The Case of the
OVERFILLED REFINERY TOWER

By Mitch Ricketts

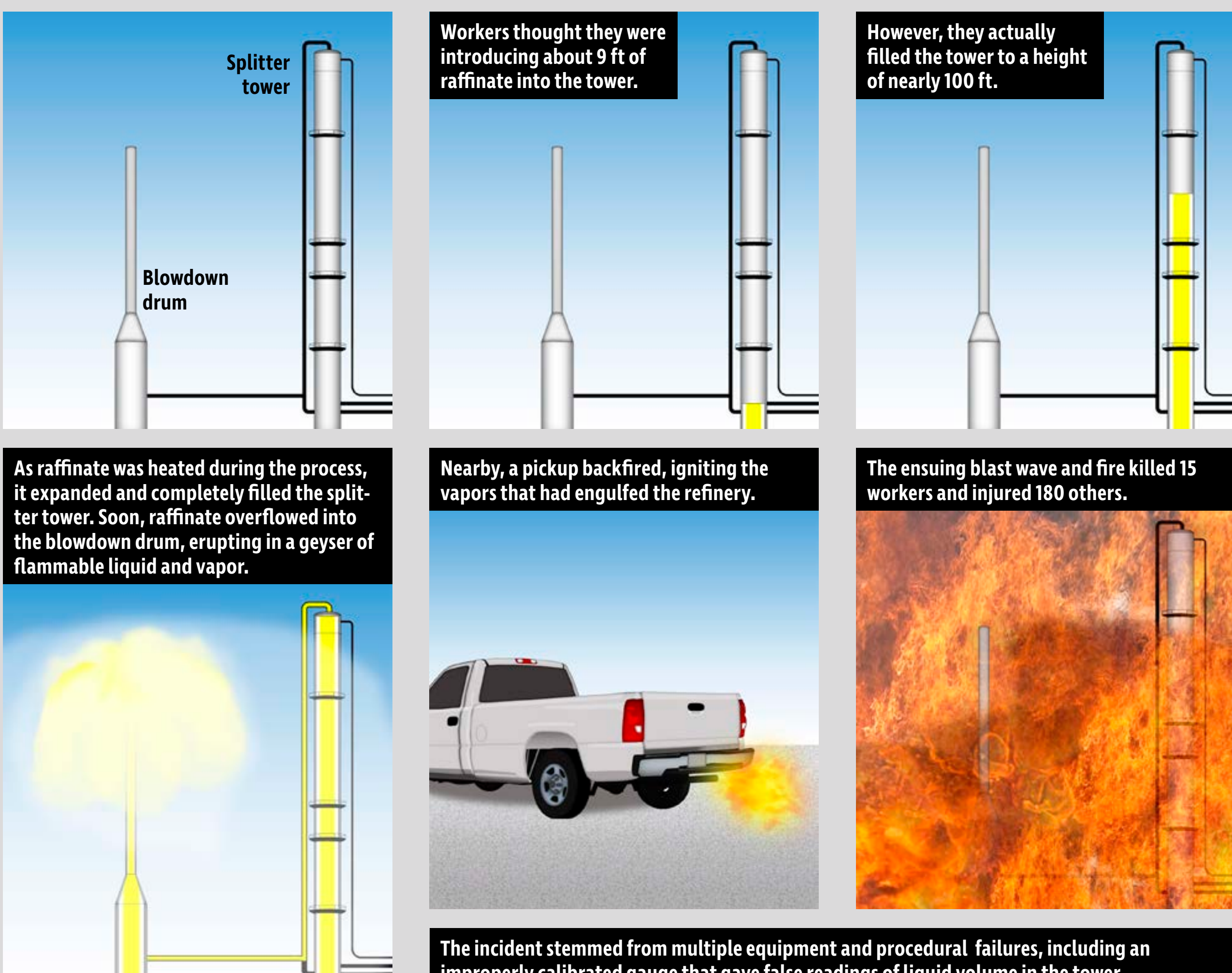
Math Toolbox is designed to help readers apply STEM principles to everyday safety issues. Many readers may feel apprehensive about math and science. This series employs various communication strategies to make the learning process easier and more accessible.

