AmericanLifelinesAlliance

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

Guide for Seismic Evaluation of Active Mechanical Equipment

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AmericanLifelinesAlliance
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1.0 Introduction

The Federal Emergency Management Agency (FEMA) formed in 1998 the American Lifelines Alliance (ALA) as a public-private partnership. In 2002, FEMA contracted with NIBS through its Multihazard Mitigation Council (MMC) to, among other things, assist FEMA in continuing ALA earlier guideline development efforts. In 2004, ALA requested George A. Antaki, PE, to develop a complete and practical Guide to help engineers evaluate and qualify the seismic adequacy of mechanical equipment relied upon to perform critical functions in case of earthquake. For example, how to seismically qualify a pump that must provide fire suppression water, a compressor that must supply critical gases in a hospital, a valve that must close to isolate a toxic or flammable spill, or a chiller unit that must function to maintain a critical cooling function.

1.1 Project Objective

The purpose of this Guide is to provide recommendations for evaluating the seismic operability of valves, pumps compressors, fans, air handling units, and chillers. The recommendations are in the form of seismic evaluation checklists, static and dynamic calculation methods and seismic testing protocols.

The Guide provides the background and technical basis for the proposed seismic evaluation methods. This background consists of equipment descriptions, analytical experience, seismic test experience, lessons learned from earthquake investigations, and observations of operating failure modes and equipment maintenance.

The Guide covers the seismic adequacy of the equipment itself, but does not address its power supplies, instrumentation and controls. These need to be addressed separately, if the equipment is required to operate during or after the earthquake.

1.2 Project Scope

Chapter 2 of the guide addresses the principles of seismic equipment engineering and provides a review of existing seismic qualification methods and standards.

Chapters 3 to 7 address the five classes of active mechanical equipment: Valves (Chapter 3), Pumps (Chapter 4), Compressors (Chapter 5), Fans and Air Handling Units (Chapter 6), and Chillers (Chapter 7).

Each one of these equipment chapters is structured in a consistent manner and addresses, in order: (1) equipment description, (2) equipment performance during earthquakes, (3) equipment performance in seismic tests, (4) methods, rules and limitations of seismic analysis, and (5) equipment vulnerabilities based on common – non-seismic – operation and failures (corrective maintenance). Each equipment chapter concludes with a seismic attributes checklist.

In addition, the guide includes two chapters that apply to all classes of equipment: anchorage to concrete (Chapter 8) and evaluation of seismic interactions (Chapter 9).

The seismic attributes checklist, together with the support and anchorage checks of Chapter 8 and the interaction checks of Chapter 9, constitute the basis for seismic qualification of the equipment.

1.3 Notations

A = pump casing diameter
a_x = lateral acceleration in x direction at the operator center of gravity, g's
B_1; B_2 = distance from projection of center of gravity onto rectangular base to both edges, in
D = pipe outside diameter, in
D = Shaft diameter at seal, in
D_b = Shaft diameter between beams, in
D_g = mean gasket 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 of member due to its weight plus the weight of the falling body, lb
f_a = Swing (sway) frequency, 1/sec (Hz)
g = gravity = 386 in/sec^2
H = height of fall, in
H = height of center of gravity above base, in
h = height of free fall, in
k = factor given in piping design code, ranges between 1.2 and 3
k = stiffness of elastic member, referenced to point of impact, lb/in
k = ratio of vertical acceleration to horizontal acceleration
k = bolt safety factor
L = distance from operator center of gravity to weak section, in
M = applied moment, in-lb
M_w = resultant moment due to sustained loads (typically weight), in-lb
M_S = resultant moment due to earthquake, in-lb
P = operating pressure concurrent with earthquake, psi
P = applied tension on bolt, lb
P_{eq} = equivalent pressure, psi
P_C = tensile capacity, lb
P_N = nominal tensile capacity (pullout strength), lb
P_U = mean measured strength, lb
S = ASME B31 allowable stress, psi
S_a = acceleration at frequency f_a, in/sec^2
S_m = ASME III code material allowable stress intensity, psi
S_u = material ultimate strength, psi
S_y = material yield stress, psi

T = distance between the impeller-side bearing and the seal, in

t = pipe wall thickness, in

V = Applied shear on bolt, lb

V_H = horizontal spectral velocity, in/sec

V_u = ultimate shear capacity, lb

V_V = vertical spectral velocity, in/sec

W = weight of falling body, lb

W_b = weight of elastic member, lb

W_P = component operating weight, lb

W_V = valve weight, lb

$X_{AS};Y_{AS}$ = anchor spacing penalty factors for tension and shear

$X_{CC};Y_{CC}$ = concrete cracking penalty factors for tension and shear

$X_{CS};Y_{CS}$ = concrete strength penalty factors for tension and shear

$X_{ED};Y_{ED}$ = edge distance penalty factors for tension and shear

$X_{EM};Y_{EM}$ = embedment length penalty factors for tension and shear

$\ddot{x}_b$ = peak horizontal excitation at base, in/sec^2

Z = pipe section modulus, in^3

σ = standard deviation of measured strengths, lb

γ = slenderness ratio

ω = natural pulsation of the swing = $2\pi f_a$ 1/sec

2.0 Seismic Equipment Engineering

The objective of seismic equipment engineering is to evaluate and qualify structures, systems, equipment and components for seismic function during or following an earthquake. Structures, systems, equipment, and components, may be classified as illustrated in Figure 2.2-1. Structure refers to buildings, structural frames, and equipment and component supports. Equipment and component supports may include steel members anchored to concrete or masonry, or welded to larger steel frames.

In Figure 2.2-1, systems, equipment and components can further be classified as electrical, instrumentation and controls, and mechanical. Although this guide is limited to mechanical systems, the seismic function of these mechanical systems will also depend on electrical systems that provide power to activate the equipment, and instrumentations and controls that govern the active functions. The Guide covers the seismic adequacy of the equipment itself, but does not address its power supplies, instrumentation and controls. These need to be addressed separately, if the equipment is required to operate during or after the earthquake.

In practice, the terms equipment and component are often used interchangeably. For the purpose of this guide, *equipment* will refer to a large unit, often floor or ground mounted, such as a compressor or a pump; while *component* will refer to either part of an equipment (for example a pump impeller) or an in-line mounted item (for example a valve or strainer). For the purpose of this guide, a mechanical system is an assembly of mechanical equipment and components meant to deliver and control the flow of fluids: liquids, vapors, gases, slurries, or mixtures (such as vapor and condensate, or liquid and gas).

As illustrated in Figure 2.2-1, mechanical equipment can be subdivided into static and active (the latter also referred to as dynamic or rotating). Static equipment include tanks (storage units with a design and operating pressure below 15 psig), pressure vessels (with a design and operating pressure above 15 psig), piping (including tubing, piping systems, pipelines), and ducts.

A simple definition of active equipment is equipment that has moving parts or controls. This guide covers the most common classes of active mechanical equipment: valves (and their operators), pumps, compressors, fans and air handling units, and chillers.

A more elaborate definition is provided in ASME QME-1, Qualification of Active Mechanical Equipment Used in Nuclear Power Plants, which defines active equipment as “equipment containing moving parts, which in order to accomplish its function, must undergo mechanical movement of those parts, or must prevent a movement of those parts to ensure that the equipment will remain in its last position”.

A seismic qualification activity must have (1) a clearly defined scope boundary for the system, equipment or component and its supports, and (2) a clearly stated seismic function. For mechanical systems and equipment, this seismic function is best specified as (a) position retention, or (b) leak tightness, or (c) operability.

To successfully undertake a seismic design or retrofit project, and optimize safety and cost, a ten step process should be followed, illustrated in Figure 2.0-1, and described below.

Step 1 – Facility safety objective: State the post-earthquake safety objective to be achieved. For example, the safety objective may be the evacuation of an industrial building, the confinement of toxic materials contained in a tank, the shutdown of a chemical reactor, the supply of critical gases to certain rooms in a hospital, etc.

Step 2 – Facility seismic scenario: Describe the environment following the earthquake. As a minimum consider the following conditions, further detailed in Section 2.1.

Offsite power	Consider two cases; (1) offsite power may be lost for up to three days, (2) offsite power may not be lost.
Seismic induced fire	The earthquake may cause a fire, unless a seismic fire hazard analysis establishes otherwise.
Non-qualified equipment	Non-seismically qualified equipment may not function or may malfunction, and should not be relied upon for post-earthquake. Non-qualified tanks, vessels and piping: non-seismically qualified tanks, vessels and piping may leak or break.
Operator action	Operators may be relied upon to perform post-earthquake functions provided these are (i) feasible, (ii) documented in emergency response procedure, and (iii) periodically drilled.

Step 3 – System Scope: List systems and subsystems that must be qualified to accomplish the functions listed in Step 1, under the environment defined in Step 2. Preferably, define the scope boundaries on system diagrams.

Step 4 – Equipment List: Prepare a list of each equipment and component in scope, as described in Sections 2.1.

Step 5 – Performance Category: For each equipment and component in the equipment list, state the required function. The function should be defined as position retention (does not fall or overturn), or leak tightness (does not leak), or operability (operates, functions, delivers or controls flow), as described in Section 2.1.

Step 6 – Qualification Method: Select the qualification method, as described in Section 2.1.2.

Step 7 – Seismic Input: Obtain or develop the seismic input, as a seismic static coefficient or a seismic response spectrum, as discussed in Section 2.2.

Step 8 – Qualification: Perform the seismic evaluations. For active mechanical equipment, apply the methods described in the individual equipment chapters of this report, Chapters 3 to 7, and the anchorage rules of Chapter 8.

Step 9 – Interaction review: Evaluate seismic interactions that could affect the integrity or operability of the equipment, as described in Chapter 9.

Step 10 – Documentation: Provide complete, clear and retrievable documentation.

2.1 Seismic Function

The most critical decision in equipment engineering is the first one: what needs to be qualified and why. The first step in seismic equipment engineering is therefore to define the post-earthquake safety objective for the facility, the scope (boundaries) of the system, equipment or component, and its required seismic function.

(1) State the facility safety objective. For example, maintain an operable emergency power supply to a hospital, safely shutdown a chemical reactor, avoid spills of flammable materials from a tank, maintain a leak tight confinement in a building processing toxic gases, permit the safe evacuation of workers from a process building.

(2) Determine the structures and systems relied upon to accomplish the facility safety objective. For example, in a facility processing toxic materials, the facility safety functions may be to (a) maintain the leak tight integrity of the building structure, (b) shutdown and isolate systems containing toxic materials, (c) evacuate personnel, (d) assure the integrity of the exhaust fans and air handling units (scrubbers, filters, flare, etc.), (e) qualify the interlock between the intake and exhaust fans to assure that the intake fan does not run if the exhaust fan is lost following the earthquake (to avoid pressurizing the building), (f) provide operational fire water pumps and piping system, etc.

(3) Define the post-earthquake condition (scenario). For example, consider the following conditions as baseline, unless explicitly established otherwise for the facility: (a) offsite power may be lost for up to three days, (b) the earthquake may cause a fire, (c) non-seismically qualified equipment may not function and may fail (pipe ruptures, tanks leak, etc.), (d) operators may be expected to perform post-earthquake functions provided these are (i) feasible, (ii) documented in emergency response procedure, and (iii) drilled.

(4) The seismic function of the equipment must be defined as one of three categories:

> (a) Position Retention (also referred to as structural integrity): The equipment is to serve no active function during or following the earthquake, but it is to remain in position, to be stable, not to fall or overturn.
>
> (b) Leak Tightness: The equipment is to remain leak tight during or following the earthquake, not to leak through its pressure boundary, and not to leak-through if it is performing a flow isolation function. Examples of no through-leakage include a gate valve that is not to leak through its seat, a closed ventilation damper that is to remain closed.

(c) Operability: The equipment is to deliver or control flow. For example, a valve is to open or close, or remain in position or continue to throttle, a pump is to keep running or be able to start-up and operate for a period of time.

The system scope of work is best defined by reference to a Piping and Instrumentation Diagram (P&ID) marked to show the boundaries of the system to be qualified. Single line system drawings and - for existing equipment - marked photographs of the equipment to be qualified may also be used.

The equipment scope should also define the equipment boundary (for example pump-to-pipe nozzles) and the equipment-structure boundary (for example the equipment anchorage to a concrete floor, where the anchorage may be placed in scope of the equipment qualification, while the concrete floor may be kept as part of the structure qualification).

In addition, a seismic equipment list (SEL) should be prepared. This SEL would list each piece of equipment and its intended function (position retention, leak tightness, or operability). It is recommended to add to each entry a comment to remind the user of the basis for the functional classification. For example, an entry to the SEL would read as shown in Table 2-1.

Equipment	Location	Function	Comment
Gate Valve V-2	Bldg. G1-D	Leak Tightness	To remain closed, leak tight through seat, to prevent leaks to downstream system. To maintain integrity of the pressure boundary to prevent leaks to the environment.
etc.	etc.	etc.	etc.

Table 2-1 Seismic Equipment List

2.2 Seismic Input

Seismic input to the qualification of a system, equipment or component is in the form of (1) a static load coefficient, displacement, velocity or acceleration, or (b) a response spectrum of displacement, velocity or acceleration versus frequency or period, or (c) a time history of displacement, velocity or acceleration as a function of time. These three forms of input are described next.

2.2.1 Building Code and ASCE 7

The seismic design of industrial equipment has generally followed the rules of the applicable Building Code, with the exception of equipment in nuclear facilities for which seismic design rules are specified in regulations such as the U.S. Code of Federal Regulations 10 CFR50. The seismic rules of the Building Codes have changed significantly in recent years, and continue to evolve. This section should therefore be reviewed for general information only, and the user must refer to the applicable seismic design rules and regulations for a particular application.

The 2000 issue of the International Building Code (IBC) contained explicit rules for developing seismic input for the analysis and qualification of equipment. In the 2003 issue of the International Building Code (IBC), the seismic design of “Architectural, Mechanical and Electrical” components refers back to ASCE 7-02 Section 9.6, with some amendments.

As a first step, ASCE 7-02 will exclude certain types of equipment from seismic design because the consequence of their failure is deemed not to represent a safety hazard. This is the case for example for equipment weighing les than 400 lb and not 4 ft above the floor. This exemption should not apply where “leak tightness” or “operability” is required during or after the earthquake.

2.2.2 Static Seismic Coefficient

Static seismic input consists typically of a static coefficient, a force or an acceleration, to be applied to the equipment or component in each of three orthogonal directions. The three directions are typically east-west, north-south and vertically up-down. The static coefficient may vary with direction, so as to have a separate value for east-west, north-south and vertical seismic excitation. For example, a ground-mounted compressor may have to be seismically designed for 1.0g east-west, 1.0g north-south and 0.7g vertical.

The seismic coefficient may be obtained from the applicable Building Code, which in turn may refer to a national standard. In ASCE 7-02, the seismic force F_P is defined as a factor (an acceleration) times the weight.

Two important considerations must be accounted for when developing a static coefficient for seismic evaluation of equipment and components: in-structure amplification, and in-line amplification.

(a) In-Structure Amplification: Equipment mounted at ground floor will experience a seismic input a_{ground}, while the same equipment mounted on an upper level will experience a larger seismic input a_{floor}, where $a_{floor} > a_{ground}$ since seismic excitation generally increases with elevation, Figure 2.2-2. The seismic input to equipment mounted on a floor above ground must therefore account for in-structure amplification. In-structure amplification is accounted for in ASCE 7-02 through a factor linked to the height of the equipment attachment to the structure.

(b) In-Line Amplification: In Figure 2.2-3, the pedestal mounted pump – at ground level – experiences a seismic excitation “p”, while the check valve on the vertical discharge leg – mounted on the pipe – will experience a different excitation “v” with $v \neq p$ because the pump seismic excitation is filtered through the piping system. The ratio v/p of line-mounted component acceleration “v” to ground or floor mounted acceleration “p” is referred to as in-line amplification. In-line amplification is not explicitly addressed in current building codes or standards as is in-structure amplification. In the absence of detailed analysis, the following guidance is provided to help determine in-line amplification: (1) locate the closest line supports on either side of the line mounted component, (2) determine the elevation of the support attachments to the structure, (3) determine the seismic coefficient applicable to the structure at the support attachment points, (4) if the span that contains the component is rigid, the coefficient determined in (3) may apply as-is; if the span is flexible, or of unknown frequency, then 1.5

times the coefficient determined in (3) may apply. Note: A flexible pipe span is a span with a natural frequency (first mode) in excess of the rigid range frequency (zero period acceleration described in section 2.2.3) or 33 Hz.

In the ASCE 7-02 procedure for developing seismic input, the seismic load F_P is to be applied independently in the longitudinal and lateral directions (for example east-west and north-south separately). The horizontal load F_P is also to be summed, vectorially, to the vertical load F_V.

2.2.3 Seismic Response Spectrum

A seismic response spectrum provides the maximum response (typically expressed as acceleration) of a single degree of freedom (SDOF) system as a function of the frequency or period. For example, a SDOF system with a natural frequency of 12 Hz and 5% damping will experience an acceleration of 0.5g if it is subject to the seismic excitation represented by the response spectrum of Figure 2.2-5.

A response spectrum can be represented as a plot or a table of accelerations versus frequencies. The spectrum may also be expressed as displacements or velocities, versus period or frequency. An example of seismic response spectrum is shown in Figures 2.2-4 and 2.2-5. The high frequency range (the constant acceleration on the right hand of the frequency spectrum, at 33 Hz and above, equal to 0.5g in the case of Figure 2.2-4 and also 0.5g at 12 Hz and above in Figure 2.2-5) is often referred to as zero period acceleration (ZPA). The maximum acceleration anywhere in the spectrum (1.35g in the case of the solid line spectrum of Figure 2.2-4, and 1.5g in Figure 2.2-5) is the peak spectral acceleration (PSA).

Five precent damping is commonly used in the seismic evaluation of mechanical systems and equipment. The seismic response spectrum varies with damping, the acceleration increasing with decreasing damping, as illustrated in Figure 2.2-6. Damping at a frequency other than 5% may be converted to 5% damping by the following approximation

$$a_{i,m} \cong a_{i,n} \sqrt{\frac{\beta_n}{\beta_m}} \geq \text{ZPA}$$

$a_{i,m}$ = acceleration at frequency i, and damping m
a_{in} = acceleration at frequency i, and damping n
β_n = damping n
β_m = damping m
ZPA = zero period acceleration

The method to be followed in developing a free field (ground level) seismic response spectrum is specified in building codes or standards. For large projects, such as the building of a power plant or petrochemical complex in an earthquake-prone zone, the response spectrum may be developed on the basis of site-specific seismological and geotechnical investigations.

As was the case with static seismic input, the spectrum must also be increased for floor or wall mounted equipment to account for in-structure amplification and in-line amplification.

2.2.4 ASCE 7-02 and IBC 2003 Seismic Response Spectra

The ASCE 7-02 seismic response spectrum is a 5% damped spectrum curve of accelerations as a function of period; it varies with the geographical location (longitude and latitude) of the facility or structure housing the equipment, and the soil at that location (from hard rock to soft liquefiable soils). The general form of the ASCE 7-02 spectrum is shown in Figure 2.2-7.

2.2.5 Seismic Time History

A time history seismic input is a plot or a digitized file of displacements, velocities, or accelerations as a function of time, as illustrated in Figure 2.2-8. It may represent a real earthquake or it can be an artificial prediction of an earthquake. Seismic time histories are used to develop site-specific response spectra, or as input to finite element analysis of the equipment to obtain movements, loads, stresses and strains as a function of time, or as input to a shake table test. For reasons of cost and complexity, time history analysis is seldom used in practice for the seismic analysis of equipment and components, except to program seismic excitation in shake table testing.

2.3 Evaluation Process

The engineering qualification of active mechanical equipment is illustrated in Figure 2.3-1. It relies on the seismic attributes checklists provided in Appendix A.

Box 1 – The equipment list defines the seismic function of the equipment as Postion Retention, Leak Tightness or Operability.

Box 2 – Review the equipment against the seismic attributes check-list.

Box 3 – Analysis is the first basis of seismic qualification, it is essential for assessment of Position Retention (anchorage, load path, stability).

Box 4 – Test experience (Box 5), earthquake experience (Box 6), and maintenance history (Box 7) are the second basis for seismic qualification, including operability integrity.

Box 8 – If the equipment does not comply with the checklist, it may be analyzed in more detailed, tested (or compared to similar tested equipment), or modified or replaced.

Box 9 – If the equipment is qualified it must still be evaluated for seismic interactions (Chapter 9).

Box 10 – Seismic evaluation data compiled in the implementation of the above steps is assembled into a seismic qualification report. A configuration management system is set in place to control future modifications, to assure that they will not degrade the seismic performance of the equipment.

2.4 Seismic Qualification Codes, Standards and Guides

Mechanical equipment is seismically designed and qualified by (a) analysis, (b) testing and/or (c) earthquake experience. Seismic design standards (how to design the equipment to resist an earthquake), qualification standards (how to demonstrate that the design is adequate), qualification methods and regulatory guides are described in this section.

The owner and the designer have to determine which standards, guides and documents apply, on the basis of the scope of each document and regulatory or jurisdictional requirements.

2.4.1 Static Mechanical Equipment

(1) Storage Tanks (design and operating pressure below 15 psig)

API 650, Welded Steel Tanks for Oil Storage, Appendix E Seismic Design of Storage Tanks, American Petroleum Institute, Washington, DC.

AWWA – D100, Standard for Welded Steel Storage tanks, American Water Works Association, Denver, CO.

Seismic Design and Evaluation Guidelines for the Department of Energy High-Level Waste Storage Tanks and Appurtenances, BNL-52361, 1995, Brookhaven National Laboratory, New York.

(2) Pressure Vessels

ASME Boiler and Pressure vessels Code, Section VIII, Pressure Vessels, American Society of Mechanical Engineers, New York.

(3) Piping Systems (above ground)

ASME Boiler and Pressure Vessel Code, Section III, Division 1, Nuclear Components, Subsections NB/NC/ND-3600.

Seismic Design and Retrofit of Piping Systems, American Lifelines Alliance, 2002, Washington, DC.

ASME B31 Code, Pressure Piping, American Society of Mechanical Engineers, New York.

NFPA-13, Sprinkler Systems, National Fire Protection Association, Quincy, MA.

(4) Piping and Pipelines (buried)

Guideline for the Design of Buried Steel Pipe, American Lifelines Alliance, 2001, Washington, DC, www.americanlifelinesalliance.org

Guidelines for the Seismic Design of Oil and Gas Pipeline Systems, American Society of Civil Engineers, 1984, Reston, VA.

ASCE 4 Seismic Analysis of Safety-Related Nuclear Structures, American Society of Civil Engineers, 1984, Reston, VA.

(5) Industrial Ducting

Seismic Restraint Manual, Guidelines for Mechanical Systems, Sheet Metal and Air Conditioning Contractors' National Association, SMACNA, 1998, Chantilly, VA.

2.4.2 Active Mechanical Equipment

(1) Nuclear Power Plant

ASME QME, Qualification of Active Mechanical Equipment Used in Nuclear Power Plants, 2002, American Society of Mechanical Engineers, New York.

Generic Implementation Procedure (GIP) for Seismic Verification of Nuclear Plant Equipment, Seismic Qualification Utility Group, 1992.

(2) Seismic Testing – Non-nuclear power application

ICBO AC 156, Acceptance Criteria for Seismic Qualification Testing of Nonstructural Components, International Conference of Building Officials, Whittier, CA.

(3) Air Handling Units

A Practical Guide to Seismic Restraint, American Society of Heating, Refrigeration and Air-Conditioning Engineers, ASHRAE, 1999.

(4) Seismic Loads

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

2.4.3 Electrical Equipment

Generic Implementation Procedure (GIP) for Seismic Verification of Nuclear Plant Equipment, Seismic Qualification Utility Group, 1992, (Electric Power Research Institute).

IEEE 323 - Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations, 1996.

IEEE 344 - Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations, 1987.

IEEE 382 - Standard for Qualification of Actuators for Power-Operated Valve Assemblies with Safety-Related Functions for Nuclear Power Plants, 1996.

IEEE 420 - Standard for the Design and Qualification of Class 1E Control Boards, Panels, and Racks Used in Nuclear Power Generating Stations, 2001.

IEEE 535 - Standard for Qualification of Class 1E Lead Storage Batteries for Nuclear Power Generating Stations, 1986.

IEEE 649 - Standard for Qualifying Class 1E Motor Control Centers for Nuclear Power Generating Stations, 1991.

IEEE C 37.81 - Guide for Seismic Qualification of Class 1E Metal-Enclosed Power Switchgear Assemblies, 1989.

IEEE C37.98 - Standard Seismic Testing of Relays, 1987

USNRC Regulatory Guide 1.100, Seismic Qualification of Electric Equipment for Nuclear Power Plants, US Nuclear Regulatory Commission, Washington, DC.

2.4.4 Support Structures

AISC Manual of Steel Construction, American Institute of Steel Construction, Chicago, IL

ACI 318, Building Code Requirements for Reinforced Concrete, Appendix D, Anchoring to Concrete, American Concrete Institute, Detroit, MI.

ASCE 7-02, Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers, Reston, VA.

2.4.5 Nuclear Power Industry Initiatives

Seismic qualification of equipment has primarily been developed by the nuclear power generating industry, to assure that in case of earthquake a nuclear power plant can continue to safely operate or be brought to a safe shutdown. Many of the codes and standards mentioned above have indeed been developed and applied in nuclear power plants. In addition, the nuclear power industry has undertaken several initiatives to facilitate the practical use of seismic engineering knowledge. These initiatives – often referred to by their acronym (such as SQUG, NARE, etc.) are coordinated, in many cases, by the Electric Power Research Institute (EPRI), and subject to peer and regulatory reviews. These industry-wide seismic engineering initiatives are available to EPRI members, and in some cases through the Nuclear Regulatory Commission public document room; they include:

SQUG: Name of the Seismic Qualification Utilities Group (SQUG) that developed the formal rules (referred to as Generic Implementation Procedure or GIP) for the evaluation of seismic adequacy of active mechanical and electrical equipment based on earthquake and test data.

STERI: Method for the Seismic Technical Evaluation of Replacement Items (STERI), documented in EPRI report NP-7484 “Guideline for the Seismic Technical Evaluation of Replacement Items for Nuclear Power Plants”.

SQUG/NARE: A combination of SQUG and STERI that extends the STERI rules to the seismic evaluation of new and replacement equipment (NARE), not only replacement parts.

G-STERI: A generic extension of STERI, with procurement guidance, documented in EPRI reports TR-104871, “Generic Seismic Technical Evaluations of Replacement Items - Pilot Project” and TR-105849 “Generic Seismic Technical Evaluations - Item Specific Evaluations”.

SQURTS: The seismic qualification reporting and testing standardization (SQURTS) is a collaborative of utilities and other members for sharing seismic shake table testing qualification services.

CGD: Commercial Grade Dedication, a process through which a commercially developed, designed and fabricated commodity (typically “off-the-shelf”) is verified to be adequate for use in safety related applications. CGD is documented in EPRI report NP-5652, “Guideline for the Utilization of Commercial Grade Items in Nuclear Safety Related Applications (NCIG-07)”. The seismic aspect of the dedication process is referred to as CCASSI, which stands for Critical Characteristics for Acceptance of Seismically Sensitive Items. Its objective is to assure that equipment originally qualified by seismic testing remains qualified when refurbished.

2.5 Methods of Seismic Qualification

There are three methods of seismic qualification: analysis (static or dynamic, linear and elastic or non-linear and inelastic), comparison to performance of similar equipment during earthquakes (earthquake experience data), and testing (static or shake table), as will described in this section.

2.5.1 Seismic Analysis

Of the three functions of mechanical equipment (position retention, leak tightness and operability), the first two can generally be established by analysis. Analysis may also be applied for operability, but to a very limited extent.

Analysis (hand calculations or computerized) is typically used for the evaluation of equipment support structures and anchorage (concrete anchor bolts, welds, braces). Analysis is also used to evaluate the load path through the equipment (appurtenances and their attachment to the equipment, and load path from the center of gravity of the equipment to its base or supports).

The use of analysis to evaluate operability is limited to the deflection of rotating shafts, compared to manufacturer limits, bearing and seal limits, and clearances between rotating and fixed parts.

As an example, the overload failure of a chiller pipe nozzle, Figure 2.5-4, can be predicted and quantified by analysis; but the operability of the chiller after such an overload (whether the moving parts and instrumentation and controls will function correctly) cannot be predicted only by analysis.

2.5.1.1 Static Analysis

Analysis may be by static methods. These static methods are often referred to as “equivalent static” since they are intended to simulate a dynamic input and response by static means. In static analysis, forces, displacements or accelerations are applied – either uniformly or at certain points – to a model of the component to obtain the distribution of reaction loads, movements, stresses or strains. For example, lateral and vertical forces may be applied at the center of gravity of a pump to obtain the reaction forces at its anchor points, as illustrated in Figure 2.5-5.

Static seismic input loads and displacements are specified in the International Building Code and ASCE-7, as described earlier in this Chapter, or they may be developed specifically for equipment in a given facility, building or floor elevation.

2.5.1.2 Dynamic Analysis

There are two forms of dynamic analysis: response spectrum and time history. The former, response spectrum analysis, accounts for the dynamic characteristic of the component and the frequency content of the input. A response spectrum (typically acceleration vs. frequency, described in Section 2.2) is applied to a model of the component, and the computer calculates as output the loads, movements, stresses or strains throughout the component. Figures 2.2-4 to 2.2-7 illustrate three response spectra.

Dynamic response spectral seismic analysis is common for distributed systems (piping, ducting, cable trays, etc.), or to obtain reaction loads on support and bracing of equipment. Dynamic seismic response spectra analysis is well suited for linear and elastic systems and components.

A time history analysis applies the seismic input (movement, velocity or acceleration) to the equipment as a function of time. It simulates the earthquake excitation throughout the duration of the event, Figure 2.2-8. The analysis is sensitive to the assumed shape of the time history and the equipment model; that is why several time histories are typically run to envelope a potential earthquake.

The time histories may be real (simulating a past earthquake) or artificial (simulated a single or multiple likely earthquakes).

The time history analysis is rarely used to seismically qualify equipment because it is more complex and more expensive than a response spectra analysis.

