PHYSICAL PROPERTIES OF HYDRAULIC FLUIDS
AND RELATED FLOW PARAMETERS

By

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Bachelor of Science

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1961

Submitted to the faculty of the Graduate School of
the Oklahoma State University
in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE
May, 1963

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PREFACE

This thesis represents a theoretical study of the influence of physical fluid properties on the thermal characteristics of hydraulic fluid systems. Findings and suggested applications to the thermal design of hydraulic systems represent a portion of the duties of the author while assigned to the Boeing Hydraulics Project as a graduate research assistant. The Boeing Hydraulics Project was conducted for the Boeing Company of Wichita, Kansas.

The writer wishes to acknowledge the help of Professor J. D. Parker during the preparation of this thesis and throughout the graduate study. Gratitude is expressed to the faculty and staff of the School of Mechanical Engineering.

The writer will always be grateful to each member of his family for encouragement and understanding given during his university career.

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CHAPTER I

INTRODUCTION

The development of high-speed airborne vehicles has given rise to more complex hydraulic systems that must operate with a high degree of reliability and often under the most severe type of operating conditions. Furthermore, the range of present aircraft places additional requirements upon the fluid system's capacity to withstand changes in environment. Modern aircraft systems may be required to operate at both sub-zero and extremely high temperature conditions within a short period of time. Polar and high altitude operations represent the cold environment conditions, while the hot conditions stem from both higher operating speeds and localized internal heating.

Hydraulic fluids play an important role in hydraulic systems. These fluids have multifold purpose for they must:

1. Transmit power
2. Act as a heat transfer medium
3. Serve as a lubricant.

Consideration is given in this thesis to the following physical properties of hydraulic fluids:

1. Viscosity
2. Viscosity Index

3. Specific Heat
4. Thermal Conductivity
5. Specific Gravity

The primary interest here is in thermal characteristics of hydraulic systems and these properties are important in understanding this part of the problem. These properties greatly influence the heat generation, heat absorption, and heat dissipation (and thus the temperature) within hydraulic fluid systems, and the very nature of their influence points toward a need to know how they vary within the system itself.

These properties place certain limitations on a fluid's application. A given application determines the fluid or group of fluids that can be used. Once specifications are set, the designer must select a fluid to best satisfy the given specifications. It is the purpose of this thesis to collect, organize, and analyze the physical properties used in thermal considerations of hydraulic fluids and the design of hydraulic fluid systems.

CHAPTER II

BACKGROUND

Most of the previous work related to physical properties of hydraulic fluids is scattered throughout technical bulletins or contained in company reports. The technical bulletin of the manufacturer contains only fluids which that particular manufacturer has, and the company report is limited to fluids which the company writing the report uses.

An attempt is made here to collect, organize, and analyze the physical properties of several fluids that are commonly used in both commercial and aircraft hydraulic systems at the present time. Property variation with temperature is given close attention. Also included is a discussion on the techniques used in fluid property determination. Further discussion includes related advantages and disadvantages of particular fluid types. Design parameters developed from the fundamental flow equations and definitions are analyzed and represented. Parameter representation is in the form of plots and nomographs containing inside diameter, velocity, flow rate, and Reynolds number as functions of temperature.

One of the most influential factors upon the physical properties of fluids is temperature, and the fact that some properties are predominantly temperature dependent necessitates an accurate collection of property versus temperature information. Temperature has considerable effect on all the physical properties mentioned in Chapter I.

Of secondary importance is property variation with pressure. Pressure has its greatest effect on viscosity and specific gravity.

CHAPTER III

PHYSICAL FLUID PROPERTIES

This chapter defines the physical properties of a fluid and discusses techniques used in property measurement. An attempt is made to keep the discussion both brief and to the point, and yet contain an adequate explanation of the subject.

