2.1 (a)

$$\begin{array}{c|c|c|c|c} 2\text{ wk} & 7\text{ d} & 24\text{ h} & 3600\text{ s} & 10^6\ \mu\text{s} \\ \hline & 1\text{ wk} & 1\text{ d} & 1\ \ \text{h} & 1\ \ \text{s} \end{array} = 1.2096\times 10^{12}\,\mu\text{s} = \underline{\underline{1\times 10^{12}\ \mu\text{s}}}$$

(b)

$$\begin{array}{c|c|c|c} 38.1\text{ ft/s} & 0.3048\text{ m} & 1\text{ km} & 3600\text{ s} \\ \hline & 1\text{ ft} & 1000\text{ m} & 1\text{ h} \end{array} = \underline{\underline{41.8\text{ km/h}}}$$

(c)

$$\begin{array}{c|c|c|c|c} 554\text{ m}^4 & 1\text{ d} & 1\text{ h} & 0.453593\text{ kg} & 1\text{ ft}^4 \\ \hline \text{d}\cdot\text{kg} & 24\text{ h} & 60\text{ min} & 1\text{ lb}_\text{m} & (0.3048\text{ m})^4 \end{array} = \underline{\underline{20.2\text{ ft}^4/\text{min}\cdot\text{lb}_\text{m}}}$$

2.2 **(a)**

$$\begin{array}{c|c|c} 1760\ \text{mi} & 0.001\ \text{km} & 1\ \ \text{h} \\ \hline \text{h} & 0.0006214\ \text{mi} & 3600\ \text{s} \end{array} = \underline{\underline{0.787\ \text{km/s}}}$$

(b)

$$\begin{array}{c|c|c} 1400\ \text{kg} & 2.20462\ \text{lb}_\text{m} & 1\ \ \text{m}^3 \\ \hline \text{m}^3 & 1\ \text{kg} & 35.3145\ \text{ft}^3 \end{array} = \underline{\underline{87.4\ \text{lb}_\text{m}/\text{ft}^3}}$$

(c)

$$\begin{array}{c|c|c} 5.37\times10^3\ \text{kJ} & 1000\ \text{J} & 1.34\times10^{-3}\ \text{hp} \\ \hline \text{s} & 1\ \text{kJ} & 1\ \text{J/s} \end{array} = 7195.8\ \text{hp} \Rightarrow \underline{\underline{7200\ \text{hp}}}$$

2.3 Assume that a baseball occupies the space equivalent to a $3 \text{ in} \times 3 \text{ in} \times 3 \text{ in}$ cube. For a classroom with dimensions $40 \text{ ft} \times 40 \text{ ft} \times 15 \text{ ft}$:

$$n_{\text{balls}} = \frac{40 \times 40 \times 15 \text{ ft}^3}{} \left| \frac{(12)^3 \text{ in}^3}{\text{ft}^3} \right| \frac{1 \text{ ball}}{3^3 \text{ in}^3} = 1.536 \times 10^6 \approx \underline{\underline{\text{1.5 million baseballs}}}$$

The estimate could vary by an order of magnitude or more, depending on the assumptions made.

2.4 $$\begin{array}{c|c|c|c|c|c|c} 4.3\ \text{light yr} & 365\ \text{d} & 24\ \text{h} & 3600\ \text{s} & 1.86\times10^{5}\ \text{mi} & 3.2808\ \text{ft} & 1\ \text{step} \\ \hline & 1\ \ \text{yr} & 1\ \text{d} & 1\ \ \text{h} & 1\ \ \ \ \text{s} & 0.0006214\ \text{mi} & 2\ \text{ft} \end{array} = \underline{\underline{7\times10^{16}\ \text{steps}}}$$

2.5

$$\text{Site A: } \begin{array}{l|l} 50 \text{ microns } (\mu m) & 100 \text{ cm} \\ \hline & 10^{6}\ \mu m \end{array} = 0.005 \text{ cm}$$

$$\text{Site B: } \begin{array}{l|l|l} 3 \text{ mil} & 10^{-3} \text{ in} & 30.48 \text{ cm} \\ \hline & 1 \text{ mil} & 12 \text{ in} \end{array} = 0.00762 \text{ cm}$$

$0.005 \text{ cm} < 0.00762 \text{ cm} \Rightarrow \underline{\underline{\text{Site B is selling the thicker liner.}}}$

2.6 Distance from the earth to the moon = 238857 miles

$$\begin{array}{r|r|r} 238857\ \text{mi} & 1\ \ \ \ \text{m} & 1\ \text{report} \\ \hline & 0.0006214\ \text{mi} & 0.001\ \text{m} \end{array} = \underline{\underline{4\times10^{11}\ \text{reports}}}$$

2.7

$$\begin{array}{c|c|c|c}
19\text{ km} & 1000\text{ m} & 0.0006214\text{ mi} & 1000\text{ L} \\
\hline
1\text{ L} & 1\ \ \text{km} & 1\text{ m} & 264.17\text{ gal}
\end{array} = 44.7\text{ mi/gal}$$

Calculate the total cost to travel x miles:

$$\text{Total Cost}_{\text{American}} = \$28{,}500 + \begin{array}{r|c|c}
\$3.25 & 1\text{ gal} & x\text{ (mi)} \\
\hline
\text{gal} & 28\text{ mi} &
\end{array} = 28{,}500 + 0.1161x$$

$$\text{Total Cost}_{\text{European}} = \$35{,}700 + \begin{array}{r|c|c}
\$3.25 & 1\text{ gal} & x\text{ (mi)} \\
\hline
\text{gal} & 44.7\text{ mi} &
\end{array} = 35{,}700 + 0.07271x$$

Equate the two costs: $x = \underline{\underline{1.7 \times 10^5\text{ miles}}}$

2.8 (a) $$\begin{array}{c|c|c|c} 100\times10^{6}\ \text{J} & 3600\ \text{s} & 24\ \text{hr} & 365\ \text{d} \\ \hline \text{s} & 1\ \text{hr} & 1\ \text{d} & 1\ \text{yr} \end{array} = \underline{\underline{3.15\times10^{15}\ \text{J/yr}}}$$

(b) The question asks “how much power does a 100 MW plant generate annually?” The answer is implied in the units. The question should ask, “How much energy does a 100 MW plant generate annually?”, e.g. in units of J/yr.

(c) The unit of MW is equivalent to J/s; power is energy/time, so MW is already a rate-based unit. We know that 100MW = 100MJ/s.

2.9 **(a)**
$$\begin{array}{c|c|c} 25.0\ \text{lb}_\text{m} & 32.1714\ \text{ft/s}^2 & 1\quad \text{lb}_\text{f} \\ \hline & & 32.1714\ \text{lb}_\text{m}\cdot\text{ft/s}^2 \end{array} = \underline{\underline{25.0\ \text{lb}_\text{f}}}$$

(b)
$$\begin{array}{c|c|c} 25\ \text{N} & 1 & 1\ \text{kg}\cdot\text{m/s}^2 \\ \hline & 9.8066\ \text{m/s}^2 & 1\ \text{N} \end{array} = 2.55\ \text{kg} \Rightarrow \underline{\underline{2.6\ \text{kg}}}$$

(c)
$$\begin{array}{c|c|c|c|c} 10\ \text{ton} & 1\ \text{lb}_\text{m} & 1000\ \text{g} & 980.66\ \text{cm/s}^2 & 1\ \text{dyne} \\ \hline & 5\times10^{-4}\ \text{ton} & 2.20462\ \text{lb}_\text{m} & & 1\ \text{g}\cdot\text{cm/s}^2 \end{array} = \underline{\underline{9\times10^9\ \text{dynes}}}$$

2.10

$$\begin{array}{r|r|r|r|c} 50\times 25\times 2\ \text{m}^3 & 35.3145\ \text{ft}^3 & 75.3\ \text{lb}_\text{m} & 32.174\ \text{ft} & 1\ \text{lb}_\text{f} \\ \hline & 1\ \text{m}^3 & 1\ \text{ft}^3 & 1\ \text{s}^2 & 32.174\ \text{lb}_\text{m}/\text{ft}\cdot\text{s}^2 \end{array} = \underline{\underline{6.6\times 10^6\ \text{lb}_\text{f}}}$$

2.11

$$\begin{array}{c|c|c|c} 500\ \text{lb}_\text{m} & 1\ \text{kg} & 1\ \text{m}^3 & 35.3145\ \text{ft}^3 \\ \hline & 2.20462\ \text{lb}_\text{m} & 12.5\ \text{kg} & 1\ \text{m}^3 \end{array} \approx 500\left(\frac{1}{2}\right)\left(\frac{1}{10}\right)\left(\frac{40}{1}\right) \approx \underline{\underline{1000\ \text{ft}^3}}$$

2.12

$$\begin{array}{c|c|c|c|c} 31{,}000\ \text{tons} & 1\ \text{lb}_\text{m} & 0.453593\ \text{kg} & 0.012\ \text{m}^3 & 365\ \text{days} \\ \hline 1\ \text{day} & 5\times10^{-4}\ \text{tons} & 1\ \text{lb}_\text{m} & \text{kg} & 1\ \text{yr} \end{array} = 1.2318\times10^{8}\ \text{m}^3/\text{yr} \Rightarrow \underline{\underline{1.2\times10^{8}\ \text{m}^3}}$$

2.13 **(a)**

(i) Electricity generated in a month by one panel :

$$=\begin{array}{c|c|c|c|c} 140\ \text{J} & 3600\ \text{s} & 5\ \text{hrs} & 30\ \text{days} & 2.778\times10^{-7}\ \text{kWh} \\ \hline \text{s} & 1\ \text{hr} & 1\ \text{day} & 1\ \text{month} & 1\ \text{J} \end{array}$$

$= 21\ \text{kWh}$

The number of panels needed $= 948\text{kWh} / 21\text{kWh} / \text{panel} = 45.11\ \text{panels} \rightarrow \underline{\underline{46\ \text{panels}}}$

Cost $= 46\ \text{panels} \times \$210 / \text{panel} = \underline{\underline{\$9660}}$

(ii) Electricity generated in a month by one panel :

$$=\begin{array}{c|c|c|c|c} 240\ \text{J} & 3600\ \text{s} & 5\ \text{hrs} & 30\ \text{days} & 2.778\times10^{-7}\ \text{kWh} \\ \hline \text{s} & 1\ \text{hr} & 1\ \text{day} & 1\ \text{month} & 1\ \text{J} \end{array}$$

$= 36\ \text{kWh}$

The number of panels needed $= 948\text{kWh} / 36\text{kWh} / \text{panel} = 26.33\ \text{panels} \rightarrow \underline{\underline{27\ \text{panels}}}$

Cost $= 27\ \text{panels} \times \$260 / \text{panel} = \underline{\underline{\$7020}}$

240W panel will be more beneficial.

