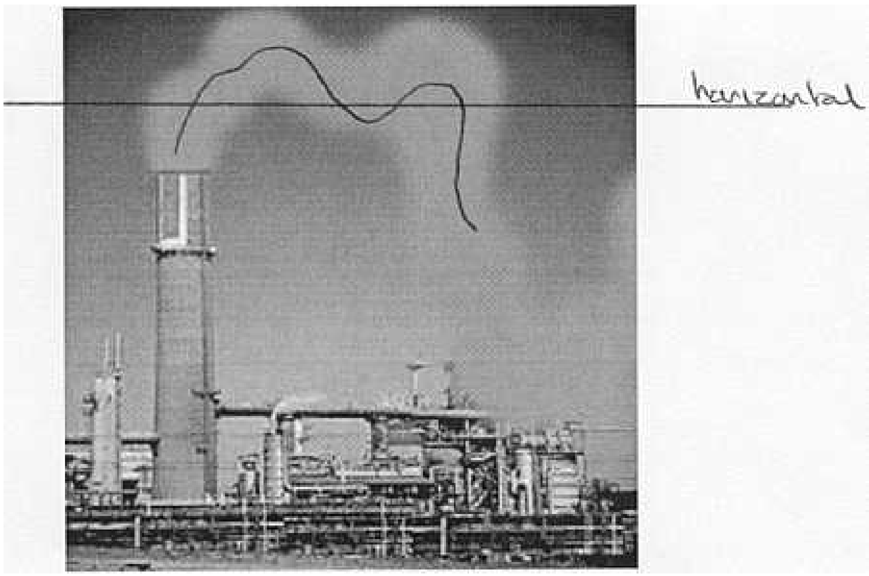
CIVE 3331 Environmental Engineering
Spring 2005 Exam #3

Name: SOLUTION

Problem 1 – (Plumes and Atmospheric Stability)

Choose the correct description for each plume image:

Plume A:



Description:

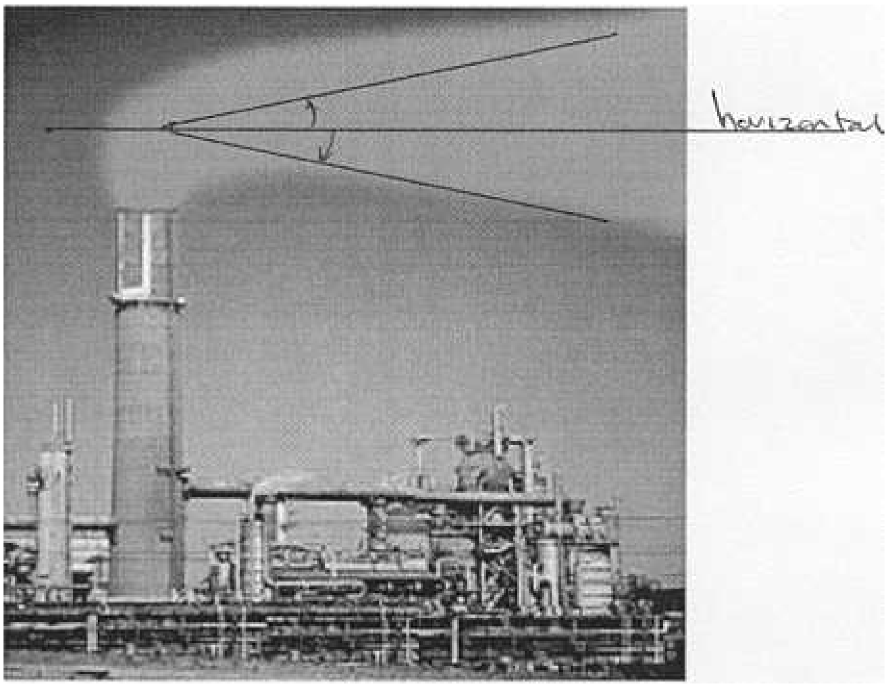
a) Fumigation: The most dangerous plume: contaminants are all coming down to ground level. They are created when atmospheric conditions are stable above the plume and unstable below. This happens most often after the daylight sun has warmed the atmosphere, which turns a night time fanning plume into fumigation for about a half an hour.
b) Lofting Plume: Favorable in the sense that fewer impacts at ground level. Pollutants go up into environment. They are created when atmospheric conditions are unstable above the plume and stable below.
c) Fanning Plume: Usually occurs at night, or 1200m-1800m above ground. There is high ground concentration if stack is short or if plume moves through rugged terrain. Occurs in stable inversion atmospheric conditions.
d) Coning Plume: standard plume, large probability of ground contact some distance downwind. Occurs in neutral atmospheric conditions.
e) Looping Plume: dissipates in patches and relatively rapidly with distance. High probability of high concentrations sporadically at ground level close to stack. Occurs in unstable atmospheric conditions.

