PIPING SYSTEMS

1. Introduction

A piping system serves as a conduit to convey fluids from one point to another. It consists of several parts. They are pipe runs; pipe fittings such as bends, tees, reducers; pipe components such as valves, strainers, flanges, and flow-meters; supports, guides and braces; fixed (static) equipment such as tanks, vessels, boilers, and heat exchangers; and rotating (dynamic) equipment such as pumps and compressors.

Whether the task at hand is a large construction project or the repair of an existing system, whether it is a new design or the investigation of a leak or a malfunction in an operating system, the foundation of piping engineering lies in four key disciplines, which in turn can each be subdivided into two activities, as illustrated in Figure 1. These activities are discussed in this article.

2. Process and System Design

2.1. Basic Process Design. Basic process design means the physical and chemical reactions that take place to produce a desired product, safely and reliably. This function is the responsibility of the process chemical engineer, and its outcome is a set of Process and Instrumentation Diagrams (P&IDs), line lists, system descriptions, operating parameters, power supplies, instrumentation and controls.

From the basic process design the parameters are established that will serve as the input for the thermohydraulic design, the next block in the process, these parameters are: Process stream chemistry; system pressures; system temperatures; physical properties of process streams; flow rates; and safety analysis (what can go wrong and how it is prevented or mitigated).

2.2. Thermo-Hydraulic Design. The objective of the thermo-hydraulic design is to select and size equipment and components: pipes, fittings, tanks, vessels, heat exchangers, pumps, compressors, valves, etc.

Pipe Size. The pipe size is selected to achieve the following objectives: (*1*) Pressure drops consistent with the desired throughput, (*2*) Flow velocity consistent

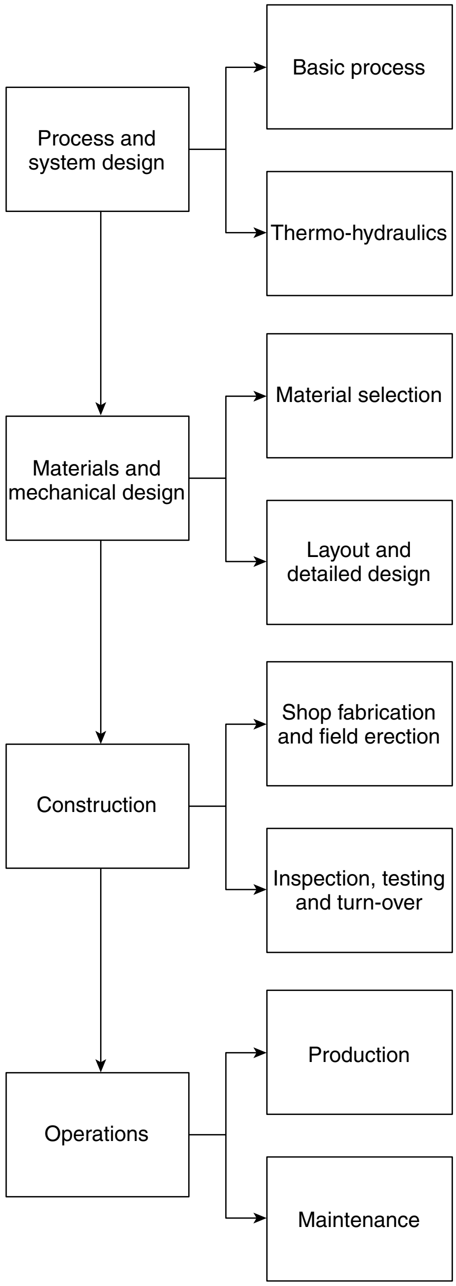

Fig. 1. The four key disciplines of piping engineering.

with the desired throughput, (*3*) Flow velocities sufficiently large to prevent fouling, (*4*) Flow velocities sufficiently low to prevent erosion.

The desired throughput is set by production and operational needs (so many gallons per minutes). The selection of the right pipe size, given the flow rate, is a

Table 1. **Costs vs. Size for an Oil Pipeline**

Costs ($\times 10^3$ \$)	Nominal pipe size (in.)			
	12	16	20	24
pumping	930	273	170	150
construction	360	530	660	860
Total	*1290*	*700*	*830*	*1010*

compromise between two competing objectives: (*1*) Large pipe to reduce pumping costs. (*2*) Small pipe to reduce materials and construction costs.

These two competing trends are illustrated in Table 1 (1). The most cost-effective pipe size is neither the smallest (excessive pressure drops, high pumping costs) nor the largest (high construction costs), but an intermediate size.

Reasonably low velocities for liquids are up to 5 ft/sec for utilities, 5 to 10 ft/sec for liquid process, and 10 to 15 ft/sec for boiler feedwater. Reasonably low velocities for steam are up to 200 ft/sec for saturated steam and 200 to 300 ft/sec for dry, superheated steam.

To understand the increase in pumping costs for smaller pipelines, consider that if the pipe is too small, the flow velocity becomes large, in turn causing large pressure drops which cause the following problems: loss of motive power (the more pressure drop the larger the pump or compressor); risk of cavitation (if the pressure drops below the vapor pressure); and turbulence, erosion, and noise.

To illustrate how pressure drop increases with flow velocity, the Darcy formula is used to estimate the pressure drop, ΔP_{100}, in 100 ft of straight pipe as a function of flow velocity, v (2,3).

$$\Delta P_{100} = 0.1294 \times \frac{f \times \rho \times v^2}{d}$$

where ΔP_{100} = pressure drop in 100 ft of straight pipe, psi
f = friction coefficient
ρ = density lb/ft^3
v = mean flow velocity, ft/sec
d = pipe inner diameter, in.
$f = 0.017$ for a 4-in. standard pipe
$\rho = 62.3$ lb/ft^3 for water at 70°F
$d = 4.026$ in. for a 4-in. standard pipe
$\Delta P = 0.034 \times v^2$

At a flow velocity of 5 ft/sec, the pressure drop is 0.85 psi/100 ft and at 15 ft/sec it becomes much worse at 7.7 psi/100 ft. Also, as the pipe gets smaller, not only does the flow velocity increase for the same flow rate, but the friction coefficient becomes larger contributing to even larger pressure drops.