(b) The amount of excess electricity in a month:

$= 27\ \text{panels} \times 36\ \text{kWh} / \text{panel} - 972\ \text{kWh} = 24\ \text{kWh}$

$$\text{Total cost savings} = \begin{array}{c|c|c|c} 24\ \text{kWh} & 12\ \text{months} & 3\ \text{yr} & \$\ 0.15 \\ \hline \text{month} & 1\ \text{yr} & & 1\ \text{kWh} \end{array} = \underline{\underline{\$129.6}}$$

Student Response

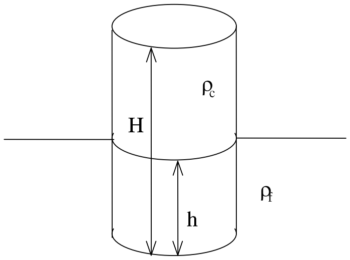
(c) Student Response

2.14 **(a)** $m_{\text{displaced fluid}} = m_{\text{cylinder}} \Rightarrow \rho_{\text{f}} V_{\text{f}} = \rho_{\text{c}} V_{\text{c}} \Rightarrow \rho_{\text{f}} h \pi r^2 = \rho_{\text{c}} H \pi r^2$

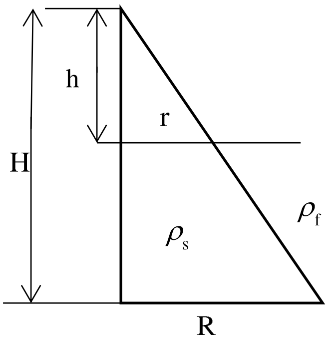
$$\rho_{\text{c}} = \frac{\rho_{\text{f}} h}{H} = \frac{(30\text{ cm} - 13.5\text{ cm})(1.00\text{ g/cm}^3)}{30\text{ cm}} = \underline{\underline{0.55\text{ g/cm}^3}}$$

(b) $$\rho_{\text{f}} = \frac{\rho_{\text{c}} H}{h} = \frac{(30\text{ cm})(0.55\text{ g/cm}^3)}{(30\text{ cm} - 18.9\text{ cm})} = \underline{\underline{1.49\text{ g/cm}^3}}$$

(c) Student Response



2.15



$$V_s = \frac{\pi R^2 H}{3}; \;\; V_f = \frac{\pi R^2 H}{3} - \frac{\pi r^2 h}{3} \;; \; \frac{R}{H} = \frac{r}{h} \Rightarrow r = \frac{R}{H} h$$

$$\Rightarrow \; V_f = \frac{\pi R^2 H}{3} - \frac{\pi h}{3}\left(\frac{Rh}{H}\right)^2 = \frac{\pi R^2}{3}\left(H - \frac{h^3}{H^2}\right)$$

$$\rho_f V_f = \rho_s V_s \Rightarrow \rho_f \frac{\pi R^2}{3}\left(H - \frac{h^3}{H^2}\right) = \rho_s \frac{\pi R^2 H}{3}$$

$$\Rightarrow \rho_f = \rho_s \frac{H}{H - \frac{h^3}{H^2}} = \rho_s \frac{H^3}{H^3 - h^3} = \rho_s \underline{\underline{\frac{1}{1 - \left(\frac{h}{H}\right)^3}}}$$

2.16 **(a)** $\underline{h = 0}$, the drum is empty:

$$V = L\left[r^2\cos^{-1}\left(\frac{r-0}{r}\right) - (r-0)\sqrt{r^2-(r-0)^2}\right] = \underline{\underline{0}}$$

$\underline{h = r}$, the drum is half full/empty:

$$V = L\left[r^2\cos^{-1}\left(\frac{r-r}{r}\right) - (r-r)\sqrt{r^2-(r-r)^2}\right] = L\left[r^2\cos^{-1}(0)\right] = \underline{\underline{\frac{\pi}{2}Lr^2}}$$

$\underline{h = 2\text{r}}$, the drum is full:

$$V = L\left[r^2\cos^{-1}\left(\frac{r-2r}{r}\right) - (r-2r)\sqrt{r^2-(r-2r)^2}\right] = L\left[r^2\cos^{-1}(-1)\right] = \underline{\underline{\pi Lr^2}}$$

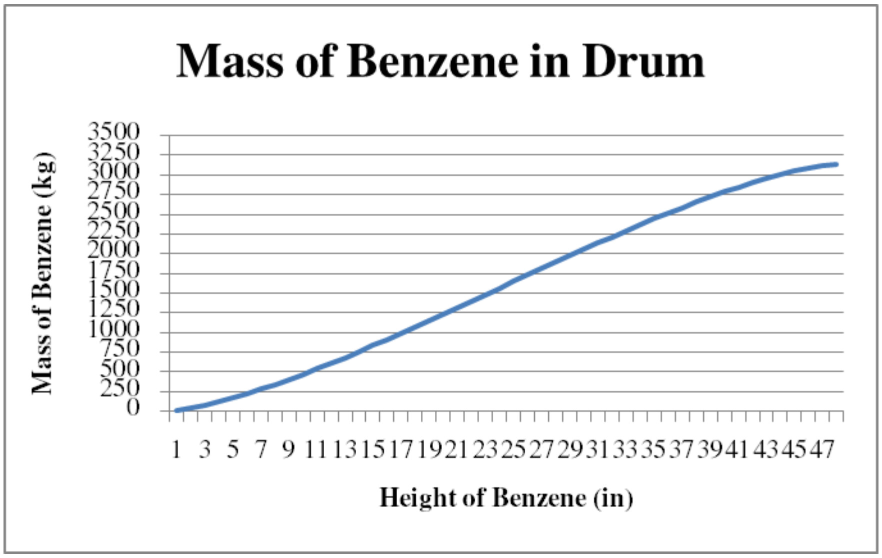
(b) $L = 10$ ft, $r = 2$ ft, $h = 4$ in, $\cos^{-1}$ found in radians

$$h = \left.\frac{4\text{ in}}{}\right|\frac{1\text{ ft}}{12\text{ in}} = 0.333\text{ ft}$$

$$V = (10)\left[(2\text{ ft})^2\cos^{-1}\left(\frac{2\text{ ft}-0.333\text{ ft}}{2\text{ ft}}\right) - (2\text{ ft}-0.333\text{ ft})\sqrt{(2\text{ ft})^2-(2\text{ ft}-0.333\text{ ft})^2}\right] = 4.99435\text{ ft}^3$$

$$m = \left.\frac{4.99435\text{ ft}^3}{}\right|\left.\frac{10^6\text{ cm}^3}{35.3145\text{ ft}^3}\right|\left.\frac{0.879\text{ g}}{1\text{ cm}^3}\right|\frac{1\text{ kg}}{10^3\text{ g}} = 124.313\text{ kg} \Rightarrow \underline{\underline{124\text{ kg}}}$$

(c)



2.17 $1\ \text{lb}_\text{f} = 1\ \text{slug}\cdot\text{ft/s}^2 = 32.174\ \text{lb}_\text{m}\cdot\text{ft/s}^2 \Rightarrow 1\ \text{slug}=32.174\ \text{lb}_\text{m}$

$1\ \text{poundal} = 1\ \text{lb}_\text{m}\cdot\text{ft/s}^2$

(a) (i) On the earth:

$$M=\begin{array}{c|c}135\ \text{lb}_\text{m} & 1\ \text{slug}\\ \hline & 32.174\ \text{lb}_\text{m}\end{array}=\underline{\underline{4.20\ \text{slugs}}}$$

$$W=\begin{array}{c|c|c}135\ \text{lb}_\text{m} & 32.174\ \text{ft} & 1\ \text{poundal}\\ \hline & \text{s}^2 & 1\ \text{lb}_\text{m}\cdot\text{ft/s}^2\end{array}=\underline{\underline{4.34\times10^3\ \text{poundals}}}$$

(ii) On the moon

$$M=\begin{array}{c|c}135\ \text{lb}_\text{m} & 1\ \text{slug}\\ \hline & 32.174\ \text{lb}_\text{m}\end{array}=\underline{\underline{4.20\ \text{slugs}}}$$

$$W=\begin{array}{c|c|c}135\ \text{lb}_\text{m} & 32.174\ \text{ft} & 1\ \text{poundal}\\ \hline & 6\ \text{s}^2 & 1\ \text{lb}_\text{m}\cdot\text{ft/s}^2\end{array}=\underline{\underline{724\ \text{poundals}}}$$

(b)

$$F=ma\Rightarrow a=F/m=\begin{array}{c|c|c|c}405\ \text{poundals} & 1\ \text{lb}_\text{m}\cdot\text{ft/s}^2 & 1\ \text{slug} & 1\ \text{m}\\ \hline 35.0\ \text{slugs} & 1\ \text{poundal} & 32.174\ \text{lb}_\text{m} & 3.2808\ \text{ft}\end{array}$$

$$=0.1096\ \text{m/s}^2\Rightarrow\underline{\underline{0.110\ \text{m/s}^2}}$$

2.18 **(a)**

$$F = ma \Rightarrow 1\text{ doozy}=(1\text{ cuz})(32.174\text{ ft/s}^2)\left(\frac{1}{6}\right)=\underline{\underline{5.3623\text{ cuz}\cdot\text{ft/s}^2}}$$

$$\Rightarrow \frac{1\text{ doozy}}{\underline{\underline{5.3623\text{ cuz}\cdot\text{ft/s}^2}}}$$

(b) On the moon: $W = \begin{array}{c|c|c} 3\text{ cuz} & 32.174\text{ ft} & 1\text{ doozy} \\ \hline & 6\quad \text{s}^2 & 5.3623\text{ cuz}\cdot\text{ft/s}^2 \end{array} = \underline{\underline{3\text{ doozies}}}$

In Lizard Lick, NC: $W = (3)(32.174)/5.3623 = \underline{\underline{17\text{ doozies}}}$

2.19 **(a)** First we need to make assumptions about how many doses were taken per day by a patient. While there are 6 four hour periods in one calendar day, it is unlikely a patient would wake up at 4 in the morning to take a dose. If a person was awake for 16 hours, they would take, at most, 4 doses (Waking, mid-day, before sleep):

$$V_{\mathrm{D}} = 4 \text{ doses } \times \frac{3 \text{ teaspoon}}{\text{dose}} = 12 \text{ teaspoons}$$

The volume of a teaspoon is roughly 5 mL/teaspoon:

$$V_{\mathrm{D}} = 12 \text{ teaspoon } \times \frac{5 \text{ mL}}{\text{teaspoon}} = \underline{\underline{60 \text{ mL}}} \text{ consumed in a day}$$

(b)
$$m_{\text{patient, max}} = \frac{60 \text{ mL}}{} \left| \frac{\text{kg body mass}}{1.4 \text{ mL}} \right| \frac{2.20462 \text{ lb}_m}{\text{kg}} = 94.5 \text{ lb}_{\mathrm{m}} \approx \underline{\underline{95 \text{ lb}_{\mathrm{m}}}}$$

<u>Anyone under 95 lb$_{\mathrm{m}}$ would be fatally poisoned.</u> The intuitive answer is that a highly poisonous substance should not be taken even if the quantities are supposedly below a lethal level. Glycol (antifreeze) poisoning is attended with severe symptoms even if death is not the ultimate result. If the lethal dose is in error or has some variability, then even those above that body mass are at risk.

(c)
$$N_{\mathrm{p}} = \frac{V}{V_{\mathrm{d}}} = \frac{240 \text{ gal}}{60 \text{ mL}} \times \frac{10^6 \text{ mL}}{264.17 \text{ gal}} = \underline{\underline{15{,}141 \text{ people}}}$$

(d)

- Research chemist might have turned up a possible alternate solvent. Definitely would have discovered DEG's poisonous qualities.
- Product made with almost nonexistent testing for quality, storage life, toxicity, etc. Proper testing would have prevented the poisoning and otherwise improved the product.
- Product released unrestricted without initial clinical field testing. Send out a test batch or two and see what the results are.

2.20 **(a)** $\approx (3)(9) = \underline{\underline{\underline{27}}}$

$(2.7)(8.632) = \underline{\underline{\underline{23}}}$

(b) $\approx \dfrac{4.0\times10^{-4}}{40} \approx \underline{\underline{\underline{1\times10^{-5}}}}$

$(3.600\times10^{-4})/45 = \underline{\underline{\underline{8.0\times10^{-6}}}}$

(c) $\approx 2+125 = \underline{\underline{\underline{127}}}$

$2.365+125.2 = \underline{\underline{\underline{127.5}}}$

(d) $\approx 50\times10^{3} - 1\times10^{3} \approx 49\times10^{3} \approx \underline{\underline{\underline{5\times10^{4}}}}$

$4.753\times10^{4} - 9\times10^{2} = \underline{\underline{\underline{5\times10^{4}}}}$

2.21 $R \approx \frac{(7\times10^{-1})(3\times10^{5})(6)(5\times10^{4})}{(3)(5\times10^{6})} \approx 42\times10^{2} \approx \underline{\underline{4\times10^{3}}}$ (Any digit in range 2-6 is acceptable)

$R_{\text{exact}} = 3812.5 \Rightarrow \underline{\underline{3810}} \Rightarrow \underline{\underline{3.81\times10^{3}}}$

2.22 **(a)** A: $R = 73.1 - 72.4 = \underline{\underline{0.7^{\circ}\mathrm{C}}}$

$$\overline{X} = \frac{72.4 + 73.1 + 72.6 + 72.8 + 73.0}{5} = \underline{\underline{72.8^{\circ}\mathrm{C}}}$$

$$s = \sqrt{\frac{(72.4 - 72.8)^2 + (73.1 - 72.8)^2 + (72.6 - 72.8)^2 + (72.8 - 72.8)^2 + (73.0 - 72.8)^2}{5 - 1}}$$

$$= \underline{\underline{0.3^{\circ}\mathrm{C}}}$$

B: $R = 103.1 - 97.3 = \underline{\underline{5.8^{\circ}\mathrm{C}}}$

$$\overline{X} = \frac{97.3 + 101.4 + 98.7 + 103.1 + 100.4}{5} = \underline{\underline{100.2^{\circ}\mathrm{C}}}$$

$$s = \sqrt{\frac{(97.3 - 100.2)^2 + (101.4 - 100.2)^2 + (98.7 - 100.2)^2 + (103.1 - 100.2)^2 + (100.4 - 100.2)^2}{5 - 1}}$$

$$= \underline{\underline{2.3^{\circ}\mathrm{C}}}$$

(b) Thermocouple B exhibits a higher degree of scatter and is also more accurate.