6
6
5
8

Name: SOLUTION

Problem 1 – (Plumes and Atmospheric Stability)

Plume B:



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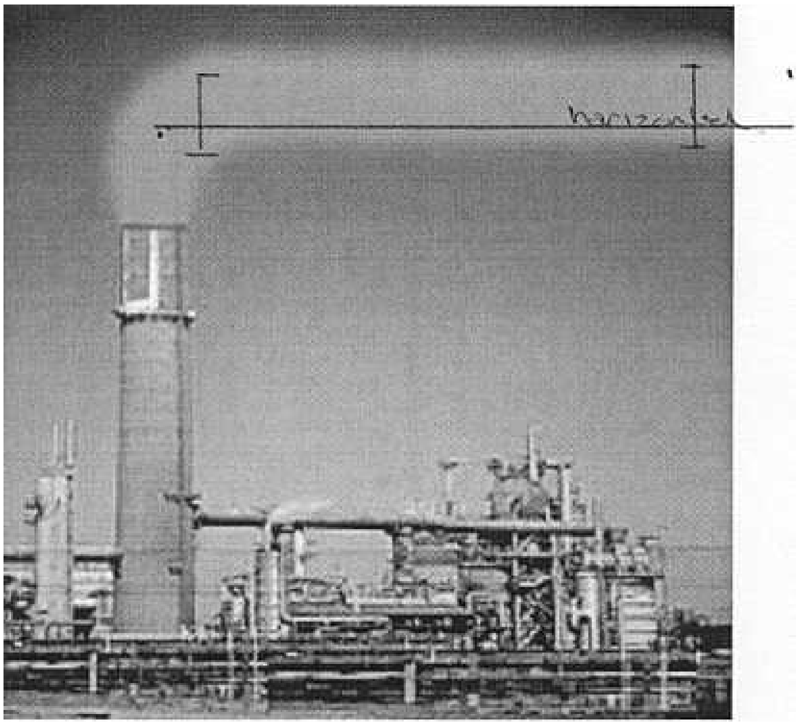
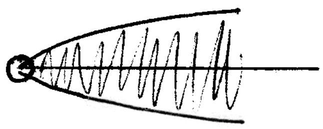


Fans in plan view



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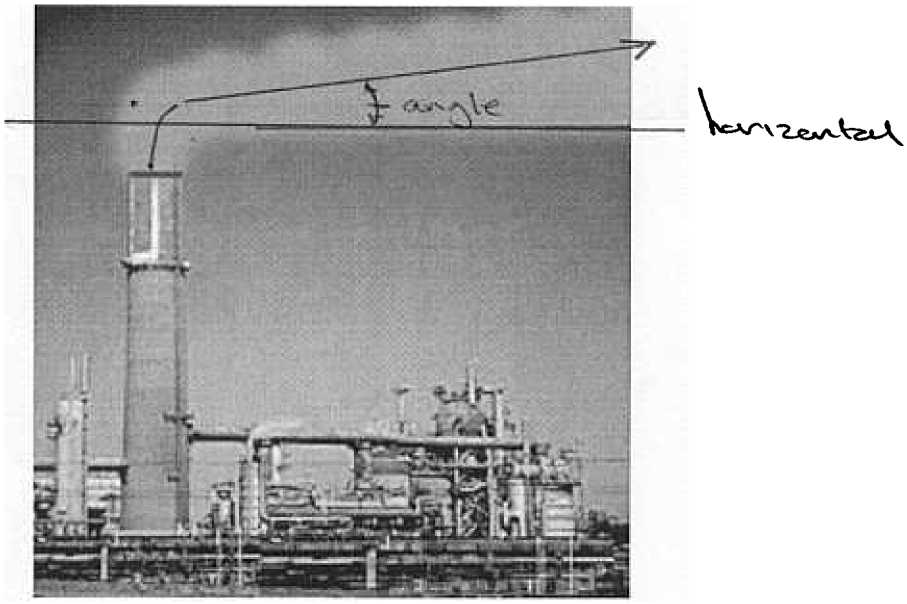