Viscosity

The viscosity of a fluid measures the fluid's resistance to flow. More technically, it is a constant of proportionality relating the shear stress to the shear rate. This constant is the absolute viscosity and is based on Newton's hypothesis that such a proportionality factor exists between the shear stress of adjacent fluid layers and the rate of shear in the direction perpendicular to the motion. It is symbolically shown as:

$$\text{stress} = \text{Force/Area} = \mu(dv/dy)$$

or

$$\mu = \frac{F/A}{dv/dy} = \frac{\text{shear stress}}{\text{shear rate}}$$

where

μ = viscosity (absolute)

F/A = force per unit area (stress)

dv/dy = slope of velocity curve (shear rate)

The temperature change of a fluid in motion is the result of (a) heat conduction, (b) expansion effects, and (c) viscous heating. (1). The amount of viscous heating is determined in part by the magnitude of the viscosity of the flowing fluid, and an increase in viscosity is accompanied by proportional increases in viscous heating. Difficulty in accurately analyzing the thermal problem is increased by the wide variation of viscosity with temperature, for this variation must be taken into account if use is to be made of the energy equation.

Viscosity is expressed in several ways, depending upon the means used to measure the resistance to flow. One unit for the absolute viscosity is the poise. In the c. g. s. system, one poise = one dyne-sec/square centimeter, or for a viscosity of μ = one poise, a force of one dyne per square centimeter is required to move two adjacent fluid layers separated by one centimeter at a rate of one centimeter per second. A smaller measure of viscosity is the centipoise (one centipoise = 0.01 poise).

The continual appearance of the ratio μ/ρ in subsequent developments has helped establish the use of the term kinematic viscosity which is defined as the ratio of the absolute viscosity to the density (both taken at the same temperature). The unit of measurement for kinematic viscosity in the c. g. s. system is the stoke, which has units of square centimeter per second. The centistoke (1 centistoke = 0.01 stoke) is used more often than the stoke.

The kinematic viscosity is often referred to as the molecular diffusivity of momentum because it is a measure of the rate of momentum transfer between the molecules. The kinematic viscosity can be pictured as a fluid's resistance to flow under its own gravity head and this concept leads to a rather simple measurement of the kinematic value of viscosity as described in the discussion which follows.

Commercial instruments such as the Saybolt Viscometer have been developed to give quick and accurate approximations of a fluid's viscosity. There are two types of the Saybolt Viscometer (Saybolt Universal Viscometer and Saybolt Furol Viscometer), and both measure the time in seconds for a given volume of fluid to flow through a standard orifice at a specified temperature. Time is measured in Saybolt Seconds Universal (SSU) and Saybolt Seconds Furol (SSF) respectively. The orifice of the Furol Viscometer is larger than that in the Universal Viscometer; consequently, the Furol Viscometer is used for measuring more viscous fluids. The viscosity of hydraulic fluids is generally measured with the Saybolt Universal Viscometer, and the value obtained (seconds) can be converted to kinematic viscosity by the following relationship:

$$\nu = 0.226\,t - 195/t \qquad t < 100 \text{ seconds}$$

$$\nu = 0.220\,t - 135/t \qquad t > 100 \text{ seconds}$$

where ν is in centistokes

and t is in Saybolt Seconds Universal (SSU)

A convenient nomograph relating Saybolt seconds and kinematic viscosity in centistokes is given in Appendix A. (2).

Another method for measuring the kinematic viscosity is with a capillary tube viscometer which measures the time required for a given volume of fluid to flow through a capillary tube.

Some viscometers measure the absolute viscosity directly. The rotating disc viscometer measures the torque that is required to rotate a disc at a low speed in a fluid, then relates the drag on the disc as recorded by the torque to the viscosity through the linear relationship between torque required and viscosity by means of a calibrated recording device. A similar approach is to rotate two concentric cylinders relative to each other which are separated by a thin layer of fluid and record the torque required to shear the fluid, then determine the viscosity from the torque required and the rate of shear.

The more common use of the kinematic viscosity in engineering work and its simplicity of measurement has led to the widespread use of instruments that measure the kinematic rather than the absolute value of viscosity. The simplicity of the Saybolt Viscometer has been the basis of its use in industry and, according to Lubrication (3), the Saybolt Viscometer is used predominantly throughout industry, although some firms do prefer the capillary type viscometer.

Viscosity Index (V. I.)

