF, AH = pipe clamps on two-bolt strut, make XYZ, size XYZ
AI = building penetration

Figure D-1 System Schematic




D
A
F
E
B
C


DANGER
AUTHORIZED PERSONNEL ONLY
PERSONAL PROTECTIVE EQUIPMENT
MANDATORY
WHILE WORKING IN THIS AREA
H
G


J
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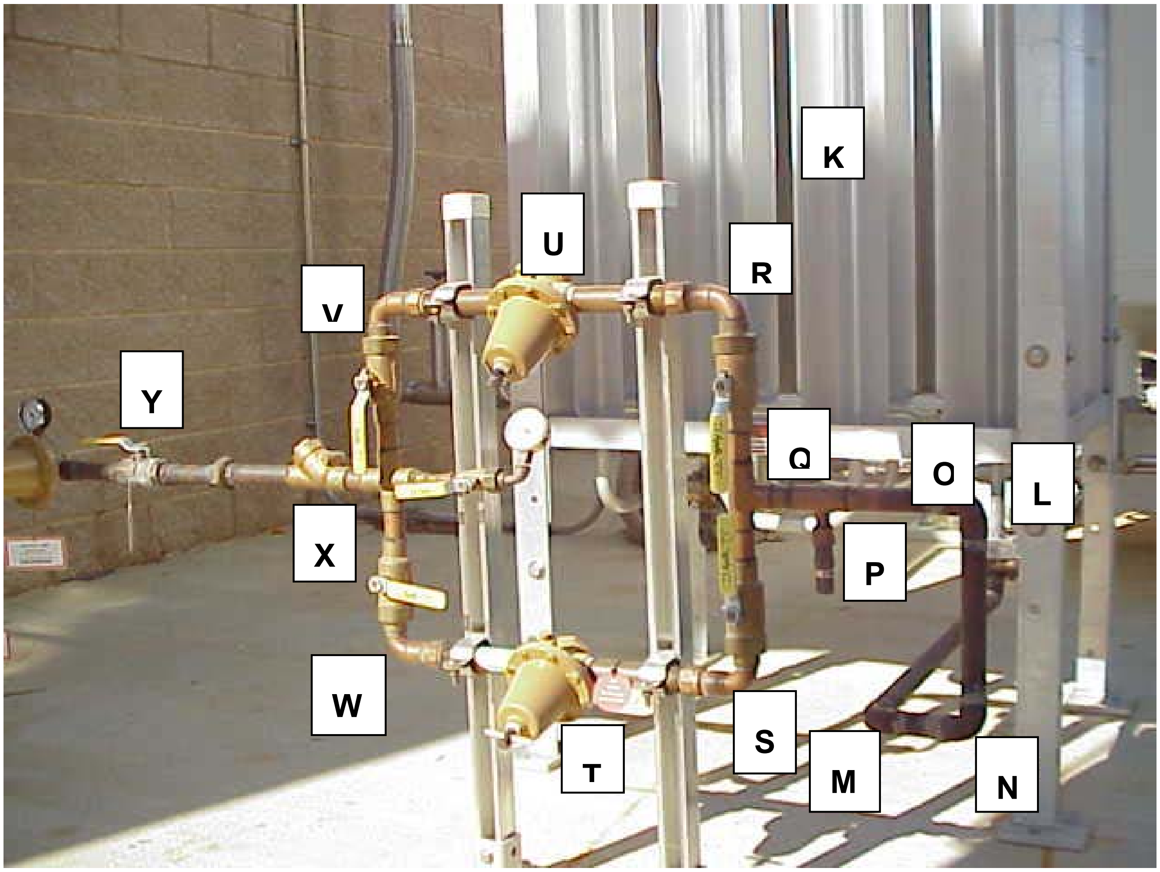
K
U
R
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