# Pressure Vessel Newsletter

Volume 2014, April Issue



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# From The Editor's Desk:

In the March issue of Mechanical Engineering magazine, one of the letters to the editor stated the following, "Nothing in mechanical engineering has come close to the advances made in microelectronics, computers, telecommunications, sensors, and the software to run them, since even before the microprocessor was introduced in 1974. Nothing in ME has produced anywhere near the technological progress, the job opportunities, the social and economic changes, and the money advances made in these fields, which are done based on entirely by electrical engineers."

Certainly not a ringing endorsement of mechanical engineering as a discipline where technical advancements and innovations flourish! The track record with respect to pressure vessels and piping is not much to write home about either. It is true that there have been progressive advances made in successive editions of the ASME Codes and Standards – but certainly not at the rate that can rival advances made in the field of electrical engineering.

I would like to propose two innovative ideas for pressure vessels.

First one applies to large pressure vessels. Perhaps we should look at designing systems that utilize several smaller pressure vessels in place of one large one. Smaller pressure vessels are easier to fabricate, transport, install and operate. They allow for greater flexibility in operation as well as allow for the luxury of keeping a few spares in the stores.

Second innovation applies to the design where the health of pressure vessels is hard wired into them. The health could be properties such as the remaining life of pressure vessels, stress distribution in the components etc. Having access to such information could be very valuable to the maintenance personnel.

Won't it be nice if pressure vessels could provide the necessary boost to innovation in mechanical engineering?





Math of real world seldom adds up due to intangible variables that cannot be easily captured. For final tally, we know we don't just have to win contracts, we must earn customer confidence too. Our main focus is customer delight achieved due to & through positive interactions, quality alertness, proactive involvement and personalized service for varying situations & requirements.

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## ABOVEGROUND STORAGE TANKS PRIMER

#### Overview

Storage tanks are an essential element in the production, refining, transportation and marketing of petroleum and chemical products. Storage tanks can be divided into two basic types: aboveground (AST) and underground (UST). AST's are used in the production, refining, marketing and pipeline operations. UST's are typically used in the marketing of gasoline at retail service stations. This article will address the AST's - primarily as a liquid storage vessel. The principles outlined here, however, will also apply generally to tanks in other applications as well. It is important to mention here that there are standards available in public domain for the UST's: *Underwriters Laboratories Standards UL58, 1746 and 1316*; and *Steel Tank Institute F841-91*.

#### Aboveground tanks

Aboveground tanks have most of their structure aboveground. The bottom of the tank is usually placed directly on an earthen or concrete foundation. The aboveground tank is usually easier to construct, costs less, and can be built in far larger capacities than underground storage tanks.

#### Underground tanks

Underground tanks are usually limited to between 5,000 and 20,000 gallons with most being less than 12,000 gallons. They have been used to store fuels as well as a variety of chemicals. They require special consideration for earth loads, buoyancy from groundwater, corrosion and means of monitoring for leakage.

#### Basic concepts

#### Physical properties of stored liquid

The primary physical characteristics of stored liquids such as corrosiveness, internal pressures of multicomponent solutions, tendency to scale or sublime, and formation of deposits and sludges are discussed here.

#### Density and specific gravity

The density of a liquid is its mass per unit volume. It plays an important role in the design of a tank. All things being equal, greater densities mean thicker required tank shell thicknesses. Specific gravity is the ratio of the density of one liquid divided by the density of water at  $60^{\circ}$ F. The table below shows some selected specific gravities:

| Liquid              | Sp. Gr. | Liquid        | Sp. Gr. | Liquid          | Sp. Gr. |
|---------------------|---------|---------------|---------|-----------------|---------|
| Acetic Acid         | 1.06    | Fluoric acid  | 1.50    | Petroleum oil   | 0.82    |
| Alcohol, commercial | 0.83    | Gasoline      | 0.70    | Phosphoric acid | 1.78    |
| Alcohol, pure       | 0.79    | Kerosene      | 0.80    | Rape oil        | 0.92    |
| Ammonia             | 0.89    | Linseed oil   | 0.94    | Sulfuric acid   | 1.84    |
| Benzene             | 0.69    | Mineral oil   | 0.92    | Tar             | 1.00    |
| Bromine             | 2.97    | Muriatic acid | 1.20    | Turpentine oil  | 0.87    |
| Carbolic acid       | 0.96    | Naphtha       | 0.76    | Vinegar         | 1.08    |
| Carbon disulfide    | 1.26    | Nitric acid   | 1.50    | Water           | 1.00    |
| Cottonseed oil      | 0.93    | Olive oil     | 0.92    | Water, sea      | 1.03    |
| Ether, sulfuric     | 0.72    | Palm oil      | 0.97    | Whale oil       | 0.92    |

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

Degrees API = 
$$\frac{141.5}{\text{Specific Gravity}} - 131.5$$

On inspection of the above equation, it can be seen that higher the specific gravity, the lower the API gravity. Water having specific gravity of 1 has an API gravity of 10.

The common indicator of specific gravities used in chemical industries is *degrees Baumé*. For liquids heavier than water,

Degrees Bé = 
$$\frac{140}{\text{Specific Gravity}} - 145$$

And for liquids lighter than water,

Degrees Bé = 
$$\frac{140}{\text{Specific Gravity}} - 130$$

#### Temperature

Most storage temperatures are at ambient or a little above or below ambient temperatures. Cryogenic liquids such as liquefied hydrocarbon gases can be as low as -330°F. Some hot liquids such as asphalt tanks can have normal storage temperatures as high as 500 to 600°F. At low temperatures, material selection becomes an important design problem to ensure that the material has sufficient toughness and to preclude the transition of the tank material to a brittle state. At higher temperatures, corrosion is accelerated, and thermal expansion of the material must be accounted for.