Changes in viscosity affect both the viscous heating in a fluid and the coefficient of heat transfer. The viscous heating effect is reflected in the energy equation where the fluid viscosity appears as a multiplier of the dissipation function, Φ. (4).

$$\rho\ g\ C_p \frac{DT}{Dt} = \frac{Dp}{Dt} + \left\{\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)\right\} + \mu\Phi$$

Since temperature causes changes in viscosity, viscous heating then becomes a function of temperature.

The change of the convective heat transfer coefficient with viscosity has long been recognized and an attempt is made in the Sieder-Tate equations to account for this change (5):[1]

$$S_t = \varphi(R)\ \psi(Pr)(\mu_b/\mu_s)^n$$

where S_t = Stanton Number
$\varphi(R)$ = function of Reynolds Number
$\psi(P_r)$ = function of Prandtl Number
μ_b = viscosity of bulk fluid
μ_s = viscosity of fluid at local wall temperature
n = constant determined from experiment

In the above equation, if the Stanton Number is known, the convective heat transfer coefficient can be calculated from:

$$h = S_t\ \rho\ V\ C_p$$

where h = convective heat transfer coefficient
ρ = density
V = velocity
C_p = specific heat

---

[1] All properties are evaluated at the average fluid bulk temperature, t_b.

The Prandtl Number is a property of the fluid and is calculated from:

$$P_r = \mu\, C_p/k$$

where P_r = Prandtl Number

μ = Viscosity

C_p = specific heat

k = thermal conductivity

Dean and Davis (6) have devised a convenient method to express the viscosity-temperature characteristics of oils by a single number. This scheme is solely empirical and is based upon a comparison of viscosity measurements from oils (L and H)[2] that represented the maximum and minimum limits of viscosity-temperature sensitivity at the time the method was introduced. These oils were assigned viscosity indices of zero and one hundred. Since the selected oils represented the extremes, all other oils were expected to fall within the 0-100 range; however, manufacturing techniques subsequently led to improved viscosity temperature characteristics, and it is now common for oils to have a V. I. number greater than 100. In general, the higher the viscosity index number, the smaller the change of viscosity with temperature.

The viscosity index of an oil is obtained by the following steps: (2).

1. Determine the viscosities at 100°F and 210°F for the oil of unknown V. I.

---

[2] L and H are arbitrary representations of the two oils.

2. Obtain the viscosities at 100°F for those oils L and H that have the same viscosity at 210°F as the unknown oil and substitute into the following equation:

$$\text{Viscosity Index} = (L-U/L-H)\ 100$$

where L = viscosity at 100°F for the zero index oil (L)
H = viscosity at 100°F for the 100 index oil (H)
U = viscosity at 100°F for the unknown oil

A schematic representation of the Viscosity Index number is given below. (2).