2.5.1.3 Qualification Criteria

In most cases, seismic analysis is elastic (linear stress-strain material properties) and stress limits are compared to design code allowable limits. Elastic analysis tends to over-predict stresses because it does not take credit for plastic deformation (strain hardening). A less conservative analysis may be applied using inelastic material properties to account for plasticity.

Response spectra analysis applies to linear systems (stiffness does not vary with direction of motion). In contrast, static, equivalent static, and time-history analyses may be linear or non-linear. Because some support structures are non-linear (one-way supports, bi-linear stiffness) the static method may be applied in these cases to reflect the non-linearities. For example, if the vertical seismic acceleration exceeds 1g it will overcome gravity and the equipment will uplift unless it is vertically restrained; in this case of uplift (non-linear response) a static analysis will provide a more accurate prediction of vertical movement where the response spectrum analysis would have to be approximated by assuming either free or restrained up-down motion.

The calculated reaction loads, movements, stresses or strains obtained by seismic analysis are compared to code and standard limits (such as ACI-318 concrete anchor bolt limits, AISC structural steel stress limits for equipment support structures, or ASME B31 at pipe nozzles) or manufacturer limits (such as pump shaft deflection) to determine the seismic adequacy of the component. The applicable codes and standards are listed in Section 2.4.

2.5.2 Earthquake Experience

The study of seismic performance of equipment through post-earthquake reconnaissance inspections dates back to the 1960’s. Since then, all large earthquakes have been investigated and documented by entities such as the Earthquake Engineering Research Institute (EERI), the Seismic Qualification Utilities Group (SQUG, Electric Power Research Institute EPRI), the Federal Emergency Management Administration (FEMA), the National Science Foundation (NSF), the American Society of Civil Engineers (ASCE), the National Fire Sprinkler Association (NFSA), and private engineering firms.

The study of the effects of earthquakes on commercial and industrial facilities provides essential insight into the “real life” performance and vulnerabilities of structures and equipment. From equipment performance in real earthquakes, the engineering community can draw practical and important lessons, learning what are the good attributes that performed well and the weaknesses that caused seismic failure or malfunctions. These attributes complement seismic testing and analytical knowledge to help develop check-lists that permit screening equipment for seismic qualification, such as the seismic attributes check-lists presented in this Guide.

Experience based methods are documented in technical reports and standards such as:

> Generic Implementation Procedure (GIP) for Seismic Verification of Nuclear Plant Equipment, Seismic Qualification Utility Group, 1992.

ASME QME, Qualification of Active Mechanical Equipment Used in Nuclear Power Plants, 2002, American Society of Mechanical Engineers, New York.

DOE/EH-0545 Seismic Evaluation procedure for equipment in U.S. Department of Energy facilities, March, 1997.

Earthquake performance data has been gathered from the study of earthquakes with 5% damped peak spectral accelerations between 1g and 2g in the 2Hz to 10 Hz range, and peak ground accelerations (zero period, high frequency spectral acceleration) between 0.4g and 0.7g.

2.5.3 Seismic Testing

The seismic operability of active equipment can be established by testing. In a few instances the test may be static, such as applying a static lateral load to a valve operator, with the load equal to the operator’s weight times the seismic acceleration. In most cases seismic qualification testing consists in anchoring the equipment to a shake table, and exciting the table with a seismic excitation equal to or larger than the design earthquake. This chapter reviews the various steps involved in conducting a successful seismic shake table test.

2.5.3.1 Functional Requirement

The first step in planning a seismic shake table test is to specify the intended function of the component or equipment to be tested. This is typically specified as one of three objectives:

Structural Integrity - the component should not break, deform or overturn during the test.

Leak Tightness - the component should not leak out of the pressure boundary (such as a valve leaking out through packing, or at nozzle connections, or through a crack in the valve body), or the component should not leak-through a flow isolation element (such as a closed valve seat leaking through from inlet to outlet, or a check valve leaking backward from outlet to inlet, or a pressure relief valve chatter with bursts of fluid discharge).

Referring to Figure 2.5-1, in order to verify seat tightness (no through leakage) of a valve during or after shake table testing, the valve outlet may be piped to a tank. For liquid service (liquid-filled valve during test) the tank is initially empty and observed for evidence of water leakage. For gas service (pressurized valve, typically with a compressed gas bottle) the tank is filled with water and observed for evidence of bubble leakage of air through the valve seat and into the tank.

Alternatively, a flow meter may be placed on the inlet or outlet pipe and the valve inlet (or outlet for check valves) is then pressurized with water or gas (typically air). The flow meter would detect leakage through the closed valve seat.

Note that in many cases valves are not leak tight, even before seismic testing (refer to Chapter 3 for valve leak rate classification). It is therefore important to establish an acceptable leak rate limit as part of the test specification.

Operability - the component should function correctly, parts moving as required during or after the test.

2.5.3.2 Types of Seismic Tests

The seismic shake table test may be conducted in one of three ways:

RRS Test - The component may be tested to an input excitation specified by the designer, and called the required response spectra (RRS).

Fragility Test - The component may be tested to failure, this type of test is labeled a fragility test.

Table Limit Test - The component may be tested above the RRS to the acceleration limit of the shake table.

2.5.3.3 Seismic Test Sequence

A typical seismic test sequence is described below. It is strongly recommended to document these steps through photographs or videotapes.

Pre-Test - Pre-test inspections are performed to identify the following parameters:

Material and assembly condition
Operability status (if required to be verified operable before testing)
Leak tightness
Mounting
Location, attachment, orientation and operability of seismic test instruments (e.g., table accelerometers and component accelerometers)

Pretest inspections should also verify the shake table input parameters and assure that all instrumentation is properly calibrated.

Test – Shake table testing, with or without functionality checks during tests, as specified by the designer in the test specification. The designer must specify whether a sine sweep test (resonance search) is necessary. A sine sweep is primarily of interest in seismic and dynamic research, but is rarely needed for industrial equipment; it is often conducted as a preliminary low-amplitude test to verify the proper mounting of equipment on the shake table. The designer must also specify how many seismic shake table tests are necessary to qualify the equipment; for example for nuclear power applications, it is common practice to run five lower amplitude seismic tests (called operating basis earthquakes or “OBE”) followed by a large amplitude seismic test (called safe shutdown earthquake or “SSE”).

Post-Test – Repeat the pre-test checks. Check operability if specified by the designer in the test specification.

2.5.3.4 Component Mounting

The component may be mounted on the shake table in different ways:

Direct Mount - The component may be directly bolted to the table.

Rack Mount - The component may be mounted onto a rack or structure representing the field installation.

In-Line Mount - A piping component (such as a valve) may be mounted between two pipe spans representing the field installation. Weights may be cantilevered off the nozzles of equipment and off electrical ports to simulate the seismic inertial effects of attached piping, ductwork or cables.

Figure 2.5-2 shows an example of shake table test arrangement, showing relays, pressure switches and voltage sensing PC boards mounted on a vertical steel frame (left arrow), an air operated valve mounted on a water filled pipe (mid arrow), and a solenoid (right arrow).

2.5.3.5 Table Input

Test Directions – Specify whether the test is single directional (single axis), bi-directional (bi-axial), or three directional (triaxial). The mounting direction of the equipment relative to the excitation axes must also be specified.

Test Input – Specify whether the test is run at a single frequency (single frequency sinusoidal input), frequency sweep (resonance search), or artificial time history (with a response spectrum that envelopes the RRS at a specified damping, typically 5% for mechanical components and equipment).

An accelerometer placed on the component measures the component acceleration during the test a_C (Figure 2.5-3). Another accelerometer placed on the table measures the table acceleration a_T; this table accelerometer is sometimes called the control accelerometer. The table with the component is then excited by a continuous sweep of sinusoids with table frequencies f_T. For example f_T may vary from 1 Hz to 50 Hz. The ratio of the component acceleration to the table acceleration a_C/a_T is recorded and plotted against the corresponding table sinusoidal frequency f_T (Figure 2.5-3). The plot a_C/a_T vs. f_T is referred to as a transmissibility plot. This plot may exhibit one or several peaks with amplification larger than a certain threshold. We may choose, for example, to consider all peaks with an amplification of at least 2. These peaks are at the resonant frequencies. The first of these peaks is at the first natural frequency of the component f_1 (first component modal frequency). The test will also provide the magnitudes of the component acceleration versus the table acceleration at these frequencies; these are the modal amplification factors (MA).

The phase between the table movement and the component movement may also be plotted, and it will show that at resonance f_1 the movement of the table and component tend to become out-of-phase (the component movement is no longer in synch with the table).

2.5.3.6 Acceptance Criteria

Test acceptance criteria are specified on the basis of the required seismic function of the system. Some performance criteria may apply only post-earthquake, while others may apply during as well as after the earthquake. This section provides examples of typical acceptance criteria for various classes of components.

Control or Isolation Valve

(1) Structural integrity:
- No broken parts, no tipping, no overturning.

(2) Leak tightness:
- Does not leak through closed seat beyond maximum permitted by design, when valve is at design pressure, as determined by applying design pressure at inlet and checking for liquid leak or gas bubbles at outlet.
- Does not leak out from nozzle connections or body with valve open or closed.
- Leak tightness may be checked during test or after test. It may also be checked at a proof test pressure larger than normal operating pressure.

(3) Operability:
- Flows normally when valve open and pressure applied at inlet nozzle.
- Valve disc (or ball, plug, gate, cylinder) free to move.
- For motor operated valves, may verify voltage to motor pins to open and close valve at pressure, during or after the test.
- For air operated valves, may verify regulator signal and actuator air pressure, during or after the test; for example applying 120 V to the solenoid coil would open the valve and initiate flow, and then the valve would close on de-energizing the solenoid coil.
- For motor or air operated valves, may verify that the valve transitions normally (open to close to open) on control signal, during or after the test.
- For solenoid valves, may verify pull-in and drop-out voltage of the solenoid element with the valve at pressure, and the high potential resistance to current flow of the dielectric insulator.
- For solenoid, air or motor operated valves, may verify opening or closing time.

Check Valve

(1) Structural integrity:
- No broken parts, no tipping, no overturning.

(2) Leak tightness:

- Does not leak backwards beyond maximum permitted by design, when valve is at design differential pressure, as determined by applying design pressure at outlet and checking for liquid leak or gas bubbles at inlet.
- Does not leak out from nozzle connections or body at design pressure.

(3) Operability:
- Flows normally when pressure applied at inlet nozzle.

Pressure Relief Valves

(1) Structural integrity:
- No broken parts, no tipping, no overturning.

(2) Leak tightness:
- Does not chatter or continuously leak through.
- Does not leak out from nozzle connections or body.

(3) Operability:
- Pressure set point: Pops open at the pre-test set pressure.
- Reseats at the pre-test reseat pressure (blowdown).

Pneumatic Damper Operator

(1) Structural integrity:
- No broken or loose parts.

(2) Leak tightness:
- Does not leak air.

(3) Operability
- Pressure to start damper rod stroke (in the order of a few psi).
- Pressure to full rod stroke (in the order of tens of psi).
- Stroke length (in the order of inches).
- Force to stroke rod (in the order of a couple of hundred pounds).

Pumps and Compressors

(1) Structural integrity:
- No broken or loose parts.
- Supports and anchorage perform well.
- No sliding or overturning.
- The concrete pedestal will have to be qualified separately by analysis.

(2) Leak tightness:
- No leakage of process fluid or lubricating fluid.

- No leaks through seals or casing.

(3) Operability:

- No damage to bearings, stuffing boxes or mechanical seals.
- No damage to motor-pump/compressor shaft coupling.
- No difficulties with oil or coolant flow to bearings and seals.
- Motor (driver) starts under normal conditions.
- Pump or compressor vibration and noise within normal operating limits.
- No overheating of bearings (thermography check).
- No friction impeller or cylinders with casing (smooth normal running sound).
- Expected discharge flow rate and temperature achieved.
- Normal suction, discharge, lubricating oil, cooling water and seal water pressure and temperature.
- Performance testing of compressors ASME PTC-10.

Fans

(1) Structural integrity:

- No broken or loose parts, no tipping, no overturning.

(2) Leak tightness:

- Air flow does not leak out of enclosure.

(3) Operability:

- Fan starts and operates normally during or after test (motor voltage and current, fan speed RPM, acceptable vibration level).
- No overheating of bearings (thermography check).
- No friction impeller with casing (smooth normal running sound).
- If belt driven, no belt damage or slack.
- Expected flow rate achieved.

Chillers

(1) Structural Integrity

- No broken or loose parts.
- Supports and anchorage perform well.
- No sliding or overturning.
- Isolation mounts and snubbers (stops) in good condition.
- Note: the concrete pedestal will have to be qualified separately by analysis.

(2) Leak Tightness

- No leakage of refrigerant, chilled water connections, or lubricating fluid.
- No leaks through seals or casing.
- Condenser and evaporator, and coils leak tight by post-shake pressure test.
- Isolation and relief valves leak tight.

(3) Operability

- Air-cooled condenser fans and their motor are operable, blades remain balanced.
- Displays and controls (set-points) operable.
- Power panels operable.
- Isolation and relief valves operable.
- Flow or pressure switches operable.
- Compressor and motor, motor starter operability.
- Variable speed drive, where applicable.

2.5.3.7 Test Documentation

Unless explicit documentation requirements are specified by applicable test standards such as ASME-QME and ICBO AC-156, the documentation of a seismic shake table test may consist of the following:

- Test item identification (with make and model).
- Test item mounting (with sketch and photographs, with orientation relative to axes of excitation).
- Contact names and organization (designer and tester).
- Type of test (axes of excitation, plots of required response spectra vs. test response spectra at 5% damping).
- Test criteria (pre-test, test and post-test checks and criteria).
- Test sequence (sine sweep, resonance search, number of seismic excitations, etc.).
- Equipment performance against test criteria.
- Description and resolution of test deviations.
- Description and photographs of equipment failures or non-conformances.
- Acceptance signature by owner or designer.

2.6 Shipping and Operating Record

Understanding the shipping integrity and operational reliability record of active equipment provides important insight on their seismic performance, for several reasons:

A supplier of noise and vibration control products estimates that “in commercial structures, if the equipment arrives on the job after normal transport and is operative upon installation it has already demonstrated a 4 g capability and that this is true minimum fragility level with no further calculation required” [Mason Industries]. This of course applies to the shipped configuration, which may contain shipping braces, wires or bumpers, removed after field installation.

The operating track record and the corrective maintenance history (break-down, failures, leaks) is a good indication of the equipment quality and operating environment. If the track record is poor, there is an increased chance that the equipment will fail to operate normally during or after an earthquake.

A good preventive and predictive maintenance program (such as periodic vibration checks or oil changes on pumps, repair and recoating of corroded parts) enhances the structural integrity of the equipment and reduces the chance of seismic induced failure.

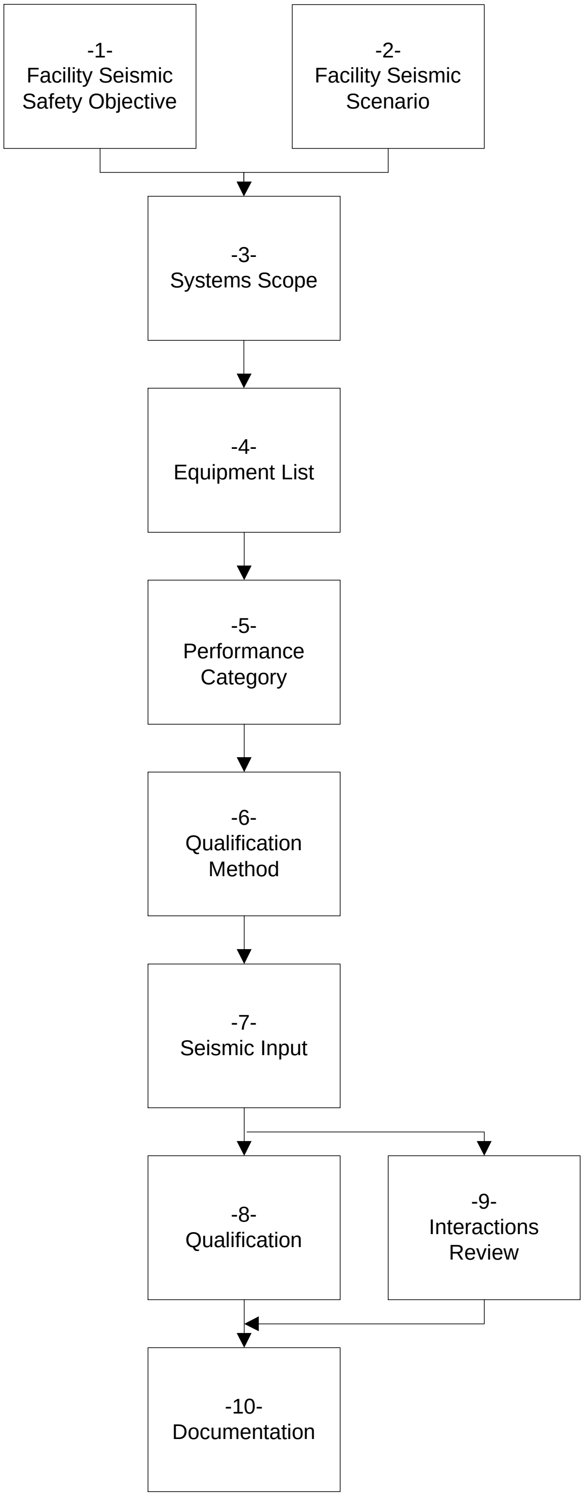


Figure 2.0-1 Seismic Project Ten Step Process

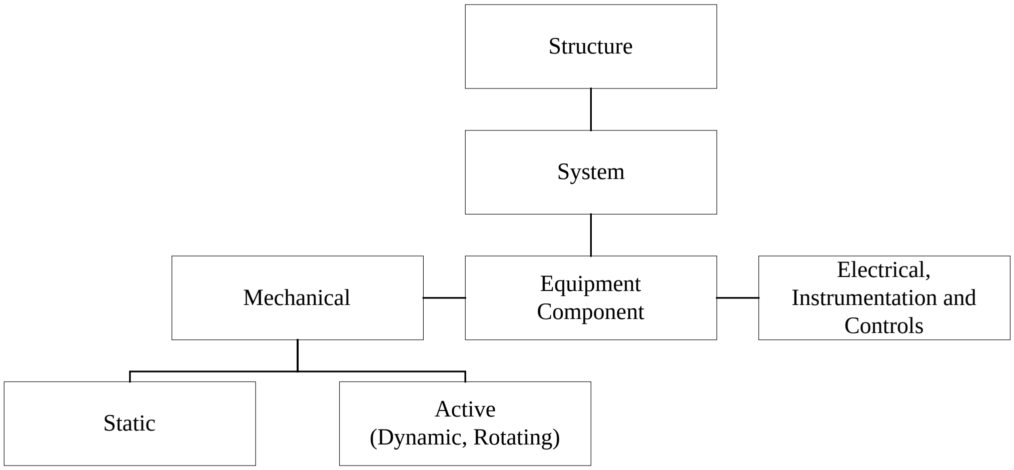


Figure 2.2-1 Structures, Systems and Components

Figure 2.2-2 Equipment Elevation

Figure 2.2-3 In-Line Check Valve

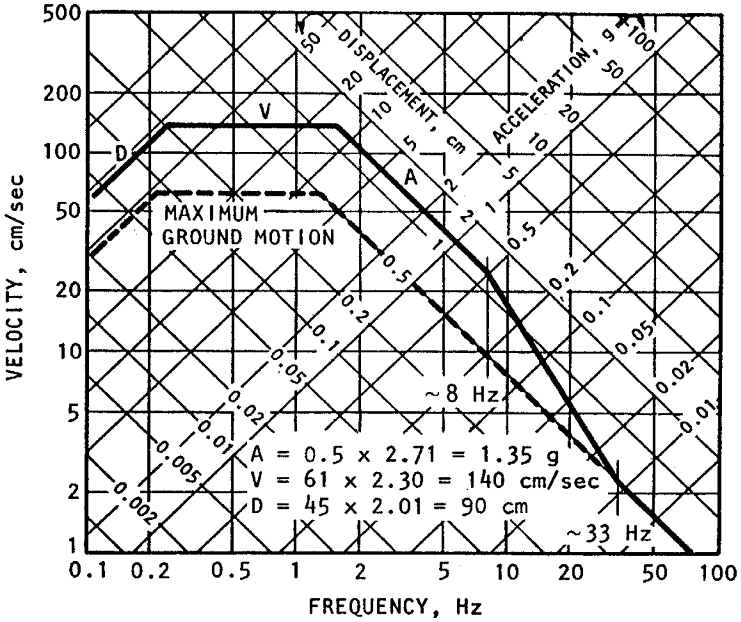


Figure 2.2-4 Seismic Response Spectra at a Given Damping

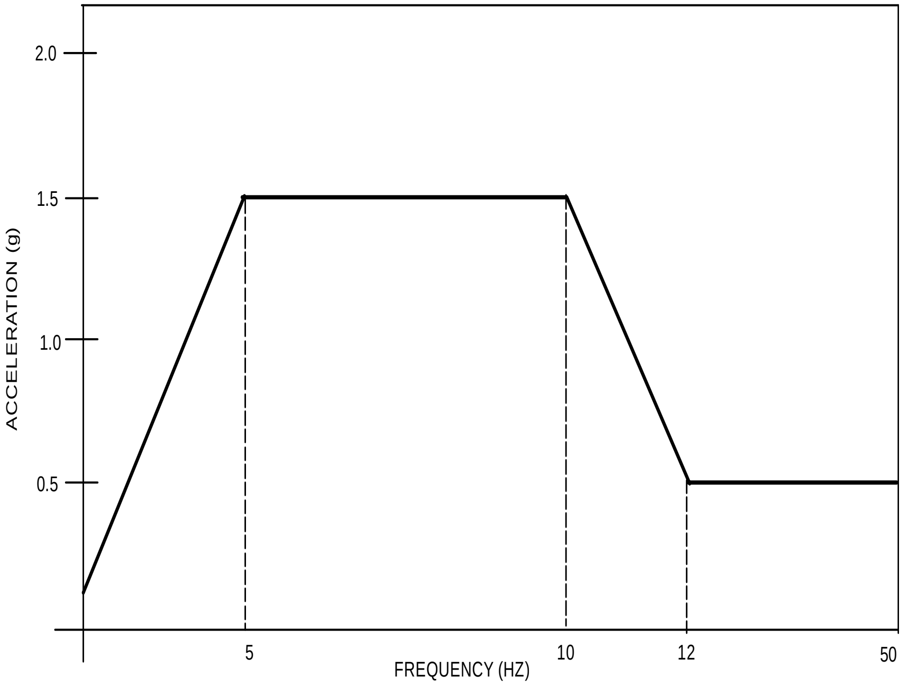


Figure 2.2-5 Seismic Response Spectra at 5% Damping

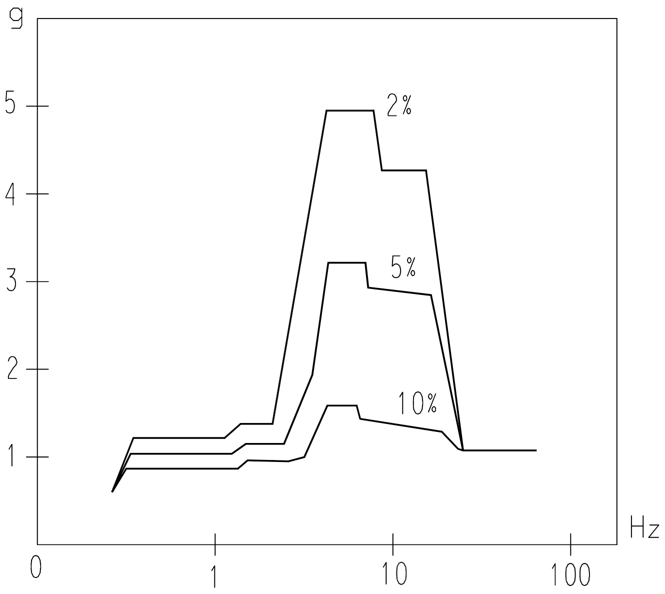


Figure 2.2-6 Seismic Floor Response Spectra at Three Damping Values

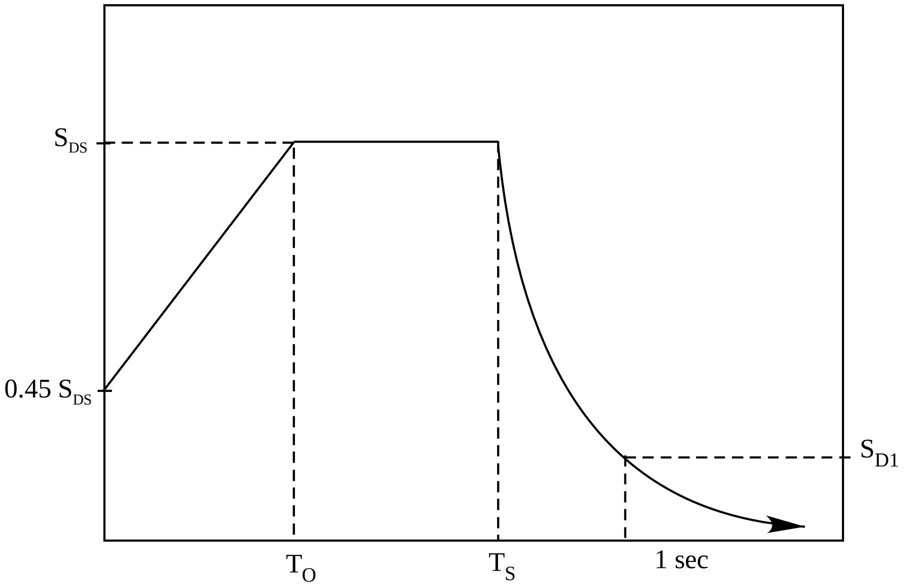


Figure 2.2-7 ASCE 7-02 Spectral Shape

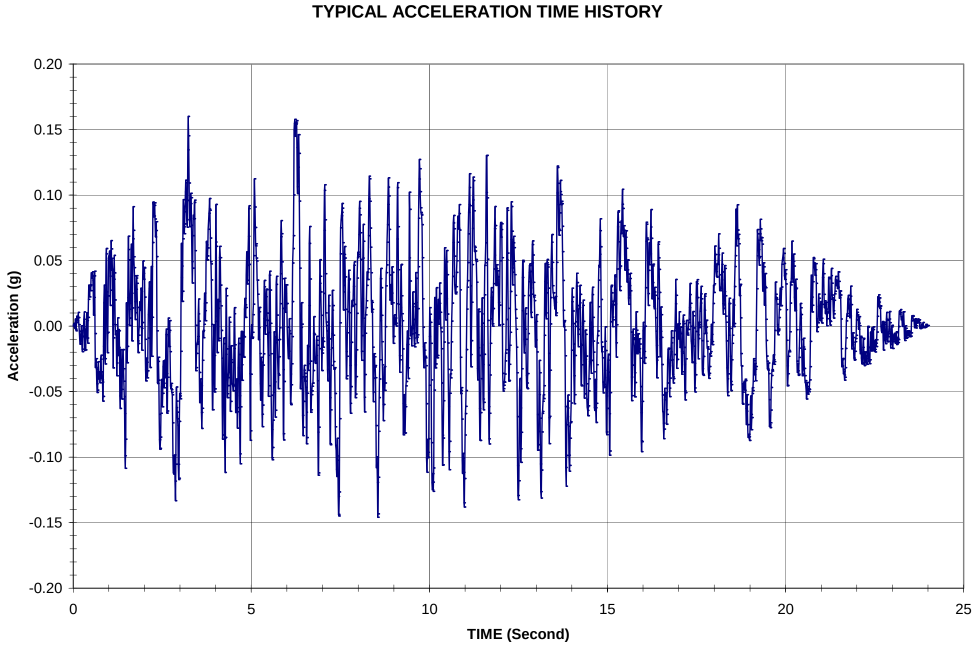


Figure 2.2-8 Seismic Time History (acceleration vs. time)

