TANKS AND PRESSURE VESSELS

Tanks are used in innumerable ways in the chemical process industry, not only to store every conceivable liquid, vapor, or solid, but also in a number of processing applications. For example, as well as reactors, tanks have served as the vessels for various unit operations such as settling, mixing, crystallization (qv), phase separation, and heat exchange. Herein the main focus is on the use of tanks as liquid storage vessels. The principles outlined, however, can generally be applied to tanks in other applications as well as to other pressure-containing equipment.

The most fundamental classification of storage tanks is based on whether they are above or below ground. The underside of aboveground tanks is usually placed directly on an earthen or a concrete foundation. Sometimes these tanks are placed on grillage, structural members, or heavy screen so that the bottom of the tank can be inspected on the underside and leaks can be easily detected. Alternatively, horizontal tanks are often placed on steel support saddles. The aboveground tank is usually easier to construct, costs less, and can be built in far larger capacities than underground storage tanks. It is also treated differently from an underground tank by the regulatory community.

Another type of aboveground tank is the elevated tank. These tanks, elevated by structural supports, are almost exclusively relegated to the domain of the municipal water supply companies. Because the municipal water supply is considered a vital public resource, tanks are often elevated for the reason that gravity as a source of pressure is considered more reliable for distribution to the market. Although the same effect can be accomplished by placing tanks on hills, where this is not possible the tanks are elevated by structural steel supports.

The other important type of tanks is the underground tank. These are usually limited to between 500–20,000 gal (2–75 m^3), although most are under 12,000 gal (45 m^3). Used to store fuels as well as a variety of chemicals, these tanks require special consideration for the earth pressure and settlement loads to which they are subjected. Because buoyancy must also be taken into account, underground tanks are often anchored into the ground so that they do not pop out when surrounded by groundwater. In addition, these tanks are subject to severe conditions of corrosion. Placement of special backfill, cathodic protection, and coatings and liners are some of the corrosion-prevention measures necessary to ensure good installations. Regulatory requirements are such that most underground tanks must have a means of being monitored for leakage. This may take the form of a double-wall tank where monitoring occurs in the interstitial space.

At retail refueling stations such as service stations, marinas, and convenience stores, fire protection codes generally restrict the use of aboveground tanks. Another reason for using underground tanks in chemical and processing plants is premium land values, where underground storage provides an answer to space needs. Moreover, temperatures underground are relatively constant, thus evaporation losses in the storage of fuels and hazardous chemicals are reduced in underground installations.

In the 1970s and 1980s the discovery of groundwater contamination in many areas of the United States resulted in the 1984 Subtitle 1 to the Resource Conservation and Recovery Act (RECRA), which required the Environmental Protection Agency (EPA) to develop regulations for all underground tanks. These rules apply to

Table 1. Specific Gravity of Liquids

Liquid	Sp gr	Liquid	Sp gr	Liquid	Sp gr
acetic acid	1.06	gasoline	0.70	petroleum oil	0.82
alcohol, commercial	0.83	kerosene	0.80	phosphoric acid	1.78
ethanol	0.79	linseed oil	0.94	rape oil	0.92
ammonia	0.89	mineral oil	0.92	sulfuric acid	1.84
benzene	0.69	muriatic acid	1.20	tar	1.00
bromine	2.97	naphtha	0.76	turpentine oil	0.87
carbolic acid	0.96	nitric acid	1.50	vinegar	1.08
carbon disulfide	1.26	olive oil	0.92	water	1.00
cottonseed oil	0.93	palm oil	0.97	water, sea	1.03
				whale oil	0.92

any tank having 10% or more of its volume underground or covered by ground. Tanks in basements or cellars are not subject to these rules.

Because there is no uniform regulation requiring registration of tanks, the number of tanks being utilized is not known. An American Petroleum Institute (API) survey indicates there are about 700,000 petroleum storage tanks (1). The EPA estimated in 1990 that there were approximately 1.3×10^6 regulated underground storage tanks and an additional unknown number of exempt underground tanks used for home heating oil and farm fuel storage. The number of tanks in use in the chemical, petrochemical, pulp and paper, food, and pharmaceutical industries is unknown.

1. Basic Concepts

Although as of this writing (ca 1997), U.S. domestic regulations are generally using metric values to specify tank sizes and vapor pressures, American industry still uses gallon or barrel to designate tank capacities. For low pressures, the inch water column (in. wc) or the ounce per square inch (osi) are common in industry. For higher pressures, the units of pounds per square inch absolute (psia) or gauge (psig) are used. Additionally, in the petroleum and chemical industries, specialized units such as barrels (bbl), Reid vapor pressure, and degrees Baumé (Bé) are often used. A barrel (bbl) is 42 U.S. gallons.

Most tanks store liquid rather than gases or solids. Characteristics and properties such as corrosiveness, internal pressures of multicomponent solutions, tendency to scale or sublime, and formation of deposits and sludges are vital for the tank designer and the operator of the tank and are discussed herein. Excluded from the discussion are the unique properties and hazards of aerosols (qv), unstable liquids, and emulsions (qv). A good source of information for liquid properties for a wide range of compounds is available (2).

1.1. Density and Specific Gravity

Water has a density, mass per unit volume, of about 62.4 lb/ft^3 (1.000 g/cc) at 0°C, whereas mercury, also a liquid, has a density of about 842 lb/ft^3 (13.5 g/cc) at the same temperature. All things being equal, greater densities mean thicker required tank shell thicknesses.

Specific gravity (sp gr) is a measure of the relative weight of one liquid compared to a universally familiar liquid, generally water. More specifically, sp gr is a ratio of the density of a liquid divided by the density of liquid water at 16°C (60°F). Specific gravities of selected liquids are shown in Table 1.

In the petroleum industry, a common indicator of specific gravities, known as the API gravity or °API, is usually applied to crude oils. The formula for the API gravity is

$$°\text{API} = \frac{141.5}{\text{sp gr}} - 131.5$$

Thus, the higher the specific gravity, the lower the API gravity. Water, having a specific gravity of 1, has an API gravity of 10.

Another common indicator of specific gravities used in the chemical industry is degrees Baumé (°Bé). For liquids heavier than water,

$$°\text{Bé}$$

For liquids lighter than water,

$$°\text{Bé} = \frac{140}{\text{sp gr}} - 130$$

When tank operators change a stored liquid, care must be exercised. If there is a significant increase in the specific gravity of the new liquid, the effective hydrostatic pressure acting on the tank walls is greater if the design liquid level is not reduced.

1.2. Temperature

Temperature may be measured on an absolute or relative scale. The two most common relative scales are the Celsius and the Fahrenheit scales. The Celsius scale is defined as 0°C at the freezing point (triple point) of water and 100°C at the boiling point. The Fahrenheit scale is arbitrarily defined by assigning it a temperature of 32 degrees at the freezing point of water and 212°F at the boiling point of water (see Temperature measurements).

The absolute temperature scale that corresponds to the Celsius scale is the Kelvin scale; for the Fahrenheit scale, the absolute scale is called the Rankine scale. The Celsius scale reads 0 when the Kelvin scale reads 273; the Fahrenheit scale reads 0 when the Rankine scale reads 460. These relationships are shown in Figure 1.

Tanks are used to store liquids over a wide temperature range. Cryogenic liquids, such as liquefied hydrocarbon gases, can be as low as −201°C(− 330°F). Some hot liquids, such as asphalt (qv) tanks, can have a normal storage temperature as high as 260–316°C (500–600°F). However, most storage temperatures are either at or a little above or below ambient temperatures.

At very high and very low temperatures, material selection becomes an important design issue. At low temperatures, the material must have sufficient toughness to preclude transition of the tank material to a brittle state. At high temperatures, corrosion is accelerated, and thermal expansion and thermal stresses of the material occur.

1.3. Vapor Pressure and Boiling Point

Vapor pressure is important in liquid storage tank considerations. It affects the design and selection of the tank evaporation losses and is crucial for characterizing fire hazards of flammable and combustible liquids. The boiling point is also important because liquids should usually be stored at temperatures well below the boiling point. Flammable and combustible liquids are expressly prohibited by the fire codes for storage at temperatures above the boiling points. The National Fire Protection Association (NFPA) uses vapor pressure to classify the degree of fire hazardousness of liquids. The lower the boiling point, the lower the vapor pressure is for liquids stored at ambient temperatures. The boiling points of selected substances are given in Table 2.

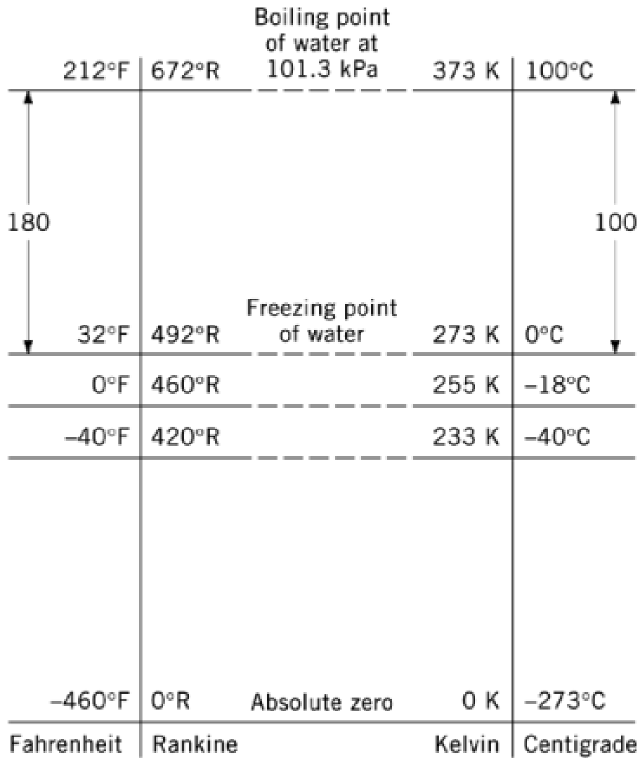

Fig. 1. Temperature scales (3).

Table 2. Boiling Points of Liquids[a]

Substance	Boiling point, °C (°F)	Substance	Boiling point, °C (°F)	Substance	Boiling point, °C (°F)
aniline	184 (363)	chloroform	60 (140)	saturated brine	108 (226)
ethanol	78 (173)	linseed oil	313 (597)	sulfur	472 (833)
ammonia	−33(− 28)	mercury	358 (676)	sulfuric acid	310 (590)
benzene	80 (176)	naphthaline	220 (428)	water, pure	100 (212)
bromine	63 (145)	nitric acid	120 (248)	water, sea	100.6 (213.2)
carbon bisulfide	48 (118)	oil of turpentine	151 (315)	wood alcohol	66 (150)

[a]At atmospheric pressure, 101.3 kPa (760 mm Hg).

The vapor pressure of a pure liquid is the pressure of the vapor space of a closed container. It is a specific function of temperature and always increases with increasing temperature (Fig. 2). If the temperature of a liquid in an open container is increased until its vapor pressure reaches atmospheric pressure, boiling occurs. The temperature of a pure liquid does not increase beyond its boiling point as heat is supplied. Rather, all the liquid evaporates at the boiling point. Because standard atmospheric pressure at sea level is 14.7 psia (101.3 kPa), this also presents the vapor pressure of a boiling liquid. Atmospheric pressure varies, however, with altitude. Water, for example, boils at 100°C (212°F) at sea level but at approximately 98°C (208°F) at 2000-ft (600-m) altitude. Barometric pressure changes slightly alter the boiling point of liquids in tanks as well.