2.23

(a)

$$\bar{X} = \frac{\sum_{i=1}^{12} X_i}{12} = 73.5 \qquad s = \sqrt{\frac{\sum_{i=1}^{12} (X - 73.5)^2}{12-1}} = 1.2$$

$$\mathrm{C}_{\mathrm{min}=} = \bar{X} - 2s = 73.5 - 2(1.2) = \underline{\underline{71.1}}$$

$$\mathrm{C}_{\mathrm{max}=} = \bar{X} + 2s = 73.5 + 2(1.2) = \underline{\underline{75.9}}$$

(b) Joanne is more likely to be the statistician, because she wants to make the control limits stricter.

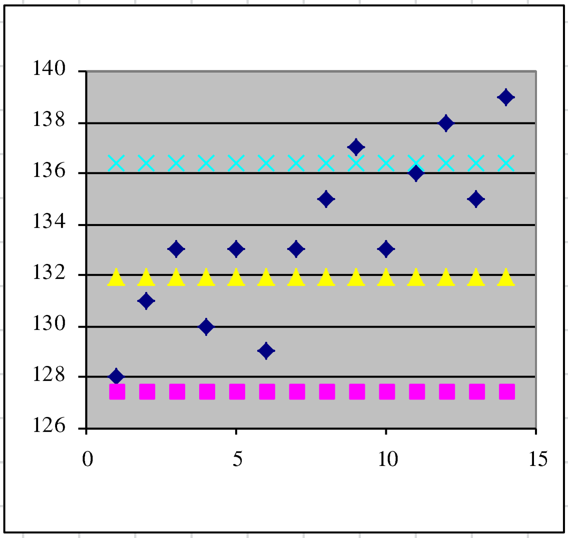
(c) Inadequate cleaning between batches, impurities in raw materials, variations in reactor temperature (failure of reactor control system), problems with the color measurement system, operator carelessness

2.24

(a),(b)

(a) Run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
X	134	131	129	133	135	131	134	130	131	136	129	130	133	130	133
Mean(X)	131.9														
Stdev(X)	2.2														
Min	127.5														
Max	136.4														

(b) Run	X	Min	Mean	Max
1	128	127.5	131.9	136.4
2	131	127.5	131.9	136.4
3	133	127.5	131.9	136.4
4	130	127.5	131.9	136.4
5	133	127.5	131.9	136.4
6	129	127.5	131.9	136.4
7	133	127.5	131.9	136.4
8	135	127.5	131.9	136.4
9	137	127.5	131.9	136.4
10	133	127.5	131.9	136.4
11	136	127.5	131.9	136.4
12	138	127.5	131.9	136.4
13	135	127.5	131.9	136.4
14	139	127.5	131.9	136.4



(c) Beginning with Run 11, the process has been near or well over the upper quality assurance limit. An overhaul would have been reasonable after Run 12.

2.25 **(a)**

$$Q' = \begin{array}{r|r|r|r} 2.36\times10^{-4}\ \text{kg}\cdot\text{m}^2 & 2.10462\ \text{lb} & 3.2808^2\ \text{ft}^2 & 1\quad \text{h} \\ \hline \text{h} & \text{kg} & \text{m}^2 & 3600\ \text{s} \end{array}$$

(b)

$$Q'_{\text{approximate}} \approx \frac{(2\times10^{-4})(2)(9)}{3\times10^3} \approx 12\times10^{(-4-3)} \approx \underline{\underline{1.2\times10^{-6}\ \text{lb}\cdot\text{ft}^2/\text{s}}}$$

$$Q'_{\text{exact}} = \underline{\underline{1.48\times10^{-6}\ \text{lb}\cdot\text{ft}^2/\text{s}}} = \underline{\underline{0.00000148\ \text{lb}\cdot\text{ft}^2/\text{s}}}$$

2.26

$$N_{\mathrm{Pr}} = \frac{C_{\mathrm{p}}\mu}{k} = \begin{array}{c|c|c|c|c} 0.583\ \mathrm{J/g\cdot{}^{o}\,C} & 1936\ \mathrm{lb_m} & 1\ \ \mathrm{h} & 3.2808\ \mathrm{ft} & 1000\ \mathrm{g} \\ \hline 0.286\ \mathrm{W/m\cdot{}^{o}\,C} & \mathrm{ft\cdot h} & 3600\ \mathrm{s} & \mathrm{m} & 2.20462\ \mathrm{lb_m} \end{array}$$

$N_{\mathrm{Pr}} \approx \dfrac{(6\times10^{-1})(2\times10^{3})(3\times10^{3})}{(3\times10^{-1})(4\times10^{3})(2)} \approx \dfrac{3\times10^{3}}{2} \approx \underline{\underline{1.5\times10^{3}}}$. The calculator solution is $\underline{\underline{1.63\times10^{3}}}$

2.27

$$\mathrm{Re} = \frac{Du\rho}{\mu} = \begin{array}{r|r|c|r|r|r|l} 0.48\ \mathrm{ft} & 1\ \ \mathrm{m} & 2.067\ \mathrm{in} & 1\ \ \mathrm{m} & 0.805\ \mathrm{g} & 1\ \ \mathrm{kg} & 10^6\ \mathrm{cm}^3 \\ \hline \mathrm{s} & 3.2808\ \mathrm{ft} & 0.43\times10^{-3}\ \mathrm{kg/m\cdot s} & 39.37\ \mathrm{in} & \mathrm{cm}^3 & 1000\ \mathrm{g} & 1\ \ \ \mathrm{m}^3 \end{array}$$

$$\mathrm{Re} \approx \frac{(5\times10^{-1})(2)(8\times10^{-1})(10^6)}{(3)(4\times10)(10^3)(4\times10^{-4})} \approx \frac{5\times10^{1-(-3)}}{3} \approx 2\times10^4 \Rightarrow \underline{\underline{\text{the flow is turbulent}}}$$

2.28

(a) $$\frac{k_\text{g} d_\text{p} y}{D} = 2.00 + 0.600\left(\frac{\mu}{\rho D}\right)^{1/3}\left(\frac{d_\text{p} u \rho}{\mu}\right)^{1/2}$$

$$= 2.00 + 0.600\left[\frac{1.00\times10^{-5}\ \text{N}\cdot\text{s/m}^2}{(1.00\ \text{kg/m}^3)(1.00\times10^{-5}\ \text{m}^2\ /\ \text{s})}\right]^{1/3}\left[\frac{(0.00500\ \text{m})(10.0\ \text{m/s})(1.00\ \text{kg/m}^3)}{(1.00\times10^{-5}\ \text{N}\cdot\text{s/m}^2)}\right]^{1/2}$$

$$= 44.426 \Rightarrow \frac{k_\text{g}(0.00500\ \text{m})(0.100)}{1.00\times10^{-5}\ \text{m}^2\ /\ \text{s}} = 44.426 \Rightarrow k_\text{g} = \underline{\underline{0.888\ \text{m}\ /\ \text{s}}}$$

(b) The diameter of the particles is not uniform, the conditions of the system used to model the equation may differ significantly from the conditions in the reactor (out of the range of empirical data), all of the other variables are subject to measurement or estimation error.

(c)

d_p (m)	y	D (m²/s)	(N-s/m²)	(kg/m³)	u (m/s)	k_g
0.005	0.1	1.00E-05	1.00E-05	1	10	0.889
0.010	0.1	1.00E-05	1.00E-05	1	10	0.620
0.005	0.1	2.00E-05	1.00E-05	1	10	1.427
0.005	0.1	1.00E-05	2.00E-05	1	10	0.796
0.005	0.1	1.00E-05	1.00E-05	1	20	1.240

2.29 (a) $\underline{\underline{200\ \text{crystals/min}\cdot\text{mm}}}$; $\underline{\underline{10\ \text{crystals/min}\cdot\text{mm}^2}}$

(b)

$$r=\left[\begin{array}{c|c|c} 200\ \text{crystals} & 0.050\ \text{in} & 25.4\ \text{mm} \\ \hline \text{min}\cdot\text{mm} & & \text{in}\end{array}\right]-\left[\begin{array}{c|c|c} 10\ \text{crystals} & 0.050^2\ \text{in}^2 & (25.4)^2\ \text{mm}^2 \\ \hline \text{min}\cdot\text{mm}^2 & & \text{in}^2\end{array}\right]$$

$$=238\ \text{crystals/min}\ \Rightarrow\ \begin{array}{c|c} 238\ \text{crystals} & 1\ \text{min} \\ \hline \text{min} & 60\ \text{s}\end{array}=\underline{\underline{4.0\ \text{crystals/s}}}$$

(c)

$$D(\text{mm})=\begin{array}{c|c} D'(\text{in}) & 25.4\ \text{mm} \\ \hline & 1\ \text{in}\end{array}=25.4D';\ r\left(\frac{\text{crystals}}{\text{min}}\right)=r'\begin{array}{c|c} \text{crystals} & 60\ \text{s} \\ \hline \text{s} & 1\ \text{min}\end{array}=60r'$$

$$\Rightarrow 60r'=200(25.4D')-10(25.4D')^2\Rightarrow \underline{\underline{r'=84.7D'-108(D')^2}}$$

(d) The equation predicts that the diameter of the crystals will increase with the size of the crystals. This corresponds to an empirical formula since, as the rate is faster, the duration time is smaller, leaving less time for mixing and larger crystals.

2.30 **(a)** $\underline{\underline{70.5\ \text{lb}_\text{m}/\text{ft}^3}}$; $\underline{\underline{8.27\times10^{-7}\ \text{in}^2/\text{lb}_\text{f}}}$

(b) $$\rho=(70.5\ \text{lb}_\text{m}/\text{ft}^3)\exp\left[\begin{array}{r|r|c} 8.27\times10^{-7}\ \text{in}^2 & 9\times10^6\ \text{N} & 14.696\ \text{lb}_\text{f}/\text{in}^2 \\ \hline \text{lb}_\text{f} & \text{m}^2 & 1.01325\times10^5\ \text{N/m}^2 \end{array}\right]$$

$$=\begin{array}{r|r|r|c} 70.57\ \text{lb}_\text{m} & 35.3145\ \text{ft}^3 & 1\quad \text{m}^3 & 1000\ \text{g} \\ \hline \text{ft}^3 & \text{m}^3 & 10^6\ \text{cm}^3 & 2.20462\ \text{lb}_\text{m} \end{array}=\underline{\underline{1.13\ \text{g/cm}^3}}$$

(c) $$\rho\left(\frac{\text{lb}_\text{m}}{\text{ft}^3}\right)=\rho'\begin{array}{c|c|c} \text{g} & 1\ \text{lb}_\text{m} & 28{,}317\ \text{cm}^3 \\ \hline \text{cm}^3 & 453.593\ \text{g} & 1\ \text{ft}^3 \end{array}=62.43\rho'$$

$$P\left(\frac{\text{lb}_\text{f}}{\text{in}^2}\right)=P'\begin{array}{c|c|c} \text{N} & 0.2248\ \text{lb}_\text{f} & 1^2\quad \text{m}^2 \\ \hline \text{m}^2 & 1\ \text{N} & 39.37^2\ \text{in}^2 \end{array}=1.45\times10^{-4}P'$$

$$\Rightarrow 62.43\rho'=70.5\exp\left[\left(8.27\times10^{-7}\right)\left(1.45\times10^{-4}P'\right)\right]\Rightarrow \underline{\underline{\rho'=1.13\exp\left(1.20\times10^{-10}P'\right)}}$$

$$P'=9.00\times10^6\ \text{N/m}^2\Rightarrow\rho'=1.13\exp[(1.20\times10^{-10})(9.00\times10^6)]=\underline{\underline{1.13\ \text{g/cm}^3}}$$

2.31

(a)

$$\begin{array}{c|c|c} t\ (\text{hr}) & 60\ \text{min} & 60\ \text{s} \\ \hline & 1\ \text{hr} & 1\ \text{min} \end{array} = 3600t\ \text{s}$$

$$V\left(\text{in}^3\right) = \begin{array}{c|c} V\ \text{cm}^3 & 1728\ \text{in}^3 \\ \hline & 28317\ \text{cm}^3 \end{array} = 0.06102V\left(\text{cm}^3\right)$$

$$\Rightarrow \underline{\underline{V\left(\text{in}^3\right) = 0.061a \cdot e^{3600b \cdot t\left(\text{hr}\right)}}}$$