The vapor pressure of a pure liquid is the pressure of the vapor space above the liquid in a closed container. It is a specific function of temperature and always increases with increasing temperature. If the temperature of a liquid in an open container is increased until its vapor pressure reaches atmospheric pressure, boiling occurs. Temperature of a pure liquid will not increase beyond its boiling point as heat is supplied; rather, all the liquid will evaporate at the boiling point.

| Substance        | Boiling Point,<br>°F | Substance         | Boiling Point,<br>°F | Substance     | Boiling Point,<br>°F |
|------------------|----------------------|-------------------|----------------------|---------------|----------------------|
| Aniline          | 363                  | Ether             | 100                  | Sulfur        | 833                  |
| Alcohol          | 173                  | Linseed oil       | 597                  | Sulfuric acid | 590                  |
| Ammonia          | -28                  | Mercury           | 676                  | Water, pure   | 212                  |
| Benzene          | 176                  | Naphthalene       | 428                  | Water, sea    | 213.2                |
| Bromine          | 145                  | Nitric acid       | 248                  | Wood alcohol  | 150                  |
| Carbon bisulfide | 118                  | Oil of turpentine | 315                  |               |                      |
| Chloroform       | 140                  | Saturated brine   | 216                  |               |                      |

The boiling points of a few selected substances are shown in the table below:

A liquid does not really burn – it is the vapor that mixes with oxygen in the atmosphere above the liquid that burns. As a liquid is heated, its vapor pressure and its evaporation rate increase. 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. For flammable and combustible liquids, the flash point is the primary basis for classifying the degree of fire hazardousness of a liquid.

#### Pressure

Pressure is defined as force per unit area and can be expressed as an absolute or gauge pressure. The difference in pressure between inside of the tank, or its vapor space, and the local barometric pressure, or

atmospheric pressure, is called the internal pressure. When the internal pressure is negative, it is simply called vacuum.

The region of the tank at roof-to-shell junction is the most complex to design because when there is internal pressure that exceeds the weight of the roof plate and the framing of the roof, this junction wants to separate from the shell. When tanks are subjected to pressures sufficient to damage them, the roof-to-shell junction is usually the first area to show damage.

Most tanks are provided with some form of venting device, usually called a pressure-vacuum valve, or a 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. They are designed to open when the internal pressure builds up to some level in excess of atmospheric pressure and to keep the internal pressure from rising high enough to damage the tank.

Internal pressure is caused by several potential sources. One source is the vapor pressure of the liquid itself. All liquids exert a characteristic vapor pressure which increases with increasing temperature. Liquids with vapor pressure equal to atmospheric pressure boil. Another source of internal pressure is the presence of 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.

External pressure implies that the pressure on the outside of the tank is greater than that on the inside of the tank. External pressures can be extremely damaging to the tanks because the surface area of tanks is usually very large and this generates high forces. The result of excessive external pressure is a buckling of the shell walls or total collapse.

#### Tank classification

A classification commonly employed by codes, standards and regulations in based on the internal pressure of the tank. The fire codes define an atmospheric tank as operating from atmospheric up to ½ psi above the atmospheric pressure. They are the most common type of tanks in operation today. Low-pressure tanks are designed to operate from ½ psig up to 15 psig. High-pressure tanks operating above 15 psig are treated separately from tanks by all codes, standards and regulations. They are referred to as pressure vessels. The ASME Boiler and Pressure Vessel Code is one of the primary standards that have been used throughout the world to ensure safe storage vessels.

The roof shape of a tank may be used to classify the type of tank. It is helpful to have a brief understanding of the effect of internal pressure on plate structures, including tanks. If a flat plate is subjected to pressure on one side, it must be made quite thick to resist visible bending or deformation. A shallow cone roof deck on a tank approximates a flat surface and is typically built of 3/16-in thick steel. It is unable to withstand more than a few inches of water column. As internal pressure increases, the practicality of fabrication practice and costs force the tank builder to use shapes which are more suitable.

Fixed roof tanks may be classified as:

#### Cone-roof tanks

These are cylindrical shells with a vertical axis of symmetry. The bottom is usually flat, and the top is made in the form of a shallow cone. This type of tank is most widely used for storage of relatively large quantities of fluids. Cone-roof tanks typically have roof rafters and support columns except in very small diameter tanks. They are commonly used for low-volatile products such as heavy oil, kerosene, diesel oil, oil, water, etc.

#### Umbrella-roof tanks

These are similar to cone-roof tanks, but the roof looks like an umbrella and hence the name. They are usually constructed to diameters not much larger than 60-ft. These tank roofs can be self-supporting structure, meaning that there are no column supports that must be run to the bottom of tank.

#### Dome-roof tanks

These are similar to umbrella-roof tanks except that that the dome more nearly approximates a spherical surface than the segmented sections of an umbrella roof. The spherical construction provides severe

strength to the tank internal pressure. This type of tank is applicable to volatile products and N<sub>2</sub> gas blanket system is commonly installed when high volatile product is stored.

Floating-roof tanks have a cover that floats on the surface of the liquid. It is a disk structure that has sufficient buoyancy to ensure that the roof will float under all expected conditions, even if leaks develop in the roof. It is built with 8- to 12-in gap between the roof and the shell, so it doesn't bind as the roof moves up and down with the liquid level. The clearance between the floating roof and the shell is sealed by a device called a rim seal. The two categories of floating-roof tanks are internal floating roof (IFR) tanks and external floating roof (EFR) tanks.

#### Inernal floating roof tanks

If the floating roof is covered by a fixed roof on top, it is called an IFR tank. The function of the cover is to reduce evaporation losses and air pollution by reducing the surface area of the liquid that is exposed to the atmosphere.

#### External floating roof tanks

If the tank is open on top, it is called an EFR tank. EFR tanks have no vapor pressure associated with them and operate strictly at atmospheric pressure. The design conditions of the external floating roof are more severe since they must handle rainfall, wind, dead load, and live load conditions comparable to those for building roofs.

#### **Tank Bottoms**

Design of tank bottoms can have a significant effect on the life of a tank. Sediments, water, or heavy phases settle at the bottom and can contribute to severe corrosion. The design needs to allow for removal of water or stock, and for ease of cleaning when the stock needs to be changed. Additionally, the design should also allow for monitoring and detection of leaks. Tank bottoms may be broadly classified as Flat, Cone-up, Cone-down, and Single slope bottoms.