Events that led to the BP Texas City refinery explosion in 2005 are depicted in Figure 1. The incident occurred when workers overfilled a distillation tower, leading to an eruption of flammable liquids and vapors. Investigators reported that the incident was caused by numerous flaws in procedures and equipment, including a faulty liquid fill-level indicator.

Safety professionals can help prevent overfilling of vessels by learning to estimate liquid levels based on hydrostatic pressure readings. We can also use externally visible pressure gauges to eliminate the hazardous practice of opening hatches for manual tank gauging in the field. Lessons from the

FIGURE 1
REFINERY EXPLOSION, TEXAS CITY, TX, 2005

Workers were distilling and separating gasoline components from a mixture of flammable liquid hydrocarbons called raffinate. They introduced raffinate into a 170-ft structure known as a splitter tower. The tower was connected to a venting device called a blowdown drum.



Note. Adapted from "Investigation Report: Refinery Explosion and Fire (Report No. 2005-04-I-TX)," by CSB, 2007.

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BP Texas City explosion can serve as a guide as we learn how hydrostatic pressure relates to the height (or depth) of liquids in containers.

How Can an OSH Professional Use Pressure Gauges to Monitor Liquids & Prevent Catastrophic Overfilling of Vessels?

To avoid mishaps, safety professionals must understand how to estimate the levels of liquids in bulk containers. We often judge fill levels in towers and tanks with pressure head calculations based on hydrostatic pressure. Let's begin with some preliminary definitions:

Hydrostatic pressure reflects the force exerted by the weight of a column of fluid. Although fluids include many flowable substances (including gases), this discussion is confined to liquids. To understand hydrostatic pressure, imagine that we place a pressure gauge at the bottom of a chemical storage tank. The deeper the liquid in the tank, the greater the pressure will be at the bottom. Furthermore, heavier liquids will exert greater pressures. Hydrostatic pressure is usually expressed as gauge pressure, for example as pounds per square inch (psi) or pounds per square foot (psf) in customary units. Metric units include newtons per square meter (N/m^2), also known as pascals (*Pa*).

Pressure head is the height (or depth, depending on your perspective) of the fluid column. Pressure head is expressed in units of distance, such as feet (ft) in the customary system or meters (m) in the metric system.

In the customary system, unit weight of a fluid is often expressed as pounds per cubic foot (lb/ft^3) or pounds per cubic gallon (lb/gal^3). Metric units include newtons per cubic meter (N/m^3). Do not confuse unit weight with mass, as explained in the pressure-head equation terms that follow.

We can determine the height (or depth) of liquid in a tank by first measuring hydrostatic pressure with a gauge and then using the equation for pressure head:

$$h_p = \frac{p}{w}$$

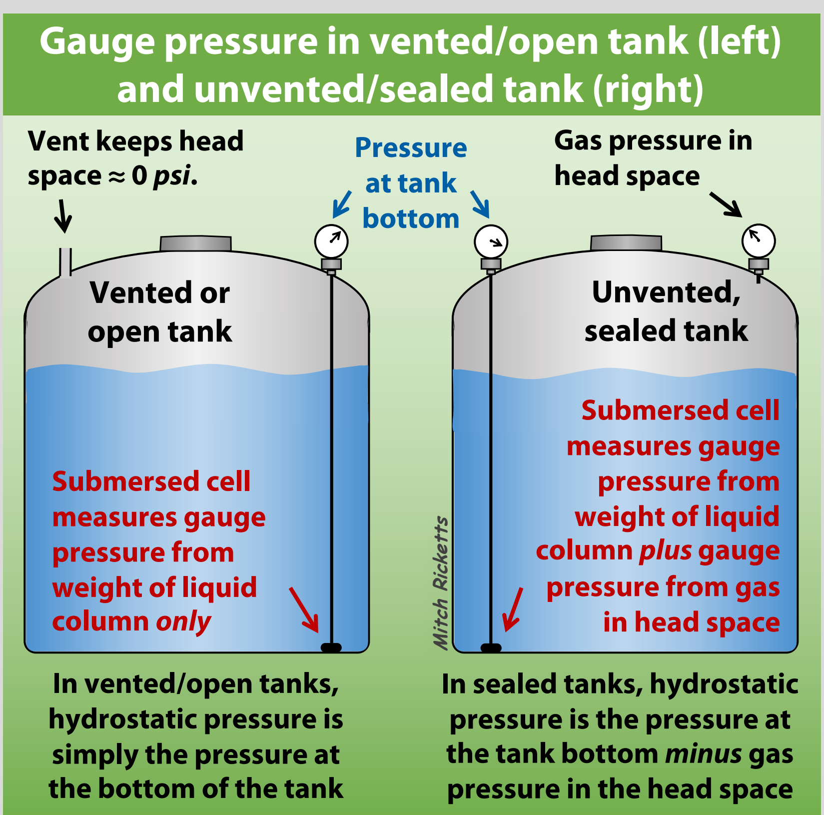
where:

h_p = pressure head (i.e., the height of fluid overlying the pressure gauge); h_p is commonly stated in ft for customary units and m for metric units

p = hydrostatic pressure exerted by the liquid in the tank; p is measured as gauge pressure, typically in psi or psf for customary units and N/m^2 (i.e., *Pa*) for metric units

w = unit weight of the liquid in the tank; w is normally stated in lb/ft^3 for customary units or N/m^3 for metric units. Important: Pressure head calculations are based on weight, rather than mass. Since kilogram is a unit of mass, problems stated in terms of kg/m^3 must be converted to N/m^3. To make the conversion, we multiply kilograms by 9.8067, as follows: $kg/m^3 \cdot 9.8067 = N/m^3$. Example: $5\ kg/m^3 \cdot 9.8067 = 49.0335\ N/m^3$; thus, $5\ kg/m^3 = 49.0335\ N/m^3$.

FIGURE 2
PRESSURE MEASUREMENTS FOR CALCULATING HYDROSTATIC PRESSURE



Note. Gauge pressure does not include pressure from earth's overlying atmosphere. For a discussion of gauge versus absolute pressure, see "The Case of the Fatal Tank Entry" (Math Toolbox, *PSJ* February 2020, pp. 47-50).

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How Can I Calculate the Pressure Head Based on Gauge Pressure?

As in the BP Texas City refinery explosion that introduced our topic, imagine a tower containing liquid raffinate with a unit weight of 40.13 pounds per cubic foot (40.13 lb/ft^3). Imagine also a pressure gauge, submersed at the bottom of the tower (under the weight of the overlying liquid, as shown for the tanks in Figure 2). Suppose the submersed pressure gauge displays a reading of 2.51 pounds per square inch (2.51 psi). Finally, imagine a pressure gauge in the headspace of the tower (headspace is the area above the liquid, where air and vapor are present; as in Figure 2). Let's say the headspace pressure gauge is reading 0 psi. Based on this information, what is the height of raffinate in the tower, in feet? In other words, what is the pressure head (h_p)?

Step 1. First, determine hydrostatic pressure. For sealed tanks, hydrostatic pressure equals submersed gauge pressure at base of the liquid column minus gas gauge pressure in the headspace, as follows: p = (submersed pressure at base of liquid column) - (gas pressure in headspace).

In our example, gas pressure in the headspace is 0 psi, so hydrostatic pressure is simply the internal pressure at the base of the tower:

$$p = 2.51 - 0 = 2.51\, psi$$

Step 2. Next, convert all measurements to compatible units. Since the unit weight of raffinate was expressed in pounds per cubic foot (40.13 lb/ft^3) and hydrostatic pressure was expressed in pounds per square inch, (2.51 psi), convert 2.51 psi to pounds per square foot (psf).

Because there are 144 square inches in 1 square foot, multiply psi by 144 to convert to psf:

$$psi \cdot 144 = psf$$

In our example:

$$p = 2.51\, psi \cdot 144 = 361.44\, psf$$

This calculation indicates the pressure of 2.51 psi is equal to 361.44 psf. Now, we have all the data needed to calculate the pressure head of raffinate in the tower:

•Hydrostatic pressure at the base of the tower is 361.44 psf. This is the value of p in the pressure head equation.