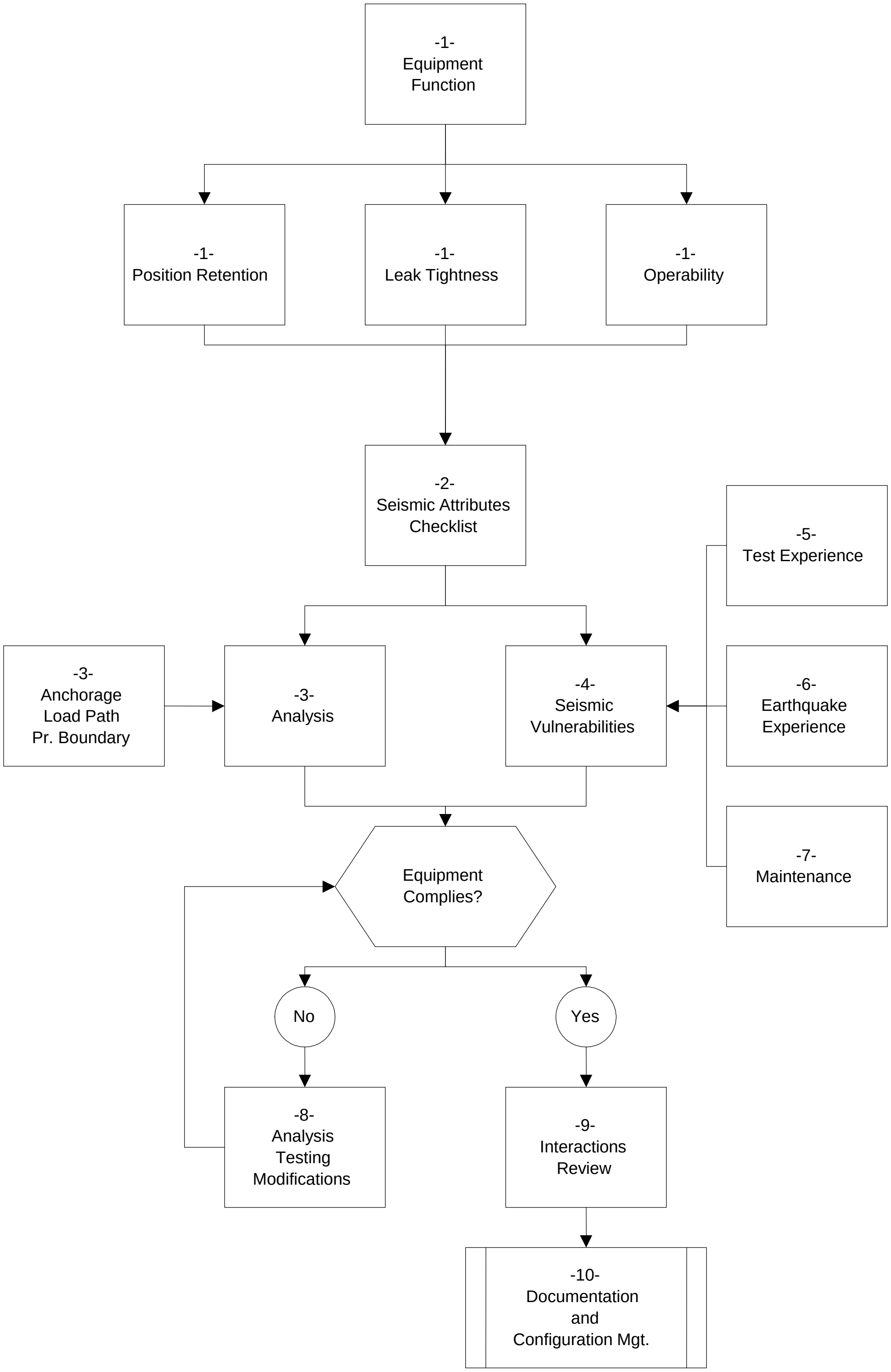


Figure 2.3-1 Seismic Evaluation Ten Step Process

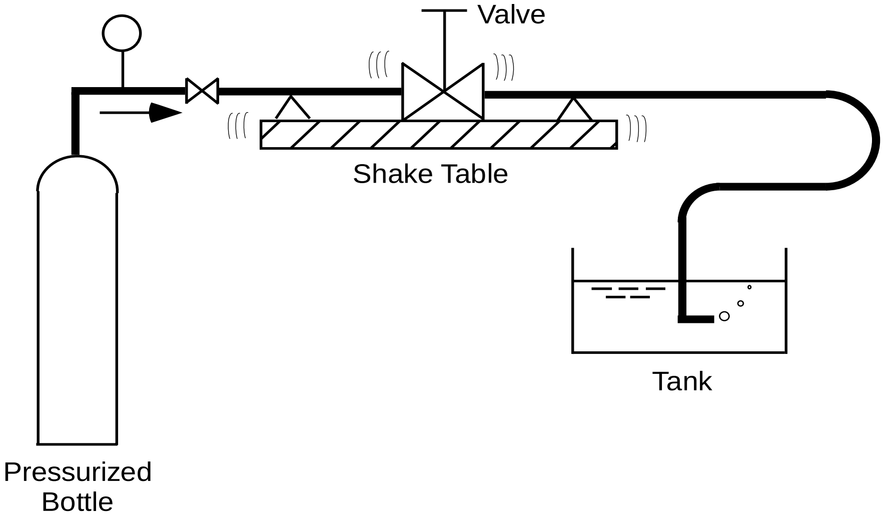


Figure 2.5-1 Through-Leak Tightness Check

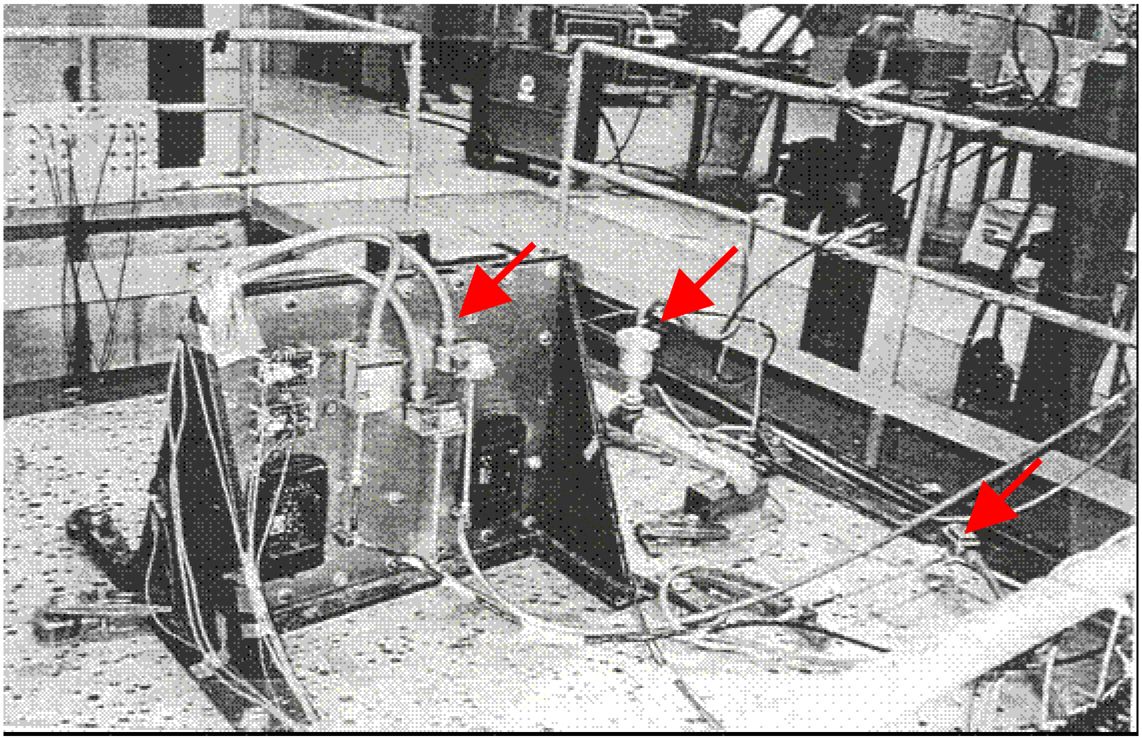


Figure 2.5-2 Seismic Shake Table

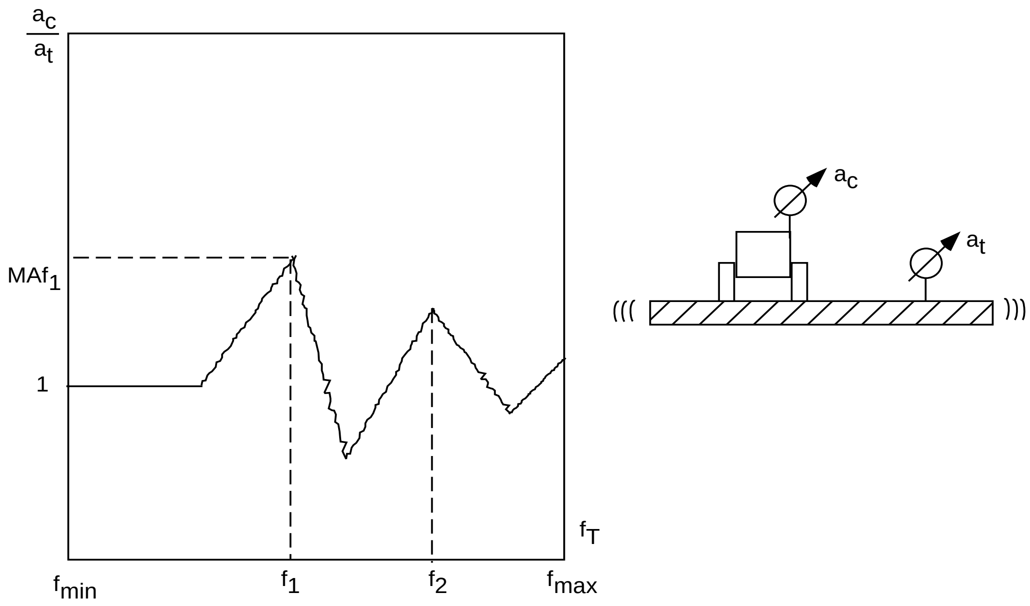


Figure 2.5-3 Natural Frequency Search

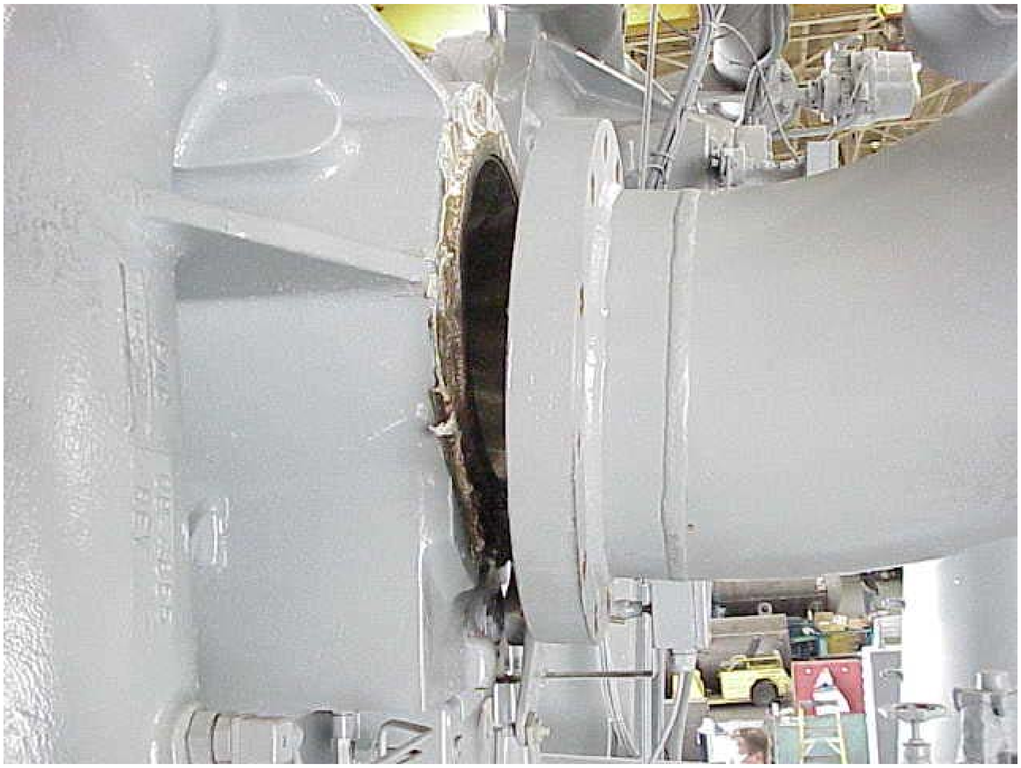
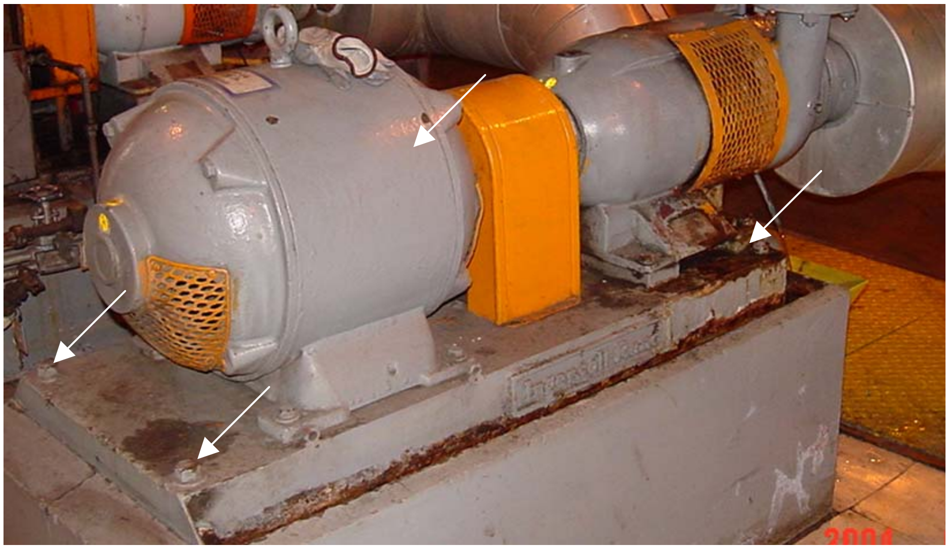


Figure 2.5-4 Overload Rupture of Chiller-Pipe Nozzle



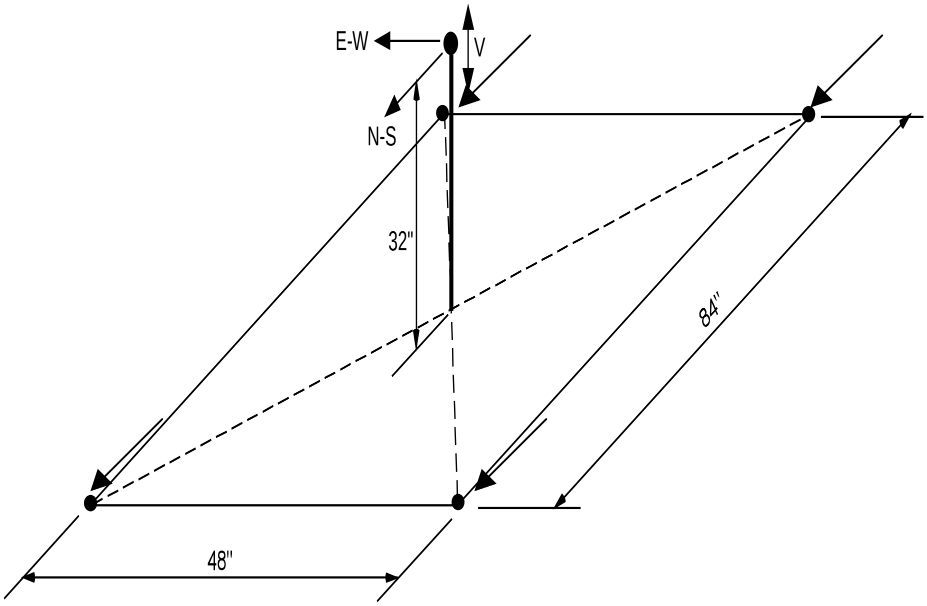


Figure 2.5-5 Pump Motor on Pedestal and Simplified Model

3.0 Valves and Valve Operators

3.1 Description

Valve System Function

Seismic qualification must differentiate between the valve component itself and the valve system. The valve component itself is a flow control element that may be manually opened for full flow, closed for flow isolation, or set at an intermediate position to throttle flow. In the case of automatic control valves, common in industrial applications, the operation of the valve component is controlled by a valve system that consists of five parts:

(a) A sensing element which measures parameters such as pressure, temperature, flow rate, or level.
(b) An instrument to compare the measured value with a desired value,
(c) A transducer transforming the sensed parameter into current; and a transmitter transforming the transducer's current to a pressure or electrical signal sent to the actuator. The transducer and transmitter (c), together with the comparator (b), constitute the valve controller.
(d) An actuator (operator) to move the valve to its desired position.
(e) The valve itself that produces the needed change in flow.

This chapter addresses the seismic qualification of the valve (part (e)) and the actuator (part (d)). The seismic qualification of instrumentation and controls – the sensing element (part (a)) and the valve controller (parts (b) and (c)) – is not addressed in this Guide, but it is typically achieved through either shake table testing [IEEE 344, ICBO], or similarity comparison to previously tested items, or, under certain conditions, comparison to earthquake experience data [SQUG].

Valve Function. As described in Chapter 2, the desired seismic function of a valve must be specified as a prerequisite to seismic qualification. The function will either be position retention, leak tightness, or operability.

(1) Position Retention: is achieved through qualification of the piping system on which the valve is mounted (for example, following the rules of ASME B31, NFPA-13). The effects of valve weight and operator weight and eccentricity must be accounted in the analysis of the piping system [ALA].

(2) Leak tightness is achieved through evaluation of the integrity of the pressure boundary (body, bonnet, packing, joints).

(3) Valve operability may be defined as one or more of the following characteristics:

(a) The ability of the valve system to perform its control-regulating function.
(b) The ability to open, close or control a manually or automatically actuated valve.
(c) The ability to maintain leak tightness through the seat.

In critical applications it may be necessary to establish that an isolation or check valve does not leak through the seat following the earthquake. Seat tightness is determined by means of standardized closure tests. To conduct a closure test, the valve is closed and pressurized from one side with air, inert gas, water or a non-corrosive liquid of same viscosity as water, the other side being open to atmosphere.

A number of seat tightness classes are defined in valve standards, in particular MSS-SP-61, MSS-SP-82, FCI 70-2, API 598, and ASME B16.34. They vary from nominal leakage (leak free shut-off is not quantified beyond “no visible leak”), low leakage (a level of tightness sufficient in many industrial applications), and “bubble tight” (extremely high degree of fluid tightness, such as required in toxic or flammable applications) [Zappe].

A word of caution: Some quarter turn manual valves (ball, plug, butterfly) have enough mechanical clearances and play in the closed position that they may still leak when shut. Valves with play in the closed position should not be used where leakage is a concern. In Figure 3.1-1, the valve has some play in the full close position and leaks through its seat.

Gate Valve

A gate valve is a block valve intended to operate fully open or fully closed. The gate, which can be solid or flexible, is moved by linear motion of the stem, Figures 3.1-2 to 3.1-5.

Globe Valve

The disc, ball or plug of a globe valve is moved by linear motion of the stem. The flow path and the disc-seat design permit reliable flow and pressure control, which makes the globe valve particularly well suited for regulating service, in addition to its use as a block valve, Figures 3.1-6 to 3.1-8.

Conventional globe valves with stem at right angle of body cause several changes in flow direction and relatively larger pressure drops than most other control valves. The Y body valves have a stem angled relative to the body, a smoother flow profile and less pressure drop. Angle body valves (L shaped) have an outlet nozzle at right angle from the inlet nozzle and stem.

The Y-body globe valve of Figure 3.1-9 is a sealed valve. The process fluid is sealed from the stem and packing to prevent leakage to atmosphere.

The disc (item 11 Figure 3.1-9) may also be a plug or a cylinder. The disc guide may be a slotted cage around the cylinder that is shaped to force the flow through specially designed slots or vanes. These slots or vanes (referred to as whisper trims or tortuous path) reduce turbulence, cavitation and noise across the valve. The design, dimension and flow sizing of globe valves is controlled by the Instrument Society of America’s standards ANSI/ISA S75.15 and S75.16.

Some globe valves may be used with flow under the plug (flow direction tends to open the plug, shielding the stem packing from high pressure when the valve is closed) or flow over the plug (flow tends to close the plug, providing better leak tightness in the closed position).

Needle Valve

A needle valve is a small globe valve, with a very narrow flow passage and a needle shaped stem that acts as stem and plug, Figure 3.1-10. The needle valve has a tight threading on the stem drive which permits precise positioning. The body of needle valves is often made of machined bar stock. Needle valves are used for the very precise control of small flow rates (metering).

Plug Valve

A plug valve is a quarter turn (rotary) valve with a cylindrical or conical plug and a shaped opening (plug port), Figure 3.1-11. Plug valves with rectangular ports are used primarily as block valves, taking advantage of the short quarter-turn motion to close. Plug valves with specially shaped ports, and plug valves with an eccentric axis of rotation can also be used for flow control (throttling service). All-metal plug valves can be lubricated to prevent excessive friction, torque and galling as the plug rotates. Alternatively, an elastomer sleeve or liner can be placed around the plug to reduce friction, eliminating the need for lubricant.

Ball Valve

A ball valve is a quarter turn (rotary) valve with a spherical ball and a round or a specially shaped (characterized) opening of the ball, Figure 3.1-12. Ball valves can be used as block valves, with good leak tightness, or as flow control valves. The ball valve is useful for service with clean or dirty fluids since the ball rotates against the body, peeling debris and cleaning itself. However, if the ball is scratched or galled, the valve will leak when closed. Leak tight closure is therefore limited in practice to clean fluids. Like plug valves, ball valves can have a metal or elastomeric sealing surface. On some valves, the ball has stops and can only rotate back and forth 90^o. Other valves have balls than can rotate 360^o.

Butterfly Valve

A butterfly valve is a quarter turn (rotary) valve with a flat disc rotating around an axis, like the extended wings of a butterfly, Figure 3.1-13. A butterfly acts as a damper; when open, the disc and axis remain in the flow stream. Their great advantage is their narrow width, light weight, low cost, their frictionless rotation that requires little torque, and the simplicity of their design. They are well suited for large size, large flows and slurry service, and are often the valve of choice for waterworks. Elastomeric seats are often used, unless leak tightness is not critical, in which case metallic seats are used. Butterfly valves are available with a number of pipe end connections. Wafer butterfly valves are sufficiently narrow to be sandwiched directly between pipe flanges.

Diaphragm Valve

A diaphragm valve is a valve with a linear motion stem that pushes a flat disc (the compressor) against a diaphragm into the flow stream, Figure 3.1-14. The diaphragm seals against a weir in the valve body or against a contoured surface at the bottom of the valve body. The valve can be used as a block valve or in throttling service. In a diaphragm valve, the fluid is not in contact with the valve internals and stem packing, which makes it particularly well suited for very clean service (pharmaceutical or food processing) and for corrosive service (where the diaphragm material can be selected for its corrosion resistance). A pinch valve is similar to a diaphragm valve, but the valve body is simply a cylinder of soft material (for example polyethylene) that can be pinched closed by the linear motion of the stem.

Check Valve

A check valve is designed to permit flow in one direction while preventing reverse flow in the opposite direction. Swing check valves have a disc hinged around a pin at the top of the flow opening, Figure 3.1-15.

The flow swings the disc open. If the flow stops, the disc weight will drive it to close. If the flow reverses before the disc has fully closed, the disc closure will now be driven by the combined effect of its own weight and the force exerted by the reversing flow, which could be quite large, causing the disc to slam shut, possibly creating a water hammer or breaking the disc by impact. It is therefore important to size a check valve so that (a) the normal flow is sufficient to lift the disc out of the flow path in normal service, and (b) the disc closes before the flow has had time to reverse and slam the valve shut. Note that valve sizing relies on the weight of the disc. Therefore, it is important not to place the valve on a vertical leg if it was sized for horizontal service.

A tilting disc check valve is hinged around a pin that passes through the disc. The disc has the advantage of a shorter closing swing, allowing less time for flow reversal and slam. The disadvantage of the tilting disc check valve is that the disc remains in the flow stream during normal flow, but its aerodynamic shape is designed to reduce friction losses and pressure drop, while having the right lift and stability characteristic.

A lift check valve is a check valve that relies on the linear motion of a plug, pushed open by flow in one direction, and closing as the flow stops or reverses, Figure 3.1-16. A spring assisted lift check valve is a cross between a globe valve, a safety valve and a check valve. The body and flow channels are similar to a globe valve, and the plug is spring assisted for closure. The flow enters from under the plug. As in the case of a safety-relief valve, the flow automatically lifts the plug. When the flow (and upstream pressure) is reduced, the spring pushes the plug shut against its seat. The valve can be installed horizontal or vertical since it does not rely significantly on the plug weight to re-close.

A butterfly check valve is a butterfly valve with angled and hinged wings. The wings swing towards each other under normal flow conditions, opening the flow area; and then spring back to close the flow path when the flow stops or is reversed. A butterfly check valve can be installed horizontally or vertically.

Pressure Regulator

A regulator is a valve that balances a supply air pressure against a spring load on a diaphragm, and provides a set downstream pressure.

Figure 3.1-17 shows a dual stage regulator, with a bottom spring for first stage (for example reducing 3000 psi bottled gas pressure down to 400 psi), and the top spring is the second stage (for example further reducing the 400 psi gas pressure down to the user specified pressure).

Safety and Relief Valve

Safety and relief valves are valves that open automatically to relieve overpressure. A safety valve is used in gas or steam service and fully opens at the set pressure, Figure 3.1-18. A relief valve is used in liquid service and has an opening characteristic that varies with flow rate. Safety and relief valves perform an essential safety function by preventing overpressure ruptures in equipment, pressure vessels, and piping systems. As a result of this safety function, their design and fabrication is closely regulated in most states and in federal facilities to comply with the requirements of the ASME Boiler and Pressure Vessel code. Compliance with the ASME code is evidenced by a stamp on the safety or relief valve. For example, a relief valve that complies with the design, fabrication and quality assurance requirements of the ASME Boiler and Pressure Vessel Code, Section VIII Division 1, is stamped “UV”.

Once placed into service, the relief valve will typically be tested periodically (every year for boiler safety valves, every three to five years for process system valves). The periodic test consists in verifying that the valve pops open at the designated pressure (set-point) and re-closes as expected. Readjusting the set point is most often performed in a valve shop certified by the National Board [ANSI/NB-23], or – if valve removal is impractical – the valve is tested in place.

Valve Operators

A valve stem may be operated by one of several methods: manually, pneumatically, electrically, electro-hydraulically or by solenoid, Figure 3.1-19. Non-manual operators require an activation signal and are called actuators. These are power devices that produce torque or thrust to move the stem [Ulanski].

Manual - Manual operation of a hand wheel, or a handle or lever for quarter turn valves, through a gear box, limiting the torque to approximately 80 ft-lb. A chain is provided to operate elevated valves, with a retaining clamp to avoid the risk of the chain falling on the operator.

Pneumatic - Pneumatic actuators rely on air pressure (air operated valves AOV). On receipt of an electric signal (of a few milliamperes) or a pneumatic signal (3 to 10 psi) from a positioner, plant air (60 to 150 psi pressure, or higher pressures to overcome high pressure flow, regulated to a pressure compatible with the actuator) is introduced into the actuator housing and deforms a diaphragm or drives a piston, which in turn moves the valve stem. Some pneumatic actuators require air to open and air to close (double-acting). Other actuators (called diaphragm-and-spring actuators) have a spring that will automatically return the valve to an open or a closed position on loss of air (single acting, fail-open or fail-closed). A direct acting valve is when the spring fully retracts the stem on loss of pressure (fail open). A reverse acting valve is when the spring fully extends the stem on loss of pressure (fail closed).

Electric – Motor operated valves (MOV) rely on electric power (often 110 V ac power) to activate a gearbox that drives the valve stem. A motor operated valve can develop very high thrust forces necessary to open or close against high pressures and high flow rates. The actuators fail in position, which can be an advantage if the fail-open or fail-closed mode of a pneumatic valve is not desired. MOVs generally have a slower motion. Motor operators tend to be heavy, and require specialized maintenance.

Electro-hydraulic - Electro-hydraulic actuators rely on a motor driving a pump to fill either side of a piston with hydraulic fluid; the piston's stroke drives the valve stem. It is generally a fast acting valve that can develop very large opening or closing thrust forces, and can provide fail-safe function.

Solenoid - The solenoid valve relies on an electromagnetic force generated through a solenoid to move a disk directly or to initiate the piloting action that allows system pressure to open the main orifice.

3.2 Earthquake Performance

The study of valve behavior during large earthquakes has lead to the understanding of several key seismic vulnerabilities:

Brittle materials:	Valves with cast iron bodies are more prone to failure than steel valve bodies, due to the low toughness of cast iron, Figure 3.2-1. Note that the ASME B31.3 Process Piping design allowable stress for cast iron is 10% of the ultimate strength; it is 20% of the ultimate strength for malleable iron, and 33% of the ultimate strength for steel. A typical failure mode for a cast-iron body is fracture at the location where the valve body necks down at the transition between the body and the nozzle flange, Figure 3.2-1. This failure mode is also typical in waterhammer-induced failures of cast iron valves.
Impact:	Valves have failed by impact on adjacent structural or building components (such as columns and hand rails) particularly when the valve is mounted on a flexible line. In Figure 3.2-2 the earthquake caused the pipe span to swing and the valve cast iron yoke impacted the column 2" away, causing the yoke to crack. The arrow in Figure 3.2-2 indicates where the yoke has been repaired by a stiffening plate.
Mechanical joints at nozzles:	If the valve is connected to the piping through non-welded mechanical joints other than pipe flanges, the nozzle joints could deform and leak, Figure 3.2-3.
Hard spot:	If the valve operator is braced directly to the wall but the pipe span is flexible, the operator could fail from large reaction loads developed as the pipe span tries to swing and is held back by the brace on the operator.
Large eccentricity:	The seismic acceleration applied to the valve center of gravity may result in excessive moments that fail the operator or its connection to the valve body. ASME-QME has adopted a moment arm limit to avoid this effect: the distance between the operator center of gravity and the pipe centerline should not exceed 45" for 4" and smaller valves, and 60" for

	valves larger than 4”.
Large motor operated valves:	Seismic induced malfunctions have been reported as a result of loss of power to motor operator, flooding of motor operator, pullout of motor operator support anchor bolts, and tilting of operator.
Solenoid operator:	Seismic malfunctions have been reported as a result of loss of power, and earthquake vibration causing erroneous signal to solenoid operator.
Valve system:	Seismic failures or malfunctions have occurred due to loss of signal or controller, loss of instrument air (tubing joint pulls open by differential motion), and erroneous signal caused by vibration and sloshing of mercury switch. In Figure 3.2-4 the earthquake caused the pilot air tubing to pull out of the threaded connection, rendering the valve inoperable.

3.3 Test Performance

The methods and criteria for shake table testing valves are described in Chapter 2. This section describes the results of shake table tests on valves. Detailed data on seismic shake table testing is not commonly published, and the overview presented here is meant more as an illustration of the common seismic weaknesses identified by testing, rather than an attempt at drawing general conclusions regarding seismic adequacy. Another difficulty with seismic testing is that shake table tests are often conducted for the nuclear power industry, at enveloping, very high seismic input, in the order of 10 g peak spectral acceleration at 5% damping, with high frequency (zero period accelerations) in the order of 2 g; a seismic level much higher than typical building code design accelerations.

Of twelve control valve tests, none showed a loss of pressure boundary integrity (out-leakage). Several valves leaked through the seat during or after the shake table test, but the leak rates (bubbles per minute or gallons per hour) were within the test acceptance limit, and in most cases the pre- and post-test leak rates were not different, in other words, the seat were not leak tight before the shake table test.

Of seven check valve tests, none malfunctioned or failed.

Of two pressure relief valve tests, both resulted in chatter (burst discharge during testing) and leakage at end of test.

3.4 Analytical Qualification

3.4.1 ASME B31

The piping and pipeline design and construction code ASME B31 refers to ANSI B16.34 for acceptable valve materials, pressure-temperature ratings, minimum wall thickness, end-to-end dimensions, shell testing (150% hydrostatic pressure test) and through-seat tightness test (110% through-seat leak test). These requirements apply to valve qualification for design and normal operating pressure and temperature, but do not seismically qualify the valve.

