Pneumatics and hydraulics

Physical Properties of Hydraulic Fluids

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outline

- Explain the primary functions of a hydraulic fluid.
- Define the term *fluid.*
- Distinguish between a liquid and a gas.
- Appreciate the properties desired of a hydraulic fluid.
- Define the terms *specific weight, density,* and *specific gravity*.
- Understand the terms *pressure, head,* and *force.*
- Calculate the force created by a pressure.
- Understand the terms *kinematic viscosity* and *absolute viscosity.*
- Convert viscosity from one set of units to another set of units.
- Explain the difference between viscosity and viscosity index.

introduction

- The single most important material in a hydraulic system is the working fluid itself.
- Hydraulic fluid characteristics have a crucial effect on equipment performance and life. It is important to use a clean, high-quality fluid in order to achieve efficient hydraulic system operation.
  - Most modern hydraulic fluids are complex compounds that have been carefully prepared to meet their demanding tasks.
  - In addition to having a base fluid, hydraulic fluids contain special additives to provide desired characteristics.

Hydraulic fluid functions and properties

- A hydraulic fluid has the following four primary functions:

1. Transmit power
2. Lubricate moving parts
3. Seal clearances between mating parts
4. Dissipate heat

- In addition a hydraulic fluid must be inexpensive and readily available.

- To accomplish properly the four primary functions and be practical from a safety and cost point of view, a hydraulic fluid should have the following properties:

1. Good lubricity
2. Ideal viscosity
3. Chemical stability
4. Compatibility with system materials
5. High degree of incompressibility
6. Fire resistance
7. Good heat-transfer capability
8. Low density
9. Foam resistance
10. Nontoxicity
11. Low volatility

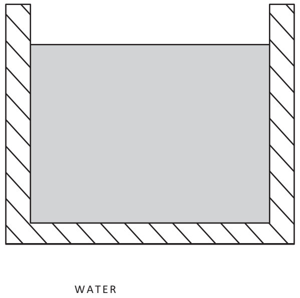
Hydraulic fluid functions and properties

- This is a challenging list, and no single hydraulic fluid possesses all of these desirable characteristics.
- The fluid power designer must select the fluid that comes the closest to being ideal overall for a particular application.
- Hydraulic fluids must also be changed periodically, the frequency depending not only on the fluid but also on the operating conditions.
- Laboratory analysis is the best method for determining when a fluid should be changed. Generally speaking, a fluid should be changed when its viscosity and acidity increase due to fluid breakdown or contamination.
- Preferably, the fluid should be changed while the system is at operating temperature.
- In this way, most of the impurities are in suspension and will be drained off.
- Much hydraulic fluid has been discarded in the past due to the possibility that contamination existed—it costs more to test the fluid than to replace it. This situation has changed as the need to conserve hydraulic fluids has developed.
- The test kit may be used on the spot to determine whether fluid quality permits continued use. Three key quality indicators can be evaluated: viscosity, water content, and foreign particle contamination level.

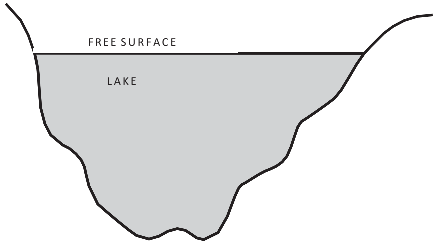
FLUIDS: LIQUIDS AND GASES

- **Liquids**

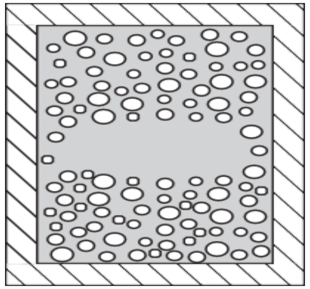
- The term *fluid* refers to both gases and liquids. A liquid is a fluid that, for a given mass, will have a definite volume independent of the shape of its container.
- This means that even though a liquid will assume the shape of the container, it will fill only that part of the container whose volume equals the volume of the quantity of the liquid. For example, if water is poured into a vessel and the volume of water is not sufficient to fill the vessel, a free surface will be formed.



- A free surface is also formed in the case of a body of water, such as a lake, exposed to the atmosphere.