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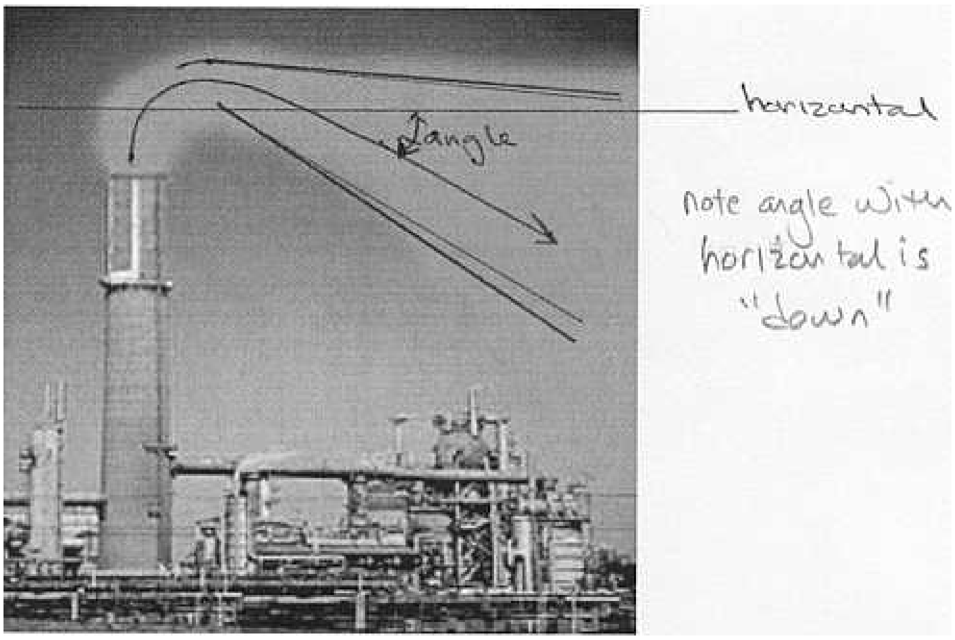

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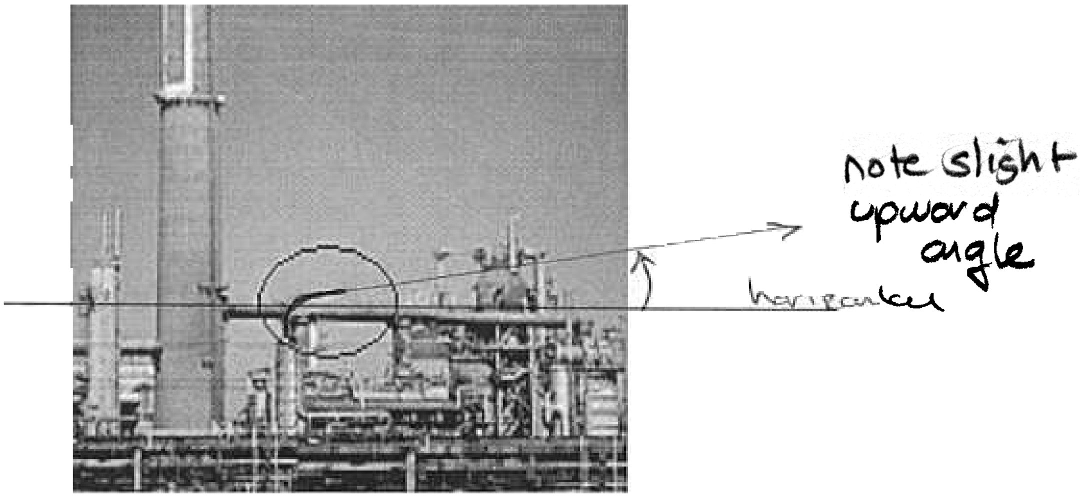

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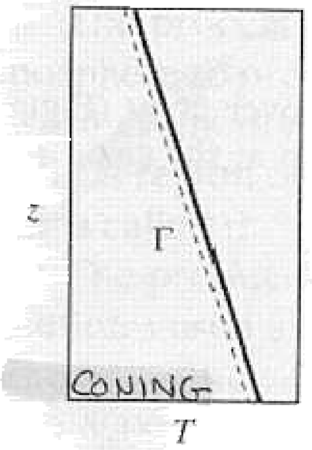
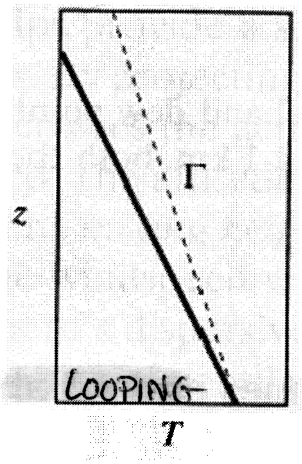
Problem 1 (Continued)

For each of the plumes above select the most probable atmospheric temperature profile.

