DESIGN-ORIENTED APPLICATION PROBLEMS

This section of the problem sets for this SIPW presents two design-oriented problems. The first problem deals with a quantitative risk assessment for a chemical facility. This is followed with a problem that involves a cost effectiveness analysis for an accidental toxic chemical release.

The purpose of this section of the workbook is to present, through the above two problems, a comprehensive review of the accident and emergency management principles covered earlier. The two so-called "design" problems are intended to acquaint the reader with more real world problems, approaches, and applications associated with this subject.

DESIGN-ORIENTED APPLICATION 1

Quantitative Risk Assessment for a Chemical Facility
(Modified; from D. C. Hendershot, Rohm and Haas Company)

Problem Statement

A risk assessment being conducted at a chemical plant is concerned with the consequences of two incidents that are defined as follows:

I. An explosion resulting from detonation of an unstable chemical (ethylene oxide).

II. A continuous 240 g/sec release of a toxic chemical (ethylene oxide) at an elevation of 125 m.

Both incidents occur at approximately the same location in the plant.

Two weather conditions are envisioned, namely a northeast wind and a southwest wind (6.0 miles/hr) with stability category "B". Associated with these two wind directions are events IIA, and IIB, respectively, defined as follows:

IIA - Toxic cloud to the southwest

IIB - Toxic cloud to the northeast

Based on an extensive literature search, the probabilities and conditional probabilities of the occurrence of the defined events in any given year are estimated as follows:

$P(I) = 10^{-6}$
$P(II) = 1/33,333$
$P(IIA \mid II) = 0.33$
$P(IIB \mid II) = 0.67$

The consequences of events I, IIA, and IIB, in terms of number of people killed, are estimated as follows:

I - All persons within 200 meters of the explosion center are killed; all persons beyond this distance are unaffected.

IIA - All persons in a pie-shaped segment 22.5 degrees width (downward of the source) are killed if the concentration of the toxic gas is above 0.33 ug/l; all persons outside of this area are unaffected.

IIB - Same as IIA.

Three people are located within 200 m of the explosion center but not in the pie-shaped segment described above. Five people are located within the pie-shaped segment southwest of the discharge center; three are 350 m downwind, two are 600 m away at the plant boundary. Another four people are located 500 m away outside the pie shaped segment but within the plant boundary. All individuals are at ground level.

Calculate the average annual individual risk based on the number of individuals potentially affected. Also calculate the average risk based on all the individuals within the plant boundary. **Hint:** Perform atmospheric dispersion calculations at distance of 350, 500, 800, 1,000, 1,500, and 2,000 m from the emission source.

Solution

1. Draw a line diagram of the plant layout and insert all pertinent data and information.

2. Draw an event tree for the process.

3. Calculate the probability of event IIA occurring. Also calculate the probability of event IIB occurring. See Hazard and Risk Assessment Problem 1.

4. Perform a dispersion calculation to determine the zones where the concentration of ethylene oxide exceeds 0.33 ug/l. Assume a continuous emission for a point source.

a. To maintain consistent units, convert wind speed from miles/hr to m/sec and concentration from ug/l to g/m^3. See Basic Operation 1.

b. Set up the Pasquill-Gifford model using the data and calculations provided above.

c. Calculate the downwind concentration that satisfies the Pasquill-Gifford equation. See "hint" in problem statement section for the possible values of the downwind distance x. Note that the concentration goes through a maximum that is in excess of 0.33 ug/l; thus, there are two solutions.

5. Determine which individuals within the pie shaped segment downwind from the source will be killed if either accident (I or II) occurs. Refer to problem statement or the line diagram obtained in step 1.

6. Determine the total annual risk, TAR, for the process. The total risk, measured in terms of the average annual total number of people killed, is obtained by multiplying the number of people in each impact zone by the sum of the probabilities of the events affecting that zone, and summing the results.

7. Calculate the average annual risk, AAR, based only on the "potentially affected" people. The average annual individual risk for the 8 people in the impact zone is obtained by dividing the total annual risk by 8.

8. Calculate the average annual individual risk for all the individuals within the plant boundary. The average is now based on 12 rather than 8 individuals.

Comment

The results given in step 7 may be interpreted as the average probability that a person in the impact zone will be killed in the course of a year as a result of the occurrence of incident I or incident II.

DESIGN-ORIENTED APPLICATION 2

Cost Effectiveness Analysis for an Accidental Toxic Chemical Release

(Modified; from DeWolf, Quass, and Bare - APCA paper #88-146.8)

Problem Statement

A vented toxic gas stream is routed through a process vent shut-off valve to a closed absorption system (a simple holding tank) to preclude routine discharge to the atmosphere. The tank is essentially a gas-sparged absorber that is partially filled with an absorption medium that is circulated by pumping through a mixing eductor where the gas dissolves and is neutralized. A recirculation relief valve is located at the inlet to the pump. A safety pressure relief valve is provided for automatic relief if a specific set pressure is exceeded in the tank. A bypass vent valve also allows manual intervention to relieve overpressure in the tank if a process upset requires it.

Three additional levels of controls are to be considered with the baseline (sparged absorber) system: (1) a packed tower scrubber in the discharge line to the atmosphere, (2) higher in-plant controls, and (3) both the packed tower scrubber and in-plant controls. (Higher in-plant controls primarily includes enhanced operator training and inspection; alarms, a second pump, a continuous pH meter, and fire monitor are also included here.)

Annual failure probabilities (from company files) for the baseline and three proposed control measures are provided below in tabular form. (The gaps in Table 1 include failure events for which probabilities are to be calculated in step 3 of the solution section.)

A summary of the costs for the baseline and three proposed control measures are provided below in Table 2. Note that the capital cost recovery factor, CRF, may be calculated from the equation,

$$CRF = (i)(1.0 + i)^n/[(1.0 + i)^n - 1]$$

where: i = interest rate, fraction
n = equipment lifetime, yr.

The gaps in Table 2 are to completed in step 4 of the solution section.

You are requested to conduct an economic study of the proposed options and render an engineering judgement on the cost effectiveness on the three proposed alternative control actions.