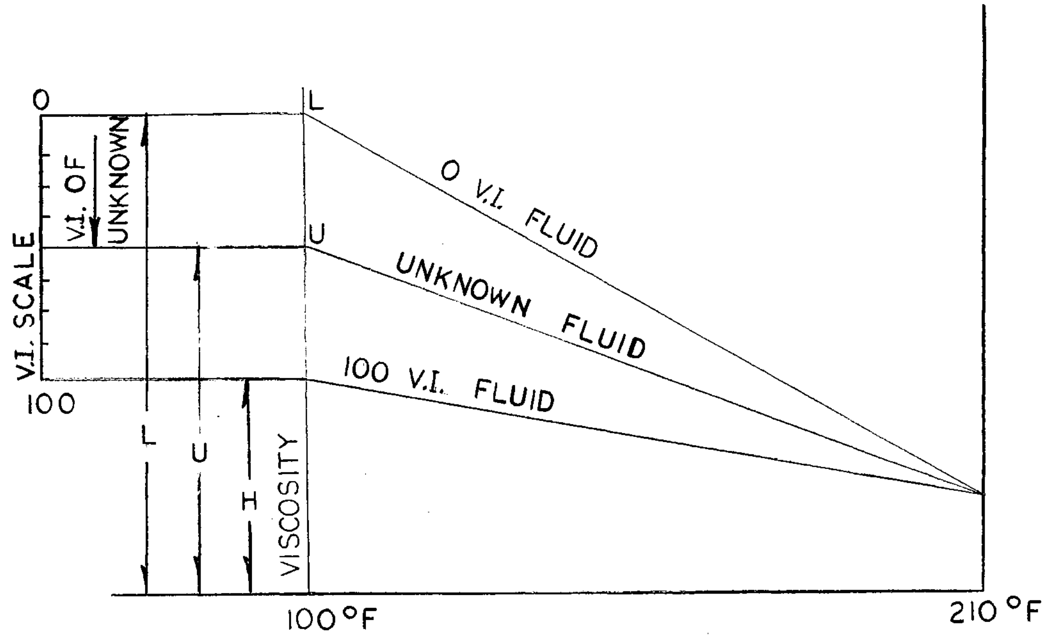

Figure 1. Schematic of Viscosity Index

Specific Heat

Specific heat is defined as the amount of heat which must be added to a unit weight of a substance to raise its temperature by a unit value. Water is taken as the standard, and one British Thermal Unit (BTU) is the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit, at 59.5 degrees Fahrenheit. More rigorously, the specific heat of a material is the first partial derivative with respect to temperature of its enthalpy (for pressure equal constant) or of its internal energy (for volume equal constant). In equation form, the specific heats are:

$$C_p = \left(\frac{\partial h}{\partial T}\right)_p$$

and

$$C_v = \left(\frac{\partial u}{\partial T}\right)_v$$

where

C_p = specific heat at constant pressure

C_v = specific heat at constant volume

h = enthalpy (BTU/lb)

u = internal energy (BTU/lb)

Specific heat is instrumental in determining rates of heating or cooling under both steady- and unsteady-state conditions. The choice of a hydraulic fluid with a given specific heat will therefore influence the thermal response characteristics of a hydraulic system and will, in part, define its thermal performance. Specific heats for real fluids are not constants, but vary with temperature. The two specific heats of a fluid (C_p and C_v) are nearly the same because of the low compressibility of normal liquids.

The heat capacity of hydraulic fluids is generally determined by calorimetry. Calorimeters are devices for determining the heat input by measuring the temperature rise of a system of known heat capacity under known conditions. The process may be either isothermal or adiabatic. The adiabatic method is often used in determining the heat capacity of hydraulic fluids. A fixed rate of power is put into a sample fluid and the heat capacity is determined by making a heat balance on the sample and the calorimeter. (7).

Mixtures calorimetry is sometimes used for determining the heat capacity of hydraulic fluids and the theory underlying this method is straightforward. A known mass of materials at a known temperature is transferred to a calorimeter at a lower temperature and the temperature rise is noted. The heat capacity is then determined by making an energy balance on the sample and the calorimeter. (8).

Another method for determining specific heats is the differential heating method where results are obtained by comparing the rates of heating for a test fluid with that for a fluid of known specific heat. The specific heat of the test liquid is calculated from the heat capacity of the reference fluid, the weight of the sample fluid, and the times required for the two fluids to go through the same temperature interval under the same conditions. The value obtained is the mean specific heat of the fluid over a short temperature range. (8).

Thermal Conductivity

Thermal conductivity is the proportionality between the heat flow per unit area of a material and the temperature gradient with respect to distance. It is that property of a material that indicates the quantity of heat transferred across a unit area if the temperature gradient is unity. Units are generally:

$$\frac{\text{BTU/hr-ft}^2}{{}^\circ\text{F/ft}} \quad \text{or} \quad \text{BTU/hr-ft-}^\circ\text{F}$$

The equation relating heat transfer, thermal conductivity, and temperature gradient is:

$$q = -k\ A\ (dt/dx)$$

where q = heat rate (BTU/hr)

k = thermal conductivity of substance through which heat is flowing (BTU/hr-ft-°F)

dt/dx = temperature gradient through the substance

The thermal conductivity of a fluid measures that fluid's ability to transmit heat by conduction. In hydraulic systems, the majority of the heat often will be rejected from the fluid in the heat exchanger by convection, although some heat transfer occurs in all parts of the system. Since the thermal conductivity is used in determination of the heat transfer coefficient, it will partially determine the rate at which heat is rejected from the fluid. Also in the hydraulic system reservoir where the fluid is at near rest, a certain amount of heat will be transferred by pure conduction to the reservoir wall.