ASME B31.1 “Power Piping” provides seismic stress limits for the piping and piping connection to the valve but not for the valve itself. In piping stress analysis, the manual valve is modeled as a concentrated weight, in-line with the pipe span. For piping, the sum of longitudinal stresses due to sustained loads (pressure and weight) and occasional loads (the earthquake in our case) are limited to a multiple of the code allowable stress

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

P = operating pressure concurrent with earthquake, psi
D = pipe outside diameter, in
t = pipe wall thickness, in
M_A = resultant moment due to sustained loads (typically weight), in-lb
M_B = resultant moment due to earthquake, in-lb
Z = pipe section modulus, in^3
k = factor given in piping design code, ranges between 1.2 and 3
S_h = code allowable stress for the pipe material at operating temperature concurrent with earthquake, psi

The need to include the operator in the piping model depends on the operator weight. Typically, if the operator weighs more than 10% the weight of the valve body-bonnet assembly than the operator is modeled as an eccentric mass in the piping analysis, otherwise the operator weight may be neglected. For example, in the seismic evaluation of the piping with the air operated valve of Figure 3.4-1, we cannot ignore the operator weight and eccentricity. Tables 3-1 and 3-2 are examples of valve and operator weights. The operator weight may vary from valve to valve, and the actual weight should be used in any evaluation.

Pipe size (in)	Class 150	Class 300	Class 400	Class 600
2”	50	100	100	100
4”	200	200	250	250
6”	400	400	550	550
8”	500	600	800	800
10”	1200	1200	1500	1500
12”	2000	2000	2400	2400

Table 3-1 Manual Steel Globe or Gate Valves, Schedule 40 (lb)

Actuator Dia.	5”	10”	15”	20”
Approx. Wt.	100	300	700	2000

Table 3-2 Pneumatic Actuators (lb)

Heavy valve operators (such as motor operators, or the air operator in Figure 3.4-1) should be modeled as a separate eccentric weight in the piping analysis. If vendor allowable loads are provided (for example nozzle limit loads or operator acceleration limits) they should be met. Otherwise, the nozzles are qualified by applying the applicable stress intensification factors in accordance with ASME B31, and – for flanged joints – the moment-equivalent-pressure rules of ASME III, which converts the applied moment at the nozzle flange (due to the seismic plus concurrent operating loads) into an equivalent pressure P_{eq}

$$P_{eq} = \frac{16M}{\pi D_g^{\,3}}$$

P_{eq} = equivalent pressure, psi
M = applied moment, in-lb
D_g = mean gasket diameter, in

The equivalent pressure P_{eq} is then added to the operating pressure P_{op} and compared to the flange rating to confirm that the flange joint will not leak during the earthquake. Alternatively, the flange-bolts-gasket assembly may be analyzed by finite element methods to verify the adequacy of the preload on the gasket (compared to gasket manufacturer or ASME VIII Div.1 Appendix 2 limits), and the stresses in the flange assembly (compared to ASME VIII Div.1 Appendix 2 limits) under combined normal operating and seismic loads.

3.4.2 ASME III

Section NB-3524 of the ASME Boiler & Pressure Vessel Code, Section III, “Nuclear Components” states that “under earthquake loadings the piping system, not the valve [body], will be limiting”. The valve operator must be evaluated separately. This evaluation of the operator “may be performed based on static forces resulting from equivalent earthquake accelerations”. Note an important point: the earthquake acceleration is transmitted to the valve through the response of the pipe which may be amplified relative to the input floor excitation. It is this amplified excitation that must be applied to the valve. An example of such “in-line” amplification is provided in IEEE-382.

These ASME III design rules address position retention and leak tightness of the pressure boundary, they do not address, and therefore do not guarantee, seismic operability of the valve or valve system, as described in section 3.1.

3.4.3 ASME QME

ASME QME Qualification of Active Mechanical equipment Used in Nuclear Power Plants provides rules, and an example, for the seismic qualification of valves by analysis. The analytical steps are:

A finite element lumped mass, beam, and plate or shell model of the valve assembly is developed.

The valve is analyzed by static, response spectrum or time history methods. Damping values are in accordance with ASME III (Chapter 2).

Loads are combined to add the seismic loads to the concurrent operating loads.

The pressure boundary components are qualified in accordance with ASME III.

3.4.4 Valve Operator

The engineer must apply judgment to recognize the few cases when a valve operator is sufficiently large and heavy to warrant a separate analysis. In this case, the analysis must estimate the seismic acceleration at the valve center of gravity a_X and a_Y, and the resulting inertial moment on the weak section of the body, body-bonnet or yoke:

$$M = W_V L \sqrt{a_X{}^2 + a_Y{}^2}$$

M = inertial moment, in-lb
W_V = valve weight, lb
L = distance from operator center of gravity to weak section, in
a_X and a_Y = lateral accelerations at the operator center of gravity, g's

Accelerations a_X and a_Y are obtained as standard output of a pipe stress analysis using commercial pipe stress analysis software. The moment M is calculated at the weakest section along the load path and compared to the section's capacity. This may be the body-bonnet bolts or the valve yoke.

In some cases, the valve manufacturer may specify nozzle load limits or valve or operator acceleration limits, typically in the range of 2g to 6g.

On the basis of work performed for the Seismic Qualification Utilities Group (SQUG), ASME QME-1 has adopted an experience-based eccentricity moment limit on motor, piston and air operated valves, as provided in 3.2.

3.5 Maintenance and Reliability

It is important to first review and understand the degradation mechanisms that can cause a valve to leak and malfunction, and then infer how these weaknesses could be compounded in case of earthquake: predictive maintenance records of equipment are a window into their seismic vulnerability. The seismic evaluation of installed, operating systems must account for the material condition, present as well as projected into the future. As a result of seismic field inspections, it is common for seismic retrofit programs to discover degraded conditions which are acted upon and result in maintenance and housekeeping improvements.

Following are parameters to consider in maintenance and reliability assessment, as they relate to seismic performance of valves.

3.5.1 Corrosion and Fouling

Corrosion or fouling (deposits) of valve internals cause valves to stick in position, and fail to open or close, Figure 3.5-1, or to leak through the seat when shut. On check valves, the deposition of dirt or corrosion products is the primary cause of through-seat leakage, with seat surface wear being the second [ICDE]. External corrosion on outdoor unpainted valves is common and is not, by itself, a cause for malfunction or seismic vulnerability, Figure 3.5-2.

3.5.2 Packing

Out-leakage of fluid through the stem packing is a common cause of corrective maintenance on valves. The packing gland has to be retightened periodically or replaced. Many types of valves and packing must also be lubricated periodically to avoid excessive friction with the moving stem. Lubrication is often required for semi-metallic packing and recommended for graphite or TFE packing.

3.5.3 Cavitation, Erosion and Wear

Cavitation, erosion or wear can cause pitting and wall thinning, which may result in leakage through the valve body (out leakage) or seat ring and seating surface (through leakage).

3.5.4 Flanged Joints

A valve nozzle-pipe and body-bonnet flange joint may leak if the flange bolts have not been torqued correctly or if the gasket is not compatible with the fluid, the pressure or temperature.

3.5.5 Aging of Elastomeric Parts

Soft goods (trims) consist of gaskets, O-ring seals, diaphragms (valve seat sealing diaphragms or air operator diaphragms), etc. They have a finite life in service depending on the environment and are often replaced at fixed intervals as part of the preventive maintenance program.

3.5.6 Stem Travel Adjustment

Sliding stems or rotary shafts are normally adjusted every time a valve is disassembled, to restore the correct travel on pneumatic or motor actuated valves.

3.6 Seismic Evaluation Checklist

On the basis of analytical, earthquake experience, test, and normal maintenance data presented, a seismic evaluation checklist is developed to assist in the qualification of the equipment. The checklists are compiled in Appendix A.

If one of these attributes is not met, seismic qualification may be established by detailed analysis, seismic testing, or by hardware modification.

Figure 3.1-1 Through-Seat Leak Test

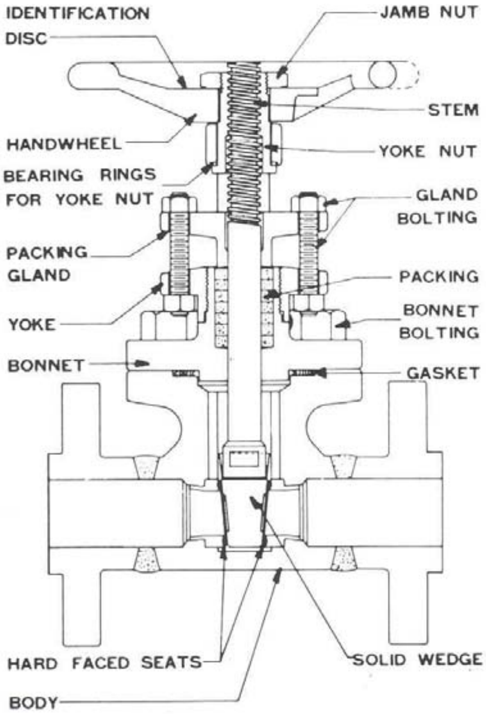


Figure 3.1-2 Solid Wedge Gate Valve

Figure 3.1-3 Valve Gate, Stem and Bonnet

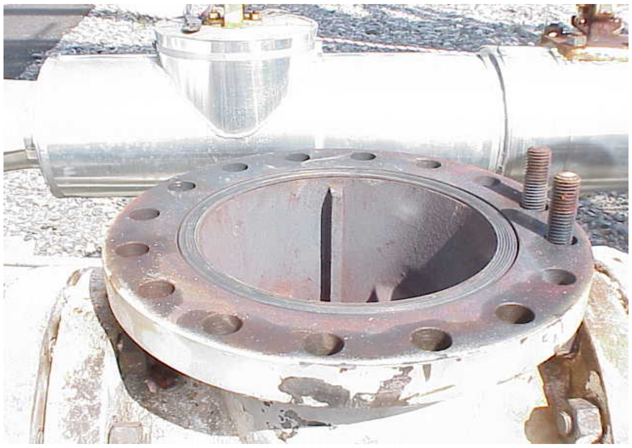


Figure 3.1-4 Valve Body and Gate Guide

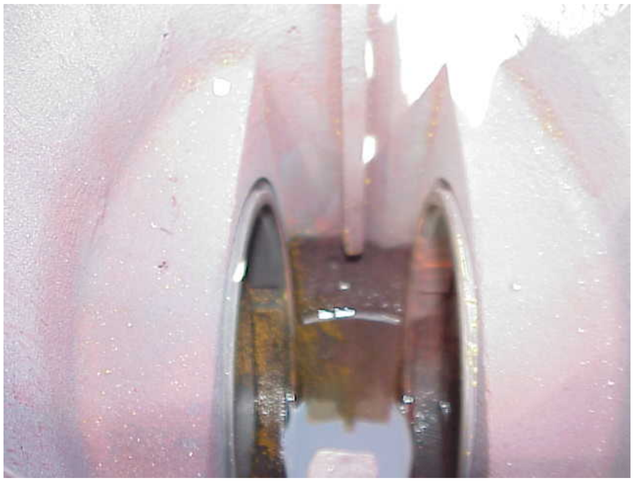


Figure 3.1-5 Gate Valve Seating Surface

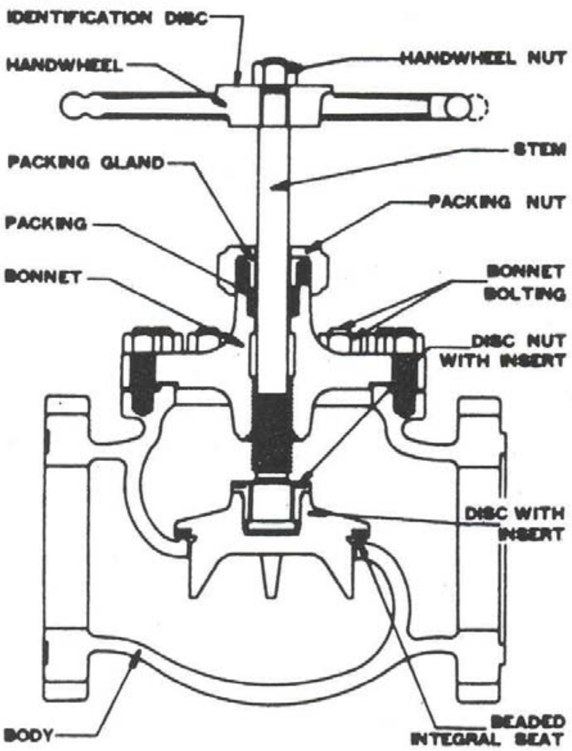


Figure 3.1-6 Globe Valve

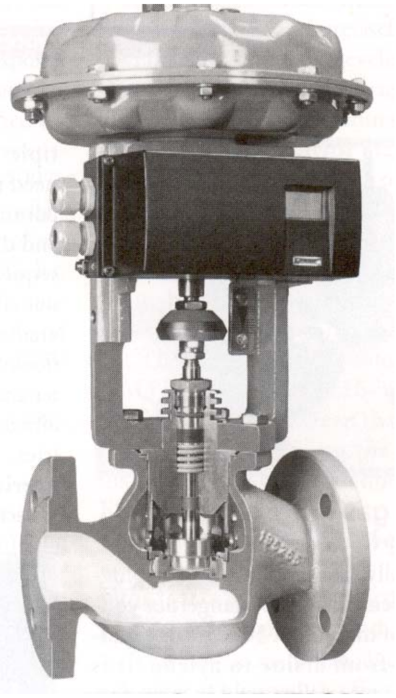


Figure 3.1-7 Air Operated Globe Valve

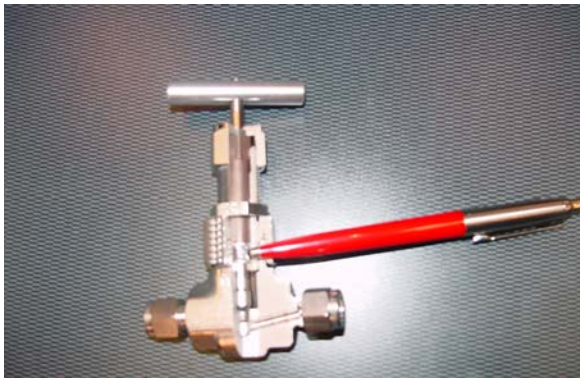


Figure 3.1-8 Instrument Tubing Globe Valve

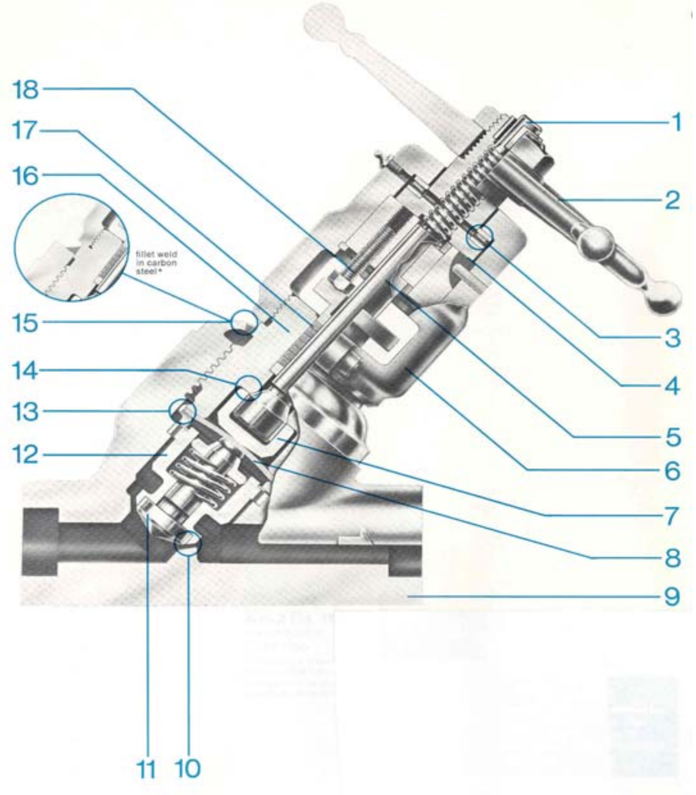


Figure 3.1-9 Y-Body Globe Valve

(1) position indicator, (2) handweel, (3) lubricated bearings to minimize torque on handweel, (4) revolving bushing to reduce stem wear and galling, (5) smooth finish stem, (6) yoke, (7) diaphragm disc, (8) flexible metal diaphragm to seal the stem area, (9) body, (10) seat, made from hard material or by weld deposition of hard face such as stellite, (11) disc, similar material as seat, (12) disc guide, (13) diaphragm seal weld, (14) secondary stem seal, (15) body-bonnet seal weld, pressure load is carried by threaded connection not by weld, this seal weld may be replaced by a bolted body-bonnet joint on many valves, (16) forged bonnet, threaded for assembly and disassembly, threads carry pressure load, (17) packing, and (18) adjustable gland screw.

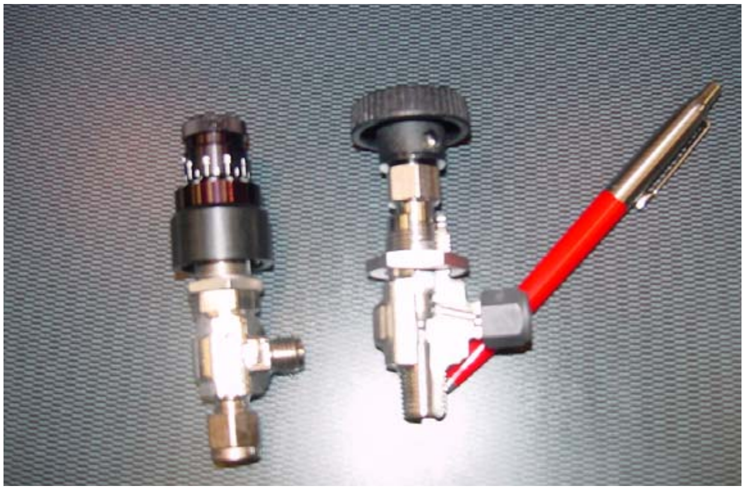


Figure 3.1-10 Left: Metering Valve, Right: Angle Needle Valve

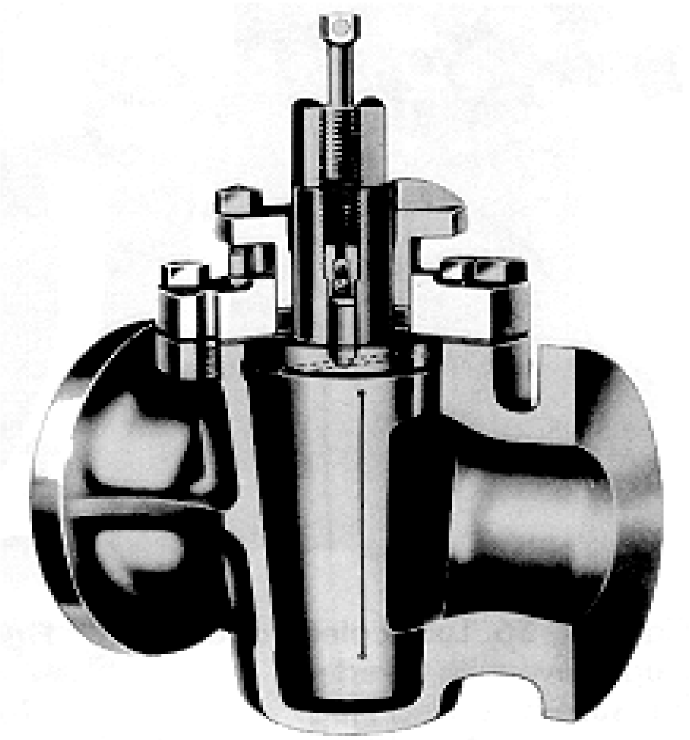


Figure 3.1-11 Conical Plug Valve

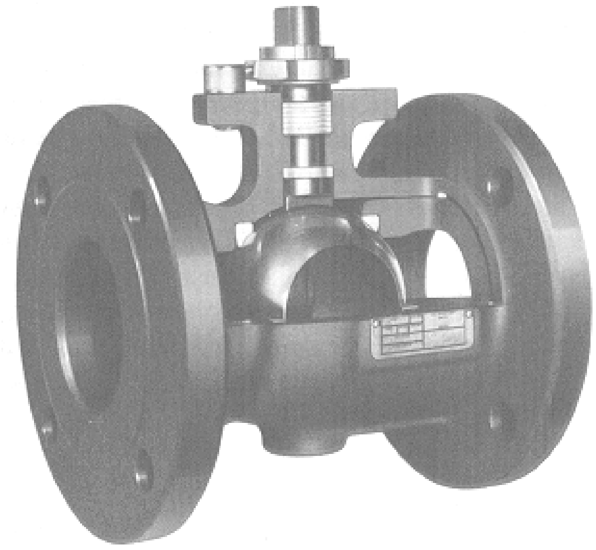


Figure 3.1-12 Ball Valve

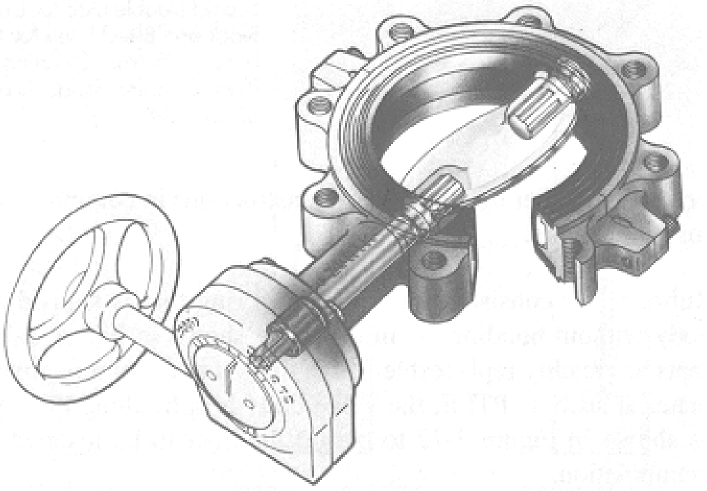


Figure 3.1-13 Butterfly Valve

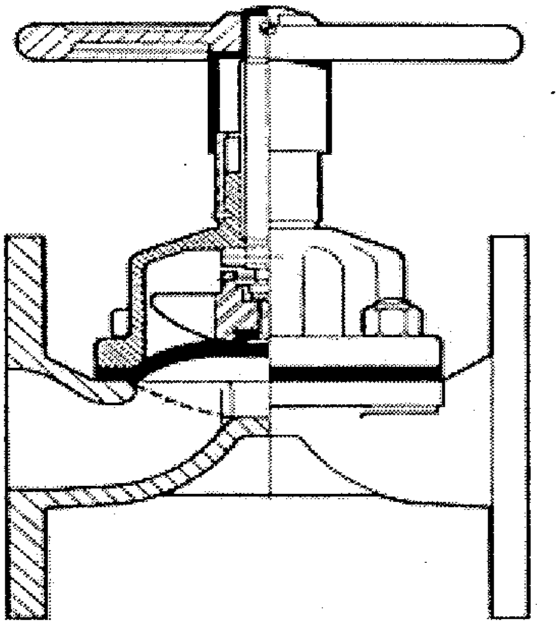


Figure 3.1-14 Diaphragm Valve

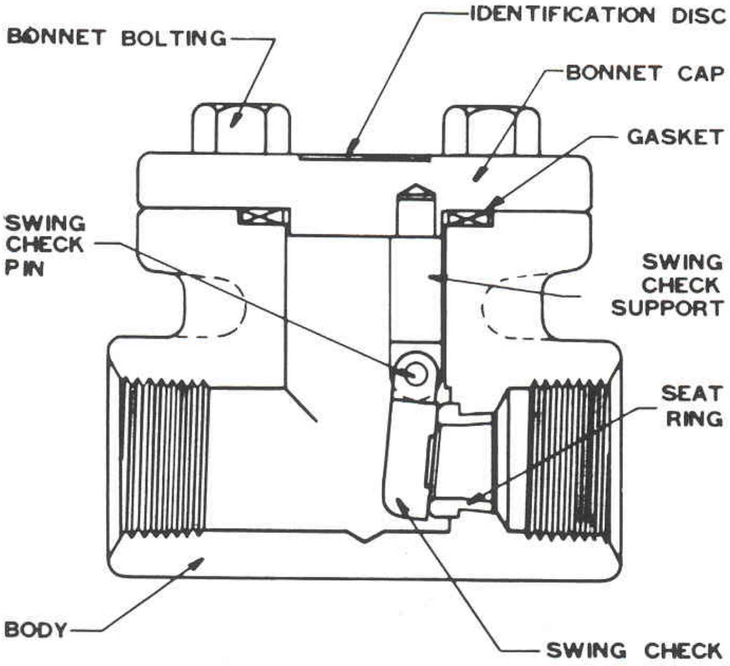


Figure 3.1-15 Swing Check Valve

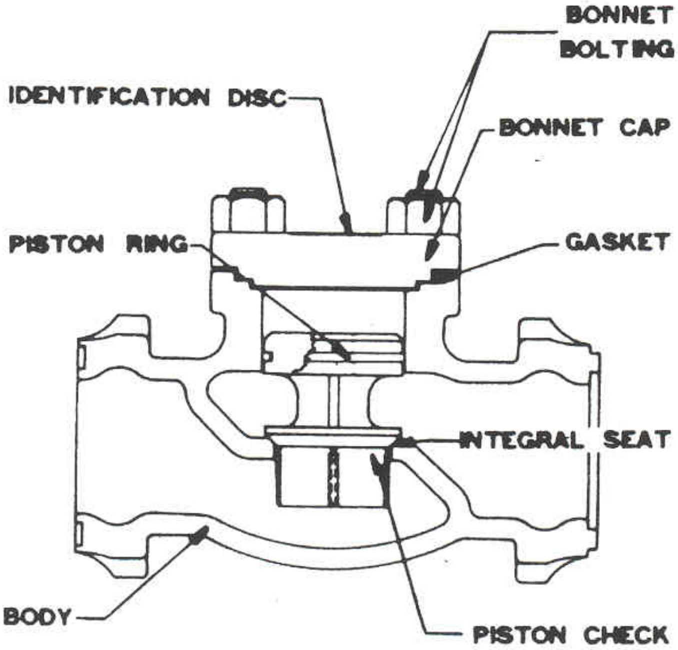


Figure 3.1-16 Lift Check Valve

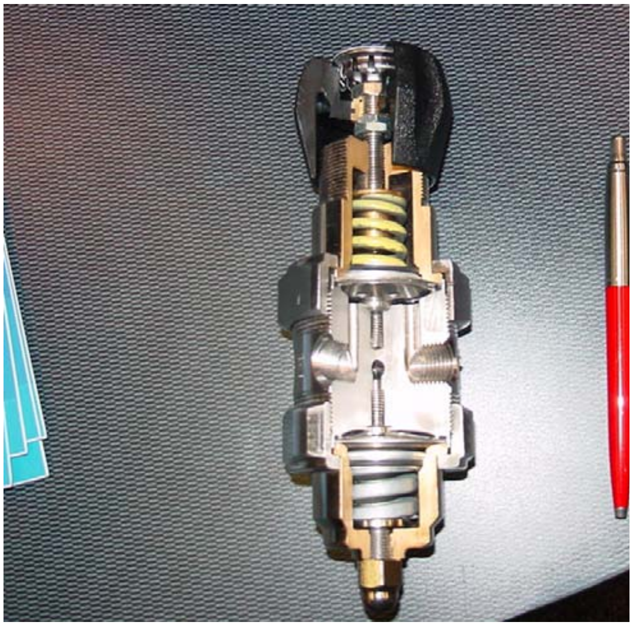


Figure 3.1-17 Dual Stage Regulating Valve

◄

Figure 3.1-18 Pressure Relief Valves

Figure 3.1-19 Valve Actuators

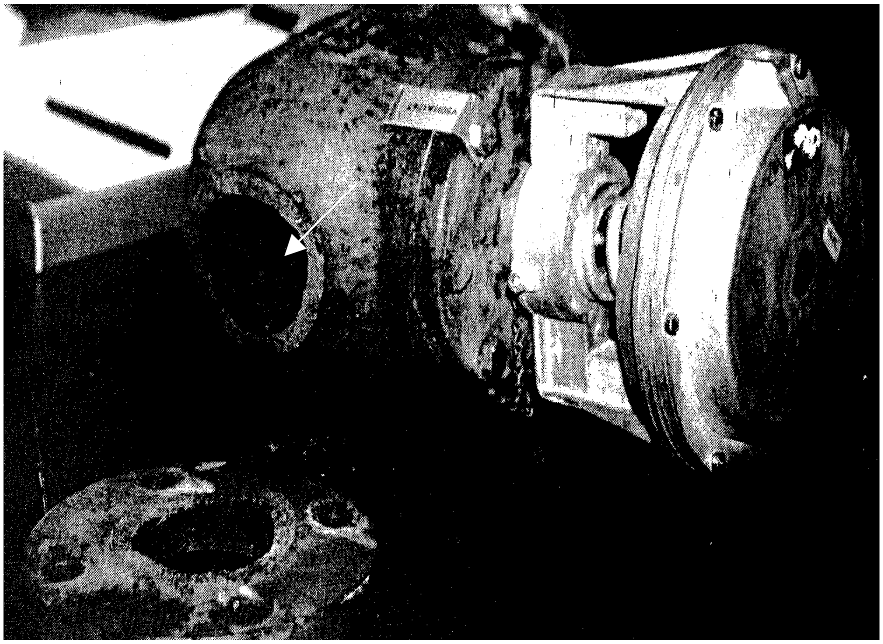


Figure 3.2-1 Failure of Cast Iron valve Body

Figure 3.2-2 Repaired Cast Iron Yoke (ABS Consulting)

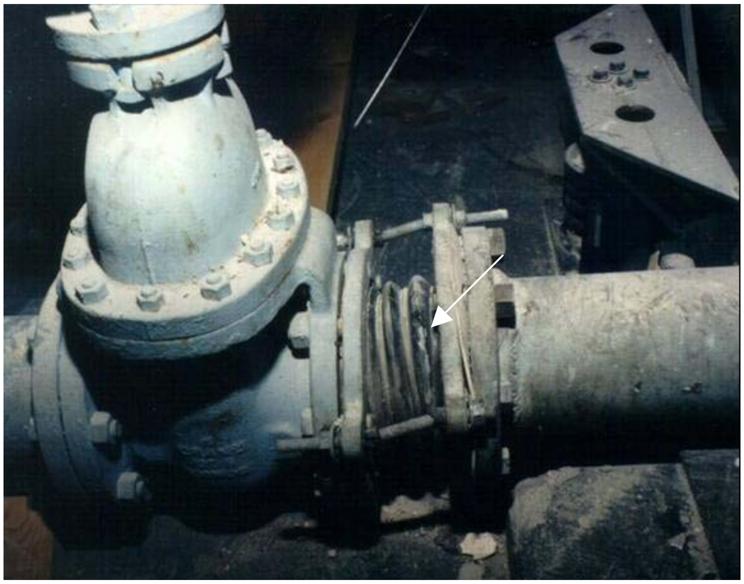


Figure 3.2-3 Bellows Joint at Valve-Pipe Nozzle (Mason Industries)

Figure 3.2-4 Failed Air Supply Tubing After Repair (ABS Consulting)

Figure 3.4-1 Air Operated Valve with Eccentric Operator

Figure 3.5-1 Corroded Valve Internal

Figure 3.5-2 External Corrosion Unpainted Valve

4.0 Pumps

4.1 Description

Pumps may be classified in two broad classes: positive displacement pumps and kinetic pumps.