Table 1. Annual Failure Probabilities

Failure Event	Baseline	Scrubber Only	Higher Level	Higher Level & Scrubber
Pump Stops	0.26	0.26	1.30×10^{-5}	1.30×10^{-5}
Circulation Valve Closed	2.60×10^{-3}	2.60×10^{-3}	1.30×10^{-3}	1.30×10^{-3}
Circulation Fails				
Process Vent Shutoff Fails	1.00×10^{-2}	1.00×10^{-2}	5.24×10^{-6}	5.24×10^{-6}
Reagent Failure	0.26	0.26	1.30×10^{-3}	1.30×10^{-3}
Excess Gas				
Gas Not Absorbed				
External Fire	2.00×10^{-2}	2.00×10^{-2}	2.00×10^{-3}	2.00×10^{-3}
Excess Pressure				
Relief Valve Failure	8.80×10^{-2}	8.80×10^{-2}	4.40×10^{-2}	4.40×10^{-2}
Release Thru Relief Valve (Open)				
Release Thru Bypass (Open)	1.00×10^{-2}	1.00×10^{-2}	5.00×10^{-3}	5.00×10^{-3}
Gas To Scrubber				
Scrubber Failure	-	0.10	-	5.00×10^{-2}
Gas Release To Environment				
Average Expected Time Between Releases, Years				

Table 2. Summary of Total System Costs for Baseline, Scrubber Only, Higher Level Controls, and Both Scrubber and Higher Level Controls

	Baseline	Scrubber Only	Higher Level	Higher Level & Scrubber
Capital Cost ($)				
Equipment	114,000	134,000	122,300	142,300
Installation	49,000	58,000	52,000	61,000
Indirect	73,000	86,000	78,000	91,000
Total	236,000	278,000	252,000	294,000
O & M Cost ($/yr)				
Labor	6,000	6,000	6,000	6,000
Maintenance	8,000	9,500	8,500	10,000
Other Direct	960	1,130	1,100	1,280
Indirect	9,500	10,170	10,330	11,000
Total	24,460	26,800	25,940	28,280
Capital Recovery Factor (@ 10 %, 10 yrs)				
Annual Capital Cost ($/yr)				
Total Annual Cost ($/yr)				
Incremental Total Annual Cost ($/yr)				
Release Frequency (Releases/yr)[a]				
Average Interval Between Releases (yr)[a]				
Cost Effectiveness ($/release free yr)				

[a] See Table 1.

Solution

1. Develop a line diagram of the process. See Basic Operation 15.

2. Develop a fault tree diagram for the above process, including the scrubber. See Basic Operation 14 and Hazard and Risk Assessment problem 10.

3. Using the annual failure frequency data provided in the problem statement (Table 1), in conjunction with the fault tree diagram, complete the failure probability calculations in Table 1 and insert the results in the fault tree diagram in step (2).

4. Complete the cost control table (see Table 2). Note that the cost effectiveness is defined as the ratio of the additional cost in dollars on an annual basis from the baseline case to the difference between the average interval between releases and the baseline case.

5. Comment on the cost effectiveness of the three proposed control options.

SOLUTIONS

Solutions are presented below for the three problem sets - Plant Applications, Dispersion, and Hazard and Risk Assessment. There are ten solutions for each set, one for each problem. These are followed by the solutions to the two Design-Oriented Application problems. The solutions provided are those of the author; they are not necessarily the only/or correct solution. In some instances another or even better solutions may be as or more appropriate for the problem in question. The solution to each problem starts with a new page.

SOLUTIONS: PLANT APPLICATIONS

Plant Application 1

1. Using the equation given above, calculate the lower flammability limit of the mixture in percent.

   LFL = 1/[(30/4.6) + (50/3.5) + (20/1.4)]
   = 0.0285
   = 28.5 %

2. Calculate the upper flammability limit of the mixture in percent.

   UFL = 1/[(30/14.2) + (50/15.1) + (20/7.8)]
   = 0.125
   = 12.5 %

Plant Application 2

1. First, calculate the ignition delay time in seconds using the equation given.

   $\ln t = [250/(460 + 150)] + 0.5$
   $= 0.9098$
   $t = 8.13$ sec

2. Calculate the average residence time, t_r, of the vapor in the four feet section of the pipe.

   $t_r = V/Q$
   $= (3.14)(1/12)^2(4)/(4.5/60)$
   $= 1.16$ sec

3. Compare the residence time of the vapor in the 4 feet section of the pipe to the ignition delay time. Will ignition take place?

   Since the residence time of 1.16 sec is less than the ignition delay time of 8.13 sec, the ignition will not take place.

Plant Application 3

1. First, determine the kinetic constant, k, from the half life data in hr^{-1}.

   $k = \ln(2)/T_{1/2}$
   $= (0.693)/(3)$
   $= 0.231\ hr^{-1}$

2. Express the tolerable concentration of Y in the body as a function of the body volume.

   $C = (9\ mg/Kg)(65\ Kg)/(1.0\ V_{body})$
   $= 585\ mg/V_{body}$

3. Determine the rate of concentration change or elimination rate, dC/dt.

   $dC/dt = k\ C$
   $= (0.231)(585)$
   $= 135.1\ mg/hr\text{-}V_{body}$

4. Calculate the intake rate of Y required in mg/hr.

   $\text{Intake rate} = (1\ V_{body})(135.1\ mg/hr\text{-}V_{body})$
   $= 135.1\ mg/hr$

5. Calculate the concentration of Y in air in mg/l.

   $C_{Y,air} = 135.1/[(45)(60)]$
   $= 0.0501\ mg/l$

Plant Application 4

1. Determine the minimum air velocity required for general foundry dust.

   V_{air} = 4000 ft/min
   = 66.67 ft/sec

2. Calculate the total air flow required in acfm.

   Q_{air} = (3000)(4)
   = 12,000 acfm

3. Calculate required cross sectional area in ft^2.

   $A = Q_{air}/V_{air}$
   = (12,000)/(4,000)
   = 3 ft^2

4. Calculate the duct diameter.

   $D = (4\ A/\pi)^{1/2}$
   = $[(4)(3)/3.14]^{1/2}$
   = 1.9544 ft
   = 24 inch

5. In order to calculate power requirements, the pressure drop across the system needs to calculated first.

   a. Calculate the Reynolds number for the above duct.