In the fire codes, the atmospheric boiling point is an important physical property used to classify the degree of hazardousness of a liquid. If a mixture of liquids is heated, it starts to boil at some temperature but continues to rise in temperature over a boiling temperature range. Because the mixture does not have a definite

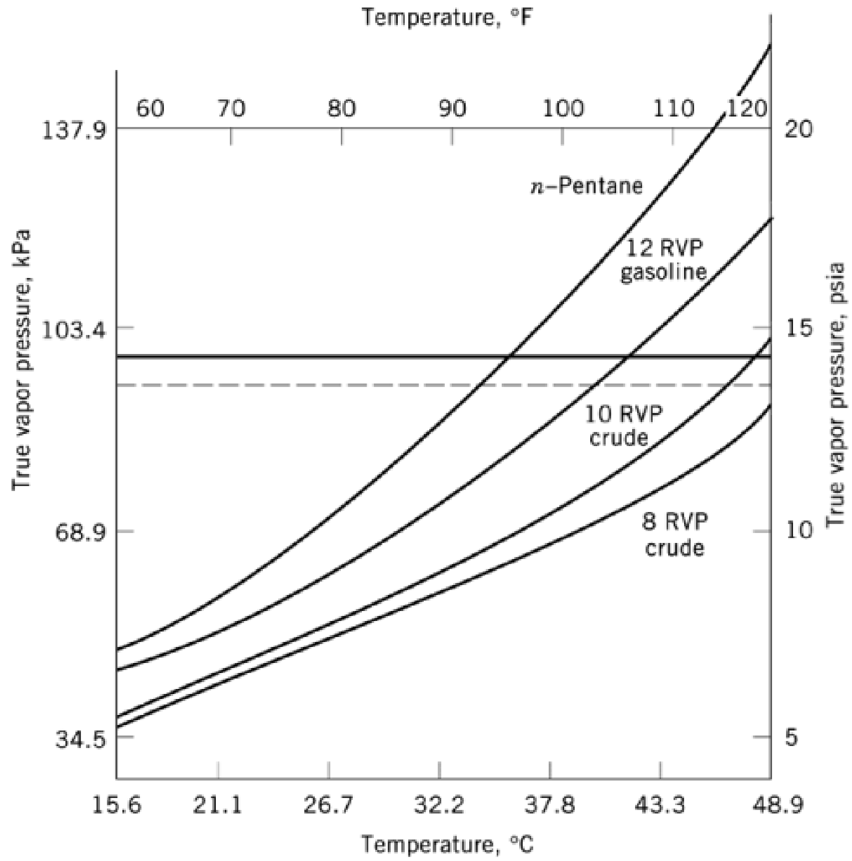

Fig. 2. Vapor pressure and temperature (4), where the bold and dashed horizontal lines represent normal atmospheric pressure at sea level and at 609.6 m (2,000 ft), respectively. RVP=Reid vapor pressure.

boiling point, the NFPA fire codes define a comparable value of boiling point for the purposes of classifying liquids. For petroleum mixture, it is based on the 10% point of a distillation performed in accordance with ASTM D86, Standard Method of Test for Distillation of Petroleum Products.

Vapor pressure has also become a means of regulating storage tank design by the EPA. Because increasing vapor pressure tends to result in an increase in volatile emissions, the EPA has specific maximum values of vapor pressure for which various tank designs may be used.

1.4. Flash Point

As a liquid is heated, its vapor pressure and, consequently, its evaporation rate increase. Although a liquid does not really burn, its vapor mixed with atmospheric oxygen does. The minimum temperature at which there is sufficient vapor generated to allow ignition of the air–vapor mixture near the surface of the liquid is called the flash point. Although evaporation occurs below the flash point, there is insufficient vapor generated to form an ignitable mixture below that point.

For flammable and combustible liquids, flash point is the primary basis for classifying the degree of fire hazardousness. NFPA Classifications 1, 2, and 3 designate the most to the least fire hazard liquids, respectively. In essence, low flash point liquids are high fire hazard liquids.

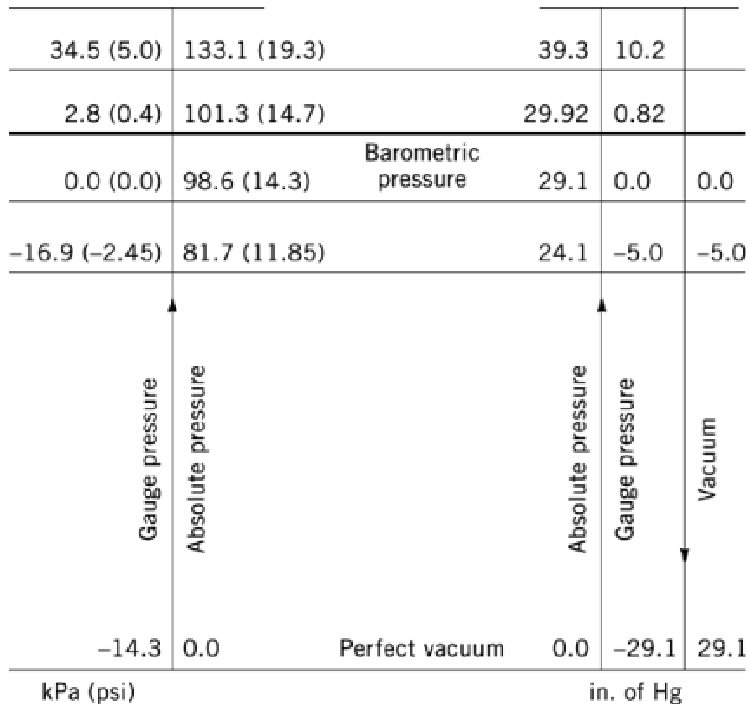

Fig. 3. Standard system of pressure measurement (3), where the bold line represents standard atmospheric pressure at sea level.

1.5. Pressure

Pressure, defined as force per unit area, can be expressed as an absolute or relative value. Although atmospheric pressure constantly fluctuates, a standard value of 101.3 kPa (14.7 psia) has been assigned as the accepted value at sea level. The "a" in the psia stands for absolute, ie, the pressure is 14.7 psi (101.3 kPa) above zero pressure or a vacuum. Most ordinary pressure-measuring instruments do not measure true pressure, but rather a pressure relative to the barometric or atmospheric pressure. This relative pressure is called gauge pressure. The atmospheric pressure is defined to be 1 psig, in which the "g" indicates that it is relative to atmospheric pressure. Vacuum is the pressure below atmospheric pressure and is, therefore, a relative pressure measurement as well. The relationship between absolute and relative pressure is shown in Figure 3 (see Pressure measurement; Vacuum technology).

For tank work, inches water column (in. wc) or ounces per square inch (osi) are commonly used to express the value of pressure or vacuum in the vapor space of a tank. These pressures are usually very low relative to atmospheric pressure. The common measures of pressure are compared as follows:

psi	in. wc	osi	Pa
1	27.68068	16	6894.7
0.03612628	1	0.5780205	249
0.0625	1.730042	1	431

Although both cylindrical shapes and spherical shells have simple theories to determine the strength and thus the thickness of tanks, the region of the tank that is most complex to design is the roof-to-shell junction. When there is internal pressure that exceeds the weight of the roof plates and framing the roof, the roof tends to separate from the shell. When tanks are subjected to pressures sufficient to cause damage, the roof-to-shell junction is usually the first area to show damage.

1.5.1. Internal and External Pressure

The difference in pressure between the inside of a tank or its vapor space and local barometric or atmospheric pressure is called internal pressure. When the internal pressure is negative it is simply called a vacuum. The pressure is measured at the top of the liquid in the tank because the liquid itself exerts hydrostatic pressure, thus increasing to a maximum value at the base of the tank.

Because tanks can be large structures, even small internal pressures can exert large forces which must be considered in design and operation. For example, a 100-ft (30.5-m) diameter tank having only 1-in. wc internal pressure exerts a force of almost 41,000 lb (9217 N) on the roof of the tank.

When the vapor space of a tank is open to the atmosphere or is freely vented, then the internal pressure is always zero or atmospheric. No pressure buildup can occur. This, of course, does not apply to dynamic conditions that occur in explosions or deflagrations. Most tanks, however, are not open to the atmosphere, but are provided with some form of venting device usually called a pressure-vacuum (PV) valve. A primary purpose of these valves is to reduce the free flow of air and vapors into and out of tanks, thereby reducing fire hazards and/or pollution. These valves are designed to open when the internal pressure builds up to some level in excess of atmospheric pressure, and keep the internal pressure from rising high enough to damage the tank. Typical flat-bottom tank design pressures range from 1 in. wc (0.25 kPa) to several psi. Conversely, the vacuum portion of the valve prevents the vacuum inside the tank from exceeding certain limits. Typical internal vacuum is 1 to 2 in. wc (249–498 Pa).

Internal pressure may be caused by several potential sources. One source is the vapor pressure of the liquid itself. All liquids exert a characteristic vapor pressure which varies with temperature. As the temperature increases, the vapor pressure increases. Liquids that have a vapor pressure equal to atmospheric pressure boil. Another source of internal pressure is the presence of an inert gas blanketing system. Inert gas blankets are used to pressurize the vapor space of a tank to perform specialized functions, such as to keep oxygen out of reactive liquids. The internal pressure is regulated by PV valves or regulators.

The most fundamental limitation on pressure is at 15 psig (101.4 kPa). Containers built to pressures exceeding this value are usually called pressure vessels and are covered by the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. For all practical purposes, tanks are defined to have internal pressures below this value.

External pressure implies that the pressure on the outside of the tank or vessel is greater than that in its interior. For atmospheric tanks, the development of an interior vacuum results in external pressure. External pressure can be extremely damaging to tanks because the surface area of tanks is usually large, generating high forces. The result of excessive external pressure is a buckling of the shell walls or total collapse. In some cases wind velocities during hurricanes have been sufficient to knock down and collapse tanks.

1.6. Miscellaneous Properties

Other properties such as viscosities, solidification temperature, pour point, and cubical rate of thermal expansion are all important for the tank designer or operator to consider and understand.

2. Tank Classification

There are many ways to classify a tank. Although there is no universal method, a classification commonly employed is based on the tank's internal pressure.

2.1. Atmospheric Tanks

By far, the most common type of tank is the atmospheric tank. These tanks are usually operated at internal pressures slightly above atmospheric pressure. Fire codes define an atmospheric tank as operating from atmospheric up to 0.5 psi (3448 Pa) above atmospheric pressure.

2.2. Low Pressure Tanks

Low pressure in the context of tanks means tanks designed for a higher pressure than atmospheric tanks. In other words, these are relatively high pressure tanks, designed to operate from atmospheric pressure up to 15 psig (101.4 kPa).