4.1.1 Positive Displacement Pumps

In positive displacement pumps, volumes of fluid are forced into motion by one or more movable boundaries, such as pistons, lobes or screws. Common positive displacement pumps are: reciprocating diaphragm and piston pumps (Figures 4.1-1 to 4.1-6) for operating ranges of approximately 10 gpm at 100,000 psi to 10,000 gpm at 10 psi; and rotary lobe or screw pumps (Figures 4.1-7 to 4.1-10) for operating ranges of approximately 10 gpm at 5,000 psi to 10,000 gpm at 10 psi.

4.1.2 Kinetic (Dynamic) Pumps

In kinetic pumps, the energy is continuously added to the fluid. The most common type of kinetic pump is the centrifugal pump. Centrifugal pumps include horizontal pumps (Figures 4.1-11 and 4.1-12), with the impeller cantilevered beyond the bearings or with impeller between bearings; and vertical pumps (Figures 4.1-13 and 4.1-14). Kinetic pumps may also be classified as In-Line (suction and discharge axes are parallel); API 610 Centerline Support; ANSI B73.1 Frame Mounted; Wet Pit Volute (submersible); Axial Flow Impeller; or Magnetic Coupled (impeller magnet floats in external radial field).

4.1.3 Foundation

A pump baseplate is a structure that provides a rigid base to the pump and its driver (motor) in order to facilitate pump lift and installation, and maintain shaft alignment. Figure 4.1-15 illustrates two types of base plates: At top is a separate motor base plate and at bottom is a common motor-pump sub-base, also shown in Figure 4.1-16. The baseplate may be (a) anchored to concrete floor or free standing. For permanent installations, the baseplate may be filled with epoxy or cement grout from the floor to the bottom face of the baseplate. While most baseplates are rigidly mounted to the foundation, it is not uncommon in the chemical process industry and in utilities applications to find flexibly mounted baseplates.

In many cases, the pump is bolted to the baseplate at the factory, and the driver is left to be mounted during field installation. Shims and alignment pins are normally provided under the pump driver to permit field alignment (Figure 4.5-3). Shims are used under the base plate to level the pump shaft and achieve the desired plane for horizontal or vertical pipe flange connections. Free standing baseplates must be sufficiently rigid to provide for 10 mils maximum parallel shaft misalignment and 0.005 in/in (0.3 degrees) angular misalignment.

Baseplates are sized to permit lifting the baseplate-pump assembly without exceeding 25% of the baseplate material yield stress and normal transport and handling will subject the baseplate to shock loads of 3g vertically [HI].

4.2 Earthquake Performance

Fewer than 10 % of horizontal pumps and 5% of vertical pumps inspected following earthquakes show indication of damage. The study of pump failures during large earthquakes has lead to several observations:

(a) Failure to operate can result from pump shaft misalignment. In particular, when the motor and the pump are not rigidly connected (for example if they are not mounted on a common skid) the inertial loads can create differential motion between pump and motor.
(b) In some cases, outdoor pumps have failed to operate as a result of soil failures under the concrete base mat. In Figure 4.2-1, the ground beneath the pump skid settled relative to the pipe, causing failure of flange connections.
(c) Pumps have failed to operate and pump anchor bolts have ruptured as a result of excessive seismic loads imparted by the inlet/outlet piping. In Figure 4.2-2 the pump discharge piping is connected to a chiller unit that moved during the earthquake, causing the pump casing to crack. Figures 4.2-3 and 4.2-4 show seismically induced failures of pipe supports at pump intake and discharge. Figure 4.2-12 illustrates a pipe-heat exchanger nozzle failure, it is presented here to indicate that cast iron, common in pump casings, can fail by brittle fracture under seismic induced pipe loads.
(d) Flexible bellows and hose at pump inlet or outlet may fail as a result of excessive seismic sway of the pipe. Figure 4.2-6 shows a flexible joint at a pump nozzle. These joints are added for ease of maintenance assembly and disassembly, and to minimize shaft misalignment during installation.
(e) Vibration isolators (typically springs providing isolation from the floor) tend to break or buckle if not guided laterally. Figure 4.2-7 shows two pumps, one with failed vibration isolators the other, identical, with intact vibration isolators. Figures 4.2-8 and 4.2-9 show more examples of failed pump vibration isolators. Figures 4.2-10 and 4.2-11 show how failure of isolators can be avoided by providing lateral stops (snubbers, bumpers) at the pump base.
(f) Failure to operate may be caused by malfunction of instrumentation and controls.
(g) Failure may result from excessive deformation of a weak member in the load path from the pump center of gravity down to the anchor bolts.

4.3 Test Performance

Functional performance testing of pumps is addressed in Hydraulic Institute Standards. [HI 1.6, 3.6, 6.6]. Unlike valves, there are few pump shake table tests, and practically none that have been published. One pump test reviewed is that of a horizontal vacuum pump; the pump performed satisfactorily during and after the test at 7g to 9g peak spectral acceleration and 4g ZPA (5% damping).

4.4 Analytical Qualification

4.4.1 ASME III Design Rules

The ASME Boiler and Pressure Vessel Code, Section III, Division 1, has explicit analytical design rules for pumps used in nuclear power plants. The design rules address the following areas:

a. Loads from connected piping must be considered in the design of the pump casing.
b. Earthquake loads must be considered with concurrent operating loads in the design of the pump, pump supports and restraints, and driver-pump structures.
c. Pressure boundary welds must be designed following pressure vessel rules.
d. Peak stresses at shape discontinuities causing stress concentration must be qualified by experimental stress analysis or satisfactory performance.
e. Inlets and outlets must be qualified as vessel openings, with a wall thickness at least that of the casing over a distance $0.5\ (rt)^{0.5}$ before tapering down to the pipe wall thickness.
f. Attachments must be designed to minimize stress concentration, following pressure vessel design rules.
g. Supports must be designed in accordance with component support design rules of ASME III Subsection NF.
h. For certain pumps, casing thickness is specified as

$$t = \frac{2}{3}\frac{PA}{S_m}$$

P = design pressure, psi
A = pump casing diameter, in
S_m = ASME III code material allowable stress intensity, psi

Qualification by analysis of pumps can be accomplished by hand calculations and finite element analysis. Qualification by analysis entails verification of the integrity of the pressure boundary (the pump casing) and pump shaft deflection. Qualification by analysis is the typical approach in verifying the adequacy of the load path and anchor bolts. Qualification by analysis does not address pump operability. To operate following the earthquake, the pump must have an intact motor, electrical supply and controls.

4.4.2 ASME QME Qualification

ASME QME Qualification of Active Mechanical equipment Used in Nuclear Power Plants provides rules, and an example, for the seismic qualification of pumps by analysis. The analytical steps are:

a. A finite element lumped mass – beam model of the pump-motor assembly is developed.
b. The pump is analyzed with static, response spectrum or time history input. Damping values are in accordance with ASME III (Chapter 2).
c. Loads are combined to add the seismic loads to the concurrent operating loads.
d. The pressure boundary components are qualified in accordance with ASME III.
e. The support structure is qualified in accordance with ASME III NF; the rules of AISC and ACI-318 Appendix D may also be used.

In order to establish operability, stress, load and differential deflections are compared to manufacturer limits. These include: pump shaft bearing pressure, motor up-thrust and down-thrust loads, shaft-bushing relative displacement, shaft-seal relative displacement. The computed relative displacements between the shaft and the bushing are typically limited to 75% of malfunction limits provided by the manufacturer.

4.4.3 Pipe Loads

Loads (forces and moments) imposed by the inlet and outlet piping will cause:

(1) Stress in pump nozzles resulting from forces and bending moments,
(2) Distortion of internal moving parts affecting critical clearances,
(3) Stresses in pump hold-down bolts,
(4) Distortion in pump supports and baseplates causing shaft misalignment.

API Standard 610 (Centrifugal Pumps for Refinery, Heavy Duty Chemical, and Gas Industry Services) provides guidelines for limiting the magnitude of nozzle loads and moments on pumps with suction nozzles 16 in (41 cm) and smaller and with casings constructed of steel or alloy steel.

If an expansion joint is used at the pump nozzle, the joint bellows tend to open as an accordion when pressurized. As a result, an unbalanced thrust force P x A (operating pressure x joint internal area) is applied to the pump nozzle as it reacts the joint tendency to open when pressurized. An anchor may be installed between the joint and the pump nozzle to react this load and prevent its application to the pump assembly.

If a braided hose is used at the pump nozzle, the seismic movements of the pump must be within the braided hose manufacturer limits. If the limits are cycle dependent, then 100 earthquake cycles may be assumed, which corresponds to a peak excitation at 5 Hz for 20 seconds.

4.4.4 Shaft Deflection

Pump manufacturers rank shaft-impeller stability under lateral load by referring to a pump stability factor defined as (Figure 4.4-1)

$$\text{Pump stability factor} = PSF = ISF + SSF + BSF$$

PSF = pump stability factor
ISF = impeller stability factor = L^3/D^4 with 20 considered very good, while 30 a maximum.
BSF = bearing stability factor = $S L^2 / D_B^4$ with 10 considered very good, and 60 high.
SSF = seal stability factor= T^3 / D^4 with 5 considered very good, and 40 high.
L = impeller-side bearing to impeller
D =shaft diameter at seal
D_B = shaft diameter between bearings
T = impeller-side bearing to seal

A large PSF indicates low stability in normal service (long, thin shafts) and as a consequence more vulnerability to lateral seismic loads.

4.5 Maintenance and Reliability

The review of maintenance records is of interest in uncovering failure causes and failure modes that could be exacerbated by an earthquake.

Large industrial pumps, subject to heavy duty, are inspected in service at a frequency set by the manufacturer or by operating experience. For continuous heavy industrial duty, pumps are inspected daily for noise and vibration. Every few weeks or months the pump vibration may be recorded and analyzed for evidence of incipient malfunction. Figures 4.5-1, 4.5-2 show recording of the vertical vibration of a centrifugal pump motor.

Periodic maintenance also includes oil analysis and thermography for hot spots indicating unusual friction. Semi-annually or annually pumps undergo an overhaul including checks, adjustments, and replacements if necessary, of packing, seals, and bearings, as well as calibration of instruments and controls. As part of the periodic predictive maintenance program, technicians also examine the general condition of the equipment for signs of wear and tear, including corrosion, Figure 4.5-3.

The evaluation of seismic adequacy of existing pumps must address the operational history of the pump, through review of its maintenance records and interview of maintenance personnel. The causes of pump malfunction may be classified as mechanical, sealing related or bearing related, with the intent of pointing out those attributes that could be caused or worsened by an earthquake, noted “(eq)” in the following list.

4.5.1 Mechanical Malfunction

- Foreign matter in impellers.
- Misalignment (eq).
- Foundation insufficiently rigid (eq).
- Loose foundation bolts (eq).
- Loose pump or motor bolts (eq).
- Inadequate grouting of baseplate.

- Excessive piping forces and moments on pump nozzles (eq).
- Improperly mounted expansion joints.
- Starting the pump without proper warm-up.
- Mounting surfaces of internal fits (at wearing rings, impellers, shaft sleeves, shaft nuts, bearing housings, and so on) not perpendicular to shaft axis (eq).
- Shaft misalignment. Alignments are in the order of 30 mils parallelism and 90 mils angular.
- Bent shaft (eq).
- Rotor out of balance (eq).
- Parts loose on the shaft.
- Shaft running off-center because of worn bearings.
- Resonance between operating speed and natural frequency of foundation, baseplate, or piping.
- Rotating part rubbing on stationary part (eq).
- Incursion of hard solid particles into running clearances.
- Improper casing gasket material.
- Inadequate installation of gasket.
- Inadequate tightening of casing bolts.
- Pump materials not suitable for liquid handled.
- Lack of lubrication.

4.5.2 Sealing Malfunction

- Shaft or shaft sleeves worn or scored at packing (eq).
- Incorrect type of packing or mechanical seal for operating conditions.
- Packing or mechanical seal improperly installed.
- Gland too tight, prevents flow of liquid to lubricate packing.
- Excessive clearance at bottom of stuffing box allows packing to be forced into pump interior.
- Rod eccentricity in stuffing box in the order of 3 mils for 10,000 psi, 7 mils for 500 psi (eq).
- Dirt or grit in sealing liquid.
- Failure to provide adequate cooling liquid to water-cooled stuffing boxes or mechanical seals.
- Incorrect type of mechanical seal for prevailing conditions.
- Mechanical seal improperly installed.

4.5.3 Bearing Malfunction

- Excessive radial thrust in single volute pumps (eq).
- Excessive axial thrust caused by excessive wear at internal clearances (eq).

- Wrong grade bearing lubrication.
- Moisture contamination of lubricant.
- Lack of lubrication.
- Improper installation of rolling element bearings.
- Dirt in bearings.
- Imbalance of hydraulic force in sleeve bearing (whirl instability).
- Rusted bearing.

4.5.4 Vibration

Earthquakes will superimpose a low frequency large amplitude vibration to the normal operating vibration. If the pump is equipped with an automatic trip on high vibration, it may shutdown automatically during the earthquake. Indeed, according to typical pump vibration charts, Figure 4.5-4, continuous service becomes unsustainable around 0.1 ips (in/sec), which for a 5 Hz seismic vibration, corresponds to an acceleration $a = \omega v = (2 \pi\ 5 \text{ Hz}) \times 0.1 \text{ in/sec} = 3.1 \text{ in/sec}^2 \sim 0.01 \text{ g}$.

It can therefore be expected that during a large earthquake a pump will be tripped off-line if it is controlled by a vibration monitor.

4.6 Seismic Evaluation Checklist

On the basis of analyses, earthquake experience, test, and normal maintenance data presented, a seismic evaluation checklist is developed to assist in the qualification of the equipment. The checklists are compiled in Appendix A.

If one of these attributes is not met, seismic qualification may be established by detailed analysis, seismic testing, or by hardware modification.

Figure 4.1-1 Diaphragm Pump

Figure 4.1-2 Removed Discharge Manifold Pipe, Two Check Valves

Figure 4.1-3 Open Liquid Side Cover Showing the Piston

Figure 4.1-4 Diaphragm Metering Pump

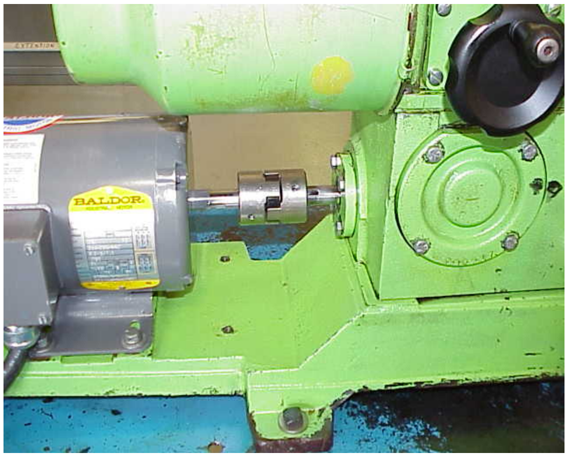


Figure 4.1-5 Motor Shaft Guard Removed to Show Flexible Coupling

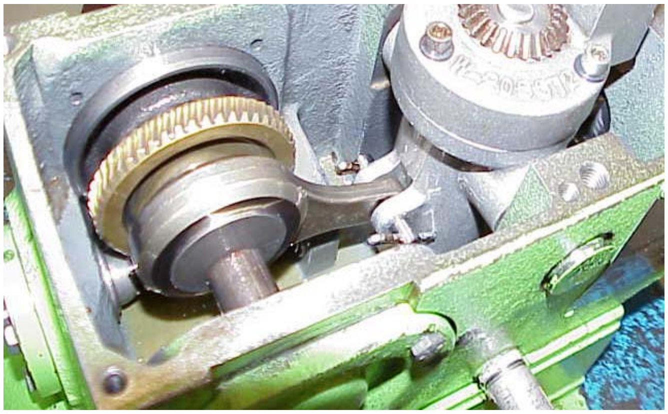


Figure 4.1-6 View of Eccentric and Speed Reducer Gear / Worm Gear

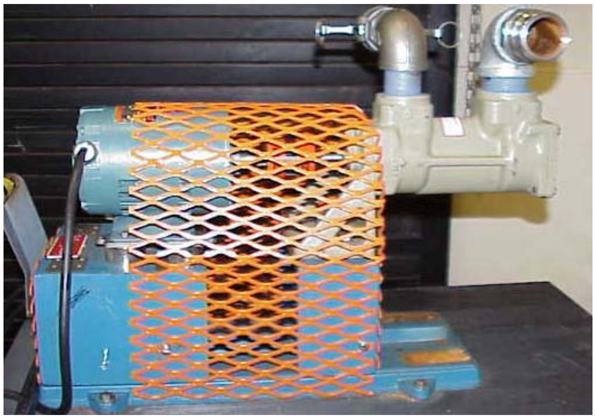


Figure 4.1-7 Rotary Screw Pump

Figure 4.1-8 Unbolt Pump from Plate

Figure 4.1-9 Power Rotor Screw

Figure 4.1-10 Two Idler Screws

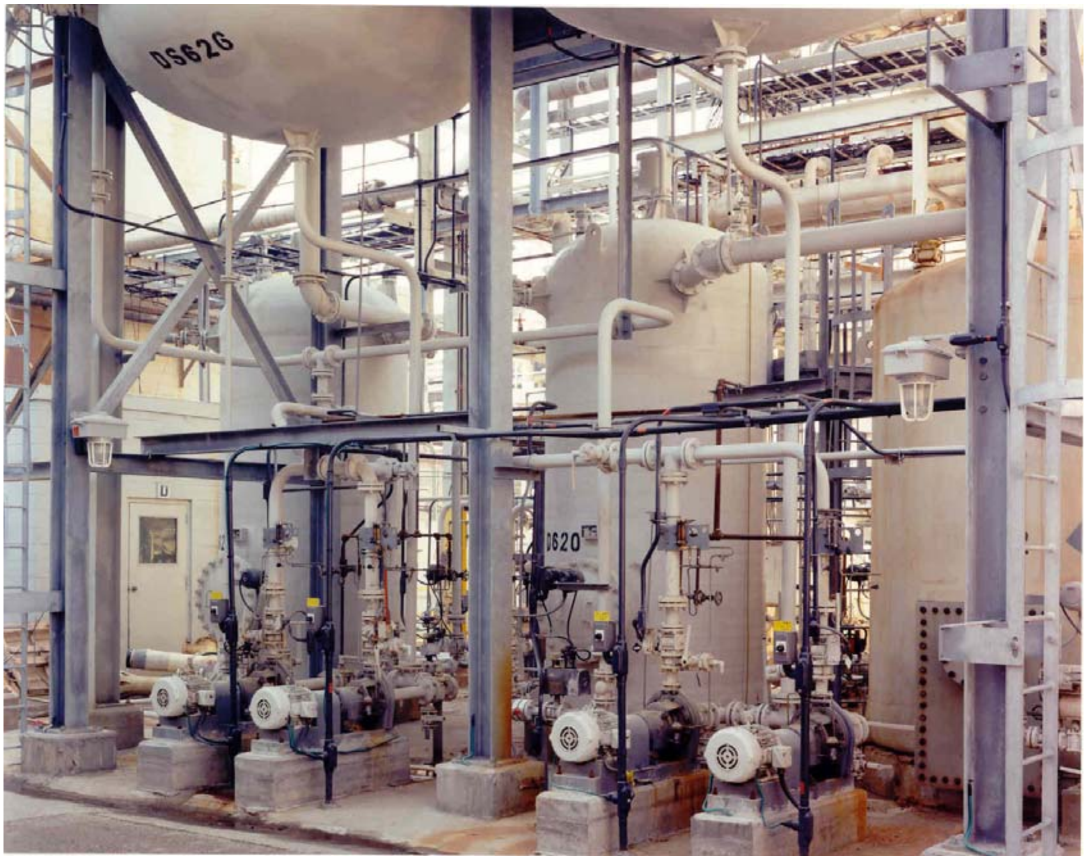


Figure 4.1-11 Four Centrifugal Horizontal Pumps on Concrete Pedestals

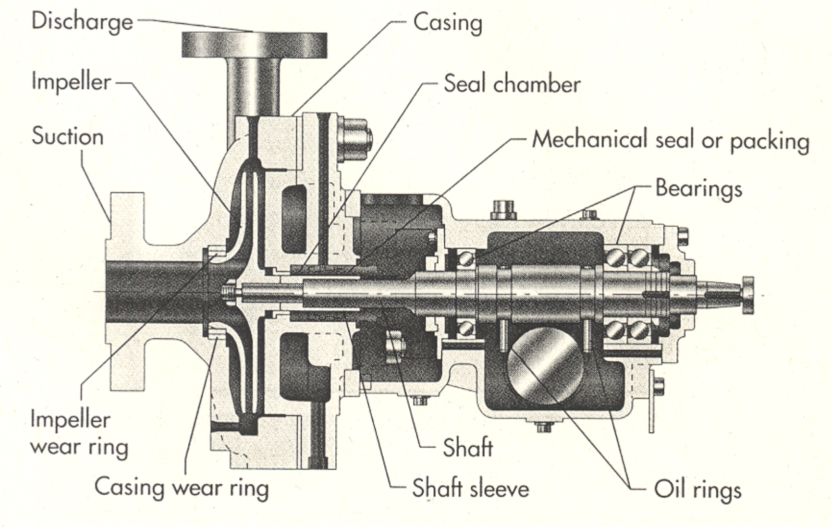


Figure 4.1-12 Centrifugal Pump

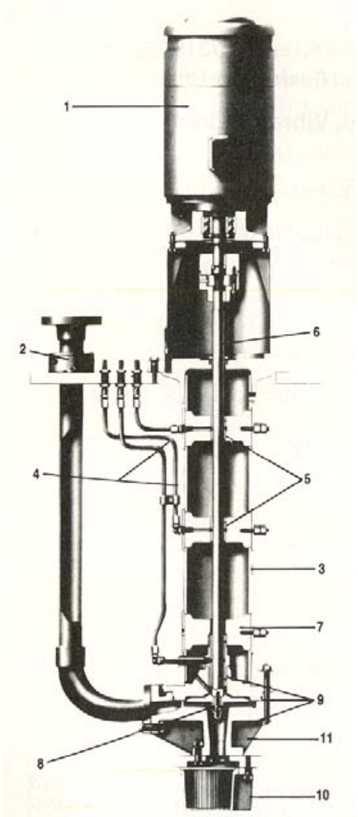


Figure 4.1-13 Vertical Immersion Pump

1 – Motor, 2 – Discharge pipe, 3 – Column, 4 – Lubricating fluid line, 5 – Shaft bearings, 6 – Shaft, 7 – Bearing retainer, 8 – Impeller, 9 – O-ring seals, 10 – Strainer basket, 11 – Impeller casing

Figure 4.1-14 Vertical Sump Pump Motor

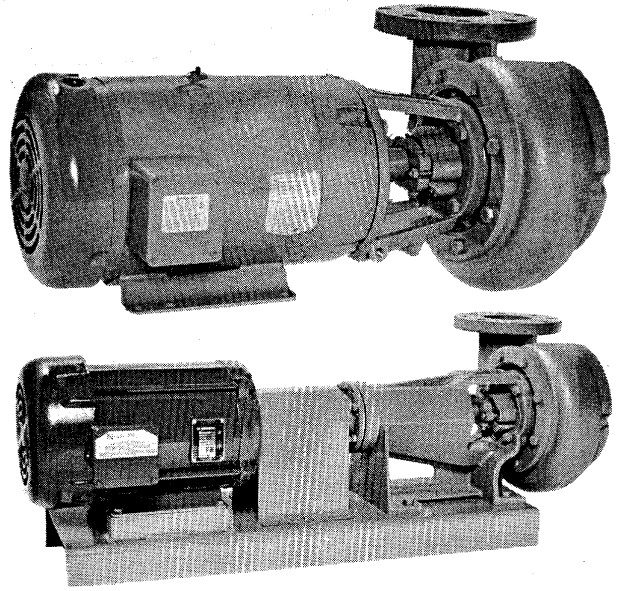


Figure 4.1-15 Pump Motor Baseplates

Figure 4.1-16 Centrifugal Pump and Motor on Common Pedestal (Mason Industries)

Figure 4.2-1 Seismic Ground Settlement (ABS Consulting)

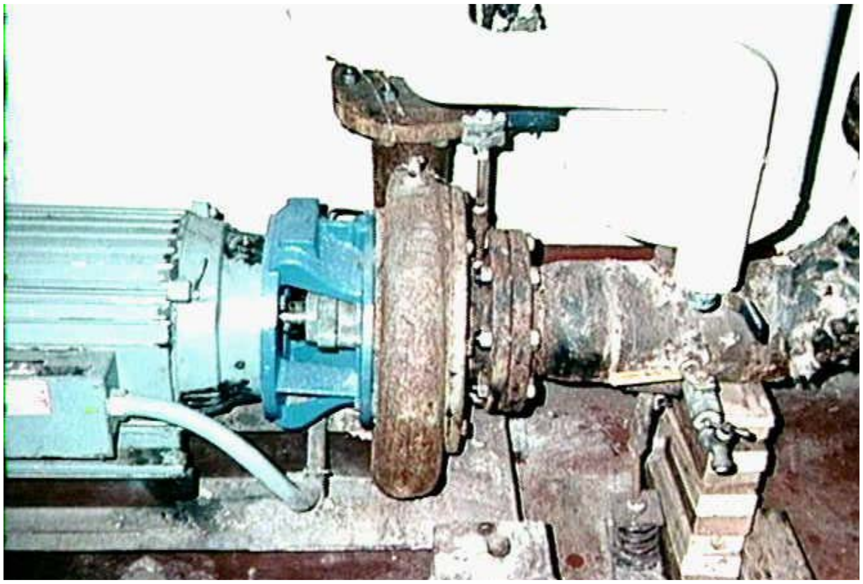


Figure 4.2-2 Large Pump Nozzle Load due to Pipe Movement (ABS Consulting)

Figure 4.2-3 Pipe Support Failure (Mason Industries)

Figure 4.2-4 Failed Pipe Support on Pump Discharge

Figure 4.2-5 Seismic Cables Restraining Pipe Sway

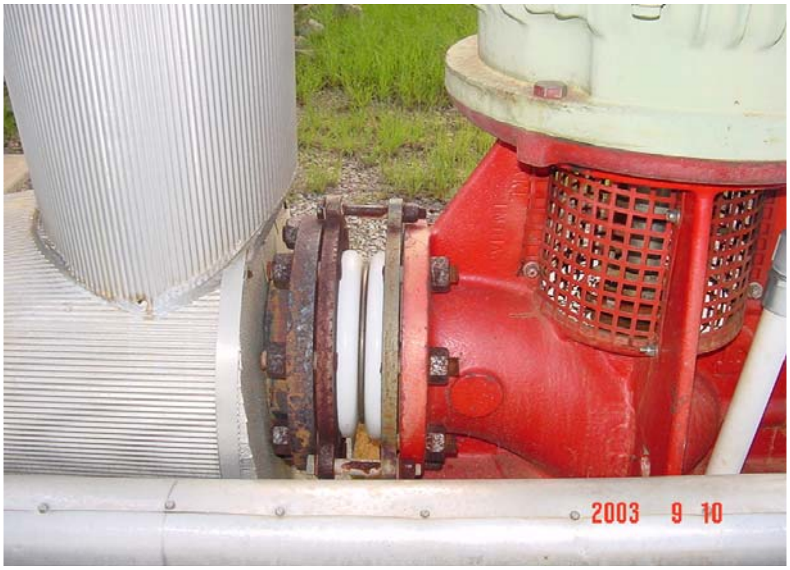


Figure 4.2-6 Flexible Joint at Pump Nozzle

Figure 4.2-7 Vibration Isolator Failure at Left

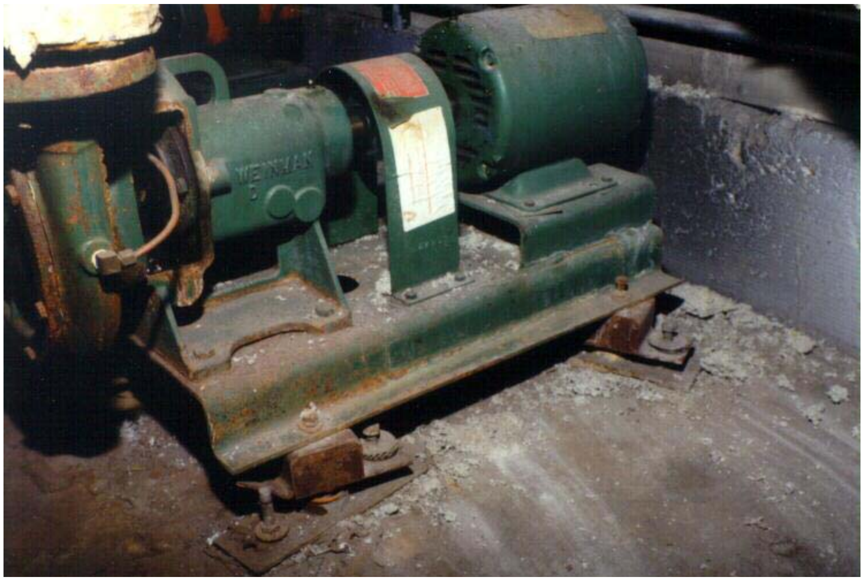


Figure 4.2-8 Pump Base Slides (Mason Industries)