  - Liquids are considered to be incompressible so that their volume does not change with pressure changes.
  - This is not exactly true, but the change in volume due to pressure changes is so small that it is ignored for most engineering applications.
  - Variations from this assumption of incompressibility is related to the parameter *bulk modulus*.
- **Gases**
- Gases, on the other hand, are fluids that are readily compressible.
- In addition, their volume will vary to fill the vessel containing them.



FLUIDS: LIQUIDS AND GASES

Chapter 2

FREE SURFACE

Parameter	**Liquid**	**Gas**
Volume	Has its own volume	Volume is determined by container
Shape	Takes shape of container but only to its volume	Expands to completely fill and take the shape of the container
Compressibility	Incompressible for most engineering applications.	Readily compressible

SPECIFIC WEIGHT, DENSITY, AND SPECIFIC GRAVITY

- All objects, whether solids or fluids, are pulled toward the center of the earth by a force of attraction. This force is called the weight of the object and is proportional to the object's mass, as defined by

$$F = W = mg \quad \textbf{(2-1)}$$

where, in the English system of units (also called U.S. customary units and used extensively in the United States) we have

$F =$ force in units of lb,

$W =$ weight in units of lb,

$m =$ mass of object in units of slugs,

$g =$ proportionality constant called the acceleration of gravity, which equals 32.2 ft/s^2 at sea level.

- A mass of 1 slug is defined as the mass of a platinum-iridium bar at the National Institute of Standards and Technology near Washington, DC.
- From Eq. (2-1), W equals 32.2 lb if m is 1 slug. Therefore, 1 slug is the amount of mass that weighs 32.2 lb.
- We can also conclude from Eq. (2-1) that 1 lb is defined as the force that will give a mass of 1 slug an acceleration of 1 ft/s^2.

Specific Weight

EXAMPLE 2-1

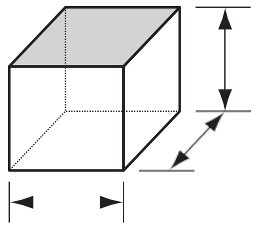
Find the weight of a body having a mass of 4 slugs.

Solution Substituting into Eq. (2-1) yields

$$W = mg = 4 \text{ slugs} \times 32.2 \text{ ft/s}^2 = 129 \text{ lb}$$

Specific weight = weight/volume

$$\gamma = w/v$$



γ = Greek symbol gamma = specific weight (lb/ft^3),

W = weight (lb),

V = volume (ft^3).

EXAMPLE 2-2

If the body of weight 129 lb has a volume of 1.8 ft^3, find its specific weight.

Solution $\gamma = W/v$

γ=129 lb/1.8 ft3 =71.6 lb/ft3

Specific gravity

- The specific gravity (*SG*) of a given fluid is defined as the specific weight of the fluid divided by the specific weight of water. Therefore, the specific gravity of water is unity by definition. The specific gravity of oil can be found using

$$(SG)_{oil} = \frac{\gamma_{oil}}{\gamma_{water}} \tag{2-4}$$

Substituting the most typical value of specific weight for oil we have

$$(SG)_{oil} = \frac{56 \text{ lb/ft}^3}{62.4 \text{ lb/ft}^3} = 0.899$$

Note that specific gravity is a dimensionless parameter (has no units).

EXAMPLE 2-3

Air at 68°F and under atmospheric pressure has a specific weight of 0.0752 lb/ft³. Find its specific gravity.

Solution

$$(SG)_{air} = \frac{\gamma_{air}}{\gamma_{water}} = \frac{0.0752 \text{ lb/ft}^3}{62.4 \text{ lb/ft}^3} = 0.00121$$

Thus, water is 1/0.00121 times, or about 830 times, as heavy as air at 68°F and under atmospheric pressure. It should be noted that since air is highly compressible, the value of 0.00121 for *SG* is valid only at 68°F and under atmospheric pressure.

Density

Density

In addition to specific weight, we can also talk about the fluid property called *density*, which is defined as mass per unit volume:

$$\rho = \frac{m}{V} \tag{2-5}$$

where ρ = Greek symbol rho = density (slugs/ft^3),
m = mass (slugs),
V = volume (ft^3).