2.3. Pressure Vessels

High pressure tanks are vessels operating above 15 psig. These are really pressure vessels and the term high pressure tank is basically never used. Pressure vessels are a specialized form of container treated separately from tanks by all codes, standards, and regulations.

When the internal design pressure of a container exceeds 15 psig (101.3 kPa), it is called a pressure vessel. The ASME Boiler and Pressure Vessel Code is one of the primary standards used throughout the world to ensure safe storage vessels. Various substances, such as ammonia (qv) and many hydrocarbons (qv), are frequently stored in spherically shaped vessels that are often referred to as tanks. Most often the design pressure is 15 psig (101.3 kPa) or above. These are really spherical pressure vessels and fall under the rules of the ASME Boiler and Pressure Vessel Code. Discussion of pressure vessels are available (5, 6); these are not covered in detail herein.

3. Tank Components

To a large extent, the vapor pressure of the substance stored determines the shape and, consequently, the type of tank used. The roof shape of a tank may be used to classify the type of tank. This classification is self-explanatory to tank fabricators and erectors. Also important is the tank bottom.

3.1. Fixed-Roof Tanks

The effect of internal pressure on plate structures, including tanks and pressure vessels, is important to tank design. If a flat plate is subjected to pressure on one side, it must be made quite thick to resist bending or deformation. A shallow cone-roof deck on a tank approximates a flat surface and is typically built of 3/16-in. (4.76-mm) thick steel (Fig. 4**a**). This is unable to withstand more than a few inches of water column pressure. The larger the tank, the more severe the effect of pressure on the structure. As pressure increases, the practicality of fabrication practice and costs force the tank builder to use shapes more suitable for internal pressure. The cylinder is an economic and easily fabricated shape for pressure containment. Indeed, almost all large tanks are cylindrical. The problem, however, is that the ends must be closed. The relatively flat roofs and bottoms or closures of tanks do not lend themselves to much internal pressure. As internal pressure increases, tank

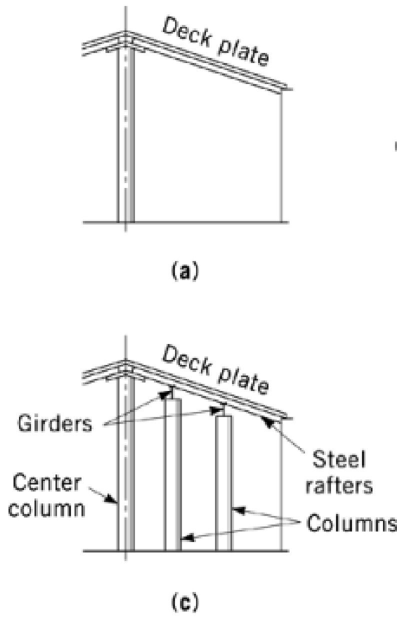

Fig. 4. Fixed-roof tanks: (**a**) self-supported cone roof; (**b**) center-supported cone roof; (**c**) column-supported cone roof; and (**d**) dome or umbrella roof.

builders use roof domes or spheres. The spherical tank is the most economic shape for internal pressure storage in terms of required thickness, but it is generally more difficult to fabricate than a dome- or umbrella-roof tank because of its compound curvature.

3.1.1. Cone-Roof Tanks

Cone-roof tanks are cylindrical shells having a vertical axis of symmetry. The bottom is usually flat and the top made in the form of a shallow cone. These are the most widely used tanks for storage of relatively large quantities of fluid because they are economic to build and the market supports a number of contractors capable of building them. They can be shop-fabricated in small sizes but are most often field-erected. Cone-roof tanks typically have roof rafters and support columns except in very small-diameter tanks when they are self-supporting (see Fig. 4**b** and **c**; Table 3).

3.1.2. Umbrella- and Dome-Roof Tanks

Umbrella-roof tanks are similar to cone-roof tanks, but have roofs that look like umbrellas. They are usually constructed to diameters not much larger than 60 ft (18 m). These tank roofs can be self-supporting, ie, having no column supports that must be run to the bottom of the tank (see Fig. 4**d**).

Dome-roof tanks are similar to umbrella-roof tanks except that the dome more nearly approximates a spherical surface than the segmented sections of an umbrella roof.

Aluminum geodesic dome roof tanks are becoming popular. These are often the economic choice. They offer superior corrosion resistance for a wide range of conditions, and are clear span structures not requiring internal supports. They can also be built to any required diameter. However, domes cannot handle more than a few inches of water column internal or external pressure.

Table 3. Comparisons of Tank Roof Types

Type	Advantages	Disadvantages
	Fixed roofs[a]	
self-supported cone roof	minimum internal obstructions; relatively inexpensive; suitable for internal protective coating; makes cost-efficient conversion to internal floating roof	may require heavier roof-deck plate; only suitable for small tanks
center-supported cone roof	simple structural design; minimum internal obstructions; relatively inexpensive; makes cost-efficient conversion to internal floating roof	less ideal for internal protective coating; tank diameter limited by span of rafters
column-supported cone roof	simple structural design; relatively inexpensive; suitable for any diameter tank	poor for internal protective coating; many internal obstructions; difficult to inspect; makes costly conversion to internal floating roof
dome or umbrella roof	good design for internal coating; excellent design for high corrosion services such as sulfur; adequate for higher internal pressures	more expensive than cone roof; suitable for only small and medium tank (20 m); roof-deck-plate-only structural support, except for larger-diameter tanks; not frangible (API 650)
	External floating roof[b]	
low deck floating pontoon	cheaper to construct than double deck for 5–50-m diameter; suitable for high vapor pressure stocks; capable of in-service repair of appurtenances; good buoyancy	poor design for roof insulation; structurally weaker than double deck; a leak could result in stock on the deck causing a fire hazard and oil in the roof drain system and an emissions violation
double-deck floating pontoon	can be easily insulated if structurally very strong; suitable for high vapor pressure stocks; capable of in-service repair of appurtenances; a leak will not put oil on the roof or in the roof drain system; better buoyancy	more expensive than pontoon; lose capacity because of the high amount of freeboard required
	Internal floating roof[c]	
vented at top of shell	good venting maximizes tank capacity	more expensive than air scoop roof; not suitable for retrofit
roof vents and shell overflow	suitable for retrofit; inexpensive installation	additional loss in tank capacity
noncontact aluminum	cheapest internal design; can be installed through shell manway; suitable for high vapor pressure stocks; rapid field installation	very weak structurally; aluminum limits sevices; not suitable for high turbulence; not suitable for high viscosity services; shorter life expectancy than steel; corrosion of aluminum
contact aluminum	can be installed through shell manway; suitable for high vapor pressure stocks; rapid field installation; easier repaired than noncontact; stronger than noncontact; less likely to sink; more fire resistant	aluminum limits services; shorter life expectancy
floating pan[d]	low cost	extremely vulverable to sinking or capsizing; fire hazard

[a]See Figure 4.
[b]See Figure 5.
[c]See Figure 6.
[d]Larger roofs have truss system and external rafters on top of deck.

3.2. Floating-Roof Tanks

All floating-roof tanks have vertical, cylindrical shells just like a fixed-cone-roof tank. These common tanks have a cover that floats on the surface of the liquid. The floating cover or roof is a disk structure that has sufficient buoyancy to ensure that the roof floats during all expected conditions, even if leaks in the roof develop. The roof is built having approximately a gap of 8 to 12 in. (20–30 cm) between the roof and shell so that the roof does not bind as it moves up and down with the liquid level. The clearance between the floating roof and the

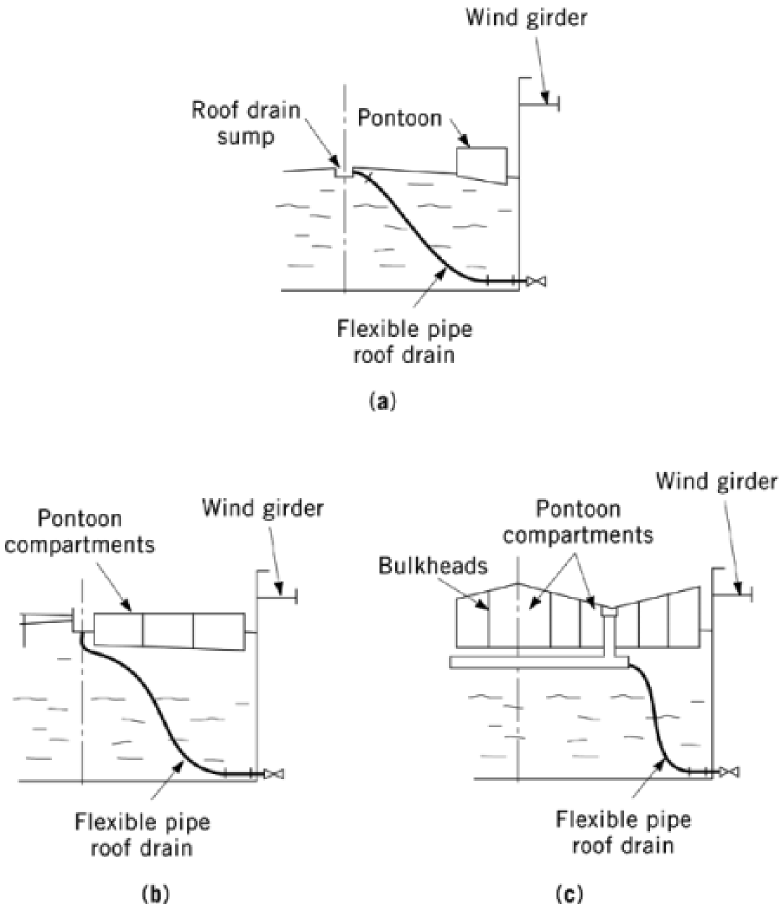

Fig. 5. External floating roofs: (**a**) low deck floating pontoon; (**b**) double-deck floating pontoon for small tanks; and (**c**) double-deck floating pontoon for large tanks.

shell is sealed by a device called a rim seal. The floating roof may be of any number of designs. The shell and bottom are similar to those of an ordinary vertical cylindrical fixed-roof tank. The two categories of floating roof tanks are external (Fig. 5) and internal (Fig. 6).

If the tank is open on top, it is called an external floating-roof (EFR) tank. If the floating roof is covered by a fixed roof on top of the tank, it is called an internal floating-roof (IFR) tank. The function of the cover is to reduce evaporation losses and air pollution by reducing the surface area of liquid that is exposed to the atmosphere. Fixed-roof tanks can easily be converted to internal floating-roof tanks by installing a floating roof inside the fixed-roof tank. Conversely, external floating-roof tanks can be easily converted to internal floating-roof tanks simply by covering the tank with a fixed roof.

EFR tanks have no vapor space pressure associated with them and operate strictly at atmospheric pressure. IFR tanks, like fixed-roof tanks, can operate at or above atmospheric pressure in the space between the floating roof and the fixed roof.