•Unit weight of raffinate was reported as 40.13 lb/ft^3. This is the value of w in the pressure head equation.

Step 3. Use the equation for pressure head:

$$h_p = \frac{p}{w}$$

where:

h_p = pressure head (i.e., the height of the overlying fluid, in this case, liquid raffinate)

p = hydrostatic pressure exerted by the liquid raffinate in the tower, measured as gauge pressure

w = unit weight of the liquid raffinate

Step 4. Insert the known values for hydrostatic pressure at the base of the tower (p = 361.44 psf) and unit weight of raffinate (w = 40.13 lb/ft^3). Then solve for pressure head (h_p):

$$h_p = \frac{361.44}{40.13} = 9.01\, ft$$

Step 5. Our calculation indicates the height of raffinate in the tower would be 9.01 ft when hydrostatic pressure equals 361.44 psf (or 2.51 psi) and unit weight of the liquid is 40.13 lb/ft^3. This is the height of raffinate operators thought they were introducing into the tower prior to the refinery explosion.

Alternate example: Let's determine how high the liquid raffinate would be at different pressure readings. For example, at the moment raffinate began overflowing the tower, investigators reported a submersed gauge pressure of about 64 psi at the tower's base and a gas gauge pressure of about 22 psi in the headspace. Assuming the unit weight of raffinate is still 40.13 lb/ft^3, let's calculate the new height of raffinate in the tower (i.e., the new pressure head, h_p).

First, determine hydrostatic pressure by subtracting gas gauge pressure in the headspace (22 psi) from submersed gauge pressure at the base of the tower (64 psi):

$$p = 64 - 22 = 42\, psi$$

Next, convert all measurements to compatible units. The unit weight of raffinate is expressed in pounds per cubic foot (40.13 lb/ft^3), so we convert the hydrostatic pressure measurement (42 psi) to pounds per square foot (psf).

$$p = 42\, psi \cdot 144 = 6{,}048\, psf$$

Inserting the known values for hydrostatic pressure (p = 6,048 psf) and unit weight of raffinate (w = 40.13 lb/ft^3), we solve for pressure head:

$$h_p = \frac{p}{w} = \frac{6{,}048}{40.13} = 150.71\, ft$$

Our calculation indicates the height of raffinate was 150.71 ft at the time it overflowed the tower. For comparison, investigators determined the actual height of the raffinate at this time was between 143 and 161 ft, depending on the temperature and resulting unit weight of the liquid. Due to turbulence from boiling, the splashing raffinate is believed to have overflowed the 170-ft tower when the average height of the churning liquid was less than the height of the tower.

You Do the Math

Apply your knowledge to the following questions. Answers are on p. 63.

1) Imagine again that the tower from the previous example contains liquid raffinate at a unit weight of 40.13 lb/ft^3. This time imagine the gauge pressure of gases in the headspace reaches 33 psi and the submersed gauge pressure at the base of the tower is 74 psi. Answer the following questions:

a) What is the hydrostatic pressure in psi? This will be the pressure at the base of the tower minus gas pressure in the headspace.

b) What is the hydrostatic pressure (p) in psf? This will be hydrostatic pressure in psi · 144.

c) What is the height of raffinate in the tower (h_p) in feet?

How Can I Use Pressure Gauges in Place of Hazardous Manual Tank Gauging?

To illustrate another application of pressure head calculations, let's reconsider "The Case of the Fatal Tank Entry" (Math Toolbox, *PSJ*, February 2020, pp. 47-50). That case involved a worker who died from overexposure to chemical vapors when he opened a storage tank and used a measuring stick to check the depth of toluol (toluene) inside. His death might have been avoided had the tank been equipped with pressure gauges that could be read from outside with the hatch closed.

Manual tank gauging refers to the practice of opening a hatch and inserting a measuring device to determine the depth of liquid inside (Figure 3). Agencies such as NIOSH and California Department of Public Health (2017) have reported that workers may be overcome by toxic gases and vapors when tank hatches are opened.