Sizing a piping system or pipeline is commonly done by computer analysis in which the pumps–valves–piping system is modeled as a network. The pump

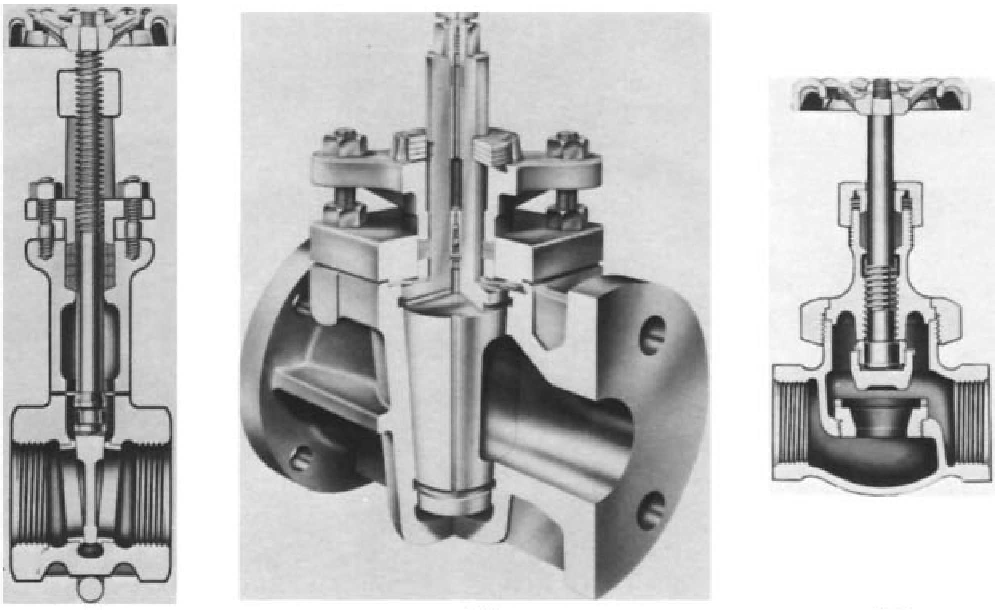

Fig. 2. (**a**) Gate valve; (**b**) plug valve; and (**c**) globe valve.

characteristic curve and valve flow characteristic are entered, and the software assigns friction coefficients to pipes and fittings. The output consists of pressure drops and flow rates at points along the system, which are then compared to the operational requirements.

Valve Selection and Sizing. Flow in piping systems is controlled by valves. There are several types of valves, each suited for a different function (4–7).

*Gate Valve (Fig. 2**a**).* A gate valve is an on-off valve, intended to operate fully open or fully closed. Flow control with a gate valve is not practical, since it can cause severe flow cavitation, erosion of the disc, valve and pipe, accompanied by noise or vibration.

*Plug or Ball Valve (Fig. 2**b**).* A plug valve and a ball valve are quarter turn valves; the plug valve has a cylindrical or conical plug, and the ball valve has a spherical ball, both have a shaped opening (plug port). Depending on the plug or ball port shape, they are used as isolation valves (on-off) or to throttle flow. When used to control flow they must be sized for the reasons listed for globe valves.

*Globe Valve (Fig. 2**c**).* A globe valve controls flow through the motion of a disc, a ball or a plug. Globe valves have to be sized correctly to achieve at least three objectives: Operate within a reasonable range, not nearly open or nearly closed; prevent cavitation (excessive pressure drop and velocities) that will cause erosion, wear and noise; not be smaller than one or two sizes below the pipe size.

Butterfly Valve (Fig. 3). A butterfly valve is a quarter turn (rotary) valve with a flat disc rotating around an axis, like the extended wings of a

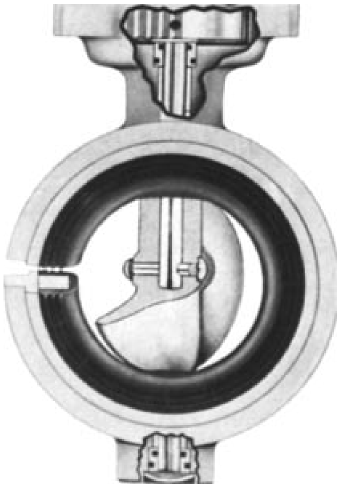

Fig. 3. Butterfly vlave.

butterfly. A butterfly acts as a damper; when open, the disc and axis remain in the flow stream. Their advantage is their narrow width and light weight.

Diaphragm Valve (Fig. 4). A diaphragm valve is a valve with a linear motion stem that pushes a flat disc against a diaphragm into the flow stream. The diaphragm seals against a weir in the valve body or against a contoured surface at the bottom of the valve body. A pinch valve is similar, but the valve body is simply a cylinder of soft material that can be pinched closed.

Check Valve. A check valves is a valve designed to permit flow automatically in one direction while preventing reverse flow in the opposite direction. Check valves have to be sized to prevent waterhammer (or, more generally, liquid hammer) on closure at flow reversal. There are four main types of check

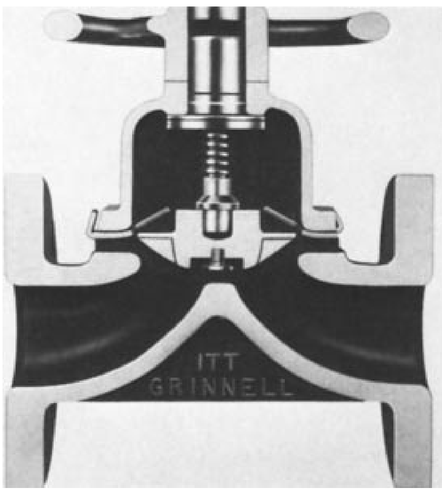

Fig. 4. Diaphragm or pinch-clamp valve.

valves: (*1*) Swing check valves have a disc hinged around a pin at the top of the flow opening. (*2*) Tilting check valves are hinged around a pin that passes through the disc. (*3*) Lift check valves rely on the linear motion of a plug, it may be spring assisted. (*4*) Butterfly check valves are butterfly valves with angled and hinged wings.

Safety and Relief Valves. Safety and relief valves are valves that open automatically to relieve over-pressure. A safety valve is used in gas or steam service and fully opens at the set pressure. A relief valve is used in liquid service and has an opening characteristic that varies with flow rate. Safety and relief valves have to be carefully sized and set to open at a given set-point to protect the system in case of accidental over-pressure. Because these valves perform a safety function, the ASME Boiler and Pressure Vessel Code stipulates specific performance requirements for their design, manufacture, selection, and sizing.

3. Materials and Mechanical Design

3.1. Materials Selection. *Types of Materials.* There are hundreds of pipe materials, which belong to two broad categories: metallic and nonmetallic. These can in turn be subdivided into a multitude of subcategories, for example (8,9):

Metallic, ferrous
- Cast iron (Fig. 5)
- Steel (carbon steel, Fig. 6)
- Alloy steel (Fig. 7)

Fig. 5. Ductile iron pipe common in waterworks.