Since the fluid conductivities are important in heat transfer design, this property must be known with some accuracy. Numerical values of conductivities are secured by experiment directly or by relationships formulated as a result of experiment. One method of measuring the thermal conductivity of liquids consists of stretching a fine wire along the axis of a tube of small bore. The tube is filled with the fluid to be tested. The determination of conductivity then consists of measuring the electrical input to the wire that is required to maintain a measured temperature difference between the wire and the tube wall and substituting into the basic conduction equation and solving for the conductivity. (7).

$$q = 2\pi kL\ [(t_1 - t_2)/\ln(r_1/r_2)]$$

where q = heat rate

k = thermal conductivity

L = length of tube

t_1 = temperature of wire

t_2 = temperature of tube

r_1 = radius of wire

r_2 = radius of tube

Specific Gravity

Specific gravity of a liquid is defined as the ratio of the weight of a unit volume of the liquid to the weight of the same unit volume of water at the same conditions. Petroleum base hydraulic fluids have specific gravities that range from 0.8 to 0.95, while fire resistant and synthetic hydraulic fluids have specific gravities as high as 1.25. (9).

Since density (mass per unit volume) is closely related to specific gravity, its variation also represents changes in specific gravity. Density is a function of both temperature and pressure. In high-temperature aircraft and missile hydraulic systems operating between extreme bulk oil temperatures of -50°F and 500°F, the specific gravity can be expected to change by as much as twenty per cent. (9). A change in specific gravity will indicate a change in total fluid volume; therefore, the reservoir will be required to accommodate for the volume change. The value of knowing the specific gravity is illustrated by an example. One method of calculating the Prandtl Number is:

$$P_r = K \nu \gamma C_p/k$$

where P_r = Prandtl Number

ν = kinematic viscosity

γ = specific weight

C_p = specific heat

k = thermal conductivity

K = constant for unit correction

In the above expression, the specific weight is evaluated at the temperature of the other properties of the fluid and can be determined by multiplying the specific gravity of the oil times the specific weight of water where both are taken at the desired temperature.

Fluids with large specific gravities (hence the more dense fluids) are capable of storing more heat per unit volume for a fixed temperature change (assuming C_p is the same) than fluids with small specific gravities. It is interesting to point out that two fluids may have the same absolute viscosity at a specified temperature but have a different kinematic viscosity due to a difference in the density of the two fluids.

CHAPTER IV

SELECTED HYDRAULIC FLUIDS

Selection of a fluid for a hydraulic system depends primarily upon the scope of application of the system, the availability of hydraulic fluids, and the cost of the fluid. The environment under which the system must operate for both short and long periods of time necessitates a careful fluid selection.

The following fluids are considered in this thesis:

1. Mil-H-5606
2. Oronite 8200
3. Oronite 8515
4. MLO-7277B
5. Skydrol 500A
6. Mil-L-7808

Table I on the following page gives some helpful information about the above listed fluids. Basis for their selection was use and popularity throughout industry. Of course, there are many other fluids which are used but this group represents a good sample of the more popular ones at the present time.

Mil-H-5606

A typical specification Mil-H-5606 hydraulic fluid is a blend comprising a mineral oil base stock, a polymetric additive (viscosity