   $Re = D\ V \rho/\mu$
   = $(1.9544)(66.67)(0.075)/(1.21 \times 10^{-5})$
   = 8.08×10^5

   b. Calculate the pressure drop in the duct in lb_f/ft^2.

   f = 0.003 since Re > 20,000
   $\Delta P_{duct} = 4\ f\ L\ V^2\ \rho/2\ g_c\ D$
   = $(4)(0.003)(400)(66.67)^2(0.075)/[(2)(32.2)(1.9544)]$
   = 12.7 lb_f/ft^2

6. Calculate the total system pressure drop.

   $\Delta P_{tot} = \Delta P_{duct} + \Delta P_{hood} + \Delta P_{cyc}$
   = 12.7 + (0.5)(5.2 lb_f/ft^2/in H_2O) + (3.5)(5.2 lb_f/ft^2/in H_2O)
   = 33.5 lb_f/ft^2

7. Calculate the power required in lb_f-ft/min and Hp.

   $Hp = 3.03 \times 10^{-5}\ \Delta P_{tot}\ Q_{air}/E$
   = 3.03×10^{-5} (33.5)(12,000)/0.4
   = 30.5 Hp

Plant Application 5

1. Convert the mass flow rate of the vinyl chloride (VC) to volumetric flow rate in cm^3/min and acfm.

   Density of VC = PMW/RT
   $= (1)(78)/(82.06)(273 + 25)$
   $= 0.00319\ g/cm^3$

   Volumetric flow rate = m/density
   $= 10/0.00319$
   $= 3135\ cm^3/min$
   Volumetric flow rate $= (3135\ cm^3/min)/[(30.48)^3\ cm^3/ft^3]$
   $= 0.1107$ acfm

2. Calculate the air flow rate (in cfm) required to meet 1 ppm PEL.

   Air flow rate, $Q_{air} = 0.1107/(1 \times 10^{-6})$
   $= 1.107 \times 10^5$ cfm

3. Apply the safety factor to calculate the actual air flow rate for dilution ventilation.

   $Q_{air,dil} = (10)(1.107 \times 10^5)$
   $= 1.107 \times 10^6$ acfm

4. Now consider local exhaust ventilation by first calculating the face area of the hood, A, in ft^2.

   $A = (30)(25)$
   $= 750\ inch^2$
   $= 5.21\ ft^2$

5. Calculate the air flow rate (in cfm) required for a face velocity of 100 ft/min.

   $Q_{air,exh}$ = (A)(face velocity)
   $= (5.21)(100)$
   $= 521$ acfm

6. Compare the flow rate of air required for dilution ventilation and local exhaust ventilation. Which method is better?

   Since the air flow rate for dilution ventilation is approximately 2000 times higher than the local ventilation air flow rate requirement and the high cost of large blowers (for higher air flow rate), the local ventilation method is better for this case.

Plant Application 6

1. Determine the gasoline usage in gal/yr and lbmole/yr

   Gasoline usage = (7.1 X 10^6 barrels/day)(365 days/yr)(42 gal/barrel)
   = 1.09 X 10^{11} gal/yr

   Molecular weight of C_8H_{18} = 114
   Gasoline usage = (1.09 X 10^{11} gal/yr)(0.8)(62.4 lb/ft^3)(ft^3/7.48 gal)(lbmole/114 lb)
   = 6.38 X 10^9 lbmole/yr

2. Calculate the fuel usage reduction in gal/yr and lbmole/yr with DurAlt FC additive.

   Fuel usage reduction = (1.09 X 10^{11} gal/yr)(0.045)
   = 4.9 X 10^9 gal/yr
   Fuel usage reduction = (4.9 X 10^9 gal/yr)(0.8)(62.4 lb/ft^3)(ft^3/7.48 gal)(lbmole/114 lb)
   = 2.87 X 10^8 lbmole/yr

3. Calculate the volume of gasoline (in gal/yr) that is discharged to the atmosphere because of incomplete combustion.

   Volume of gasoline discharged = (1.09 X 10^{11} gal/yr)(0.01)
   = 1.09 X 10^9 gal/yr

4. Calculate the mass of the gasoline that is discharged to the atmosphere (in lb/yr) because of incomplete combustion.

   Mass of gasoline discharged = (1.09 X 10^9 gal/yr)(0.8)(62.4 lb/ft^3)(ft^3/7.48 gal)(lbmole/114 lb)
   = 7.27 X 10^9 lbs/yr

5. Write the stoichiometric equation for the combustion of gasoline, C_8H_{18}, and oxygen, O_2.

   $C_8H_{18} + 12.5\ O_2 \longrightarrow 8\ CO_2 + 9\ H_2O$

6. Using the result generated in step 2 and the reaction equation obtained in step 5, calculate the reduction in CO_2 generated in lbmole/yr and lb/yr.

   For every lbmole of C_8H_{18} combusted, 8 lbmoles of CO_2 are generated.
   lbmole of CO_2 reduction = (8)(2.87 X 10^8 lbmole/yr)
   = 2.30 X 10^9 lbmoles CO_2/yr
   lb of CO_2 reduction = (2.30 X 10^9 lbmole/yr)(44 lb/lbmole)
   = 1.01 X 10^{11} lbs CO_2/yr

7. Calculate the annual savings to the consumer through the use of DurAlt FC.

   a. Calculate the savings due to fuel usage reduction through the use of DurAlt FC.

      Savings = $(4.9 \times 10^9$ gal/yr)(0.94 \$/gal)
      $= 4.61 \times 10^9$ \$/yr

   b. Calculate the cost of using DurAlt FC.

      Cost = $(1.09 \times 10^{11}$ gal/yr)(0.01 \$/gal)
      $= 1.09 \times 10^9$ \$/yr

   c. Calculate the annual savings.

