Chapter 12

12-1 Given: d_{max} = 25 mm, b_{min} = 25.03 mm, l/d = 1/2, W = 1.2 kN, μ = 55 mPa·s, and N = 1100 rev/min.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{25.03 - 25}{2} = 0.015 \text{ mm}$$

$r \approx 25/2 = 12.5$ mm

$r/c = 12.5/0.015 = 833.3$

$N = 1100/60 = 18.33$ rev/s

$P = W/(ld) = 1200/[12.5(25)] = 3.84$ N/mm^2 = 3.84 MPa

Eq. (12-7): $$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 833.3^2 \left[\frac{55\left(10^{-3}\right)18.33}{3.84\left(10^6\right)}\right] = 0.182$$

Fig. 12-16: $h_0/c = 0.3$ $\Rightarrow$ $h_0 = 0.3(0.015) = 0.0045$ mm *Ans.*

Fig. 12-18: $f\,r/c = 5.4$ $\Rightarrow$ $f = 5.4/833.3 = 0.006\,48$

$T = f\,Wr = 0.006\,48(1200)12.5(10^{-3}) = 0.0972$ N·m

$H_{loss} = 2\pi TN = 2\pi(0.0972)18.33 = 11.2$ W *Ans.*

Fig. 12-19: $Q/(rcNl) = 5.1$ $\Rightarrow$ $Q = 5.1(12.5)0.015(18.33)12.5 = 219$ mm^3/s

Fig. 12-20: $Q_s/Q = 0.81$ $\Rightarrow$ $Q_s = 0.81(219) = 177$ mm^3/s *Ans.*

12-2 Given: d_{max} = 32 mm, b_{min} = 32.05 mm, l = 64 mm, W = 1.75 kN, μ = 55 mPa·s, and N = 900 rev/min.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{32.05 - 32}{2} = 0.025 \text{ mm}$$

$r \approx 32/2 = 16$ mm

$r/c = 16/0.025 = 640$

$N = 900/60 = 15$ rev/s

$P = W/(ld) = 1750/[32(64)] = 0.854$ MPa

$l/d = 64/32 = 2$

Eq. (12-7): $$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 640^2 \left[\frac{55\left(10^{-3}\right)15}{0.854}\right] = 0.797$$

Eq. (12-16), Figs. 12-16, 12-19, and 12-21

	l/d	y_∞	y_1	$y_{1/2}$	$y_{1/4}$	$y_{l/d}$
h_0/c	2	0.98	0.83	0.61	0.36	0.92
$P/p_{\max}$	2	0.84	0.54	0.45	0.31	0.65
$Q/rcNl$	2	3.1	3.45	4.2	5.08	3.20

$h_0 = 0.92\,c = 0.92(0.025) = 0.023$ mm *Ans.*

$p_{\max} = P / 0.65 = 0.854/0.65 = 1.31$ MPa *Ans.*

$Q = 3.20\,rcNl = 3.20(16)0.025(15)64 = 1.23\,(10^3)\ \text{mm}^3/\text{s}$ *Ans.*

12-3 Given: $d_{\max} = 3.000$ in, $b_{\min} = 3.005$ in, $l = 1.5$ in, $W = 800$ lbf, $N = 600$ rev/min, and SAE 10 and SAE 40 at 150°F.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{3.005 - 3.000}{2} = 0.0025 \text{ in}$$
$$r \approx 3.000 / 2 = 1.500 \text{ in}$$
$$l / d = 1.5 / 3 = 0.5$$
$$r / c = 1.5 / 0.0025 = 600$$
$$N = 600 / 60 = 10 \text{ rev/s}$$
$$P = \frac{W}{ld} = \frac{800}{1.5(3)} = 177.78 \text{ psi}$$

Fig. 12-12: SAE 10 at 150°F, $\mu' = 1.75\ \mu$reyn

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 600^2 \left[\frac{1.75(10^{-6})(10)}{177.78}\right] = 0.0354$$

Figs. 12-16 and 12-21: $h_0/c = 0.11$ and $P/p_{\max} = 0.21$

$h_0 = 0.11(0.0025) = 0.000\,275$ in *Ans.*

$p_{\max} = 177.78 / 0.21 = 847$ psi *Ans.*

Fig. 12-12: SAE 40 at 150°F, $\mu' = 4.5\ \mu$reyn

$$S = 0.0354\left(\frac{4.5}{1.75}\right) = 0.0910$$

$$h_0 / c = 0.19, \quad P / p_{\max} = 0.275$$

$$h_0 = 0.19(0.0025) = 0.000\ 475 \text{ in} \quad \textit{Ans.}$$

$$p_{\max} = 177.78 / 0.275 = 646 \text{ psi} \quad \textit{Ans.}$$

12-4 Given: $d_{\max} = 3.250$ in, $b_{\min} = 3.256$ in, $l = 3$ in, $W = 800$ lbf, and $N = 1000$ rev/min.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{3.256 - 3.250}{2} = 0.003$$

$$r \approx 3.250 / 2 = 1.625 \text{ in}$$

$$l / d = 3 / 3.250 = 0.923$$

$$r / c = 1.625 / 0.003 = 542$$

$$N = 1000 / 60 = 16.67 \text{ rev/s}$$

$$P = \frac{W}{ld} = \frac{800}{3(3.25)} = 82.05 \text{ psi}$$

Fig. 12-12: SAE 20W at 150°F, $\mu' = 2.40\ \mu$ reyn

Note to instructors: Some students may obtain a higher value of viscosity (2.85) from Fig. 12-14. The value from Fig. 12-12 is used here as the preferred value since this figure is specifically for single-viscosity oils.

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 542^2\left[\frac{2.40(10^{-6})(16.67)}{82.05}\right] = 0.143$$

From Eq. (12-16), and Figs. 12-16 and 12-21:

	l/d	y_∞	y_1	$y_{1/2}$	$y_{1/4}$	$y_{l/d}$
h_0/c	0.923	0.82	0.44	0.26	0.14	0.42
$P/p_{\max}$	0.923	0.83	0.44	0.31	0.21	0.42

$$h_0 = 0.42c = 0.42(0.003) = 0.001\ 26 \text{ in} \quad \textit{Ans.}$$

$$p_{\max} = \frac{P}{0.42} = \frac{82.05}{0.42} = 195 \text{ psi} \quad \textit{Ans.}$$

Fig. 12-14: SAE 20W-40 at 150°F, $\mu' = 4.4\ \mu$ reyn

$$S = 542^2\,\frac{4.4(10^{-6})(16.67)}{82.05} = 0.263$$

From Eq. (12-16), and Figs. 12-16 and 12-21:

	l/d	y_∞	y_1	$y_{1/2}$	$y_{1/4}$	$y_{l/d}$
h_0/c	0.923	0.91	0.6	0.38	0.2	0.58
P/p_{max}	0.923	0.83	0.48	0.35	0.24	0.46

$$h_0 = 0.58c = 0.58(0.003) = 0.001\ 74 \text{ in} \quad \textit{Ans.}$$

$$p_{max} = \frac{P}{0.46} = \frac{82.05}{0.46} = 178 \text{ psi} \quad \textit{Ans.}$$

12-5 Given: $d_{max} = 2.000$ in, $b_{min} = 2.0024$ in, $l = 1$ in, $W = 600$ lbf, $N = 800$ rev/min, and SAE 20 at 130°F.

