CHAPTER C10
HAZARDOUS PIPING SYSTEMS

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INTRODUCTION

Recent serious accidents[1] involving unwanted release of hazardous materials in the process industries worldwide have focused attention on the need to provide a process by which such accident occurrences can be prevented. This chapter discusses one aspect of that process—the design, construction, operation, maintenance, and modification of hazardous piping systems. The organization generally follows the sequence of piping design, construction, and operation discussed in greater depth in other chapters of this book. However, this chapter focuses on those elements of the design, construction, and operation of hazardous piping systems that are of particular importance to the owner, designer, and operator. Some of the elements discussed herein have been safely neglected in the design of more benign piping, but are mentioned here because it is felt they should be considered for hazardous piping. This chapter does not discuss in any depth the requirements or methods to perform process safety management, except to note elements of piping systems which may be susceptible to piping failures and need to be considered in any system designed to prevent fluid handling system failures. Lastly, this chapter does not discuss piping systems intended to handle nuclear power or nuclear power waste materials. These piping systems are highly regulated, and prescribed requirements are published elsewhere.

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The American Society of Mechanical Engineers, Code for Pressure Piping, B31.3 *Process Piping*[2] defines a hazardous fluid service as:

> "a fluid service in which the *potential* for personnel exposure is *judged* to be *significant* and in which a single exposure to a *very small quantity* of a toxic fluid, caused by leakage, can produce *serious* irreversible harm to persons on breathing or bodily contact, even when *prompt* restorative measures are taken [*emphases added*]."

The emphasized words in the definition are all qualitative, and what may constitute a hazard in one condition (steam in a confined space, for example) may not constitute a hazard under other circumstances (i.e., steam in an open field). A fluid that may be a hazard to the uninformed general public, if exposed to it, may not be considered a hazard if knowledgeable service personnel are handling it. The responsibility of what constitutes a hazard ultimately resides with the owner, and the designer of a hazardous fluid handling system in concert with the owner. The responsibility for a hazardous fluid handling system does not end with its design and construction. Responsibility extends beyond system start-up to the owner to operate and maintain the system safely and provide for the emergency conditions of hazardous fluid releases.

Piping typically will only be part, perhaps even a small part, of a fluid handling system. Pressure vessels, pumps, heat exchangers, turbines, compressors, and other primary fluid handling equipment items may represent greater capital investments and contain greater quantities of hazardous fluids, but all parts of the fluid handling system, including the piping, must be designed, operated, and maintained so as to limit the release of the hazardous contents to nonhazardous levels.

It must be emphasized that during the service life of a plant (as high as 40 years or more), only diligent stewardship will ensure safe, reliable operation of hazardous piping systems. This stewardship begins at the early design phase, and continues through detail design into the construction, erection, and test phase and operation. However, this is only the beginning—a comprehensive monitoring and preventative maintenance program must be developed and implemented to ensure a hazard-free system. And finally, any modifications or repairs need to be performed with the same care and considerations required for the original design and construction, amplified by the recognition that hazardous residues may be present and reactive at and adjacent to the interface between the existing construction and any new or additional fabrications.

Table C10.2 at the end of this chapter summarizes many of the design and operation recommendations developed herein.

TERMS USED IN THIS CHAPTER

Definitions

Some of the terms used in reference to hazardous systems are defined below. Other common piping-related terms are defined in Chap. A1 of this book;

however, the following definitions of owner and designer are specific to this chapter.

Designer. The person responsible for the design decisions to be made regarding the hazardous piping design. It is important that the designer have considerable piping design experience and have access to relevant expertise in the hazardous materials being handled and regarding possible interaction between the hazardous materials and the materials of construction. Professional engineering registration would seem to be a necessity, complemented by an understanding of the intentions of the various codes and standards which may be used in the design, construction, operation, and maintenance of hazardous piping systems.

Explosive. Extremely rapid combustion of a material such that a high-pressure wave is formed and propagated away from the source, often causing extreme damage to nearby objects.

Flammability. The degree of susceptibility to ignition or combustion of a material under specific environmental conditions.

Owner. The organization which will operate the constructed hazardous piping system. The owner is typically viewed by legal systems as having the overall responsibility for the safe design, construction, and operation of owned facilities and, as such, has the primary responsibility for the identification of hazards. While the designer may have some shared responsibility and provide the owner with expertise with which to evaluate hazards, it is nonetheless usually held that the final responsibility for the identification of hazards lies with the owner. Further, it does not seem plausible that hazardous piping would ever be constructed in a speculative environment, and if an engineering construction is purchased by an organization not involved in its design, the new owner should closely evaluate piping systems which handle hazardous and potentially hazardous materials.

Process hazard analysis. A comprehensive review designed to identify potential hazards and to produce specific recommendations that will reduce the probability of a hazard occurring.

Process safety management. The systematic process of design, operation, maintenance, emergency planning, and training by which the unwanted release of hazardous materials is sought to be prevented or mitigated.

Reactivity. The susceptibility of materials to release energy either by themselves or in combination with other materials.

Risk-based inspection. A process by which the evaluation of the risks of failure are prioritized for the purpose of developing a system inspection program to limit system failures and the adverse consequences of those failures.

Safeguarding. The provision of protective and preventative measures that reduce the probability of hazardous conditions occurring.

Toxicity. The ability of a chemical molecule or compound to produce injury once it reaches a susceptible site in or on the body.

Acronyms and Abbreviations

29CFR1910	OSHA, ‘‘Process Safety Management of Highly Hazardous Chemicals; Explosives and Blasting Agents’’
AIChE	American Institute of Chemical Engineers

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
B16.5	ASME B16.5 “Pipe Flanges and Flanged Fittings”
B16.9	ASME B16.9 “Factory Made Wrought Steel Buttwelding Fittings”
B16.11	ASME B16.11 “Forged Fittings, Socket Welding and Threaded”
B31	ASME B31 “Code for Pressure Piping”
B31.1	ASME B31.1 *Power Piping*
B31.3	ASME B31.3 *Process Piping*
B31.8	ASME B31.8 *Gas Transmission and Distribution Piping Systems*
BPS	Bonding Procedure Specification
CFR	Code of Federal Regulations
HAZOP	Hazards and Operability Study
MSS	Manufacturers Standardization Society of the Valve and Fittings Industry
NACE	National Association of Corrosion Engineers
NBBPVI	National Board of Boiler and Pressure Vessel Inspectors
NDE	Nondestructive examination
NFPA	National Fire Protection Association
NIOSH	National Institute of Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
RBI	Risk Based Inspection
PHA	Process Hazard Analysis
PQR	Procedure Qualification Record
PSM	Process Safety Management
WPS	Welding Procedure Specification

CODES, STANDARDS, AND REGULATIONS

The latest edition and addendum of an applicable code or standard should be used for the design and construction of hazardous piping. It may be assumed that the latest edition and addendum of most codes is the clearest interpretation of the requirements of that code. The codes and standards mentioned in this chapter are U.S. codes and standards, but could be reasonably replaced by comparable foreign codes and standards.

New-construction piping codes and standards set forth engineering requirements, normally considered minimum, to assure the safe design and construction of piping systems. Codes and standards use simplified approaches to gain the widest possible usage. Codes and standards typically caution the owner and designer that these documents are not handbooks; that not all service conditions and environmental effects can be known; and, further, that requirements cannot be written to evaluate all such conditions and effects. The owner and designer are asked to use their experience and engineering judgment to meet the safety factors inherent or explicit in the codes and standards. This necessity is compounded when the possibility of a hazard exists with a breach of the fluid-containing boundary.

At present there are few codes or standards which address the area of operations and maintenance of fluid handling systems, much less hazardous piping systems. There is a growing awareness of the problem as evidenced by recent U.S. PSM regulations[3] and efforts by industry to develop approaches to operation and maintenance, such as new and proposed codes and standards by the AIChE, API, ASME, and NBBPVI. However, specific guidance for component evaluation in these new and proposed codes and standards is limited; rather these documents tend to outline procedural requirements and often rely on new-construction rules to guide the operation and maintenance of fluid-handling systems.

The jurisdiction and the obligations of the various parties with regard to codes and standards are discussed at length in Chap. A4.

Piping codes and standards do not list hazardous substances; therefore the owner and designer must identify such materials. However, codes and standards may assist in the identification process. The following is a listing of codes and standards, or documents which may loosely be described as a code or standard, that may assist the owner and designer to identify hazardous materials, to properly design and construct hazardous piping systems, and to evaluate the performance of existing piping systems.

API 570, ‘‘Piping Inspection Code: Inspection, Repair, Alteration, and Rerating of In-service Piping Systems’’

API RP 574, ‘‘Inspection of Piping, Tubing, Valves, and Fittings’’

API RP 750, ‘‘Management of Process Hazards’’

ASME B31 ‘‘Code for Pressure Piping.’’ The ASME B31 Code for Pressure Piping consists of several sections: B31.1 *Power Piping,* B31.3 *Process Piping,* etc. (see Chap. A4). All the sections, published as separate books, may have useful information relevant to the design and construction of hazardous piping systems for their particular application. B31.3, however, is the only section that includes a chapter on hazardous piping systems.

ASME B31G, ‘‘Remaining Strength of Corroded Pipe’’

ASME Boiler and Pressure Vessel Code, Section VIII, Divisions 1 and 2, ‘‘Rules for Construction of Pressure Vessels’’

NBBPVI, ‘‘National Board Inspection Code’’

NIOSH, ‘‘Registry of Toxic Effects of Chemical Substances’’

NFPA 30, ‘‘Flammable and Combustible Liquids Code’’

NFPA 49, ‘‘Hazardous Chemical Data’’

NFPA 325M, ‘‘Fire Hazard Properties of Flammable Liquids, Gases, and Volatile Solids’’

NFPA 491M, ‘‘Manual of Hazardous Chemical Reactions’’

The references also include several miscellaneous noncode or standard publications which may assist the owner and designer in their efforts toward the identification of hazardous fluids and meeting PSM requirements.[4,5]

In addition, U.S. regulations have been published (1992) which require establishing procedures to ensure the integrity of systems handling hazardous materials.