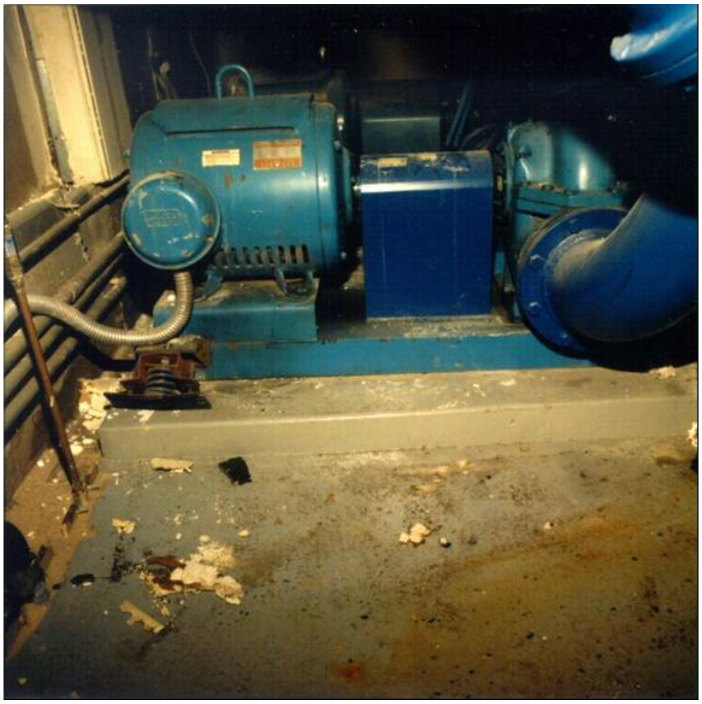


Figure 4.2-9 Failure of Vibration Isolators (Mason Industries)

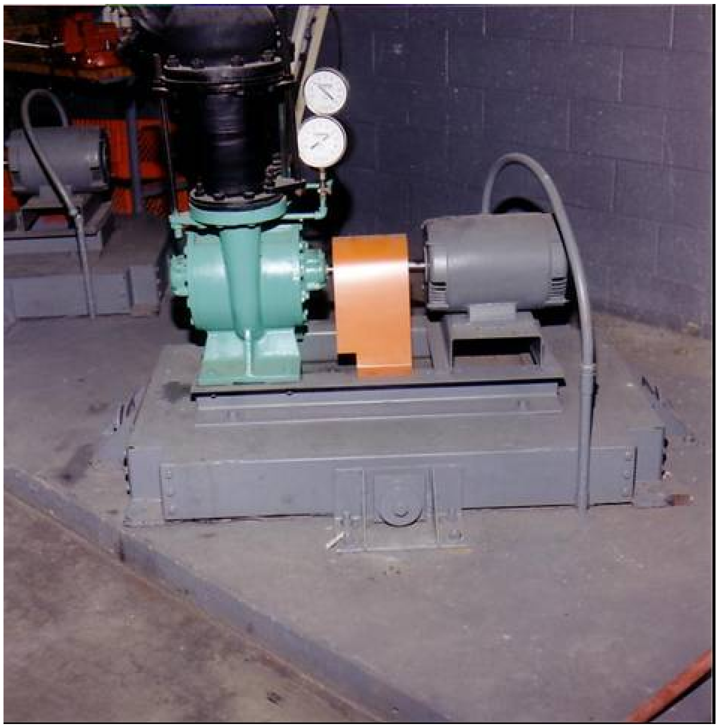


Figure 4.2-10 Lateral Seismic Stops at Pump Base (Mason Industries)

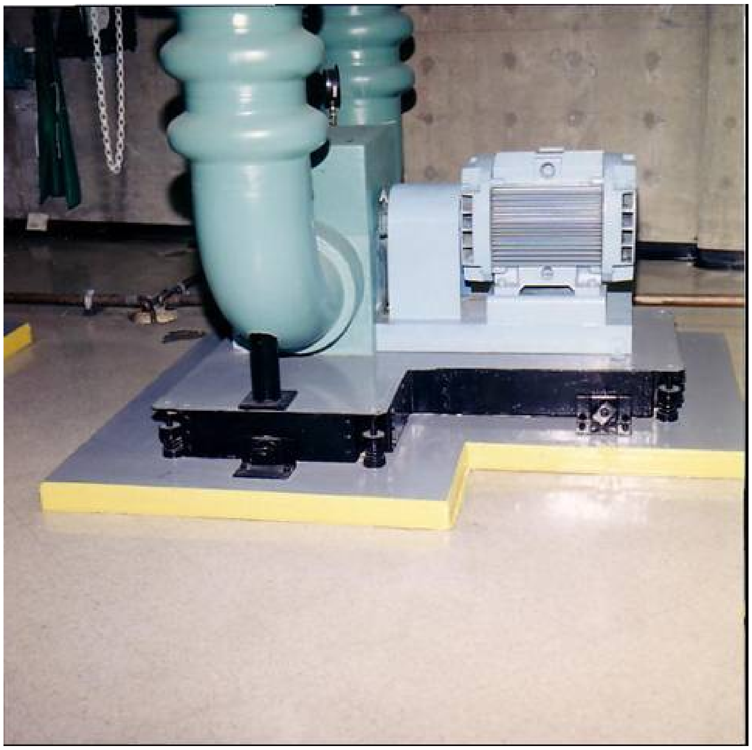


Figure 4.2-11 Lateral Seismic Stops at Pump Base (Mason Industries)

Figure 4.2-12 Tearing Rupture of Heat Exchanger Nozzle (Mason Industries)

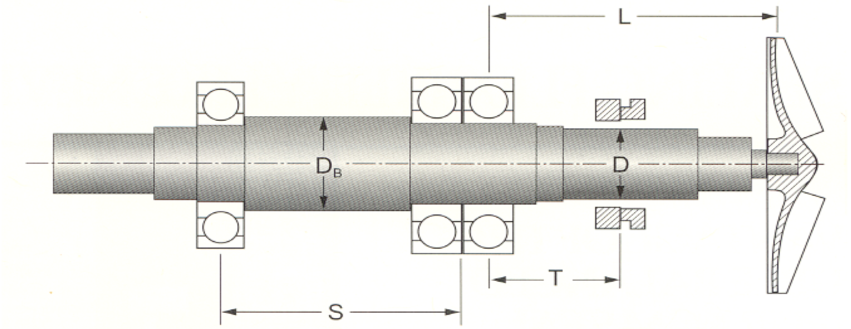


Figure 4.4-1 Pump Shaft Strength (Environamics)

Figure 4.5-1 Horizontal Pump Vibration Reading

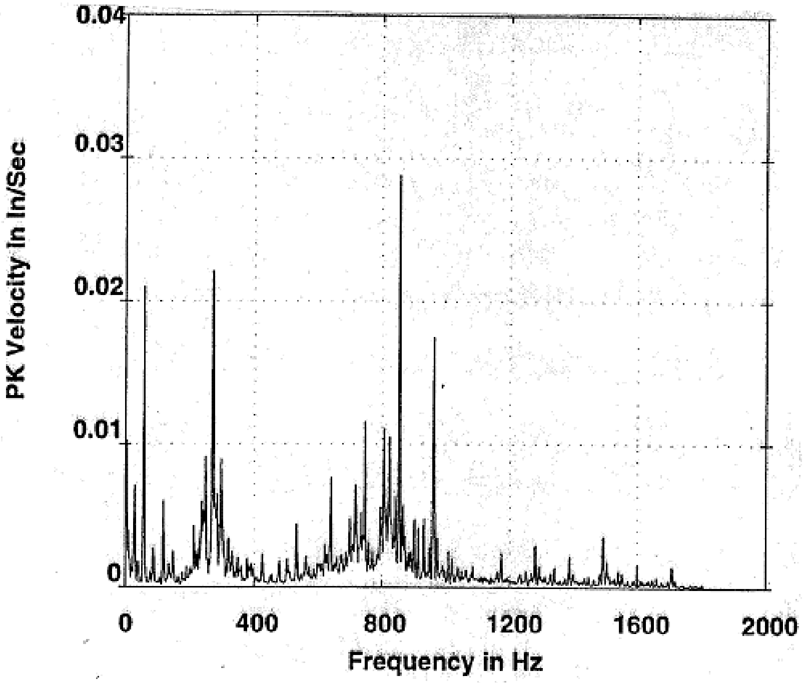


Figure 4.5-2 Spectral Plot of Pump Vibration

Figure 4.5-3 Corroded Pump Base and Alignment Pins

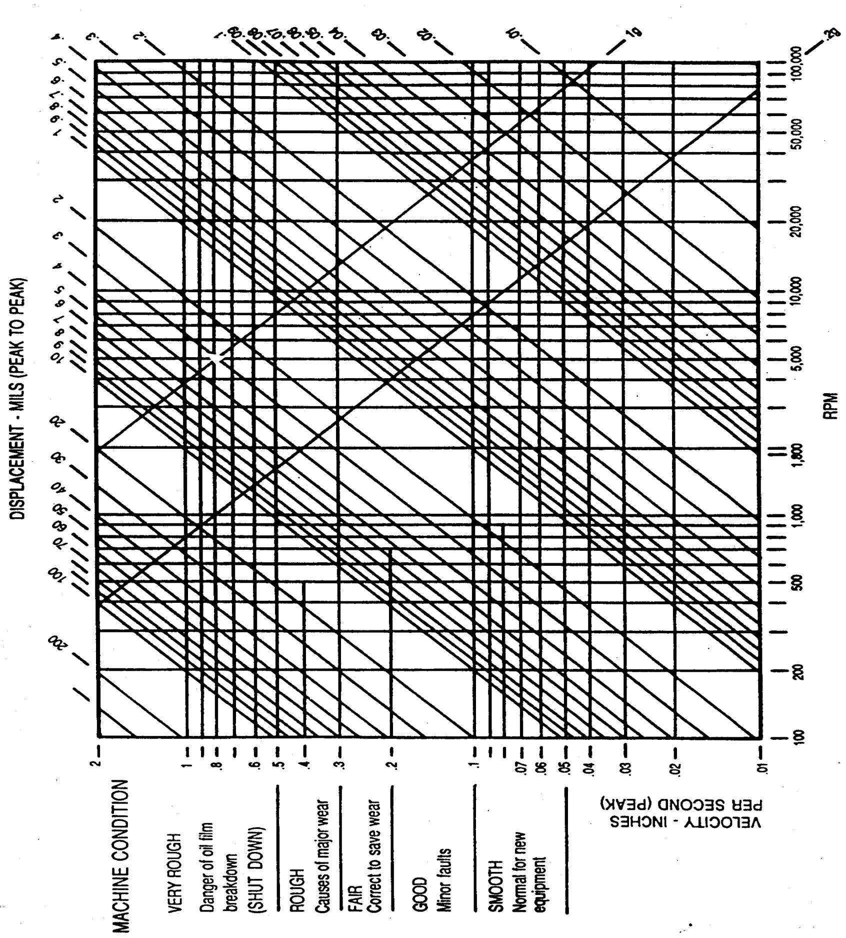


Figure 4.5-4 Pump Vibration Chart

5.0 Compressors

5.1 Description

Compressors may be divided into positive displacement and continuous flow. Positive displacement compressors may in turn be divided into reciprocating (piston, Figures 5.1-1 and 5.1-2) or rotary (rotary screw, Figure 5.1-3, vanes or lobes). Reciprocating compressors are typically used to obtain high outlet-inlet pressure ratios, with discharge pressures ranging from 100 psi to 40,000 psi, and flow rates of 100 scfm to 100,000 scfm.

Figure 5.1-1 shows a reciprocating compressor, with – from bottom to top – the crankshaft, crankshaft seal, piston rod, piston rod guide bearing, piston rod gland, labyrinth piston, and the compressor valves. A compressor assembly will also include the motor and controls driving the compressor, and peripherals such as filters, after coolers, moisture separators, dryers, and gas receivers. Many peripherals can be seismically evaluated by analysis as static equipment.

Continuous flow compressors may be divided into axial, Figure 5.1-4, or centrifugal (fan) flow, including turbo compressors, Figure 5.1-5. Centrifugal (fan) compressors are more common in high volume, low pressure ratio applications.

5.2 Earthquake Performance

Of close to 130 compressors studied following earthquake none indicated signs of failure to the compressor unit itself. Failures of compressed gas systems were recorded, caused by the following conditions: (a) loss of power or power surge caused by the earthquake, (b) pipe or braided hose rupture.

5.3 Test Performance

There are no published seismic shake table test data of compressors.

5.4 Analytical Qualification

The analytical seismic evaluation for compressors is limited to the load path (weak members from the center of gravity down to the anchorage), and the evaluation of anchor bolts and welds to the foundation.

5.5 Maintenance and Reliability

Like pumps, large industrial compressors will be subject to a predictive maintenance program that includes vibration analysis. Vibration displacement amplitude of the compressor shaft is measured on the shaft by non-contacting probes. Vibration limits are specified as a function of rotating speed, for example 3 mils at 1,000 RPM down to 0.5 mils at 30,000 RPM.

Corrosion at the bottom of air receiver tanks is common, and is either due to condensate settling at the bottom of the tank or to atmospheric corrosion, Figures 5.5-1 and 5.5-2.

5.6 Seismic Evaluation Checklist

On the basis of analytical, earthquake experience, test, and normal maintenance data presented, a seismic evaluation checklist is developed to assist in the qualification of the equipment. The checklists are compiled in Appendix A.

If one of these attributes is not met, seismic qualification may be established by detailed analysis, seismic testing, or by hardware modification.

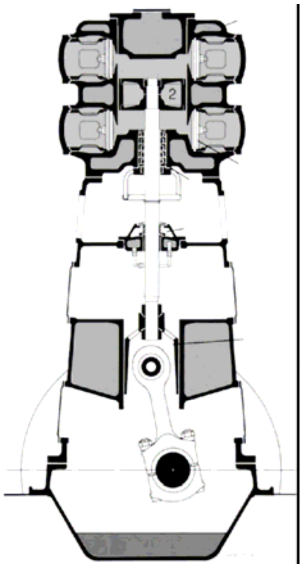


Figure 5.1-1 Reciprocating (Piston) Compressor

Figure 5.1-2 Reciprocating Compressor with Two Pistons

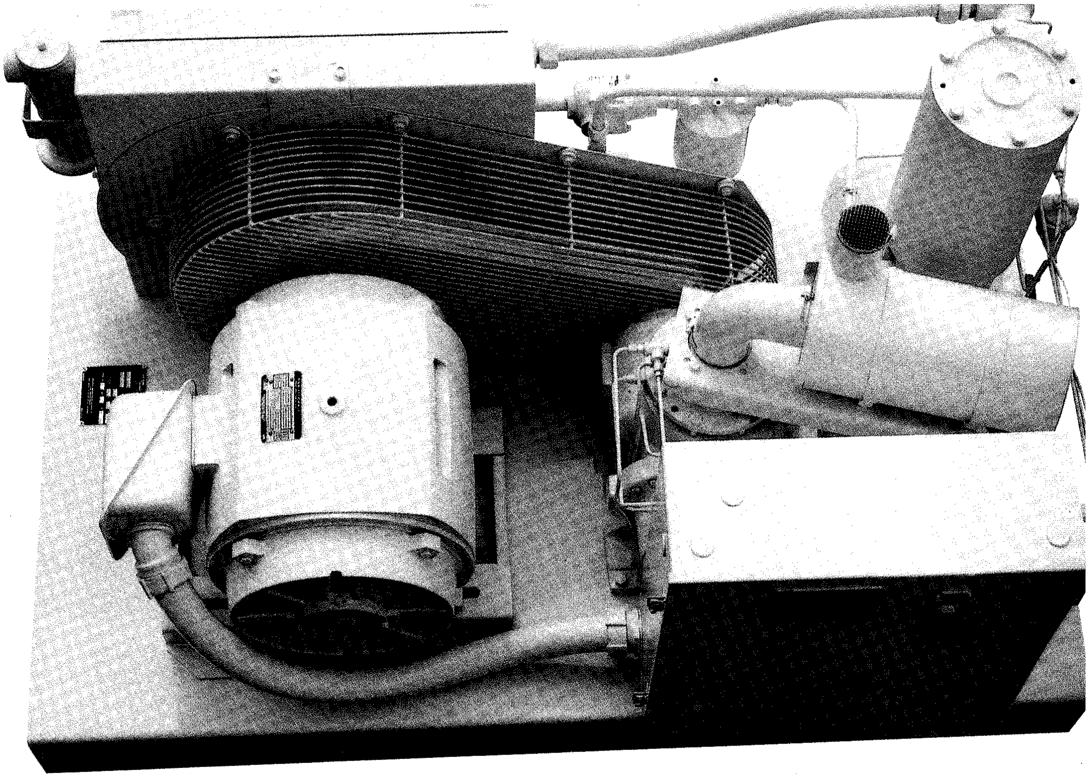


Figure 5.1-3 Rotary Screw Compressor Skid

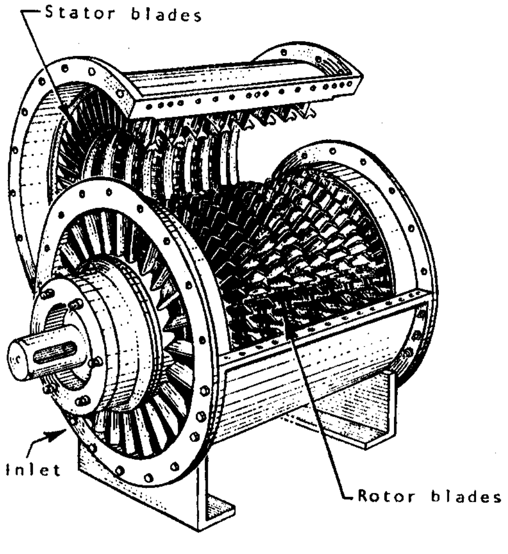


Figure 5.1-4 Continuous Flow Axial

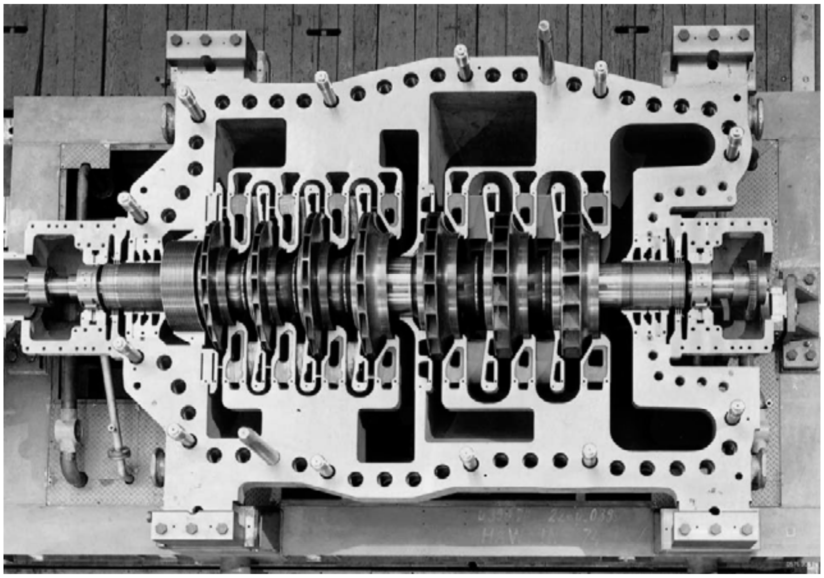


Figure 5.1-5 Turbo-Compressor with Narrow Impellers Welded to Cover Discs

Figure 5.5-1 Reciprocating Compressor atop Air Receiver

Figure 5.5-2 Corrosion in Air Receiver Tank of Outdoor Air Compressor Unit

6.0 Fans and Air Handling Units

6.1 Description

6.1.1 System Description

Fans are part of heating, ventilating and air conditioning (HVAC) systems. Fans consist of a motor driving the fan shaft on which are mounted the fan impellers. Centrifugal fans are most common in large ducted systems. In a centrifugal fan the air enters the impeller axially and is discharged radially. Axial fans are more common in roof exhaust units and small duct systems. In an axial fan the air enters and leaves the fan axially. Some units include downstream or upstream guide vanes to correct air swirl.

Air handling units (AHU) are factory made or custom built on-site. They consist generally of an air intake unit, possibly a chamber to mix intake and recirculating air, a primary filter, cooling coils, a heater unit, the fan or fans, possibly another set of filters and a humidifier, and the plenum connection to HVAC ducts, Figures 6.1-1 to 6.1-4. AHU’s are often roof mounted.

Fans are sized and selected on the basis of air flow rate (ft^3/min. = cfm) and static pressure, to provide the desired air flow, and prevent stalling and excessive noise. AHU’s are tested pre- and post-installation for operability, air balance, seal tightness, vibration and noise.

6.1.2 Functional Requirement

The functional requirement, which as described in Chapter 2 is a prerequisite to seismic evaluation, must be defined as position retention, leak tightness or operability.

For position retention, the SMACNA standards have explicit formulas to calculate loads on ducts, by treating duct spans as equivalent beams (Section 6.4).

Operability of air handling units may be acceptable even without a guarantee of leak tightness. For example, it may be satisfactory to have a running exhaust fan even though the duct and plenum seams have opened to a limited extent. This is because the exhaust duct operates at negative pressure and will still suck air through leaking seams. However the fan excess capacity must be confirmed before permitting unlimited duct seam failures.

If the opening of duct and plenum seams is not acceptable, then leak tightness is required and ducts and plenums must be seismically analyzed to determine forces and moments on seams and stiffeners and compare them to manufacturer limits. For the seismic analysis of very large industrial ducts (such as ducts with 10 ft x 10 ft sheet metal side panels) an alternative approach would be to convert the seismic inertia load into an equivalent pressure on the sheet metal, and then determine the adequacy of duct gage thickness, reinforcement spacing and size for this equivalent pressure.

As with other active mechanical equipment, where operability is required, the power supplies and controls to fans and air handling units (damper actuators) must be qualified separately.

6.2 Earthquake Performance

Earthquake induced malfunctions have been primarily due to failure of vibration (spring) isolators under lateral seismic loads. The vibration isolators are designed to absorb small amplitude vertical vibration in service but they readily buckle or overturn under seismic lateral load, as illustrated in Figures 6.2-1 to 6.2-7. Chapter 8 addresses how this problem can be resolved by providing lateral bumpers or guides (snubbers) as illustrated in Figure 6.2-8.

Unanchored fan units have failed by sliding off their concrete pedestals, Figure 6.2-9.

Failure of air handling units have also been caused by failure of the overhead duct, Figure 6.2-10, and excessive loads imposed by ducting on the fan housing or heater units.

6.3 Test Performance

There are few seismic shake table tests of fans and air handling units. From the little data available, we note the following, at high acceleration (over 10 g peak spectral acceleration):

- One fan assembly and one small blower test resulted in no malfunction.
- One complete air handling unit, including sheet metal enclosure (approximately 10,000 lb weight) was seismically shake table tested in three concurrent directions, with peak spectral accelerations up to approximately 1.5g in the two horizontal directions, and 0.5g vertically. The thermostat control panel was also tested on a separate fixture for evidence of relay chatter. There was no malfunction due to seismic shaking.

6.4 Analytical Qualification

An essential aspect of the analytical evaluation of fans and air handling units is the equipment load path, its anchorage, the stability of the duct system, and the loads imparted by the duct on the plenums and fans. SMACNA Rectangular Industrial Duct Construction Standards, SMACNA Round Industrial Duct Construction Standards, SMACNA HVAC Construction Standards Metal and Flexible, and SMACNA Seismic Restraint Manual Guidelines for Mechanical Systems can be applied in evaluating the seismic adequacy of the duct system.

6.5 Maintenance and Reliability

Typical maintenance activities for a powered fan include periodic vibration analysis, removing debris; checking integrity of attachments; checking that fan impeller turns freely; checking electrical connections to fan; cleaning, lubricating or adjusting moving parts; checking running current against data plate, checking instruments and controls; cleaning or replacing filters, heater batteries, etc. [Snow]

6.6 Seismic Evaluation Checklist

On the basis of analytical, earthquake experience, test, and normal maintenance data presented, a seismic evaluation checklist is developed to assist in the qualification of the equipment. The checklists are compiled in Appendix A.

If one of these attributes is not met, seismic qualification may be established by detailed analysis, seismic testing, or by hardware modification.

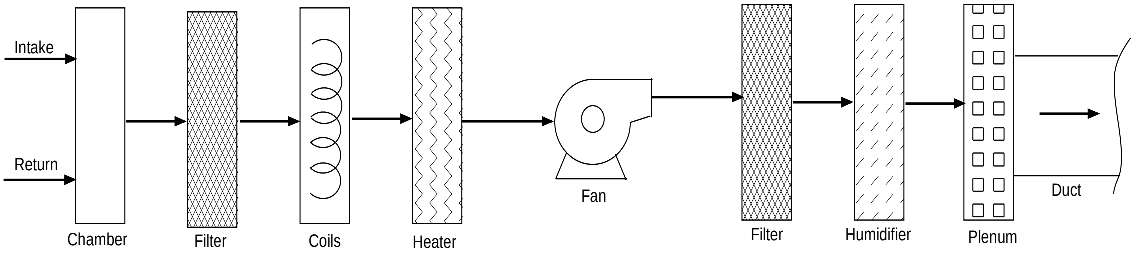


Figure 6.1-1 Components Diagram of Air Handling Units

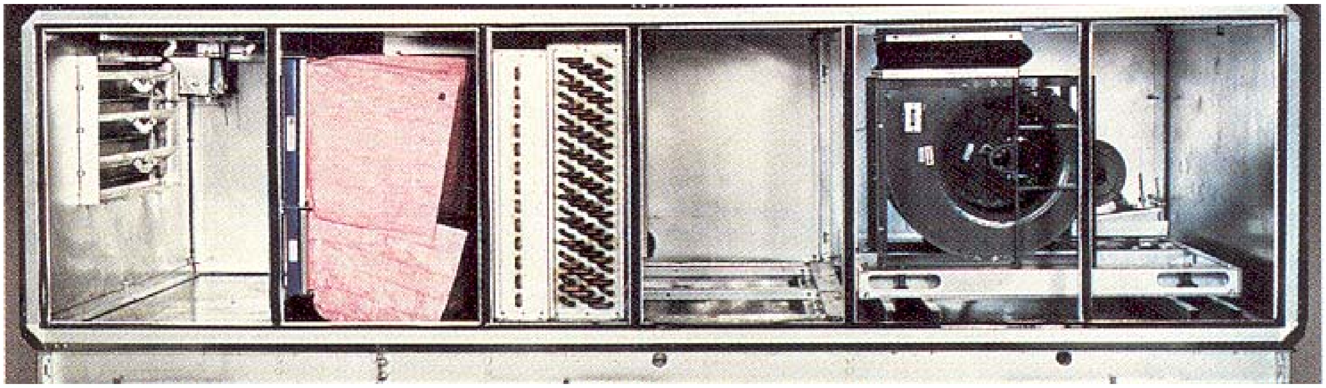


Figure 6.1-2 Air Handling Unit [York]

Figure 6.1-3 Fan Enclosure

Figure 6.1-4 Fan on Vibration Isolation Springs

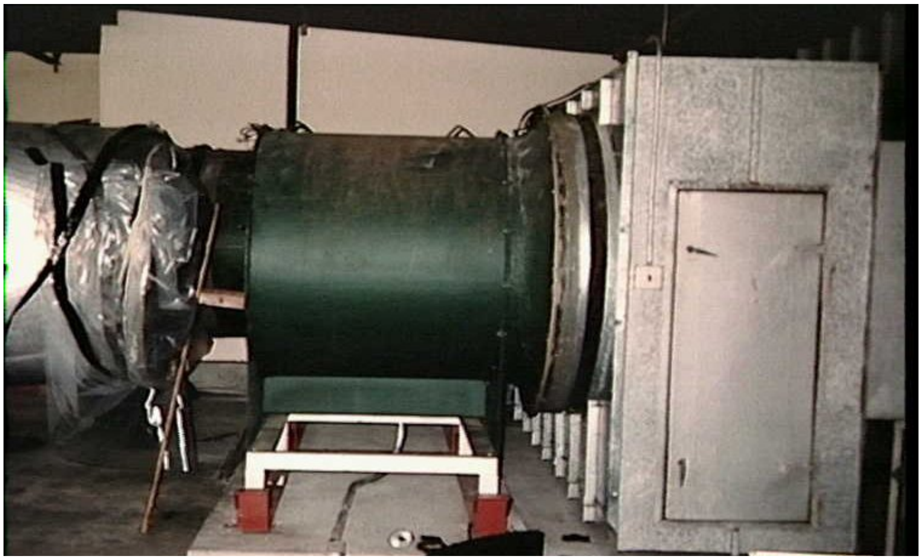


Figure 6.2-1 Fan Shifts Off Vibration Isolators (ABS Consulting)

Figure 6.2-2 Failure of spring isolators (ABS Consulting)

Figure 6.2-3 Shift of Roof-Top Unit (Mason Industries)

Figure 6.2-4 Failure of Spring Isolator (Mason Industries)

Figure 6.2-5 Failure of Spring Mounts (Mason Industries)

Figure 6.2-6 Damage Caused by Failure of Spring Mounts (Mason Industries)

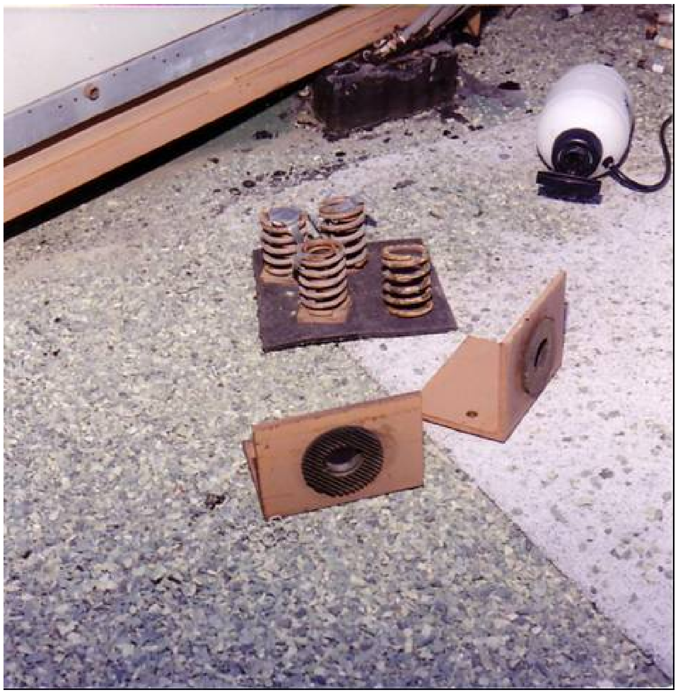


Figure 6.2-7 Failure of Spring Isolators (Mason Industries)

Figure 6.2-8 Side Bumpers (Snubbers)

Figure 6.2-9 Unit Slides off Pedestal

Figure 6.2-10 Falling of Overhead Duct (Mason Industries)

7.0 Chillers

7.1 Description

Chiller units consist of a circuit that contains:

(a) An evaporator (cooler) where the process or utility air or water is cooled by losing its heat to a refrigerant that vaporizes, Figure 7.1-1.
(b) The compressors that circulate the refrigerant downstream of the evaporator. The compressor drive is typically centrifugal, reciprocating or screw.
(c) A condenser where the refrigerant rejects its heat (by heat transfer to water or air, Figure 7.1-2) and turns liquid.
(d) An expansion valve that reduces the refrigerant pressure reducing its temperature before the refrigerant re-enters the evaporator.
(e) The units also contain power supplies with a terminal box, the compressor motor, an electro-mechanical or solid state starter, controls, instrumentation and display boards, isolation valves and filters, refrigerant flow control orifice, piping and relief valves. For operability, the seismic qualification of the power supply and the instruments and controls must be addressed separately.