#### Flat Bottoms

For tanks less than 20- to 30-ft in diameter, the inclusion of small slope does not provide any substantial benefit, so the tank bottoms for such tanks are fabricated as close to flat as practical. Figure 1 shows the important characteristics of flat-bottom tanks.

#### Cone-up Bottoms

These bottoms are built with a high point in the center of the tank. This is accomplished by crowning the foundation and constructing the tank on crown. The slope is limited to 1- to 2-in per 10-ft run. Therefore, the bottom may appear flat, but heavy stock or water will tend to drain to the edge, where it can be removed almost completely from the tank. Figure 2 lists the advantages and disadvantages of cone-up bottom design.

#### Cone-down Bottoms

This bottom design slopes towards the center of the tank. Usually, there is a collection sump at the center. Piping under the tank is then drained to a well or a sump at the periphery of the tank. Although very effective for water removal from tanks, this design is inherently more complex because it requires a sump, underground piping, and an external sump outside the tank. It is also particularly prone to corrosion problems unless very meticulous attention is paid to the design and construction details such as corrosion allowance and coatings or cathodic protection. See Figure 3 for important characteristics of cone-down bottom design for tanks.

#### Single-slope Bottoms

This design uses a planar bottom but it is tilted slightly to one side. This allows for drainage to be directed to the low point on the periphery, where it may be effectively collected. Since 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 usually limited to a tank diameter of 100-ft. See Figure 4 for important characteristics of single-slope bottom design for tanks.



Figure 1: Flat Bottom Tank Design

(From "Aboveground Storage Tanks" by Philip E. Myers)

#### Materials of construction

Selection of material of construction is based upon the cost of material, ease of fabrication, resistance to corrosion, compatibility with stored liquid, and availability of the material. Some common materials and their usage in the construction of storage tanks are described in the table below. Please note that the usage of aluminum and concrete in the construction of storage tanks is very low.

| Carbon steel, or mild steel         | Most common material for tank construction. Readily available. Ease of fabrication. Low overall costs.   |
|-------------------------------------|--|
| Stainless steel                     | Used for storage of corrosive-liquids. Readily available. Ease of fabrication. Cost significantly higher than carbon steel.  |
| Fiberglass reinforced plastic (FRP) | Resistant to chemicals where stainless steel or aluminum are not acceptable. Fabrication and construction techniques more specialized. Lack of fire resistance. Not used to store flammable or combustible liquids. Used for storing water, water-treating chemicals, fire-fighting foam, wastes, lubricants and non-flammable chemicals and corrosives. |
| Aluminum                            | Historically used for cryogenic applications because aluminum remains ductile at such low temperatures. However, nickel steels and stainless steel are now used for such applications. Aluminum now used for some acids, fertilizers, and demineralized water applications. Use of aluminum for storage tanks very low.                                  |
| Concrete                            | Historically used in water and sewage treatment applications. However, not in common use today because of high costs.  |



#### Figure 2: Cone-up Bottom Tank Design

(From "Aboveground Storage Tanks" by Philip E. Myers)

#### Standards and Regulations

Most of the design codes and standards for tanks provide good assurance that critical factors are not overlooked by the designer. In particular, the tank standards issued by API have reduced the risks of catastrophic results that can occur when one fails to consider material selection, brittle fracture, insufficient welding, joining, inspection methods, fabrication methods and the like. Following is a list of standards issued by API for the construction of aboveground storage tanks:

| Spec 12B | Bolted Tanks for Storage of Production Liquids  |
|----------|---|
| Spec 12D | Field-Welded Tanks for Storage of Production Liquids  |
| Spec 12F | Shop-Welded Tanks for Storage of Production Liquids   |
| Spec 12P | Fiberglass Reinforced Plastic Tanks   |
| API 650  | Welded Steel Tanks for Oil Storage. This document governs the construction of tanks storing products with internal pressures up to 2.5 psig.              |
| API 620  | Design and Construction of Large Welded Low Pressure Storage Tanks. This document covers the construction of tanks with internal pressures up to 15 psig. |



Figure 3: Cone-Down Bottom Tank Design

(From "Aboveground Storage Tanks" by Philip E. Myers)

Production tanks constructed to API 12 Series specifications are usually much smaller than the API 650 and 620 tanks and are often subject to different operating conditions. API certifies tank manufacturers at this time only to Specifications 12B, 12D and 12F, but not to Specification 12P, or to Standards 620 or 650.

There are several API standards that support API 650 and 620. These are:

| API 651  | Cathodic Protection for Aboveground Petroleum Storage Tanks      |
|----------|--|
| API 652  | Lining of Aboveground Petroleum Storage Tanks                    |
| API 653  | Tank Inspections, Repair, Alteration, Repair, and Reconstruction |
| API 2000 | Venting Atmospheric and Low Pressure Storage Tanks               |
| API 2517 | Evaporating Losses from External Floating Roof Tanks             |
| API 2519 | Evaporating Losses from Internal Floating Roof Tanks             |
| API 2350 | Overfill Protection for Petroleum Storage Tanks                  |
| API 2015 | Cleaning Petroleum Storage Tanks                                 |
|          |  |



Figure 4: Single-slope Bottom Tank Design



Regulations and laws are mandatory requirements with which a tank operator must comply, or else suffer the consequences of civil or even criminal liability. Most regulatory requirements are channeled through an agency whose general responsibility is the safety, wellbeing, and the protection of the public or the environment. The general rule of thumb is that most tank facilities are subject to multiple authorities having jurisdiction over them. When this is so and the rules have overlapping or even conflicting provisions, the facility must comply with all the requirements of the multiple authorities.