TABLE C10.1 Materials Having High Toxicity or Reactivity

Acetaldehyde
Acrolein (2-Propenal)
Acrytyl chloride
Allyl chloride
Allytamine
Alkylaluminums
Ammonia, Anhydrous
Ammonia solutions
Ammonium perchlorate
Ammonium permanganate
Arsenic hydride (also called Arsine)
Arsine (also called Arsenic hydride)
Bis(chloromethyl) ether
Boron trichloride
Boron trifluoride
Bromine
Bromine chloride
Bromine pentafluoride
Bromine trifluoride
3-Bromopropyne (also called Propargyl bromide)
Butyl hydroperoxide (tertiary)
Butyl perbenzoate (tertiary)
Carbonyl chloride (also called Phosgene)
Carbonyl nitrate
Chlorine
Diisopropyl peroxydicarbonate
Dilaluroyl peroxide
Dimethyldiclorosilane
Dimethylhydrazine, 1,1-
Dimethylamine, anhydrous
2, 4-Dinitroaniline
Ethyl methyl ketone peroxide (also called Methyl ethyl ketone peroxide)
Ethyl nitrite
Ethylamine
Ethylene fluorohydrin
Ethylene oxide
Ethyleneimine
Fluorine
Formaldehyde (Formalin)
Fuming sulfuric acid (also called Oleum)
Furan
Hexafluoroacetone
Hydrochloric acid, anhydrous
Hydrofluoric acid, anhydrous
Hydrogen bromide
Hydrogen chloride
Hydrogen cyanide, anhydrous
Hydrogen fluoride
Hydrogen peroxide
Hydrogen selenide
Nitric acid
Nitric oxide
Nitroaniline
Nitromethane
Nitrogen dioxide
Nitrogen oxides (NO; NO_2; N_2O_4; N_2O_3)
Nitrogen peroxide (also called Nitrogen tetroxide)
Nitrogen tetroxide (also called Nitrogen peroxide)
Nitrogen trifluoride
Nitrogen trioxide
Oleum (also called Fuming sulfuric acid)
Osmium tetroxide
Oxygen difluoride (Fluorine monoxide)
Ozone
Pentaborane
Peracetic acid (also called Peroxyacetic acid)
Perchloric acid
Perchloromethyl mercaptan
Perchloryl fluoride
Peroxyacetic acid (also called Peracetic acid)
Phophoryl chloride (also called Phosphorus oxychloride)
Phosgene (also called Carbonyl chloride)
Phosphine (Hydrogen phosphide)

TABLE C10.1 Materials Having High Toxicity or Reactivity *(Continued)*

Chlorine dioxide
Chlorine pentrafluoride
Chlorine trifluoride
Chlorodiethylaluminum (also called Diethylaluminum chloride)
1-chloro-2, 4-dinitrobenzene
Chloromethyl methyl ether
Chloropicrin
Chloropicrin and Methyl bromide mixture
Chloropicrin and Methyl chloride mixture
Cumene hydroperoxide
Cyanogen
Cyanogen chloride
Cyanuric fluoride
Diacetyl peroxide
Diazomethane
Dibenzoyl peroxide
Diborane
Dibutyl peroxide (tertiary)
Dicloro acetylene
Diclorosilane
Diethylaluminum chloride (also called Chlorodiethylaluminum)
Diethylzinc
Hydrogen sulfide
Hydroxylamine
Iron, pentacarbonyl
Isopropylamine
Ketene
Methacrylaldehyde
Methacryloyl chloride
Methacryloyloxyethel isocyanate
Methyl acrylonitrile
Methylamine, anhydrous
Methyl bromide
Methyl chloride
Methyl chloroformate
Methyl ethyl ketone peroxide (also called Ethyl methyl ketone peroxide)
Methyl fluoroacetate
Methyl fluorosulfate
Methyl hydrazine
Methyl iodide
Methyl isocyanate
Methyl mercaptan
Methyl vinyl ketone
Methyltrichlorosilane
Nickel carbonyl (Nickel tetracarbonyl)
Phosphorus oxychloride (also called Phosphoryl chloride)
Phosphorus trichloride
Propargyl bromide (also called 3-Bromopropyne)
Propyl nitrate
Sarin
Selenium hexafluoride
Stibine (Antimony hydride)
Sulfur dioxide (liquid)
Sulfur pentafluoride
Sulfur tetrafluoride
Sulfur trioxide (also called Sulfuric anhydride)
Sulfuric anhydride (also called Sulfur trioxide)
Tellurium hexafluoride
Tetrafluoroethylene
Tetrafluorohydrazine
Tetramethyl lead
Thionyl chloride
Trichloro (Chloromethyl) silane
Trichloro (Dichlorophenyl) silane
Trichlorosilane
Trifluorochloroethylene
Trimethyloxysilane

International efforts follow similar paths. In the United States, 29CFR1910, App. 2 lists 140 chemicals with high toxicity and reactivity which OSHA considers highly hazardous above the concentrations and threshold the quantities listed there. The chemicals only are listed in Table C10.1. For concentrations, threshold quantities, and revisions to the list of chemicals in Table C10.1, the latest CFR document should be consulted. Note that not all of the materials listed are in a liquid form capable of being piped.

IDENTIFICATION OF HAZARDOUS PIPING

The identification of the hazards associated with the materials to be handled by a system is the first and most important step in the piping design process. Complicating the process are human error and inadequate management of mechanical systems, which have been said to be the largest causes of hazardous accidents. Various methods may be used to identify these hazards. The ''Emergency Planning and Community Right-to-Know Act'' passed by the U.S. Congress in 1986 established a framework for community emergency planning programs to deal with chemical releases. Additional federal actions eventually led to the publication of 29CFR1910 and identification of the hazardous materials listed in Table C10.1. It would not be typical for the piping designer to be as involved in community emergency planning as the owner. However, the piping designer may be more involved in the facility's mandatory PHA, if covered by 29CFR1910, or more informal hazards assessment, if not covered by 29CFR1910. From the designer's involvement in these tasks, it may be a simple matter to establish whether a piping system needs to be designed as hazardous. If the designer is not involved in any hazard analysis, it is incumbent upon the owner to ensure that all relevant knowledge developed from these analyses is communicated to the designer. It is the responsibility of both the designer and the owner to be sure that all of the relevant information has been received and appropriately applied. Further, the designer is responsible to clearly communicate the design intent to the fabricator and erector and to provide the operator with clear guidance as to the proper operation of the constructed piping system.[6] A composite system diagram (see Fig. C10.1) may be useful in organizing piping system design features and in communicating them to the operator.

Various methods are used to perform PHA or less formal assessments such as HAZOPs (Hazard and Operability Studies), ''what if'' checklists, FMEAs (Failure Mode and Effect Analyses), and ''Fault-Tree Analyses.'' These methods often can be used jointly, complementing each other, to produce a higher quality product. While it is beyond the scope of this chapter to describe the different hazard assessment techniques, they all have some basic objectives:

Identify hazardous contents or functions relating to safe handling of such contents

Evaluate the operational and environmental effects and their potential to cause a failure which would result in a hazard

Evaluate the consequences of a postulated failure

Develop specific recommendations to contain, control, or limit the identified hazard.

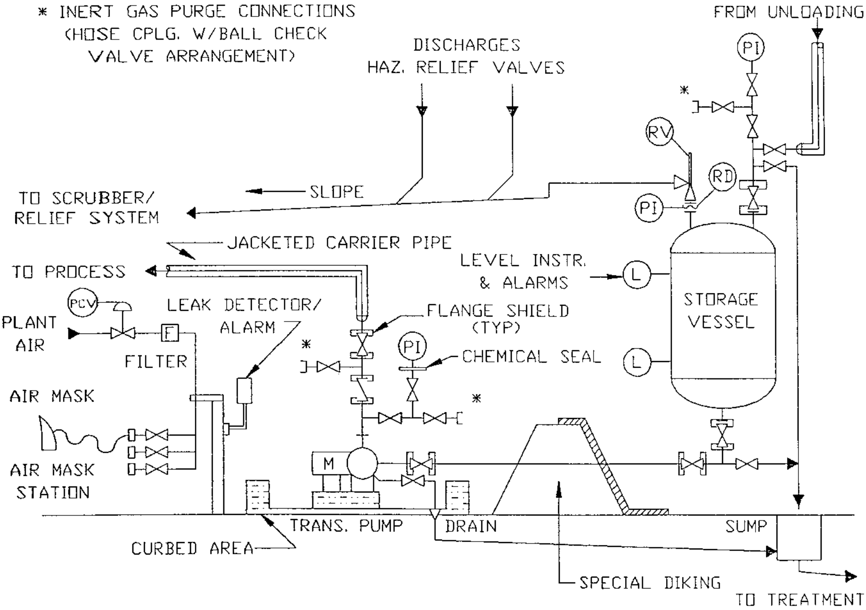

FIGURE C10.1 Composite system diagram.