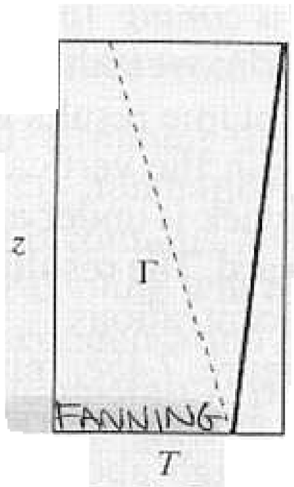
Plume ID	Profile ID
A	B
B	A
C	C
D	E
E	D
F	E



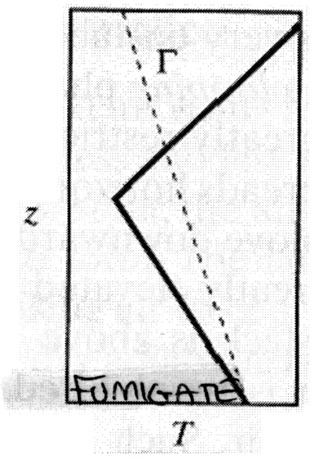
Profile A



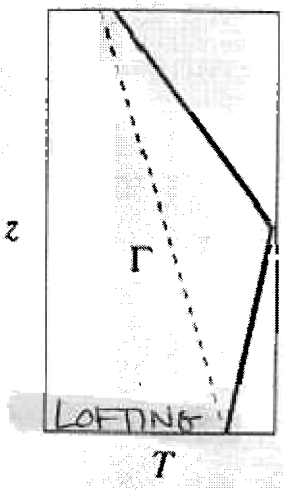
Profile B



Profile C



Profile D



Profile E

Sketches from textbook

Step 1: label sketch

Step 2: match sketch with description

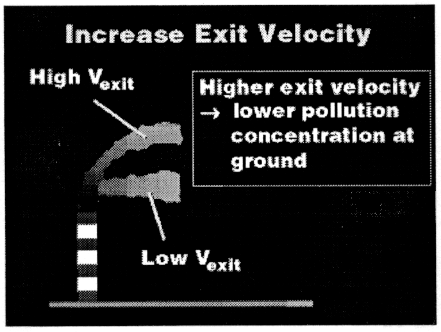
Name: Solution

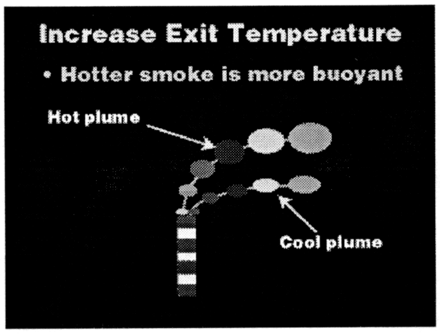
Problem 1 – (Continued)

The ventilation factor gives us a way of relating the pollution concentration to the parameters that control dispersion of the pollution in the local environment. Basically, increasing either the mixing height or the wind speed increases the effective volume in which pollutants are allowed to mix. The larger the volume, the lower the pollution concentration. Engineers have little control over windspeed but we can affect the mixing height.

One option is to increase the stack height, which makes sense if the source is a new source, but it is infeasible to raise existing stacks significantly.

Engineers can affect the exit speed of pollutants in a stack, conceptually the faster the smoke gushes out, the more momentum it has, and the higher it will fly before it levels out and disperses toward the ground. Engineers can also affect the exit temperature of pollutants in a stack, conceptually the higher the temperature, the greater the positive buoyancy in smoke streaming out of the smokestack, so the smoke has to rise higher before it has adiabatically cooled to a neutral buoyancy temperature. These two impacts are depicted in the two figures below.





Two possible methods to increase the exit temperature are to heat the smoke before it exits the stack and to run a hotter combustion process.

