Solutions Manual for

Chemical Process Safety

Fundamentals with Applications

Third Edition

Daniel A. Crowl
Joseph F. Louvar

PRENTICE HALL

Upper Saddle River, NJ • Boston • Indianapolis • San Francisco
New York • Toronto • Montreal • London • Munich • Paris • Madrid
Capetown • Sydney • Tokyo • Singapore • Mexico City

Visit us on the Web: InformIT.com/ph

ISBN-10: 0-13-276251-X
ISBN-13: 978-0-13-276251-9

Chapter 1

1-1 FAR = 4 @ 10^8 exposed hours

Deaths per person per year

$$= \left(\frac{4 \text{ hrs}}{\text{shift}}\right)\left(\frac{200 \text{ shifts}}{\text{year}}\right)\left(\frac{4 \text{ deaths}}{10^8 \text{ hrs}}\right)$$

$$= \underline{3.2 \times 10^{-5}} \text{ deaths/person-year}$$

1-2 Three process units – FAR's: 0.5, 0.3, 1.0

a) Assuming exposure to all three units

Net FAR = $\sum$ FAR's = 0.5 + 0.3 + 1.0 = $\underline{1.8}$

b) 20% of time in area 1 with FAR 0.5
40% " " " " 2 " " 0.3
40% " " " " 3 " " 1.0

Net FAR = (0.2)(0.5) + (0.4)(0.3) + (0.4)(1.0)

= $\underline{.62}$

1-3 From Table 1-4, FAR travelling by car

= 57 deaths/10^8 exposed hours

or 1 death per $\frac{10^8}{57} = 1.75 \times 10^6$ hours

$$(1.75 \times 10^6 \text{ hours})\left(\frac{50 \text{ miles}}{\text{hour}}\right) = \underline{87.5} \text{ million miles}$$

1-4 Normal working hours are approximately 2000 hours per year. For 500 years, we have

$$(500 \text{ years})\left(\frac{2000 \text{ hrs}}{\text{year}}\right) = 1 \times 10^6 \text{ hours}$$

We can assume 1 death every 10^6 exposed hours. But FAR's are based on 10^8 exposed hours. This means

$$\frac{10^8}{10^6} = 100 \text{ deaths per } 10^8 \text{ hours} \quad \therefore \text{FAR} = 100$$

The workers should be alarmed! For an average chemical plant, FAR = 4 deaths/10^8 hrs

$$\text{Deaths per year} = (2000 \text{ hrs})\left(\frac{4 \text{ deaths}}{10^8 \text{ hrs}}\right) = 8 \times 10^{-5}$$

$$\text{Years per death} = \frac{1}{8 \times 10^{-5}} = 12{,}500$$

Chances should be 1 in 12,500 years of exposure.

1-5 Total working hours per year

$$= (1500 \text{ workers})\left(\frac{2000 \text{ hrs}}{\text{worker}}\right) = 3 \times 10^6 \text{ hrs}$$

$$\text{Deaths per year} = (3 \times 10^6 \text{ hrs})\left(\frac{5 \text{ deaths}}{10^8 \text{ hrs}}\right)$$

$$= .15 \text{ deaths}$$

A death can be expected every 6.6 years.

1-6 FAR of rock climbing = 4000
FAR of travelling by car = 57

$$\frac{4000}{57} = \underline{70.2} \text{ hrs travel by car}$$

1-7 a) Initiation - cutting into 10-inch propane line

Propagation - leakage of propane
- formation of vapor cloud
- ignition of vapor cloud
- destruction of fire pump equipment

Termination - blocking in of the propane

b) Initiation - improper closing of valve
- cleaning of strainer with escape of butane

Propagation - ignition of vapor cloud
- rupturing of pipeline
- falling of fractionation tower and breaking of pipeline

Termination - isolation of fuel source

1-8 Airline industry has fewest deaths per passenger mile, but, due to high rate of speed of the aircraft, many miles are accumulated. From Table 1-4, FAR for:

Car - 57

Bicycle - 96

Air - 240

Thus, on a per hour basis, travelling by plane is almost 5 times more dangerous than travelling by car.

To compute the FAR, we need the total hours exposed. This would require an average speed. Suppose the average speed is 200 MPH.

$$\text{Total hours exposed} = \frac{10 \times 10^6 \text{ miles}}{200 \text{ mi/hr}}$$

$$= 50{,}000 \text{ hrs}$$

$$FAR = \frac{4 \times 10^8}{50{,}000 \text{ hrs}} = \underline{8{,}000}$$ which is larger than the 240 reported in Table 1-4.