With regard to piping systems, the *hazard assessment* task should at least consider the following:

- What is the amount and hazard level of the contents in the materials handling system?
- How much of the materials handling system contents could be released if the piping pressure boundary is breached?
- What is the effect on the materials handling system if the piping system fails to operate?
- What is the size of the piping (small piping can be more robust relative to large piping, but small piping can also be more easily abused by activities around the piping system)?
- Where is the piping located (who will be exposed, and in what form will the exposure take place, should a release of the hazardous material occur, and how knowledgeable are those who might be exposed)?
- Are the piping materials of construction compatible with the hazardous contents?
- What are the normal and abnormal service conditions (are the service conditions, so extreme, above and below ambient conditions, or even the ambient conditions themselves, that extra care appears prudent)?
- What is the potential for the piping system to experience a lot of service cycling or be subject to hammering or slugging or flow or mechanically induced

vibrations (high flow rates and two-phase flow can accelerate erosion and corrosion effects, excite piping system modes of vibration, or impose significant hydraulic loads)?

- What are the environmental conditions (is the plant location, or the piping configuration or elevation such that extreme environmental loads can be expected)?
- What is the expected piping system service life (is the time during which the piping system is to be operated of such duration that the probability of failure, such as, creep, fatigue, or erosion/corrosion damage, is significantly increased)?
- What protective measures are appropriate, (for example, guarded piping, structural separation, leak sensing, measures to mitigate the effects of leaks)?

Hazard assessments can be conducted at various stages of a project:

- A preliminary hazard assessment can be conducted early in the project to highlight major potential hazards and define those areas where further study is needed.
- A design hazard assessment can be performed after the process design has been completed to ensure that the process hazards have been identified and necessary corrective recommendations have been implemented.
- A design verification assessment can be performed after the piping system has been designed, to ensure that all items relating to previous hazard assessments have been satisfactorily resolved.
- An operational readiness assessment can be conducted prior to plant start-up to ensure that the design measures established as a result of the various hazards assessments have been incorporated into the construction and planned operation of the piping system.
- Operating assessments can be performed on a routine basis during operating and outage periods to ensure that proper operation, maintenance, and repair procedures are being adhered to.

Note that even if a piping system does not handle a hazardous substance, if the piping system is critical to the operation of a hazardous substance handling system it may need to be designed, constructed, and operated with the object of maintaining its operability under all conceivable operating and environmental conditions. Where there is any question regarding the toxicity or reactivity of a chemical, experienced technical personnel knowledgeable about that chemical should be consulted. The exclusion of a chemical from Table C10.1 should not imply that piping is not hazardous if the contents are released under unfavorable conditions, in an unfavorable location, and in a sufficient amount. When in doubt, a conservative approach would be to adopt appropriate provisions of this chapter. In B31.3 services it is not uncommon to adopt the provisions for hazardous fluid service without referring to the service as such.

QUALITY ASSURANCE AND QUALITY CONTROL

Quality Assurance (QA) and Quality Control (QC) programs are normally associated with the design and construction activities, respectively. To some extent the hazards assessment process can be used to implement and complement both activities. However, the design process for hazardous piping systems, even if a formal QA program is not used, should incorporate document controls covering all relevant calculations, specifications, and drawings; a system whereby all relevant calculations, specifications, and drawings are checked by an independent knowledgeable person; and the calculation, specification, and drawing originator(s) and checker(s) acknowledging their activities by signature and dates; and a documented periodic review of the design activities by supervisory, technically knowledgeable personnel.

It would be expected to find formal QC programs implemented by quality manufacturing, fabrication, and construction organizations. In the construction of hazardous piping systems it is probably not a good idea to use any product from or service by an organization that does not have a functioning QC program. A functioning QC program is one which appears to have been used and revised periodically to meet new operating conditions, organizational changes, or improve the conformance to the way the organization works. A lack of revisions might indicate a lack of commitment to the QC program. A QC program will be able to document work performed; provide proof of materials, workmanship, and conformance to the construction documents; and maintain a segregation of parts and materials throughout the manufacturing, fabrication, and construction process.

DESIGN CONSIDERATIONS

The hazardous piping system should be designed for the entire range of possible design conditions. More information about the operating, possible abnormal, and environmental conditions should be understood than typically may be necessary for a more benign piping system. The designer should have access to a greater variety and level of expertise (e.g., in materials, welding, erosion/corrosion, thermal hydraulics, structural dynamics, chemical interactions, and systems operation) than would be typically necessary for more benign systems. The designer should be skeptical of untried methods and product forms without sound test data to back up analytic presentations. Common sense and reasonable conservatism are necessary to design a hazardous piping system.

Piping Failure Modes

The piping failure modes of greatest concern are *rupture, mechanical joint disengagement*, or *excessive deformations* and *collapse*. These represent the ‘‘worst case’’ failure scenarios. A rupture has the potential to release a large amount of the piping system contents. Disengagement of a mechanical joint has a like potential. Excessive deformations or collapse may cause active equipment (e.g., valves, pumps, turbines, and compressors) to bind and not function and other piping components to pinch or otherwise impede fluid flow.

Other piping failure modes of lesser but still significant concern are the effects of cyclic behavior or the excessive deformations of mechanical joints. Cyclic effects can lead to a fatigue failure, either resulting in a leak or possibly a rupture. Excessive deformation of a flange can also result in a leak but probably not a rupture.

Design Conditions

The design pressures and temperatures should represent the highest (or lowest if the piping system is to operate below ambient conditions) coincident pressures and temperatures the piping is expected to experience during any normal or abnormal operating condition, including any possible environmental effects. Possible variations in normal and abnormal operating conditions should not be allowed to exceed the design pressures and temperatures. The design pressures and temperatures and the maximum coincident external (hydraulic, mechanical, and environmental) loadings should be used to establish the design wall thicknesses and classes for all fittings. Note that considering the effect of external loads may necessitate higher classes of fittings than would be necessary for pressure-temperature conditions alone. Based on variations in external loads, the classes of fittings may vary within the piping system.

Material Selection

Highly ductile materials should be used for hazardous piping. The use of low-ductility materials, such as cast-iron or glass, should be avoided. Materials with demonstrated brittle behavior or sensitivity to thermal and mechanical shock loadings limit their serviceability and range of use. Low-ductility materials are susceptible to brittle failure in hazard mitigation situations, for example from thermal shock when exposed to fire or fire-fighting measures.[8] Impact testing should be used to verify material ductility.

Proprietary materials may be used if the designer is confident of the suitability of the materials for the range of normal and abnormal conditions the material will be exposed to. Materials without sufficient service experience should be avoided.

Material selection should take into account the suitability of the piping to resist deterioration in service. Information should be sought to determine material performance in corrosion or erosion environments.[9,14] Information may be provided; either qualitatively (e.g., acceptable or not acceptable) or quantitatively (e.g., expressed as a uniform corrosion rate). Quantitative information is used to establish corrosion or erosion allowances; qualitative information to select a material that will minimize erosion/corrosion damage. Obviously, the qualitative approach is preferable.

The designer should be aware that in actual service corrosion and erosion will typically be localized and not occur uniformly throughout the piping system. Corrosion is a function of many parameters, such as trace elements in the material, temperature, flow geometry, and flow rate. Corrosion is usually accelerated at crevices, under backing rings, in threaded joints, in socket-welded joints, at weld metal areas and heat-affected zones, or in other stagnant, low-flow areas of the piping system. Erosion is typically accelerated where high flow velocities exist, for example, in undersized pipe, at elbows, branches, reducers, or other locations where there are flow disturbances.

In addition to evaluating the piping base materials, the method of pipe or piping component manufacture should be considered. Joints, material postforming treatment, and manufacturing processes can render piping less resistant to erosion/corrosion than the base materials.

Metallic Piping. Metallic material identification for hazardous piping systems is out of the scope of this chapter. Numerous sources can provide meaningful data for use in the materials selection process.[9,14] But the final choice of material should at least be reviewed by an expert in the chemical and erosion and/or corrosion performance of the candidate material.

Metallic and weld material selection should consider the potential adverse effects of any dissimilar materials that may be in contact, as galvanic action at dissimilar joints can promote accelerated corrosion where it would not otherwise be expected to occur. Material test reports should be sought for all pipe and components so they are available during maintenance activities to determine more realistic factors of safety against failure.

Time-dependent material properties must also be addressed during the material selection process. At high temperatures, typically over 700 to 800° F (370 to 430° C), and over a period of time ferrous materials lose ductility, decrease in strength, and flow (creep). Other metallic materials (e.g., copper, aluminum) experience this phenomenon at lower temperatures and are typically not used where creep would affect performance. It may be wise to select a conservative design temperature when the hazardous piping system must operate in the creep regime. Additional supports and the judicious use of rigid supports can reduce pipe sag and pipe migration during service.

Nonmetallic Piping. Nonmetallic piping typically creeps at room temperature and can suffer degradation due to temperature effects or exposure to sunlight. Consideration should be given to additional supports and protection from sunlight. Using a nonmetallic lining in pipe or a metallic frame around the nonmetallic material may offer protection or additional support. Providing protection for nonmetallics during operation by isolation, double containment, or other means may also be appropriate.

Nonmetallics are attractive because of their corrosion-resistant properties and low cost, but typically they are not erosion resistant. Also, nonmetallics are susceptible to undetectable damage due to impact during transport, storage, and installation. Pipe-joining procedures require care that must be observed, but because nonmetallics are perceived as ''low tech,'' such procedures are often abridged.

Nonmetallics typically exhibit highly anisotropic behavior. Seeking the actual material properties (e.g., yield and tensile strengths, elastic modulus) in the transverse and longitudinal directions may be warranted to assist in maintenance activities for the same reason they are sought for when using metallic materials.

Because of nonmetallic piping's low elastic modulus, internal pressure can cause significant expansion of the pipe that is similar to thermal expansion in metallic pipe. The performance of nonmetallics under cyclic loadings is not well understood because of the wide range of nonmetallic materials, many being proprietary, the lack of material standards, and their typically nonisotropic behavior. If loads are expected to cycle more than a couple of hundred times, including pressure cycles, fatigue testing of the material may be warranted.