      Annual savings = $4.61 \times 10^9 - 1.09 \times 10^9$
      $= 3.52 \times 10^9$ \$/yr
      $\cong$ 3.5 billion dollars per year

Plant Application 7

1. Write the describing equation for the equilibrium concentration.

   $C_{eq} = (m)\{1 - \exp[-((1/t_d) + k)t]\}/[Q(1 + kt_d)]$
   Setting $t = \infty$,
   $C_{eq} = (m)/[Q(1 + kt_d)]$

2. Assign values to the equation given in step 1.

   $m = (120{,}000 \text{ lb/hr})(11 \text{ hr})(1 \text{ ft}^3/62.4 \text{ lb})(1 \text{ liter}/0.0353 \text{ ft}^3)(10^6 \text{ PCi/liter})$
   $= 5.99 \times 10^{11} \text{ PCi}$
   $Q = (200)(3600)$
   $= 7.2 \times 10^5 \text{ ft}^3/\text{hr}$
   $k = 0.23 \text{ hr}^{-1}$
   $t_d = 3.6 \times 10^8/7.2 \times 10^5$
   $= 500 \text{ hr}$

3. Using the equation given in step 1, calculate the equilibrium concentration in units of PCi/ft^3 and PCi/l.

   $C_{eq} = (5.99 \times 10^{11})/[(7.2 \times 10^5)(1 + 0.23(500))]$
   $= 7{,}172 \text{ PCi/ft}^3$
   $= (7{,}712)(0.0353 \text{ ft}^3/\text{l})$
   $= 253.2 \text{ PCi/l}$

4. Calculate the maximum concentration that will result from the radioactive waste discharge in units of PCi/l.

   $C = (m)\{1 - \exp[-((1/t_d) + k)t]\}/[Q(1 + kt_d)]$
   $= (253.2)\{1 - \exp[-((1/500) + 0.23)(11)]\}$
   $= 233.5 \text{ PCi/l}$

5. Calculate the time, θ, after the termination of the waste discharge that the concentration will reach an acceptable level.

   $C = C_{eq} \exp\{-[(1/t_d) + k]\theta\}$
   $10 = 253.2 \exp\{-[(1/500) + 0.23]\theta\}$
   $10/253.2 = \exp(-0.232\theta)$
   $\ln(10/253.2) = -0.232\theta$
   $-3.23 = -0.232\theta$
   $\theta = 13.9 \text{ hrs}$

6. Calculate the time from the start of the discharge that the concentration will reach the acceptable level.

   $t = \theta + 11$
   $= 13.9 + 11$
   $= 24.9 \text{ hrs}$

7. Discuss the limitations of the above approach.

   In reality, a concentration profile will exist in the body of water. An average or mean concentration may not be realistic over this short period of time since complete mixing will probably not occur.

Plant Application 8

1. First, calculate the partial pressure of substance A in mm Hg.

$$p_{v,A} = (700 \times 10^{-6})(760)$$
$$= 0.532 \text{ mm Hg}$$

2. Determine the ratio of vapor pressures, $P_{v,A}/p$.

$$P_{v,A}/p = (60)/(0.532)$$
$$= 112.8$$

3. Calculate the amount of A_s adsorbed per 100 g of charcoal using the equation given, in cm^3/100 g charcoal.

$$\log_{10} C_A = -0.11 \{[(85 + 273)/100] \log_{10}(112.8)\} + 2.2$$
$$= 1.392$$
$$C_A = 24.65 \text{ cm}^3/100 \text{ g}$$

4. Calculate the mass of the substance A adsorbed in the cartridge (in g) at 80 % saturation (i.e., at breakthrough).

$$m = (0.8)(C_A)(80/100)(1.12)$$
$$= 17.67 \text{ g}$$

5. Next, calculate the volumetric flow rate of A inhaled through the cartridge from the vapor pressure and breathing rate.

$$Q_{air} = (700 \times 10^{-6})(45{,}000) \text{ cm}^3/\text{min}$$
$$= 31.5 \text{ cm}^3/\text{min}$$

6. Calculate the intake mass flow rate of A.

$$m_A = P\ Q\ MW/(R\ T)$$
$$= (1)(31.5)(110)/[(82.06)(273 + 85)]$$
$$= 0.118 \text{ g/min}$$

7. Calculate the time for breakthrough in minutes.

$$t = 17.67/0.118$$
$$= 150 \text{ min}$$

Plant Application 9

1. First, write the combustion reaction equation for 1 mole of pentane with stoichiometric air.

$C_5H_{12} + 8\ O_2 + 30.1\ N_2 \longrightarrow 5\ CO_2 + 6\ H_2O + 30.1\ N_2$

Note that $n_{N2} = (0.79/0.21)\ n_{O2}$
$= (0.79/0.21)(8)$
$= 30.1$

2. Determine the number of moles initially and finally present, and the change in the number of moles.

$n_{in} = (1) + (8) + (30.1)$
$= 39.1$

$n_{out} = (5) + (6) + (30.1)$
$= 41.1$

3. Express the constant volume heat capacity as a function of the constant pressure heat capacity.

$C_v = C_p - R;\ R = 1.987$ cal/gmole-°K

	a	a - R	b	c	d	n_i
N_2	6.529	4.542	0.149×10^{-2}	-0.0227×10^{-5}	0	30.1
CO_2	5.316	3.329	1.429×10^{-2}	-0.8362×10^{-5}	1.784×10^{-9}	5
H_2O	6.970	4.983	0.345×10^{-2}	-0.0483×10^{-5}	0	6

$$\sum (n_i C_{v,i})_{out} = [(4.542)(30.1)+(3.329)(5)+(4.893)(6)] + [(0.149\times10^{-2})(30.1)+(1.429\times10^{-2})(5)+(0.345\times10^{-2})(6)]T + [(-0.0227\times10^{-5})(30.1)+(-0.8362\times10^{-5}(5)+(-0.0483\times10^{-5})(6)]T^2 + [(1.784\times10^{-9})(5)]T^3$$