TABLE I

HYDRAULIC FLUIDS

Fluid	Useful Temperature Range °F	Viscosity (Centistokes)	Specific Gravity	Specific Heat BTU/lb-°F	Thermal Conductivity BTU/lb-ft-°F	Viscosity Index	Application
5606	-65	2000	.9	--	--	225	Aircraft and missile hydraulic system
	160	7	.83	.5	062		
	275	3.6	.8	.576	.052		
500A	-65	2500	1.12	.33	---	238	Fire resistant aircraft hydraulic system
	100	11	1.05	.39	.077		
	225	3.50	.99	.44	.078		
7808	-50	2400	--	--	---		Turbine lubricating oil. Aircraft hydraulic control systems
	100	13	.915	.416	.0855		
	200	3.4	.876	.525	.082		
8200	-65	1950	---	---	---	177	High temperature aircraft and missile hydraulic systems
	300	5.9	.845	.53	.0598		
	450	3.4	.78	.65	.0455		
8515	-65	2000	.98	.38	.095	188	High temperature aircraft and missile hydraulic systems
	300	4.3	.83	.56	.066		
	450	2.3	.77	.65	.055		
7277B	20	2812	.97	.41	.0748	69.5	High temperature aircraft and missile hydraulic systems
	300	3	.836	.545	.067		
	450	1.55	--	.62	.0628		

index improver) plus lesser amounts of anti-wear and oxidation inhibitors. The major bulk of the fluid is the mineral oil base stock. This fluid, which is being used extensively in aircraft and commercial hydraulic systems at the present time is recommended for use from -65°F to 275°F where it shows good viscosity-temperature characteristics. Because of its upper temperature limit, other fluids are rapidly being developed for future high-temperature use.

8200 and 8515

Oronite high-temperature fluids 8200 and 8515 are considered for application in the range -80°F to 550°F, with the primary application being for use in the field of supersonic aircraft, missiles, and space vehicles. These two non-petroleum base fluids conform with the requirements of specification Mil-H-8446B. Fluid 8200 is composed predominantly of a specific disiloxane derivative with a silicone thickener. Fluid 8515 is essentially the composition of 8200 except that it contains fifteen per cent by weight of a diester which gives it compatibility with a greater number of elastomeric seals. Both the Convair B-58 and the North American X-15 utilized the 8515 fluid while the 8200 fluid is being tested extensively for use in the B-70 hypersonic bomber.

7277B

Oronite 7277B, which was recently developed by the California Chemical Company, is a high-temperature fluid that was developed to meet Boeing specifications for the Dyna-Soar hydraulic systems. The

Dyna-Soar, a manned research vehicle designed to extend the X-15 program by actually orbiting in the upper fringes of the atmosphere, will encounter severe aerodynamic heating problems; thus, its hydraulic system required a fluid that would operate satisfactorily in the 0°F to 500°F temperature range. One outstanding characteristic of this fluid is its ability to maintain a relatively high viscosity at elevated temperatures.

Mil-L-7808

Mil-L-7808, a derivative of the diester fluid group, is a high-temperature aircraft turbine engine lubricating oil that is also used as a hydraulic fluid in control systems. It has a continuous working temperature range of -40°F to 400°F and is considered to be an excellent hydraulic fluid because of its resistance to foam formation, good lubricating characteristics, and resistance to shear breakdown. One main disadvantage of this fluid is that it has a greater change of viscosity with temperature than other hydraulic fluids, thus being too viscous at low temperatures for many applications.

500A

Skydrol 500A is a fire-resistant hydraulic fluid that is now being used in aircraft and industrial systems that have a normal operating temperature range of -65°F to 225°F. This fluid, basically a phosphate ester, also has good heat transfer capabilities, but it is rather limited by its 225°F upper temperature range.

CHAPTER V

EFFECT OF TEMPERATURE AND PRESSURE ON PHYSICAL PROPERTIES

In present hydraulic systems, temperature probably has the greatest single effect upon limiting a system's capability because of its effect upon many properties of the fluid itself. Aircraft and missile hydraulic systems are required to operate within a wide range of temperatures, and as this range increases, hydraulic fluids have to be developed to satisfy the added requirements. The hydraulic system temperature problem is intensified in some cases by the proximity of hydraulic lines to combustion chambers and to the exhaust of jet or gas turbine engines. Polar and high altitude environments cause portions of a hydraulic system to be at very low temperatures, thus restricting fluid flow.

A hydraulic fluid should possess a relatively high viscosity at elevated temperatures both to insure optimum pump performance and to reduce system leakage. Although high viscosity at high temperatures is desirable, a fluid should not be too viscous at low temperatures, since flow problems may result. One of the main problems in the development of high temperature aircraft and missile fluids has been the attainment of both high viscosity at high temperatures and relatively low viscosity at low temperatures with a single fluid. Viscosity-temperature relationships are given in Figs. 2 and 3.