The designer should also be aware that nonmetallics can often be combustible and may require fire protection.

At this time (1999) there are no proven volumetric NDE methods available. Visual and dye penetrant methods are used, but these methods are limited to the pipe surfaces, and usually to the outside surfaces. Ultrasonic methods have been suggested as offering a potential volumetric examination, but these are thus far unproven. Refer to Chapter B13 and Part D of this handbook.

Design Criteria

Hazardous piping should be designed to a recognized piping code or standard. B31.3 has a chapter dedicated to the design of hazardous piping, but other codes and standards could be used with proper consideration of the hazards and mitigating design attributes. Safety codes and standards, however, do not address levels of hazard. The designer should consider specifying greater safety attributes for hazardous piping to the degree he feels they may be necessary. A review of the B31.3 nonmandatory App. F, Precautionary Considerations, and G, Safeguarding[2] may provide the designer with ideas for enhancing the safety of the hazardous piping system.

If the designer plans to use nonstandard or unlisted materials and components or to use more rigorous analysis or alternative examination methods, the justification for the use of such materials and components under all the possible operating and environmental conditions and the reasons for justifying the use of such analysis and examination methods should be fully documented for the owner's approval before the release of specifications and drawings for construction.

PRESSURE DESIGN

The most significant safety attribute of piping is *pressure containment*. Hazardous piping should be designed for the most severe condition of coincident pressure, temperature, and loading. B31.3 does not permit, nor should any hazardous piping be allowed, to exceed design values, even for short periods of time. It may, in fact, be wise to overdesign the pipe for pressure (i.e., specify a thicker wall than is required by the piping code used). Other loadings may be increased by thicker pipe walls, but these other loadings, such as thermal expansion, may be compensated for by adding to the length and location of pipe in the anchor-to-anchor piping runs.

Straight Pipe

The design of straight pipe should be in accordance with the specified piping code. Flow velocities should be limited to a maximum of about 10 ft/s (3 m/s) for liquids and about 140 ft/s (43 m/s) for gases, especially where the potential for erosion and corrosion exists. Higher velocities may be justified by thorough investigation of the erosion/corrosion potential, but higher velocities may result in undesirable flow-induced vibrations and noise.

The additional wall thickness provided to allow for erosion and corrosion should be based not only on the expected rate of wall loss and the anticipated life of the system, but also on the expected examination interval of the in-service inspection program.

Since hazardous piping is often small piping, protection of the piping from damage after installation is also advisable. An additional wall thickness could be provided, or the piping may be isolated or located in channels, cable trays, or double containments.

Standard Components

Standard piping components are discussed at length in this and other books (see Chap. A2). The designer, however, should be confident that components supplied as standard actually meet the standards specified; for example, the manufacturer should be able to provide evidence that the B16.9 fitting furnished or a comparable fitting has met the burst test provisions of B16.9.

The designer should be careful to ensure that components are specified to match the pipe to which they are connected. Further, the designer should request to be advised if the fabricator or erector deviates from matching components to the pipe or uses a nonstandard fitting in place of a standard fitting (e.g., using a Schedule 160 fitting rather than Schedule 80 fitting, or replacing a standard welding tee with a fabricated branch connection). Such deviations can result in stresses not considered in the design.

The designer should also be aware that velocities will increase locally in nonstraight pipe components over the mass (bulk) velocity in straight pipe and thus can increase the local potential for erosion and corrosion.

Valves

A valve is usually defined by the piping codes as a standard piping component. As is the case with other standard components, the designer should be aware that fluid velocities, particularly in the vicinity of the valve seat, will be higher than in matching pipe and can result in erosion and corrosion problems.

The selection of valve type, style, and valve body and trim materials should be based on hazardous fluid properties, required operating characteristics, and ease of maintenance. When locating valves, the designer should consider required operability and service access. Selection of valve materials and location should also include consideration of potential accidents (e.g., fire). The valve construction (i.e., bolted bonnet versus pressure seal or welded) should include consideration for pressure boundary integrity required to prevent leakage of hazardous material (see Fig. C10.2). It is recommended that the valve meet recognized piping code requirements for design, materials, and manufacture.

Isolation and Control Valves. The number and locations of isolation valves should be based on system requirements and include consideration for potential release of hazardous materials in the event of pipe rupture or inadvertent improper operation.

Metal-seated gate valves should be of the flexible disc, split wedge, or double disc design which provide tighter shut-off than solid wedge designs, and prevent jamming of the gate, if the valve cools down in the closed position. The wedge and/or body seat should be hard-faced to prevent galling.

Remote-controlled valves (with motor operators, air operators, etc.) versus manual valves should be considered for more rapid valve operation and operation in a contaminated area. Similarly, remote manual operating devices, such as extension rods and chain-wheel operators, should be considered for ease of and safe valve manipulation. For large valves where motor operators cannot be justified, but where a valve may be required for isolation in an emergency, consider using portable air drives to assist in rapid valve closure. Also, for large manual valves consider ''impact'' handwheels to assist in the seating or unseating of the disc.

Valve and operator type should be such that valve position is easily visually determined (for example, see Fig. C10.2). For valves essential to plant safety, consider the use of remote position indication. To preclude the possibility of inadvertent, improper valve operation, consideration should be given to using valve position-locking devices.

Permissible valve leakage (i.e., leakage across the seat[s] when closed) should be based on the properties of the fluid media and hazard presented by leakage.

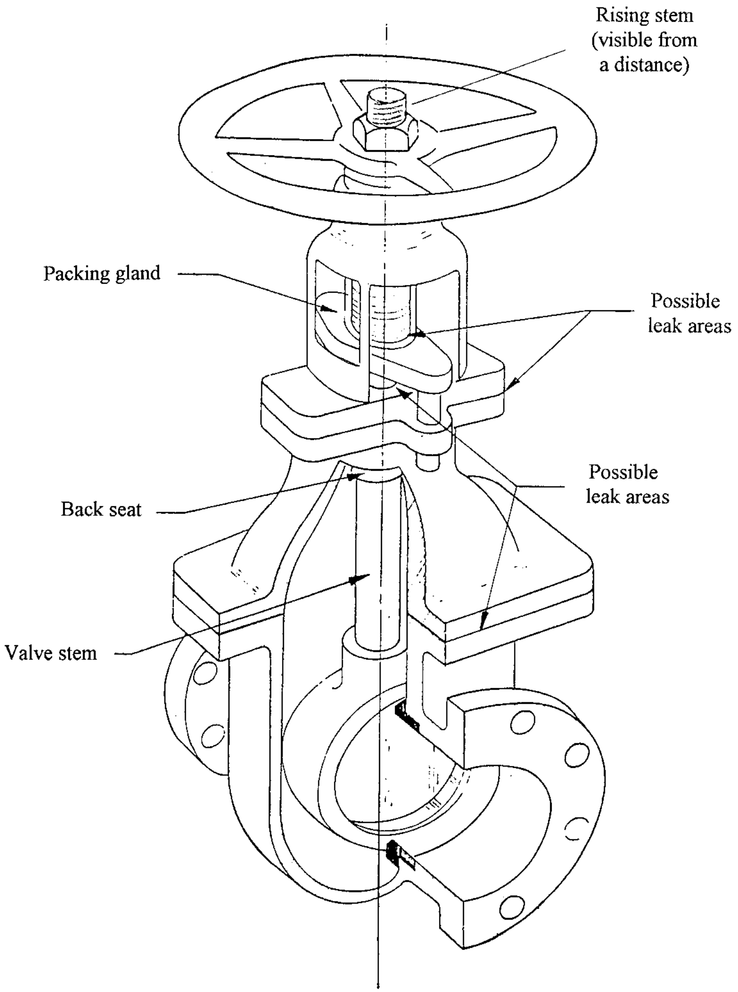

FIGURE C10.2 Conventional gate valve.

Valve backseat capability should be considered for gland repacking while the system is energized. The design of valve gland injection or leakoff collection devices should also be based on the properties of the fluid media and hazard presented by leakage. Valve body drains should be considered for removal of fluid media from the lower cavities for ease of maintenance activities.

Control valve redundancy (i.e., parallel installations) should be considered based on required system operation. The designer should be aware that cavitation can occur in the piping downstream of control valves and can result in severe erosion/corrosion problems. Control valve positioner linkage materials need to be compatible with the external environment and contained fluids.

Although service failures in valves have resulted from shrinkage cavities in cast valve walls,[7] through-wall cracking of valves is rare. On the other hand, leakage through the stem/bonnet is relatively common.[11] Recent design enhancements have produced valves with sophisticated devices to eliminate valve stem leakage. Most of these designs employ a proprietary bellows-like device to effect a hermetic seal. These devices, along with conventional backup seals, may provide a solution to the problem of fugitive emissions emanating from valve stem areas.

Relief and Safety Valves. Relief and safety valves should conform to a recognized pressure component code which requires overpressure protection of the pressure boundary. B31.3 requires that the design pressure shall not be exceeded by more than 10 percent during a pressure-relieving event. Note that this is in conflict with the B31.3 requirement that piping shall be designed for the most severe condition of coincident pressure, temperature, and loading. It is recommended that the design pressure and temperature include values expected during the pressure-relieving event. However, should the 10 percent requirement of B31.3 be applied, the designer should consider including a temperature correction, if the design temperature is also exceeded during the pressure-relieving event.

Unless the pressure-relieving system is designed to regularly recycle or eliminate the hazardous contents, the set pressures of relief and safety valves should be set sufficiently above the normal and recoverable abnormal operating conditions such that the pressure-relieving system is not activated except in an emergency.