The fundamental requirements for floating roofs are dependent on whether the roof is for an internal or an external application. The design conditions of the external floating roof are more severe in that these must

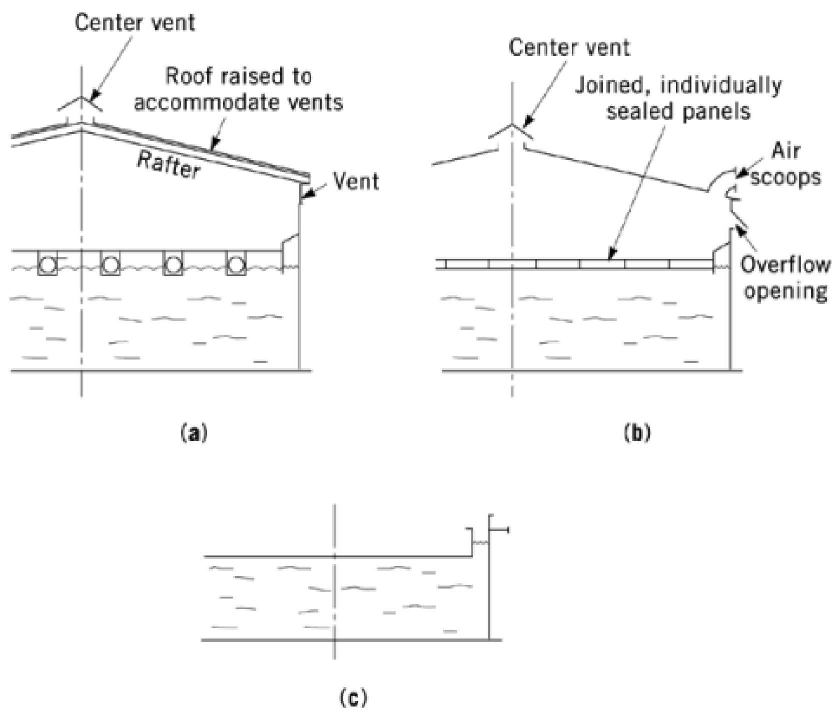

Fig. 6. Internal floating roofs: (**a**) vented at top of shell; (**b**) contact aluminum; and (**c**) floating pan.

handle rainfall, wind, as well as dead-load and live-load conditions comparable to, and at least as severe as, building roofs.

3.2.1. External Floating Roofs

Pontoon roofs are common for floating roofs from diameters of approximately 30–100 ft (10–30 m). The roof is simply a steel deck having an annular compartment that provides buoyancy (Fig. 5**a**). Double-deck roofs (Fig. 5**b** and 5**c**) are built for very small floating roofs up to about 30 ft (10 m) in diameter. These are also used on diameters that exceed about 100 ft (30 m). These roofs are strong and durable because of the double deck and are suitable for large-diameter tanks.

3.2.2. Internal Floating Roofs

Pan roofs are simple sheet steel disks where the edge is turned up for buoyancy. These roofs are prone to capsizing and sinking owing to the fact that a small leak can cause them to sink (see Fig. 6).

The bulkhead pan roof has open annular compartments at the periphery to prevent the roof from sinking should a leak develop.

Skin and pontoon roofs are usually constructed of an aluminum skin supported on a series of tubular aluminum pontoons. These have a vapor space between the deck and the liquid surface.

The honeycomb roof is made from a hexagonal cell pattern similar to a beehive in appearance. The honeycomb is glued to a top and bottom aluminum skin that seals it. This roof rests directly on the liquid.

The plastic sandwich roof is made from rigid polyurethane foam panels sandwiched inside a plastic coating.

3.3. Tank Bottoms

The shape of cylindrical tank closures, both top and bottom, is a strong function of the internal pressure. Because of the varying conditions to which a tank bottom may be subjected, several types of tank bottoms (Fig. 7; Table 4) have evolved. These may be broadly classified as flat bottom, conical, or domed or spherical. Flat-bottom tanks only appear flat. These usually have designed slope and shape and are subclassified according to the following: flat, cone up, cone down, or single slope.

Table 4. Comparisons of Tank Bottoms

Type	Uses	Advantages	Disadvantages
flat bottom[a]	mostly small tanks of $\leq 20-$ft dia; suitable for filed-run tanks, gauge tanks, treating tanks, etc; widely used by chemical industry	simple and economical to fabri-cate and install in small sizes; bottom connections accessible for inspection and mainte-nance, similar to cone-up and single-slope bottom tanks	difficult to drain thoroughly on account of low spots (bird baths) caused by foundation settling and bottom plate warping; siphon does not drain completely because must clear bottom
cone-up bottom[b]	widely used by petroleum industry	less likely to collect water under bottom than flat horizontal or cone-down bottom tanks; better drainage than flat horizontal bottom tanks; shell and bottom connections accessible for inspection and maintenance; permits increased differential settlement of tank bottom; suit-able for stock having specific gravity > water (>1.0 sp gr); easy to construct	less capacity than the conedown bottom tanks[c]; does not drain clean to low peripheral line; settlement reduces bottom slope and causes buckles, resulting in bird baths; drains to shell but does not drain well peripherally to water draw, at same elevation
cone-down bottom[d] and cone-down bottom with sump[e]	suitable for refined products where minimum contact of product with water is desired, eg, marketing bulk plant tanks $>20-$ft dia	good for tanks that undergo frequent product changes and in which complete drainage and/or water removal is required; complete drainage and drawdown; center sump decreases area of water in contact with product and with tank bottom	invites corrosion problem from collection of water under bottom plates; requires internal piping to tank center; reduced capacity for differential settlement; center drain should not be rigidly attached to bottom, merely guided; siphon drain only acceptable type
single slope[f]	suitable for tanks $<100-$ft dia; good for tanks that undergo frequent product change and in which complete drainage and/or water removal is required	improved drainage over cone-up and flat horizontal bottom tanks; bottom connections accessible for inspection and maintenance	installed cost more than cone-up or cone-down bottom tanks because of design and cost of foundation and erection shell; shallow slope problematic for sediment-containing tanks; sediment can form water pockets that do not drain

[a]See Figure 7**a.**
[b]See Figure 7**b.**
[c]1160 bbls for a 100-ft-dia tank and bottom slopes as shown in Figure 7**b.**
[d]See Figure 7**c.**
[e]See Figure 7**d.**
[f]See Figure 7**e.**

Tank bottom slope is important because sediment, water, and heavy phases settle at the bottom. Corrosion is usually the most severe at the bottom, and the design of the bottom can have a significant effect on the life of the tank. In addition, if the liquid stock is changed, it is usually desirable to remove as much as the previous stock as possible. Therefore, designs that allow for the removal of water or stock and the ease of tank cleaning have evolved. In addition, specialized tank bottoms have resulted from the need to monitor and detect leaks.

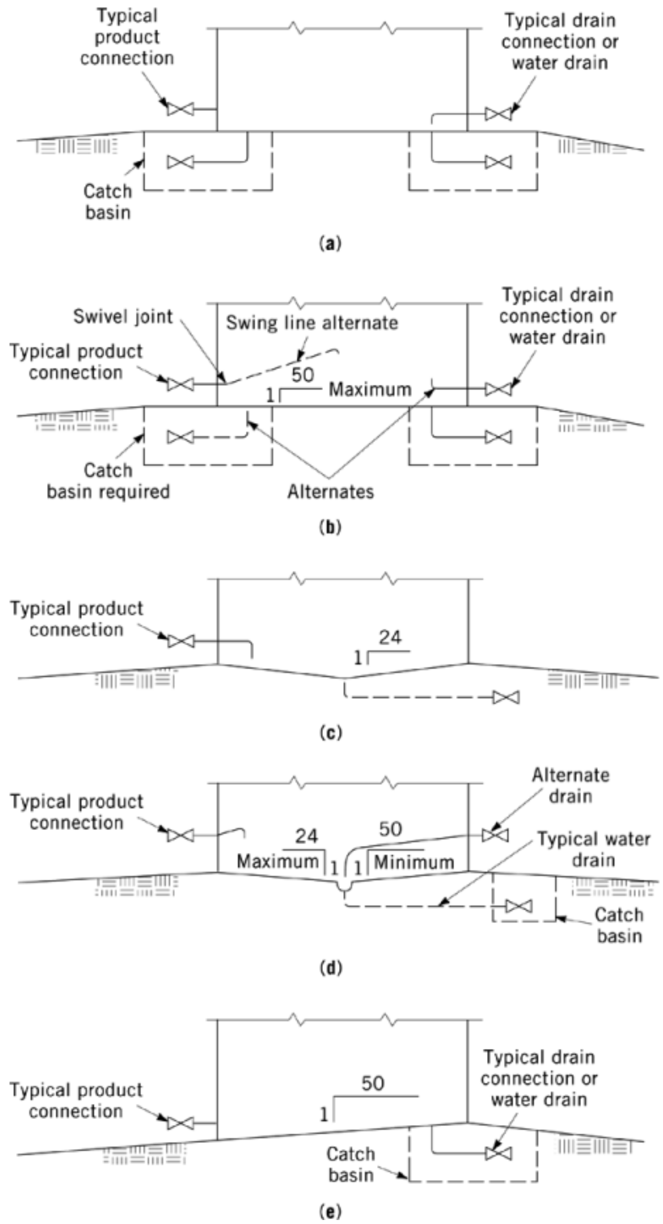

Fig. 7. Tank bottom designs: (**a**) flat bottom; (**b**) cone-up bottom; (**c**) cone-down bottom; (**d**) cone-down bottom with sump; and (**e**) single slope. In (**c**), buried lines are not used frequently because of the difficulty of inspection and possibility of accelerated corrosion.

Tank bottoms in contact with the soil or foundations are one of the primary sources of leaks from aboveground tanks.

3.3.1. Flat

For tanks less than 20–30 ft (6–10 m) in diameter, a flat bottom is used (Fig. 7**a**). The inclusion of a slope does not provide a substantial benefit, so they are fabricated as close to flat as practical.

3.3.2. Cone Up

Cone-up tank bottoms are built to have a high point in the center of the tank (Fig. 7**b**). This is accomplished by crowning the foundation and constructing the tank on the crown. The slope is limited to about 1–2 in. (2.5–5 cm) for every 10 ft (3 m) of run. Therefore, the bottom may appear flat, but heavy stock or water tends to drain to the edge where it can be removed almost completely from the tank.

3.3.3. Cone Down

The cone-down design slopes toward the center of the tank (Fig. 7**c**). Usually, there is a collection sump at the center (Fig. 7**d**). Piping under the tank is then drained to a wall or sump at the tank periphery. Although very effective for water removal from tanks, this design is inherently more complex because of underground piping and the external sump. The design is also particularly prone to corrosion problems unless very meticulous attention is given to design and construction.

3.3.4. Single Slope

The single-slope design uses a planar bottom, but is tilted slightly to one side (Fig. 7**e**), allowing for drainage to be directed to the low point on the perimeter where it may be effectively collected. Because there is a constant rise across the diameter of the tank, the difference in elevation from one side to the other can be quite large. Therefore, this design is limited to about 100 ft (30 m) maximum.

3.3.5. Steep-Angle Conical Bottoms

Tanks often have a conical bottom where the slope exceeds 15–20° from the horizontal. This provides for complete drainage or even solids removal. Because these types of tanks are more costly, they are limited to smaller sizes. Such tanks are often found in the chemical industry or in processing plants.

4. Small Tanks

Numerous types of small tanks have been developed as a result of increasingly stringent regulations regarding leaks, spills, and containment.