In the United States, the federal regulations for the aboveground storage tanks tend not to be aimed at spill prevention, but rather at spill response. This can be understood by considering the fact that they were enacted after some of the most calamitous oil spills in the history (e.g. Ashland Oil, Exxon's Valdez). At present, all the regulations that affect the petroleum, chemical and petrochemical industries are derived from nine statutes. They address the issues of:

- Limiting the 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
- Reporting of data, incidents, and information that may affect the regulatory agencies for enforcing the regulations associated with the statutes

Following is the listing of the statutes:

- Clean Air Act (CAA)
- Clean Water Act (CWA)

- Resource Conservation and Recovery Act (RCRA)
- Comprehensive Environmental Response, Compensation and Liability Act (CERCLA)
- Superfund Amendment and Reauthorization Act Title III (SARA Title III)
- Occupational Safety and Health Act (OSHA)
- Toxic Substances Control Act (TSCA)
- Hazardous Materials Transportation Act (HMTA)
- Safe Drinking Water Act (SDWA)

The relationship of standards to the regulatory framework should be clearly understood. By themselves, standards have no authority. However, the government jurisdictions that have the authority over tanks usually rely on the standards to form the technical basis for their requirements.

#### Spills, leaks and prevention

Because leaks and spills are associated with groundwater which is then associated with public water supplies and irrigation, the public has very little tolerance for environmental accidents that can lead to spillage of tank contents into the ground. There are numerous causes for leaks and spills from the tanks. They can be categorized as follows:

#### <u>Corrosion</u>

Large surfaces of aboveground tanks cannot be easily inspected; therefore, the leaks that develop from corrosion tend to go on for long periods with large underground contamination pools resulting. Corrosion can be mitigated by proper foundation design and material selection, use of linings and coatings for both topside and bottom side 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 undetected for long periods of time.

#### **Operations**

- Overfill of tanks due 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.
- Another occurrence is the leakage through roof drains on external floating roof tanks and out at the roof drain discharge nozzles. These spills are sometimes caused by equipment failure, but also result from operator error or lack of training.
- Another significant cause of contamination is draining the water bottoms from tanks. This water escapes through the secondary containment system or stagnates in pools on the ground, resulting in contamination. A change in operation, as well as the inclusion of procedures for disposal of tank water bottoms in an overall tank management program, eliminates this form of leak and spill.

A comprehensive tank management program is required to address all problems resulting from operations.

#### Tank Breakage

Tank breakage, due to either brittle fracture or ductile tearing during earthquakes or some uncorrected settlement problems, result in sudden and total loss of the tank contents. Fortunately, these occurrences are extremely rare. Proper engineering and design regarding material selection, application of the various standards, and carefully detailed designs can prevent these accidents.

#### Maintenance

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

#### Vandalism

Vandalism is a surprisingly significant cause of spills. If a facility adopts a tank management program aimed at preventing leaks and spills, one element should address facility security.

#### Piping

Piping is a major cause of leaks and spills. It has many of the same characteristics of tank leaks and spills because piping is always connected to tankage. Most significant leaks have resulted from pressurized underground piping.

#### <u>Design</u>

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

#### 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 will prevent many problems. Compliance with API and NFPA codes is a 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.

Leak and spill prevention comprises a system of programs which, when all working together, virtually eliminate the possibility of leaks and spills. Some of the elements of this type of program are given below.

#### Engineering Controls

The design, engineering and maintenance of storage tanks strongly affect the potential for leaks and spills. Some parameters subject to engineering controls are corrosion resistance, instrumentation, brittle fracture, fabrication and inspection, foundation and settlement, seismic capability, fire resistance, and resistance to vandalism.

#### **Operational Controls**

Standard written operating instructions go a long way toward ensuring that operators not only know what to do but also have sufficient understanding to act effectively in the event of a leak or spill. These instructions should include information on the material stored and their properties, notification of the appropriate authorities in the event of spills, emergency shutdown procedures, and availability and use of emergency and protective equipment.

#### Secondary Containment

One of the most effective methods for mitigating large and catastrophic spills is the use of secondary containment. In this concept, the entire tank field is surrounded with an impoundment area within which the volume of the largest tank can be contained. Thus, even if the tank were to fail from sudden and total release, the contents would be captured in the secondary containment area for immediate removal and disposal.

#### Leak Detection

The methods can be sub-classified as to whether they are on the tank or not on the tank. Some of the common on-tank detection systems are leak detection bottoms, precision mass and volumetric methods, hydrocarbon sensors, tracer methods, sensing cables and acoustic emissions. Some of the common off-tank leak detection systems are monitoring wells and inventory reconciliation.

#### Use of Liners

The use of impermeable liners and membranes under tanks is extremely effective as leak detection and prevention method and may be the most effective method. On new tanks, it is relatively easy to install these systems; however, for existing tanks, it could 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 as effective as a substitute for liners.

#### Inspection Programs

One of the most effective ways to reduce leaks and spills resulting from mechanical failure or corrosion is to implement as inspection program. The API has issued API standard 653, which provides a rational and reasonable approach to the problem of inspecting tanks.

#### Tank selection criteria

A simplified example of tank selection by fluid stored is shown in the table below.

| Chemical              | Tank Type | Chemical                  | Tank Type |                     | Tank Type |
|-----------------------|-----------|---------------------------|-----------|---------------------|-----------|
| Acetaldehyde          | Н         | Cyclohexane               | L         | Isoprene            | L         |
| Acetamide             | А         | Dichloromethane           | L         | Methyl acrylate     | Α         |
| Acetic acid           | А         | Diesel oil                | А         | Methyl amine        | Α         |
| Acetone               | L         | Diethyl ether             | L         | Methylchloride      | Α         |
| Acetonitrile          | L         | Dimethylformanide         | А         | Methyl ethyl ketone | Α         |
| Acetophenone          | А         | Dimethyl phthalate        | А         | Methyl formate      | L         |
| Acrolein              | L         | Dioxane                   | L         | Naphtha             | Α         |
| Acrylonitrile         | L         | Epichlorohydrin           | А         | Nitrobenzene        | Α         |
| Allyl alcohol         | L         | Ethanol                   | L         | Nitrophenol         | Α         |
| Ammonia               | н         | Ethyl acetate             | L         | Nitrotoluene        | А         |
| Benzene               | L         | Ethyl benzene             | A         | Pentane             | L         |
| Benzoic acid          | А         | Ethylene diamine          | А         | Petroleum oil       | Α         |
| Butane                | L         | Ethylene dichloride       | L         | Propane             | н         |
| Carbon disulfide      | L         | Ethylene glycol           | А         | Pyridine            | Α         |
| Carbon tetrachloride  | A         | Elene glycol<br>monoethyl | A         | Styrene             | Α         |
| Chlorobenzene         | L         | Ether                     | L         | Sulfuric acid       | Α         |
| Chloroethanol         | А         | Formic acid               | А         | Sulfur trioxide     | L         |
| Chloroform            | L         | Freons                    | н         | Tetrachloroethane   | А         |
| Chloropicrin          | L         | Furfural                  | А         | Tetrahydrofuran     | L         |
| Dichlorosulfonic acid | А         | Gasoline                  | А         | Toluene             | Α         |
| Cumene                | A         | Glycerine                 | А         | Trichloroethylene   | L         |
| Cyclohexanone         | Α         | Hydrocyanic acid          | L         | Xylene              | Α         |