A) What are some disadvantages of heating the smoke?

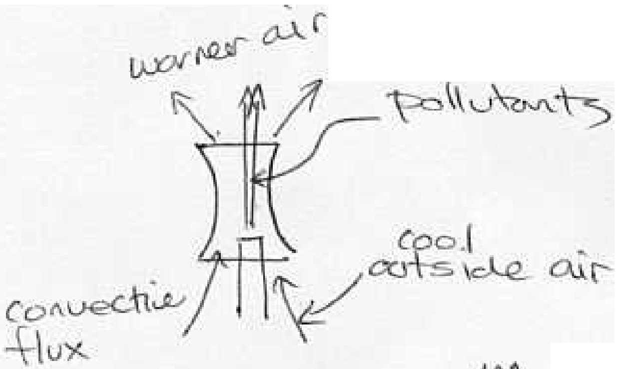
- need to use fuel just to heat smoke ⇒ "waste heat"
- risk of ignition of exhaust gas (unless using afterburning)
- increase thermal NO_x in afterburning
- increase reaction rates

B) What are some disadvantages of running a hotter combustion process?

- increased thermal NO_x
- increased risk of run-away reaction(s)
- increased fuel use just to heat process
- machinery wear at higher temps

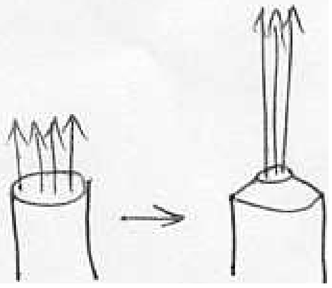
C) What is one way to increase stack velocity?

- blowers & fans
- Venturi type stack



D) What is another way to increase stack velocity?

- reduce stack diameter (area)

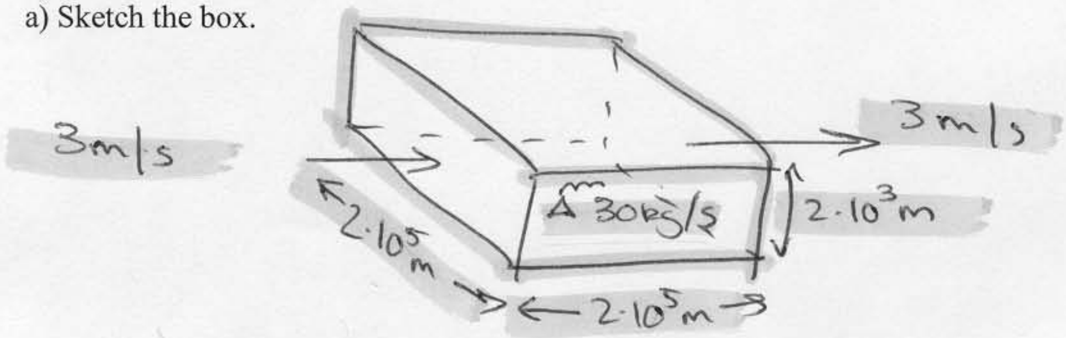


Name: SOLUTION

Problem 2 – (Box Models)

Consider a box model for an airshed over a city 2 x 10^5 meters on a side with a mixed depth of 2000 meters. Winds with negligible SO_2 blow at 3 m/s on one side of the box. SO_2 is emitted within the box at a rate of 30kg/s (assume that within the box the pollutant completely mixes).

a) Sketch the box.



b) Write the relevant governing equation(s).

$$\frac{dC\forall}{dt} = \forall\frac{dC}{dt} = C_{IN}Q_{IN} - CQ_{OUT} + \text{SOURCE} - \underset{(\text{SINK})}{\text{DECAY}}$$

$C_{IN} = 0$ (Negligible SO_2)

$Q_{IN} = Q_{OUT} = V_{IN}A_{IN}$

$V_{IN} = 3\text{m/s}$

$A_{IN} = A_{OUT} = (2 \cdot 10^5\text{m})(2 \cdot 10^3\text{m}) = 4 \cdot 10^8\text{m}^2$

$\forall = (2 \cdot 10^5\text{m})(2 \cdot 10^5\text{m})(2 \cdot 10^3\text{m}) = 8 \cdot 10^{13}\text{m}^3$

SOURCE = 30kg/s

DECAY = $KC\forall$

Name: SOLUTION

Problem 2 – (Box Models)

c) If SO_2 is conservative, estimate the steady state concentration of SO_2 in the airshed.