4.1. Single Wall

Single-wall tanks are usually cylindrical and may have either vertical or horizontal orientation. Horizontal tanks are generally supported by two saddle supports and use more space than vertical tanks. Horizontal tanks have an advantage in that leaks can be seen as they occur. Water can also easily be drained from a drain valve located on the bottom.

4.2. Double Wall

Double-wall tanks have become more common for both above- and underground applications because the outer tank can contain a leak from the inner tank. This also serves as a means of detecting leaks. Such tanks are usually cylindrical tanks and may have either vertical or horizontal orientation.

4.3. Diked or Unitized Secondary Containment

Small tanks can have a secondary-containment dam built integrally into the tank. This is essentially within a steel box. These tanks may be either vertically or horizontally oriented in both cylindrical and rectangular shapes. The secondary-containment dikes may be open or closed. Closing the dikes makes access to the primary-containment tank more difficult, but keeps out rainwater.

4.4. Vaulted

Vaulted tanks are installed inside a concrete vault. The vault, itself a liquid-tight compartment, reduces the fire protection requirements as the NFPA and the International Fire Code Institute (IFCI) recognize these tanks as fire-resistant aboveground storage tanks. The vault provides a two-hour fire wall, thermal protection that minimizes tank breathing losses and pollution, secondary containment, and ballistic protection.

5. Engineering Considerations

5.1. Required Component Thicknesses

The tank design codes consider all strength calculations to be independent of temperature from ambient up to some upper limit. For example, when the temperature exceeds 93.3°C (200°F), the designer must reduce the allowable stresses. At high design temperatures, the various codes provide derating factors for steel, aluminum, and stainless steel. However, these codes provide little guidance for handling temperature-dependent effects, such as thermal expansion and creep. The tank designer must use good principles and practices to avoid problems such as fatigue or excessive distortions.

When the design temperatures are significantly below ambient temperature, the primary threat to tank integrity is failure of the material by brittle fracture. The tank design codes usually provide thorough treatment of this topic to prevent catastrophic failure. Additionally, there is the consideration of corrosion allowance, defined as extra thickness added beyond that required for strength. Corrosion allowance is not discussed herein.

5.1.1. Tank Bottom

In the fabrication of large steel structures, the minimum thickness is often governed by the minimum necessary for weldability and fabricability and not necessarily by strength requirements. A good example is the thickness requirements specified by the tank design codes for flat-bottom tanks: typically 0.25 in. (6 mm). The design codes treat the bottom as simply a spillproof membrane without any particular requirement for stresses. However, after settlement occurs, significant stresses may develop. API Standard 653 provides guidelines for the maximum degree of settlement while maintaining the tank bottom within allowable stresses.

5.1.2. Tank Shell

Another example of where thickness is set by minimums for fabricability but not for strength is in small-diameter tanks. For example, a water storage tank built using a steel of an allowable stress of 20,000 psi (138 mPa), 9 ft (3 m) in diameter by 21-ft (7-m) high, requires a shell thickness to resist hoop stress of only 0.023-in. (0.58-mm) thick. However, if built to API Standard 650, the shell would be fabricated at least 0.1875-in. (4.76-mm) thick. The code requires this thickness so that when fabrication, welding, and tolerances are considered, a tank of acceptable quality and appearance meeting the requirements of most services in most locations is provided.

In the large-diameter vertical cylindrical tanks, because hoop stress is proportional to diameter, the thickness is set by the hydrostatic hoop stresses. Although the hydrostatic forces increase proportionally with the depth of liquid in the tank, the thickness must be based on the hydrostatic pressure at the point of greatest depth in the tank. At the bottom, however, the expansion of the shell owing to internal hydrostatic pressure is limited so that the actual point of maximum stress is slightly above the bottom. Assuming this point to be about 1 ft (0.305 m) above the tank bottom provides tank shells of adequate strength. The basic equation modified for this anomaly is

$$t = \frac{\rho (H - H_0) D}{2\sigma_{\text{allow}}}$$

where t is the required wall thickness exclusive of corrosion allowance; ρ, the fluid density;H, the maximum shell design liquid level; H_o, 12 in. (30.48 cm); D, the tank diameter; and σ_{allow}, the shell material allowable stresses. This 1-ft (0.305-m) equation is slightly conservative. For tanks over 200 ft (61 m) in diameter, it is worthwhile using the variable point computation which takes into account the actual point of maximum hoop stress. This iterative procedure is illustrated in API Standard 650.

When tanks are built having an open top, the wind pressure may cause buckling of the shell. A wind girder of sufficient section modulus is used to stiffen the open top according to

$$Z = 5.8 \times 10^{-8} D^2 H$$

where Z is the minimum required section modulus;D, the tank diameter; and H, the tank height.

5.1.3. Tank Roof

The roof of a vertical cylindrical tank is treated like a building structure and uses the same basic rules as the building codes. For example, the API codes require a roof to be designed for the dead load plus a 122-kg/m^2 (25-lb/ft^2) live load. The minimum fabrication thickness of roof plates is 3/16 in. (4.8 mm).

Live and dead loads generate hoop forces in the area of the roof-to-shell junction for a tank having a cone roof. For dead loads plus live loads, the roof-to-shell junction is assumed to carry most of the tensile forces generated. The minimum area required is computed assuming that the membrane force transmitted to the roof-to-shell junction varies with the sine of the angle of the roof:

$$\sigma = \frac{PD^2}{8A\sin\alpha}$$

where σ_y is the stress in the roof-to-shell region; P, the live load plus dead load repressed as pressure; D, the tank diameter; A, the roof-to-shell area which acts to resist the hoop forces; and α, the angle of conical roof.

For tank internal pressures that do not exceed the weight of the roof plates, most tanks have conical roofs because these are the simplest and most cost-effective. When the pressure is increased beyond the weight of the roof plates, the roof-to-shell area goes into hoop compression. A small portion of the roof, the roof-to-shell angle, and the top few centimeters of the shell act as a compression ring to resist the unbalanced forces from internal pressure on the conical roof. The internal design pressure for this case may be

$$A = \frac{W}{2\pi\sigma_y \tan\theta}$$

where σ_y is the yield strength of steel, W the weight of shell and framing supported by the shell, and θ the angle the roof makes from the horizontal.

5.2. Materials of Construction

Tanks are constructed from a number of materials based on cost and availability of the material, ease of fabrication, resistance to corrosion, and compatibility with stored fluid. Sometimes specialized composites and techniques are used in tank construction. These are the exception.

Carbon steel, or mild steel, is by far the most common material for tank construction. It is readily available and, because of the ease with which it is fabricated, machined, formed, and welded, results in low overall costs. Austenitic 300 series stainless steel is another important material used for storage of corrosive chemicals and liquids. Although the cost of the austenitic group of stainless steels is significantly more than steel itself, the stainless steels offer the same advantages of fabricability and availability as carbon steel. The API 650 Standard provides details on how to design stainless steel tanks. Fiber glass-reinforced plastic (FRP) tanks are noted for resistance to chemicals. Many times stainless steel or aluminum tanks are not acceptable. The fabrication and construction techniques for FRP are somewhat more specialized than for metals fabrication. Because of the lack of fire resistance, FRP tanks are not normally used to store flammable or combustible liquids. FRP tanks have been used to store water, water-treating chemicals, fire-fighting foam, wastes, lubricants, and nonflammable chemicals and corrosives. Aluminum tanks are suitable for a limited number of materials. Historically, FRP tanks were used for cryogenic applications owing to the fact that aluminum remains ductile at temperatures much lower than carbon steel. However, nickel steels and stainless steels have largely supplanted the market for aluminum tanks. Aluminum is still used for some acids, fertilizers, and demineralized water applications. However, in general, the use of aluminum for storage tanks has been low. Concrete tanks have been used in the water and sewage treatment business for a long time. However, because of the relatively high cost, these are not in common use in the 1990s.

5.3. Tank Selection Criteria

The selection of tanks is a complex process optimizing an array of information to yield a particular design. Figure 8 gives some guidelines. Once the specific liquid(s) to be stored is established, the liquid's physical properties determine the range of possible tank types. Although vapor pressure is a principal component in tank selection, other properties such as flash point, potential for explosion, temperature, and specific gravity all factor in the selection and design of tanks. A simplified example of tank selection by fluid stored is shown in Table 5. In addition to fundamental physical properties influencing tank selection, size, regulations, best practices, external loads such as wind, snow, and seismic loads, as well as numerous additional engineering issues, all play a role. Material selection, corrosion prevention systems, and environmental requirements and considerations may also influence the selection. Layout of the tank within existing or new facilities is always an important consideration as the limited plot space for the tank is a factor on the type of tank selected. The requirements of the fire authority having jurisdiction almost always have property line and public way setbacks as well as distance requirements between tanks and equipment or other tanks. The ultimate selection criteria are keenly dependent on such factors as the actual site-specific conditions, local regulations, cost considerations, required operating life, space availability, and potential for fires and explosion. These should all be evaluated and considered by the responsible engineering designer and documented for the protection of the plant owner and operator.

5.4. Special Engineering Considerations

Because tanks are used in so many different ways, some specialized applications have been developed that have become fairly commonplace.