Key:

A = atmospheric, less than 0.5 psig

L = low pressure, less than 15 psig but greater than 0.3 psig

H = high pressure, greater than 15 psig

Source: Ecology and Environment, 1982

Source: Myers, Philip E., Aboveground Storage Tanks

# Would you like your company information to appear in Pressure Vessel Directory?

Send the following information to <u>info@codesignengg.com</u> today:

Company name, Full postal address, Telephone number, Website, Company contacts (name, title, email id, telephone number), Product types



#### **DESIGN & FABRICATION OF PRESSURE VESSELS: ASME SECTION VIII, DIVISION 1**

Pressure vessels, along with tanks, are the workhorses for storage and processing applications in the chemical, petroleum, petrochemical, power, pharmaceutical, food and paper industries. ASME BPV, Section VIII, Div. 1 Code is used as a standard for the design and fabrication of pressure vessels by most companies across the world.

We would like to announce training course for "Design and Fabrication of Pressure Vessels: ASME Section VIII, Div. 1" on May 29-31, 2014 at Mumbai. This course provides the information that will help you understand the ASME requirements for the design and fabrication of pressure vessels. The course material follows the contents of 2010 edition of the code, and is replete with worked examples covering important aspects of pressure vessel construction. This hands-on learning will allow you to master in 3 days what would otherwise take up to a year or more of on-job training.

The contents of the training course will be as follows:

- Introduction to Boiler and Pressure Vessel Code
- Materials of Construction
- Low Temperature Operation
- Joint Efficiencies
- Design of Components
- Openings and Reinforcements
- Fabrication, Inspection and Tests
- Markings and Reports
- Tall Towers and Pressure Vessel Supports
- Nozzle Loads
- Fatigue Analysis
- Introduction to ASME Section VIII, Division 2

The instructor, Ramesh Tiwari, is internationally recognized specialist in the area of pressure vessels, heat exchangers, materials, and codes and standards. He holds Bachelor's and Master's degrees in mechanical engineering from universities in India and United States. He is also a registered Professional Engineer in the State of Maryland in the United States. Mr. Tiwari is a member of ASME Boiler & Pressure Vessel, Section VIII Subgroup on Heat Transfer Equipment, and a member of ASME International Working Group on B31.1 for Power Piping in India. In this capacity, he has made invaluable contribution in resolving technical issues in compliance with the ASME codes for Code users. Mr. Tiwari has over 24 years of design engineering experience on a variety of projects spanning industries such as oil & gas, power, nuclear, chemical, petrochemical, pharmaceutical, food etc. He has provided engineering advice and code interpretations to senior management and guidance to several companies he has worked for in the US, India and Germany. He has initiated and implemented numerous innovative ideas to improve working process and quality, and developed and conducted training programs for peers as well as clients. Mr. Tiwari is an approved pressure vessel instructor at NTPC, a premier thermal power generating company in India and at several other companies, both public and private.

Registration fee for the training course is Rs. 25,300 for professionals and Rs 16,000 for students (inclusive of service tax). Discount of 15% is available for group registration of 2 or more participants. Additionally, early bird discount of 15% is available if registration is done on or before May 1<sup>st</sup>. Registration fee includes training, a collection of articles on design and fabrication of pressure vessels, copy of the presentation, certificate from CoDesign Engineering, and beverages and lunch on all days. It excludes travel to and from Mumbai, accommodation, and meals and beverages other than those provided during the course. We invite you to make nominations.

In case of any queries, including the registration process, please email at <u>learning@codesignengg.com</u>, or call at +91 98109 33550.

## HEAT EXCHANGER FOULING

Fouling can be defined as the accumulation of undesirable substances on the heat exchanger surface. In general, the collection and growth of unwanted material results in inferior performance of the surface. A heat exchanger must affect a desired change in thermal conditions of the process streams within allowable pressure drops and continue to do so for a specified time period. During operation, the heat transfer surface fouls resulting in increased thermal resistance and often an increase in pressure drop and pumping power as well. Both of these effects complement each other in degrading performance of the heat exchanger. The heat exchanger may deteriorate to the extent that it must be withdrawn from service for replacement or cleaning.

Fouling may significantly influence the overall design of a heat exchanger and may determine the amount of the material employed for construction. Special operational arrangements may be required to facilitate satisfactory performance between cleaning schedules. Consequently, fouling causes an enormous economic loss as it directly impacts the initial cost, operating cost, and heat exchanger performance.

#### Effects of Fouling

Lower heat transfer and increased pressure drop resulting because of fouling decrease the effectiveness of a heat exchanger. A simple visualization of fouling, shown in Figure 1, depicts fouling buildup on the inside and outside of a circular tube. It is evident that fouling adds an insulating layer to the heat transfer surface.