The evaporator and condenser may be positioned side-by-side, with the compressor mounted atop. Chiller units are typically designed and fabricated in accordance with ASHRAE 15, and range from small packages of 50 to 100 ton (Figure 7.1-2), to very large units (Figure 7.1-1) of over 8,000 tons (multi-stage), where 1 ton of refrigeration capacity is equivalent to 12,000 Btu/hr. One ton multiplied by 3.516 provides kilowatts refrigerating capacity (kWR).

7.2 Earthquake Performance

Approximately three percent of chiller units surveyed post-earthquake suffered damage. The damage was caused by failed vibration isolation springs, as illustrated in Figure 7.2-1 and 7.2-2, or by the failure of concrete anchor bolts, Figure 7.2-3.

7.3 Test Performance

One complete chiller unit (weight close to 10,000 lb) was seismically shake table tested in three concurrent directions, up to 1.2g – 1.7g in the two horizontal directions, and 0.5g vertically. The unit was checked for operability, current draw, and water, oil and refrigerant leaks after the shaking. There was no leak or malfunction due to seismic shaking.

7.4 Analytical Qualification

The condenser and evaporator (pressure vessels) and the interconnecting piping system can be qualified by analysis for integrity of the pressure boundary. However, the compressor and the expansion valve would have to be qualified for operability using the techniques described in

Chapter 3 for valves and Chapter 5 for compressors. The power supply and controls would have also have to be qualified for operability as electrical components.

7.5 Maintenance and Reliability

Chiller maintenance consists of preventive (fixed interval) maintenance and corrective (repair) maintenance. A review of corrective maintenance helps understand natural vulnerabilities of the equipment, some of which may be amplified under seismic shaking conditions, leading to premature failure or malfunction.

Chiller units must be level on pads or springs, within ~ ¼” end to end, and all pads or springs should be equally deflected, shims may be used to achieve this even deflection. Piping connections (chilled water, condenser water, refrigerant relief) should not be supported off the compressor, they should be supported separately; pipe-nozzle flange bolts should be inserted without binding.

A review of chiller corrective maintenance experience leads to the following failure modes and effects: Leaking water supply joint, faulty filter, failure of fan motor or motor contactors, locked compressor, fouling and corrosion of condenser tubes, fouling in sensor tubing, failed condenser tube leads to water contamination on refrigerant side.

7.6 Seismic Evaluation Checklist

On the basis of analytical, earthquake experience, test, and normal maintenance data presented, a seismic evaluation checklist is developed to assist in the qualification of the equipment. The checklists are compiled in Appendix A.

If one of these attributes is not met, seismic qualification may be established by detailed analysis or seismic testing, or by hardware modification.

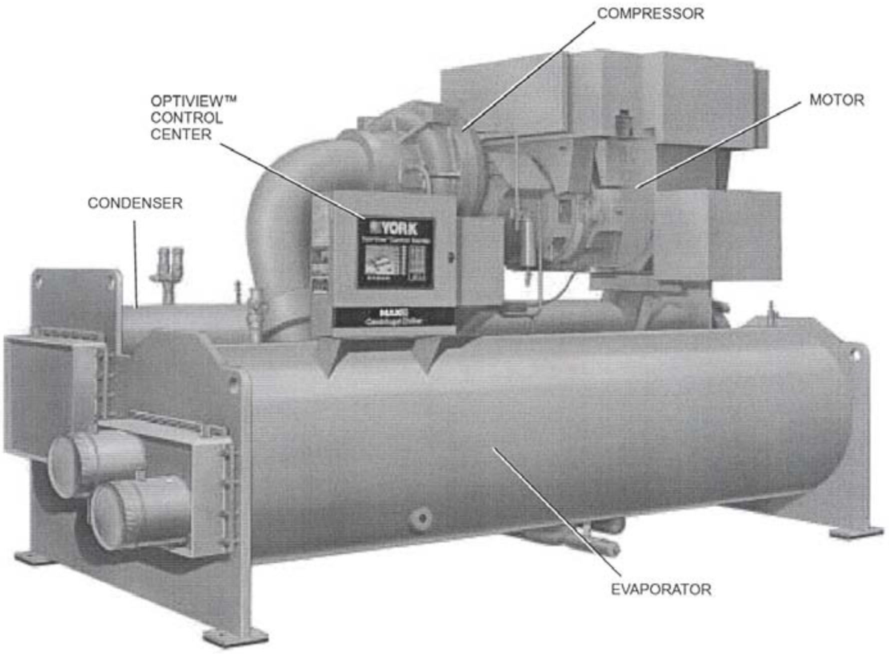


Figure 7.1-1 Skid Chiller Unit (York)

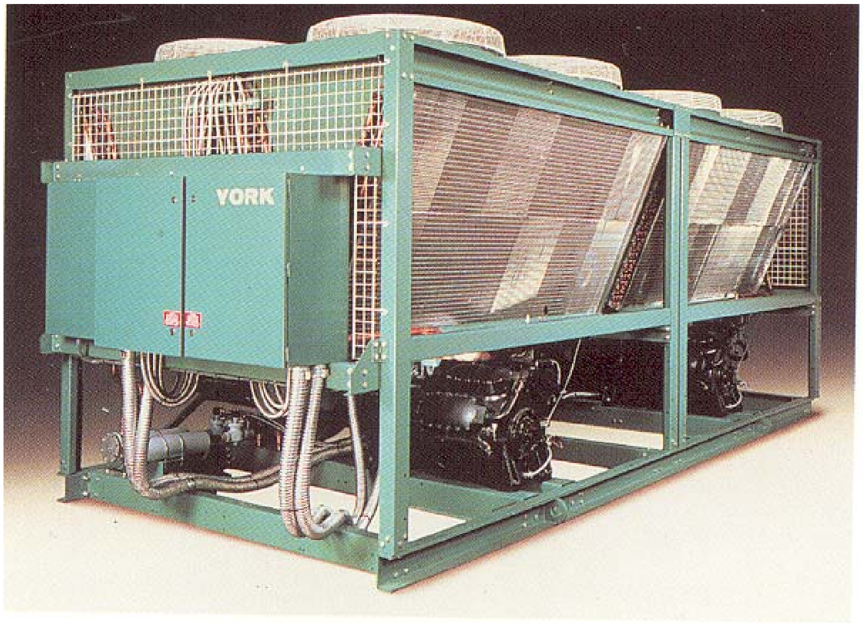


Figure 7.1-2 Air-Cooled Chiller Unit (York)

Figure 7.2-1 Failed Vibration Isolators (Mason Industries)

Figure 7.2-2 Failed Vibration Isolators (Mason Industries)

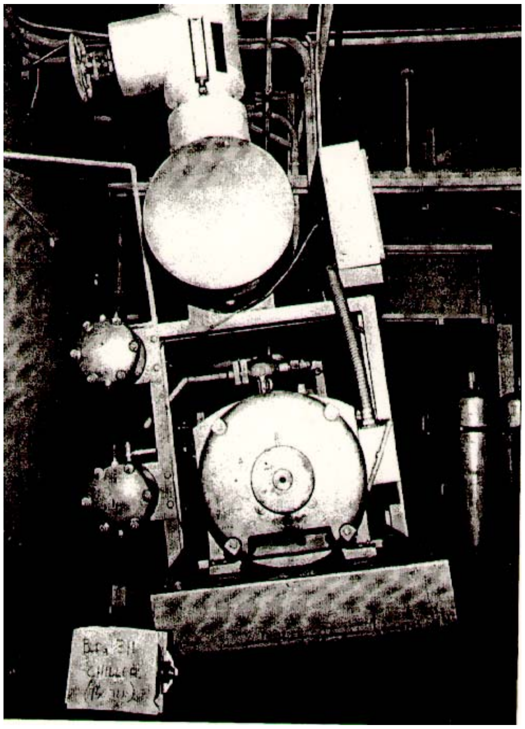


Figure 7.2-3 Failed Anchorage

8.0 Equipment Hold Down

8.1 Anchors and Welds

In industrial applications, floor mounted mechanical equipment (pumps, compressors, fans, chillers) are in almost all cases anchored to a concrete floor by anchor bolts, or welded to a steel plate or angle that, in turn, is anchored to the concrete base. In this chapter we will address the evaluation of seismic adequacy of concrete anchor bolts and welds.

8.2 Concrete Anchors

Equipment such as pumps, compressors, fans and chillers are typically anchored to concrete pads or directly to floor slabs. There are two types of concrete anchor bolts: cast-in-place and post-installed, Figures 8.2-1 and 8.2-2.

8.2.1 Cast-in-Place Anchors

When the location of the equipment is known sufficiently early, then concrete anchor bolts can be cast-in-place when pouring the concrete pad or slab. There are several types of cast-in-place anchors, bottom of Figure 8.2-1, from left to right: headed bolt, headed stud, J hook.

8.2.2 Post-Installed Anchors

When the equipment is placed after the concrete pad or slab has been poured, anchor bolts are drilled into the hardened concrete. These types of concrete anchor bolts are referred to as post-installed anchors. There are many types of post-installed anchors, Figure 8.2-2, but they can be grouped in two common categories: expansion anchors and undercut anchors.

Expansion anchors rely on bearing or friction to transfer load from the bolt to the concrete; they may be classified as shell or non-shell anchors. Shell anchors rely on friction between the concrete and a female-threaded shell inserted into a hole in the concrete and expanded by tightening a male bolt or threaded rod into the shell, Figure 8.2-1 top left and Figure 8.2-3. Shell anchors are commonly used as ceiling inserts for threaded rods, Figure 8.2-4. Non-shell anchors rely on a wedge or sleeve expanded against the sides of the drilled hole, Figure 8.2-5.

Undercut anchors rely on the engagement of an expanded disc into a groove cut into the sides of the concrete hole.

8.3 Snubbers and Vibration Isolators

As used in equipment installation, the term snubber refers to “a device used to increase the stiffness of an elastic system whenever the displacement exceeds the design value; a seismic restraint used on isolated systems with an air gap and neoprene cushioning” [ASHRAE]. Therefore, in these applications, a snubber is an engineered bumper.

In piping systems, a snubber refers to a different type of device. A piping snubber is a linear dynamic restraint (either mechanical or hydraulic) that permits relatively free movement at low velocity or acceleration, but locks into place under dynamic load [ASME QME, ASME III NF]. In these applications, a snubber is an engineered and qualified telescoping device that acts as a seat belt: expanding or contracting somewhat freely under slow motion but latching under rapid motion.

In this section, for the seismic restraint of mechanical equipment (pumps, compressors, fans, HVAC units), we will apply ASHRAE's definition of snubber (the snubber as a bumper).

Many types of rotating or positive displacement equipment (pumps, compressors, fans) are mounted on vibration isolators, selected and sized by acoustical-mechanical engineers to isolate the floor from equipment vibration during service, Figure 8.3-1. Lateral seismic forces have caused these vibration isolation devices to fail, and the equipment to shift, slide or overturn, Figure 8.3-2. Starting with the 1971 San Fernando (CA) earthquake, snubbers have been developed and used in tandem with vibration isolators to limit seismic movements and failures. They may be built into or they may encase the vibration isolation mount, Figures 8.3-3 to 8.3-5, or they may be separate, Figures 8.3-6 to 8.3-8. They generally consist of a steel attachment to the equipment, a steel attachment to the floor, and an ASTM quality neoprene or rubber element sandwiched between the equipment and floor attachments. Seismic snubbers are stiffness, load or deformation rated and must be selected and sized on the basis of the expected seismic force or displacement. A gap of 1/8" to 1/4" is typically provided so that the snubber will not interfere with the vibration isolator during normal service.

8.4 Concrete Pads

The following describes three types of concrete pads typically used for equipment mounting; listed from least to most resistant:

(a) Unreinforced pads, simply poured over the floor slab: This type of pad must be avoided in seismic applications, as it tends to break or slide in earthquakes, Figure 8.4-1.

(b) Reinforced pads, simply poured over the floor slab, not tied down to the floor: This type of pad should be retrofitted by the use of post-installed anchors that will tie the equipment pad to the floor slab.

(c) Reinforced pads, connected to the floor slab: The pad reinforcing rebars, and the dowelling anchors to the floor slab, must be sized in function of the pad area and the lateral load imparted by the equipment onto the pad [ASHRAE].

8.5 ACI 318 Capacity of Anchor Bolts

The rules of ACI 318-02 Appendix D are typically followed to size and qualify concrete anchor bolts in new installations. The general steps for the ACI 318-02 Appendix D evaluation are as follows:

8.5.1 Demand Load Calculation

The calculated demand on the concrete anchorage is determined by a simplified representation of the equipment consisting of the location of the center of gravity above the baseplate the location of anchorage points relative to the center of gravity, as illustrated in Figure 2-5.5.

The normal operating loads (for example the weight of the equipment and contents) and the seismic loads are applied to the center of gravity, as indicated in Figure 2-5.5. The seismic loads at the center of gravity are three-directional, typically east-west, north-south, and vertically up-down. The combined loads generate forces and moments, which are resisted by tension and shear in each bolt. The tension and shear in each bolt constitute the demand on the bolt.

8.5.2 Bolt Capacity

The tensile and shear bolt capacity are calculated following the rules of ACI 318-02 Appendix D. The capacity depends on a number of bolt and concrete properties and factors, such as bolt size, bolt material strength and ductility, bolt spacing and edge distance, type of bolt (post-installed or cast-in-place), bolt installation and gaps to concrete, concrete strength, concrete cracking, concrete failure pyramidal area (what used to be a failure cone in earlier ACI rules). In most cases, anchor bolt manufacturer catalogs provide guidance for selecting the appropriate anchor bolt consistent with ACI provisions.

8.5.3 Qualification of Demand vs. Capacity

Demand is compared to capacity for tension, shear and combined tension and shear, to evaluate the integrity of the anchorage system.

8.6 Alternate Approach for Bolt Capacity

An alternate method to determine the capacity of concrete anchor bolts has been used in the nuclear power industry for the seismic retrofit of existing (installed and operating) anchored mechanical and electrical equipment. This alternate approach was developed by the nuclear power industry’s Seismic Qualification Utilities Group (SQUG, EPRI), and is also documented in the Department of Energy’s DOE-EH-0545. The capacity of an anchor bolt in tension and the capacity in shear are set equal to a nominal value multiplied by penalty factors to account for embedment depth (EM), anchor spacing (AS), edge distance (ED), concrete strength (CS), and concrete cracks (CC).

$$P_C = P_N\ X_{EM}\, X_{AS}\, X_{ED}\, X_{CS}\, X_{CC}$$

$$V_C = V_N\, Y_{EM}\, Y_{AS}\, Y_{ED}\, Y_{CS}\, Y_{CC}$$

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 nominal capacities are then set at a fraction of the ultimate load. Ultimate loads are established by tension and shear tests, in accordance with standard procedures established by certifying organizations, such as ICBO, UL, FM and city or state jurisdictions. The nominal capacities in tension and shear are determined as

$$P_N = \frac{P_U}{SF}$$

$$V_N = \frac{V_U}{SF}$$

P_N = nominal tensile capacity, lb
V_N = nominal shear capacity, lb
P_U = ultimate tensile capacity, lb
V_U = ultimate shear capacity, lb
SF = safety factor

The safety factor may be established by regulations, contract, or by the design agency. It is typically in the order of 4 to 5. Details on the penalty factors may be obtained from the reference reports [GIP, DOE-EH-0545].

As an alternative to applying a safety factor to obtain nominal capacities, NEHRP-97, Section 9.2 recommends a statistically determined 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

8.7 Cast-in-Place Bolts

An example of approximate pullout and shear capacities of headed studs is provided in Table 8-3 [UCRL].

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 Example of Cast-in-Place Capacities

8.8 Bolt Shear-Tension Interaction

For code design, as well as the alternate approach of section 8.6, the demand vs. capacity is evaluated as an interaction formula

$$\left(\frac{P}{P_C}\right)^n + \left(\frac{V}{V_C}\right)^n < 1$$

P = applied tension, 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, and is summarized in Table 8-4.

Standard	n
NEHRP-97	2
ASCE 7	2
UBC-97	2 and 5/3
ACI-349 Ap.B	1
ACI 318-02 Ap. D	1

Table 8-4 Interaction Exponent

8.9 Anchor Bolt Installation

The capacity of concrete anchor bolts is dependent on the quality of installation. The installation must follow the manufacturer instructions to develop the full anchor capacity. In particular, the following cautions apply:

(a) Trained personnel.
(b) Follow manufacturer instructions.
(c) Install in 28-day (min.) concrete.
(d) Clean the drilled hole.
(e) Do not weld on anchor, unless weldable.
(f) Follow torque requirement.
(g) Avoid conditions leading to penalties X and Y, unless accounted for in design.
(h) Rebar cutting should be pre-approved by civil engineering.
(i) Torque check installed bolts: 20% torque (existing) to 100% (new).
(j) If repairing, drill larger, deeper hole for larger anchor.

8.10 Tightness Check

Newly installed expansion anchors may be tightness checked 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, as provided for example in Table 8-5.

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 8-5 Tightness Check

8.11 Welded Joints

In some cases, equipment is fillet welded to a base plate or channel, which may in turn be anchored to the concrete. The welds may be continuous, or stitch. In seismic qualification, it is necessary to calculate the demand on the equipment welds, and compare the demand to a capacity. As was the case with anchor bolts, the equipment is first represented by a simplified free body diagram, and normal operating and seismic loads are applied to the simplified model to generate the loads (moments and forces) at the base welds.

Applying the method of O.W. Blodgett [Blodgett], to determine the weld size, the weld is treated as a line. The applied loads are used to calculate the linear force on the weld. For example

$$f_a = \frac{P}{A_w}$$

$$f_b = \frac{M}{S_w}$$

$$f_T = \frac{Tc}{J_w}$$

$$f_v = \frac{V}{A_w}$$

f_a = unit tensile force, lb/in
f_b = unit bending force lb/in
f_T = unit torsion induced force, lb/in
f_w = unit shear induced force, lb/in
P = tensile force, lb
A_w = weld area per unit length, in^2/in
M = bending moment, in-lb
S_w = weld section modulus, treated as a line, in^3/in
T = torsion, in-lb
c = maximum distance from centroid of the weld pattern, in
J_w = polar moment of inertia, weld treated as a line, in^4/in
V = shear force, lb

The calculated linear forces f_i are combined by square root sum of the squares to obtain the resultant load f per unit length of weld (lb/in), which is then divided by the allowable weld stress (psi, lb/in^2) to obtain the size of the weld leg. The allowable stresses in welds may be obtained from structural or welding design standards [AISC, AWS].

8.12 Workmanship

The quality of installation of anchor bolts, and the quality of welding are as important as the bolt or weld size. In designing new systems, the responsible engineer should verify that bolt installers and welders are qualified and follow a qualified procedure. For welding, these may be American Welding Society (AWS) or ASME qualifications. For bolting, these may be bolt vendor training and certifications. In the seismic retrofit of existing systems, the seismic evaluation should address weld and bolt installation quality at the time of installation.

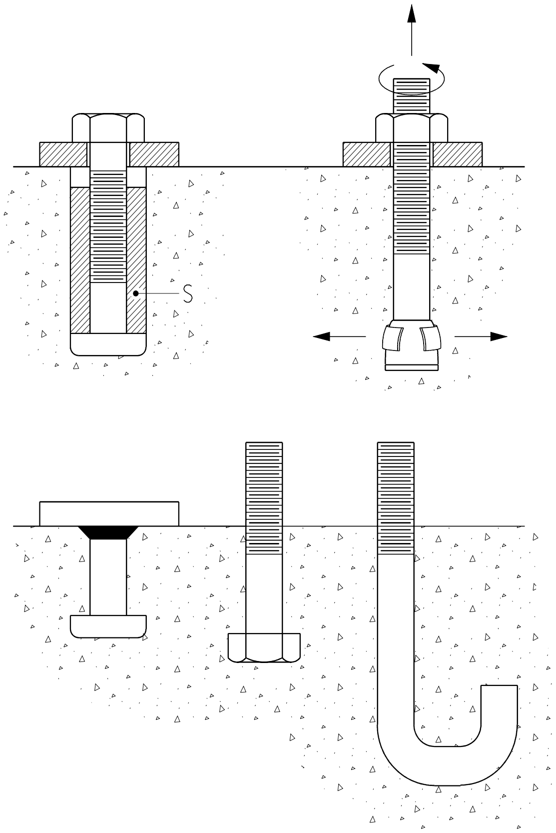


Figure 8.2-1 Post-Installed (top) and Cast-in-Place (bottom)

Figure 8.2-2 Cast-in-Place (bottom left) and Post-Installed Anchors

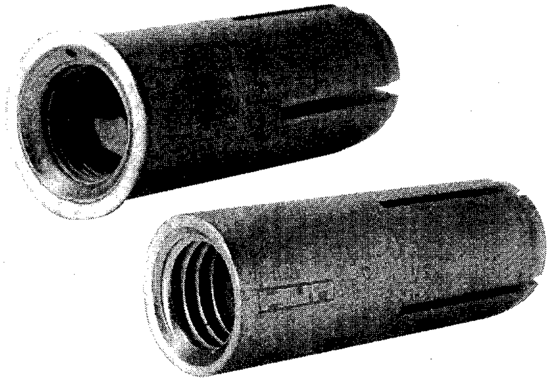


Figure 8.2-3 Anchor Shells

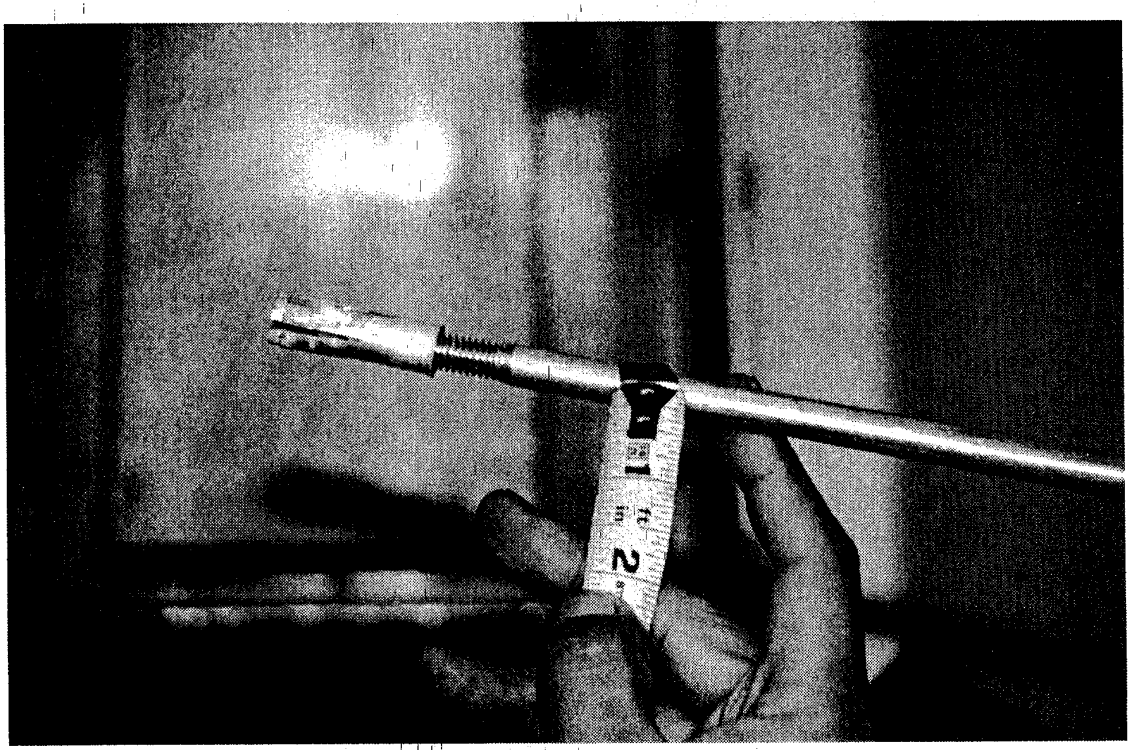


Figure 8.2-4 Shell Pulled out from Ceiling

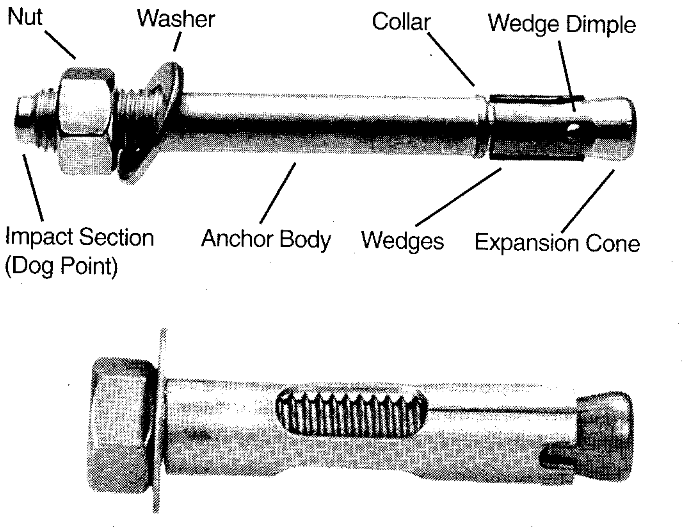


Figure 8.2-5 Examples of Non-Shell Anchors

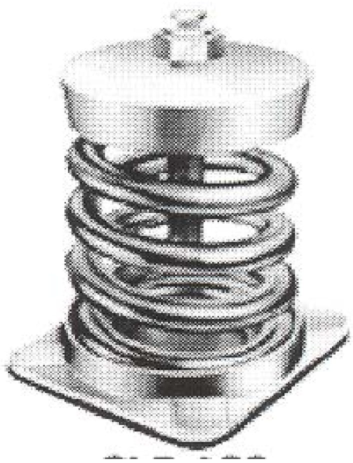


Figure 8.3-1 Spring Mount Vibration Isolator (Mason Industries)

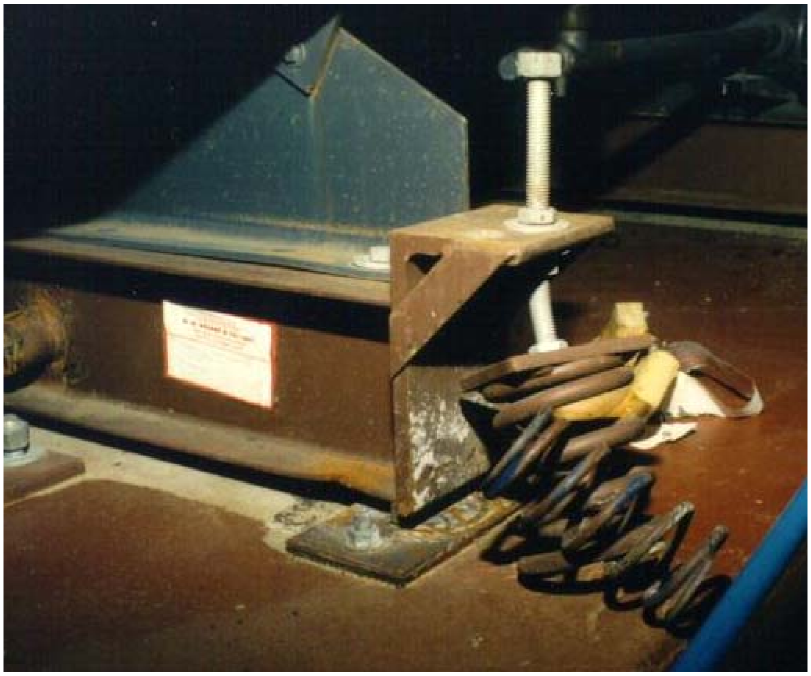


Figure 8.3-2 Failed Spring Vibration Isolator (Mason Industries)

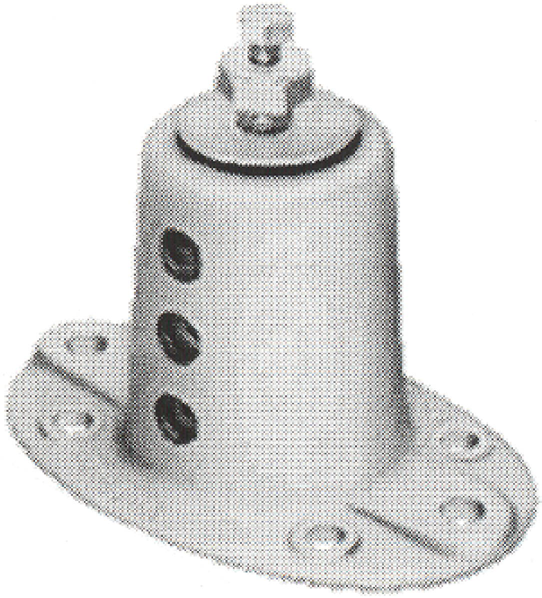


Figure 8.3-3 Seismic and Vibration Isolator Combined Mount (Mason Industries)

Figure 8.3-4 Skid Mounted Equipment on Combined Mount (Mason Industries)

Figure 8.3-5 Vibration Isolator with Motion Limiter (Mason Industries)

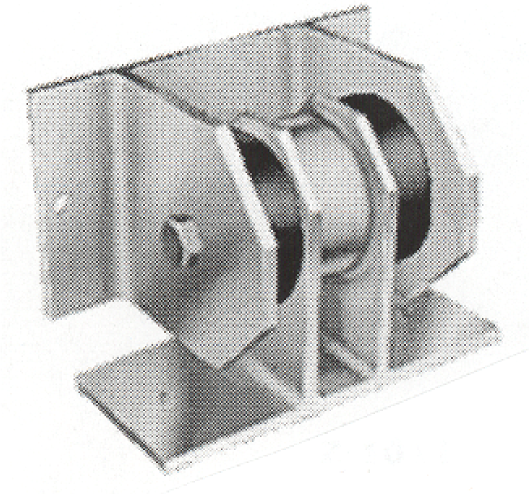


Figure 8.3-6 Seismic Snubber (Mason Industries)

Figure 8.3-7 Seismic Snubber Separate from Isolators

Figure 8.3-8 Seismic Snubber Separate from Isolators

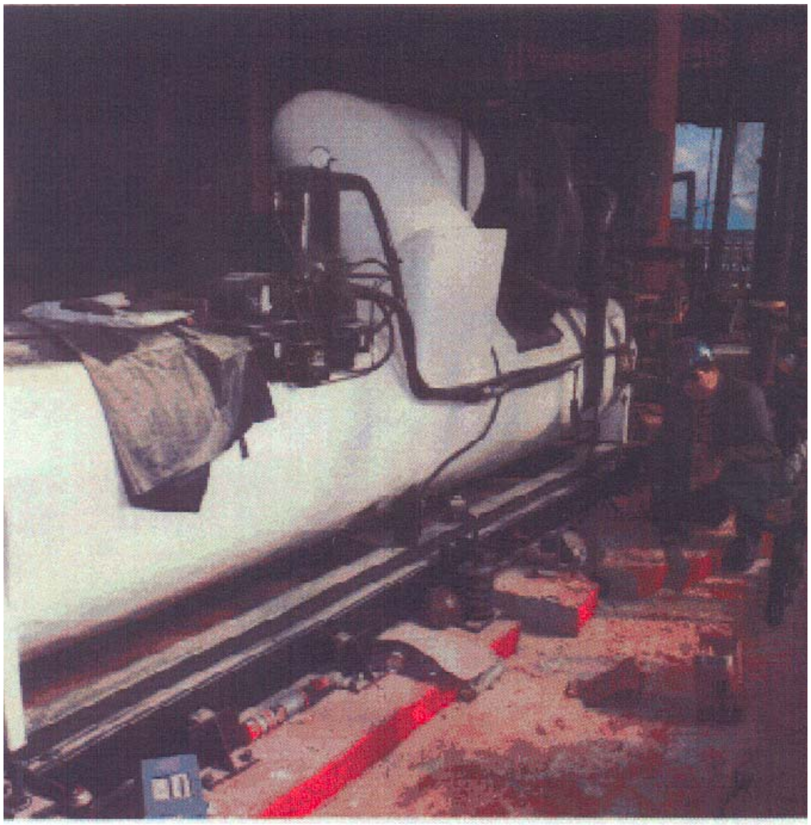


Figure 8.4-1 Failure of Concrete Pad (Mason Industries)

Figure 8.6-1 Crack in Concrete Pad Through Bolt

9.0 Seismic Interactions

Seismic interactions refer to the potential for failure of the equipment as a result of the seismic induced failure or malfunction of another structure, system or component. A common form of seismic interaction is the fall of suspended ceiling tiles on the equipment during an earthquake, Figure 9.1-1.