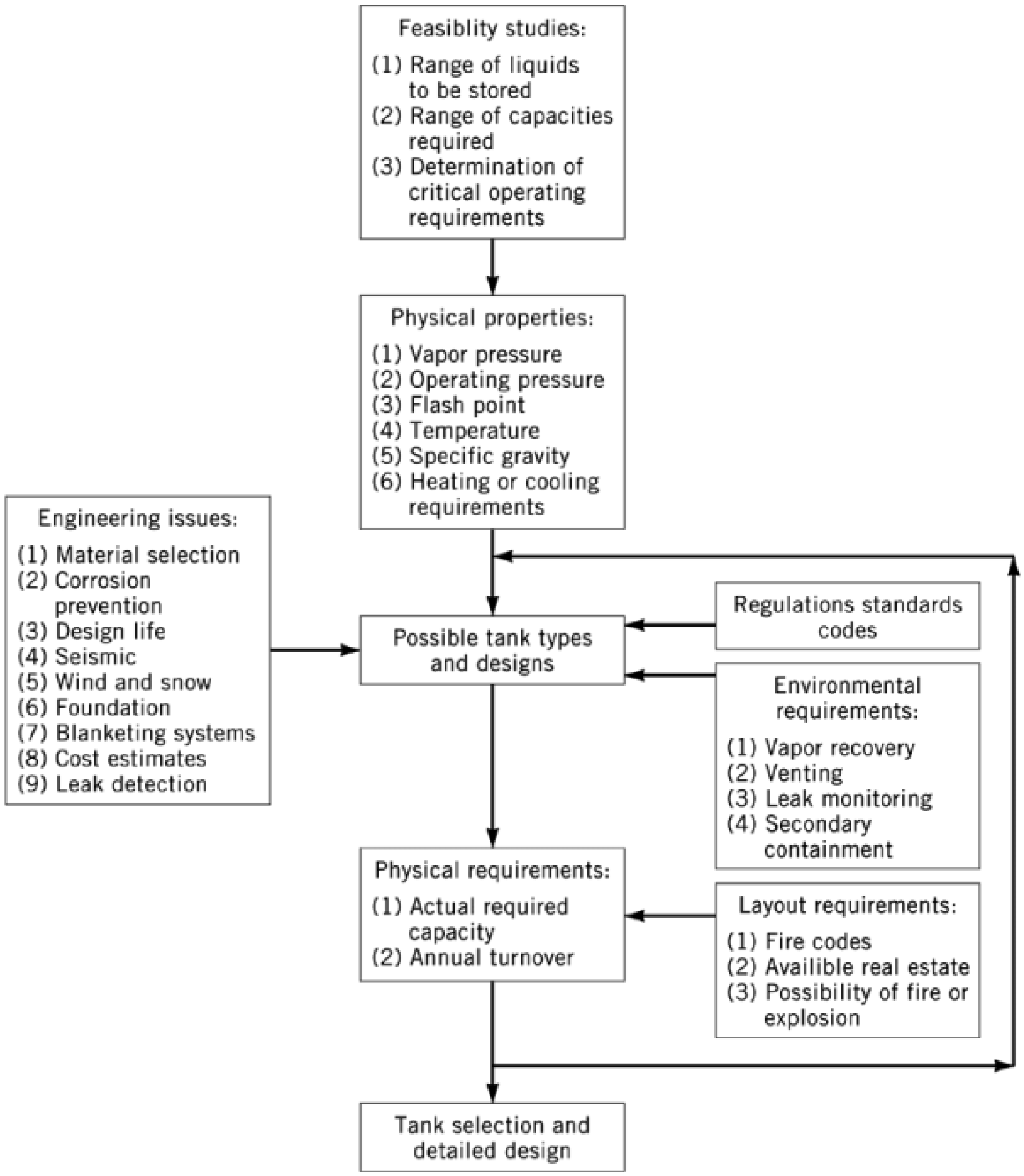

Fig. 8. Tank selection criteria.

5.4.1. Cryogenic Tanks

Low temperature tanks are used for liquefied hydrocarbon gases (LHG); liquefied natural gas (LNG); various liquefied gases such as air, nitrogen (qv), or oxygen (qv), and ammonia (qv); and other refrigerated liquids (see Cryogenics; Liquefied petroleum gas). As a general rule, larger quantities of stored liquids that have high vapor pressures favor low temperature or cryogenic storage. Although the use of these products may be in the gaseous state, a higher quantity can be stored in the liquid state, so cryogenic storage is often the preferred method

Table 5. Storage Tank Type for Liquids at 25°C (77°F)[a]

Chemical	Tank type[b]	Chemical	Tank type[b]
acetaldehyde	H	ethylenediamine	A
acetamide	A	ethylene dichloride	L
acetic acid	A	ethylene glycol	A
acetone	L	ethylene glycol monoethyl ether	A
acetonitrile	L	formic acid	L
acetophenone	A	freons	H
acrolein	L	furfural	A
acrylonitrile	L	gasoline	A
allyl alcohol	L	glycerine	A
ammonia	H	hydrocyanic acid	L
benzene	L	isoprene	L
benzoic acid	A	methyl acrylate	A
butane	L	methyl amine	A
carbon disulfide	L	methylchloride	A
carbon tetrachloride	A	methyl ethyl ketone	A
chlorobenzene	L	methyl formate	L
chloroethanol	A	naphtha	A
chloroform	L	nitrobenzene	A
chloropicrin	L	nitrophenol	A
dilorosulfonic acid	A	nitrotoluane	A
cumene	A	pentane	L
cyclohexane	L	petroleum oil	A
cyclohexanane	A	propane	H
dichloromethane	L	pyridine	A
diesel oil	A	styrene	A
diethyl ether	L	sulfuric acid	A
dimethylformanide	A	sulfur trioxide	L
dimethyl pthalate	A	tetrachloroethane	A
dioxane	L	tetrahydrofuran	L
epichlorohydrin	A	toluene	A
ethanol	L	trichloroethylene	L
ethyl acetate	L	xylene	A
ethylbenzene	A		

[a]Ref. 7.
[b]A = atmospheric pressure, <0.5 psig; L = low pressure, <15 psig but >0.3 psig; H = high pressure, >15 psig.

for storing large quantities of gases. Not only must these materials be cooled to temperatures substantially below ambient, they may need to be kept under pressure as well. Because of these requirements, the tanks often require accessory cooling systems. Some of these systems cool the vapor in the tank space and return it to the tank; others cool the liquid. In addition, to reduce the size of the cooling equipment and conserve energy consumption, these tanks must be insulated. For flammable materials such as LNG or LHG, additional fire code requirements may stipulate that a secondary containment tank be provided which can contain the contents of the inner tank in case of failure.

Careful material selection is required to prevent brittle failure of tanks at low temperatures. In addition, for tanks where the service temperatures are reduced, it is essential that an engineering analysis be performed to ensure that the tanks are not subject to brittle failure at the house temperature. The tank and vessel codes usually specify allowable materials based on design temperature. Further information about selection of metals for low temperature is available (8).

5.4.2. Heated Tanks

Many compounds either freeze, solidify, or thicken to the point where they cannot be transferred through piping and equipment unless maintained at some minimum temperature. Examples are heavy oils, asphalts, sulfur, highly concentrated salt solutions, caustic soda solutions, or even molasses and foodstuffs. The storage tanks for these fluids must be heated and maintained to some minimum temperature. There are several ways to heat tanks, as shown in Figure 9. Heat transfer raises a rather complex engineering optimization problem to minimize the heat-transfer surfaces because these tend to be costly. This is done by mixing and/or pumping the fluids, varying the insulation requirements of the tank, picking the proper heat-transfer medium such as steam (qv), or optimizing the type of heat-transfer surface (extended or finned surface versus tubular). Of particular importance in establishing heating requirements is the rate of bringing a cold tank up to temperature versus the rate of heat needed to maintain a minimum temperature under design conditions. If the heatup rate is too high, a large heating system is required; if it is too small, the tank can take excessively long to heat up or it may not heat up to its design minimum under adverse conditions. The temperature of the heating fluid must be kept low where the product is heat-sensitive so that the product does not suffer degradation. Another case where temperature levels of the heat-transfer surface must be limited is where stress corrosion cracking can occur, as in some saline solutions or caustic solutions. Other design requirements involve the prevention of stratification of hot and cold layers and the ability to remelt or heat up the tank quickly and efficiently. These considerations usually involve use of mixers and eductors or of thermal circulation within the tank (see Mixing and blending).

The exposed surface area of a tank is relatively large, thus heated tanks are almost always insulated. Another reason for insulating is that the external corrosion rate of the steel owing to atmospheric conditions increases with increasing temperature. Insulation, if properly installed, reduces external corrosion. Many types of insulation systems are available. The difficulty with most is that if rainwater gets into them, the water becomes trapped inside and tends to accelerate corrosion. Much of the more recent improvements have been directed in keeping water out of the insulation.

An extremely important safety consideration for both heated and cryogenic tanks is that lower boiling liquids must not be introduced into the tank. These liquids can boil and cause a frothover or a violent evolution of vapor, followed by tank failure.

5.5. Design Considerations

Most of the design codes and standards for tanks provide checklists and concepts to prevent the designer from making gross mistakes. In particular, tank standards are issued by the American Petroleum Institute (API), which remove most of the risks of the catastrophic results that can occur without considering material selection, brittle fracture, insufficient welding or joining methods, fabrications methods, etc. In fact, these standards are recognized worldwide to be of the highest caliber. As a result, they have been used in industries such as chemicals, pulp and paper, food, and a host of others. Even using API standards many site-specific considerations still exist that can have a substantial impact on the design life of the tank as well as its safe operations. All of these considerations should be documented in records maintained by the owner or operator of the tank. Some of these elements are determination of appropriate standard and code to build the tank; compliance with fire codes; material selection; linings and coatings; cathodic protection; wall thickness selection; appurtenance design, eg, ladders, internal piping, and instrumentation; establishing and designing for external anticipated loads, eg, seismic or snow loads; venting and emergency venting; foundation and settling criteria; pollution prevention, eg, secondary containment, leak detection, and seal selection; fabrication, erection, inspection, and testing; and electrical area classification.

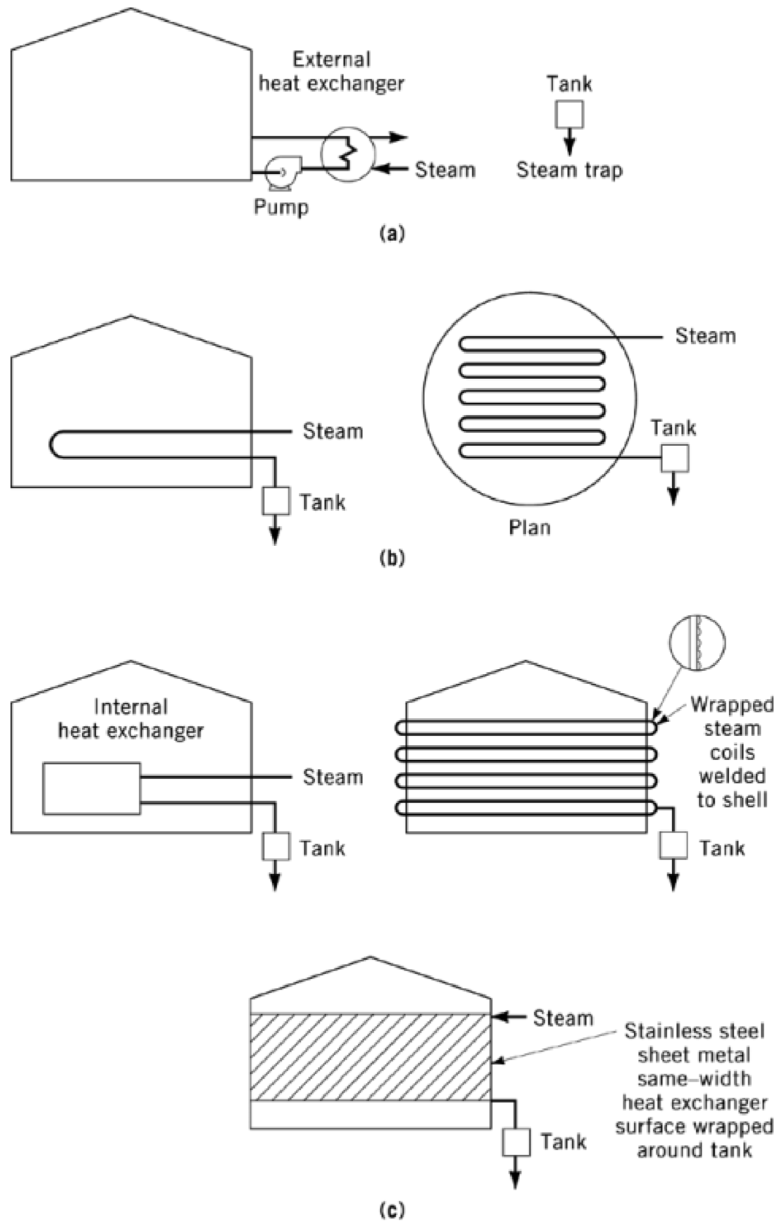

Fig. 9. Methods of heating tanks: (**a**) external heat exchanger; (**b**) serpentine steam coils; and (**c**) plate coils.