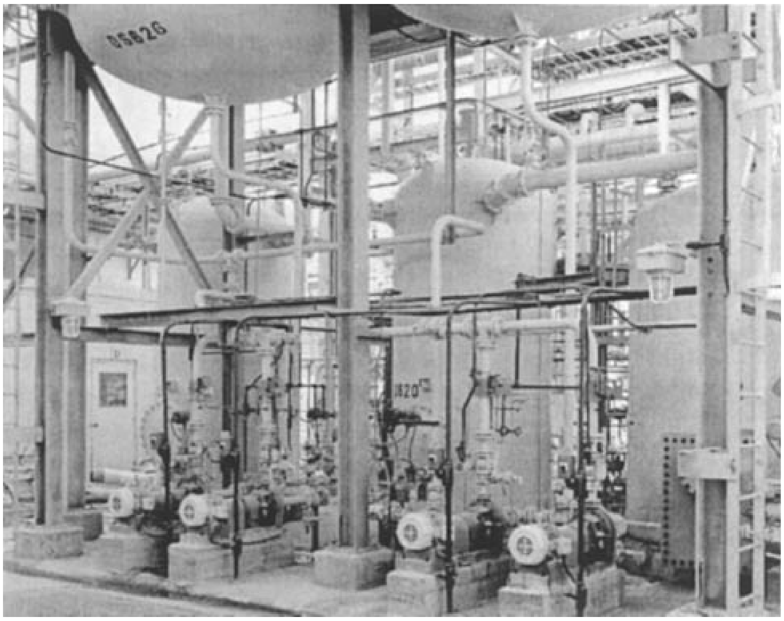

Fig. 6. Painted carbon steel common in process plants.

Fig. 7. Stainless steel for corrosion resistance.

Metallic, nonferrous
  Copper and alloys
  Aluminum and alloys
  Nickel and alloys
  Titanium and alloys
Nonmetallic
  Plastics (PVC, CPVC, Polyethylene, etc, Fig. 8)
  Concrete
  Fiberglass and fiber-reinforced plastics
  Glass
Metallic lined with non-metals

Material Selection. Pipe and fitting materials are selected based on their compatibility with several parameters (10–14). They are the process fluid, the system pressure, the flow rate, the operating and extreme temperatures (maximum hot and minimum cold), and the operating environment.

Fig. 8. Polyethylene pipe for water and gas applications.

In addition to compatibility, materials are selected taking into consideration two more characteristics: cost and weldability.

Material selection is one of the most difficult decisions in the piping engineering process because corrosion rates are quite sensitive to small changes in any one of a multitude of parameters, for example: the chemical composition of the process fluid, the presence of small quantities of contaminants or oxidants, the atmosphere around the pipe (the temperature, humidity, corrosiveness of the atmosphere or soil), the temperature, the flow rate, the amount of dissolved oxygen, the phase of the fluid (liquid, vapor or gas), the pH of the solution, the process condition (operation, shutdown, wash, etc), the mechanical properties of the metal (hardness, cold work, grain size, etc.), the presence of welds, the component shape (the presence of crevices, local turbulence, etc.), the condition of coatings and linings, the relative size of anodic and cathodic regions, the solubility of corrosion products, the addition of corrosion inhibitors: type, quantity and distribution, and the type of component (casting, forging, extruded or cold worked, etc.).

Because corrosion depends on so many variables, where the consequence of premature degradation, and possibly leakage or rupture is unacceptable, the selection of material commonly relies on three principles: (*1*) Experience with similar systems under similar operating conditions. (*2*) Laboratory corrosion testing, under representative or accelerated conditions (for example, increasing the fluid temperature). (*3*) Corrosion monitoring in-service, either though nondestructive examination or using corrosion coupons.

Over the years, individual plants, operating and engineering companies, and even whole industries have developed material selection guides and standards based on their operating experience and laboratory testing. These efforts are sometimes coordinated through industry groups such as the National Association of Corrosion Engineers (NACE), the Electric Power Research Institute (EPRI), the Gas Technology Institute (GTI), the American Petroleum Institute (API), and the American Water Works Association (AWWA).

Material Properties. In addition to compatibility with the process fluid, cost and weldability, the material of a piping system is selected on the basis of its two mechanical properties (15–17): (*1*) Strength measured by a tensile test is the ability of the material to sustain a tensile load and to resist fracture by ductile tearing. (*2*) Toughness is the ability of the material to sustain an impact load and to resist fracture by crack propagation.

A material's strength is fully defined by its stress–strain curve, and characterized by its elastic yield limit (the yield stress S_y) and its failure strength (ultimate stress S_u), Figure 9. The material specifications stipulate minimum values for S_y and S_u which are verified by sampling during manufacturing of the base metal, pipe or component.

A material's toughness is defined in several manners. The most common measure of toughness is the Charpy V-notch toughness which measures the ability of the notched material to sustain the impact of a swinging pendulum. Other toughness measures include the fracture toughness test and the drop weight tear test.

Mechanical properties, strength and toughness, depend on the material's chemical composition, microstructure (and hence its fabrication and heat

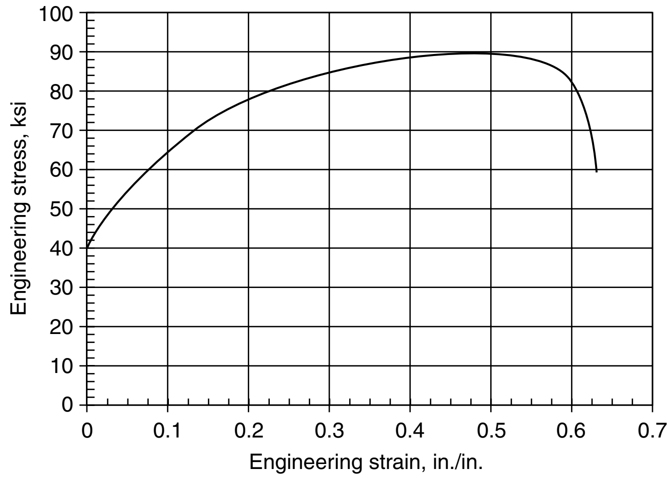

Fig. 9. Example of stress–strain curve for stainless steel.

treatment), temperature, and condition (for example, hydrogen that migrates into steel can reduce its toughness).