#### <u>Heat Transfer</u>

For a plain tubular heat exchanger, the overall heat transfer coefficient under fouled conditions  $U_f$  can be obtained by adding the inside and outside thermal resistances in equation (1):

$$U_f = \frac{1}{A_o/A_i h_i + A_o R_{fi}/A_i + A_o \ln(d_o/d_i)/2\pi k L + R_{fo} + 1/h_o}$$
(1)

Fouling resistances  $R_{fi}$  or  $R_{fo}$  are sometimes referred to as "fouling factors". The fouling thickness is zero when the surface is clean. The heat exchanger requires cleaning when the fouling thickness reaches a maximum value often called the design value.  $U_f$  in equation (1) can relate to the clean surface overall heat transfer coefficient  $U_c$  as:

$$U_f = \frac{1}{U_c} + R_{ft} \tag{2}$$

where  $R_{ft}$  is the total fouling resistance given as:

$$R_{ft} = \frac{A_o R_{fi}}{A_i} + R_{fo} \tag{3}$$

The heat transfer rate under the fouled conditions  $Q_f$  can be expressed as:

$$Q_f = U_f A_f \Delta T_{mf} \tag{4}$$

If  $A_c$  is the required surface area of a clean heat exchanger, then

$$\frac{A_f}{A_c} = 1 + U_c R_{ft} \tag{5}$$

The factor  $U_c R_{tt}$  in equation (5) represents the additional surface area required because of fouling of heat exchanger. Obviously, the added surface is small if  $U_c$  is low even though the total fouling resistance may be high. However for high  $U_c$  even a small fouling resistance results in a substantial increase in the required heat transfer surface area. A 100% increase in surface area due to fouling alone is not uncommon.

#### Pressure Drop

More heat exchangers are removed from service for cleaning due to excessive pressure drop than for the inability to meet heat transfer requirements. Fouling always results in a finite, although sometime small, layer. The change resulting in the flow geometry affects the flow field and the pressure drop (hence the pumping power). For example, in tubular heat exchangers, the fouling layer roughens the surface, decreases the inside diameter, and increases the outside diameter of the tubes. The effects of fouling on pressure drop in the shell side are difficult to quantify because of the complex flow passages.

As mentioned, the fouling layer decreases the inside diameter and roughens the tube wall resulting in an increase in the pressure drop. Table 1 below depicts the added pressure drops (tube side) for some typical fouling materials. It is seen that for the assumed fouling resistance, the pressure drop increases by up to 70% in some instances.

| Material            | Thermal<br>Conductivity, k<br>W/(m.K) | Fouling<br>Thickness, t<br>mm | Percentage<br>Area Remaining | Percentage<br>Increase in<br>Pressure Drop |
|---------------------|---------------------------------------|-------------------------------|------------------------------|--|
| Hematite            | 0.6055                                | 0.24                          | 95.7                         | 11.6                                       |
| Biofilm             | 0.7093                                | 0.28                          | 95.0                         | 13.7                                       |
| Calcite             | 0.9342                                | 0.37                          | 93.5                         | 18.4                                       |
| Serpentine          | 1.0380                                | 0.41                          | 92.8                         | 20.7                                       |
| Gypsum              | 1.3148                                | 0.51                          | 90.9                         | 26.9                                       |
| Magnesium Phosphate | 2.1625                                | 0.83                          | 85.5                         | 47.9                                       |
| Calcium Sulphate    | 2.3355                                | 0.90                          | 84.4                         | 52.6                                       |
| Calcium Phosphate   | 2.5950                                | 0.99                          | 82.9                         | 59.9                                       |
| Magnetic Iron Oxide | 2.8718                                | 1.09                          | 81.2                         | 68.2                                       |
| Calcium Carbonate   | 2.9410                                | 1.12                          | 80.8                         | 70.3                                       |

#### Table 1: Added Pressure Drop (Tube Side) for Typical Fouling Materials

#### Cost of Fouling

Fouling of heat transfer equipment introduces an additional cost to the industrial sector. The added cost is in the form of (1) increased capital expenditure, (2) increased maintenance cost, (3) loss of production, and (4) energy losses.

In order to compensate for fouling, the heat transfer area of a heat exchanger is increased. Pumps and fans are oversized to compensate for over-surfacing and the increased pressure drop resulting from reduction in the flow area. Duplicate heat exchangers may have to be installed in order to ensure continuous operation while the fouled heat exchanger is cleaned. High cost materials such as titanium, stainless steel or graphite may be required for certain fouling situations. Cleaning equipment may be required for on-line cleaning. All of these items contribute to increasing the capital expenditure.

On-line and off-line cleaning add to the maintenance cost. Fouling increases the normally scheduled time incurred in maintaining and repairing the equipment. Loss of production because of operation at reduced capacity or downtime can be costly. Finally, energy losses due to reduction in heat transfer and increase in pumping power requirements can be a major contributor to the cost of fouling.

#### Aspects of Fouling

In this section, some fundamental aspects that help in understanding the types and mechanisms of fouling are discussed. The commonly used methods that aid in developing models to predict fouling are also outlined.

#### Categories of Fouling

Fouling can be classified in a number of different ways. These may include the type of heat exchanger service (boiling, condensation), the type of fluid stream (liquid, gas), or the kind of application (refrigeration, power generation). One such classification, developed by Epstein, has received wide acceptance. Accordingly fouling is classified into the following categories: particulate, crystallization, corrosion, biofouling, and chemical reaction. It must be recognized that most fouling situations involve a number of different types of fouling, and some of the fouling processes may complement each other.

#### Particulate

Fouling

The accumulation of solid particles suspended in the process stream onto the heat transfer surface results in particulate fouling. In boilers this may occur when unburned fuel or ashes are carried over by the combustion gases. Air cooled condensers are often fouled because of dust deposition. Particles are virtually present in any condenser cooling water. The matter involved may cover a wide range of materials (organic, inorganic) and sizes and shapes (from the submicron to a few millimeters in diameter). Heavy particles settle on a horizontal surface because of gravity. However, other mechanisms may be involved for fine particles to settle onto a heat transfer surface at an inclination.

#### Crystallization Fouling

A common way in which heat exchangers become fouled is through the process of crystallization. Crystallization arises primarily from the presence of dissolved inorganic salts in the process stream which exhibit super-saturation during heating or cooling. Cooling water systems are often prone to crystal deposition because of the presence of salts such as calcium and magnesium carbonates, silicates and phosphates. These are inverse solubility salts that precipitate as the cooling water passes through the condenser (i.e. as the water temperature increases). The problem becomes serious if the salt concentration is high. The deposits may result in a dense, well bonded layer (scale) or a porous, soft layer (soft scale, sludge or powdery deposit).