6. Regulations

Regulations and laws are mandatory requirements with which a tank owner or operator must comply. Most regulatory requirements are channeled through an agency whose general responsibility is the safety, well-being, and protection of the public or the environment. The authority having jurisdiction may be a federal, state, local, or regional agency, an individual such as a fire chief or marshal, a labor or health department, or a building official or inspector.

The general rule of thumb is that most tank facilities are subject to multiple authorities. When this is the case and the rules have overlapping or even conflicting provisions, the facility must comply with all the requirements of the multiple authorities. In short, one authority's requirements does not preempt or even satisfy the requirements of the other agency even if they accomplish exactly the same thing. There are many examples of this type of inefficiency in regulations.

For aboveground tanks, there is no comprehensive regulation or program as there is for underground tanks under the RECRA program. Most tanks are unregulated or regulated only if they contained flammable liquids under the jurisdiction of local fire authorities. This is likely to change.

6.1. Federal Regulations

Federal regulations tend not to be aimed at spill and tank-bottom leak prevention but rather on spill response. These therefore address issues such as containment of spills, financial liability and responsibility, discharge of contaminated stormwater, reporting, and response requirements.

6.1.1. Statues

The framework from which all regulations that affect the petroleum, chemical, and petrochemical industries are derived is essentially the result of nine statues shown in Figure 10. These statues address the issues of limiting exposure of substances that may be harmful to human health or the environment to acceptably low levels; assigning financial as well as criminal responsibility for damaging human health or the environment; and reporting of data, incidents, information that may affect the regulatory agencies for enforcing the regulations associated with the listed statues.

The relationship of codes and standards to the regulatory framework should be clearly understood. By themselves, industry codes and standards have no authority. However, an examination of both regulations and codes shows that the governmental jurisdictions that have authority over tanks usually rely on the codes and standards to form the technical basis of their requirements. In many cases, they simply refer to the code or standard by name, which then elevates the latter to a legal requirement. Frequently, the authority having jurisdiction often adds other requirements, such as registration fees, to their technical requirements to support the administrative costs of implementing the inspection and enforcement of their responsibilities. Identifying and using codes and standards is one of the first steps to take when considering a new tank installation, regulating it, or simply trying to understand it.

7. Spills, Leaks, and Prevention

Leaks and spills from aboveground storage tank (AST) facilities have had more impact on change in the way tanks are regulated and will be regulated, as well as on the design and operation of tanks, than any other single factor. Leaks and spills have had a substantial impact on public awareness as well. Leaks and spills are associated with groundwater, which in turn is associated with public water supplies and irrigation, thus the public has had little tolerance for environmental accidents.

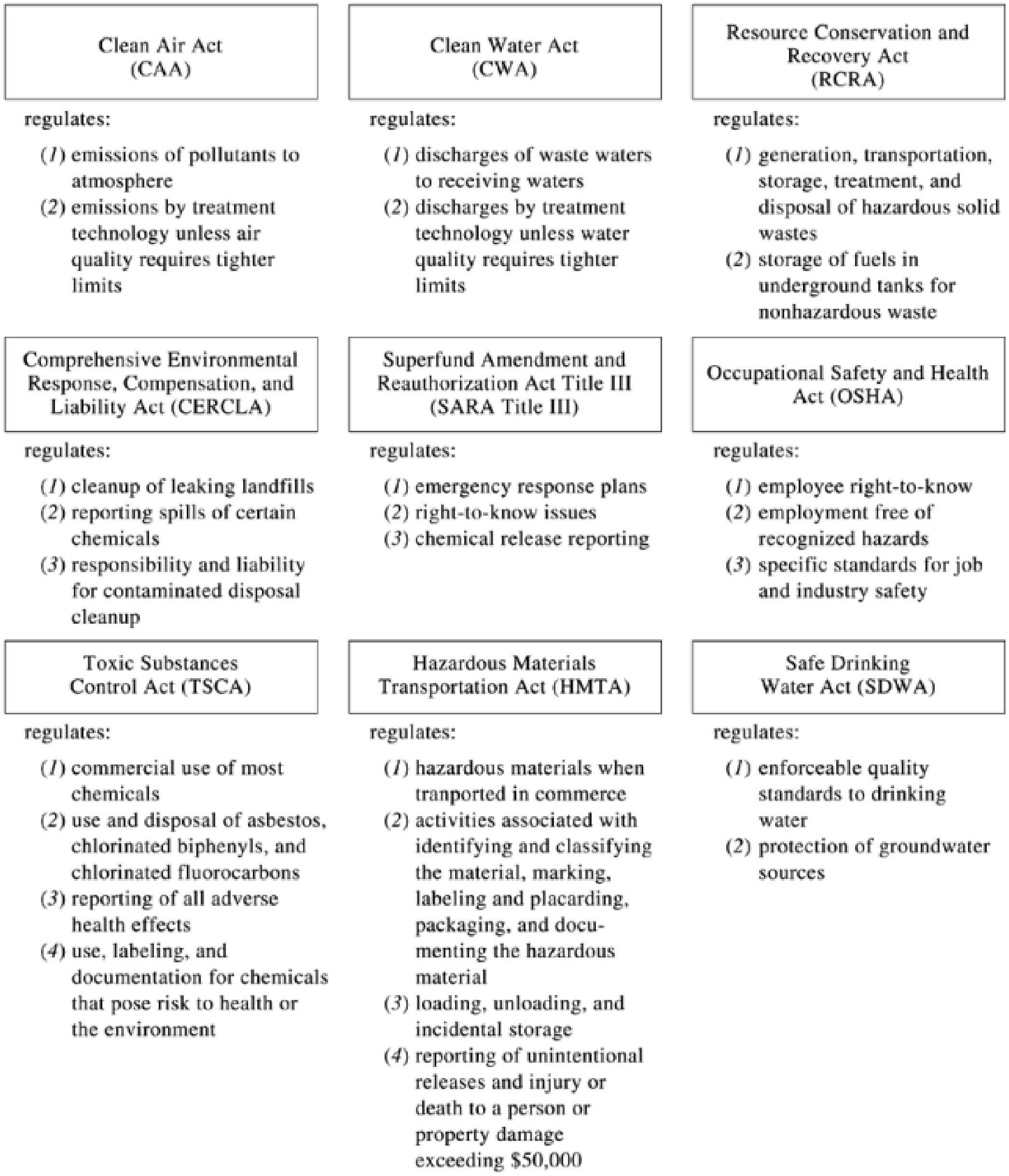

Fig. 10. Summary of principal environmental laws (9).

7.1. Causes of Spills and Leaks

There are numerous causes of tank leaks and spills. Some examples, as well as causes for bulk storage and handling facilities and piping, are noted in Table 6.

Table 6. Causes of Leaks and Spills

Leak or spill source	Characteristics	Root causes	Preventive measures
corrosion	most common in tank bottoms and underground piping; low rate; lack of warning; may continue for years undetected; large volumes released over long periods; common	corrosion; materials selection; costs of corrosion prevention methods	careful design and engineering; inspection per API 653; tank management program
operations			
overfills or transfers	larger quantities released; quickly discovered; hazardous potential for fires; relatively common	operator error; instrumentation or equipment failure; lack of training; failure to maintain overfill system	tank management program having written operating procedures; training and drills; periodic testing of instrumentation
roof drains	large volumes released; easily discovered; usually occur in stormy weather; relatively rare	equipment failure; failure to use secondary containment properly	tank management program having written operating procedures; training and drills; periodic testing of instrumentation
leaks	leaks relatively common in piping, valves, and fittings, pump seals, or in penetrations through secondary-containment areas		tank management program having written operating procedures; training and drills; periodic testing of instrumentation
tank breakage			
brittle fracture	occurs in cold weather; catastrophic failure mode; entire tank contents can empty; extemely rare	materials selection; poor fabrication details; failure to hydrotest	careful design and actual solution; assessment of brittle fracture and seismic after each significant charge of service; assessment of fabrication details per API 653; documentation of all work and engineering performed on all tasks
seismic	damage to piping; tearing of repads and appurtenances; loss of tank contents; relatively rare	ground acceleration	careful design and actual solution; assessment of brittle fracture and seismic after each significant charge of service; assessment of fabrication details per API 653; documentation of all work and engineering performed on all tasks
maintenance	corrosion leaks; instrumentation malfunction	poor tank management programs	establish tank management pro-gram; periodically test all instrumentation; establish API 653 program; document all work on all tasks
vandalism	damage from opening valves; damage from gunfire; ignition of tank contents; bombs or explosions	poor security	improve security systems
piping	principal cause of leaks; failure to provide sufficient capacity to diked areas; leakage of product through second-containment penetration; poor or improper tank materials selection, corrosion prevention, design; charge of services	inadequate or no design engineering or periodic assessment	comply with API 570

Table 6. ***Continued***

Leak or spill source	Characteristics	Root causes	Preventive measures
fire or explosion	spills inside and outside secondary containment; fire likely to spread to all leaking tanks; rim seal fires relatively minor; spill fires can quickly become dangerous	improper design or operation	set up tank management program; ensure compliance with NFPA; conduct fire and safety audits; document results; establish emergency command system and resources; conduct process management safety review

7.1.1. Corrosion

Corrosion is one of the most prevalent and insidious causes of leaks. Because the large surface area of either aboveground or underground tanks cannot be easily inspected, leaks that develop tend to go on for long periods of time and large underground contamination pools can result. Corrosion can be mitigated by proper material selection, use of lining and coatings for both topside and bottomside corrosion, cathodic protection, and chemical inhibition. A good tank inspection program, such as API 653, which requires periodic internal inspections, is one of the best ways to ensure that leaks do not go on undetected for long periods of time.

7.1.2. Operations

Overfill of tanks, owing to any number of reasons, is a common occurrence. This results from inoperative or failed equipment such as level alarms, instrumentation, and valves, as well as operator error or lack of training. A comprehensive tank management program addresses these kinds of problems.

Another occurrence is the leakage of product through the roof drains on external floating-roof tanks and out at the roof drain discharge nozzle. These spills are sometimes caused by equipment failures but also result from operator error or lack of training. Because it is easier to leave secondary-containment valves and roof drain valves open so that they do not need to be opened in periods of rainfall, the effectiveness of this equipment is reduced. This may be classified as operator error. A comprehensive tank management program addresses these kinds of problems.

Yet another significant cause of contamination is draining the water bottoms from tanks. This escapes through the secondary-containment system or stagnates in pools on the ground, resulting in contamination. A change in operation, as well as inclusion of the procedures for disposal of tank water bottoms in an overall tank management program, eliminates this form of leak and spill.

7.1.3. Tank Breakage

Tank breakage, owing to either brittle fracture or ductile tearing during earthquakes or some uncorrected settlement problems, results in sudden and total loss of the tank contents. Such occurrences are relatively rare. Proper engineering and design, such as materials selection, application of the various codes and standards, and carefully detailed designs, can prevent these incidents.