$$c_{min} = \frac{b_{min} - d_{max}}{2} = \frac{2.0024 - 2}{2} = 0.0012 \text{ in}$$

$$r \approx \frac{d}{2} = \frac{2}{2} = 1 \text{ in}, \quad l/d = 1/2 = 0.50$$

$$r/c = 1/0.0012 = 833$$

$$N = 800/60 = 13.33 \text{ rev/s}$$

$$P = \frac{W}{ld} = \frac{600}{2(1)} = 300 \text{ psi}$$

Fig. 12-12: SAE 20 at 130°F, $\mu' = 3.75\ \mu$reyn

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 833^2 \left[\frac{3.75(10^{-6})(13.3)}{300}\right] = 0.115$$

From Figs. 12-16, 12-18 and 12-19:

$$h_0/c = 0.23, \quad rf/c = 3.8, \quad Q/(rcNl) = 5.3$$

$$h_0 = 0.23(0.0012) = 0.000\ 276 \text{ in} \quad \textit{Ans.}$$

$$f = \frac{3.8}{833} = 0.004\ 56$$

The power loss due to friction is

$$H = \frac{2\pi f\ WrN}{778(12)} = \frac{2\pi(0.004\ 56)(600)(1)(13.33)}{778(12)}$$

$$= 0.0245 \text{ Btu/s} \quad \textit{Ans.}$$

$$Q = 5.3rcNl$$

$$= 5.3(1)(0.0012)(13.33)(1)$$

$$= 0.0848 \text{ in}^3/\text{s} \quad \textit{Ans.}$$

12-6 Given: d_{max} = 25 mm, b_{min} = 25.04 mm, l/d = 1, W = 1.25 kN, μ = 50 mPa·s, and N = 1200 rev/min.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{25.04 - 25}{2} = 0.02 \text{ mm}$$
$$r \approx d/2 = 25/2 = 12.5 \text{ mm}, \quad l/d = 1$$
$$r/c = 12.5/0.02 = 625$$
$$N = 1200/60 = 20 \text{ rev/s}$$
$$P = \frac{W}{ld} = \frac{1250}{25^2} = 2 \text{ MPa}$$

For μ = 50 mPa · s, $\quad S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 625^2 \left[\frac{50(10^{-3})(20)}{2(10^6)}\right] = 0.195$

From Figs. 12-16, 12-18 and 12-20:

$$h_0/c = 0.52, \quad f\,r/c = 4.5, \quad Q_s/Q = 0.57$$
$$h_0 = 0.52(0.02) = 0.0104 \text{ mm} \quad \textit{Ans.}$$
$$f = \frac{4.5}{625} = 0.0072$$
$$T = f\,Wr = 0.0072(1.25)(12.5) = 0.1125 \text{ N} \cdot \text{m}$$

The power loss due to friction is

$$H = 2\pi T N = 2\pi\,(0.1125)(20) = 14.14 \text{ W} \quad \textit{Ans.}$$

$Q_s = 0.57Q$ The side flow is 57% of Q *Ans.*

12-7 Given: d_{max} = 1.25 in, b_{min} = 1.252 in, l = 2 in, W = 620 lbf, μ' = 8.5 μ reyn, and N = 1120 rev/min.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{1.252 - 1.25}{2} = 0.001 \text{ in}$$
$$r = d/2 = 1.25/2 = 0.625 \text{ in}$$
$$r/c = 0.625/0.001 = 625$$
$$N = 1120/60 = 18.67 \text{ rev/s}$$
$$P = \frac{W}{ld} = \frac{620}{1.25(2)} = 248 \text{ psi}$$
$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 625^2 \left[\frac{8.5(10^{-6})(18.67)}{248}\right] = 0.250$$
$$l/d = 2/1.25 = 1.6$$

From Eq. (12-16), and Figs. 12-16, 12-18, and 12-19

	l/d	y_∞	y_1	$y_{1/2}$	$y_{1/4}$	$y_{l/d}$
h_0/c	1.6	0.9	0.58	0.36	0.185	0.69
fr/c	1.6	4.5	5.3	6.5	8	4.92
$Q/rcNl$	1.6	3	3.98	4.97	5.6	3.59

$h_0 = 0.69\,c = 0.69(0.001) = 0.000\,69$ in *Ans.*

$f = 4.92/(r/c) = 4.92/625 = 0.007\,87$ *Ans.*

$Q = 1.6\,rcNl = 1.6(0.625)\,0.001(18.57)\,2 = 0.0833\ \text{in}^3/\text{s}$ *Ans.*

12-8 Given: $d_{\max} = 75.00$ mm, $b_{\min} = 75.10$ mm, $l = 36$ mm, $W = 2$ kN, $N = 720$ rev/min, and SAE 20 and SAE 40 at 60°C.

$$
\begin{aligned}
c_{\min} &= \frac{b_{\min} - d_{\max}}{2} = \frac{75.10 - 75}{2} = 0.05\ \text{mm} \\
l/d &= 36/75 = 0.48 \approx 0.5 \quad \text{(close enough)} \\
r &= d/2 = 75/2 = 37.5\ \text{mm} \\
r/c &= 37.5/0.05 = 750 \\
N &= 720/60 = 12\ \text{rev/s} \\
P &= \frac{W}{ld} = \frac{2000}{75(36)} = 0.741\ \text{MPa}
\end{aligned}
$$

Fig. 12-13: SAE 20 at 60°C, $\mu = 18.5\ \text{mPa}\cdot\text{s}$

$$
S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 750^2\left[\frac{18.5(10^{-3})(12)}{0.741(10^6)}\right] = 0.169
$$

From Figures 12-16, 12-18 and 12-21:

$$
\begin{aligned}
&h_0/c = 0.29, \quad fr/c = 5.1, \quad P/p_{\max} = 0.315 \\
&h_0 = 0.29(0.05) = 0.0145\ \text{mm} \quad \textit{Ans.} \\
&f = 5.1/750 = 0.0068 \\
&T = fWr = 0.0068(2)(37.5) = 0.51\ \text{N}\cdot\text{m}
\end{aligned}
$$

The heat loss rate equals the rate of work on the film

$H_{\text{loss}} = 2\pi TN = 2\pi(0.51)(12) = 38.5$ W *Ans.*
$p_{\max} = 0.741/0.315 = 2.35$ MPa *Ans.*

Fig. 12-13: SAE 40 at 60°C, $\mu = 37\ \text{mPa}\cdot\text{s}$

$S = 0.169(37)/18.5 = 0.338$

From Figures 12-16, 12-18 and 12-21:

$$h_0 / c = 0.42, \quad f\, r / c = 8.5, \quad P / p_{\max} = 0.38$$
$$h_0 = 0.42(0.05) = 0.021 \text{ mm} \quad \textit{Ans.}$$
$$f = 8.5 / 750 = 0.0113$$
$$T = f\, Wr = 0.0113(2)(37.5) = 0.85 \text{ N} \cdot \text{m}$$
$$H_{\text{loss}} = 2\pi TN = 2\pi(0.85)(12) = 64 \text{ W} \quad \textit{Ans.}$$
$$p_{\max} = 0.741 / 0.38 = 1.95 \text{ MPa} \quad \textit{Ans.}$$

12-9 Given: $d_{\max} = 56.00$ mm, $b_{\min} = 56.05$ mm, $l = 28$ mm, $W = 2.4$ kN, $N = 900$ rev/min, and SAE 40 at 65°C.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{56.05 - 56}{2} = 0.025 \text{ mm}$$
$$r = d / 2 = 56 / 2 = 28 \text{ mm}$$
$$r / c = 28 / 0.025 = 1120$$
$$l / d = 28 / 56 = 0.5, \quad N = 900 / 60 = 15 \text{ rev/s}$$
$$P = \frac{2400}{28(56)} = 1.53 \text{ MPa}$$