4. Express the change in internal energy by integrating the internal energy change equation.

$$\int_{T_{in}}^{T_{out}} \sum (n_i C_{v,i})_{out} = [(4.542)(30.1)+(3.329)(5)+(4.893)(6)](T_{out}-298) + [(0.149\times10^{-2})(30.1)+(1.429\times10^{-2})(5)+(0.345\times10^{-2})(6)][(T_{out})^2-(298)^2]/2 + [(-0.0227\times10^{-5})(30.1)+ (-0.8362\times10^{-5}(5)+(-0.0483\times10^{-5})(6)][(T_{out})^3-(298)^3]/3 + [(1.784\times10^{-9})(5)][(T_{out})^4-(298)^4]/4$$

5. Solve the equation obtained in step 4 for T_{out} by trial and error until the right hand side of the equation has the value of the internal energy of reaction at 25 ° C given previously.

$$777.46 \times 10^3 = [(4.542)(30.1)+(3.329)(5)+(4.893)(6)](T_{out}-298) + [(0.149\times10^{-2})(30.1)+(1.429\times10^{-2})(5)+(0.345\times10^{-2})(6)][(T_{out})^2-(298)^2]/2 + [(-0.0227\times10^{-5})(30.1)+(-0.8362\times10^{-5}(5)+(-0.0483\times10^{-5})(6)][(T_{out})^3-(298)^3]/3 + [(1.784\times10^{-9})(5)][(T_{out})^4-(298)^4]/4$$

By trial and error calculation, T_{out} = 2870 °K

6. Calculate the final pressure in the vessel.

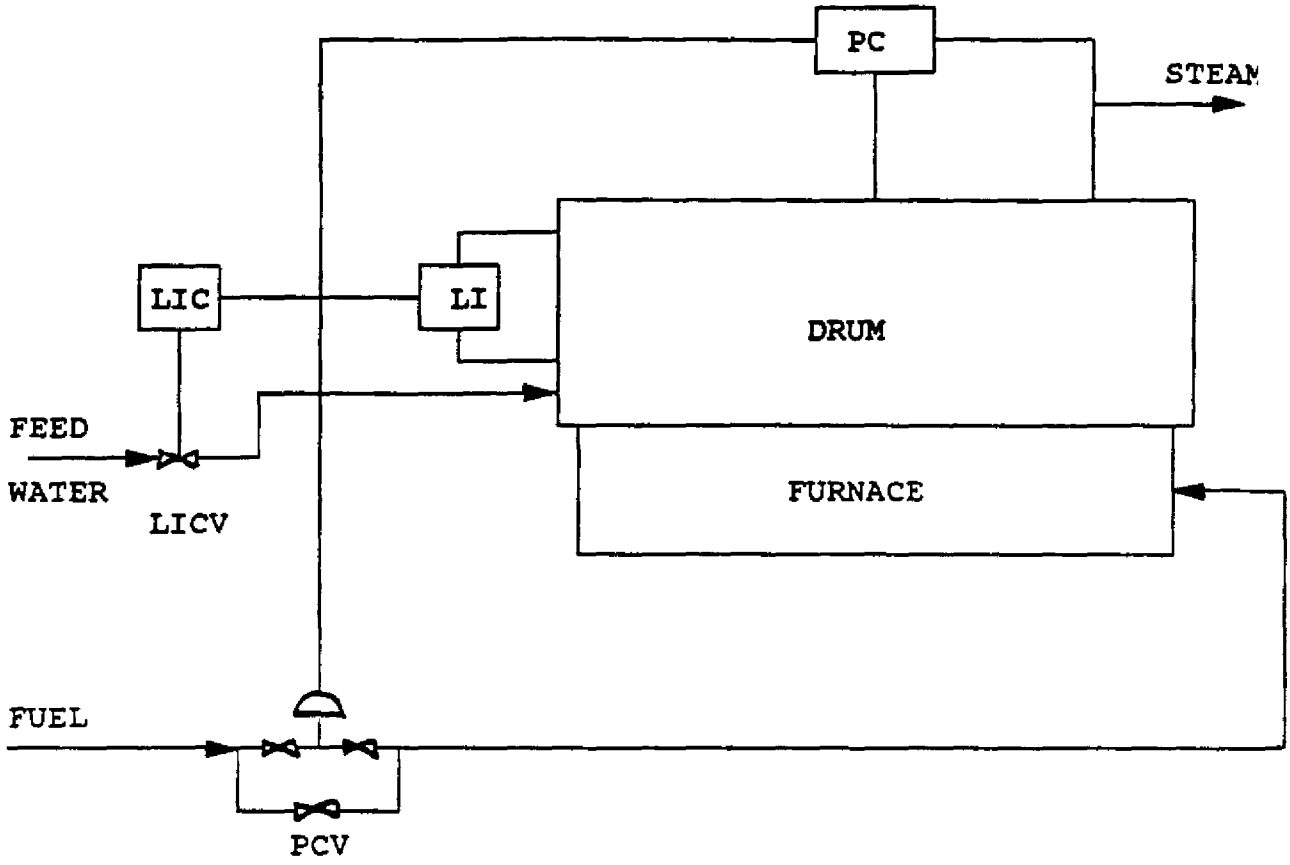
$$P_f = (14.7 + 5)(41.1/39.1)(2870/298)$$
$$= 200.9 \text{ psia}$$
$$= 186.2 \text{ psig}$$

7. Can the knockout drum withstand the explosion?

Since the final pressure of 186.2 psig is less than the burst pressure of 200 psig, the vessel will withstand the explosion.

Plant Application 10

1. Draw a line diagram of the system.



2. Apply the first guide word NO to the system and list the deviation(s), cause(s), and consequnece(s).

Deviations	Causes	Consequences
NO flow of feed water	LICV closed.	Loss of level in drum and explosion of drum by flame impingement on dry shell if flame continues.
NO level in drum.	Loss of feedwater pressure.	Same as above.
	Massive leak.	Flame extinguished.
NO fuel flow.	Fuel line closed.	No steam generation.