7.1.4. Maintenance

The lack of maintenance and investment in inspection programs results in not only poor housekeeping but unnoticed leaks due to corrosion, leaking flanges and valves, and inoperative instrumentation that could prevent spills.

7.1.5. Vandalism

Vandalism is a surprisingly significant cause of spills. If a facility adopts a tank management program aimed at preventing leaks and spills, one of its elements addresses facility security.

7.1.6. Piping

Piping is a principal cause of leaks and spills, having many of the same characteristics as tank leaks and spills. Indeed, piping is always connected to tankage. Perhaps the most significant leaks have resulted from pressurized underground piping.

7.1.7. Design

Design deficiencies can result in almost any combination of the problems described above. It can also result in catastrophic and significant spills. The best prevention is to use established codes, such as those provided by the API.

7.1.8. Fire and Explosion

Most fires are associated with spills from overfills or leaking pump seals that form pools and clouds of flammable material. Periodic fire compliance and safety reviews can prevent many problems. Compliance with API and NFPA codes is good insurance. If fires do develop, then a program of emergency response and preparedness, as well as the establishment of an incident command system, can mitigate unforeseeable disasters. Careful design details and operational procedures are more effective than pumping resources into costly fire-fighting equipment in general.

7.1.9. Spill Anatomy and Remediation

Contrary to past arguments that leaks or spills from aboveground tanks would stay near the surface, they go straight down into the aquifer and spread out. Various obstacles, such as clay lenses, rock, or impermeable layers of soil, simply divert the downward path. Slow leaks from tank bottoms tend to form a narrow plume, whereas larger spills cover much wider areas. When the contaminant reaches groundwater, it tends to be dispersed in the direction of the groundwater current and movement.

The properties of the material spilled, of course, play a key role in the dispersion of the spill. Not only are the various hazardous properties (toxicity, flammability, reactivity) important for affecting the levels at which these substances can damage the environment or health of life forms, but these properties also play a crucial role in dispersion and, consequently, potential for cleanup. Most petroleum products are relatively insoluble in water and therefore tend to remain in distinct and separate phases when they contact groundwater. Because petroleum is lighter than water, it tends to collect in pools above the groundwater and can be withdrawn by drilling wells into the high point of these pockets. However, petroleum also moves with the groundwater and often seeps into creeks, lakes, or rivers. Miscible products such as alcohols, oxygenates used for motor fuels, and various chemicals can mix with the groundwater. Once mixed, the entire groundwater current that passes through the spill region must be treated in order to remove the contaminant. Products having specific gravities greater than 1.0, such as halogenated hydrocarbons, tend to sink to the bottom of the aquifer. In spite of efforts to remove spilled chemicals by withdrawal from the ground through wells, a substantial amount remains embedded in the soil and groundwater in the form of coated particles or dissolved in the moisture of the soil and aquifers. Sometimes portions of the groundwater stream are pumped to the surface for treatment and reinjection, or neutralizing chemicals or oxidizers, such as air, are injected into the ground to reduce the effects of the spill and leak. None of these methods, however, is 100% effective.

7.2. Spill Prevention and Detection

It is far better to prevent a leak or a spill than to clean one. The fundamental rule of leak and spill prevention is to reduce the possibility for contamination by directing resources as close to the source as possible (Fig. 11). In addition to increasing the effectiveness of a spill and leak prevention program, the costs are lower if the focus is placed on preventing the occurrence in the first place. Regulatory trend, however, is to require methods

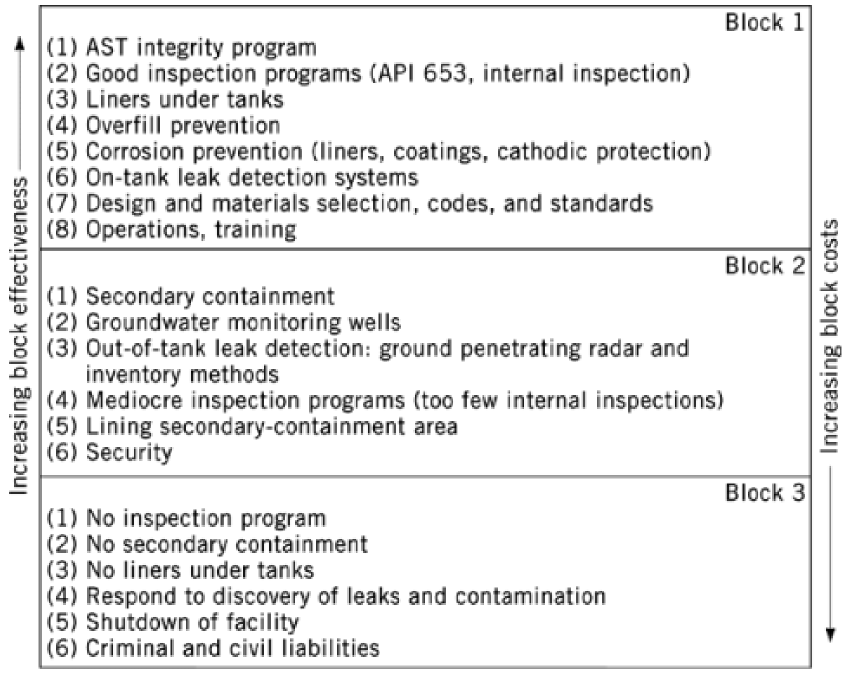

Fig. 11. Leak and spill prevention.

that respond to leaks after they occur. In addition to being more costly, this type of requirement is often a disincentive to prevent the leaks in the first place, because of the additional cost.

Leak and spill prevention comprises a system of management or a program embodying many facets which, when all working together, virtually eliminate the possibility of leaks and spills. In all cases, documentation and recordkeeping of all aspects of the tank management system are good practice.

7.2.1. Engineering Controls

The design, engineering, and maintenance of storage tanks strongly affect the potential for leaks and spills. For example, corrosion resistance can be increased substantially by use of coatings or cathodic protection. Instrumentation can be designed that reduces the likelihood of overfills, fires, or other accidents. Good engineering practice can virtually eliminate brittle fracture. Control of fabrication and inspection of new or repaired tanks can reduce the chances of all kinds of failures. Other parameters subject to engineering controls are foundation design and settlement, seismic capability, fire resistance, resistance to vandalism, etc.

7.2.2. Operation Controls

Standard written operating instructions go a long way to ensure that operators not only know what to do but have sufficient understanding to act effectively in the event of a leak or spill. These instructions should include information on the material stored and its properties, notification of the appropriate authorities in the event of spills, emergency shutdown procedures, and availability and use of emergency and protective equipment. Operational controls should have provisions for inspection. One of the most effective leak prevention methods available is a daily walk-through in the plant by an experienced operator. As a result, operation controls should include provisions for regular training, which should address contract personnel as well. Spill response and planning should be an integral part of the operational controls.

7.2.3. Secondary Containment

One of the most effective methods for mitigating large and catastrophic spills is the concept of secondary containment, where the entire tank field is surrounded with a dike wall or impound area from which the volume of the largest tank can be contained. This way, even if the tank were to fail from a sudden and total release, the contents would be captured in the secondary-containment area for immediate removal and disposal. In fact, any facility near a navigable waterway must use secondary containment according to the Spill Prevention Control and Countermeasures (SPCC) rules enacted by the EPA. However, if the drain valves that allow rainwater to escape are left open, the secondary-containment area can fail to operate as intended. Only operating procedure, knowledge, training, and practice can ensure that these systems work as intended.

7.2.4. Leak Detection

Leak detection methods may be subclassified according to whether or not they are on the tank. On-tank leak detection systems operate immediately upon leakage.

7.2.4.1. On-Tank Leak Detection Systems. Tanks having leak detection bottoms have a means of directing any leaks to the outside of the tank perimeter where these can be visually observed. Before any significant contamination can occur, the leaks are discovered and the tank taken out of service to address the leak.

Precision mass and volumetric methods use very precise measurements of pressure and/or level in the tank to detect leaks. The tank must be closed so that no liquid enters or leaves the tank. The threshold of detection and funnel required to perform a reliable test become greater as tank size increases.

Hydrocarbon sensors (qv) placed directly below the tank bottoms can be effective. However, old contamination or contamination from other tanks or piping can yield misleading results. In addition, the low permeability of some areas in the soil can prevent the migration of vapors to the sensing ports under the tank bottom.

Tracer methods involving chemical markers injected into the contents of the tank may be used. Instrumentation capable of picking up the chemical marker can then determine the presence of a leak caused by seepage of the tracer into the ground. This, like the hydrocarbon sensing method, is generically referred to as soil vapor monitoring. This method suffers the same weaknesses that have to do with undertank soil permeabilities.

By listening to the sound emitted from leaking tanks, it is possible to estimate not only the existence of, but also the location of, leaks in tank bottoms. Much work needs to be done in this area before it can be considered reliable.

7.2.4.2. Off-Tank Leak Detection Systems. Monitoring wells, drilled near the tank site, are effective only after large losses and resulting contamination have occurred. Inventory reconciliation, a method of detecting discrepancies in receipts and disbursements of product through metered piping, is sometimes employed. This method is relatively inaccurate, however, and a substantial leak can escape detection. The advantage to this method, which depends on a substantial amount of lost product and contamination, is that it requires little capital investment as most of the metering is usually already in place.

7.2.5. Use of Liners

The use of impermeable liners and membranes, often called release prevention barriers (RPBs) under tanks, may be the most effective leak detection and prevention method. On new tanks, it is relatively easy to install these systems, and large numbers of tanks are being built with this type of system in the 1990s. For existing tanks, however, it would be very costly if not impractical to install liners. For existing tanks, the combination of other methods as well as an effective inspection program can be more effective as a substitute for a release prevention barrier.

There has been much debate about using liners for the entire secondary-containment area in addition to the area under the tank. Lining the entire secondary-containment area is costly and probably ineffective for the following reasons. (*1*) Large spills and leaks into a secondary-containment area are not left for long periods of time where these can permeate into the ground, but are generally cleaned up immediately. Most secondary-containment areas are relatively impermeable for the short duration for which spills reside. (*2*) Lining the secondary-containment area is difficult to achieve completely. At walls, partitions, piping penetrations, and equipment foundations there are joints and cracks which permit fluids to migrate under the liner. Once under the liner, the fluids cannot be cleaned up. From this perspective, it is worse to use a liner. (*3*) According to the API, it may be cheaper to remediate than to provide lining. (*4*) A small fraction of the resources poured into liners would do far more good for the environment if used as prevention, eg, inspection, leak detection, operator training, and tank programs.

7.2.6. Inspection Programs

One of the most effective ways to reduce leaks and spills resulting from mechanical failure or corrosion is to implement an inspection program. The American Petroleum Institute has issued API Standard 653, which provides a rational and reasonable approach to the problem of inspecting tanks. Because tanks are very costly to empty, remove from service, clean, and prepare for internal inspection, past practices requiring the entry of inspectors into the interior of tanks have been avoided. As a result, there have been numerous long-term leaks resulting from corrosion that have gone undetected. API Standard 653 provides a basis for scheduling internal inspection based on anticipated corrosion rates. For existing tanks that cannot easily be fitted with leak detection systems or liners, the use of this type of inspection program with appropriately spaced internal inspections is effective in reducing leaks.

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