Fig. 12-13: SAE 40 at 65°C, $\mu = 30$ mPa · s

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 1120^2 \left[\frac{30(10^{-3})(15)}{1.53(10^6)}\right] = 0.369$$

From Figures 12-16, 12-18, 12-19 and 12-20:

$$h_0 / c = 0.44, \quad f\, r / c = 8.5, \quad Q_s / Q = 0.71, \quad Q / (rcNl) = 4.85$$
$$h_0 = 0.44(0.025) = 0.011 \text{ mm} \quad \textit{Ans.}$$
$$f = 8.5 / 1000 = 0.007\,59$$
$$T = f\, Wr = 0.007\,59(2.4)(28) = 0.51 \text{ N} \cdot \text{m}$$
$$H = 2\pi TN = 2\pi(0.51)(15) = 48.1 \text{ W} \quad \textit{Ans.}$$
$$Q = 4.85\, rcNl = 4.85(28)(0.025)(15)(28) = 1426 \text{ mm}^3\text{/s}$$
$$Q_s = 0.71(1426) = 1012 \text{ mm}^3\text{/s} \quad \textit{Ans.}$$

12-10 Consider the bearings as specified by

minimum f: $\quad d^{+0}_{-t_d}, \quad b^{+t_b}_{-0}$

maximum W: $\quad d'^{+0}_{-t_d}, \quad b^{+t_b}_{-0}$

and differing only in d and d'.

Preliminaries:

$$l\,/\,d = 1$$
$$P = W\,/\,(ld) = 700\,/\,(1.25^2) = 448 \text{ psi}$$
$$N = 3600\,/\,60 = 60 \text{ rev/s}$$

Fig. 12-16:

minimum f: $\quad \mathrm{S} \approx 0.08$

maximum W: $\quad S \approx 0.20$

Fig. 12-12: $\quad \mu = 1.38(10^{-6})$ reyn

$$\mu N/P = 1.38(10^{-6})(60/448) = 0.185(10^{-6})$$

Eq. (12-7):

$$\frac{r}{c} = \sqrt{\frac{S}{\mu N\,/\,P}}$$

For minimum f:

$$\frac{r}{c} = \sqrt{\frac{0.08}{0.185(10^{-6})}} = 658$$
$$c = 0.625\,/\,658 = 0.000\,950 \approx 0.001 \text{ in}$$

If this is $c_{\min}$,

$$b - d = 2(0.001) = 0.002 \text{ in}$$

The median clearance is

$$\bar{c} = c_{\min} + \frac{t_d + t_b}{2} = 0.001 + \frac{t_d + t_b}{2}$$

and the clearance range for *this* bearing is

$$\Delta c = \frac{t_d + t_b}{2}$$

which is a function only of the tolerances.

For maximum W:

$$\frac{r}{c} = \sqrt{\frac{0.2}{0.185(10^{-6})}} = 1040$$
$$c = 0.625\,/\,1040 = 0.000\,600 \approx 0.0005 \text{ in}$$

If this is $c_{\min}$

$$b - d' = 2c_{\min} = 2(0.0005) = 0.001 \text{ in}$$
$$\bar{c} = c_{\min} + \frac{t_d + t_b}{2} = 0.0005 + \frac{t_d + t_b}{2}$$
$$\Delta c = \frac{t_d + t_b}{2}$$

The difference (mean) in clearance between the *two* clearance ranges, c_{range}, is

$$\begin{aligned} c_{\text{range}} &= 0.001 + \frac{t_d + t_b}{2} - \left(0.0005 + \frac{t_d + t_b}{2}\right) \\ &= 0.0005 \text{ in} \end{aligned}$$

For the minimum f bearing

$$b - d = 0.002 \text{ in}$$

or

$$d = b - 0.002 \text{ in}$$

For the maximum W bearing

$$d' = b - 0.001 \text{ in}$$

For the same b, t_b and t_d, we need to change the journal diameter by 0.001 in.

$$\begin{aligned} d' - d &= b - 0.001 - (b - 0.002) \\ &= 0.001 \text{ in} \end{aligned}$$

Increasing d of the minimum friction bearing by 0.001 in, defines d' of the maximum load bearing. Thus, the clearance range provides for bearing dimensions which are attainable in manufacturing. *Ans.*

12-11 Given: SAE 40, N = 10 rev/s, T_s = 140°F, l/d = 1, d = 3.000 in, b = 3.003 in, W = 675 lbf.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{3.003 - 3}{2} = 0.0015 \text{ in}$$
$$r = d / 2 = 3 / 2 = 1.5 \text{ in}$$
$$r / c = 1.5 / 0.0015 = 1000$$
$$P = \frac{W}{ld} = \frac{675}{3(3)} = 75 \text{ psi}$$

Trial #1: From Figure 12-12 for T = 160°F, μ = 3.5 μ reyn,

$$\Delta T = 2(160 - 140) = 40°F$$
$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 1000^2 \left[\frac{3.5(10^{-6})(10)}{75}\right] = 0.4667$$

From Fig. 12-24,

$$\frac{9.70\Delta T}{P} = 0.349\,109 + 6.009\,40(0.4667) + 0.047\,467(0.4667)^2 = 3.16$$
$$\Delta T = 3.16\frac{P}{9.70} = 3.16\frac{75}{9.70} = 24.4°\text{F}$$

Discrepancy = 40 – 24.4 = 15.6°F

Trial #2: T = 150°F, μ = 4.5 μ reyn,

$$\Delta T = 2(150 - 140) = 20°F$$
$$S = 1000^2\left[\frac{4.5\left(10^{-6}\right)10}{75}\right] = 0.6$$

From Fig. 12-24,

$$\frac{9.70\Delta T}{P} = 0.349\,109 + 6.009\,40(0.6) + 0.047\,467(0.6)^2 = 3.97$$
$$\Delta T = 3.97\frac{P}{9.70} = 3.97\frac{75}{9.70} = 30.7°\text{F}$$

Discrepancy = 20 – 30.7 = – 10.7°F

Trial #3: T = 154°F, μ = 4 μ reyn,

$$\Delta T = 2(154 - 140) = 28°F$$
$$S = 1000^2\left[\frac{4\left(10^{-6}\right)10}{75}\right] = 0.533$$

From Fig. 12-24,

$$\frac{9.70\Delta T}{P} = 0.349\,109 + 6.009\,40(0.533) + 0.047\,467(0.533)^2 = 3.57$$
$$\Delta T = 3.57\frac{P}{9.70} = 3.57\frac{75}{9.70} = 27.6°\text{F}$$

Discrepancy = 28 – 27.6 = 0.4°F *O.K.*

T_{av} = 140 +28/2 = 154°F *Ans.*

$$T_1 = T_{\text{av}} - \Delta T\ /\ 2 = 154 - (28\ /\ 2) = 140°F$$
$$T_2 = T_{\text{av}} + \Delta T\ /\ 2 = 154 + (28\ /\ 2) = 168°F$$
$$S = 0.4$$

From Figures 12-16, 12-18, to 12-20:

$$\frac{h_0}{c} = 0.75, \quad \frac{f\,r}{c} = 11, \quad \frac{Q}{rcN\,l} = 3.6, \quad \frac{Q_s}{Q} = 0.33$$

$$h_0 = 0.75(0.0015) = 0.001\,13 \text{ in} \quad Ans.$$

$$f = \frac{11}{1000} = 0.011$$

$$T = f\,Wr = 0.0075(3)(40) = 0.9 \text{ N} \cdot \text{m}$$

$$H_{\text{loss}} = \frac{2\pi f\,WrN}{778(12)} = \frac{2\pi(0.011)675(1.5)10}{778(12)} = 0.075 \text{ Btu/s} \quad Ans.$$

$$Q = 3.6rcN\,l = 3.6(1.5)0.0015(10)3 = 0.243 \text{ in}^3\text{/s} \quad Ans.$$

$$Q_s = 0.33(0.243) = 0.0802 \text{ in}^3\text{/s} \quad Ans.$$

12-12 Given: d = 2.5 in, b = 2.504 in, $c_{\min}$ = 0.002 in, W = 1200 lbf, SAE = 20, T_s = 110°F, N = 1120 rev/min, and l = 2.5 in.