Evaluation of seismic interactions involves identifying sources and targets. An interaction target is the active mechanical equipment item that is being seismically qualified. An interaction source is a structure or component that, by its failure, would cause unacceptable damage to the target

Qualifying equipment for seismic interactions involves two steps:

(1) Identify whether an interaction can physically occur, i.e. is the interaction credible.

(2) If the interaction can occur, identify whether it can damage the equipment, i.e. is the interaction significant.

The seismic evaluation of equipment must confirm that the structure in which the equipment is located is itself qualified. Earthquake experience indicates that suspended ceilings and block walls are often credible sources of interaction (Figures 9.1-2 and 9.1-3). They must be explicitly addressed in the interaction review process.

Not all credible interaction sources are significant. For example, unreinforced masonry walls are typically credible and significant sources of interactions (Figures 9.1-2 and 9.1-3). This is in contrast to a light weight ceiling tile that may be a credible but insignificant interaction on a compressor casing. However, all impacts on electrical equipment, electronics, instrumentation and controls are typically considered significant interactions.

Significant impacts include any one of the following conditions:

(a) They affect instruments and controls.

(b) The source is a pipe larger than a target pipe.

(c) The source is a portion of a wall or structure.

(d) The source is a heavy component.

(e) The source is an overhead architectural feature or ceiling.

(f) The source is an overhead grating.

Figures 9.7-1 and 9.7-2 illustrate the fall of overhead pipe or conduit, and suspended ceiling. The significance of the seismic interaction source depends on the sensitivity of the target to impact.

For the purpose of seismic retrofit of installed equipment, seismic interaction consists in the review of existing structures, systems and components to determine whether they could adversely affect the seismic adequacy of the equipment being qualified. For new equipment, the planned location of the equipment needs to be evaluated to determine the potential for adverse interactions. Where credible and significant sources of interaction are identified, they must be seismically designed or upgraded to prevent failure, as will be described in this Chapter, or the interaction target must be shielded to protect the equipment from interactions.

Seismic interactions are typically assigned to one of the following categories::

Falling – A falling interaction is an impact on a critical component due to the fall of overhead or adjacent equipment or structure. Note that pressurized gas bottles, should they fall and rupture a nozzle, will also be a projectile.

Swing – A swing interaction is an impact due to the swing or rocking of adjacent component or suspended system. It is a typical concern with suspended piping, cable trays, and ducts.

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

System – 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.

9.1 Interaction Review

An interaction review consists of five steps:

(1) Determine the seismic input to the interaction source.
(2) Identify credible and significant sources of interactions.
(3) Evaluate capacity vs. demand for interaction sources.
(4) Document findings from assessment of interaction sources.
(5) Design seismic upgrades where demand exceeds capacity.

Step 1 – Determine the Seismic Input to the Interaction Source

The source seismic input (static or response spectrum) has to be consistent with the target seismic input. For example, if the target is seismically qualified based on the static coefficient method of ASCE 7 with an importance factor $I_P = 1.5$, then the source must also be evaluated based on the ASCE 7 seismic coefficient with $I_P = 1.5$. If the target is seismically evaluated based on a building specific seismic response spectrum, the same spectrum should be applied to evaluate the source of interaction.

When applying ASCE 7, the input used for interaction assessment needs to be modified to reflect the seismic coefficients a_P, R_P and elevation z of the source.

Step 2 – Identify Credible and Significant Interactions

This task involves the identification and documentation of credible and significant sources of interaction and relies primarily on engineering judgment. The rules of this Chapter may be followed to assist in this step, however they don't replace the need for experienced judgment. It is therefore recommended that seismic interactions be evaluated by personnel having at least 5 years of experience, including the three aspects of seismic design: analysis, testing and earthquake experience.

Where system interactions are of concern, the written input of a system engineer is in order.

Step 3 – Evaluate Demand vs. Capacity for the Sources

The seismic demand on the source (defined in Step 1) is used to determine if the source has sufficient capacity to preclude a seismic interaction. To establish the structural integrity and leak tightness of the source, the source is evaluated following the same procedures used to evaluate the target. When judging whether a source has sufficient capacity, some ductile deformation may be acceptable, provided it does not result in failure or in leakage where leak tightness is required.

Step 4 - Documentation

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 in which a visual interaction review is performed for an exiting installation, a photographic record of the interaction review should be maintained.

The documentation of interaction reviews should address each target separately. An example of seismic interaction review check-list is enclosed in Appendix A.

Step 5 – Design of Seismic Interaction Upgrades

Identification of a significant and credible interaction source can be resolved by upgrading the source to improve its seismic capacity. Seismic upgrades should be designed to current design codes (ASME, ASCE, AISC, ACI, ASHRAE, SMACNA, IEEE, etc.).

9.2 Falling Interactions

Identification of credible falling interactions requires an evaluation of whether or not a falling source can impact a target. If impact is considered possible, the target must be evaluated for the resulting impact force from the source.

9.2.1 Zone of Influence

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

$$R = V_H \left(\frac{-V_V}{g} + \sqrt{\left(\frac{V_V}{g}\right)^2 + \frac{2H}{g}} \right)$$

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

For a single degree of freedom, the velocity can be approximated as

$$V = a / (2\pi f)$$

V = spectral velocity, in/sec
A = spectral acceleration, in/sec^2
f = natural frequency, 1/sec

9.2.2 Impact Force

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 [Pilckey]

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

P = impact force, lb
W = weight of falling body, lb
W_b = weight of elastic member, lb
k = stiffness of elastic member, referenced to 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 of member due to its weight plus the weight of the falling body, lb

This estimate of the impact force P is an upper bound because it does not account for rebound, deformation of the source and friction and heat loss at impact.

9.3 Interaction from Swaying, Sliding, or Rocking

In addition to falling, common forms of interactions involve the swaying, sliding or rocking of potential sources. Simple rules for determining whether an interaction is possible through these mechanisms are provided in this section.

9.3.1 Sway

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

$$d = 1.3 \frac{S_a}{\omega^2}$$

d = sway (swing) amplitude, in
S_a = spectral acceleration at frequency f_a, in/sec^2
ω = natural pulsation of the swing = $2\pi f_a$ 1/sec
f_a = swing frequency, 1/sec

The swing frequency of a simple pendulum of length L is

$$f_a = \frac{1}{2\pi}\sqrt{\frac{g}{L}}$$

f_a = swing frequency, 1/sec
g = gravity, 386 in/sec^2
L = length of pendulum, in

For a compendium of natural frequency solutions for other, more complex shapes, refer to Blevins [Blevins].

9.3.2 Rocking or Sliding

The results of extensive studies of the potential for seismic induced rocking or sliding of unanchored equipment have been published in “easy-to-use” diagrams [Shao, Zhu, Gates] as shown in Figure 9.6-1.

The parameters a and c in Figure 9.6-1 are defined as follows:

$$a = \frac{\ddot{x}_b}{1 + \ddot{y}_b}$$

$$c = \frac{\ddot{x}_b}{1 - \ddot{y}_b}$$

$\ddot{x}_b$ = peak horizontal excitation at base, g
$\ddot{y}_b$ = peak vertical acceleration, g

The parameter μ is the coefficient of friction of the sliding or rocking equipment with the base. Examples of coefficients of Friction are given in Table 9-1 [Baumeister]

	Static		Sliding	
	Dry	Greasy	Dry	Greasy
Hard Steel-Steel	0.78	0 to 0.23	0.42	0.03 to 0.12
Mild Steel-Steel	0.74	-	0.57	0.09 to 0.19
Mild Steel-Cast Iron	-	0.183	0.23	0.133
Al.-Mild Steel	0.61	-	0.47	-
Teflon-Teflon	0.04	-	-	0.04
Teflon-Steel	0.04	-	-	0.04

Table 9-1 Friction Coefficients

Methods for the prediction of seismic induced sliding and rocking of unanchored equipment are also being developed by the American Society of Civil Engineers, ASCE, Working Group for Seismic Design Criteria for Nuclear Facilities, of the Dynamic Analysis of Nuclear Structures Subcommittee, of the Nuclear Standards Committee.

9.4 Spray

During earthquakes overhead or adjacent piping can rupture or leak through a crack. The consequence of such failures can be a liquid, gas or steam spray or jet on critical equipment.

9.4.1 Pipe Failure

Without a detailed analysis, it is difficult to assess the likelihood of pipe failure. Short of an analysis, the following rule has been applied [SRP 3.6]: The failure must be assumed to occur at the worst location (the location that results in the most damage to the target), but consider only one failure at a time.

9.4.2 Leak or Break

Where a break (large fracture or guillotine separation) is not acceptable, but a leak of a limited size is not significant, it becomes necessary to determine whether a failure will be by leak or break. An approximate evaluation of leakage vs rupture may be performed by stress and fracture mechanics analyses, however this requires a detailed knowledge of the applied loads, the stress distribution in the component (including residual stresses) and the material toughness properties. These pre-requisites may be difficult and costly to obtain in practice.

Short of a detailed analysis, the following rule has been applied [SRP 3.6]: A welded or flanged metallic piping system, well supported, well constructed and maintained, operating at a temperature less than 200 ^{o}F and an internal pressure less than 275 psi can be assumed to leak. Other piping (non-metallic piping or piping systems rated at higher temperatures or pressures) should be assumed to fail by guillotine break.

9.5 System Interactions

There are cases where the seismic event can cause erroneous signals to active equipment (valve operators, pumps, compressors, fans, motors) causing them to start or stop unintentionally. Where such possibility causes unacceptable consequences, it has to be identified as a credible and significant interaction.

For example, consider a building containing toxic materials and therefore maintained at a slightly negative pressure through a system of intake and exhaust fans. If the earthquake causes an erroneous signal to shutdown the exhaust fan while the intake fan is still running, the building pressure could increase, causing unacceptable toxic leaks to the outside. In this case, it may be necessary to seismically qualify an interlock between the intake and exhaust fans, so that the shutdown of the exhaust fan will cause the automatic shutdown of the intake fan.

Another example of system interaction would be the unintended opening of an isolation valve as a result of relay chatter during the earthquake.

Some system interactions may not occur if the power supply is lost; but in defining the equipment list, two scenarios must be considered: earthquake with loss of power, and earthquake without loss of power (Chapter 2).

It is therefore necessary, when developing the seismic scenario and the equipment list, to identify sources of credible and significant seismic system interactions. In complex systems, this may necessitate the development of a seismic fault tree analysis.

Figure 9.1-1 Seismic Induced Failure of Suspended Ceiling

Figure 9.1-2 Seismic Induced Failure of Block Walls

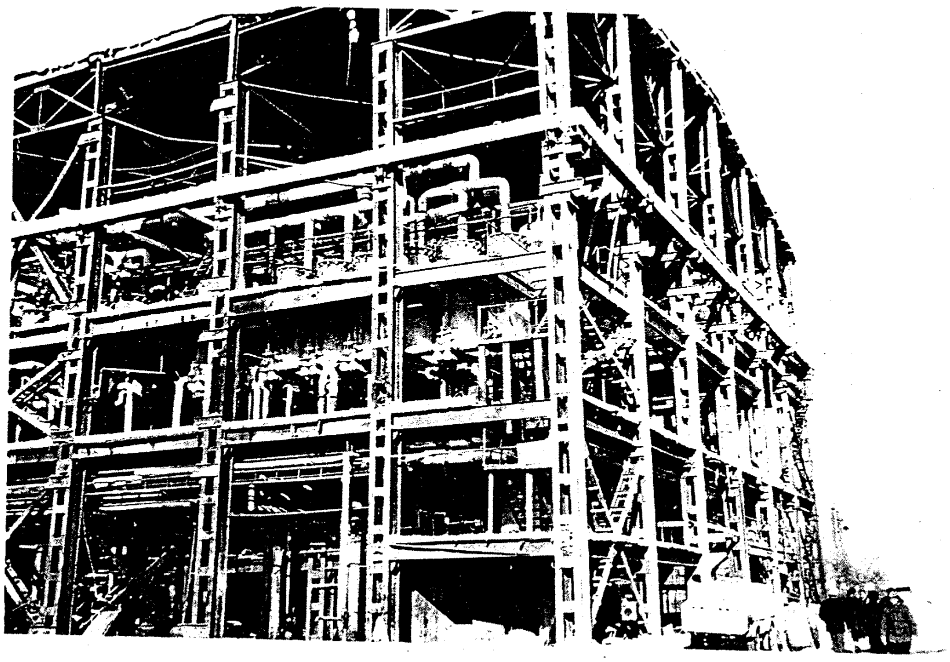


Figure 9.1-3 Factory Building had External Brick Walls

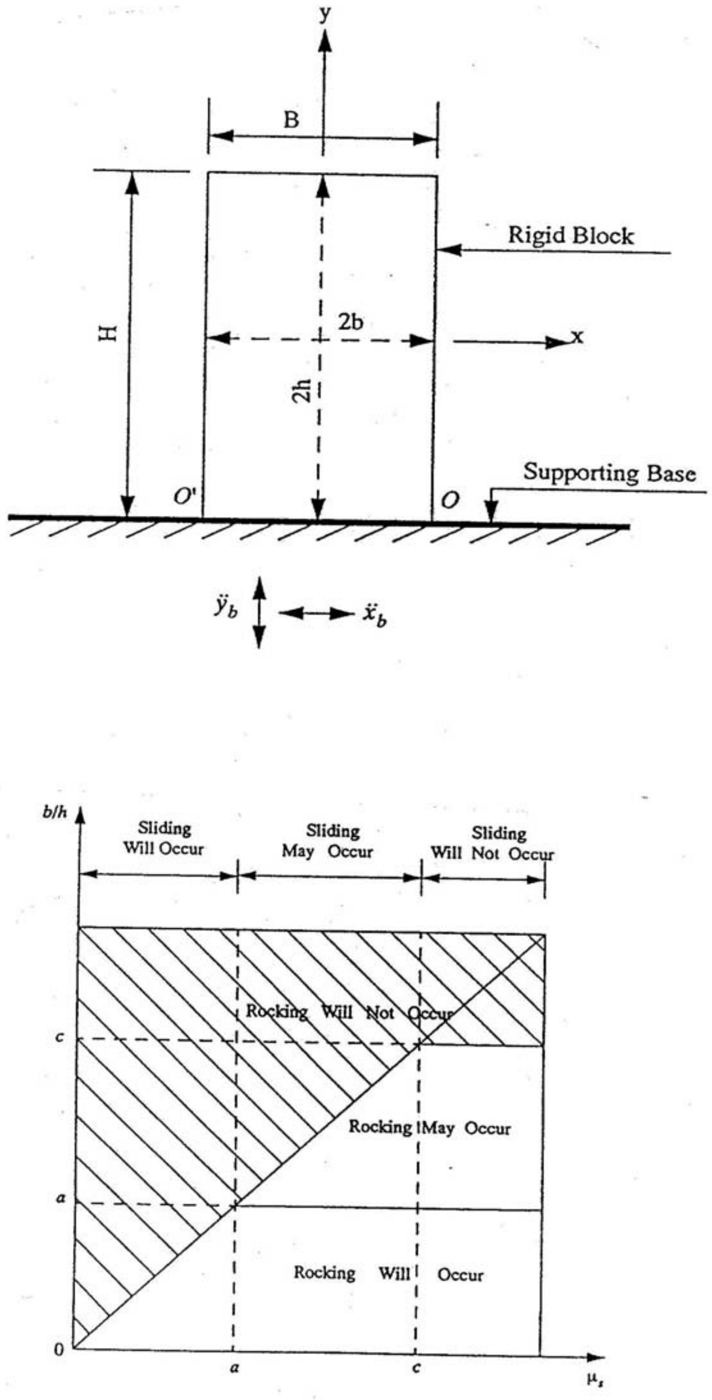


Figure 9.6-1 Sliding and Rocking Diagram

Figure 9.7-1 Fall of Overhead Pipe or Conduit

Figure 9.7-2 Fall of Overhead Suspended Ceiling

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Appendix A Seismic Evaluation Checklists

The Seismic Evaluation Checklists (SEC's) in this Appendix, or similar checklists, are a useful tool in the walk-down and seismic evaluation of existing equipment. They are meant to help identify seismic vulnerabilities.

In practice, the SEC's are supplemented by sketches, drawings, photographs, calculations of load path and anchorage, which can then be attached as to constitute a full documentation package.

Seismic Evaluation Checklist **Valves**

System --

Valve No. ----------------------------------- Location ---

Seismic Function ---

Seismic Input ---

○ Material condition: the installation is of good quality, with no fabrication or installation defects; and no missing, inadequate or broken parts.

○ Maintenance: The component is maintained in good operating condition, free of corrosion or other degradation, and periodically inspected or tested.

○ Ductility: The body and yoke are not be made of cast iron or of a material that has low ductility at normal operating temperature (for example, elongation at rupture below 20%).

○ Hard spot: The valve operator is not braced directly to the wall with the pipe span flexible, free to swing.

○ Eccentricity: The moment applied by the CG at the pipe centerline is limited to approximately D in-kips for 6” and smaller valves (where D is the nominal pipe size) and 5D in-kips for valves larger than 6”.

○ Where operability is required for hydraulic (including air), motor or solenoid operated valves, the valve system (instrumentation and controls) is seismically qualified.

○ The installed component is not subject to credible and significant seismic interactions
(Chapter 9).

○ No other concerns.

Prepared by -- Date -------------------

Enclosed ---------------- pages
(enclose photographs, calculations, sketches and drawings, notes).

Seismic Evaluation Checklist **Pumps**

System --

Pump No. ----------------------------------- Location --

Seismic Function --

Seismic Input ---

○ Material condition: the installation is of good quality, with no fabrication or installation defects; and no missing, inadequate or broken parts.

❍ Maintenance: Pump and driver maintained in good operating condition, free of degradation, with good on-going preventive and predictive maintenance.

❍ Foundation: Pump and driver on common stiff foundation.

❍ Foundation: Competent soil or floor, not prone to seismic failure or movement.

❍ Load Path: No weak members or attachments in load path down to base anchorage.

❍ Vibration Isolators: Isolators guided to prevent lateral movement in excess of capacity.

❍ Piping: Loads from pipes do not overload nozzles causing failure, leaks or shaft misalignment.

❍ Piping: Suction and discharge piping qualified, including seismic differential movements at flexible connections if used.

❍ Shaft: Deflection of long vertical shaft will not cause impeller-casing interference.

❍ Power Supply and Controls: Where operability is required, the power supply and controls and instrumentation must be qualified separately.

❍ Anchorage: Anchors, vibration isolators if any, pedestals qualified (Chapter 8).

❍ Interactions: Pump free of credible and significant interactions (Chapter 9).

❍ No other concerns.

Prepared by -- Date -------------------

Enclosed ---------------- pages
(enclose photographs, calculations, sketches and drawings, notes).

Seismic Evaluation Checklist **Compressors**

System ---

Compressor No. ---------------------------------- Location --------------------------------

Seismic Function ---

Seismic Input ---

○ Material condition: the installation is of good quality, with no fabrication or installation defects; and no missing, inadequate or broken parts.

❍ Maintenance: Compressor and driver maintained in good operating condition, free of degradation, with good on-going preventive and predictive maintenance.

❍ Foundation: Compressor and driver on common stiff foundation.

❍ Foundation: Competent soil or floor, not prone to seismic failure or movement.

❍ Load Path: No weak members or attachments in load path down to base anchorage.

❍ Vibration Isolators: Isolators guided to prevent lateral movement in excess of capacity.

❍ Piping: Loads from pipes do not overload nozzles causing failure, leaks or shaft misalignment.

❍ Piping: Suction and discharge piping qualified, including seismic differential movements at flexible connections if used.

❍ Power Supply and Controls: Where operability is required, the power supply and controls and instrumentation must be qualified separately.

❍ Anchorage: Anchors, vibration isolators if any, pedestals qualified.

❍ Interactions: Compressor free of credible and significant interactions.

❍ No other concerns.

Prepared by -- Date -------------------

Enclosed --------------- pages
(enclose photographs, calculations, sketches and drawings, notes).

Seismic Evaluation Checklist **Fans and Air Handling Units**

System --

Fan AHU No. ----------------------------------- Location --

Seismic Function ---

Seismic Input ---
○ Material condition: the installation is of good quality, with no fabrication or installation defects; and no missing, inadequate or broken parts.

❍ Maintenance: Fan and driver maintained in good operating condition, free of degradation, with good on-going preventive and predictive maintenance.

❍ Foundation: Fan and driver on common stiff foundation.

❍ Foundation: Competent soil or floor, not prone to seismic failure or movement.

❍ Load Path: No weak members or attachments in load path down to base anchorage. For air handling units and chiller units, the load path check includes the internal units and components.

❍ Vibration Isolators: Isolators guided to prevent lateral movement in excess of capacity.

❍ Ductwork and plenum: Loads from ducts and plenum do not overload nozzles causing failure, leaks or shaft misalignment.

❍ Ductwork and plenum: Suction and discharge ductwork assemblies and plenum qualified, including seismic differential movements at flexible connections if used.

❍ Shaft: Deflection of long vertical shaft will not cause impeller-casing interference.

❍ Damper actuators on air handling units are evaluated using valve checklist.

❍ Anchorage: Anchors, vibration isolators if any, pedestals qualified. For air handling units and chiller units, anchorage check includes the internal units and components.

○ The installed component is not subject to credible and significant seismic interactions (Chapter 9).

❍ No other concerns.

Prepared by --- Date --------------------

Enclosed ---------------- pages
(enclose photographs, calculations, sketches and drawings, notes).

Seismic Evaluation Checklist **Chillers**

System --

Chiller No. ---------------------------------- Location --

Seismic Function --

Seismic Input ---

○ Material condition: the installation is of good quality, with no fabrication or installation defects; and no missing, inadequate or broken parts.

❍ Maintenance: Chiller maintained in good operating condition, free of degradation, with good on-going preventive and predictive maintenance.

❍ Foundation: Competent soil or floor, not prone to seismic failure or movement.

❍ Load Path: No weak members or attachments in load path down to base anchorage.

❍ Vibration Isolators: Isolators guided to prevent lateral movement in excess of capacity.

❍ Compressor: Evaluated using the compressor evaluation checklist.

❍ Piping: Suction and discharge piping qualified, including seismic differential movements at flexible connections if used.

❍ Power Supply and Controls: Where operability is required, the power supply and controls and instrumentation must be qualified separately.

❍ Anchorage: Anchors, vibration isolators if any, pedestals qualified, with separate evaluation for evaporator, compressor, condenser, and piping system.

○ The installed component is not subject to credible and significant seismic interactions (Chapter 9).

❍ No other concerns.

Prepared by -- Date --------------------

Enclosed ---------------- pages
(enclose photographs, calculations, sketches and drawings, notes).

Seismic Evaluation Checklist Interactions

System --

Interaction Target No. ------------------------- Location --

Seismic Function of Target --

Seismic Input --

❍ Potential Credible and Significant Sources.

❍ Assessment of Structural Integrity of Sources (Demand vs. Capacity).

❍ Assessment of Leak Tightness of Sources (Demand vs. Capacity).

❍ Assessment of System Interactions.

❍ No other concerns.

❍ Recommended Interaction Upgrades

Prepared by -- Date -------------------

Enclosed ---------------- pages
(enclose photographs, calculations, sketches and drawings, notes).

Attachment B Electrical Distribution System

Operability of mechanical equipment implies that the power supply, often times an emergency power supply, must also be qualified to run the equipment following an earthquake. Although the electrical distribution system is not in the scope of this report, Figure B-1 provides a general highlight of its main parts.

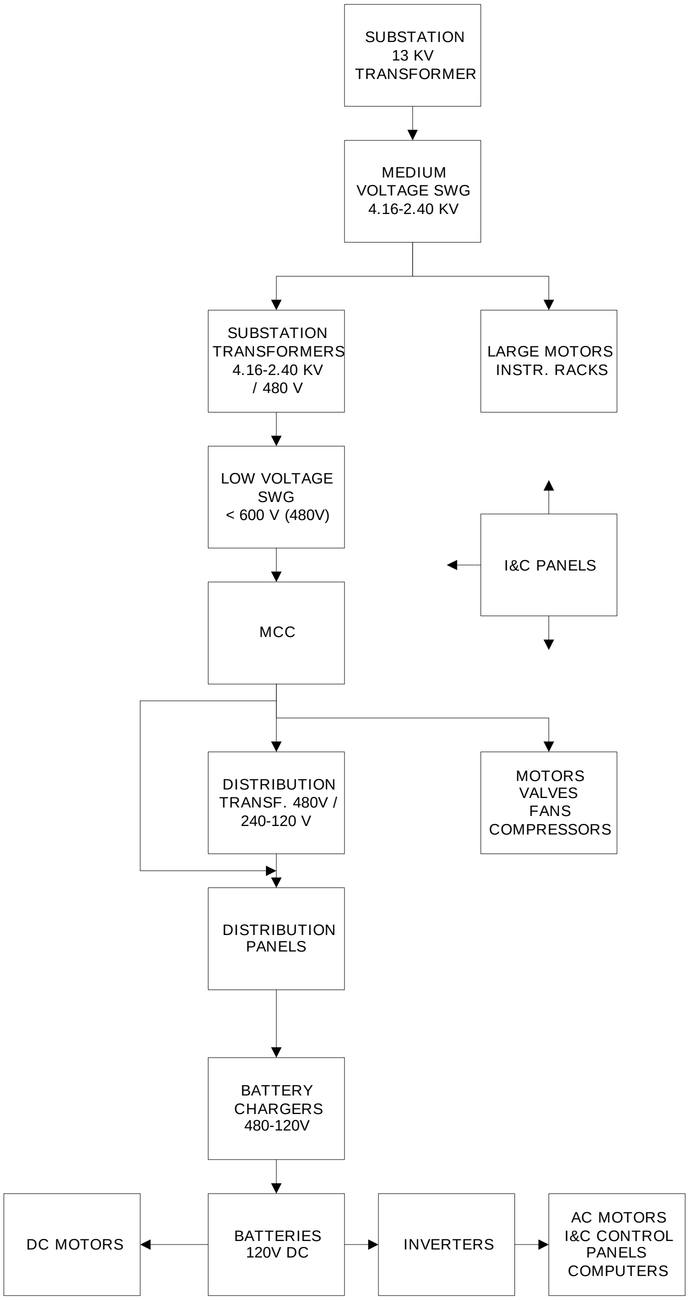

Figure B-1 Simplified Electrical Distribution