3. Apply the second guide word MORE to the system and list the deviation(s), cause(s), and consequence(s).

Deviation	Cause	Consequence
MORE level in drum than 40%.	Level control fault.	Excessive entrainment in steam.

4. Apply the guide word LESS to the system.

Deviation	Cause	Consequence
LESS level in drum than 30 %	Similar to NO level.	Same as NO level.

5. Apply the guide word AS WELL AS to the system.

Deviation	Cause	Consequences
Contaminants as well as feedwater.	Water treatment fault.	Fouling of boiler. Corrosive steam.

6. Apply the guide word PART OF to the system.

Deviation	Cause	Consequences
Part of feedwater (treatment chemical) omitted.	Water treatment fault.	Same as above.

7. Apply the guide word REVERSE to the system.

Deviation	Cause	Consequence
Reverse flow in feedwater line.	Loss of feedwater pressure.	Steam in feedwater system.

8. Apply the guide word OTHER THAN to the system.

Deviations	Cause	Consequences
Unplanned shutdown (other than normal operation).	Utility failure.	Does LICV fail closed or open? Same consequences as NO level in drum or MORE level in drum.
Other than feedwater.	Not possible.	

SOLUTIONS: DISPERSION

Dispersion 1

1. First, calculate the volume of the hydrocarbon leaked.

   $V = 23{,}000/(0.91)(62.4)$
   $= 405\ ft^3$

2. Calculate the spill area, assuming that the thickness of the hydrocarbon on a sandy soil base is 0.75 inch.

   $A = V/thickness$
   $= (405)/(0.75/12)$
   $= 6480\ ft^2$

3. Calculate the emission flux, E, using ILEPA's equation.

   $E = 0.0012\ c\ P_v/(760 - d\ P_v)$

   $c = 154/28.9$
   $= 5.33$

   $d = 1 - c$
   $= 1 - 5.33$
   $= -4.33$

   $E = (0.0012)(5.33)(375)/[760 - (-4.33)(375)]$
   $= 0.00101\ g/cm^2\text{-sec}$

4. Calculate the mass emission (or evaporation) rate, m.

   $m = (E)(A)$
   $= (0.00101)(6480)(30.48)^2$
   $= 6080.3\ g/sec$

5. Calculate the time for total evaporation.

   $t = M/m$
   $= (23{,}000)(454)/6080.3$
   $= 1717\ sec$
   $= 28.6\ min$

Dispersion 2

1. First calculate the Schmidt number.

$$Sc = \mu / \rho D_{AB}$$
$$= (1.8462 \times 10^{-5})/(1.1774)(1.32 \times 10^{-5})$$
$$= 1.1879$$

2. Calculate the molar flux in kg/m^2-sec.

$$N_A = 0.0021(u/L)^{0.5}[(D_{AB})^{0.5} \rho /(Sc)^{0.167}] (P_A/P_o)$$
$$= 0.0021(0.04/0.1)^{0.5} [(1.32 \times 10^{-5})^{0.5}(1.1774)/ (1.1879)^{0.167}](0.0789/1)$$
$$= 4.584 \times 10^{-6} \text{ kg/m}^2\text{-sec}$$

3. Convert the molar flux calculated above to g/m^2-hr

$$N_A = (4.584 \times 10^{-6})(1000)(3600)$$
$$= 16.5 \text{ g/m}^2\text{-hr}$$

Dispersion 3

1. Calculate the values of $(y + a)/\sqrt{4Dt}$ and $(y - a)/\sqrt{4Dt}$.

$$a = 100/2 = 50$$

$$(y + a)/\sqrt{4Dt} = (25 + 50)/[(40)(61)(8)]^{0.5} = 1.7$$

$$(y - a)/\sqrt{4Dt} = (25 - 50)/[(40)(61)(8)]^{0.5} = -0.566$$

2. Determine the values of the error function.

$$\text{erf}\,[(y + a)/\sqrt{4Dt}] = \text{erf}(1.7) = 0.98379$$

$$\text{erf}\,[(y - a)/\sqrt{4Dt}] = \text{erf}(-0.566) = -\text{erf}(0.566) = -0.57655$$

3. Calculate the concentration of the toxic waste.

$$C_{A0}(y=25\text{ ft},\ t=8\text{ hrs}) = (C_{A0}/2)(\text{erf}[(y + a)/\sqrt{4Dt}] - \text{erf}[(y - a)/\sqrt{4Dt}])$$
$$= (0.23/2)[0.98379 - (-0.57655)]$$
$$= 0.18\ \text{lbmole/ft}^3$$

Dispersion 4

1. Calculate x_f to determine which plume equation applies.

   a. Calculate x^*.

   $$x^* = 14\ (F)^{5/8} \text{ since F is less than 55 } m^4/sec^3$$
   $$= (14)(50)^{5/8}$$
   $$= 161.43 \text{ m}$$

   b. Calculate x_f.

   $$x_f = (3.5)(x^*)$$
   $$= (3.5)(161.43)$$
   $$= 565.0 \text{ m}$$

2. Calculate the plume rise.

   $$h = 1.6\ (F)^{1/3}(u)^{-1}(x_f)^{2/3} \text{ since } x >= x_f$$
   $$= (1.6)(50)^{1/3}(4)^{-1}(565)^{2/3}$$
   $$= 101 \text{ m}$$

Dispersion 5

1. Complete the table below for stability category A using Appendix II.

X (m)	σ_y (m)
200	50.5
4000	700
6000	1000
60000	7000

2. Linearize the equation $\sigma_y = b(y)\ x^{a(y)}$ by taking the natural logarithm of both sides of the equation.

   $\ln \sigma_y = \ln b(y) + a(y) \ln x$
   Therefore, the above equation is of the form:
   $Y = A + B X$
   where: $Y = \ln \sigma_y$
   $A = \ln b(y)$
   $B = a(y)$
   $X = \ln x$

3. Regress the data from step 1 using the method of least squares and generate the linear coefficients A and B.

   $\ln(50.5) = A + B \ln(200)$
   $\ln(700) = A + B \ln(4000)$
   $\ln(1000) = A + B \ln(6000)$
   $\ln(7000) = A + B \ln(60000)$

   Coefficients A and B are obtained by the least squares method.