Since small safety/relief valves (sentinel valves) have a tendency not to reseat once they lift, they should have the spring cap drilled and tapped for a gag which should be attached to the valve to facilitate closure.

Rupture disc and breaking pin devices are normally unsuitable for relieving pressure in hazardous piping.

Nonstandard Components

Special fabrications, forgings, castings, and other specialties may complicate the design and cause difficulties later, if replacements are required. However, if used they should be qualified for pressure design in accordance with a recognized piping code or standard proof test, such as found in B16.9. The proof test procedure and the results should be reviewed and approved by the designer. The proof test should prove the nonstandard component's capability to function at 110 percent of the piping system's design pressure, adjusted for the design temperature, with the factor of safety inherent in the piping code used for design.

Expansion Joints and Flexible Hose

Expansion joints and flexible hose should be avoided unless absolutely necessary to accommodate thermal movements where expansion loops are not feasible or to decouple the piping from potential sources of mechanical vibration, (e.g., rotating equipment). If used, it should be realized that portions of the joint or hose are typically highly stressed and can degrade rapidly in an adverse environment or if manufactured with materials unsuitable for the service. If tie rods are not used, the pipe supports must be designed for the very large loads resulting from pressure thrust. The designer should follow the recommendations of the manufacturer and the Expansion Joint Manufacturers Association.[16]

JOINT DESIGN

Piping joints, whether welded or mechanical, must be suitable for the anticipated pressure, temperature, and external loading conditions. The designer should also be aware that joints may be sensitive to the type of loading or be subject to selective attack by the erosive or corrosive nature of the fluid handled. Barriers and shields should be considered for mechanical joints to protect personnel from leakage.

Welding

Welding is the preferred method of making a joint in hazardous piping. Welding should be performed in accordance with the ASME Boiler and Pressure Vessel Code, Sec. IX, *Welding and Brazing Qualifications*. While welds between pipe supports or other attachments and the pressure-retaining boundary should also be in accordance with Sec. IX, welds between pipe support items may not need to be Sec. IX welds if they conform to an acknowledged structural welding code.

Meeting the requirements of Sec. IX should assure the quality of welding. Section IX requires the preparation of a written welding procedure specification (WPS). The procedure is qualified in a procedure qualification record (PQR) which documents physical testing proving that welds made in accordance with the WPS provide the required mechanical properties, essentially equivalent to the base material properties. Just as important is the qualification of the welder, which is done to prove the ability of the welder to make sound welds in accordance with the WPS. This is also proven by testing sample weldments done by the welder. For hazardous service, the designer may wish to require more stringent testing of either or both the procedure and welder and in-process checks to ensure the desired weld quality.

To minimize any adverse effects from welding, the designer should review and approve the welding procedures and qualifications of the manufacturer, fabricator, and erector. The welding processes chosen should be based on the materials being welded, the quality level desired, and the availability of personnel capable of depositing sound weld metal. The filler material should be selected to essentially match the chemical composition and material properties of the base materials. Corrosive environments, low temperatures (requiring toughness considerations), and high temperatures (requiring creep considerations) may necessitate special attention to welding processes.

Longitudinal welds used to manufacture pipe are typically made in accordance with Sec. IX, but also typically these welds are penalized, using a joint efficiency factor to reduce the allowable base material stress resulting in a thicker weld. Some care should be exercised if welded pipe is to be used for hazardous piping. B31 joint efficiency factors have been subjectively developed and do not take into account possible operating degradation (e.g., due to creep). If the joint efficiency factors are less than 1.0, using B31 specified NDE can improve the joint efficiency factors to a value of 1.0, but this should not necessarily be construed as removing the metallurgical or geometric discontinuity that the weld joint represents. Consideration should be given to using seamless pipe in hazardous piping. On the other hand, high-resolution NDE in conjunction with a mill hydrotest has been shown to produce a high-quality weld seam in welded pipe. Because anisotropic properties are a typical result of the pipe manufacturing process (with more disparity expected in seamless pipe), the designer may consider testing for both transverse and longitudinal, yield and tensile properties as it is not unusual to have the maximum properties given in material test reports.

Butt welding is also the preferred method of joining two pieces of pipe because it typically produces a relatively small local stress riser in the form of surface imperfections,[15] compared to other types of welded joints, and a butt weld joint can be readily examined by most conventional nondestructive techniques.

Typically, with hazardous materials, a smooth internal root condition is desired. In order to achieve this, the gas tungsten arc-welding (GTAW) process is often chosen, sometimes with the additional application of automatic welding. This is true because the GTAW process characteristics allow for close control of heat input. Other processes may be used to fill the weld joint after the initial layers are deposited.

Socket welds can be used if the designer evaluates and accepts its deficiencies. Several problems could be anticipated with the use of socket welds. Socket welds are susceptible to failures due to pressure cycling. The gaps required for fit-up and crevices in the socket are also potential debris collectors and places where corrosive elements can accumulate. Recent improvements in automatic welding in the field renders such a reasonably viable alternative to socket welding. Backing rings used for butt welds may also be subject to problems similar to the crevices in socket welds and it may be wise to avoid their use.

Branch connections are often made using proprietary products (so-called ‘‘integrally reinforced’’ weld-on fittings). It is important to obtain the manufacturer’s recommendations for welding, in particular the attachment weld profiles, prior to their specification in the design. It is also important to specify a cover weld for the attachment weld to the header similar to the requirements of the various B31 codes. If the branch connection is large, cover welds larger than those required by code would be prudent. Details of the required weld should be specified in the engineering design.

If fatigue is a problem, consideration should be given to grooming the surface of the finished circumferential and branch welds. For cleanliness, and if the inside of the pipe is accessible, grooming the inside surface of the weld might also be considered.

Dissimilar metal welds should not be used unless the thermal expansion effects of the two materials are evaluated. If the dissimilar metal weld is necessary, it should be a butt weld, not a socket weld or a branch connection weld.

Brazing and Soldering

Brazing and soldering should not be used in hazardous piping.

Bonding

It is obvious that the bonding of nonmetallic piping is critical to the construction of a safe hazardous piping system. However, the designer should recognize the fact that many bonds are carelessly made because the use of plastic pipe is not typically treated with the same regard as metallic piping.

The bonding of nonmetallic piping components should be done in accordance with a written bonding procedure specification (BPS). The BPS should be qualified by testing the mechanical properties of an assembly made in accordance with the BPS. All bonders should be qualified by preparing an assembly in accordance with the BPS that is tested to prove the bonder can make acceptable bonds. Refer to Chaps. D1 and D2 of this handbook.

Flanges

It bears repeating that flanges should be designed for the maximum coincident pressure, temperature, and loading. This is a fact that is often missed because typically flange standards list pressure and temperature ratings only. If piping loads are significant and if the flange is not properly sized, then the flange will inevitably leak. Increasing the flange class (e.g., using a Class 300 flange where the pressure and temperature would indicate the use of a Class 150 flange) will result in a joint less likely to leak and in flange bolts that are less likely to be overstressed. The equivalent pressure method described in *Design of Piping Systems*[8] is suitable for sizing flanges with external loads and has been incorporated into a number of piping codes.

Flanges conforming to B16.5 are recommended. Flanges manufactured to other recognized consensus standards may need to be used for large-diameter piping and would be acceptable with due consideration given to external loads and fit-up.

Standard flanges include flat face, raised face, tongue and groove, ring joint, and lap joint flanges. Gasket materials include rubber, cork, elastomeric composition, spiral wound and laminated metallic-elastomer mixes, and solid metal rings. The effects of the hazardous contents on the gasket material should be considered.

These flanges offer the advantages of ease of joint assembly, standardized dimensions, and general availability. A disadvantage is that assembly requires high bolt loading during initial seating to retain sufficient gasket pressure in service. This should be a consideration if the joint is subject to high cyclic loads or operates in the creep regime of the flange materials.

Proprietary flanges are nonstandard components and should meet the requirements described for nonstandard components. The designer or the manufacturer should also understand how the flange will perform when subject to external loadings. These joints typically have fine surface finishes and tight tolerances. They usually require great care in assembly, and the tight gaps may create the potential for crevice corrosion.

Published flange ratings (pressure-temperature-material class) presume the proper selection of gasketing and bolting materials. The flange joint is an assembly of flange, gasket, and bolting. In most cases the gasket seating surface is critical to proper joint sealing. Should the designer be inattentive to the interdependency of the flange assembly components, the flanged joint may not withstand the operating and environmental loadings.

The designer should endeavor to locate flanged joints where external loads are low. The loading on a flanged joint includes internal pressure, bolt loads, and the piping operating and environmental loads.

Weld-neck flanges are recommended for hazardous piping systems. Other flanges may be used if due consideration is given to their deficiencies. Other flanges, excepting lap joint flanges, are typically joined to the pipe with a fillet weld, which is less desirable than a butt weld. The attachment (strength) fillet weld is typically more highly stressed and subject to a stress amplification due to its geometry. Slip-on flanges, if used, should be double-welded with the seal (or back) weld at a minimum distance from the face of the flange. Care must be taken to avoid having the seal weld interfere with the proper function of the flange. Threaded flanges should be avoided due to their susceptibility to crevice corrosion and because threads represent significant stress risers. Socket welding flanges should only be used for NPS 2 (DN 50) and smaller. When using socket welding flanges care must be used regarding fit-up to ensure a minimum gap between the pipe and the bottom of the socket. Plate flanges (flanges without hubs) should be avoided unless double-welded and the flange thickness is increased to offset the high attachment weld stresses. Lap joint flanges are susceptible to crevice corrosion and potential sealing problems. Crevices in any of the flanges may collect contaminates, and the collected contaminates could present a problem when servicing flanged piping and equipment.