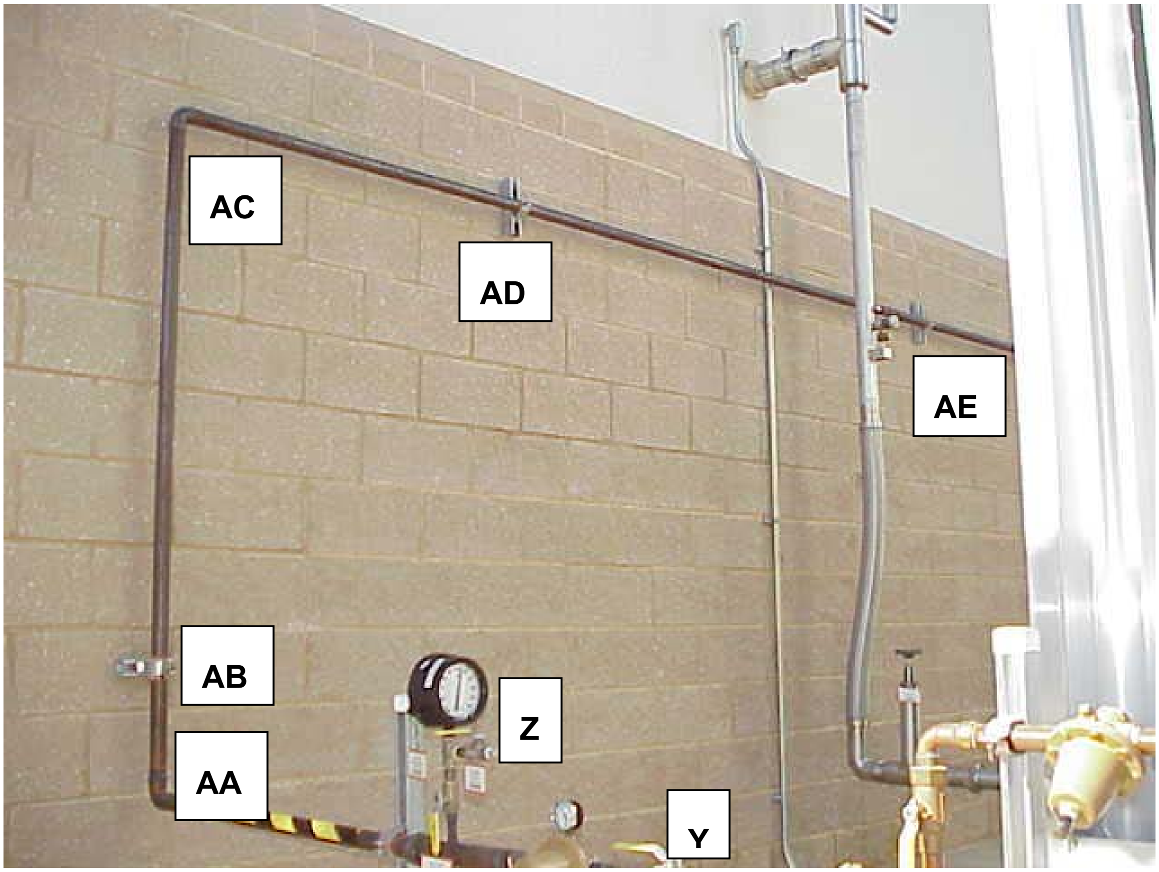
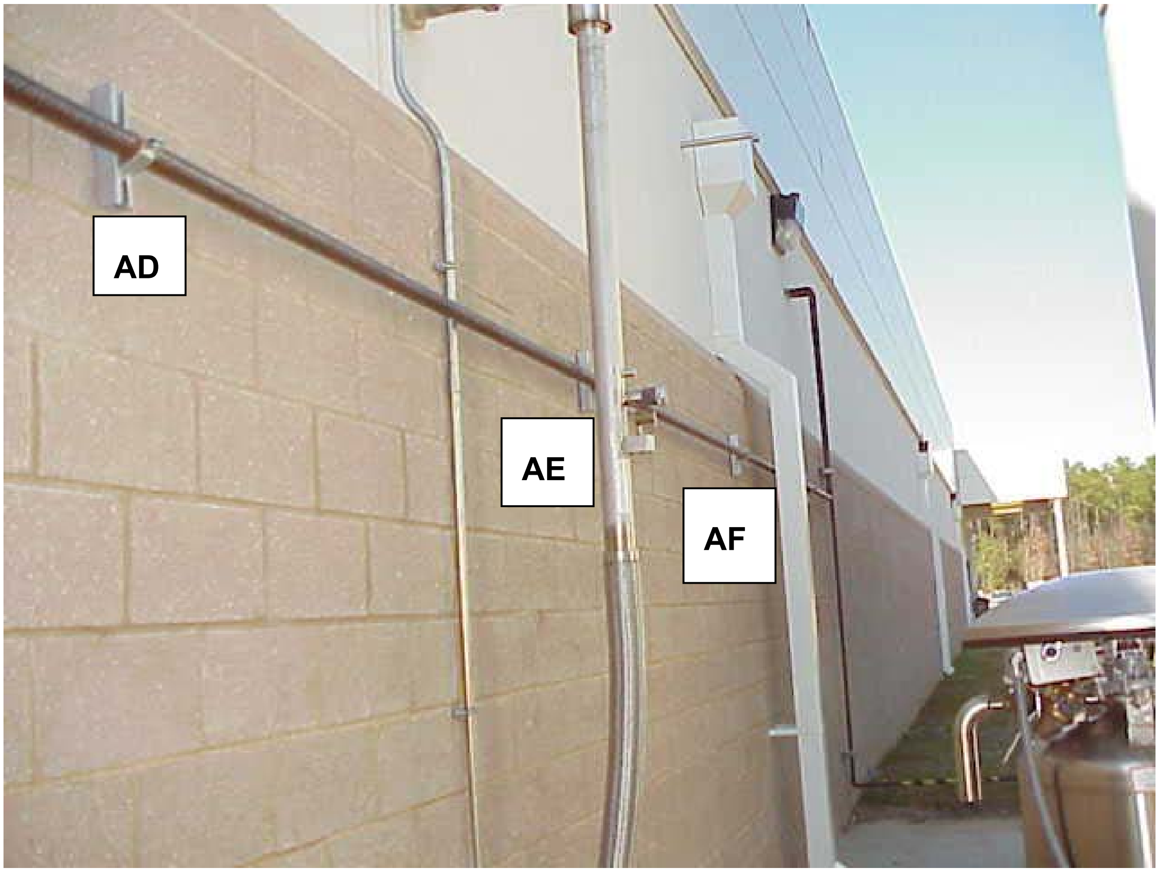
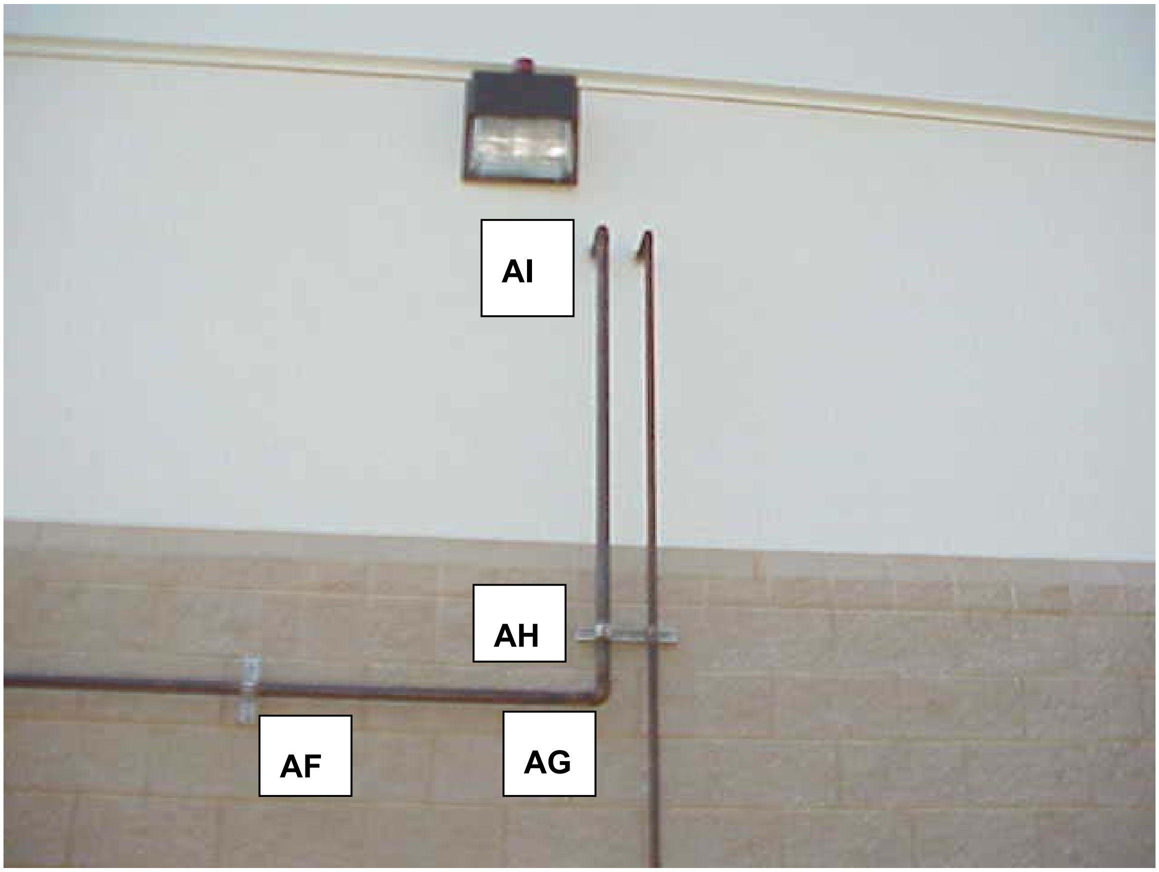

AC
AD
AE
AB
Z
AA
Y


AD
AE
AF


AI
AH
AF
AG