To illustrate how pressure gauges are used in place of manual tank gauging, imagine a tank of toluol (toluene, CAS 108-88-3). Suppose it is a warm day and the temperature of liquid inside the tank has reached 95 °F. Further imagine the submersed gauge pressure at the bottom of the tank is 2.2 psi. Finally, imagine the tank is vented to the atmosphere.

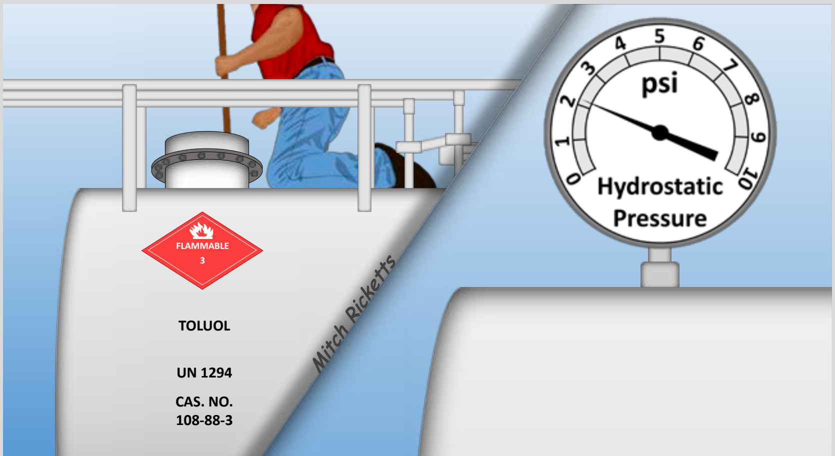
In vented tanks, gases and vapors can pass back and forth between the interior and the air outside. This keeps the gauge pressure of gases in the headspace close to 0 psi. Thus, for vented tanks, hydrostatic pressure is simply the submersed gauge pressure, measured at the bottom of the tank (see Figure 2).

To complete the necessary data for this example, we must find the unit weight of toluol at the temperatures existing within the tank. Unit weights can be found in safety data sheets and in more comprehensive sources such as the *National Institute for Standards and Technology* (NIST, 2018) *Chemistry WebBook*. At the temperature stated in the example (95 °F), the unit weight of toluol is 53.24 lb/ft^3.

To summarize the data, the tank contains liquid toluol with a unit weight of 53.24 lb/ft^3 and a submersed gauge pressure at the bottom of the tank of 2.2 psi.

FIGURE 3
MANUAL TANK GAUGING

Manual tank gauging exposes workers to potentially hazardous gases and vapors. In contrast, hydrostatic pressure gauges can be read safely while tank hatches are closed.



Replace hazardous manual tank measurements (left) with hydrostatic pressure gauges (right)

Manual tank gauging refers to the practice of opening a hatch and inserting a measuring device to determine the depth of liquid inside. Agencies such as NIOSH and California Department of Public Health (2017) have reported that workers may be overcome by toxic gases and vapors when tank hatches are opened.

Since the tank is vented, assume the gas pressure in the headspace is about 0 psi. What is the depth of toluol in the tank (h_p) in feet?

Step 1. Determine hydrostatic pressure by subtracting gas gauge pressure in the headspace (0 psi) from submersed gauge pressure at the base of the tank (2.2 psi):

$$p = 2.2 - 0 = 2.2\,psi$$

Step 2. Convert all measurements to compatible units. Since the unit weight of toluol was expressed in pounds per cubic foot (53.24 lb/ft^3), we convert the hydrostatic pressure measurement (2.2 psi) to pounds per square foot (psf):

$$p = 2.2\,psi \cdot 144 = 316.8\,psf$$

We now have all the data needed to calculate the pressure head of toluol in the tank:

•The hydrostatic pressure (p) at the bottom of the tank is 316.8 psf.

•Unit weight (w) of toluol is 53.24 lb/ft^3.

Step 3. Use the equation for pressure head:

$$h_p = \frac{p}{w}$$

Step 4. Insert the known values for hydrostatic pressure at the base of the tank (p = 316.8 psf) and unit weight of toluol (w = 53.24 lb/ft^3). Then solve for pressure head (h_p):

$$h_p = \frac{316.8}{53.24} = 5.95\,ft$$

Step 5. The calculation indicates that the depth of toluol in the tank is 5.95 ft if hydrostatic pressure equals 316.8 psf (or 2.2 psi) at the unit weight of 53.24 lb/ft^3.