$P = W/(ld) = 1200/(2.5)^2 = 192$ psi, $\quad N = 1120/60 = 18.67$ rev/s

For a trial film temperature, let T_f = 150°F

Table 12-1: $\quad \mu' = 0.0136 \exp[1271.6/(150 + 95)] = 2.441\ \mu$ reyn

Eq. (12-7): $$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = \left(\frac{2.5/2}{0.002}\right)^2 \frac{2.441\left(10^{-6}\right)18.67}{192} = 0.0927$$

Fig. 12-24:

$$\Delta T = \frac{192}{9.70}\left[0.349\,109 + 6.009\,40(0.0927) + 0.047\,467\left(0.0927^2\right)\right]$$
$$= 17.9\text{°F}$$

$$T_{\text{av}} = T_s + \frac{\Delta T}{2} = 110 + \frac{17.9}{2} = 119.0\text{°F}$$

$$T_f - T_{\text{av}} = 150 - 119.0 = 31.0\text{°F}$$

which is not 0.1 or less, therefore try averaging for the new trial film temperature, let

$$(T_f)_{\text{new}} = \frac{150 + 119.0}{2} = 134.5\text{°F}$$

Proceed with additional trials using a spreadsheet (table also shows the first trial)

Trial T_f	μ'	S	ΔT	T_{av}	$T_f - T_{av}$	New T_f
150.0	2.441	0.0927	17.9	119.0	31.0	134.5
134.5	3.466	0.1317	22.6	121.3	13.2	127.9
127.9	4.084	0.1551	25.4	122.7	5.2	125.3
125.3	4.369	0.1659	26.7	123.3	2.0	124.3
124.3	4.485	0.1704	27.2	123.6	0.7	124.0
124.0	4.521	0.1717	27.4	123.7	0.3	123.8
123.8	4.545	0.1726	27.5	123.7	0.1	123.8

Note that the convergence begins rapidly. There are ways to speed this, but at this point they would only add complexity.

(a) $\mu' = 4.545(10^{-6}), \quad S = 0.1726$

From Fig. 12-16: $\dfrac{h_0}{c} = 0.482, \quad h_0 = 0.482(0.002) = 0.000\ 964 \text{ in}$

From Fig. 12-17: $\phi = 56°$ *Ans.*

(b) $e = c - h_0 = 0.002 - 0.000\ 964 = 0.001\ 04$ in *Ans.*

(c) From Fig. 12-18: $\dfrac{f\ r}{c} = 4.10, \quad f = 4.10(0.002/1.25) = 0.006\ 56$ *Ans.*

(d) $T = f\,Wr = 0.006\ 56(1200)(1.25) = 9.84 \text{ lbf} \cdot \text{in}$

$$H = \frac{2\pi T\,N}{778(12)} = \frac{2\pi(9.84)(1120\ /\ 60)}{778(12)} = 0.124 \text{ Btu/s} \quad \textit{Ans.}$$

(e) From Fig. 12-19: $\dfrac{Q}{rcNl} = 4.16$

$$Q = 4.16(1.25)(0.002)\left(\frac{1120}{60}\right)(2.5) = 0.485 \text{ in}^3\text{/s} \quad \textit{Ans.}$$

From Fig. 12-20: $\dfrac{Q_s}{Q} = 0.6, \quad Q_s = 0.6(0.485) = 0.291 \text{ in}^3\text{/s}$ *Ans.*

(f) From Fig. 12-21: $\dfrac{P}{p_{\max}} = 0.45, \quad p_{\max} = \dfrac{W\ /\ (ld)}{0.45} = \dfrac{1200\ /\ 2.5^2}{0.45} = 427 \text{ psi}$ *Ans.*

From Fig. 12-22: $\phi_{p_{\max}} = 16°$ *Ans.*

(g) From Fig. 12-22: $\phi_{p_0} = 82°$ *Ans.*

(h) From the trial table, $T_f = 123.8°F$ *Ans.*

(i) With $\Delta T = 27.5°F$ from the trial table, $T_s + \Delta T = 110 + 27.5 = 137.5°F$ *Ans.*

12-13 Given: $d = 1.250$ in, $t_d = 0.001$ in, $b = 1.252$ in, $t_b = 0.003$ in, $l = 1.25$ in, $W = 250$ lbf, $N = 1750$ rev/min, SAE 10 lubricant, sump temperature $T_s = 120°F$.

$$P = W/(ld) = 250/1.25^2 = 160 \text{ psi}, \quad N = 1750/60 = 29.17 \text{ rev/s}$$

For the clearance, $c = 0.002 \pm 0.001$ in. Thus, $c_{\min} = 0.001$ in, $c_{\text{median}} = 0.002$ in, and $c_{\max} = 0.003$ in.

For $c_{\min} = 0.001$ in, start with a trial film temperature of $T_f = 135°F$

Table 12-1: $\mu' = 0.0158 \exp[1157.5/(135 + 95)] = 2.423\ \mu$reyn

Eq. (12-7): $$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = \left(\frac{1.25/2}{0.001}\right)^2 \frac{2.423\left(10^{-6}\right)29.17}{160} = 0.1725$$

Fig. 12-24:

$$\begin{aligned}\Delta T &= \frac{160}{9.70}\left[0.349\,109 + 6.009\,40(0.1725) + 0.047\,467\left(0.1725^2\right)\right] \\ &= 22.9°F\end{aligned}$$

$$T_{\text{av}} = T_s + \frac{\Delta T}{2} = 120 + \frac{22.9}{2} = 131.4°F$$
$$T_f - T_{\text{av}} = 135 - 131.4 = 3.6°F$$

which is not 0.1 or less, therefore try averaging for the new trial film temperature, let

$$(T_f)_{\text{new}} = \frac{135 + 131.4}{2} = 133.2°F$$

Proceed with additional trials using a spreadsheet (table also shows the first trial)

Trial T_f	μ'	S	ΔT	T_{av}	$T_f - T_{\text{av}}$	New T_f
135.0	2.423	0.1725	22.9	131.4	3.6	133.2
133.2	2.521	0.1795	23.6	131.8	1.4	132.5
132.5	2.560	0.1823	23.9	131.9	0.6	132.2
132.2	2.578	0.1836	24.0	132.0	0.2	132.1
132.1	2.583	0.1840	24.0	132.0	0.1	132.1

With T_f = 132.1°F, ΔT = 24.0°F, μ'= 2.583 μ reyn, S = 0.1840,

$$T_{\max} = T_s + \Delta T = 120 + 24.0 = 144.0\text{°F}$$

Fig. 12-16: $h_0/c = 0.50$, $h_0 = 0.50(0.001) = 0.000\ 50$ in

$\int = 1 - h_0/c = 1 - 0.50 = 0.05$ in

Fig. 12-18: $r\,f/c = 4.25$, $f = 4.25/(0.625/0.001) = 0.006\ 8$

Fig. 12-19: $Q/(rcNl) = 4.13$, $Q = 4.13(0.625)0.001(29.17)1.25 = 0.0941$ in^3/s

Fig. 12-20: $Q_s/Q = 0.58$, $Q_s = 0.58(0.0941) = 0.0546$ in^3/s

The above can be repeated for c_{median} = 0.002 in, and $c_{\max}$ = 0.003 in. The results are shown below.