Flanged joints in hazardous fluid service can be safeguarded with flange shields to confine any escaping fluid.

Threaded Connections

Threaded connections should be avoided, if possible. Their vulnerability to fatigue damage is significant, especially where exposed threads are subject to corrosion. Note that materials susceptible to corrosion will corrode if exposed to unconditioned air. If used then, external piping loads should also be kept as low as possible. Seal welds covering the exposed threads may reduce external damage, but exposed threads within piping may also pose erosion, corrosion, and fatigue problems. Construction documents should specify seal welds where appropriate.

Other Mechanical Joints

There are a number of proprietary mechanical joints which may be acceptable if consideration is given to their deficiencies. Generally these mechanical joints have crevices which can trap fluids and would be susceptible to crevice corrosion. These proprietary joints should be treated as nonstandard components and meet the requirements previously set forth. In addition, the mechanical joint's ability to withstand the operating and environmental loads to which it will be subjected must be verified. Proprietary joints meeting industry standards may not necessarily be suitable for hazardous service. There are instances where industry standards do not comply with the factors of safety inherent in recognized piping codes.

Requirements for Leak Testing

B31.3 requires a sensitive leak test in addition to other required leak testing. It is recommended that a sensitive leak test be performed regardless of the piping design code used and such should be specified in the engineering design. If the design is in accordance with a piping code other than B31.3 or if the designer concludes a greater sensitivity is required than that required by B31.3, the required sensitivity should also be specified.

EXTERNAL LOADS DESIGN

There are two components to piping system design. The first is component design as previously discussed. The second is analyzing the designed pressure components as a postulated anchor-to-anchor structural system, subjecting the system to the possible external (operating and environmental) loads, judiciously adding supports to limit stresses due to weight and other loads, but not unduly restraining the piping.

Piping System Considerations

The design should provide for possible isolation means and/or devices to monitor and contain or recover inadvertent discharges of hazardous contents.[10] Open air process units lessen the potential for concentrating hazardous vapors, but increase the potential exposure to personnel near hazardous piping.

Double containment systems offer the opportunity to protect the hazardous piping plus an additional barrier to the release of the hazardous contents of the ''carrier'' pipe (see Chap. B13). The annulus between the carrier and outer pipe can provide insulation, but more important, a location for a leak monitoring system to detect failures of the carrier pipe.[13] The design of double containment systems may present difficulties in accommodating thermal expansion effects and problems in ease of construction.

Hazardous fluids, if released, should be collected in a dedicated system for safe removal and to eliminate any cross-contamination with other services. If the release of hazardous liquids is to the open air, a diked area should be used to contain the spill, and a system for safe removal of the fluid and fumes would be required. If the release is a hazardous gas, a ventilation system may be used to remove hazardous vapors, mists, and dust and supply fresh air to the vicinity of the failed pipe. Such a ventilation system should be equipped with a scrubber to strip the vented air of hazardous materials prior to its release to atmosphere.

Piping Layout

Every effort should be used to ''hard-pipe'' systems using seamless, matching standard pipe and components. Layouts should be routed near possible support points; the support hardware should preferably attach to straight pipe, rather than piping components. The developed (total) length of pipe should be minimized. Expansion loops, unequal Z-bends, and unequal offsets should be used to accommodate thermal expansion effects; while the use of mechanical devices to accommodate thermal expansion or contraction should be avoided. Layouts should facilitate operation and maintenance and protect piping from activities not related to the piping system function or maintenance. Drains and vents should be provided and piping sloped to facilitate liquid drainage and gas venting.

Early identification of hazardous systems will allow layout considerations to be incorporated into the plant housing the system. A structural ''flexibility'' analysis, typically evaluating the startup-shutdown cycle, should be performed to determine if the piping system layout is not unduly restrained. The allowable flexibility stress-range will need to be reduced if the startup-shutdown cycle occurs once a day or more.

System Controls and Safety Systems

Process controls need to be provided to monitor system conditions to protect the system from excessive excursions of pressure, temperature, and fluid flow. The controls should limit the quantity of hazardous fluid that can escape in the event of a pipe rupture.

A systematic monitoring and leak detection program designed to identify small leaks and potential problems as early as possible should be implemented.

It would be unusual for a hazardous piping pressure relief or safety relief system to directly discharge hazardous material into the atmosphere. Most often hazardous systems will be relieved into a closed system of piping and holding or treatment vessels. In this case, the relieving systems must be designed to accommodate the full volume of the maximum possible release. Obviously, the piping portion of the pressure relieving system must also be identified as a hazardous piping. The relieving event will typically introduce significant momentum change forces and possibly dynamic amplification of the discharge forces.

Where hazardous piping is connected to a vessel requiring entry, two stop valves with a ''free blow'' drain, in between, should be provided as close to the vessel as possible.

External Loads Analyses

The evaluation of sustained stresses due to weight is normally less of a concern than limiting the displacements (sag) between supports. Limiting the sag between supports to about ⅛ in (3 mm) will limit weight stresses and, in vapor systems, the pooling of condensibles. Long vertical risers or downcomers may require vertical supports to limit weight stresses not typically calculated using piping code compliance computer programs.

Short-term sustained load stresses, such as single-phase flow pressure transients, two-phase flow transients, wind, and earthquake, should be evaluated. In general, limiting the displacements due to these short-term loadings will limit their potential to cause a piping collapse or rupture and likewise limit the fatigue damage, if these loadings are frequent. Two-phase flow transient forces may also be reduced by reducing flow velocities. Piping displacements can be limited by active supports, such as hydraulic and mechanical snubbers and sway braces, or passive supports, such as gapped framing around the pipe. Passive supports are preferred over active supports because active supports typically require periodic maintenance. Gapped supports and the piping may each suffer impact loads during these short-term loadings. Passive protection for the piping can be provided by special coverings, sleeves surrounding the insulation, devices or materials designed to take impact, heavier pipe walls, or pads in the vicinity of the gapped support.

The startup-shutdown thermal stress-range (usually based on normal operating conditions, rather than design conditions) is typically analyzed to assure adequate piping flexibility. But all temperature ranges, whether due to normal or abnormal excursions, should be considered and evaluated along with the startup-shutdown range, if significant. Further, all other load ranges, such as due to pressure and short-term hydraulic and mechanical excursions, result in some cyclic (fatigue) damage. However, if an excursion does not often occur and the stress-range of the excursion is less than half the allowable startup-shutdown stress-range, it will probably not result in significant fatigue damage. Remember that because of a low elastic modulus, nonmetallics will experience significant pressure expansion effects similar to thermal expansion, often requiring consideration of their startup-shutdown stress-range. Pressure expansion will occur in metallic piping too, but it is usually only a small fraction of coincident thermal expansion.

The designer should be aware that significant fatigue damage can result from relative anchor motions from any cause and need to be considered in the cyclic (fatigue) analysis. The greatest number of piping failures due to earthquake motions have been caused by excessive relative anchor motions. The number of times that any significant cyclic stress-range occurs must be estimated to properly evaluate a piping system for fatigue.

Creep damage from external loads should only occur from long-term sustained loadings. Using the design temperature to determine the allowable stress for sustained loads should limit external load creep damage.

Evaluation of local stresses may be necessary as the result of rapid fluid temperature changes at geometric discontinuities and at a material discontinuity due to any temperature change.

The magnitudes of flow and mechanically induced vibrations are hard to predict, although they should be expected if flow rates are high or in the vicinity of reciprocating and rotating machinery. If expected, a conservative estimate of their magnitudes may be necessary for analysis or the design should incorporate features to mitigate their effects. Vibration may only be realized after system operation begins and may need to be evaluated then.

Pipe Support Design and Analysis

Pipe supports are part of a piping system and should be of concern in hazardous piping because improper support design and their attachment to the pipe wall have caused failures in piping systems.[7] For example, a support lug welded directly to the wall of a high-temperature pipe under the insulation, with the other end of the lug exposed to the atmosphere can ‘‘pull’’ a crack in the pressure boundary because of the lack of lug flexibility near the pipe wall.

Attachment welds to and a portion of the attachment nearest the pipe wall should be considered as part of the pressure boundary and evaluated and constructed accordingly. A distance no less than $2t$ from the pressure boundary, where t is the thickness of the pressure boundary, should be considered the ‘‘portion of the attachment nearest the pipe wall.’’ This means that within $2t$ materials should be pressure boundary materials and welds should conform to Section IX. Beyond that distance, support materials should be suitable for the service. Note that B31.1 requires support materials for metallic piping to be listed, but that this could be interpreted as the attachment material should be listed for the purpose of considering the interaction between the attachment and the pressure boundary.

The design locations of supports and the method of attachment to the pipe should be reviewed with the piping designer, and to the building with the building designer, for large piping, to assure that those locations and the method of attachment are acceptable.

Generally, supports need not be integrated with the analysis of the piping system (i.e., the support stiffness need not be incorporated in the analysis of the piping system). Incorporating support stiffnesses in the piping analysis will typically reduce loads on the supports. This should only be necessary if the piping loads are very high. However, supports should be stiffer than the pipe at the support point or they may not support the pipe. This should be able to be assessed merely by observation by an experienced support designer.

Pipe supports should support the pipe in the operating condition. For this reason, pipe supports should typically be adjustable and the piping system reviewed during normal operation and pipe supports adjusted as necessary. Pipe supports should also be designed to facilitate sloping the pipe for drainage or venting.

Mechanical expansion anchors in concrete should be avoided; cast in place or epoxy grouted or equivalent anchors are preferable.

Threaded hangers should be designed so that the threads are not subject to bending.