(b) $a = \text{cm}^3$, $b = \text{s}^{-1}$

2.32 **(a)** $\underline{\underline{3.00\text{ mol/L}}}$, $\underline{\underline{2.00\text{ min}^{-1}}}$

(b) $t=0 \Rightarrow C = 3.00\ \exp[(-2.00)(0)]=3.00\text{ mol/L}$

$t=1 \Rightarrow C = 3.00\ \exp[(-2.00)(1)]=0.406\text{ mol/L}$

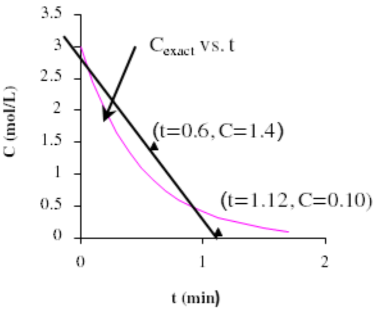
For t=0.6 min: $C_{\text{int}} = \dfrac{0.406-3.00}{1-0}(0.6-0)+3.00 = \underline{\underline{1.4\text{ mol/L}}}$

$C_{\text{exact}} = 3.00\ \exp[(-2.00)(0.6)]=\underline{\underline{0.9\text{ mol/L}}}$

For C=0.10 mol/L: $t_{\text{int}} = \dfrac{1-0}{0.406-3}(0.10-3.00)+0 = \underline{\underline{1.12\text{ min}}}$

$t_{\text{exact}} = -\dfrac{1}{2.00}\ln\dfrac{C}{3.00} = -\dfrac{1}{2}\ln\dfrac{0.10}{3.00} = \underline{\underline{1.70\text{ min}}}$

(c)

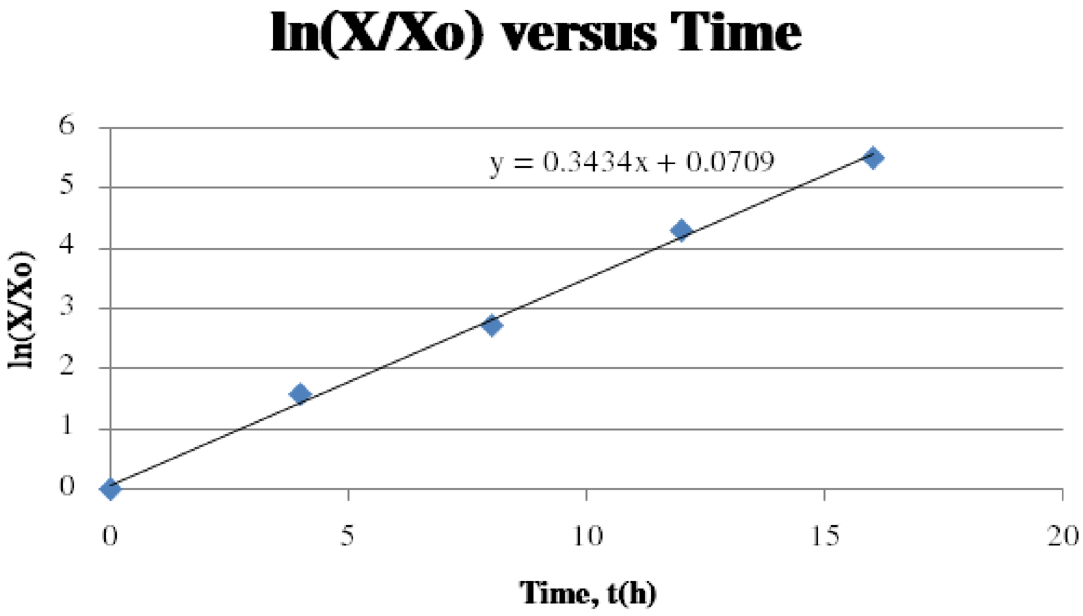


2.33 **(a)** $\mu = \text{h}^{-1}$

(b) i. $\ln\left(X/X_0\right)$ vs. t on rectangular axes.

ii. X/X_0 vs. t on semi-log axes.

(c)



μ is a slope of the graph, so $\mu = \underline{\underline{0.3434\ \text{h}^{-1}}}$

(d)

For doubling the ratio $X/X_0 = 2$

$\ln\left(X/X_0\right) = \mu t + b$

$t = (\ln(2) - 0.0709)/0.3434 \Rightarrow \underline{\underline{t = 1.81\ \text{hr}}}$

2.34 (a)

time, t (h)	Concentration, C	ln C
0 (8am)	x	ln x
3 (11am)	3850	8.2558
9 (5am)	36530	10.5059

i) exponential growth: $C = C_0 e^{kt} \Rightarrow \ln C = \ln C_0 + kt$

$$\begin{cases} 8.2558 = \ln C_0 + 3k \\ 10.5059 = \ln C_0 + 9k \end{cases} \Rightarrow \begin{array}{l} \underline{\underline{k = 0.375}} \\ \ln C_0 = 7.13075 \Rightarrow \underline{\underline{C_0 = 1250}} \end{array}$$

ii) linear growth: $C = C_0 + kt$

$$\begin{cases} 3850 = C_0 + 3k \\ 36530 = C_0 + 9k \end{cases} \Rightarrow \begin{array}{l} \underline{\underline{k = 5446.7}} \\ \underline{\underline{C_0 = -12490}} \end{array}$$

C_0 becomes negative, so linear relationship is not reasonable.

iii) power-law growth: $C = kt^b \Rightarrow \ln C = \ln k + b \ln t$

$$\begin{cases} 8.2558 = \ln k + b \ln 3 \\ 10.5059 = \ln k + b \ln 9 \end{cases} \Rightarrow \begin{array}{l} \ln k = 6.0057 \\ b = 2.048 \end{array}$$

$\underline{\underline{k = 405.7}}$

C_0 cannot be determined, so power-law relationship is not reasonable.

(b) exponential growth: $C = C_0 e^{kt}$ (see calculations below in Part (a) to verify)

(c) At $t = 0$, using the exponential growth relationship, $C = kt^b \Rightarrow \ln C = \ln k + b \ln t$

$\underline{\underline{C = C_0 = 1250}}$ -- Assumptions: Student response.

(d)

$C = 2$ million cells $= 2 \times 10^6$ cells

$\ln C = \ln C_0 + kt$

$\ln(2 \times 10^6) = 7.131 + 0.375t$

$\Rightarrow t = 19.67$ hr ≈ 20 hr

$\therefore \underline{\underline{\text{4 am}}}$

In the future, you might plant to start the experiment at a more convenient time so that you don't have to make late night trips to the lab.

2.35

(a) Since the bacteria catalyze the production reaction, we would like to have an abundant population as soon as possible, which means we want a high bacterial growth rate, *dC/dt.* For a given concentration, *C*, the growth rate is μC, so a $\underline{\underline{\text{high}}}$ value of μ is desirable.

(b) To integrate this expression, separate the variables (bring all functions of *C* to one side and all functions of *t* to the other), and then integrate each side from the initial condition ($t=0$, $C=C_o$):

$$\frac{dC}{dt}=\mu C \Rightarrow \frac{dC}{C}=\mu dt \Rightarrow \int_{C_o}^{C}\frac{dC}{C}=\mu\int_0^t dt \Rightarrow \underline{\underline{\ln C-\ln C_o=\mu t}}$$

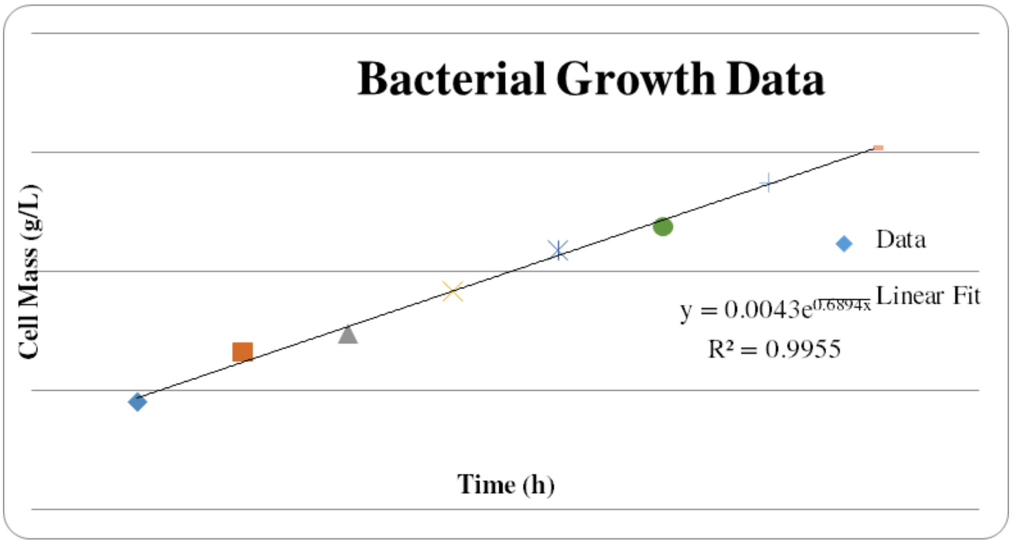
(Note: Since dC/C is dimensionless, $\mu(dt)$ must be as well, which means that μ must have units of inverse time. If t is in hours, then μ has units of h^{-1}.)

If the given expression is rewritten to $\ln C = \mu t + \ln(C_o)$, it follows that

(ln *C*) vs. *t* on rectangular coordinates → straight line, slope μ, intercept $\ln(C_o)$

C vs. *t* on semilog coordinates → straight line, slope μ, intercept C_o

(c) A semilog plot of the data in the table is shown below. The linearity of the plot indicates that balanced growth applies over the period of data collection.



From the slope of the plot, the specific growth rate is $\underline{\underline{\mu = 0.689\ \text{h}^{-1}}}$.

(d) To determine the doubling time, we can find the value of *t* for a value of $C = 2C_0$.

$$\ln C - \ln C_0 = \ln\frac{C}{C_0} = \mu t \xrightarrow[t=t_{1/2}]{C=2C_0} \ln 2 = \mu t_{1/2} \Rightarrow \underline{\underline{t_{1/2} = \frac{\ln 2}{\mu} = \frac{\ln 2}{0.689\ \text{h}^{-1}} = 1.0\ \text{h}}}$$

2.36 **(a)** This is a power law relationship: $\underline{\underline{y = a\,(x^b)}}$

(b) Express the equation as ln(y) = ln (a) + b (ln(x))

$$\text{Slope } (=b) = \frac{\ln(C_{D2}) - \ln(C_{D1})}{\ln(C_{C2}) - \ln(C_{C1})} = \frac{\ln(2.27) - \ln(1.4)}{\ln(10) - \ln(2.8)} = 0.379$$

ln(2.95) = ln (a) + 0.379 ln (20)

ln(a) = -0.054

a = 0.948

$$\underline{\underline{C_D = 0.948 C_c^{0.379}}}$$

(c) When $C_D = 10$,

$10 = 0.948\, C_C^{0.379}$

Concentration of $\underline{\underline{C_C = 502.25 \text{ mol/L}}}$

(d) Arguments for **not** stopping the reaction until $C_D = 13$ mol/L: More product C would be produced.

Arguments for **stopping** the reaction prior to $C_D = 13$ mol/L: Too close to the explosive limit of 15 mol/L, more hazardous product D to deal with.