A fatality rate would require the total number of passengers in the 10^7 miles. Suppose each trip averaged 300 miles.

$$\text{Total passengers} = \frac{10^7 \text{ miles}}{300 \text{ mi/person}} = 33,333 \text{ passengers}$$

$$\text{Fatality rate} = \frac{4}{33,333} = 1.2 \times 10^{-4}, \text{ which is high}$$

1-9 A university had about 1200 full-time employees. In a particular year, this university had a total of 38 reportable lost time injuries with a resulting 274 lost workdays. Compute the OSHA incidence rate based on injuries and lost workdays.

Solution:

(a) $$\text{OSHA injury rate} = \frac{\text{No. of Injuries}}{\text{Total hours worked}} \times 200{,}000 \text{ hrs}$$

Total hours worked

$$= (1200 \text{ employees})\left(2000 \frac{\text{hours}}{\text{employee}}\right)$$

$$= 2.4 \times 10^6 \text{ Hours}$$

$$\text{OSHA injury rate} = \left(\frac{38 \text{ injuries}}{2.4 \times 10^6 \text{ Hours}}\right)(200{,}000 \text{ hours})$$

$$= 3.17$$

(b) OSHA LOST WORKDAYS

$$= \left(\frac{274 \text{ LOST workdays}}{2.4 \times 10^6}\right)(200{,}000 \text{ hours})$$

$$= 22.8$$

1-10 Based on workplace fatalities (Figure 1-4) and assuming you are responsible for a safety program of an organization, what would you emphasize?

Solution:

You could probably dedicate 45% of your time on transportation safety, 17% on violent acts, 17% on equipment safety, 13% on falls, 10% on exposures and 3% on fires and explosions. Fires and explosions, however, should be given more effort because a single fire or explosion could be a catastrophic event (many injuries and fatalities) and the concepts are relatively difficult to comprehend, learn, and apply.

1-11 Based on the causes of the largest losses, Figure 1-7, what would you emphasize in a safety program?

Solution:

Based on these statistics, it is clear that emphasis needs to be given to mechanical and process designs and to operator training. Additionally, it should be recognized and emphasized, that all accidents are ultimately the result of people making mistakes. Design and Training require a significant effort, because small errors in the beginning of a project may evolve into major problems.

1-12 After reviewing the answers of problems 1-10 and 1-11, can inherent safety help?

Solution:

Clearly, the concepts of minimization, substitution, moderation, and simplification can have major impacts on plant safety. Moderation and simplification are concepts that can be practiced throughout the life cycle of a plant. The concept of keeping it simple should be applied to instructions, design changes, training, communication, etc.

1-13 What conclusions can you derive from Figure 1-9?

Solution:

Clearly, the major losses are continuing to increase in number and dollar magnitude. Although PSM (initiated in 1992) may be affecting the results, the last five year period results are still higher than all the results prior to 1987. Therefore, we need to do more if we want to change the trend. In summary, PSM is not enough, our current industrial training is not enough, and our university training is not enough.

Some believe that we can turn these negative trends around by (a) adding safety to university courses, (b) add more training within industry, and (c) aquire high level support in universities and industries to teach the important concepts of chemical process safety.

1-14 What is the worst thing that could happen to you as a chemical engineer in industry?

Solution:

Most people would probably agree that the worst thing that could happen to you as a chemical engineer is to be responsible for the death of a fellow employee or friend. A typical response from some students might be that the worst thing that could happen to them is to make a mistake in a calculation! This is most likely due to the calculational nature of the ChE curriculum.

1-15 An explosion has occurred in your plant and an employee has been killed. An investigation showed that the accident was the fault of the dead employee who manually charged the wrong ingredient to a reactor vessel. What is the appropriate response from the following groups?

a. the other employees who work in the process area affected

b. the other employees elsewhere in the plant site

c. middle management

d. upper management

e. the president of the company

f. the union

Solution:

Our society is much too hung-up on finding fault. The problem this creates is that once the "guilty party" has been identified, many people believe the problem has been solved.

The most appropriate response from <u>all</u> groups is to ask the question "What can we do to prevent this accident from occurring again in the future?" and then work together to achieve this objective. Thus, the following activities might be initiated by the indicated groups:

Employees in process area affected:
- redesign work situation to reduce human error
- design interlocks to prevent problem
- look elsewhere for similar problems

Employees elsewhere at plant site:
    look at process to identify similar problems

Management:
    employee training program
    safety audits
    invoke hazard identification methods
    improve management systems

Union:
    review employee and management performance to insure that corrections are implemented and are actually working
    insuring that employees understand the nature of the problem are have the correct attitude to work towards its solution

1-16 You have just begun work at a chemical plant. After several weeks on the job you determine that a) the plant manager runs the plant with an iron fist. He is a few years away from retirement after working his way up from the very bottom. b) a number of unsafe practices are performed at the plant, including some that could lead to catastrophic results.