$$\underbrace{\cancel{\forall \frac{dC}{dt}}}_{=0 \text{ steady state}} = -C V_{OUT} A_{OUT} + S - \underbrace{\cancel{K} C \forall}_{=0 \text{ conservative}}$$

$$C = \frac{S}{V_{OUT} A_{OUT}} = \frac{30\,kg/s}{(3\,m/s)(4 \cdot 10^8\,m^2)} = \frac{30\,kg/\cancel{s}}{12 \cdot 10^8\,m^3/\cancel{s}}$$

$$= \frac{30\,kg}{12 \cdot 10^8\,m^3} = 0.025 \cdot 10^{-6}\,kg/m^3$$

$$= 25 \cdot 10^{-9}\,kg/m^3$$

d) If the SO_2 is **NOT** conservative and instead has a first order reaction rate of 0.23/hr estimate the steady state concentration over the airshed.

$$\underbrace{\cancel{\forall \frac{dC}{dt}}}_{0 \text{ steady state}} = -C V_{OUT} A_{OUT} + S - K C \forall$$

$$C = \frac{S}{V_{OUT} A_{OUT} + K \forall} = \frac{30\,kg/s}{(3\,m/s)(4 \cdot 10^8\,m^2) + (0.23/hr)\left(\frac{1\,hr}{3600\,s}\right)(8 \cdot 10^{13}\,m^3)}$$

$$= \frac{30\,kg/s}{1.2 \cdot 10^9\,m^3/s + 5.11 \cdot 10^9\,m^3/s} = \frac{30\,kg/\cancel{s}}{6.31 \cdot 10^9\,m^3/\cancel{s}}$$

$$= 4.79 \cdot 10^{-9}\,kg/m^3$$

lwf16 → lwf14

Name:______________________________

Problem 3- (Gas Tracers, Air Exchange, Mass Balance Models)

A tracer gas is used to determine the air exchange rate in a building. By injecting a stable gas into the building and then monitoring the decay in concentration with time we can estimate the air exchange. Typical units are air changes per hour (ach).

The governing equation (to find ach) is

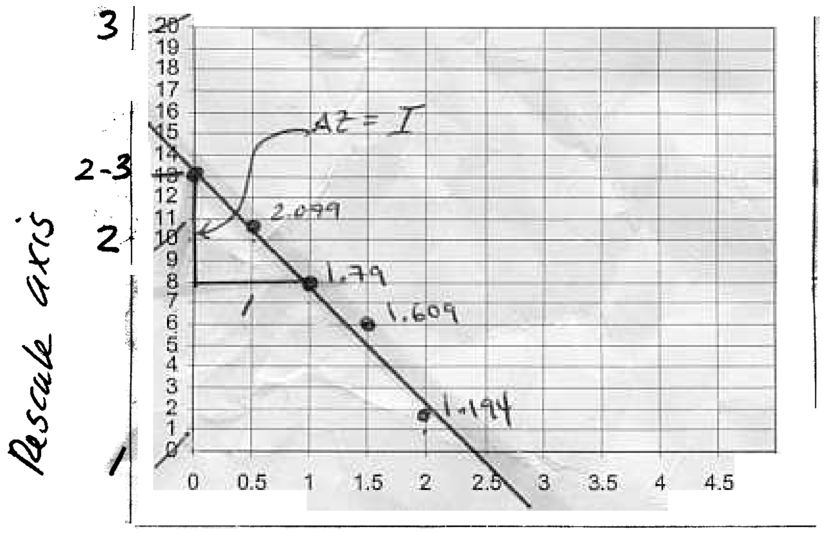
$$C = C_o e^{-It}$$

where I is air changes per hour, and t is time in hours.

a) Use this model to estimate the value of I for the following tracer data (the negative of the slope of a plot of lnC versus time should equal the infiltration rate):

Time (hr)	Concentration (ppm)	ln(c)
0	10.0	2.302
	8.0	2.079
1.0	6.0	1.791
1.5	5.0	1.609
2.0	3.3	1.194

1 1/2
2.362
1.791
0.511



Note:
Graph Not "required" – can simply use several points in ln(c) to estimate I.
Trial-and-error also OK.

$$\Delta Z = \frac{2.302 - 1.791}{1} = 0.511$$

$I = 0.511$

Name: SOLUTION

Problem 3- (Continued)

b) Verify that your value of *I* reasonable by computing the concentration for each time using the value just estimated. Put your results into the table below:

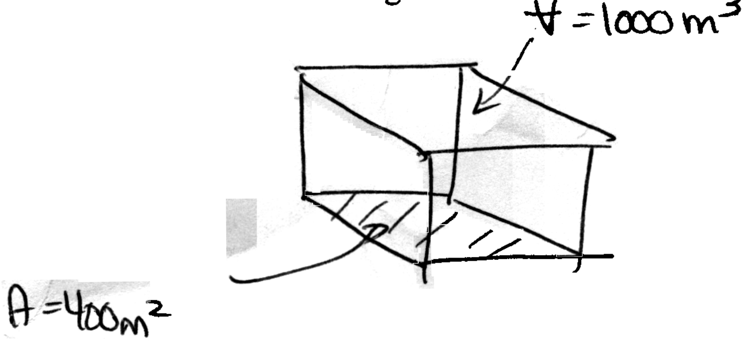
$C = C_0 e^{-0.511 t}$

Time (hr)	Observed (ppm)	Estimated (ppm)	Rounded
0	10.0	10.0	10
0.5	8.0	7.745	7.75
1.0	6.0	5.998	6
1.5		4.646	4.65
2.0		3.598	3.6

conclude "close" to observed ∴ .51 is reasonable

of
of floor
-sec (0.6

Sketch of the building:



Governing equation(s) (Hint: Mass balance)

0 No internal source

0 steady state

$\underbrace{[0.6\ pCi/m^2\text{-}sec][400\ m^2]}_{= C_{IN} Q_{IN}}$

≠0, but decay rate not supplied - will solve with & without decay

SINK = KCV

* ALSO COULD SET $C_{IN} Q_{IN} = \phi$ AND TREAT .6 pCi/m²/sec AS A SOURCE

Name: SOLUTION

Problem 3- (Continued)

$0 = C_{IN}Q_{IN} - C_{OUT}Q_{OUT}$ SINK

$Q_{OUT} = ?$ 0.51 air changes per hour

1 air change = $1000\ m^3$

$Q_{OUT} = (0.51)(1000) = 510\ m^3/hr$

Neglect decay rate (i.e SINK = 0)

$$C_{OUT} = \frac{C_{IN}Q_{IN}}{Q_{OUT}} = \frac{(0.6\ pCi/m^2/sec)(400\ m^2)}{(510\ m^3/hr)\left(\frac{1hr}{3600\ sec}\right)}$$

$= 1694\ pCi/m^3$

INCLUDE decay rate (SINK = $KC\forall$)

$K = 7.6 \cdot 10^{-3}/hr$ (Table 7.15)

$$C_{OUT}Q_{OUT} = C_{IN}Q_{IN} - KC_{OUT}\forall$$

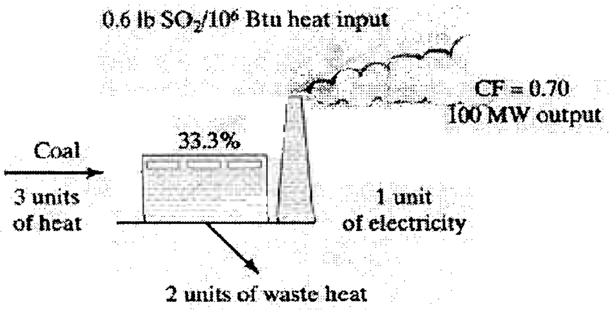
$$C_{OUT} = \frac{C_{IN}Q_{IN}}{Q_{OUT} + K\forall} = \frac{(0.6)(400)}{\left[(510/3600) + \left(\frac{7.6 \cdot 10^{-3}}{3600}\right)(1000)\right]}$$

$= 1669\ pCi/m^3$

Name: SOLUTION

Problem 4- (Energy Balance and Fuel Selection)

A 100-MW, 33.3 percent efficient coal fired power plant operates at full power 70 percent of the time and idles (no power) 30 percent of the time.