	$c_{\min}$ 0.001 in	c_{median} 0.002 in	$c_{\max}$ 0.003 in
T_f	132.1	125.6	124.1
μ'	2.583	3.002	3.112
S	0.184	0.0534	0.0246
ΔT	24.0	11.1	8.2
$T_{\max}$	144.0	131.1	128.2
h_0/c	0.5	0.23	0.125
h_0	0.00050	0.00069	0.00038
$\int$	0.50	0.77	0.88
fr/c	4.25	1.8	1.22
f	0.0068	0.0058	0.0059
$Q/(rcNl)$	4.13	4.55	4.7
Q	0.0941	0.207	0.321
Q_s/Q	0.58	0.82	0.90
Q_s	0.0546	0.170	0.289

12-14 Computer programs will vary.

12-15 In a step-by-step fashion, we are building a skill for natural circulation bearings.
- Given the average film temperature, establish the bearing properties.
- Given a sump temperature, find the average film temperature, then, establish the

bearing properties.

- Now we acknowledge the environmental temperature's role in establishing the sump temperature. Sec. 12-9 and Ex. 12-5 address this problem.

Given: $d_{\text{max}} = 2.500$ in, $b_{\text{min}} = 2.504$ in, $l/d = 1$, $N = 1120$ rev/min, SAE 20 lubricant, $W = 300$ lbf, $A = 60\text{ in}^2$, $T_\infty = 70°$F, and $\alpha = 1$.

600 *lbf load with minimal clearance:* We will start by using $W = 600$ lbf ($n_d = 2$). The task is to iteratively find the average film temperature, T_f, which makes H_{gen} and H_{loss} equal.

$$c_{\text{min}} = \frac{b_{\text{min}} - d_{\text{max}}}{2} = \frac{2.504 - 2.500}{2} = 0.002 \text{ in}$$

$N = 1120/60 = 18.67$ rev/s

$$P = \frac{W}{ld} = \frac{600}{2.5^2} = 96 \text{ psi}$$

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = \left(\frac{1.25}{0.002}\right)^2 \frac{\mu'\left(10^{-6}\right)18.67}{96} = 0.0760\mu'$$

Table 12-1: $\mu' = 0.0136 \exp[1271.6/(T_f + 95)]$

$$H_{\text{gen}} = \frac{2545}{1050} WNc\left(\frac{f\,r}{c}\right) = \frac{2545}{1050}(600)18.67(0.002)\frac{f\,r}{c}$$
$$= 54.3\frac{f\,r}{c}$$

$$H_{\text{loss}} = \frac{\hbar_{\text{CR}} A}{\alpha + 1}\left(T_f - T_\infty\right) = \frac{2.7(60/144)}{1+1}\left(T_f - 70\right)$$
$$= 0.5625\left(T_f - 70\right)$$

Start with trial values of T_f of 220 and 240°F.

Trial T_f	μ'	S	$f\,r/c$	H_{gen}	H_{loss}
220	0.770	0.059	1.9	103.2	84.4
240	0.605	0.046	1.7	92.3	95.6

As a linear approximation, let $H_{\text{gen}} = mT_f + b$. Substituting the two sets of values of T_f and H_{gen} we find that $H_{\text{gen}} = -0.545\,T_f + 223.1$. Setting this equal to H_{loss} and solving for T_f gives $T_f = 237°$F.

Trial T_f	μ'	S	$f\,r/c$	H_{gen}	H_{loss}
237	0.627	0.048	1.73	93.9	94.0

which is satisfactory.

Table 12-16: $h_0/c = 0.21$, $h_0 = 0.21\,(0.002) = 000\ 42$ in

Fig. 12-24:

$$\Delta T = \frac{96}{9.7}\left[0.349\,109 + 6.009\,4(0.048) + 0.047\,467(0.048^2)\right]$$

$$= 6.31°\,\text{F}$$

$$T_1 = T_s = T_f - \Delta T = 237 - 6.31/2 = 233.8°\text{F}$$

$$T_{max} = T_1 + \Delta T = 233.8 + 6.31 = 240.1°\text{F}$$

Trumpler's design criteria:

$0.002 + 0.000\ 04d = 0.002 + 0.000\ 04(2.5) = 0.000\ 30 \text{ in} < h_0$ *O.K.*

$T_{max} = 240.1°\text{F} < 250°\text{F}$ *O.K.*

$$\frac{W_{st}}{ld} = \frac{300}{2.5^2} = 48 \text{ psi} < 300 \text{ psi} \qquad O.K.$$

$n_d = 2$ (assessed at $W = 600$ lbf) *O.K.*

We see that the design passes Trumpler's criteria and is deemed acceptable.

For an operating load of $W = 300$ lbf, it can be shown that $T_f = 219.3°\text{F}$, $\mu' = 0.78$, $S = 0.118$, $f\,r/c = 3.09$, $H_{gen} = H_{loss} = 84$ Btu/h, $h_0 =$, $\Delta T = 10.5°\text{F}$, $T_1 = 224.6°\text{F}$, and $T_{max} = 235.1°\text{F}$.

12-16 Given: $d = 3.500^{+0.000}_{-0.001}$ in, $b = 3.505^{+0.005}_{-0.000}$ in, SAE 30, $T_s = 120°\text{F}$, $p_s = 50$ psi, $N = 2000/60 = 33.33$ rev/s, $W = 4600$ lbf, bearing length = 2 in, groove width = 0.250 in, and $H_{loss} \le 5000$ Btu/hr.

$$c_{min} = \frac{b_{min} - d_{max}}{2} = \frac{3.505 - 3.500}{2} = 0.0025 \text{ in}$$

$$r = d/2 = 3.500/2 = 1.750 \text{ in}$$

$$r/c = 1.750/0.0025 = 700$$

$$l' = (2 - 0.25)/2 = 0.875 \text{ in}$$

$$l'/d = 0.875/3.500 = 0.25$$

$$P = \frac{W}{4rl'} = \frac{4600}{4(1.750)0.875} = 751 \text{ psi}$$

Trial #1: Choose $(T_f)_1$ = 150°F. From Table 12-1,

$$\mu' = 0.0141 \exp[1360.0/(150 + 95)] = 3.63\ \mu \text{ reyn}$$

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 700^2 \left[\frac{3.63(10^{-6})(33.33)}{751}\right] = 0.0789$$