3.2. Layout and Detailed Design. *Pressure Design.* The first step in detailed design is the selection of the right pressure rating for pipes, fittings (bends, tees, reducer, etc.), and components (valves, flow elements, etc). First, the pipe wall thickness is selected on the basis of the design code. In the U.S. the common design code for industrial applications is the ASME B31 Pressure Piping Code which is subdivided into separate books by industry and application, these are (18):

- *ASME B31.1 Power Piping*: power plant piping systems.
- *ASME B31.3 Process Piping*: hydrocarbons and others. Hydrocarbons includes refining and petrochemicals. Others includes chemical process, making of chemical products, pulp and paper, pharmaceuticals, dye and colorings, food processing, laboratories, offshore platform separation of oil and gas, etc.
- *ASME B31.4 Liquid Petroleum Transportation Piping*: upstream liquid gathering lines and tank farms, downstream transport and distribution of hazardous liquids (refined products, liquid fuels, carbon dioxide).
- *ASME B31.5 Refrigeration Piping*: heating ventilation an air conditioning in industrial applications.
- *ASME B31.8 Gas Transmission and Distribution Piping*: upstream gathering lines, onshore and offshore, downstream transport pipelines and distribution piping.
- *ASME B31.9 Building Services Piping*: low pressure steam and water distribution.
- *ASME B31.11 Slurry Transportation Piping*: mining, slurries, suspended solids transport, etc.

The missing numbers (B31.2, B31.6, etc.) are obsolete code books.

The code for design of nuclear power plant piping systems is the ASME Boiler & Pressure Vessel Code, Section III.

The standard for waterworks (water supply and effluents) is a series of American Water Works Association (AWWA) standards which includes AWWA C151 (ductile iron), AWWA C200 series and M11 (steel), AWWA C300 series and M9 (concrete), AWWA C900 series and M23 (plastics), AWWA M45 (fiberglass), etc.

Finally, the International Building Code plumbing codes apply to commercial and private distribution and use of water and effluents.

Each of these codes includes rules for the selection of the pipe wall thickness, given the material, the design pressure and the design temperature. For example, for piping in a chemical process plant, ASME B31.3 would apply, and the corresponding wall thickness equation is (19):

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

t = minimum required wall thickness, excluding manufacturing tolerance and allowances for corrosion (in)

P = internal design pressure, psi

D_o = outside diameter of pipe, in.

E = joint efficiency factor

y = temperature coefficient

S = maximum allowable stress in material, psi

Of these parameters, E, y and S are specified in the design code, while P and D_o are selected by the designer. For example, the minimum required wall thickness of a 14-in. pipe ($D_o = 14$ in.) seamless ($E = 1$), with a design pressure of 450 psi ($P = 450$ psi), ASTM A 106 Grade B carbon steel with a design temperature of 100°F ($y = 0.4$ and $S = 20{,}000$ psi) is

$$t = \frac{450 \times 14}{2 \times (20,000 \times 1 + 450 \times 0.4)} = 0.156 \text{ in.}$$

To this thickness, a corrosion allowance is added, selected by the designer on the basis of past experience with similar materials and services, for example a corrosion allowance of 1/16 in., and then the pipe mill fabrication tolerance of the material specification is added, 12.5% in the case of ASTM A 106 carbon steel pipe, to obtain the final required wall thickness:

$$t_{\text{required}} = (0.156 + 0.060) \times 1.125 = 0.243 \text{ in.}$$

Because of cost and delivery time, it is preferable not to order custom-made pipe sizes, so the closest, larger, available commercial size is selected. The standard ASME B36.10 standard size for 14 in. carbon steel pipe is schedule 30, with a wall thickness of 0.375 in.; this is more than the 0.243 in. needed but will be selected for ease of procurement.

Once the pipe wall thickness is obtained, butt welded fittings and components are procured to the same schedule as the pipe (ASME B16.9), flanges and flanged valves are selected on the basis of pressure class (ASME B16.5, B16.34, B16.47), and threaded and socket welded fittings are selected on the basis of pressure class (ASME B16.11). Specialty fittings are procured on the basis of catalogs, with pressure ratings established by the manufacturer, with safety margins against leakage consistent with the applicable ASME B31 design code.

Design for Sustained Loads. A preliminary pipe layout is selected based on the hydraulic design, plot plans, equipment locations, functional requirements, and rules of good practice (20,21). This preliminary layout is analyzed for sustained loads. Sustained loads are loads sustained by the piping system in normal service, they include: pressure, weight, and temperature. The sustained load analysis consists of following three steps (*1*) Rules of good practice to place weight supports spaced along the pipe. (*2*) Stress analysis to compare the stresses due to sustained loads to code specified limits, called allowable stress S. (*3*) Deflection and flexibility analysis to confirm that, under sustained loads, the pipe deflections will be reasonable and will not cause leaks, ruptures or malfunctions.

Today, this check of stress and deflections is carried-out by PC-based stress analysis, the piping system is modeled, the loads applied to the model, and the distribution of stresses and displacements along the pipe is obtained by analysis and compared to the code stress limits and operational displacement limits.

As a result of this design step, pipe supports, hangers and guides are selected and designed, Figures 10–12. The common design codes for supports are the American Institute of Steel Construction (AISC) design manual for steel support structures, and the American Concrete Institute (ACI) 318 Appendix D for anchor bolts to concrete.

Design for Occasional Loads. Occasional loads are loads that are not expected to occur in normal service, but can credibly occur at some point in time eg, pressure transients (water hammer), high winds on outdoor pipe, seismic

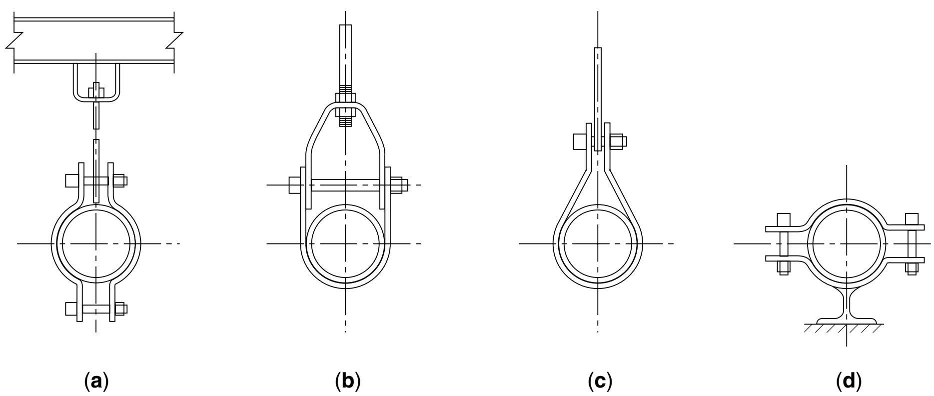

Fig. 10. Nonintegral pipe attachments: (**a**) pipe clamp, rigid-type hanging support; (**b**) Clevis; (**c**) sling; and (**d**) clamped shoe.