2.37 **(a)**

$$p^* = \frac{60-20}{199.8-166.2}(185-166.2)+20 = \underline{\underline{42 \text{ mm Hg}}}$$

(b)

$$p^*_{148.2} = 1+(100-1)\frac{148.2-98.5}{215.5-98.5} = \underline{\underline{43.05 \text{ mm Hg}}}$$

$$\left|\frac{10-43.05}{10}\right| \times 100 = \underline{\underline{330.5\%}}\ \underline{\underline{\text{error}}}$$

Student Response

2.38 (b) $\ln y = \ln a + bx \Rightarrow y = ae^{bx}$

$$b = (\ln y_2 - \ln y_1)/(x_2 - x_1) = (\ln 2 - \ln 1)/(1-2) = -0.693$$

$$\ln a = \ln y - bx = \ln 2 + 0.63(1) \Rightarrow a = 4.00 \Rightarrow \underline{\underline{y = 4.00e^{-0.693x}}}$$

(c) $\ln y = \ln a + b\ln x \Rightarrow y = ax^{b}$

$$b = (\ln y_2 - \ln y_1)/(\ln x_2 - \ln x_1) = (\ln 2 - \ln 1)/(\ln 1 - \ln 2) = -1$$

$$\ln a = \ln y - b\ln x = \ln 2 - (-1)\ln(1) \Rightarrow a = 2 \Rightarrow \underline{\underline{y = 2/x}}$$

(d) $\ln(xy) = \ln a + b(y/x) \Rightarrow xy = ae^{by/x} \Rightarrow y = (a/x)e^{by/x}$ [can't get $y = f(x)$]

$$b = [\ln(xy)_2 - \ln(xy)_1]/[(y/x)_2 - (y/x)_1] = (\ln 807.0 - \ln 40.2)/(2.0 - 1.0) = 3$$

$$\ln a = \ln(xy) - b(y/x) = \ln 807.0 - 3\ln(2.0) \Rightarrow a = 2 \Rightarrow xy = 2e^{3y/x} \Rightarrow \underline{\underline{y = (2/x)e^{3y/x}}}$$

(e) $\ln(y^2/x) = \ln a + b\ln(x-2) \Rightarrow y^2/x = a(x-2)^b \Rightarrow y = [ax(x-2)^b]^{1/2}$

$$\begin{aligned} b &= [\ln(y^2/x)_2 - \ln(y^2/x)_1]/[\ln(x-2)_2 - \ln(x-2)_1] \\ &= (\ln 807.0 - \ln 40.2)/(\ln 2.0 - \ln 1.0) = 4.33 \end{aligned}$$

$$\ln a = \ln(y^2/x) - b(x-2) = \ln 807.0 - 4.33\ln(2.0) \Rightarrow a = 40.2$$

$$\Rightarrow y^2/x = 40.2(x-2)^{4.33} \Rightarrow \underline{\underline{y = 6.34x^{1/2}(x-2)^{2.165}}}$$

2.39 **(b)** Plot y^2 vs. x^3 on rectangular axes. Slope $= m$, Intcpt $= -n$

(c) $\frac{1}{\ln(y-3)} = \frac{1}{b} + \frac{a}{b}\sqrt{x} \Rightarrow$ Plot $\frac{1}{\ln(y-3)}$ vs. $\sqrt{x}$ [rect. axes], slope = $\frac{\text{a}}{\text{b}}$, intercept = $\frac{1}{\text{b}}$

(d) $\frac{1}{(y+1)^2} = a(x-3)^3 \Rightarrow$ Plot $\frac{1}{(y+1)^2}$ vs. $(x-3)^3$ [rect. axes], slope $= a$, intercept $= 0$

OR

$2\ln(y+1) = -\ln a - 3\ln(x-3)$

Plot $\ln(y+1)$ vs. $\ln(x-3)$ [rect.] or (y+1) vs. (x-3) [log]

$\Rightarrow$ slope=$-\frac{3}{2}$, intercept=$-\frac{\ln a}{2}$

(e) $\ln y = a\sqrt{x} + b$

Plot $\ln y$ vs. $\sqrt{x}$ [rect.] or y vs. $\sqrt{x}$ [semilog], slope = a, intercept = b

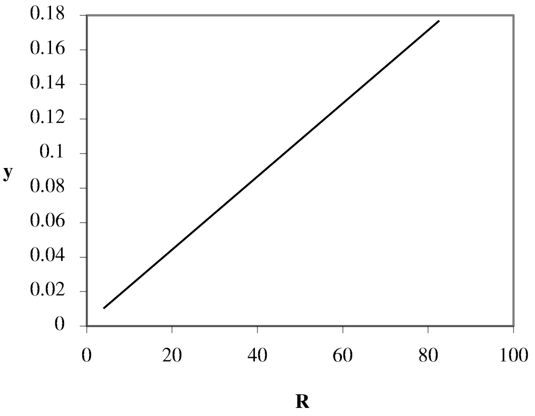
(f) $\log_{10}(xy) = a(x^2 + y^2) + b$

Plot $\log_{10}(xy)$ vs. $(x^2 + y^2)$ [rect.] $\Rightarrow$ slope=a, intercept=b

(g) $\frac{1}{y} = ax + \frac{b}{x} \Rightarrow \frac{x}{y} = ax^2 + b \Rightarrow$ Plot $\frac{x}{y}$ vs. x^2 [rect.], slope=a, intercept=b

OR $\frac{1}{y} = ax + \frac{b}{x} \Rightarrow \frac{1}{xy} = a + \frac{\text{b}}{x^2} \Rightarrow$ Plot $\frac{1}{xy}$ vs. $\frac{1}{x^2}$ [rect.] , slope=b, intercept = a

2.40 **(a)** A plot of y vs. R is a line through ($R = 5$, $y = 0.011$) and ($R = 80$, $y = 0.169$).

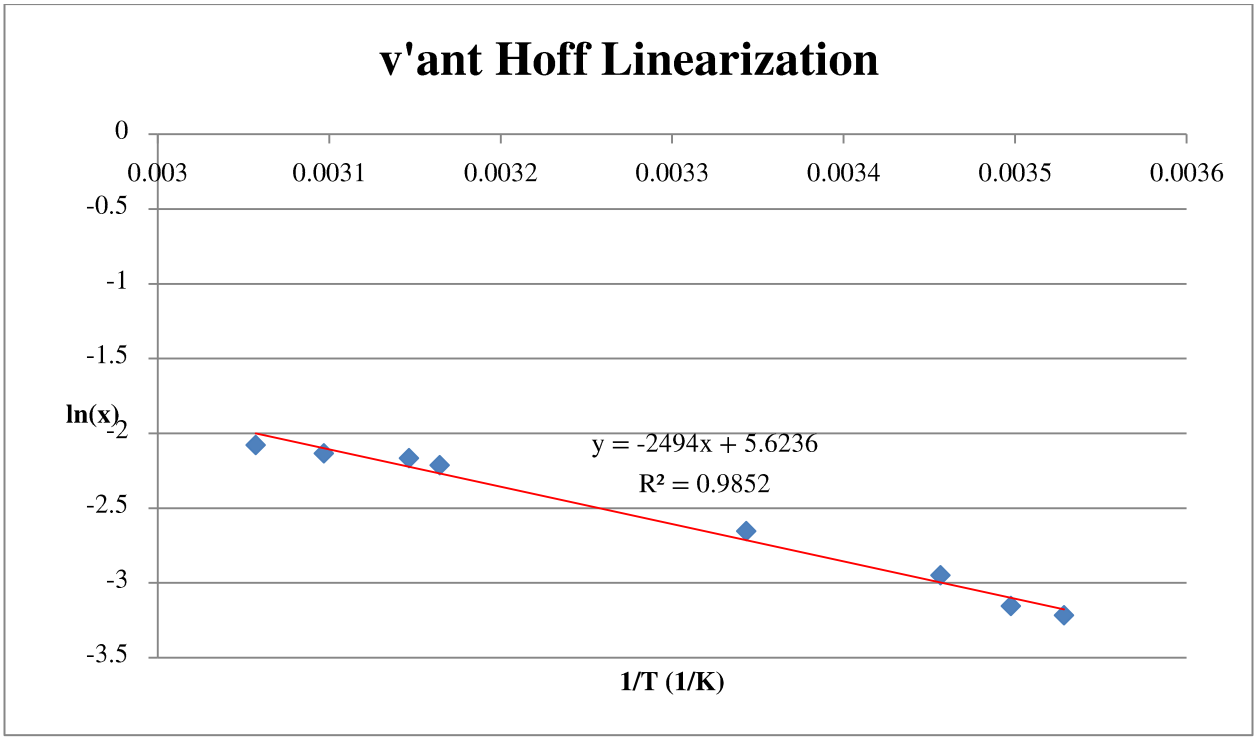


$$y = aR + b \qquad \left.\begin{array}{l} a = \dfrac{0.169 - 0.011}{80 - 5} = 2.11\times10^{-3} \\ b = 0.011 - \left(2.11\times10^{-3}\right)\left(5\right) = 4.50\times10^{-4} \end{array}\right\} \Rightarrow \underline{\underline{y = 2.11\times10^{-3}R + 4.50\times10^{-4}}}$$

(b) $R = 43 \Rightarrow y = \left(2.11\times10^{-3}\right)\left(43\right) + 4.50\times10^{-4} = 0.092\ \text{kg H}_2\text{O}/\text{kg}$

$$\left(1200\ \text{kg}/\text{h}\right)\left(0.092\ \text{kg H}_2\text{O}/\text{kg}\right) = \underline{\underline{110\ \text{kg H}_2\text{O}/\text{h}}}$$

2.41



a = -2494 ˚K, *b* = 5.624 (unitless)

2.42 (a) $\ln T = \ln a + b \ln\phi \Rightarrow T = a\phi^b$

$$b = (\ln T_2 - \ln T_1)/(\ln\phi_2 - \ln\phi_1) = (\ln 120 - \ln 210)/(\ln 40 - \ln 25) = -1.19$$

$$\ln a = \ln T - b\ln\phi = \ln 210 - (-1.19)\ln(25) \Rightarrow a = 9677.6 \Rightarrow \underline{\underline{T = 9677.6\phi^{-1.19}}}$$

(b) $T = 9677.6\phi^{-1.19} \Rightarrow \phi = \left(9677.6/T\right)^{0.8403}$

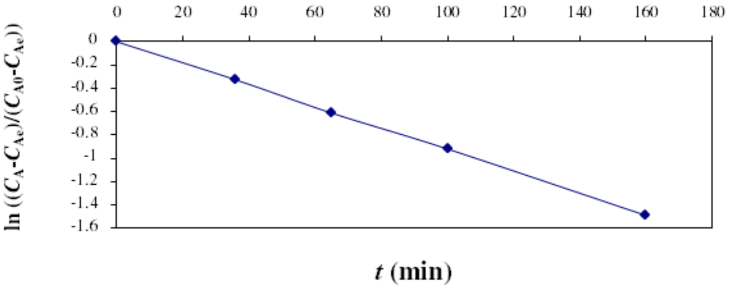
$$T = 85^{\circ}C \Rightarrow \phi = \left(9677.6/85\right)^{0.8403} = \underline{\underline{53.5\text{ L/s}}}$$

$$T = 175^{\circ}C \Rightarrow \phi = \left(9677.6/175\right)^{0.8403} = \underline{\underline{29.1\text{ L/s}}}$$

$$T = 290^{\circ}C \Rightarrow \phi = \left(9677.6/290\right)^{0.8403} = \underline{\underline{19.0\text{ L/s}}}$$

(c) The estimate for T=175°C is probably closest to the real value, because the value of temperature is in the range of the data originally taken to fit the line. The value of T=290°C is probably the least likely to be correct, because it is farthest away from the date range.

2.43 **(a)** Yes, because when $\ln[(C_{\text{A}} - C_{\text{Ae}})/(C_{\text{A0}} - C_{\text{Ae}})]$ is plotted vs. *t* in rectangular coordinates, the plot is a straight line.



$$\text{Slope} = -0.0093 \Rightarrow \underline{\underline{k = 9.3\times 10^{-3}\ \text{min}^{-1}}}$$

(b)

$$\ln[(C_{\text{A}} - C_{\text{Ae}})/(C_{\text{A0}} - C_{\text{Ae}})] = -kt \Rightarrow C_{\text{A}} = (C_{\text{A0}} - C_{\text{Ae}})e^{-kt} + C_{\text{Ae}}$$

$$C_{\text{A}}(t = 120\,\text{min}) = (0.1823 - 0.0495)e^{-(9.3\times 10^{-3})(120)} + 0.0495 = 9.300\times 10^{-2}\ \text{g/L}$$

$$C_A(\text{t} = 120\ \text{min}) = m/V \Rightarrow m_A = CV = \left(9.300\times 10^{-2}\ \text{g/L}\right)\left(125\ \text{L}\right) = 11.625\ \text{g A}$$

$$m_{A0} = C_{A0}V = \left(0.1823\ \text{g/L}\right)\left(125\ \text{L}\right) = 22.787\ \text{g A}$$

This means that (22.787 - 11.625) = 11.16g of A have been consumed at t = 120 min. Since the reaction is 1:1, $\underline{\underline{11.16\ \text{g B}}}$ have been generated.