From Figs. 12-16 and 12-18: $\int = 0.9$, $f\,r/c = 3.6$

From Eq. (12-24),

$$\Delta T = \frac{0.0123(f\ r\ /\ c)SW^2}{\left(1 + 1.5\grave{o}^2\right) p_s\, r^4}$$

$$= \frac{0.0123(3.6)0.0789\left(4600^2\right)}{\left[1 + 1.5(0.9)^2\right]50\left(1.750^4\right)} = 71.2°\text{F}$$

$$T_{\text{av}} = T_s + \Delta T / 2 = 120 + 71.2/2 = 155.6°\text{F}$$

Trial #2: Choose $(T_f)_2$ = 160°F. From Table 12-1

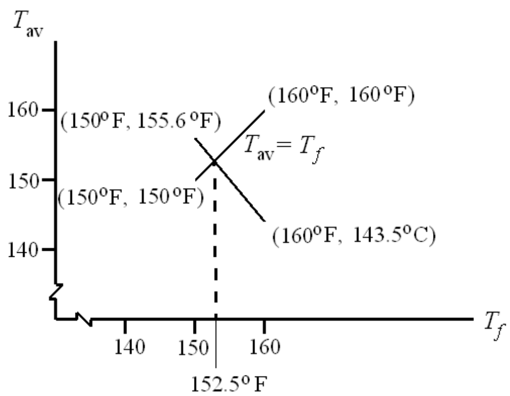
$$\mu' = 0.0141 \exp[1360.0/(160 + 95)] = 2.92\ \mu \text{ reyn}$$

$$S = 0.0789\left(\frac{2.92}{3.63}\right) = 0.0635$$

From Figs. 12-16 and 12-18: $\int = 0.915$, $f\,r/c = 3$

$$\Delta T = \frac{0.0123(3)0.0635\left(4600^2\right)}{\left[1 + 1.5\left(0.915^2\right)\right]50\left(1.750^4\right)} = 46.9°\text{F}$$

$$T_{\text{av}} = 120 + 46.9/2 = 143.5°\text{F}$$



Trial #3: Thus, the plot gives $(T_f)_3$ = 152.5°F. From Table 12-1

$$\mu' = 0.0141 \exp[1360.0/(152.5 + 95)] = 3.43\ \mu \text{ reyn}$$

$$S = 0.0789\left(\frac{3.43}{3.63}\right) = 0.0746$$

From Figs. 12-16 and 12-18: $\int = 0.905$, $fr/c = 3.4$

$$\Delta T = \frac{0.0123(3.4)0.0746\left(4600^2\right)}{\left[1+1.5\left(0.905^2\right)\right]50\left(1.750^4\right)} = 63.2\text{°F}$$

T_{av} = 120 + 63.2/2 = 151.6°F

Result is close. Choose $\bar{T}_f = \dfrac{152.5 + 151.6}{2}$ = 152.1°F Try 152°F

Table 12-1: μ' = 0.0141 exp[1360.0/(152 + 95)] = 3.47 μ reyn

$$S = 0.0789\left(\frac{3.47}{3.63}\right) = 0.0754$$

$$\frac{f\ r}{c} = 3.4, \quad \text{ò} = 0.902, \quad \frac{h_0}{c} = 0.098$$

$$\Delta T = \frac{0.0123(3.4)0.0754\left(4600^2\right)}{\left[1+1.5\left(0.902^2\right)\right]50\left(1.750^4\right)} = 64.1\text{°F}$$

T_{av} = 120 + 64.1 / 2 = 152.1°F O.K.

h_0 = 0.098(0.0025) = 0.000 245 in

$T_{\max} = T_s + \Delta T$ = 120 + 64.1 = 184.1°F

Eq. (12-22):

$$Q_s = \frac{\pi p_s r c^3}{3\mu l'}\left(1+1.5\text{ò}^2\right) = \frac{\pi(50)1.750\left(0.0025^3\right)}{3(3.47)10^{-6}(0.875)}\left[1+1.5\left(0.902^2\right)\right]$$
$$= 1.047\ \text{in}^3/\text{s}$$

$H_{\text{loss}} = \rho\, C_p Q_s\, \Delta T$ = 0.0311(0.42)1.047(64.1) = 0.877 Btu/s
= 0.877(60^2) = 3160 Btu/h *O.K.*

Trumpler's design criteria:

0.0002 + 0.000 04(3.5) = 0.000 34 in > 0.000 245 *Not O.K.*
$T_{\max}$ = 184.1°F < 250°F *O.K.*
P_{st} = 751 psi > 300 psi *Not O.K.*
n = 1, as done *Not O.K.*

12-17 Given: $d = 50.00^{+0.00}_{-0.05}$ mm, $b = 50.084^{+0.010}_{-0.000}$ mm, SAE 30, T_s = 55°C, p_s = 200 kPa, N = 2880/60 = 48 rev/s, W = 10 kN, bearing length = 55 mm, groove width = 5 mm, and

$H_{\text{loss}} \le 300$ W.

$$c_{\min} = \frac{b_{\min} - d_{\max}}{2} = \frac{50.084 - 50}{2} = 0.042 \text{ mm}$$

$r = d/2 = 50/2 = 25$ mm

$r/c = 25/0.042 = 595$

$l' = (55 - 5)/2 = 25$ mm

$l'/d = 25/50 = 0.5$

$$P = \frac{W}{4rl'} = \frac{10\left(10^3\right)}{4\left(25\right)25} = 4 \text{ MPa}$$

Trial #1: Choose $(T_f)_1 = 79$°C. From Fig. 12-13, $\mu = 13$ mPa · s.

$$S = \left(\frac{r}{c}\right)^2 \frac{\mu N}{P} = 595^2 \left[\frac{13(10^{-3})(48)}{4(10^6)}\right] = 0.0552$$

From Figs. 12-16 and 12-18: ∫ = 0.85, $f\,r/c = 2.3$
From Eq. (12-25),

$$\Delta T = \frac{978(10^6)}{1 + 1.5\grave{o}^2} \frac{(f\ r\ /\ c)SW^2}{p_s\, r^4}$$

$$= \frac{978(10^6)}{1 + 1.5(0.85)^2} \left[\frac{2.3(0.0552)(10^2)}{200(25)^4}\right] = 76.3\text{°C}$$

$T_{\text{av}} = T_s + \Delta T/2 = 55 + 76.3/2 = 93.2$°C

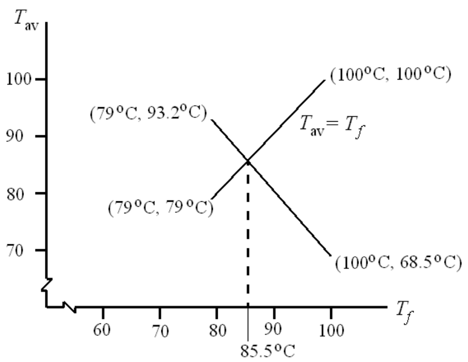
Trial #2: Choose $(T_f)_2 = 100$°C. From Fig. 12-13, $\mu = 7$ mPa · s.

$$S = 0.0552\left(\frac{7}{13}\right) = 0.0297$$

From Figs. 12-16 and 12-18: ∫ = 0.90, $f\,r/c = 1.6$

$$\Delta T = \frac{978(10^6)}{1 + 1.5(0.9)^2} \left[\frac{1.6(0.0297)(10^2)}{200(25)^4}\right] = 26.9\text{°C}$$

$T_{\text{av}} = 55 + 26.9/2 = 68.5$°C



Trial #3: Thus, the plot gives $(T_f)_3$ = 85.5°C. From Fig. 12-13, μ = 10.5 mPa · s.