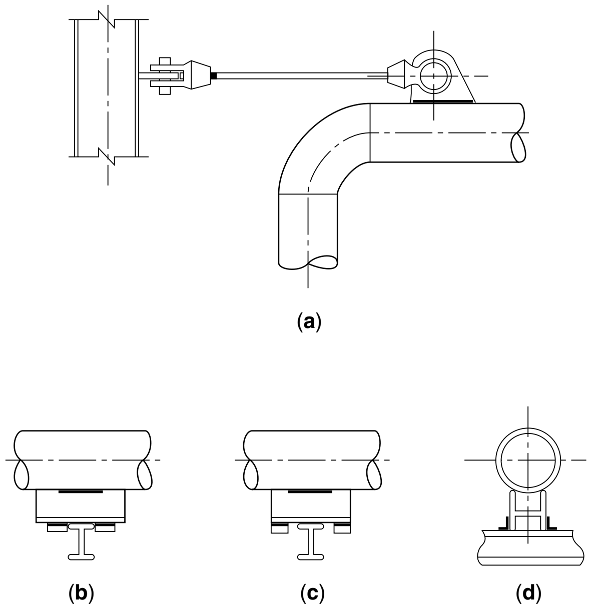

Fig. 11. Restraints: (**a**) single-directional; (**b**) full restraint along pipe axis; (**c**) partial restraint along pipe axis; and (**d**) guide perpendicular to pipe axis.

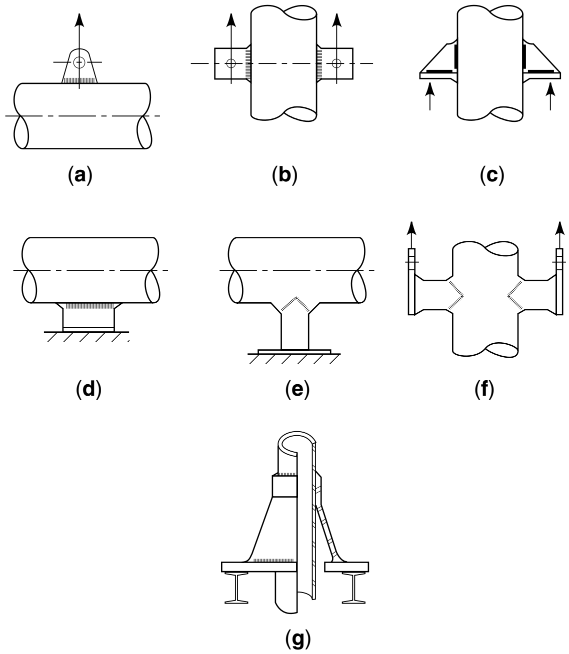

Fig. 12. Integral pipe attachments: (**a**) and (**b**), ears; (**c**) lug; (**d**) shoe; (**e**) and (**f**), cylindrical trunnions; and (**g**) skirt.

motions in earthquake active areas, thermal shocks from malfunctions or abnormal operations, etc. Note that pipe vibration does not figure on the list of occasional loads; this is because vibration is usually monitored during preoperational testing or startup and eliminated if excessive.

Like the design for sustained loads, the design for occasional loads is commonly carried out by computer analysis.

As a result of this design step, it may be necessary to add supports and sway braces to restrain the pipe from excessive movements under occasional loads. If this is the case, the sustained load design and flexibility of the system has to be re-checked with the new braces.

Deliverables. The outcome of the detailed design process consists of several documents that will permit procurement of materials and construction of the system, these include: Three-dimensional isometrics of the pipe layout, indicating fitting and component positions, and pipe supports and braces; bill of materials with component size, pressure rating, material specification; and support drawings, including bill of materials and weld details. The design process is also linked to the operating procedures as it defines design pressure and temperatures, and operating cycles, which then constitute operating envelopes that should not be exceeded in service.

In many industrial applications, the piping design process is not considered complete until after construction, when the installed configuration (referred to as "as-built") is compared to the original design, and discrepancies, if any, are resolved, this final stage is referred to as "as-built reconciliation".

Therefore, the design process is based on two critical inputs: (*1*) The magnitude of the design loads, sustained and occasional; and (*2*) the projected corrosion allowance.

In cost-critical and safety-critical applications it is common practice to monitor operations for evidence of loads in excess of the design loads, and periodically inspect the system for evidence of corrosion or damage in excess of the original design allowance.

4. Construction

4.1. Shop Fabrication and Field Erection.

Construction is a general term that refers to shop fabrication and field erection. Construction is based on the design output documents (isometrics, bill of materials) which have been converted into fabrication spool drawings. The shop-fabricated spools and subassemblies are then transported to the field for joining and erection.

Construction of metallic piping systems relies on the following forms of joining:

Mechanical joints: Flanges, threads, grooved fittings, clamps, swaged, bell-and-spigot, etc.

Welding: Arc welding (by far the most common form of welding for piping systems), or other forms of welding (resistance, laser, electron beam, etc.).

Soldering or brazing: Unlike welding, soldering and brazing do not involve melting the base metal, only the filler.

Construction of nonmetallic pipe, such as plastics, also relies on mechanical joints and fused joints, and also, in the case of plastics, glued joints.

The quality of construction of industrial piping systems (power plants, process plants, pipelines, large utilities, etc.), relies on two key principles:

1. *The adequacy of the joining procedure*: In the case of welding this would be the weld procedure which defines the key welding parameters: weld joint design, welding position, fixture, weld backing, composition of filler metal and flux, type of electrode, electrode diameter, welding current (ac, dc, polarity), arc length (electrode-work gap), travel speed, welding technique (oscillatory weave or straight stringer, arc starting and stopping), arc voltage, shielding gas flow, preheat, interpass temperature control, and postweld heat treatment. In the case of flanged joints, the joining procedure would address gasket placement, cleanliness, adequacy and alignment of flange faces, bolt torque and torque sequence, etc. In the case of specialty joints, the joining procedure would be provided by the manufacturer. Construction codes, such as ASME B31, have specific forms and requirements to develop and qualify welding procedures.
2. *The qualification of the construction craft*: Shop and field joining in industrial applications (welding, soldering, mechanical joining, or bonding) is not left up to the "skill of the craft", instead the construction codes explicitly require that the craft be trained, qualified and regularly certified in the use of specific welding or joining procedures. There are specific requirements for welding "pressure boundary" components (such as pipes, valves, and fittings) and different requirements for welding nonpressure boundary components (such as steel support structures).