   $A = -0.64614$
   $B = 0.865592$

   The corresponding standard error of the Y estimate and standard error of coefficient B are 0.029684 and 0.007314, respectively. The value of R^2 is 0.999857 (the closer R^2 is to 1.0, the better the estimate by the least squares method).

4. Obtain the constants a(y) and b(y).

   $a(y) = B$
   $= 0.8656$

   $b(y) = \exp(A)$
   $= \exp(-0.64614)$
   $= 0.5240$

5. Repeat the above steps for stability categories B, C, D, E, and F.

For category B:

Selecting x values of 400, 600, 8000, 30000, and 80000 m yield:
a(y) = 0.8702
b(y) = 0.3850

For category C:
Selecting x values of 2000, 8000, and 60000 m yield:
a(y) = 0.8797
b(y) = 0.2527

For category D:
Selecting x values of 100, 700, 1000, 5000, and 70000 m yield:
a(y) = 0.9029
b(y) = 0.1321

For category E:
Selecting x values of 1000, 7000, 60000, and 100000 m yield:
a(y) = 0.8879
b(y) = 0.1109

For category F:
Selecting x values of 100, 3000, 7000, and 20000 m yield:
a(y) = 0.9140
b(y) = 0.0597

6. Repeat all of the above steps for dispersion coefficient σ_z.

For Catergory A:

x (m)	σ_z (m)
200	30
800	290
2000	1950
3000	6000

For category A, A = -6.93843
B = 1.924592

a(z) = 1.9246
b(z) = exp(A)
= exp(-6.93843)
= 0.00097

For category B:
Selecting x values of 400, 4000, 7000, and 30000 m yield:
a(z) = 1.1511
b(z) = 0.0377

For category C:
Selecting x values of 300, 800, 8000, 10000, and 100000 m yield:
a(z) = 0.9441
b(z) = 0.0887

For category D:
Selecting x values of 2000, 5000, 6000, and 40000 m yield:
a(z) = 0.5941
b(z) = 0.5600

For category E:
Selecting x values of 300, 900, 4000, 10000, and 100000 m yield:
a(z) = 0.5196
b(z) = 0.5734

For category F:
Selecting x values of 200, 400, 7000, 20000, and 40000 m yield:
a(z) = 0.5322
b(z) = 0.2789

Dispersion 6

1. First calculate the sulfur dioxide emission rate, m, in g/sec.

   m = (12)(0.025)(2)
   = 0.6 ton/hr
   = (0.6)(2000)(454)/(3600)
   = 151.3 g/sec

2. Determine the stability category.

   Since it is night time, the sky is clear, and the wind speed is 2 m/sec. Therefore, the stability category is F.

3. Determine the values of σ_y and σ_z for each downward distance for stability category F from Appendix II.

   x = 0.1 km; σ_y = 4 m, σ_z = 2.3 m
   x = 1.0 km; σ_y = 34 m, σ_z = 14.0 m
   x = 5 km; σ_y = 148 m, σ_z = 34.0 m
   x = 10 km; σ_y = 275 m, σ_z = 46.5 m
   x = 20 km; σ_y = 510 m, σ_z = 60.0 m
   x = 25 km; σ_y = 610 m, σ_z = 64.0 m
   x = 30 km; σ_y = 720 m, σ_z = 68.0 m
   x = 50 km; σ_y = 1120 m, σ_z = 78.0 m
   x = 70 km; σ_y = 1500 m, σ_z = 64.0 m

4. The appropriate equation is as follows:

   Since the maximum concentration along the x axis is desired and the maximum concentration occurs along the centerline of the plume,

   $$C(x,0,0,H_e) = (m/\pi\,\sigma_y\,\sigma_z\,u)[\exp(-0.5(H_e/\sigma_z)^2)]$$

5. Calculate the concentration of sulfur dioxide at the same downward distances by completing the table below.

   For example,
   $C(1.0,0,0,H_e) = [(151.3)/(3.14)(34)(14)(2)]$
   $[\exp(-0.5(120/14)^2]$
   $= 5.61 \times 10^{-18}$ g/cm^3

x (km)	C (g/cm^3)
0.1	0 (infinitely small)
1.0	5.61×10^{-18}
5	9.41×10^{-6}
10	6.72×10^{-5}
20	1.06×10^{-4}
25	1.06×10^{-4}
30	1.03×10^{-4}
50	8.41×10^{-5}
70	7.03×10^{-5}

6. Determine the maximum concentration and its location.

   From the table obtained in step 5, the maximum concentration is 1.06×10^{-4} g/cm^3 and the corresponding location is between 20 and 25 km.

Dispersion 7

1. First determine the stability category from the **Comment** section of Dispersion problem 5.

   Since it is early evening and the wind speed is 4 m/sec, Stability category = D

2. Calculate the source strength per unit distance, q.

   a. First calculate the number of vehicles per meter.

      $n = (8000)/(40)(1609)$
      $= 0.1243$ vehicles/m

   b. Calculate the source strength per unit length, q, from n and the emission rate per vehicle.

      $q = (n)(0.02)$
      $= (0.1243)(0.02)$
      $= 2.49 \times 10^{-3}$ g HC/sec-m

3. Obtain the vertical dispersion coefficient, σ_z for stability category D from Appendix II.

   $\sigma_z = 12$ m; at x = 300 m

4. Determine the height of the building, H_b.

   $H_b = (6)(3.5)$
   $= 21$ m

5. Calculate the concentration 300 m downwind at ground level conditions.

   $C(x,y,0,H_e) = (2q/\sqrt{2\pi}\,\sigma_z\,u)[\exp(-0.5(H_e/\sigma_z)^2]$
   $C(300,0,0,0) = \{(2)(2.49\times10^{-3})/[(2)(3.14)]^{1/2}(12)(4)\}(1)$
   $= 4.2 \times 10^{-5}$ g/m^3

   Note that the exponential term becomes 1.0 if $H_e = 0$.