Alternate example: Imagine a 20-ft-high tank of methanol (CAS 67-56-1). The temperature of liquid inside the tank is 70 °F. *NIST Chemistry WebBook* reports the unit weight of methanol is 49.31 lb/ft^3 at 70 °F. Let's also imagine the tank is sealed, and the gauge pressure of gases in the headspace is 2 psi. What is the pressure head (height) of methanol in feet if the submersed pressure at the bottom of the tank is 7 psi?

First, determine hydrostatic pressure by subtracting gas gauge pressure in the headspace (2 psi) from submersed gauge pressure at the bottom of the tank (7 psi):

$$p = 7 - 2 = 5\,psi$$

Next, convert all measurements to compatible units. The unit weight of methanol was expressed in pounds per cubic foot (49.31 lb/ft^3), so we convert the hydrostatic pressure measurement (5 psi) to pounds per square foot (psf):

$$p = 5\,psi \cdot 144 = 720\,psf$$

Inserting the known values for hydrostatic pressure (p = 720 psf) and unit weight of methanol (w = 49.31 lb/ft^3), we solve for pressure head:

$$h_p = \frac{p}{w} = \frac{720}{49.31} = 14.60\,ft$$

Our calculation indicates the height of methanol in the tank is 14.60 ft if hydrostatic pressure equals 720 psf (or 5 psi) at the unit weight of 49.31 lb/ft^3.

You Do the Math

Apply your knowledge to the following question. Answers are on p. 63.

2) Imagine a 50-ft-high tank contains water at a temperature of 56 °F. The *NIST Chemistry WebBook* reports the unit weight of water is 62.38 lb/ft^3 at 56 °F. Also, imagine that the tank is vented to the atmosphere, so the gauge pressure of gases in the headspace is 0 psi. Finally, imagine the submersed pressure at the bottom of the tank is 8.3 psi. Answer the following:

a) What is the hydrostatic pressure in psi (submersed pressure at the bottom of the tank minus gas pressure in the headspace)?

b) What is the hydrostatic pressure (p) in psf? This will be hydrostatic pressure in psi · 144.

c) What is the height of water in the tank (pressure head, h_p) in feet?

What Are Some Limitations of Pressure Head Calculations?

Pressure head calculations can provide accurate estimates of liquid heights and depths, but there are limitations. First, the unit weights of liquids may vary according to temperature. In fact, raffinate is one liquid for which unit weight is highly temperature dependent. This means pressure head calculations must be based on unit weights at temperatures actually measured in the field. Fortunately, the *NIST Chemistry WebBook* provides unit weights for liquids at broad ranges of temperatures. Once we know the unit weights likely to exist at the temperatures in our tanks, we can develop charts for field personnel, indicating liquid heights that correspond to gauge pressures at various temperatures. Alternatively, we can purchase software to calculate the numbers automatically.

As another limitation, pressure head calculations assume the liquid is at rest, has an even unit weight throughout the liquid column and is not subject to boiling or other disturbances. To account for errors that may result from extreme conditions, it is wise to confirm pressure head calculations with other monitoring devices such as sight-glass indicators and electronic high-level alarms.

Although not a limitation, it is worth noting that some data sources may provide specific gravity (*SG*), rather than unit weight for liquids. In the context of pressure head, specific gravity is the ratio of a liquid's unit weight to that of water. The unit weight of water is often rounded to 62.4 lb/ft^3. The unit weight of any liquid is its specific gravity (*SG*) multiplied by the unit weight of water. In other words, unit weight (*w*) in lb/ft^3 is:

$$w = SG \cdot 62.4\ lb/ft^3$$

For example, if the *SG* of chemical X is 0.8, its unit weight is 0.8 · 62.4 = 49.92 lb/ft^3. Likewise, if the *SG* of chemical Y is 1.2, its unit weight is 1.2 · 62.4 = 74.88 lb/ft^3.

How Much Have I Learned?

Try these problems on your own. Answers are on p. 63.