(c) $\ln\left(\dfrac{C_{\text{A}} - C_{\text{Ae}}}{C_{\text{A0}} - C_{\text{Ae}}}\right) = -kt \Rightarrow t = \dfrac{-1}{k}\ln\left(\dfrac{C_{\text{A}} - C_{\text{Ae}}}{C_{\text{A0}} - C_{\text{Ae}}}\right)$

$\rightarrow C_{\text{A}} = 1.1C_{\text{Ae}} = 1.1\left(0.0495\ \text{g/L}\right) = 0.05445\ \text{g/L}$

$$t = \frac{-1}{0.0093\ \text{min}^{-1}}\ln\left(\frac{0.05445\ \text{g/L} - 0.0495\ \text{g/L}}{0.1823\ \text{g/L} - 0.0495\text{g/L}}\right) = 353.705\ \text{min} \Rightarrow \underline{\underline{354\ \text{min}}}$$

$m_{\text{A}} = \left(0.05445\ \text{g/L}\right)\left(125\ \text{L}\right) = 6.80625\ \text{g A}$

As in part (b), $m_{\text{B}} = 22.787 - 6.80625 = \underline{\underline{15.98\ \text{g B}}}$

$\rightarrow C_{\text{A}} = 1.05C_{\text{Ae}} = 1.1\left(0.0495\ \text{g/L}\right) = 0.051975\ \text{g/L}$

$$t = \frac{-1}{0.0093\ \text{min}^{-1}}\ln\left(\frac{0.051975\ \text{g/L} - 0.0495\ \text{g/L}}{0.1823\ \text{g/L} - 0.0495\text{g/L}}\right) = 428.237\ \text{min} \Rightarrow \underline{\underline{428\ \text{min}}}$$

$m_{\text{A}} = \left(0.051975\ \text{g/L}\right)\left(125\ \text{L}\right) = 6.49875\ \text{g A}$

$m_{\text{B}} = 22.787 - 6.49875 = \underline{\underline{16.29\ \text{g B}}}$

$$\rightarrow C_{\mathrm{A}} = 1.01 C_{\mathrm{Ae}} = 1.1\left(0.0495 \text{ g/L}\right) = 0.049995 \text{ g/L}$$

$$t = \frac{-1}{0.0093 \text{ min}^{-1}} \ln\left(\frac{0.049995 \text{ g/L} - 0.0495 \text{ g/L}}{0.1823 \text{ g/L} - 0.0495\text{g/L}}\right) = 601.2948 \text{ min} \Rightarrow \underline{\underline{601 \text{ min}}}$$

$$m_{\mathrm{A}} = \left(0.049995 \text{ g/L}\right)\left(125 \text{ L}\right) = 6.249375 \text{ g A}$$
$$m_{\mathrm{B}} = 22.787 - 6.249375 = \underline{\underline{16.54 \text{ g B}}}$$

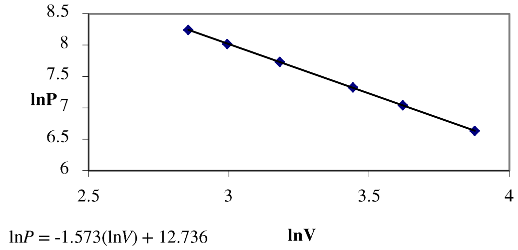
2.44 (a) ft^3 and h^{-2}, respectively

(b) $\ln(V)$ vs. t^2 in rectangular coordinates, slope=2 and intercept= $\ln(3.53\times10^{-2})$; or

V(logarithmic axis) vs. t^2 in semilog coordinates, slope=2, intercept= 3.53×10^{-2}

(c) $\underline{\underline{V(\text{m}^3)=1.00\times10^{-3}\exp(1.5\times10^{-7}t^2)}}$

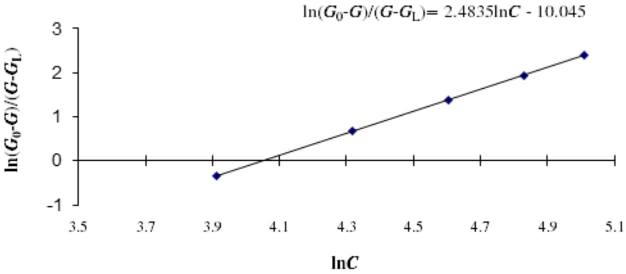
2.45 $PV^k = C \Rightarrow P = C / V^k \Rightarrow \ln P = \ln C - k \ln V$



$$k = -\text{slope} = -(-1.573) = \underline{\underline{1.573}} \text{ (dimensionless)}$$

$$\text{Intercept}=\ln C = 12.736 \Rightarrow C = e^{12.736} = \underline{\underline{3.40 \times 10^5 \text{ mm Hg} \cdot \text{cm}^{4.719}}}$$

2.46 (a) $\dfrac{G-G_{\mathrm{L}}}{G_0-G}=\dfrac{1}{K_{\mathrm{L}}C^m}\Rightarrow\dfrac{G_0-G}{G-G_{\mathrm{L}}}=K_{\mathrm{L}}C^m\Rightarrow\ln\dfrac{G_0-G}{G-G_{\mathrm{L}}}=\ln K_{\mathrm{L}}+m\ln C$



$m=\text{slope}=\underline{\underline{2.483}}$ (dimensionless)

Intercept=ln $K_{\mathrm{L}}=-10.045\Rightarrow K_{\mathrm{L}}=\underline{\underline{4.340\times10^{-5}\ \text{ppm}^{-2.483}}}$

(b) $C=475\Rightarrow\dfrac{G-1.80\times10^{-3}}{3.00\times10^{-3}-G}=4.340\times10^{-5}(475)^{2.483}\Rightarrow G=\underline{\underline{1.806\times10^{-3}}}$

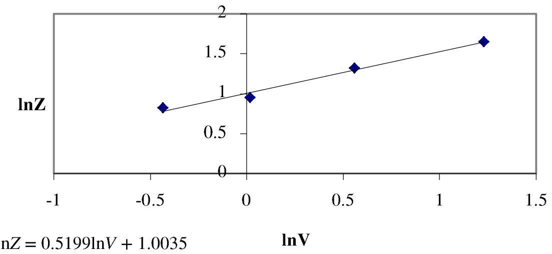
C=475 ppm is well beyond the range of the data.

2.47 **(a)** For runs 2, 3 and 4:

$$Z = a\dot{V}^b p^c \Rightarrow \ln Z = \ln a + b\ln\dot{V} + c\ln p$$

$$\left.\begin{aligned} \ln(3.5) &= \ln a + b\ln(1.02) + c\ln(9.1) \\ \ln(2.58) &= \ln a + b\ln(1.02) + c\ln(11.2) \\ \ln(3.72) &= \ln a + b\ln(1.75) + c\ln(11.2) \end{aligned}\right\} \Rightarrow \begin{aligned} b &= \underline{\underline{0.68}} \\ c &= \underline{\underline{-1.46}} \\ a &= \underline{\underline{86.7 \text{ volts}\cdot\text{kPa}^{1.46}/(\text{L/s})^{0.678}}} \end{aligned}$$

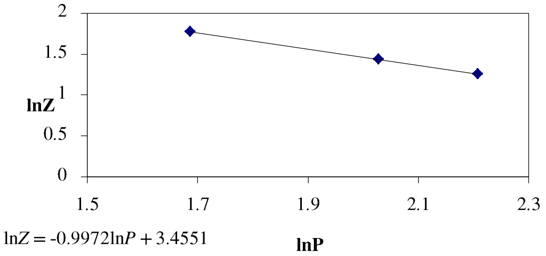
(b) When P is constant (runs 1 to 4), plot $\ln Z$ vs. $\ln\dot{V}$. Slope=b, Intercept= $\ln a + c\ln p$



$$b = \text{slope} = \underline{\underline{0.52}}$$

$$\text{Intercept}= \ln a + c\ln P = 1.0035$$

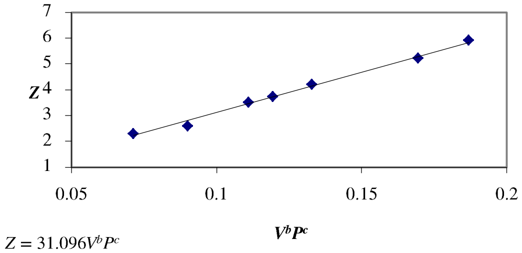
When $\dot{V}$ is constant (runs 5 to 7), plot ln$Z$ vs. ln$P$. Slope=c, Intercept= $\ln a + c\ln\dot{V}$



$$c = \text{slope} = -0.997 \Rightarrow \underline{\underline{1.0}}$$

$$\text{Intercept}= \ln a + b\ln\dot{V} = 3.4551$$

Plot Z vs $\dot{V}^b P^c$. Slope=a (no intercept)



$$a = \text{slope} = \underline{\underline{31.1 \text{ volt}\cdot\text{kPa/(L/s)}^{.52}}}$$

The results in part (b) are more reliable, because more data were used to obtain them.

2.48 (a)

$$s_{\mathrm{xy}} = \frac{1}{n}\sum_{i=1}^{n} x_{\mathrm{i}} y_{\mathrm{i}} = [(0.4)(0.3) + (2.1)(1.9) + (3.1)(3.2)] / 3 = 4.677$$

$$s_{\mathrm{xx}} = \frac{1}{n}\sum_{i=1}^{n} x_{\mathrm{i}}^{2} = (0.3^{2} + 1.9^{2} + 3.2^{2}) / 3 = 4.647$$

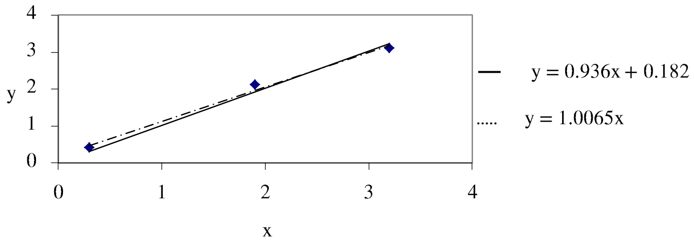
$$s_{\mathrm{x}} = \frac{1}{n}\sum_{i=1}^{n} x_{\mathrm{i}} = (0.3 + 1.9 + 3.2) / 3 = 1.8; \quad s_{\mathrm{y}} = \frac{1}{n}\sum_{i=1}^{n} y_{\mathrm{i}} = (0.4 + 2.1 + 3.1) / 3 = 1.867$$

$$a = \frac{s_{\mathrm{xy}} - s_{\mathrm{x}} s_{\mathrm{y}}}{s_{\mathrm{xx}} - \left(s_{\mathrm{x}}\right)^{2}} = \frac{4.677 - (1.8)(1.867)}{4.647 - (1.8)^{2}} = 0.936$$

$$b = \frac{s_{\mathrm{xx}} s_{\mathrm{y}} - s_{\mathrm{xy}} s_{\mathrm{x}}}{s_{\mathrm{xx}} - \left(s_{\mathrm{x}}\right)^{2}} = \frac{(4.647)(1.867) - (4.677)(1.8)}{4.647 - (1.8)^{2}} = 0.182$$

$$\underline{\underline{y = 0.936x + 0.182}}$$

(b) $a = \dfrac{s_{\mathrm{xy}}}{s_{\mathrm{xx}}} = \dfrac{4.677}{4.647} = 1.0065 \Rightarrow \underline{\underline{y = 1.0065x}}$



2.49 (a)

$<t> =$	5.0
$<T> =$	32.9
$<t^2> =$	36.667
$<t>^2 =$	25
$<t*T> =$	182.933

$T = mt + b$

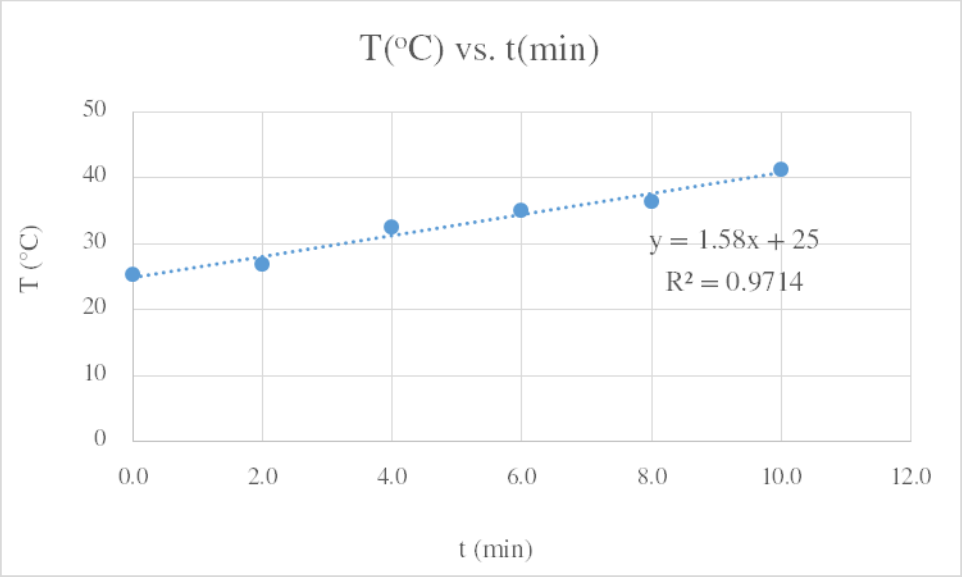
$$m = \frac{<tT> - <t><T>}{<t^2> - <t>^2} = 1.56$$

$$b = <T> - m<t> = 25$$

$$\Rightarrow \underline{\underline{T = 1.56t + 25}}$$

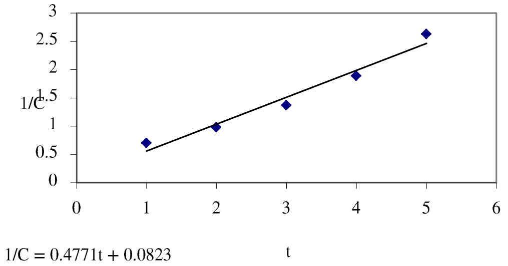
Convert it to a formula for $t(T)$: $t = \dfrac{T-25}{1.56} = \underline{\underline{0.641T - 16.03}}$