$$S = 0.0552\left(\frac{10.5}{13}\right) = 0.0446$$

From Figs. 12-16 and 12-18: $\epsilon = 0.87$, $f\,r/c = 2.2$

$$\Delta T = \frac{978(10^6)}{1+1.5(0.87^2)}\left[\frac{2.2(0.0457)(10^2)}{200(25)^4}\right] = 58.9°\text{C}$$

$$T_{\text{av}} = 55 + 58.9/2 = 84.5°\text{C}$$

Result is close. Choose $\bar{T}_f = \dfrac{85.5 + 84.5}{2} = 85°\text{C}$

Fig. 12-13: μ = 10.5 mPa · s

$$S = 0.0552\left(\frac{10.5}{13}\right) = 0.0446$$

$$\epsilon = 0.87, \quad \frac{f\,r}{c} = 2.2, \quad \frac{h_0}{c} = 0.13$$

$$\Delta T = \frac{978(10^6)}{1+1.5(0.87^2)}\left[\frac{2.2(0.0457)(10^2)}{200(25^4)}\right] = 58.9°\text{C} \quad \text{or} \quad 138°\text{F}$$

$$T_{\text{av}} = 55 + 58.9\ /\ 2 = 84.5°\text{C} \quad \text{O.K.}$$

From Eq. (12-22)

h_0 = 0.13(0.042) = 0.005 46 mm or 0.000 215 in

$T_{\max} = T_s + \Delta T$ = 55 + 58.9 = 113.9°C or 237°F

$$Q_s = (1+1.5\epsilon^2)\frac{\pi p_s r c^3}{3\mu l'} = \left[1+1.5\left(0.87^2\right)\right]\left[\frac{\pi(200)25\left(0.042^3\right)}{3(10.5)10^{-6}(25)}\right]$$

$$= 3156\ \text{mm}^3/\text{s} = 3156\left(25.4^{-3}\right) = 0.193\ \text{in}^3/\text{s}$$

$H_{\text{loss}} = \rho C_p Q_s \Delta T$ = 0.0311(0.42)0.193(138) = 0.348 Btu/s
= 1.05(0.348) = 0.365 kW = 365 W *not O.K.*

Trumpler's design criteria:

0.0002 + 0.000 04(50/25.4) = 0.000 279 in > h_0 *Not O.K.*
$T_{\max}$ = 237°F *O.K.*
P_{st} = 4000 kPa or 581 psi > 300 psi *Not O.K.*
n = 1, as done *Not O.K.*

12-18 So far, we have performed elements of the design task. Now let's do it more completely. The values of the unilateral tolerances, t_b and t_d, reflect the routine capabilities of the bushing vendor and the in-house capabilities. While the designer has to live with these, his approach should not depend on them. They can be incorporated later.

First we shall find the minimum size of the journal which satisfies Trumpler's constraint of $P_{st} \le 300$ psi.

$$P_{st} = \frac{W}{2dl'} \le 300$$

$$\frac{W}{2d^2 l'/d} \le 300 \;\Rightarrow\; d \ge \sqrt{\frac{W}{600(l'/d)}}$$

$$d_{\min} = \sqrt{\frac{900}{2(300)(0.5)}} = 1.73 \text{ in}$$

In this problem we will take journal diameter as the nominal value and the bushing bore as a variable. In the next problem, we will take the bushing bore as nominal and the journal diameter as free.

To determine where the constraints are, we will set $t_b = t_d = 0$, and thereby shrink the design window to a point.

We set $d = 2.000$ in
$b = d + 2c_{\min} = d + 2c$
$n_d = 2$ (This makes Trumpler's $n_d \le 2$ tight)

and construct a table.

c	b	d	$\bar{T}_f$ *	$T_{\max}$	h_0	P_{st}	$T_{\max}$	n	fom
0.0010	2.0020	2	215.50	312.0	×	√	×	√	–5.74
0.0011	2.0022	2	206.75	293.0	×	√	√	√	–6.06
0.0012	2.0024	2	198.50	277.0	×	√	√	√	–6.37
0.0013	2.0026	2	191.40	262.8	×	√	√	√	–6.66
0.0014	2.0028	2	185.23	250.4	×	√	√	√	–6.94
0.0015	2.0030	2	179.80	239.6	×	√	√	√	–7.20
0.0016	2.0032	2	175.00	230.1	×	√	√	√	–7.45
0.0017	2.0034	2	171.13	220.3	×	√	√	√	–7.65
0.0018	2.0036	2	166.92	213.9	√	√	√	√	–7.91
0.0019	2.0038	2	163.50	206.9	√	√	√	√	–8.12
0.0020	2.0040	2	160.40	200.6	√	√	√	√	–8.32

*Sample calculation for the first entry of this column.

Iteration yields: $\bar{T}_f = 215.5°\text{F}$

With $\bar{T}_f = 215.5°\text{F}$, from Table 12-1

$$\mu = 0.0136(10^{-6})\exp[1271.6 / (215.5 + 95)] = 0.817(10^{-6}) \text{ reyn}$$

$$N = 3000 / 60 = 50 \text{ rev/s}, \quad P = \frac{900}{4} = 225 \text{ psi}$$

$$S = \left(\frac{1}{0.001}\right)^2 \left[\frac{0.817(10^{-6})(50)}{225}\right] = 0.182$$

From Figs. 12-16 and 12-18: $\int = 0.7, \quad f\,r/c = 5.5$
Eq. (12–24):

$$\Delta T_F = \frac{0.0123(5.5)(0.182)(900^2)}{[1 + 1.5(0.7^2)](30)(1^4)} = 191.6°\text{F}$$

$$T_{\text{av}} = 120°\text{F} + \frac{191.6°\text{F}}{2} = 215.8°\text{F} \approx 215.5°\text{F}$$

For the nominal 2-in bearing, the various clearances show that we have been in contact with the recurving of $(h_0)_{\min}$. The figure of merit (the parasitic friction torque plus the pumping torque negated) is best at c = 0.0018 in. For the nominal 2-in bearing, we will place the top of the design window at $c_{\min}$ = 0.002 in, and $b = d + 2(0.002) = 2.004$ in. At this point, add the b and d unilateral tolerances:

$$d = 2.000^{+0.000}_{-0.001} \text{ in}, \quad b = 2.004^{+0.003}_{-0.000} \text{ in}$$

Now we can check the performance at $c_{\min}$, $\bar{c}$, and $c_{\max}$. Of immediate interest is the fom of the median clearance assembly, – 9.82, as compared to any other satisfactory bearing ensemble.
If a nominal 1.875 in bearing is possible, construct another table with $t_b = 0$ and $t_d = 0$.

c	b	d	$\bar{T}_f$	$T_{\max}$	h_0	P_{st}	$T_{\max}$	n	fom
0.0020	1.879	1.875	157.2	194.30	×	√	√	√	– 7.36
0.0030	1.881	1.875	138.6	157.10	√	√	√	√	– 8.64
0.0035	1.882	1.875	133.5	147.10	√	√	√	√	– 9.05
0.0040	1.883	1.875	130.0	140.10	√	√	√	√	– 9.32
0.0050	1.885	1.875	125.7	131.45	√	√	√	√	– 9.59
0.0055	1.886	1.875	124.4	128.80	√	√	√	√	– 9.63
0.0060	1.887	1.875	123.4	126.80	×	√	√	√	– 9.64

The range of clearance is $0.0030 < c < 0.0055$ in. That is enough room to fit in our design window.

$$d = 1.875^{+0.000}_{-0.001} \text{ in}, \quad b = 1.881^{+0.003}_{-0.000} \text{ in}$$

The ensemble median assembly has a fom = – 9.31.
We just had room to fit in a design window based upon the $(h_0)_{\min}$ constraint. Further

reduction in nominal diameter will preclude any smaller bearings. A table constructed for a d = 1.750 in journal will prove this.

We choose the nominal 1.875-in bearing ensemble because it has the largest figure of merit. *Ans.*

12-19 This is the same as Prob. 12-18 but uses design variables of nominal bushing bore b and radial clearance c.

The approach is similar to that of Prob. 12-18 and the tables will change slightly. In the table for a nominal b = 1.875 in, note that at c = 0.003 in the constraints are "loose." Set

$$b = 1.875 \text{ in}$$
$$d = 1.875 - 2(0.003) = 1.869 \text{ in}$$

For the ensemble

$$b = 1.875^{+0.003}_{-0.001} \text{ in}, \quad d = 1.869^{+0.000}_{-0.001} \text{ in}$$

Analyze at $c_{\min}$ = 0.003 in, $\bar{c}$ = 0.004 in and $c_{\max}$ = 0.005 in

At $c_{\min} = 0.003$ in: $\bar{T}_f = 138.4°$F, $\mu' = 3.160\ \mu$reyn, $S = 0.0297$, $H_{\text{loss}} = 1035$ Btu/h and the Trumpler conditions are met.