You bring up these problems to your immediate supervisor but he decides to do nothing in fear that the plant manager will be upset. After all, he says, "We've operated this plant for forty years without an accident." What would you do in this situation?

SOLUTION:

Some possible responses are:
- Quit job and look for employment elsewhere
- Go over immediate supervisor directly to plant manager
- Send anonymous letter to OSHA detailing problems
- Secretly work with other plant people to solve problems
- Amass technical information to convince supervisor that you are correct and problems must be corrected

The last response is probably the "best" way to handle the problem, at least in the short term. You might consider developing a few "quick fixes" for existing safety problems that can be done easily and with minimal cost to build up confidence with your supervisor.

1-17 a. You walk into a store and after a short while you decide to leave, preferring not to do any business there. What did you observe to make you leave? What conclusions might you reach about the attitudes of the people who manage and operate this store?

b. You walk into a chemical plant and after a short while you decide to leave, fearing that the plant might explode at any moment. What did you observe to make you leave? What conclusions might you reach about the attitudes of the people who manage and operate this chemical plant?

Comment on the similarities of parts a and b.

SOLUTION:

a. You might observe that the store is a mess or the employees are not providing the correct service. In any case, you decide that the people who manage or operate the store simply do not care. If they cared about their store then it would be operated efficiently and cleanly with salespeople with the correct attitude.

b. You might observe that the chemical plant is a mess, proper safety procedures are lacking, or the employees do not have the correct attitude with respect to safety. In any case, you decide that the people who manage or operate the chemical plant simply do not care. If they cared about the plant then it would be operated efficiently and safely with employees who have the correct attitude.

Both cases are amazingly similar. The essential ingredient, however, is that the people who manage and operate the plant must care. Furthermore, in order for the employees to care, the management must care. In order for management to care, the president must also care.

1-18

Without the high level alarm, the operator was required to pay attention to the tank level as the tank was filled. However, once the high level alarm was installed the operator decided that he or she could rely on the alarm to alert him or her when the tank was filled. The reliability of the high level alarm was less than the reliability of the operator manually filling the tank. Thus, the number of overfills increased.

1-19

If you pronounce "J1001" and "JA1001" they both sound the same. Thus, when the operator was told to prepare JA1001, he heard J1001 since they sound the same.

Equipment must be clearly identified, even with respect to pronunciation.

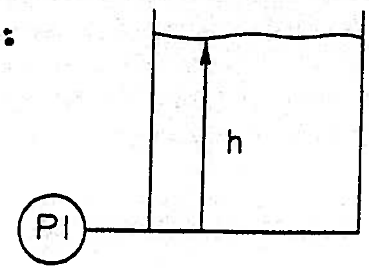
1-20

The bolts should be loosened, but not removed. Then the cover plate is pried up to loosen it. If liquid comes out the bolts can be re-tightened to stop the flow.

A simple change in this procedure has a clear impact on safety.

1-21 The liquid level in a tank 10 meters in height is determined by measuring the pressure at the bottom of the tank. The level gauge was calibrated to work with a liquid having a specific gravity of 0.9. If the usual liquid is replaced with a new liquid with a specific gravity of 0.8, will the tank be overfilled or underfilled? If the actual liquid level is 8 meters, what is the reading on the level gauge? Is it possible that the tank will overflow without the level gauge indicating the situation?

SOLUTION:



The force at the bottom of the tank is given by

$$F = m\left(\frac{g}{g_c}\right)h$$

where

F is the force,
m is the mass,
g is the acceleration due to gravity,
g_c is the gravitational constant,
h is the height of the mass.

Dividing by the area over which the force is exerted gives the pressure, *P*,

$$\frac{F}{A} = P = \left(\frac{m}{A}\right)\left(\frac{g}{g_c}\right)h$$

But $\rho = \left(\frac{m}{A}\right)$ so

$$P = \rho\left(\frac{g}{g_c}\right)h$$

For the same pressure reading, based on two different liquids,

$$\rho_2 h_{reading} = \rho_1 h_{actual}$$

where

$h_{reading}$ is the level indicated on the gauge, and
h_{actual} is the actual level.

For the numbers provided,

$$h_{reading} = \left(\frac{\rho_1}{\rho_2}\right)h_{actual} = \left(\frac{0.8}{0.9}\right)(8\ \text{m}) = 7.11\ \text{m}$$

The gauge will indicate a level below the actual.