The density and specific weight of a given fluid changes with pressure and temperature. For most practical engineering applications, changes in the density and specific weight of liquids with pressure and temperature are negligibly small; however, the changes in density and specific weight of gases with pressure and temperature are significant and must be taken into account.

Force and pressure

Force and Pressure

Pressure is defined as force per unit area. Hence, pressure is the amount of force acting over a unit area, as indicated by

$$p = \frac{F}{A} \tag{2-8}$$

where p = pressure,
F = force,
A = area.

Note that p will have units of lb/ft^2 if F and A have units of lb and ft^2, respectively. Similarly, by changing the units of A from ft^2 to in^2, the units for p will become lb/in^2. Let's go back to our 1-ft^3 container of Figure 2-5. The pressure acting on the bottom of the container can be calculated using Eq. (2-8), knowing that the total force acting at the bottom equals the 62.4-lb weight of the water:

$$p = \frac{62.4\ \text{lb}}{1\ \text{ft}^2} = 62.4\ \text{lb/ft}^2 = 62.4\ \text{psf}$$

Units of lb/ft^2 are commonly written as psf. Also, since 1 ft^2 = 144 in^2, the pressure at the bottom of the container can be found in units of lb/in^2 as follows using Eq. (2-8):

$$p = \frac{62.4\ \text{lb}}{144\ \text{in}^2} = 0.433\ \text{lb/in}^2 = 0.433\ \text{psi}$$

Units of lb/in^2 are commonly written as psi.

Head

Head

We can now conclude that, due to its weight, a 1-ft column of water develops at its base a pressure of 0.433 psi. The 1-ft height of water is commonly called a *pressure head*.

Let's now refer to Figure 2-6, which shows a 10-ft high column of water that has a cross-sectional area of 1 ft^2. Since there are 10 ft^3 of water and each cubic foot weighs 62.4 lb, the total weight of water is 624 lb. The pressure at the base is

$$p = \frac{F}{A} = \frac{624 \text{ lb}}{144 \text{ in}^2} = 4.33 \text{ psi}$$

Thus, each foot of the 10-ft head develops a pressure increase of 0.433 psi from its top to bottom.

What happens to the pressure if the fluid is not water? Figure 2-7 shows a 1-ft^3 volume of oil. Assuming a weight density of 57 lb/ft^3, the pressure at the base is

$$p = \frac{F}{A} = \frac{57 \text{ lb}}{144 \text{ in}^2} = 0.40 \text{ psi}$$

$$p = \gamma H$$

where p = pressure at bottom of liquid column,
γ = specific weight of liquid,
H = liquid column height or head.