3) In one investigative scenario for the BP Texas City refinery explosion, investigators assumed that the average temperature of raffinate may have reached 300 °F. Under these conditions, the unit weight of raffinate may have been as low as 34.32 lb/ft^3 (this is in contrast to our earlier calculations based on a reported unit weight of 40.13 lb/ft^3 at operating temperatures of about 140 °F.) Imagine the submersed pressure at the base of the raffinate tower is 63 psi, gas pressure in the headspace is 21 psi, and the unit weight of raffinate is now 34.32 lb/ft^3. Answer the following:

a) What is the hydrostatic pressure in psi? This is the submersed pressure at the base of the tower minus gas pressure in the headspace.

b) What is the hydrostatic pressure (*p*) in psf? This is hydrostatic pressure in psi · 144.

c) What is the height of raffinate in the tower (pressure head, h_p) in feet?

4) Imagine a 30 ft-high tank containing octane (CAS 111-65-9) at a temperature of 66 °F. The *NIST Chemistry WebBook* reports the unit weight of octane is 43.89 lb/ft^3 at 66 °F. Also, imagine the tank is sealed and the gauge pressure of gases in the headspace is 8 psi. Finally, imagine the submersed pressure measured at the bottom of the tank is 15 psi. Answer the following:

a) What is the hydrostatic pressure in psi? This is the submersed pressure at the base of the tank minus gas pressure in the headspace.

b) What is the hydrostatic pressure (*p*) in psf? This is hydrostatic pressure in psi · 144.

c) What is the height of octane in the tank (pressure head, h_p) in feet?

Lessons from the BP Texas City explosion can serve as a guide as we learn how hydrostatic pressure relates to the height (or depth) of liquids in containers.

The Language of Hydrostatic Pressure

Readers will encounter the following concepts in codes, certification exams and conversations with other professionals. Match the numbered concepts with their paraphrased definitions (lettered). If you have trouble, you can look up the concepts in the text of this article and in "The Case of the Fatal Tank Entry" (Math Toolbox, *PSJ*, February 2020). Answers are on p. 63.

Concepts

5) atmospheric pressure (see Math Toolbox, *PSJ*, February 2020)
6) fluid
7) gauge pressure (see Math Toolbox, *PSJ*, February 2020)
8) headspace (see Math Toolbox, *PSJ*, February 2020)
9) hydrostatic pressure (*p*)
10) manual tank gauging
11) pressure head (h_p)
12) specific gravity (*SG*)
13) unit weight (w)

Definitions (in random order)

a) Pressure exerted by the weight of a column of fluid.

b) The pressure within a closed container, relative to atmospheric pressure. It is positive if it is greater than atmospheric pressure. It is zero if it equals atmospheric pressure. It is negative if it is below the pressure of the atmosphere.

c) Height or depth of fluid that creates the hydrostatic pressure measured at the bottom of a container.

d) Weight of a fluid per unit of volume, often as lb/ft^3 or N/m^3.

e) Area where vapor may form above a liquid in a tank or other closed container.

f) Also known as barometric pressure, this is the pressure exerted by the weight of the overlying air. At sea level on earth, this pressure is equal to about 14.7 psi.

g) Ratio of a liquid's unit weight to that of water.

h) A flowable substance, such as a liquid, gas or plasma.

i) The practice of opening a hatch and inserting a device to measure the depth of liquid in a tank. This practice may expose workers to toxic gases and vapors.

For Further Study

Learn more from the following source: *ASSP's ASP Examination Prep: Program Review and Exam Preparation*, edited by Joel M. Haight, 2016. PSJ

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PREVENT DROPPED OBJECTS WITH THREE Ts

By Joseph Solheid

Whether a new employee or a 20-year veteran, drops can happen to anyone. Gravity does not discriminate. Just because it has not happened yet is no reason to think it will not happen. In fact, the most serious nuclear threat in U.S. history was the result of a dropped object.

In 1980, an airman performing maintenance on a Titan II missile dropped a single 8-lb wrench socket, which fell more than 70 ft and punched a hole in a fuel tank. This led to an explosion that forced a 9-megaton warhead completely out of the ground, killed a serviceman and injured 20 other people.