It is likely the tank will be overfilled because the level gauge indicated a lower than actual level.

1-22 One of the categories of inherent safety is simplification/error tolerance. What instrumentation could you add to the tank described in Problem 1-21 to eliminate problems?

SOLUTION: Use a level guage that is not dependent on the specific gravity, such as: a) float type, b) ultrasonic, c) sight glass, etc.

1-23 Pumps can be shut-in by closing the valves on the inlet and outlet sides of the pump. This can lead to pump damage and/or a rapid increase in the temperature of the liquid shut inside of the pump.

A particular pump contains 4 kg of water. If the pump is rated at 1-HP, what is the maximum temperature increase expected in the water in °C/hour? Assume a constant water heat capacity of 1 kcal/kg/°C. What will happen if the pump continues to operate?

SOLUTION:

The shaft work (mechanical energy) is converted to thermal energy which heats the liquid in the pump. Assume no heat losses from the pump to acquire the maximum heating rate.

The total energy balance: $Q = \Delta H = m C_p (T - T_{ref})$

Taking the time derivative: $\frac{dQ}{dt} = m c_p \frac{dT}{dt}$

Therefore:

$$\frac{dT}{dt} = \frac{1}{m C_p} \frac{dQ}{dt}$$

$$\frac{dQ}{dt} = (1\ \text{HP})\left(\frac{745.7\ \text{J/s}}{\text{HP}}\right)\left(\frac{3600\ \text{s}}{\text{hr}}\right)\left(\frac{1\ \text{cal}}{4.184\ \text{J}}\right)\left(\frac{1\ \text{kcal}}{1000\ \text{cal}}\right)$$

$$= 641.6\ \text{kcal/hr.}$$

$$\frac{dT}{dt} = \frac{1}{(4\ \text{kg})(1\ \text{kcal/kg/°C})}\left(641.6\ \text{kcal/hr}\right)$$

$$= 160\ \text{°C/hr}$$

It is possible that the liquid could heat up to its boiling point, causing the pump to rupture. Many pumps thermal shutdown controls to prevent this scenario.

1-24 Water will flash into vapor almost explosively if heated under certain conditions.

a. What is the ratio in volume between water vapor at 300K and liquid water at 300K, at saturated conditions?

b. Hot oil is accidentally pumped into a storage vessel. Unfortunately, the tank contains residual water which flashes into vapor and ruptures the tank. If the tank is 10m in diameter and 5m high, how many kg of water at 300°K are required to produce enough water vapor to pressurize the tank to 8-inches of water gauge pressure, the burst pressure of the tank?

Solution:

Water flashes explosively to rupture the vessel at approximately 8" of water pressure.

a) Use the Steam Table and acquire the saturated conditions at 300 °K.

For liquid: $V_L = 0.001004 \ m^3/kg$

For Vapor: $V_g = 39.10 \ m^3/kg$

$$\text{Volume ratio} = \frac{V_g}{V_L} = \frac{39.1}{0.001004} = 38{,}900$$

This is a very large difference in volumes!

b) Use the ideal gas law to determine the vapor required to rupture the tank at 8" water (gage).

1 atm = 33.91 ft/Water = 406.9" Water

Pressure = (8" of water)/(406.9"/Atm) = 0.0197 atm

∴ The total absolute pressure = 1.0197 atm

Volume of vessel = $\frac{\pi D^2}{4} h$

$= (3.14) \frac{(10 m)^2}{4} (5 m) = 392.5 \ m^3$

Using the ideal gas law;

$$m = \frac{PV}{RT} = \frac{(1.0197 \text{ atm})(397.5 \ m^3)}{\left(0.082057 \frac{m^3 \text{ atm}}{\text{kg-mole } ^\circ K}\right)(300 \ ^\circ K)}$$

$= 16.3$ kg-mole of Water

$= 293$ kg of water

This is about 77 gallons of water

1-25 Another way of measuring accident performance is by the LTIR or Lost Time Injury Rate. This is identical to the OSHA incidence rate based on incidents in which the employee is unable to continue their normal duties.

A plant site has 1200 full-time employees working 40 hours per week and 50 weeks per year. If it had two lost time incidents last year, what is the LTIR?

Solution:

$$LTIR = \frac{(\text{No. of lost time incidents})(200{,}000 \text{ hrs})}{\text{Total hours worked}}$$

Total hours worked = $(1200 \text{ employees})\left(40 \frac{\text{hrs}}{\text{wk}}\right)\left(50 \frac{\text{wk}}{\text{yr}}\right)$

$= 2.4 \times 10^6$ Hrs

$$LITR = \frac{(2)(200{,}000)}{2.4 \times 10^6} = 0.167$$

This is low; 2 or 3 is typical

22-141 50 SHEETS
22-142 100 SHEETS
22-144 200 SHEETS

1-26 A car leaves New York City and travels the 2800 mile distance to Los Angeles at an average speed of 50 miles per hour. An alternative travel plan is to fly via a commercial airline for 4½ hours. What are the FAR's for the two methods of transportation? Which travel method is safest, based on the FAR?