At $\bar{c} = 0.004$ in: $\bar{T}_f = 130°$F, $\mu' = 3.872\ \mu$reyn, $S = 0.0205$, $H_{\text{loss}} = 1106$ Btu/h, fom = –9.246 and the Trumpler conditions are *O.K.*
At $c_{\max} = 0.005$ in: $\bar{T}_f = 125.68°$F, $\mu' = 4.325\mu$reyn, $S = 0.014\ 66$, $H_{\text{loss}} = 1129$ Btu/h and the Trumpler conditions are *O.K.*

The ensemble figure of merit is slightly better; this bearing is *slightly* smaller. The lubricant cooler has sufficient capacity.

12-20 Table 12-1: $\mu\,(\mu\,\text{reyn}) = \mu_0\,(10^6)\exp\,[b\,/\,(T + 95)]$ b and T in °F

The conversion from μ reyn to mPa·s is given on p. 612. For a temperature of C degrees Celsius, $T = 1.8\ C + 32$. Substituting into the above equation gives

$$\mu\,(\text{mPa·s}) = 6.89\ \mu_0\,(10^6)\exp\,[b\,/\,(1.8\ C + 32 + 95)]$$

$$= 6.89\ \mu_0\,(10^6)\exp\,[b\,/\,(1.8\ C + 127)] \qquad \textit{Ans.}$$

For SAE 50 oil at 70°C, from Table 12-1, $\mu_0 = 0.0170\ (10^{-6})$ reyn, and b = 1509.6°F. From the equation,

$$\mu = 6.89(0.0170)\ 10^{-6}(10^6)\exp\,\{1509.6/[1.8(70) + 127]\}$$

$= 45.7$ mPa·s *Ans.*

From Fig. 12-13, $\mu = 39$ mPa·s *Ans.*

The figure gives a value of about 15 % lower than the equation.

12-21 Originally

$$d = 2.000^{+0.000}_{-0.001} \text{ in}, \quad b = 2.005^{+0.003}_{-0.000} \text{ in}$$

Doubled,

$$d = 4.000^{+0.000}_{-0.002} \text{ in}, \quad b = 4.010^{+0.006}_{-0.000} \text{ in}$$

The radial load quadrupled to 3600 lbf when the analyses for parts (a) and (b) were carried out. Some of the results are:

Part	$\bar{c}$	μ'	S	$\bar{T}_f$	$f\,r/c$	Q_s	h_0/c	$\int$	H_{loss}	h_0	Trumpler h_0	f
(a)	0.007	3.416	0.0310	135.1	0.1612	6.56	0.1032	0.897	9898	0.000 722	0.000 360	0.005 67
(b)	0.0035	3.416	0.0310	135.1	0.1612	0.870	0.1032	0.897	1237	0.000 361	0.000 280	0.005 67

The side flow Q_s differs because there is a c^3 term and consequently an 8-fold increase. H_{loss} is related by a 9898/1237 or an 8-fold increase. The existing h_0 is related by a 2-fold increase. Trumpler's $(h_0)_{min}$ is related by a 1.286-fold increase.

12-22 Given: Oiles SP 500 alloy brass bushing, $L = 0.75$ in, $D = 0.75$ in, $T_\infty = 70°$F, $F = 400$ lbf, $N = 250$ rev/min, and $w = 0.004$ in.

Table 12-8: $K = 0.6(10^{-10})$ in^3·min/(lbf·ft·h)

$$P = F/(DL) = 400/[0.75(0.75)] = 711 \text{ psi}$$

$$V = \pi DN/12 = \pi(0.75)250/12 = 49.1 \text{ ft/min}$$

From Table 12-10, interpolation gives

V	f_1	
33	1.3	
49.1	f_1	=> $f_1 = 1.42$
100	1.8	

Table 12-11: $f_2 = 1.0$

Table 12-12: PV_{max} = 46 700 psi·ft/min, P_{max} = 3560 psi, V_{max} = 100 ft/min

$$P_{max} = \frac{4}{\pi}\frac{F}{DL} = \frac{4}{\pi}\frac{400}{0.75^2} = 905 \text{ psi} < 3560 \text{ psi} \quad O.K.$$

PV = 711 (49.1) = 34 910 psi·ft/min < 46 700 psi·ft/min   *O.K.*

Eq. (12-32) can be written as

$$w = f_1 f_2 K \frac{4}{\pi}\frac{F}{DL} Vt$$

Solving for t,

$$t = \frac{\pi DLw}{4 f_1 f_2 KVF} = \frac{\pi(0.75)0.75(0.004)}{4(1.42)1.0(0.6)10^{-10}(49.1)400}$$

$$= 1056 \text{ h} = 1056(60) = 63\ 400 \text{ min}$$

Cycles = Nt = 250 (63 400) = 15.9 (10^6) cycles   *Ans.*

12-23 Given: Oiles SP 500 alloy brass bushing, w_{max} = 0.002 in for 1000 h, N = 200 rev/min, F = 100 lbf, $\hbar_{CR}$ = 2.7 Btu/(h·ft^2·°F), T_{max} = 300 °F, f_s = 0.03, and n_d = 2.

Using Eq. (12-38) with $n_d F$ for F, f_s = 0.03 from Table 12-9, and $\hbar_{CR}$ = 2.7 Btu/(h · ft^2 · °F), gives

$$L \geq \frac{720\ f_s n_d FN}{J\hbar_{CR}\left(T_f - T_\infty\right)} = \frac{720(0.03)2(100)200}{778(2.7)(300-70)} = 1.79 \text{ in}$$

From Table 12-13, the smallest available bushing has an ID = 1 in, OD = $1\frac{3}{8}$ in, and L = 2 in. With L/D = 2/1 = 2, this is inside of the recommendations of Eq. (12-33). Thus, for the first trial, try the bushing with ID = 1 in, OD = $1\frac{3}{8}$ in, and L = 2 in. Thus,

Eq. (12-31): $$P_{max} = \frac{4}{\pi}\frac{n_d F}{DL} = \frac{4}{\pi}\frac{2(100)}{1(2)} = 127.3 \text{ psi} < 3560 \text{ psi} \quad \text{(OK)}$$

$$P = \frac{n_d F}{DL} = \frac{2(100)}{1(2)} = 100 \text{ psi}$$

Eq. (12-29): $V = \dfrac{\pi DN}{12} = \dfrac{\pi(1)\,200}{12} = 52.4\ \text{ft/min} < 100\ \text{ft/min}$ (OK)

$$PV = 100(52.4) = 5240\ \text{psi}\cdot\text{ft/min} < 46\,700\ \text{psi}\cdot\text{ft/min} \quad \text{(OK)}$$

From Table 12-10, interpolation gives

V	f_1	
33	1.3	
52.4	f_1	=> $f_1 = 1.445$
100	1.8	

Eq. (12-32), with Tables 12-8 and 12-10:

$$w = \frac{f_1 f_2 K n_d F N t}{3L} = \frac{1.445(1)\,6\left(10^{-11}\right)2(100)\,200(1000)}{3(2)} = 0.000\,578\ \text{in} < 0.001\ \text{in} \quad \text{(OK)}$$

Answer Select ID = 1 in, OD = $1\frac{3}{8}$ in, and L = 2 in.