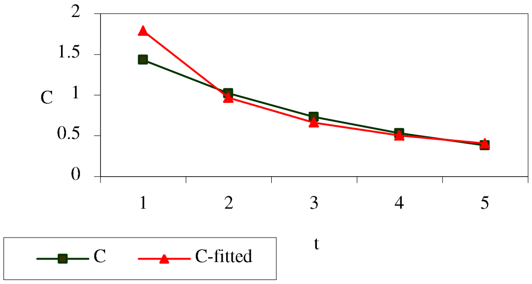
(b)



2.50 (a) $\underline{\underline{1/C\text{ vs. }t}}$ Slope = $\underline{\underline{b}}$, intercept = $\underline{\underline{a}}$

(b) $b = \text{slope} = \underline{\underline{0.477\text{ L/g}\cdot\text{h}}}$; $a = \text{Intercept} = \underline{\underline{0.082\text{ L/g}}}$





(c) $C = 1/(a+bt) \Rightarrow 1/[0.082+0.477(0)] = \underline{\underline{12.2\text{ g/L}}}$

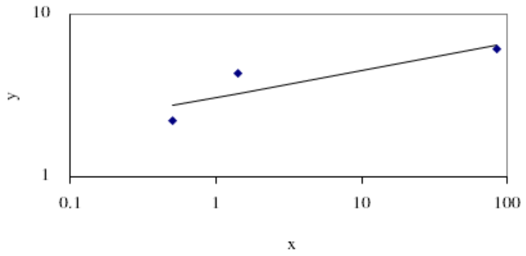
$$t = (1/C - a)/b = (1/0.01 - 0.082)/0.477 = \underline{\underline{209.5\text{ h}}}$$

(d) t = 0 and C = 0.01 are out of the range of the experimental data.

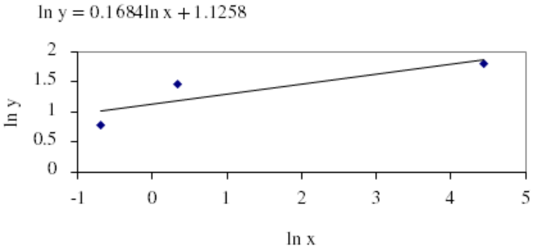
(e) The concentration of the hazardous substance could be enough to cause damage to the biotic resources in the river; the treatment requires an extremely large period of time; some of the hazardous substances might remain in the tank instead of being converted; the decomposition products might not be harmless.

(f) Student Response

2.51 (a) and (c)



(b) $y = ax^b \Rightarrow \ln y = \ln a + b \ln x$; Slope=b, Intercept=ln a

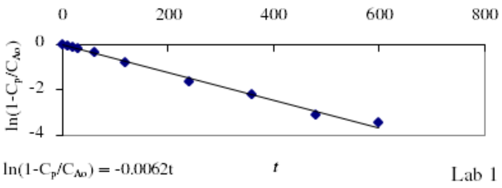


$b = \text{slope} = \underline{\underline{0.168}}$

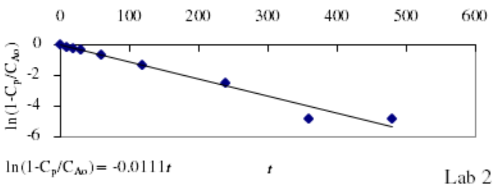
Intercept=ln $a = 1.1258 \Rightarrow a = \underline{\underline{3.08}}$

2.52 (a) $\ln(1-C_p/C_{A0})$ vs. t in rectangular coordinates. Slope=$-k$, intercept=0

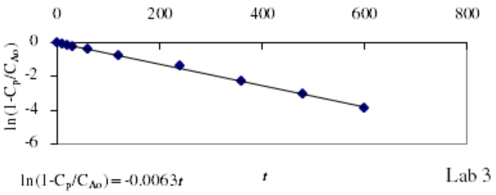
(b)



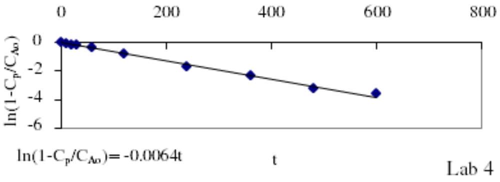
$k = \underline{\underline{0.0062\ \text{s}^{-1}}}$



$k = \underline{\underline{0.0111\ \text{s}^{-1}}}$



$k = \underline{\underline{0.0063\ \text{s}^{-1}}}$



$k = \underline{\underline{0.0064\ \text{s}^{-1}}}$

(c) Disregarding the value of k that is very different from the other three, k is estimated with the average of the calculated k's. $k = \underline{\underline{0.0063\ \text{s}^{-1}}}$

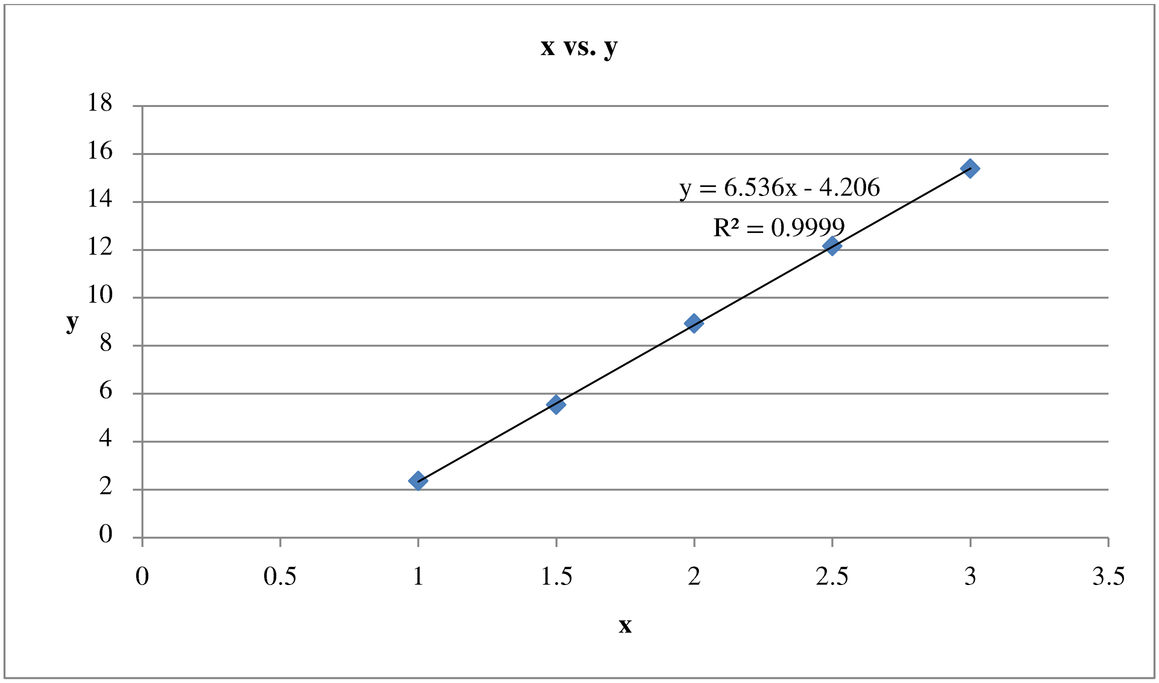
(d) Errors in measurement of concentration, poor temperature control, errors in time measurements, delays in taking the samples, impure reactants, impurities acting as catalysts, inadequate mixing, poor sample handling, clerical errors in the reports, dirty reactor.

2.53

$$y_{\mathrm{i}} = ax_{\mathrm{i}} \Rightarrow \phi(a) = \sum_{i=1}^{n} d_{\mathrm{i}}^{2} = \sum_{i=1}^{n} \left(y_{\mathrm{i}} - ax_{\mathrm{i}}\right)^{2} \Rightarrow \frac{d\phi}{da} = 0 = \sum_{i=1}^{n} 2\left(y_{\mathrm{i}} - ax_{\mathrm{i}}\right)x_{\mathrm{i}} \Rightarrow \sum_{i=1}^{n} y_{\mathrm{i}} x_{\mathrm{i}} - a\sum_{i=1}^{n} x_{\mathrm{i}}^{2} = 0$$

$$\Rightarrow \underline{\underline{a = \sum_{i=1}^{n} y_{\mathrm{i}} x_{\mathrm{i}} \,/ \sum_{i=1}^{n} x_{\mathrm{i}}^{2}}}$$

2.54



x	y	y=ax+b (Excel)	Deviation	Absolute Deviation
1	2.35	2.33	0.02	0.02
1.5	5.53	5.598	-0.068	0.068
2	8.92	8.866	0.054	0.054
2.5	12.15	12.134	0.016	0.016
3	15.38	15.402	-0.022	0.022

The average deviation is 0.036, which indicates a good fit (consistent with the $R^2 = 0.999$). The linear parameters are obtained from Excel: $a = 6.536 \quad b = -4.206$

2.55 (a) E(cal/mol), D_0 (cm^2/s)

(b) ln D vs. 1/T, Slope = -E/R, intercept = ln D_0.

(c)

T(K)	D(cm2/s)		1/T	ln D
347.0	1.34E-06		0.0028818	-13.52284
374.2	2.50E-06		0.0026724	-12.89922
396.2	4.55E-06		0.002524	-12.30038
420.7	8.52E-06		0.002377	-11.67309
447.7	1.407E-05		0.0022336	-11.17147
471.2	1.999E-05		0.0021222	-10.82028

Use points (0.02882, -13.523) and (0.002672, -12.899)

$$\begin{cases} -13.523 = 0.002882a + b \\ -12.899 = 0.002672a + b \end{cases}$$

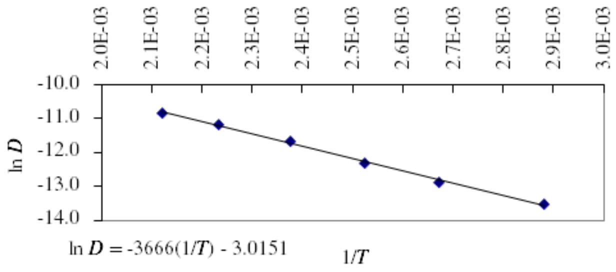
solve these equations for a and b

$$a = -2971.43 = -\frac{E}{R} \Rightarrow E = (2971.43\text{ K})(1.987\text{ cal/mol}\cdot\text{K}) = \underline{\underline{5904\text{ cal/mol}}}$$

$$b = -4.959 = \ln D_0 \Rightarrow D_0 = \exp(-4.959) = \underline{\underline{0.00702\text{ cm}^2/\text{s}}}$$

$$\text{Slope} = -E/R = \text{-3666 K} \Rightarrow E = (3666\text{ K})(1.987\text{ cal/mol}\cdot\text{K}) = \underline{\underline{7284\text{ cal/mol}}}$$

(d) Using a spreadsheet:



$\ln D_0 = -3.0151$

$D_0 = \exp(-3.0151) = \underline{\underline{0.0490\ \text{cm}^2/\text{s}}}$

Slope $= -E/R =$ -3666 K $\Rightarrow E =$ (3666 K)(1.987 cal/mol$\cdot$K) = $\underline{\underline{\text{7284 cal/mol}}}$

CASE STUDY 2

SO_2 Removal from Power-Plant Stack Gases*

Numerous inventories of the world's energy reserves have shown that coal is the most abundant practical source of energy for the next several decades. Two immediate problems have become apparent as the use of coal has increased: mining can be costly, both economically and environmentally, and air pollutant emissions are relatively high when coal is burned. Stack gases from coal-fired furnaces contain large quantities of soot (fine unburned carbon particles) and ash; moreover, most coals contain significant amounts of sulfur, which when burned forms sulfur dioxide, a hazardous pollutant. In this case study we examine a process to reduce pollutant emissions from coal-fired power plant boiler furnaces.