4.2. Inspection, Testing, and Turnover.

In addition to explicit joining procedures and qualifications, pipe construction codes rely on inspection and testing for quality control. The type and extent of inspections, more correctly referred to as examinations in the context of quality control of fabrication, is specified in the construction code, which is sometimes augmented by the owner. The construction codes often link the extent of examinations to the consequence of leaks and ruptures: more critical systems (high pressure, high temperature, toxic or flammable materials) will be subjected to more examinations.

Examination of construction quality is nondestructive, and relies on several techniques (22–26):

Visual examination (or visual testing, VT) is used to detect surface defects of base material and welds.

Magnetic particle testing (MT) detects on the disturbance of a magnetic field created on the surface of the part by a surface, or shallow subsurface, defect.

Liquid penetrant testing (PT) relies on the detection of a penetrant that seeps and remains trapped into surface cracks.

In radiographic testing (RT) a source of X-rays or gamma-rays (from radioactive elements such as iridium 192, or cobalt 60) is placed on one side of the specimen or pipe wall, and a film or a fluoroscope (for real-time examination)

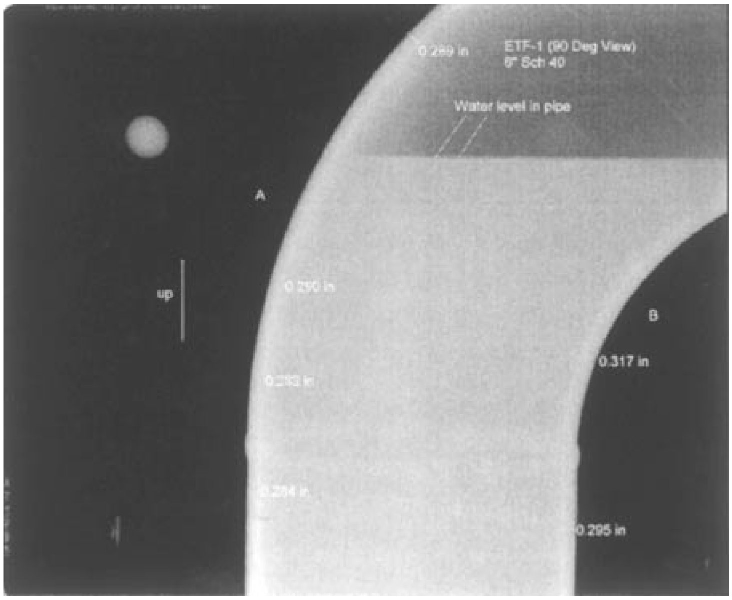

Fig. 13. Digital radiography showing liquid-line and wall thickness.

is placed on the opposite face, as close as possible to the wall. Volumetric defects appear as changes in density on the radiographic film. Current radiographic techniques, such as digital radiography, permit direct viewing on a computer screen, Figure 13.

Ultrasonic testing (UT) relies on the detection of ultrasonic waves emitted by a transducer into the body of the pipe or component, either normal to the surface (straight beam) to check wall thickness and detect flaws (Fig. 14), or at an angle (angle beam) to detect flaws and particularly cracks. Another UT technique (time of flight diffraction, TOFD) relies on the change in amplitude in an ultrasonic wave emitted by a transmitting transducer and collected by a receiving unit, caused by a defect.

Fig. 14. Ultrasonic testing of wall thickness.

While VT, MT, PT, RT and UT are the most commonly used NDE techniques in the quality control examination of piping systems, there is a host of other techniques that can be used, such as acoustic emission, eddy currents, etc, each with its advantages and shortcomings.

Construction codes specify the key parameters of examinations such as method, quantity, location, sensitivity, acceptance criteria, and qualifications of the examiner.

Following NDE, the assembled system is tested for leak tightness, using one of three testing techniques: (*1*) Pressure testing at a pressure above the system design pressure, with water (hydrostatic testing), another liquid, or air (pneumatic testing) or another gas. (*2*) Sensitive leak testing with helium or by drawing a negative pressure or a vacuum. (*3*) In-service leak testing by visual observation during system start-up for evidence of leaks.

Not only is pressure testing useful to detect leaking joints, it can also catch flaws in base material or errors in design as the system is subject to a high pressure and, in the case of hydrotesting, the weight of water. In Figure 15, a valve defect was detected during hydrostatic testing, preventing a costlier and more dangerous problem if the failure would have occurred in service.

Following NDE and pressure or leak testing, the piping system is subject to operational testing. This is typically achieved by starting and stopping pumps, opening and closing valves, checking instruments and controls, verifying flow and process parameters, as part of a start-up pre-operational functional test. The absence of significant vibration and noise and the correct movement, expansion or contraction, of hot or cold lines, consistent with the movements predicted in design are design checks also during this preoperational test phase.

Upon satisfactory completion of the pre-operational testing process, the system is turned over by the designer-constructor to the owner–operator. The system has been commissioned and is ready for service, within the design envelope.

5. Operations

5.1. Production. As the system goes into service, three things will happen:

1. The fluid and the environment will steadily degrade the material. If the process parameters stay within the design limits, the corrosion rate should remain within the corrosion allowance. If not, the material will sustain accelerated corrosion.
2. The service will subject the system to unanticipated transients. For example, the system may experience unusual vibration, or pressure or temperature excursions.
3. The system may experience external damage, for example a buried pipe may shift due to ground settlement, an above ground pipe or component may be damaged by accidental impact.

Fig. 15. Valve and pipe failure during hydrotest. Courtesy of Kiefner & Associates, Inc.

While such degradation can be reduced, it cannot be eliminated. It is therefore essential to identify critical systems, and inspect them periodically to detect damage and take measures to prevent leakage or failure. This is the role of a good maintenance program.

5.2. Maintenance. The maintenance of industrial and municipal piping systems consists in periodically inspecting the system, and repairing it when necessary. This is a three-step decision process: (*1*) What to inspect versus what to run-to-failure. (*2*) Where, when and how to inspect. (*3*) What to do with the inspection results, how to make run-or-repair decisions.