The bad news: Dropped objects are the second most common cause of injuries to construction workers (OSHA, 2019). In 2018, 278 fatalities from dropped objects were reported in the U.S., a 15% increase from the previous year (BLS, 2019).

The good news: As of 2018, a national standard exists to distinguish proper tethering solutions, providing formal guidance to help OSH professionals develop effective dropped object safety programs. ANSI/ISEA 121-2018, American National Standard for Dropped Object Prevention Solutions, addresses equipment used to tether or contain hand tools, components, structure and other objects from falling from at-height applications.

To protect employees working at heights, OSH professionals must consider the risk factors that contribute to dropping tools:
- elements (e.g., wind, snow, sea motion);
- body effects (e.g., sweaty or numb hands, fatigue);
- instinctively trying to catch a falling object;
- tool pulling worker down with it if tethered improperly;
- poor housekeeping.

It is all about prevention. Just as personal fall prevention provides the ABCs (anchor, body support, connectors), dropped object prevention involves the three Ts: trapping, tethering and topping.

Trapping

Trapping describes the installation of retrofit attachment points on tools and primary anchoring locations. The majority of tools do not come with them built in. Anchor attachments should be installed onto locations that are secure and are never intended for heavier tools if applied to a person.

Tethering

Often using lanyards, tethering is retention of tools and equipment being used to attach to the anchor points that hold them.

Topping

Topping refers to the containers that workers use to bring tools and equipment to and from heights. Regardless of type or mode of transportation, these containers should have a secure closure or top that can cover contents and prevent them from spilling if tipped. Tool pouches and bags are typically carried on individuals to keep the contents at hand while working. These often remain stationary. Hoist buckets and bags are transferred by different means, typically by lifting them in a portable fashion to and from heights.

Controls

ANSI/ISEA 121-2018 covers four active controls or tethering and container solutions that workers actively employ to mitigate dropped object hazards. The scope includes:
- anchor attachments: retrofit attachment points installed onto fixed anchor locations;
- tool attachments: retrofit attachment points installed onto tools and equipment;
- tool tethering: lanyards that connect tools to an anchor point;
- containers: bags, buckets and pouches that are used to transport tools and equipment around work zones.

The standard was crafted based on input from major product manufacturers, including competitors that recognized the need to work together to bring consistency and clarity to the market. Not included in this new measure are preventive solutions such as netting and toe boards.

Conclusion

As a first-of-its-kind standard, it will take time for the impact to ripple to the marketplace, but many of the requirements are already being met by leading manufacturers. Businesses with employees who work at heights need to keep the Three Ts in mind. Trapping, tethering and topping can prevent work stoppages and save lives. **PSJ**

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MR_TWISTER/ISTOCK/GETTY IMAGES PLUS

Math Toolbox, continued from pp. 52-56

Answers: The Case of the Overfilled Tower

You Do the Math

Your answers may vary slightly due to rounding.

1a) $p = 74 - 33 = 41\ psi$

1b) $p = 41 \cdot 144 = 5{,}904\ psf$

1c) $h_p = \dfrac{p}{w} = \dfrac{5{,}904}{40.13} = 147.12\ ft$

2a) $p = 8.3 - 0 = 8.3\ psi$

2b) $p = 8.3 \cdot 144 = 1{,}195.2\ psf$

2c) $h_p = \dfrac{p}{w} = \dfrac{1{,}195.2}{62.38} = 19.16\ ft$

How Much Have I Learned?

Your answers may vary slightly due to rounding.

3a) $p = 63 - 21 = 42\ psi$

3b) $p = 42 \cdot 144 = 6{,}048\ psf$

3c) $h_p = \dfrac{p}{w} = \dfrac{6{,}048}{34.32} = 176.22\ ft$

4a) $p = 15 - 8 = 7\ psi$

4b) $p = 7 \cdot 144 = 1{,}008\ psf$

4c) $h_p = \dfrac{p}{w} = \dfrac{1{,}008}{43.89} = 22.97\ ft$

The Language of Hydrostatic Pressure

5) f; 6) h; 7) b; 8) e; 9) a; 10) i; 11) c; 12) g; 13) d.