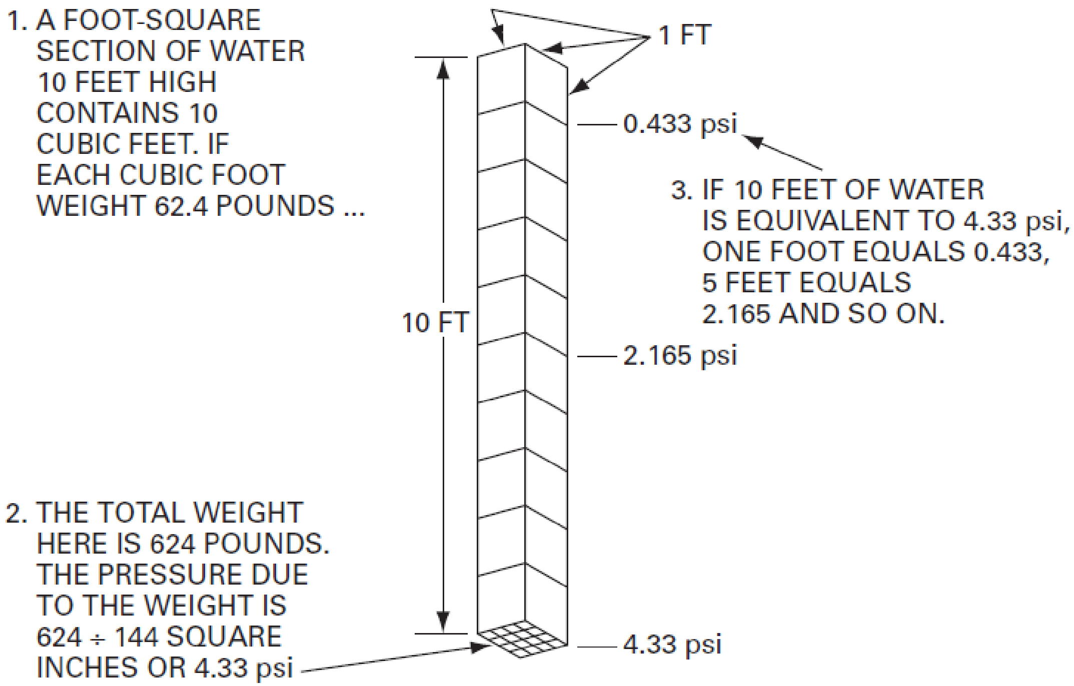


Figure 2-6. Pressure developed by a 10-ft column of water. *(Courtesy of Sperry Vickers, Sperry Rand Corp., Troy, Michigan.)*

Head

$$p = \gamma H$$

where p = pressure at bottom of liquid column,
γ = specific weight of liquid,
H = liquid column height or head.

EXAMPLE 2-5

Find the pressure on a skin diver who has descended to a depth of 60 ft in fresh water.

Solution Using Eq. (2-9) we have

$$p(\text{lb/in}^2) = \gamma(\text{lb/in}^3) \times H(\text{in}) = 0.0361 \times (60 \times 12) = 26.0 \text{ psi}$$

SI metric system

THE SI METRIC SYSTEM

Introduction

The SI metric system was standardized in June 1960 when the International Organization for Standardization approved a metric system called *Le Système International d'Unités*. This system, which is abbreviated SI, has supplanted the old CGS (centimeter-gram-second) metric system, and U.S. adoption of the SI metric system is considered to be imminent.

In the SI metric system, the units of measurement are as follows:

Length is the meter (m).
Mass is the kilogram (kg).
Force is the newton (N).
Time is the second (s).
Temperature is the degree Celsius (°C).

A mass of 1 kilogram is defined as the mass of a platinum-iridium bar at the International Bureau of Weights and Measures near Paris, France.

SI metric system

Length, Mass, and Force Comparisons with English System

The relative sizes of length, mass, and force units between the metric and English systems are given as follows:

One meter equals 39.4 in = 3.28 ft.

One kilogram equals 0.0685 slugs.

One newton equals 0.225 lb.

Per Eq. (2-1) a newton is defined as the force that will give a mass of 1 kg an acceleration of 1 m/s^2. Stated mathematically, we have

$$1 \text{ N} = 1 \text{ kg} \times 1 \text{ m/s}^2$$

Since the acceleration of gravity at sea level equals 9.80 m/s^2, a mass of 1 kg weighs 9.80 N. Also, since 1 N = 0.225 lb, a mass of 1 kg also weighs 2.20 lb.

SI metric system

Pressure Comparisons

The SI metric system uses units of pascals (Pa) to represent pressure. A pressure of 1 Pa is equal to a force of 1 N applied over an area of 1 m^2 and thus is a very small unit of pressure.

$$1 \text{ Pa} = 1 \text{ N/m}^2$$

The conversion between pascals and psi is as follows:

$$1 \text{ Pa} = 0.000145 \text{ psi}$$

Atmospheric pressure in units of pascals is found as follows, by converting 14.7 psi into its equivalent pressure in pascals:

$$p_{\text{atm}}(\text{Pa}) = 14.7 \text{ psi (abs)} \times \frac{1 \text{ Pa}}{0.000145 \text{ psi}} = 101{,}000 \text{ Pa (abs)}$$

Thus, atmospheric pressure equals 101,000 Pa (abs) as well as 14.7 psia.

Since the pascal is a very small unit, the bar is commonly used:

$$1 \text{ bar} = 10^5 \text{ N/m}^2 = 10^5 \text{ Pa} = 14.5 \text{ psi}$$

Thus, atmospheric pressure equals 14.7/14.5 bars (abs), or 1.01 bars (abs).

SI metric system

Temperature Comparisons

The temperature (T) in the metric system is measured in units of degrees Celsius (°C), whereas temperature in the English system is measured in units of degrees Fahrenheit (°F). Figure 2-11 shows a graphical representation of these two temperature scales using a mercury thermometer reading a room temperature of 68°F (20°C).