A) How much electricity (kWhr/yr) will the plant produce?
B) How much electricity could the plant produce if it operates at full power all the time (no idle time)?
C) How many Btu of heat per year are needed to generate the electricity produced in (A)? (At 33.3% efficiency, 3kWhr of heat at 3412 Btu/kWhr, are needed to produce 1 kWhr of electricity as shown in the sketch)?
D) Suppose this plant emits 0.6 lb of SO_2 per million Btu of heat input, and suppose it has enough SO_2 allowances to continue to do so. If the power company switches this plant to a natural gas plant (no SO_2 emissions) how many pounds of SO_2 emissions are "saved" in one year.
E) If 8800 Btu-lb coal costs $65/ton (April 15, 2005 Spot Price) what is the annual fuel cost for the existing plant?
F) If natural gal costs $7per 1million Btu (April 15, 2005 Spot Price), what is the annual fuel cost for the plant if it switches fuel?
G) If the SO_2 allowances are trading at $1500 per 2000 lbs, does the fuel switch make economic sense? (Ignore the capital costs of the plant retrofit?). If not, how much must the allowances sell for to make the switch economically break-even?

a) $100\ MW = 100 \cdot 10^3\ kW$

$= 100{,}000\ kW$

Produces power 70% of the time

Annual production

$$100{,}000\ kW \cdot \frac{24\ hrs}{1\ day} \cdot \frac{365\ day}{1\ yr} \cdot 0.7 = 6.132 \cdot 10^8\ kW\text{-}hr$$

b) No idle time

$$100{,}000\ kW \cdot \frac{24\ hrs}{1\ day} \cdot \frac{365\ day}{1\ yr} = 8.76 \cdot 10^8\ kW\text{-}hr$$

c) To produce $6.132 \cdot 10^8\ kW\text{-}hr$ takes how much input energy?

$$\text{effic.} = \frac{\text{output}}{\text{input}}$$

$$\therefore \text{input} = \frac{\text{output}}{\text{effic.}} = \frac{6.132 \cdot 10^8\ kW\text{-}hr}{0.333} = 1.840 \cdot 10^9\ kW\text{-}hr$$

in Btus

$$1.840 \cdot 10^9\ kW\text{-}hr \times \frac{3412\ Btu}{kW\text{-}hr} = 6.277 \cdot 10^{12}\ Btu$$

d) SO_2 emmissions $0.6\ lb/10^6\ Btu$

$$6.277 \cdot 10^{12}\ Btu \times \frac{0.6\ lbs}{1 \cdot 10^6\ Btu} = 3.766 \cdot 10^6\ lbs\ SO_2$$

e) \$/yr for fuel – coal fired

$8800\ \frac{Btu}{lb}$ coal costs $\$65/2000\ lbs$

$$\therefore \frac{8800\ Btu}{lb} \cdot 2000\ lbs = \$65$$

$$1.76 \cdot 10^7\ Btu = \$65$$

$$\Rightarrow \frac{6.277 \cdot 10^{12}\ Btu}{yr} \cdot \frac{\$65}{1.76 \cdot 10^7\ Btu} =$$

$$= 2.318 \cdot 10^7\ \$/yr$$

Name: SOLUTION

Problem 4- (Continued)

f) \$/yr for gas fired (assume also 1/3 efficient)

$$\frac{\$7}{1\cdot10^{6}\,Btu} * 6.277\cdot10^{12}\,\frac{Btu}{yr} = 4.394\cdot10^{7}\,\$/yr$$

Economic Analysis

Coal Fired	Gas Fired
fuel costs: $2.318\cdot10^{7}\,\$/yr$	$4.394\cdot10^{7}\,\$/yr$: fuel costs

$$-\left(3.766\cdot10^{6}\,lbs\ SO_2\right)\left(\frac{\$1500}{2000\,lbs}\right)$$

sell emissions credits

Revenue is "negative cost"

$$\begin{array}{r} 4.394\cdot10^{7}\,\$/yr \\ -\,2.825\cdot10^{6}\,\$/yr \\ \hline 4.111\cdot10^{7}\,\$/yr \end{array}$$

@ \$1500/ton SO_2 sales, still cheaper to burn coal

Find \$/ton to break even

$$\begin{array}{r} 4.394\cdot10^{7} \\ -\,2.318\cdot10^{7} \\ \hline 2.076\cdot10^{7}\,\$/yr \end{array}$$

← Revenue needed from emmissions credits to break even

$$\frac{2.076\cdot10^{7}\,\$/yr}{3.766\cdot10^{6}\,lbs\ SO_2}\,\frac{2000\,lbs}{ton} = \$$$

$$= 1.102\cdot10^{4}\,\$/ton$$

($\approx$11,000\$/ton)

Note: Gas fired plants can be run more efficent than coal; so assumption in (f) is not realistic (but necessary in this problem)