OPERATING MANUAL PREPARATION

After completing the design, the designer should prepare an operating manual which describes the normal and abnormal operating and environmental conditions assumed in the design of the hazardous piping. Recommended operating and maintenance instructions for active components should be included. Manufacturers of active components, such as valves, pumps, instrumentation, and snubbers, will typically provide operating and maintenance instructions. All design drawings, including component manufacturer's design drawings, should also be included. The operating manual should include any other information the designer concludes is necessary to guide the operator in operating and maintaining the hazardous piping system safely. Recall, as was previously stated, that a composite system diagram (see Fig. C10.1) may be useful to communicate the piping system's design features to the operator.

FABRICATION AND ERECTION

Fabrication and erection of hazardous piping should be performed in as clean conditions as possible to avoid any contamination that would compromise the process that is to occur with the finished system.

Forming

It would be wise to verify that piping code required heat treatment is performed on identified materials after cold or hot forming of components.

Welding and Bonding

The welding and bonding procedures established by the fabricator's and erector's QC programs should be followed. The fabricator and erector may augment the required examination by additional spot checking of the welding or bonding being performed.

Butt Welds. A butt weld is expected to fill the weld groove between two pieces of pipe from the inside surface to the outside surface of the pipe. Any deviations from this practice, such as between two heavier than nominal pipe fittings, should be reviewed with the designer.

The piping layout and shop fabrications should consider how to facilitate field welding; for example, a field weld should not be located too near a wall such that the welder must use a mirror or other device to finish the weld.

Butt weld joints should be made without the use of backing rings and inserts, unless otherwise permitted by the engineering design.

Branch Connection Welds. Shop welding of branch connections is preferred to field fabrication. Non-90° branches are more difficult to fabricate than 90° branches. The engineering design may detail required branch connections. If not, it is recom-

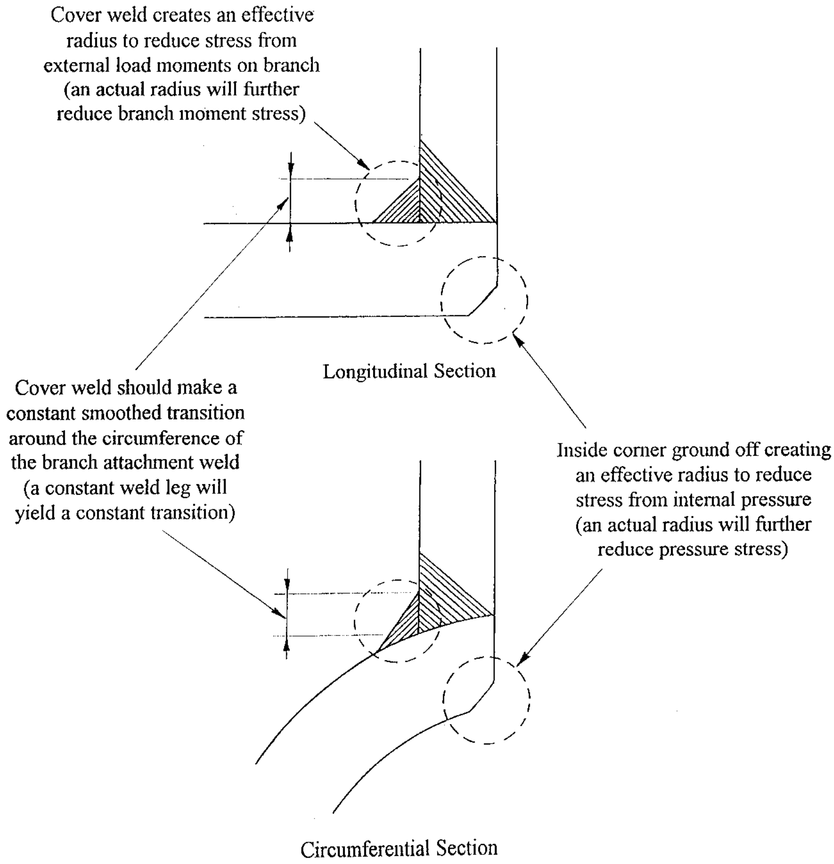

FIGURE C10.3 Recommended branch connection details.

mended that the fabricator or erector consider the following good practices to provide quality branch connections (see Fig. C10.3):

The sharp inside corner of large high-pressure branch connections should be ground off, creating an effective inside radius. The outside welds to the header should not have abrupt corners; cover welds, such as those specified in B31 codes, should be used to provide an effective radius between the branch attachment weld and the header. The cover weld should effectively make a constant smoothed transition around the circumference between the attachment weld and the header. For large branch connections, the cover weld should probably be larger than the minimum typically required by the B31 codes.

Socket Welds. Unless otherwise specified in the engineering design, a socket weld is expected to be a 45° fillet filling the joint created by inserting the pipe into a

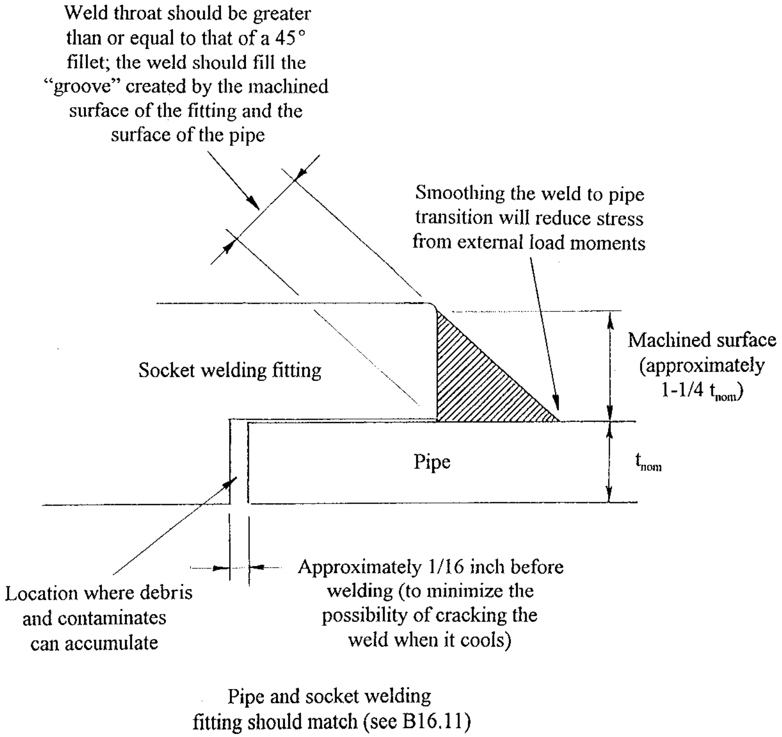

FIGURE C10.4 Recommended socket weld details.

matching socket welding fitting (see Fig. C10.4). The weld is expected to fill the joint to the edge of the machined boss on the face of the fitting. This means the leg length (size) of the fillet weld is approximately 1¼ times the nominal matching pipe thickness. Weld buildup on the unmachined surface of the socket welding fitting is not expected. Piping codes may mention a preference for a concave (smoothed) weld, but such a weld should not reduce the throat of the weld below that of the 45° fillet expected. The concave smoothing should only be done at the toe of the weld.

Bonding. The fabricator and erector should take care that nonmetallic components and bonding materials are protected from damage or deterioration prior to assembly.

The fabricator and erector should be careful during fit-up that joints to be bonded are well supported and that the bond is allowed to cure for the time required by the BPS before construction supports are moved.

Mechanical Joints

Mechanical joints should be assembled in accordance with the requirements of the fabricator or erector's QC program.

Flanges. Large flanges and their gaskets need to be carefully aligned prior to bolting. The torquing of the bolts needs to follow a sequence to achieve the required bolt efficiency (i.e., bolt tightness) without overloading the flange or overstressing the bolts. The gasketing, if not specified in the engineering design, needs to be reviewed with the designer.

Small flanges may not need to comply with the alignment requirements of the piping codes. The flexibility of the attached small piping may be sufficient to not overstress the flange elements; however, this should be reviewed with the designer.

Threaded Connections. Where the erector uses threaded connections not specified, but not prohibited, in the construction documents, the erector should verify the acceptability of such. Where the erector finds threaded connections specified in the construction documents but seal welds are not, the erector should consult the designer regarding his intentions.

Other Mechanical Joints. Fabricators and erectors should make sure that all mechanical joints are properly assembled by following the manufacturer's recommendations, which typically describe a method to verify proper assembly. Documentation of the verification may be warranted.

Erection. The piping should be erected in accordance with the engineering design and the piping code used in the design. Deviations from the design required for constructability should be reviewed with the designer.

Bending or forming required for fit-up or alignment may require postforming heat treatment in accordance with the piping design code.

Temporary supports for erection should not damage the piping or allow excessive deformations of the piping or equipment to which the piping is attached.

After completing the installation of the piping the original design drawings should be revised to show all changes made; that is, the piping system drawings should be "as-built" and made part of the turn-over documentation.

EXAMINATION, INSPECTION, AND TESTING

Most piping codes distinguish between *examination* and *inspection*, examination being the responsibility of the manufacturer, fabricator, or erector, and inspection being the responsibility of the owner. There is a tendency to limit examination and inspection to the welds, but more than the welds should be looked at prior to piping system startup, especially for hazardous piping.