Relative to Figure 2-11 the following should be noted: The Fahrenheit temperature scale is determined by dividing the temperature range between the freezing point of water (set at 32°F) and the boiling point of water (set at 212°F) at atmospheric pressure into 180 equal increments. The Celsius temperature scale is determined by dividing the temperature range between the freezing point of water (set at 0°C) and the boiling point of water (set at 100°C) at atmospheric pressure into 100 equal increments.

The mathematical relationship between the Fahrenheit and Celsius scales is

$$T(°F) = 1.8T(°C) + 32 \tag{2-11}$$

Thus, to find the equivalent Celsius temperature corresponding to room temperature (68°F), we have:

$$T(°C) = \frac{T(°F) - 32}{1.8} = \frac{68 - 32}{1.8} = 20°C$$

SI metric system

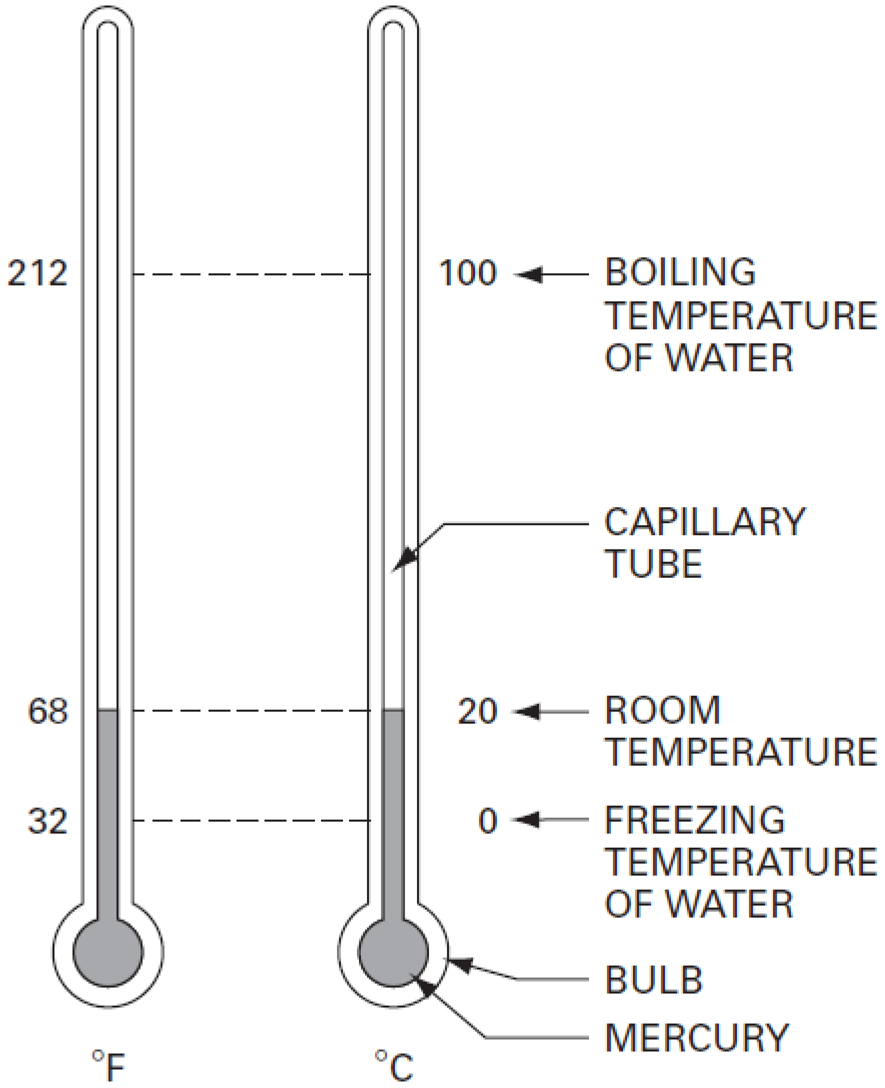


Figure 2-11. Comparison of the Fahrenheit and Celsius temperature scales.