What to Inspect. This decision should be based on risk: inspect those systems that have the highest likelihood of failure and the worst financial, health-and-safety or environmental consequence. This logical inspection strategy is called Risk-Based Inspection (RBI). It is common and standardized in critical industries such as hydrocarbon processing, oil and gas pipelines, and nuclear power plants. It is also gaining favor in the chemical process industry.

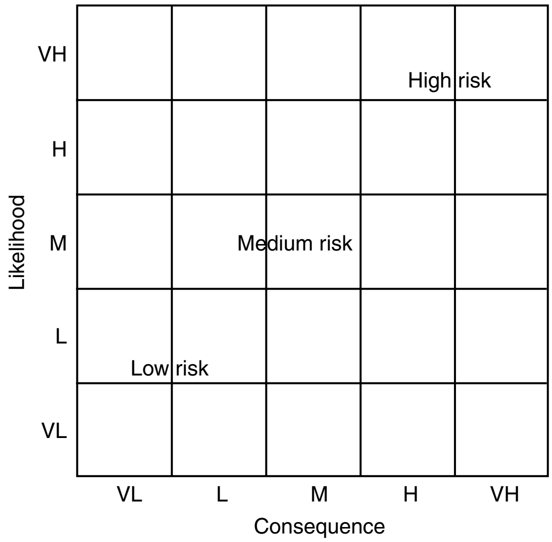

Fig. 16. Risk-based inspection matrix.

Piping systems and all other systems in the plant are ranked on the basis of their risk of failure and malfunction. This ranking could be a list, for example from the highest risk down to the no-risk systems, or a matrix that plots likelihood vs. consequence, Figure 16. The high risk systems are then scheduled for periodic inspection. In some industries, such as oil and gas pipelines and nuclear power plants, risk based inspection is mandated by regulation.

Where, When and How to Inspect. Where to inspect is the most difficult decision. There are very few systems that can be fully inspected over their entire length; one such system would be an oil pipeline inspected by a "pig" propelled inside the line and recording wall thickness around the full circumference, either by magnetic flux leakage or by ultrasonic sensors, Figure 17. Otherwise, inspections are generally limited to selected areas, and the difficulty is to select those areas where degradation could be worst. Failures have occured only feet away from a region that was inspected and found acceptable.

To correctly decide where to inspect, one needs to understand the degradation mechanisms that are at play and where they are likely to be most active. There are no codes or standards to do that. Some industries have developed tools to search for specific degradation mechanisms, for example, the nuclear power industry has methods and software to select inspection locations for the detection of erosion-corrosion in steam and water lines.

When to inspect is typically driven by the measured rate of corrosion. If, eg, there is a piping system with the following parameters: initial wall thickness 0.5 in., measured wall thickness after 5 years of service 0.4 in., minimum safe wall thickness 0.2 in.; then, the next inspection may be conducted at a time given by

$$t_{\text{insp}} = \frac{8}{0.5 - 0.4} \times \frac{0.4 - 0.2}{2} = 5 \text{ years}$$

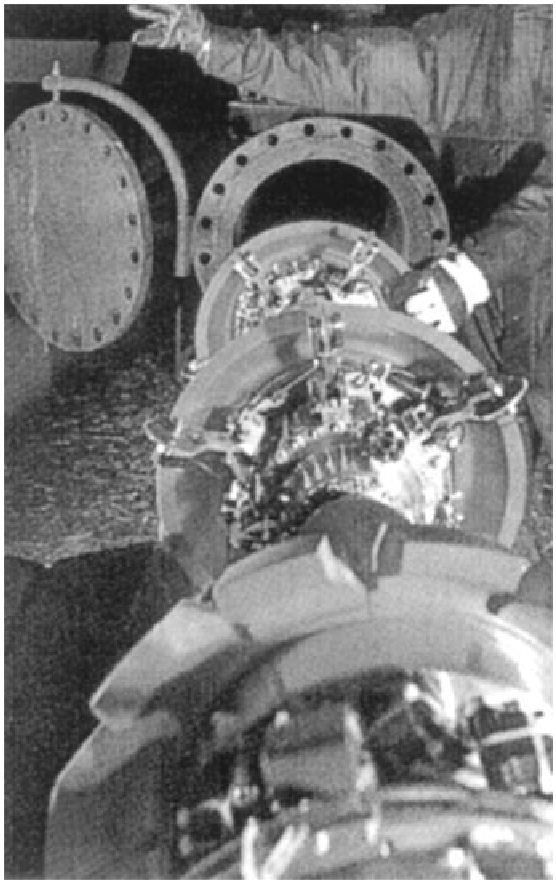

Fig. 17. Pipeline pig ready for launching.

This is “half the remaining life”, half the ten years that it would take to thin down from the currently measured 0.4 in. to the lowest safe limit of 0.2 in., provided the corrosion rate stays constant! This last provision is really an assumption: depending on the operating conditions and environment the corrosion rate may not be constant. In critical applications, because the corrosion rate may not be constant, it will be prudent to not take half the remaining life, but rather to inspect again at maybe one quarter 5f the remaining life.

Finally, how to inspect will depend upon what is being detected. If the degradation is superficial and on an accessible wall, then surface inspection techniques apply such as visual (VT), penetrant testing (PT), or magnetic particle testing (MT) may be used. If the degradation is volumetric or on an internal wall, not directly accessible, then volumetric techniques apply such as ultrasonic testing (UT), radiography (RT), or eddy current testing (ET).

Evaluation of Inspection Results. After gathering the inspection results, it must be decided whether the pipe, fitting or component is safe and reliable for continued service and for how long. This topic, the remaining life of piping, vessels and tanks, has received considerable attention throughout the 1990s, culminating in an exemplary guide for '*Fitness-for-Service*' by the American Petroleum Institute, API Recommended Practice 579 (27).

The fitness-for-service assessment of piping, vessels and tanks, depends greatly on the degradation mechanism:

- Wall thinning is judged against two criteria: (*1*) Is the remaining wall sufficiently thick to hold the pressure (no fracture), and (*2*) is the remaining wall sufficiently thick not too leak (no pin hole leak)?
- Cracking is judged against two criteria: (*1*) Is the remaining ligament behind the crack in danger of sudden brittle fracture, and (*2*) is the remaining ligament behind the crack in danger of progressive tearing?
- Mechanical damage (dents, gouges, grooves, distortions, etc.) is generally judged on the basis of a stress analysis of the damage with, in the case of gouges, the assessment of altered mechanical properties at the gouge.
- Creep (strain or metallurgical damage at high temperature, on the order of 900°F and more for steel) is judged on the basis of accumulated strain, high temperature corrosion assessment, and metallographic inspection (such as surface replication) for evidence of creep voids in the microstructure, Figure 18.