The manufacturer and erector can use various NDE methods to minimize substandard workmanship, and the owner can employ the same or different methods to verify the manufacturer's or erector's work. However, most piping codes specify the examination (NDE) methods with little opportunity for variations. Along with the prescribed methods, these same piping codes specify acceptance criteria appropriate to the type and extent of required examination. Code inspection is normally limited to the owner reviewing the manufacturer, fabricator, or erector's work to the extent that the inspector is confident that the manufacturer, fabricator, or erector has performed the proper examinations and has made repairs where appropriate. However, the owner's inspection should include an overall review to assure that the construction meets the engineering design.[2]

Because the piping is considered hazardous, the owner or designer may wish to impose more rigorous examination requirements (i.e., either NDE methods or acceptance criteria) than is required by the piping code being used. For example, the designer may want to limit the porosity in a butt weld to less than that permitted in a highly corrosive, high cyclic service. But more rigorous or multiple NDE methods may not be required by the code being used and the acceptance criteria of the codes is only appropriate for the required examination. This is true for all ASME pressure component codes and is illustrated by paraphrasing a 1985 B31.1 Interpretation.[17]

> *Paraphrased Question*: When an NDE method is not required by B31.1, but is used, must the acceptance criteria meet the requirements of B31.1?
>
> *Paraphrased Reply*: The acceptance criteria are not within the scope of B31.

In addition, piping codes typically specify NDE methods that have been proven over long periods of use. Thus, if more rigorous, alternate, or newer NDE methods are imposed by the owner or designer, then acceptance criteria appropriate for the NDE method and extent of examination must also be developed and provided in the engineering design. It should be noted that the code examination methods and their acceptance criteria do not correlate well to specific failure modes. Defects detected by NDE methods are typically repaired because they are perceived rather than relating the defect to a specific failure mechanism. The detection of defects having little or no bearing on piping component performance may result in unnecessary, and sometimes counterproductive repairs.[7] Fracture mechanics holds the promise of one day being able to correlate defects with failure modes, but that is not necessarily a given in 1999.

Adapting the B31.3 in-process examination for nonmetallic piping may be prudent.

The owner's inspection should include a detailed review of the erected system prior to startup to ensure that the pipe components and sizes, support types and orientation, valve types and orientation, and specialty items are in accordance with the engineering design. The materials of construction could be verified by spot checks or more rigorous forms of examination, if this was not already performed during construction. During startup the owner's inspection should also include verification that piping moves as is intended (e.g., spring hanger indicators move to the hot location) and that no undue vibrations or movements are observed.

Examination of a branch connection and socket weld joints is normally limited to visual and surface examinations. However, with careful interpretation, radiography can provide relevant information about these fabrications and, further, it might be expected that the welding done could be of better quality if the manufacturer's, fabricator's, or erector's welders knew that some of their fabrications were going to be evaluated by radiography. Recall from the previous discussion that this examination may be beyond the requirements of the design piping code, and acceptance criteria would need to be based on a prior agreement between the owner and the contractor.

Leak testing of the erected piping system is a normal requirement of piping codes and should be performed as required by the piping code used in the design. The required leak testing should be performed before the hazardous piping system is painted or the insulation is applied so that the system welds and other joints may be viewed as completed or assembled. Where a hydrotest is impractical, a pneumatic test or more rigorous examination may often be substituted. A sensitive leak test[2] should be used to augment whatever other leak testing methods are used. If testing requirements are not specified in the engineering design, the erector should review with the designer the expected leak-testing requirements.

A recent and very practical B31.3 code change permits exempting "closure" welds from hydrotesting, if in-process and either radiography or ultrasonic examinations are substituted. This exemption is also useful for dealing with additions of small piping (e.g., instrumentation taps) to piping already tested.

OPERATION AND MAINTENANCE

The operator should operate the piping system within the design parameters of the system. The operator should be trained to understand the design parameters, other possible events that could cause a failure, and operating conditions that can degrade the system over time. The operator should be familiar with the hazardous material handling system in sufficient detail to be able to identify signs of system distress should they appear. One possible source of this information is the plant hazards analysis study and the results of any continuing hazards analyses.

If design pressures or temperatures exceed the design limits by more than 10 percent, consideration should be given to having an engineering evaluation of the excursion performed. The same consideration should be given if the piping system experiences an abnormal operation not considered in the original design or is exposed to a severe environmental event (e.g., hurricane or major earthquake).

It would be wise to maintain an operating log (time versus operating pressures and temperatures, including outage time) to be able to evaluate fatigue and creep damage. This need not be a minute by minute log, but could log average values over a given period between identified maximums and minimums, with excursions beyond the maximums and minimums documented. Based on an understanding of the materials of construction, the original designer could be consulted or an engineering study be used to devise such a log.

Maintenance of the hazardous piping system should include establishing an in-service inspection program to detect system deterioration before such deterioration can cause a failure. The in-service inspection could be based on emerging (in 1999) risk-based technology, tailored to the piping system. Risk-based technology seeks to rank the piping system components as to the probability of failure and the consequences of failure and implement inspection based on the ranking. The ranking is based on the component and the fluid contents: component materials, geometry, and the history of like components; and fluid content's chemistry, conditioning, flow, and temperature. Through-insulation radiography has been successfully used in such a program to screen sections of a piping system for local thinning, followed by ultrasonic testing to refine thickness measurements. Other existing and developing NDE methods can be used for in-service monitoring, should they prove to be appropriate. Acoustic emission is possibly one such appropriate developing method; the acoustic emission methods endeavor to identify locations of high stress by "listening" for material grain-structure fracturing.

As of 1999, several efforts are under way to develop standards for flow evaluation and inspection planning. These include:

- B31.1 is revising its nonmandatory appendix ‘‘Recommended Practice for Operation, Maintenance, and Modification of Power Piping Systems’’ and considering making it mandatory.
- B31.8 and the API are developing ‘‘fitness for service’’ rules.
- ASME and the API are developing RBI guidelines for the power and petrochemical industries.
- ASME Post-Construction Committee is developing new standards for post-construction conditions.

These activities should be monitored for the completion and publication of their efforts.

The operator should maintain maintenance records of the system and its critical components.[12] These records should be of sufficient detail to provide information of any significant change to the physical structure of the pipe or piping components. Any changes in operating parameters should also be documented, since changes in temperature, pressure, flow, or the amount of cycling, or the chemical composition of contents, can result in increased corrosion, erosion, decreased serviceability of components, or a decrease in the life expectancy of materials.

Piping which operates in the creep range or is subjected to high thermal expansion stresses will self-spring (or shake down). Caution must be exercised when unbolting flanges or cutting loose piping that has self-sprung. Large movements of the flanges or pipe ends may result. If no problems existed with the previous operation of near equipment, reassembly of the piping should be done by pulling the flanges or pipe ends together and rebolting or rewelding.

The pipe supports may offer considerable information about system performance. Lift off or adjustments to maintain piping in its design location may be an indication of piping system drift or the results of system loads not considered in the original design. Spring supports should be monitored to see if operating between the operating and ambient conditions moves the load indicator between the operating and ambient marks on the spring hanger assembly; nonmovement would obviously indicate the spring is not functioning; variations from the expected movements may indicate piping system drift or loads at variance with the predicted design loads.

MODIFICATIONS AND REPAIRS

Hazardous piping system modifications should be made in accordance with the latest piping codes. The interaction between the new piping and the existing piping should be evaluated. Piping system drawings should be revised to show the modifications.

Repairs should also be made in accordance with the latest piping codes. The effect that the repair will have on the piping system should be considered. The repair should be fully documented as to the cause necessitating the repair and whatever repairs are made. Any revisions to the piping drawings necessary to reflect the repair should be made (e.g., due to erosion/corrosion damage a segment of pipe might be repaired by a replacement segment of a more corrosion-resistant material).

TABLE C10.2 Design and Operation Recommendations for Hazardous Piping

"DO"	"DON'T"
Identify and give hazardous piping systems special consideration.	View hazardous piping systems as conventional systems.
Evaluate consequence of piping failure (for example, quantities released, personnel exposure, harm to the environment).	Assume piping system cannot fail.
Understand operating modes of the system, including variations in normal and abnormal operating conditions.	Expect operating conditions to be without variation.
Consider dynamic effects, such as fluid hammering, vibrations, earthquake.	Overlook potential dynamic effects.
Perform stress analysis incorporating all the loadings expected.	Disregard short-term loadings combined with sustained loads or the fatigue effects of short-term loadings.
Select materials that will not deteriorate in service.	Choose materials sensitive to corrosion or erosion.
Use ductile materials.	Use low-ductility materials, such as cast-iron or glass.
Eliminate or minimize the use of mechanical joints.	Use mechanical joints without considering means to safeguard them.
Provide smooth transitions at welded joints.	Have abrupt changes in joint geometry.
Choose valves to be consistent with hazardous service.	Use stem packing designs that can leak.
Provide designs to minimize fugitive emissions.	Forget to perform a sensitive leak test with an appropriate sensitivity.
Use appropriate NDE methods to assure quality fabrication and erection.	Limit NDE methods to those in codes and standards if newer methods will give reliable results.
Try to provide advice to plant designers regarding piping layout needs.	Believe that plant designers will understand hazardous piping layout needs.
Use piping geometry to compensate for thermal expansion and contraction.	Use expansion joints.
Provide a collection and disposal system for pressure relief of hazardous systems.	Vent directly to atmosphere without proper treatment.
Segregate hazardous piping systems during fabrication, erection, and testing to facilitate all requirements being met.	Treat hazardous piping like other systems.
Design and maintain supports as part of the piping system.	Treat piping supports as independent components.
Provide design details of critical elements to construction.	Leave critical fabrication and assembly details to be provided by field.
Provide mechanism for positive identification of piping materials of construction.	Rely on specifying materials with no follow-up.
Provide an in-service monitoring program for early detection of problems.	Wait for a catastrophic event.
Maintain service records throughout life of system.	Repair piping without documenting it.
Periodically examine critical elements.	Install system and forget about it.

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