SI metric system

Prefix Name	SI Symbol	Multiplication Factor
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}

Figure 2-12. Prefixes used in metric system to represent powers of 10.

Bulk modulus

BULK MODULUS

The highly favorable power-to-weight ratio and the stiffness of hydraulic systems make them the frequent choice for most high-power applications. The stiffness of a hydraulic system is directly related to the incompressibility of the oil. Bulk modulus is a measure of this incompressibility. The higher the bulk modulus, the less compressible or stiffer the fluid.

Mathematically the bulk modulus is defined by Eq. (2-12), where the minus sign indicates that as the pressure increases on a given amount of oil, the oil's volume decreases, and vice versa:

$$\beta = \frac{-\Delta p}{\Delta V / V} \tag{2-12}$$

where β = bulk modulus (psi, kPa),
Δp = change in pressure (psi, kPa),
ΔV = change in volume (in^3, m^3),
V = original volume (in^3, m^3).

The bulk modulus of an oil changes somewhat with changes in pressure and temperature. However, for the pressure and temperature variations that occur in most fluid power systems, this factor can be neglected. A typical value for oil is 250,000 psi (1.72×10^6 kPa).

Bulk modulus

EXAMPLE 2-11

A 10-in^3 sample of oil is compressed in a cylinder until its pressure is increased from 100 to 2000 psi. If the bulk modulus equals 250,000 psi, find the change in volume of the oil.

Solution Rewriting Eq. (2-12) to solve for ΔV, we have

$$\Delta V = -V\left(\frac{\Delta p}{\beta}\right) = -10\left(\frac{1900}{250{,}000}\right) = -0.076 \text{ in}^3$$

This represents only a 0.76% decrease in volume, which shows that oil is highly incompressible.

VISCOSITY

- Viscosity is probably the single most important property of a hydraulic fluid. It is a measure of a fluid's resistance to flow.
- In reality, the ideal viscosity for a given hydraulic system is a compromise.
- Too high a viscosity results in
- **1.** High resistance to flow, which causes sluggish operation.
- **2.** Increased power consumption due to frictional losses.
- **3.** Increased pressure drop through valves and lines.
- **4.** High temperatures caused by friction.
- On the other hand, if the viscosity is too low, the result is
- **1.** Increased oil leakage past seals.
- **2.** Excessive wear due to breakdown of the oil film between mating moving parts.
- These moving parts may be internal components of a pump (such as pistons reciprocating in cylinder bores of a piston pump) or a sliding spool inside the body of a valve

Absolute viscosity

- The absolute viscosity of the oil can be represented mathematically as follows:

$$\mu = \frac{\tau}{\upsilon/y} = \frac{F/A}{\upsilon/y} = \frac{\text{shear stress in oil}}{\text{slope of velocity profile}}$$

where τ = Greek symbol tau = the shear stress in the fluid in units of force per unit area (lb/ft^2, N/m^2); the shear stress (which is produced by the force F) causes the sliding of adjacent layers of oil;

υ = velocity of the moving plate (ft/s, m/s);

y = oil film thickness (ft, m);

μ = Greek symbol mu = the absolute viscosity of the oil;

F = force applied to the moving upper plate (lb, N);

A = area of the moving plate surface in contact with the oil (ft^2, m^2).

Kinematic viscosity

- Calculations in hydraulic systems often involve the use of kinematic viscosity rather than absolute viscosity. Kinematic viscosity equals absolute viscosity divided by density:

$$\nu = \frac{\mu}{\rho} \tag{2-14}$$

where ν = Greek symbol nu = kinematic viscosity.

Units for kinematic viscosity are given as follows: English: ft^2/s, SI metric: m^2/s, and CGS metric: cm^2/s.

VISCOSITY

- For most hydraulic applications, the viscosity normally equals about 150 SUS at 100°F.
- It is a general rule of thumb that the viscosity should never fall below 45 SUS or rise above 4000 SUS regardless of the temperature.
- Figure 2-17 shows how viscosity changes with temperature for several liquid petroleum products. Note that the change in viscosity of a hydraulic oil as a function of temperature is represented by a straight line when using American Society for Testing and Materials (ASTM) standard viscosity temperature charts such as the one used in Figure 2-17.
- Displayed in the chart of Figure 2-17 is the preferred range of viscosities and temperatures for optimum operation of most hydraulic systems.