Solution: See Table 1-4

For car travel FAR = 57 deaths / 10^8 Hrs

For an airplane FAR = 240

On a per hour basis, airplane travel is much more hazardous!

For New York to LA trips:

$$\text{Car Hours is } \frac{2800 \text{ miles}}{50 \text{ mile/hr}} = 56 \text{ hours}$$

$$\text{Expected deaths} = (56 \text{ hrs})\left(\frac{57 \text{ deaths}}{10^8 \text{ hrs}}\right)$$

$$= 3.19 \times 10^{-5} \text{ deaths}$$

For airplane trip the expected deaths =

$$= (4.5 \text{ hrs})\left(\frac{240 \text{ deaths}}{10^8 \text{ hrs}}\right) = 1.08 \times 10^{-5} \text{ deaths}$$

∴ the safest mode of trave is via airplanes!!

1-27 A column was used to strip low-volatile materials from a high temperature heat transfer fluid. During a maintenance procedure, water was trapped between two valves. During normal operation, one valve was opened and the hot oil came in contact with the cold water. The result was almost sudden vaporization of the water, followed by considerable damage to the column.

Consider liquid water at 25°C and 1 atm. How many times does the volume increase if the water is vaporized and vapor at 100°C and 1 atm?

Solution:

From the steam tables at 25°C and 1 atm, $v_l = 1.000\ cm^3/gm$. At 100°C and 1 atm, $v_g = 1673.0\ cm^3/gm$. Thus, the volume expansion ratio between the liquid and the vapor is 1673 times. Liquid water exposed to hot oil will flash explosively, leading to considerable damage due to the expansion of the liquid.

1-28

(a) Area of tank roof $= \frac{\pi D^2}{4} = \frac{(3.14)(30)^2}{4}$

$= 706.5\ ft^2$

$= (706.5)(144) = 1.017 \times 10^5\ IN^2$

$P = F/A = \frac{200\ lb}{1.017 \times 10^5\ IN^2} = 1.97 \times 10^{-3}$ psia

Since 1 atm = 14.7 psia = 33.91 ft of H_2O

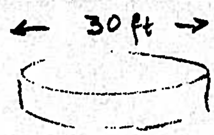
$\equiv$ 406.9 in of water

Therefore

$P = (1.97 \times 10^{-3}\ \text{psia})\left(\frac{406.9\ \text{in } H_2O}{14.7\ \text{psia}}\right)$

P = 0.054 IN. of water (Not much)

b)



$V = hA = (0.667\ ft)(706.5\ ft^2) = 471\ ft^3$

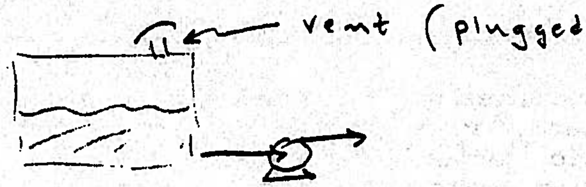
Since 1 ft^3 of water weighs 62.4 lb

Total weight = $(471\ ft^3)(62.4\ lb/ft^3)$

$\approx$ 29,000 pounds

Very large!!

c)



As liquid is pumped out, liquid volume in the tank decreases and lowers the pressure. The pressure dropped to less than 2.5 inches of water vacuum.

1-29 a) use a fork truck with a blast plate to move the drum to an isolated area.*

or b) Use remotely actuated device to pierce the top of the drum to remove the pressure.*

c) Send sample to the lab for identification

d) Use proper disposal procedures

* Note: Make sure that the site emergency response team is a part of this problem solution.

1-30 The plant has been down for extensive maintenance and repair. You are in charge of bringing the plant up and on-line. There is considerable pressure from the sales department to deliver product. About 4 a.m. a problem develops. A slip plate or blind has accidentally been left in one of the process lines. A very experienced maintenance person suggest that she can remove the slip plate without depressurizing the line. She said that she routinely performed this operation years ago. Since you are in charge, what would you do?

Solution:

a) Don't ~~take advice~~ ~~this~~ take this advice from maintenance.

b) Shut the plant down using normal procedures

c) Remove the slip plate

d) Re-start the plant.

e) Improve the procedure for keeping track of slip plates to prevent similar problems in the future