#### Corrosion Fouling

A heat transfer surface exposed to a corrosive fluid may react producing corrosion products. These corrosion products can foul the surface provided the pH value of the fluid is not such that it dissolves the corrosion products as they are formed. For example, impurities in fuel like alkali metals, sulphur and vanadium can cause corrosion in oil-fired boilers. Corrosion is particularly serious on the liquid side. Corrosion products may also be swept away from the surface where they are produced and transported to other parts of the system.

#### Bio-fouling

Deposition and/or growth of material of biological origin on a heat transfer surface results in bio-fouling. Such material may include microorganisms (e.g. bacteria, algae, and molds) and their products result in microbial fouling. In other instances, organisms such as seaweed, water weeds, and barnacles form deposits known as microbial fouling. Both types of bio-fouling may occur simultaneously. Marine or power plant condensers using seawater are prone to bio-fouling.

#### Chemical Reaction Fouling

Fouling deposits are formed as a result of chemical reaction(s) within the process stream. Unlike corrosion fouling, the heat transfer surface does not participate in the reaction although it may act as a catalyst. Polymerization, cracking and coking of hydrocarbons are prime examples.

#### Fundamental Processes of Fouling

The fouling mechanisms are initiation, transport, attachment, removal, and aging, and are described in the following section.

#### Initiation

During initiation, the surface is conditioned for the fouling that will take place later. Surface temperature, material, finish, roughness and coatings strongly influence the initial delay induction or incubation period. For example, in crystallization fouling the induction period tends to decrease as the degree of super-saturation increases with respect to the heat transfer surface temperature. For chemical reaction fouling, the delay period decreases with increasing temperature because of the acceleration of induction reactions. Surface roughness tends to decrease the delay period. Roughness projections provide additional sites for crystal nucleation thereby promoting crystallization, while grooves provide regions for particulate deposition.

#### Transport

During this phase, fouling substances from the bulk fluid are transported to the heat transfer surface. Transport is accomplished by a number of phenomena including diffusion, sedimentation, and thermophoresis. The difference between the fouling species, oxygen or reactant concentration in the bulk fluid  $C_b$  and that in the fluid adjacent to the heat transfer surface  $C_s$  results in transportation by diffusion. Because of gravity, particulate matter in a fluid is transported to the inclined or horizontal surface. This phenomenon, known as sedimentation, is important in applications where particles are heavy and fluid velocities are low. Thermophoresis is the movement of small particles in a fluid stream when a temperature gradient is present. Thermophoresis is important for particles below 5  $\mu$ m in diameter and becomes dominant at about 0.1  $\mu$ m.

#### Attachment

Part of the fouling material transported attaches to the surface. Considerable uncertainty about this process exists. Probabilistic techniques are often used to determine the degree of adherence. Forces acting on the particle as they approach the surface are important in determining attachment. Additionally, properties of the material such as density, size and surface conditions are important.

#### Removal

Some material is removed from the surface immediately after deposition and some is removed later. In general, shear forces at the interface between the fluid and the deposited fouling layer are considered responsible for removal. Shear forces, in turn, depend on the velocity gradients at the surface, the viscosity of the fluid, and surface roughness. Dissolution, erosion, and spalling have been proposed as plausible mechanisms for removal.

#### Aging

Once the deposits are laid on the surface, aging begins. The mechanical properties of the deposits can change during this phase because of the changes in the crystal or chemical structure, for example. Slow poisoning of micro-organisms due to corrosion at the surface may weaken the bio-fouling layer. A chemical reaction taking place at the deposit surface may alter the chemical composition of the deposit, and thereby change its mechanical strength.

#### Prediction of Fouling

The overall result of the fouling processes is the net deposition of material on the heat transfer surface. Clearly the deposit thickness is time dependent. For heat exchanger design, a constant fouling resistance, interpreted as the value reached in a time period after which the heat exchanger will be cleaned, is used. Predicting how fouling progresses over time determines the cleaning cycle. Such information is also required for proper operation of the heat exchanger.

Most fouling behavior in heat exchangers can be represented by the time dependence curve shown in Figure 2. The shape of the curves relates to the phenomena occurring during the fouling process.

If the deposition rate is constant and the removal rate is negligible or if the difference between the deposition and removal rates is constant, the fouling-time curve will be a straight line as shown in Figure 2. This type of linear fouling is generally represented by tough, hard, adherent deposits. Fouling in such cases will continue to build up unless some type of cleaning is employed.



Figure 2: Time Dependence of the Fouling Resistance

A widely observed form of fouling is the asymptotic fouling that results when the deposition rate is constant and the removal rate is proportional to the fouling layer thickness, thus suggesting that the layer's shear strength decreases with time, or another mechanism deteriorates the stability of the layer. Such a situation will generally occur if the deposits are soft since they flake easily. The fouling factor in such cases reaches an asymptotic value.

Decreasing deposition fouling lies between the linear and the asymptotic fouling curves. Such behavior may result if the deposition rate is inversely proportional to the fouling thickness. A periodic change in operating conditions results in the sawtooth pattern fouling. This situation is typical of commercial cooling tower water

The qualitative effects of increasing certain parameters on the deposition and removal rates and the asymptotic fouling factor are summarized in Table 2. Velocity is the only parameter whose increase causes a reduction in the asymptotic fouling factor even though there may be some exceptions.

| Parameter Increased | Deposition Rate | Removal Rate | Asymptotic Fouling |
|---------------------|-----------------|--------------|--------------------|
| Stickiness          | Increases       | Decreases    | Increases          |
| Surface Temperature | Increases       | Questionable | Increases          |
| Toughness           | Questionable    | Decreases    | Increases          |
| Roughness           | Increases       | Increases    | Questionable       |
| In-situ Corrosion   | Increases       | Questionable | Increases          |
| Ex-situ Corrosion   | Increases       | Questionable | Increases          |
| Velocity            | Decreases       | Increases    | Decreases          |

| Table 2: Effects o | f parameters | on Fouling |
|--------------------|--------------|------------|
|--------------------|--------------|------------|