Management of Change. When studying failures of piping systems, whether they are simply a nuisance or are, as has happened several notorious cases, quite serious, many failures occur as a result of a change to the system. This can be avoided if the four steps of Figure 1 are followed during the modification process:

1. *Design*: How does the change affect system performance? Is the change designed and qualified to the design code?
2. *Materials*: Will the new material prevent the problem that caused the need for repair, What is the expected design life of the change or repair?

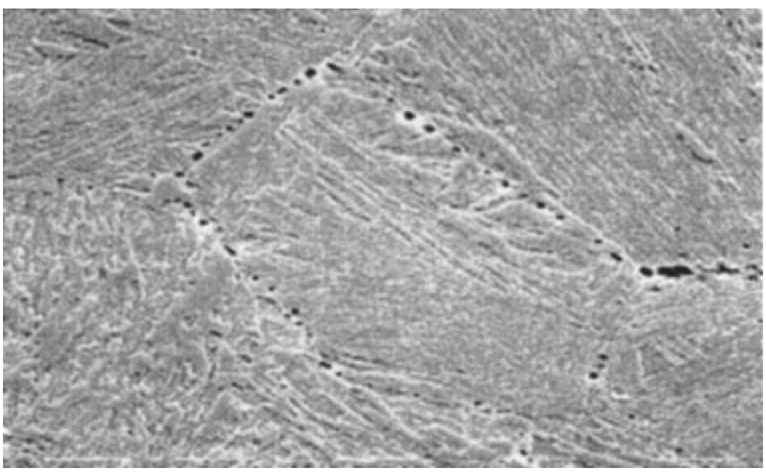

Fig. 18. Creep voids at grain boundaries.

3. *Fabrication*: Are the joining procedures qualified in accordance with the construction code? Is construction craft qualified?
4. *Examination*: Will the change be examined to the same rigor as new construction? Are the examination requirements specified, including personnel qualifications?
5. *Testing*: Will the change be pressure or leak tested? Will the change be operationally tested?

This systematic planning of the change or repair process is referred to as Management of Change (MoC). The principle of MoC is that there are no "temporary" or "permanent" modifications and repairs, instead, each modification or repair should have a design life, based on a competent assessment of the projected degradation mechanisms, in light of the operating record and past corrosion performance.

BIBLIOGRAPHY

"Pipes and Valves" in *ECT* 1st ed., Vol. 10, pp. 712–722, by R. L. Feder, Allied Chemical & Dye Corp.; "Piping Systems" in *ECT* 2nd ed., Vol. 15, pp. 646–675, by S. E. Handman and J. T. McKeon, The M. W. Kellogg Co.; in *ECT* 3rd ed., Vol. 17, pp. 929–957, by S. E. Handman, The M. W. Kellogg Co.; in *ECT* 4th ed., Vol. 19, pp. 113–143, by S. E. Handman, Consultant; "Piping Systems" in *ECT* (online), posting date: December 4, 2000, by S. E. Handman, Consultant.

CITED PUBLICATIONS

1. J. P. Tilus, *Hydraulics of Pipelines*, John Wiley & Sons, New York, 1989.
2. Flow of Fluids, Crane Technical Paper No. 410, Crane Co., Joliet, Il.
3. F. R. Spellman, and J. Drinan, *Pumping, Technomic Publishing Co., Lancaster, Pa.*
4. P. L. Skousen, *Valve Handbook*, McGraw Hill, New York, 2004.
5. E. Smith and B. E. Vivian. *An Introductory Guide to Valve Selection*, Mechanical Engineering Publications Limited, London.
6. W. Ulanski, *Valve and Actuator Technology*, McGraw-Hill, New York.
7. R. W. Zappe, *Valve Selection Handbook*, Gulf Publishing, Houston, Jul. 1991.
8. ASM, *Metals Reference Book*, ASM International, Materials Park, Ohio.
9. *ASTM A 941, Terminology Relating to Steel, Stainless Steel, Related Alloys, and Ferroalloys*, ASTM International, West Conshohocken, Pa.
10. D. A. Jones, *Principles and Prevention of Corrosion*, Prentice-Hall, Englewood Cliffs, N.J., 1996.
11. C. P. Dillon, ed., *Forms of Corrosion Recognition and Prevention*, NACE, Houston, Tex.
12. C. P. Dillon, *Corrosion Control in the Chemical Process Industry*, McGraw Hill.
13. *ASM Handbook, Corrosion*, American Society of Metals, Materials Park, Ohio, Vol. 13.
14. *ASM Handbook of Corrosion Data*, American Society of Metals, Materials Park, Ohio.
15. *ASTM A 370, Standard Test Methods and Definitions for Mechanical Testing of Steel Products*, ASTM International, ASTM International, West Conshohocken, Pa.
16. *ASTM E 1820, Standard Test Method for Measurement of Fracture Toughness*, ASTM International, West Conshohocken, Pa.

17. J. M. Barsom and S. T. Rolfe, *Fracture and Fatigue Control in Structures*, ASTM International, West Conshohocken, Pa.
18. G. A. Antaki, *Piping and Pipeline Engineering*, Dekker Publishing, New York.
19. ASME B31.3 process Piping, American Society of Mechanical Engineers, New York.
20. L. G. Lamit, *Piping Systems Drafting and Design*, Prentice Hall, Englewood Cliffs, N.J.
21. E. W. McAliister, ed., *Pipe Line Rules of Thumb Handbook*, Gulf Publishing Company, Houston, Tex., 2005.
22. O. J. Huber, *Fundamentals of Nondestructive Testing*, Metals Engineering Institute, Metals Park, Ohio, 1984.
23. J. R. Lilley and C. D. Perrie, *Developments in NDT, AEA Technology*, NIL Project, October, 1997.
24. W. J. McGonagel, *Testing of Thin Plates, Document No. NDP 93-40*. Stelwagen, March, 1995, *Nondestructive Testing*, McGraw-Hill, New York, 1961.
25. NTIAC, *NDE Capabilities Data Book*, Nondestructive Testing Information Analysis Center, Austin, Tex.
26. NTIAC, *Probability of Detection (POD) for Nondestructive Evaluation*, Nondestructive Testing Information Analysis Center, Austin, Tex.
27. *API RP 579, Fitness-for-Service*, American Petroleum Institute, Washington, D.C.

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