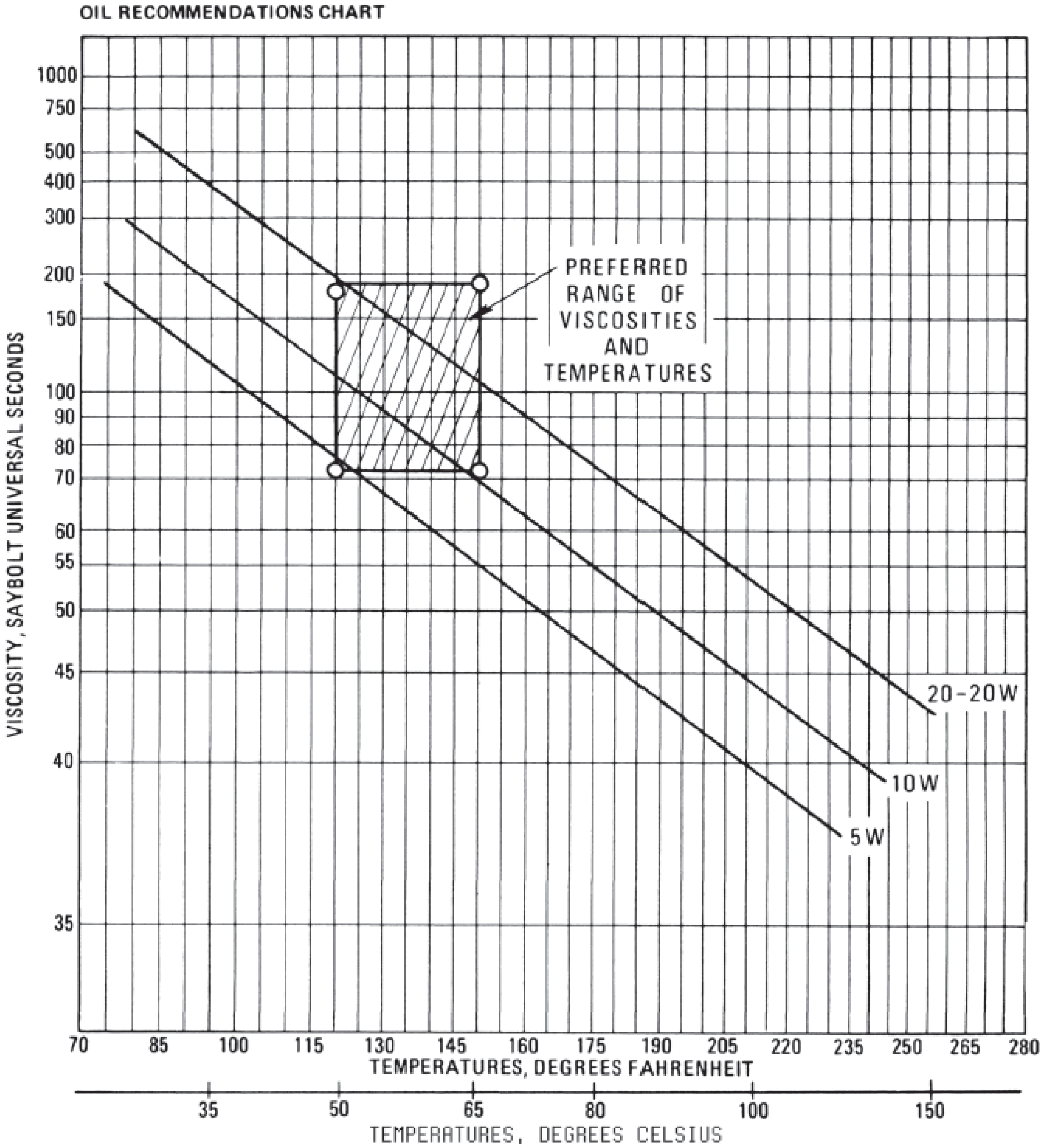


Figure 2-17. Preferred range of oil viscosities and temperatures. *(Courtesy of Sperry Vickers, Sperry Rand Corp., Troy, Michigan.)*