6. Calculate the concentration at 300 m downwind at the top of the building.

   $C(300,0,0,H_b) = (2q/\sqrt{2\pi}\,\sigma_z\,u)[\exp(-0.5(H_e/\sigma_z)^2]$
   $= \{(2)(2.49\times10^{-3})/[(2)(3.14)]^{1/2}(12)(4)\}$
   $\{\exp(-0.5(21/12)^2]\}$
   $= 9.08 \times 10^{-6}$ g/m^3

7. Determine how much lower the concentration, in percent, will be at the top of the building.

   % = 100(ground conc. - top conc.)/(ground conc.)
   $= 100(4.2 \times 10^{-5} - 9.08 \times 10^{-6})/(4.2 \times 10^{-5})$
   $= 78.4$ %

Dispersion 8

1. Determine the stability category from the **Comment** section of Dispersion problem 5.

   Since it is a thinly overcast night and the wind speed is 2.5 m/sec,
   Stability category = E

2. Calculate the initial standard deviation, σ_{yo}.

$$\sigma_{yo} = s/4.3$$
$$= 1524/4.3$$
$$= 354 \text{ m}$$

3. Obtain the virtual point source distance, x_y using σ_{yo} of 354 m from Appendix II.

   x_y = 8.4 km for σ_{yo} = 354 m and stability category E

4. Calculate the total distance, x_t.

$$x_t = 8.4 + 1.524$$
$$= 9.924 \text{ km}$$

5. Obtain σ_y, which corresponds to an x_t of 9.924 km, from Appendix II.

$$\sigma_y = 410 \text{ m}$$

6. Determine the value of σ_z.

   Since the area source can be assumed to be well mixed, σ_z may be obtained at x = 1524 m.

$$\sigma_z = 28.2 \text{ m}$$

7. Calculate the concentration at point A because of point D.

$$C(1524,0,0,H) = (m/\pi \sigma_y \sigma_z u)[\exp(-0.5(H_e/\sigma_z)^2)]$$
$$= [(6)/(3.14)(410)(28.2)(2.5)]$$
$$[\exp(-0.5(20/28.2)^2]$$
$$= 5.14 \times 10^{-5} \text{ g/m}^3$$

8. Calculate the concentration from point B.

$$C(1524,1524,0,H) = (m/\pi \sigma_y \sigma_z u)[\exp(-0.5(y/\sigma_y)^2)]$$
$$[\exp(-0.5(H_e/\sigma_z)^2)]$$
$$= [(6)/(3.14)(410)(28.2)(2.5)]$$
$$[\exp(-0.5(1524/410)^2][\exp(-0.5(20/28.2)^2]$$
$$= 5.07 \times 10^{-8} \text{ g/m}^3$$

9. Calculate the ratio of the contribution to point A from points B and D.

Ratio of contribution from B to D = $5.07 \times 10^{-8} / 5.14 \times 10^{-5}$
= 0.001

Percent contribution of B = 0.001 X 100
= 0.1 %

Dispersion 9

1. First determine the total amount of toxic gas released, m_T.

   $m_T = (400)(3)(60)$
   $= 72,000$ g

2. Determine the values of the three standard deviations from Appendix II.

   $\sigma_x = \sigma_y = 15$ m at downwind distance = 200 m and stability category D
   $\sigma_z = 8.5$ m at downwind distance = 200 m and stability category D

3. Calculate the time at which the maximum concentration will occur at the school.

   t = downwind distance/wind speed
   = (200)/(3.5)
   = 57.1 sec

4. Calculate the maximum concentration at the school.

$$C(200,50,0,20) = 2\, m_T/((2\pi)^{1.5}\, \sigma_x \sigma_y \sigma_z)[\exp(-0.5((x-ut)/\sigma_x)^2)][\exp(-0.5(H/\sigma_z)^2)][\exp(-0.5(y/\sigma_y)^2)]$$
$$= \{(2)(72,000)/[(2)(3.14)]^{1.5}(15)(15)(8.5)\}[1][\exp(-0.5(20/8.5)^2][\exp(-0.5(50/15)^2]$$
$$= 1.16 \times 10^{-3}\ g/m^3$$

   Note that for the maximum concentration, x = ut, and the first exponential term becomes 1.0.

5. Convert the above concentration to ug/l.

$$C(200,50,0,20) = (1.16 \times 10^{-3})(10^6/10^3)$$
$$= 1.16\ ug/l$$

6. Is there any impact on students in the school?

   Yes, since the maximum concentration calculated above is 1.16 ug/l which is greater than 1.0 ug/l.

Dispersion 10

1. First determine the values of the dispersion coefficients, σ_y and σ_z from the **Introduction** section of Dispersion problem 10.

   σ_y = 300 m
   σ_z = 220 m

2. Assign a value to the dispersion coefficient σ_x.

   $\sigma_x = \sigma_y$ = 300 m (see the **Introduction** section of Dispersion problem 9)

3. Assign a value to the term H.

   H = 0 since the explosion occurs at ground level.

4. Set the LHS of the instantaneous "puff" equation to the maximum GLC allowed and solve for the time, t.

$$C(x,y,0,H) = 2\, m_T/((2\pi)^{1.5}\,\sigma_x\,\sigma_y\,\sigma_z)[\exp(-0.5((x-ut)/\sigma_x)^2)][\exp(-0.5(H/\sigma_z)^2)][\exp(-0.5(y/\sigma_y)^2)].$$

$$1 \times 10^{-9} = \{(2)(1000)(1000)/[(2)(3.14)]^{1.5}(300)(300)(220)\}\{\exp[-0.5((4000-6t)/300)^2]\}\{1\}\{\exp[-0.5(1000/300)^2]\}$$

$$1 \times 10^{-9} = (0.006413)\{\exp[-0.5((4000-6t)/300)^2]\}(0.003866)$$

$$4.0332 \times 10^{-10} = \exp[-0.5((4000-6t)/300)^2]$$
$$-10.12 = -0.5[(4000-6t/300)^2]$$

Solving for t,
t = 441.7 sec
  = 7.36 min