Sulfur dioxide (SO_2) emissions from coal-fired furnaces whose construction began after August 17, 1971, must, by Environmental Protection Agency (EPA) regulation, contain less than 1.2 lb_m, SO_2 per 10^6 Btu (heating value of fuel fed to the boiler). When coal containing a relatively high quantity of sulfur is to be burned, the emissions standard may be satisfied by removing sulfur from the coal prior to combustion or by removing SO_2 from the product gases before they are released to the atmosphere. The technology for removing SO_2 from stack gases is currently more advanced than that for sulfur removal from coal, and a large number of stack gas desulfurization processes are currently in various stages of commercial development.

Sulfur dioxide removal processes are classified as regenerative or throwaway, according to whether the agent used to remove SO_2 is reusable.[1] Regenerative processes have two major steps: the removal of SO_2 from stack gases by a separating agent, and removal of SO_2 from the separating agent. An example of such a procedure is the Wellman-Lord process-absorption of SO_2 by a solution of Na_2SO_3 to produce $NaHSO_3$, followed by the release of SO_2 by partial vaporization of the $NaHSO_3$ solution. In this process the Na_2SO_3 solution is regenerated for reuse as the absorbent.

$$Na_2SO_3 + SO_2 + H_2O \rightarrow 2NaHSO_3 \quad \text{(absorption)}$$

$$2NaHSO_3 \rightarrow Na_2SO_3 + SO_2 + H_2O \quad \text{(regeneration)}$$

Throwaway processes utilize a separating agent to remove SO_2, followed by the disposal of both SO_2 and the separating agent. Wet limestone scrubbing is one of the most advanced throwaway processes in terms of industrial acceptance. Several versions of this process have been developed, one of which is examined in detail in this case study. Parts of the process have proved troublesome, particularly those involving deposition of solids on surfaces of the process equipment. Participants in the case study may find it interesting to learn where the trouble spots are and to check recent technical articles on SO_2 removal processes for discussions of approaches to solving these problems. Such articles are published frequently in *Chemical Engineering Progress*, *Environmental Science and Technology*, and other technical journals.

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* This case study was prepared for the first edition of the text with the assistance of Norman Kaplan of the U.S. Environmental Protection Agency.

[1] Alternatively, the processes may be classified according to whether the sulfur is recovered as a saleable product.

BOILER-INJECTION, WET-LIMESTONE PROCESS DESCRIPTION

The plant to be described is to produce 500 MW of electrical power. The flow rates, compositions, stream conditions, and other details to be given are representative of such installations. The key step in removing SO_2 from the stack gas is the reaction of SO_2 with CaO and oxygen to produce $CaSO_4$, an insoluble stable compound. Four major components of the process will be traced: the coal-limestone-stack gas streams, the scrubber water, the cooling-heating water cycle, and the generated steam cycle.

The composition of coal can vary considerably, but that shown in Table CS 2.1 is typical of that used in this process. During coal combustion the sulfur in the coal reacts to form SO_2 and very small amounts of SO_3. Eighty-five percent of the ash in the coal leaves the boiler in the stack gas as fly ash; nitrogen emerges as N_2, and the carbon, hydrogen, and sulfur in the fuel are oxidized completely to CO_2, H_2O, and SO_2.

Finely ground limestone, whose composition is given in Table CS 2.2, is injected directly into the furnace where complete calcination occurs.[2]

$$CaCO_3 \rightarrow CaO + CO_2$$

The limestone feed rate to the furnace is 10% in excess of that required for complete consumption of the generated SO_2. Both limestone and coal enter the process at about 77°F. A waste stream consisting of 15% of the limestone inerts and coal ash is removed from the furnace at 1650°F.

TABLE CS 2.1 Coal Properties

1. Composition (ultimate analysis)

Component	Dry Wt%
Ash	7.2
Sulfur	3.5
Hydrogen	5.0
Carbon	75.2
Nitrogen	1.6
Oxygen	7.5

Moisture: 4.58 lb_m/100 lb_m wet coal

2. Heat capacities
   Dry coal: $C_p = 0.25$ Btu/$lb_m \cdot$F
   Ash: $C_p = 0.22$ Btu/$lb_m \cdot$F
3. Heating value of coal: 13,240 Btu/lb_m dry coal

TABLE CS 2.2 Limestone Properties

1. Composition

Component	Dry Wt%
$CaCO_3$	91.8
Inerts	8.2

Moisture: 10 wt% water

2. Heat capacity of inerts
   $C_p(\text{Btu/lb}_m \cdot \text{F}) = 0.180 + 6.00 \times 10^{-5} T(°\text{F})$

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[2] Direct injection of limestone is the method of operation in this case study, but in conventional practice the flue gas and a limestone slurry are contacted in an external scrubber.

Air at 110°F and 30% relative humidity is brought to 610°F in an air preheater, and the heated air is fed to the furnace. The air feed rate is 40% in excess of that required to burn the coal completely. Gases from the furnace containing fly ash, CaO, and $CaSO_4$ and at 890°F are cooled in the air preheater and then split into three trains. The gas in each train is cooled further to 177°F, and fed to a scrubber where it is contacted with an aqueous slurry of CaO and $CaSO_4$. Sulfur dioxide is absorbed in the slurry and reacts with the CaO. The gas leaving each scrubber contains 3.333% of the SO_2 and 0.3% of the fly ash emitted from the boiler furnace. The effluent gas from the scrubber, which is at 120°F and saturated with water, is heated and mixed with the gas streams from the other trains. The combined gas stream is sent to a blower where its pressure is increased from 13.3 psia to 14.8 psia; it is then exhausted through a stack to the atmosphere.

The liquid feed enters the scrubber at 117°F and contains 10.00 wt% solids; it is fed at a rate such that there are 6.12 lb_m liquid per lb_m inlet gas. Liquid scrubber effluent at 120°F is sent to a holding tank where it is mixed with fresh makeup water and water recycled from a settling pond. From the holding tank, one stream is recycled to serve as liquid feed to the scrubber and another is pumped to the settling pond for solids removal.

Generation of steam and its utilization in the production of electricity in this plant is typical of many power cycles. Steam is generated in the boiler and leaves the boiler and superheater tubes at 1400°F and 2700 psia. It is expanded through a turbine where its pressure and temperature are reduced to 5 psia and 200°F. The low-pressure steam is then condensed at constant pressure and pumped isothermally to the inlet boiler tubes.

The temperature of the water used to cool the gas entering the scrubber is 148°F. The hot water at 425°F is then used to reheat the effluent gas stream from the scrubber. (The water thus undergoes a closed cycle.)

The power company for which you work is contemplating adding an SO_2 scrubber to one of its generation stations and has asked you to do the preliminary process evaluation. In solving the following problems, you may neglect the formation of SO_3 in the furnace, and assume that $CaSO_4$ and CaO are the only calcium compounds present in the slurry used in the scrubber (i.e., neglect the sulfite, bisulfite, and bisulfate compounds that are present to some extent in the real process).

PROBLEMS

Problems CS 2.2 through CS 2.7 should be answered using a basis of 100 lb_m/min of wet coal fed to the boiler.

CS 2.1. Construct a flowchart of the process, labeling all process streams. Show the details of only one train in the SO_2 scrubber operation.

CS 2.2. From the data on coal composition given in Table CS 2.1, determine the molar flow rate of each element other than ash in the dry coal.

CS 2.3. Determine the feed rate of O_2 required for complete combustion.

CS 2.4. If 40% excess O_2 is fed to the boiler, calculate:

- **(a)** The air feed in
    - **(i)** lb-mole/min.
    - **(ii)** Standard cubic feet/min.
    - **(iii)** Actual cubic feet/min.
- **(b)** The molar flow rate of water in the air stream.

CS 2.5. Determine the rate of flow of $CaCO_3$, inerts, and H_2O in the limestone feed.

CS 2.6. Estimate the rate at which each component in the gas leaves the furnace. What is the waste removal rate from the boiler?

CS 2.7. At what rate must heat be removed from the furnace?

CS 2.8. Plants of the type under consideration operate at an efficiency of about 35%; that is, for each unit of heat extracted from the combustion process, 0.35 units are converted to electrical energy. From this efficiency and the specified power output of 500 MW, determine:

(a) Coal feed rate in lb_m/h.

(b) Air feed rate in

  (i) lb-mole/min.

  (ii) Standard cubic feet/min.

(c) The flow rate of each component in the gas leaving the furnace.

CS 2.9. How much additional coal is consumed in the boiler because of the addition of limestone?

CS 2.10. Calculate the feed rate of liquid to each scrubber in lb_m/h.

CS 2.11. Estimate the composition and flow rates of the gas and liquid streams leaving the scrubber. Are the EPA requirements satisfied?

CS 2.12. Determine the rate at which water (fresh water and recycled water from the pond) must be mixed with the effluent from the scrubber to reduce the solids content (ash, CaO, $CaSO_4$) to 10 wt%.

CS 2.13. If essentially all the solids in the waste stream fed to the settling pond are precipitated, and if the pond surface area is such that half of the water in the waste stream is evaporated, at what rate, in gallons per minute, must fresh water be fed to the process?

CS 2.14. Determine the temperature of the gas stream as it leaves the heat exchanger following the boiler.

CS 2.15. What is the water circulation rate through the heat-recovery loop; that is, the flow rate of the stream that cools the gases entering the scrubber and heats the absorber effluent? What is the minimum pressure at which this cycle can operate with liquid water? To what temperature is the gas leaving the scrubber reheated before it is mixed with gas from other trains?

CS 2.16. One of the design specifications for power plant boilers is the amount of excess air used in burning coal. Evaluate the heat removed from the boiler for 20% and 100% excess air if the temperature of the exit gases and slag is 890°F. What are the ramifications of altering the ratio of air to coal?

CS 2.17. At first glance it might appear that there is no need to split the exit gases into three streams, only to remix them later in the process. However, for the scrubbers under consideration, the maximum allowable velocity of the gas through the empty column is given by

$$v_m(\text{ft/s}) = 0.15[(\rho_L - \rho_G)/\rho_G]^{0.5}$$

where ρ_G and ρ_L are the densities of the gas and liquid phases. Estimate the minimum column diameters for one-, two-, and three-train operations. Why is the three-train operation used?

CS 2.18. Why is the gas leaving the scrubber reheated before it is sent to the stack? (Think about it—the answer is not contained in the process description.)

CS 2.19. If 2.5% of the heat removed from the boiler is lost to the surroundings, at what rate is steam generated?

CS 2.20. Neglecting kinetic and potential energy changes across the steam turbine, calculate the rate at which work is produced in megawatts.

CS 2.21. What is the flow rate or cooling water through the steam condenser if the water temperature is allowed to increase by 25°F?

CS 2.22. The pump that transports the steam condensate from the condenser to the boiler has an efficiency of 55% (i.e., 55% of the energy input to the pump is converted to useful work on the condensate). Neglecting friction losses in the condensate flow and changes in kinetic and potential energy, what is the required energy input to the pump in horsepower?

CS 2.23. It is estimated that the total capital costs for the SO_2-removal portion of this plant will be $25 million. The lifetime of the plant is determined to be 25 years, assuming 7000 hours per year operation. The annual operating costs, including labor, maintenance, utilities, and the like, are estimated to be about $10.5 million. Using current costs for electrical energy, estimate the incremental cost per kilowatt for the desulfurization process. (*Note:* The costs are based on 1978 estimates. The cost figures can be updated using available cost indices.)

Additional Problems for Study

CS 2.24. Power companies have objected to the wet-limestone scrubbing process, claiming it creates more environmental problems than it solves. What environmental problems are created by this process?

CS 2.25. As pointed out earlier, many of the problems associated with boiler injection of limestone have proved to be insurmountable. Discuss what you think some of the problems might be, and propose an alternative processing scheme that retains the essential features of wet limestone scrubbing. Feel free to use available references.

CS 2.26. There have been many changes in technology and regulations since this case study was originally prepared. Search the internet for at least one modification in regulations and/or one new technology associated with removing SO_2 from power-plant stack gases.