#### Design of Heat Exchangers Subject to Fouling

Although fouling is time dependent, only a fixed value can be prescribed during the design stage. Therefore, the operating characteristics and cleaning schedules of the heat exchanger depend on the design fouling factor. Many heat exchangers operate for long periods without being cleaned while others might require frequent cleaning. Table 3 identifies the type and the extent of fouling that may occur in various industry groups. This information is useful in determining the impact of fouling when a particular heat exchanger is designed.

| Industry Group             | Type of Fouling that Occurs in Heat<br>Exchange Equipment | Usual Extent |
|----------------------------|---|--------------|
| Food and Kindred Products  | Chemical reaction   | Major        |
|                            | Crystallization (Milk processing)                         | Major        |
|                            | Biofouling  | Medium       |
|                            | Particulate (Gas side) (Spray drying)                     | Minor/major  |
|                            | Corrosion   | Minor        |
| Textile Mill Products      | Particulate (Cooling water)                               |              |
|                            | Biofouling (Cooling water)                                |              |
| Lumber and Wood Products   | Crystallization (Liquid, cooling water)                   | Major        |
| Including Paper and Allied | Particulate (Process side, cooling water)                 | Minor        |
| Products                   | Biofouling (Cooling water)                                | Minor        |
|                            | Chemical reaction (process side)                          | Minor        |
|                            | Corrosion   | Medium       |
| Chemical and Allied        | Crystallization (Process side, cooling)                   | Medium       |

#### Table 3: Fouling of Heat Transfer Surfaces by Industry Groups

#### Providing a Fouling Allowance

If fouling is anticipated, provisions should be made during the design stage. The current approaches for providing an allowance for fouling include specifying the fouling resistances, the cleanliness factor, or the percentage over surface.

A common practice is to prescribe a fouling resistance or fouling factor on each side of the surface where fouling is anticipated. The result is a lower overall heat transfer coefficient. Consequently, excess surface area is provided to achieve the specified heat transfer. The heat exchanger will perform satisfactorily until the specified value of the fouling resistance is reached, after which it must be cleaned. The cleaning interval is expected to coincide with the plant's regular maintenance schedule so that additional shutdowns can be avoided. Tables found in the standards of the Tubular Exchanger Manufacturers Association (TEMA) are probably the most referenced source of fouling factors used in the design of heat exchangers. Proprietary research data, plant data, and personnel or company experience are other sources of fouling resistances.

Another approach that allows for fouling is specifying the cleanliness factor (CF), a term used in the steam power industry. CF relates to the overall heat transfer coefficients under fouled and clean conditions as:

$$CF = \frac{U_f}{U_c} \tag{6}$$

It is apparent from equation (6) that the CF provides a fouling allowance in proportion to the overall heat transfer coefficient under clean conditions. Using equations (2) and (6), the CF and the total fouling resistance can be related as:

$$R_{ft} = \frac{1 - CF}{U_c CF} \tag{7}$$

or,

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$$CF = \frac{1}{1 + R_{ft} U_c} \tag{8}$$

A given CF corresponds to a higher total fouling resistance  $R_{tt}$  if the overall heat transfer coefficient Uc is low. Such a trend is desirable for designing steam condensers where  $U_c$  is proportional to the velocity. Although the CF results in favorable trends, the engineer is left with the problem of selecting the appropriate CF for a given application. Typical condenser designs are based on a CF of 0.80 to 0.85. However, use of other CF for other applications would require careful evaluation.

In the Percentage over Surface approach, the engineer simply adds a certain percentage of clean surface area to account for fouling. The added surface implicitly fixes the total fouling resistance depending on the clean surface overall heat transfer coefficient. In a shell-and-tube heat exchanger, the additional surface can be provided either by increasing the length of tubes or by increasing the number of tubes (hence the shell diameter). The resulting change will also affect the design conditions such as flow velocity, number of cross passes, or baffle spacing. Therefore, the new design, with increased surface area, should be re-rated to achieve optimum conditions.

#### Design Features to Minimize Fouling

Fouling may not be avoided in many situations. However, its extent can be minimized by good design practice. In shell-and-tube heat exchangers, proper allocation of fluid streams to the tube-side and the shell-side is very important. In general, a fouling prone fluid stream should be placed on the tube side since cleaning the tubes is easier. Moreover it is less expensive to provide fouling resistant material on the tube side.

The engineer often has several combinations of operating parameters that will meet the design thermohydraulic requirements. In general, higher fluid velocity and lower tube wall temperature impede fouling buildup. A tube-side velocity of 1.8 m/s (6 ft/s) is a widely accepted figure. Operation above the dew point for acid vapor and above freezing for fluids containing waxes prevents corrosion and freeze fouling from occurring.

In shell-and-tube heat exchangers, the velocity distribution on the shell-side is non-uniform because baffles are present. Fouling deposits tend to accumulate in the baffle-to-shell corners where the velocity is low and the flow recirculatory. Baffle cuts of 20% to 25% of the shell diameter are appropriate to minimize fouling.

#### Design Features to Facilitate Fouling Control

A good design practice alone may not completely eliminate fouling. It should be expected that the heat exchanger will require cleaning at certain time intervals. The cleaning cycle can be extended if on-line cleaning is employed to control fouling. Assurance for continuous cleaning can also result in requiring a smaller fouling allowance. On-line cleaning systems are available and most easily installed when the plant is initially constructed.

Horizontal heat exchangers are easier to clean than the vertical ones. The G, H, and K types (TEMA Standards) are normally oriented horizontally while the other types can be oriented horizontally or vertically. A heat exchanger with removable heads and a straight tube would be easy to clean. Space and provision to remove tube bundles need to be available. Valves isolating the exchanger and connecting cleaning service hoses should be incorporated, thus facilitating on-site chemical cleaning.

Source: Sadik Kakac, Boilers, Evaporators and Condensers

# **NEWS AND EVENTS**

### On a Sad Note ...

James Farr, 85, died on April 6, 2014 after an extended illness. Jim was a fellow of the American Society of Mechanical Engineers and co-author of the books "Structural Analysis and Design of Process Equipment" and "Guidebook to the Design of ASME Section VIII Pressure Vessels".

# Intergraph<sup>®</sup> Acquires GT STRUDL<sup>®</sup> from the Georgia Tech Research Corporation

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