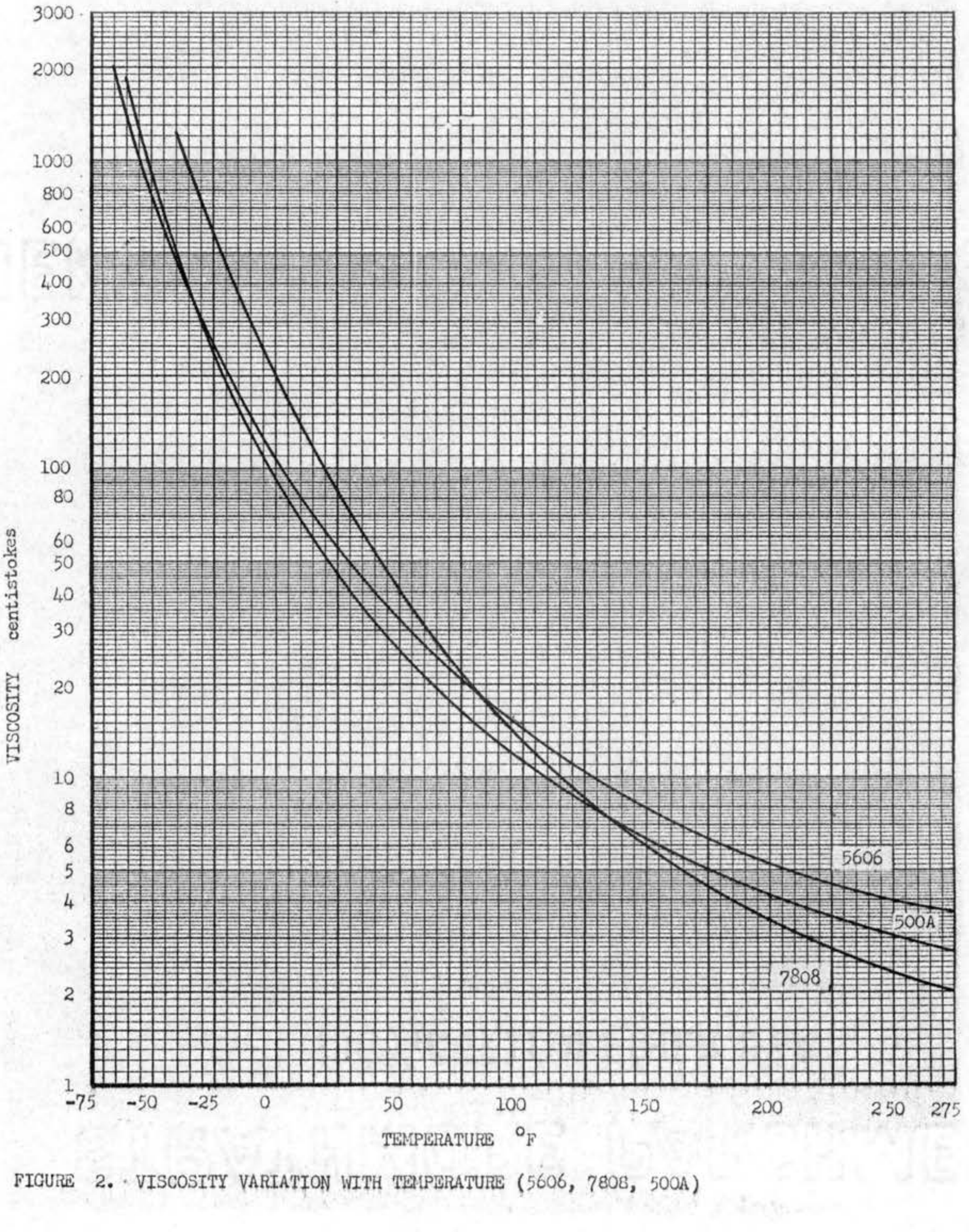

FIGURE 2. VISCOSITY VARIATION WITH TEMPERATURE (5606, 7808, 500A)

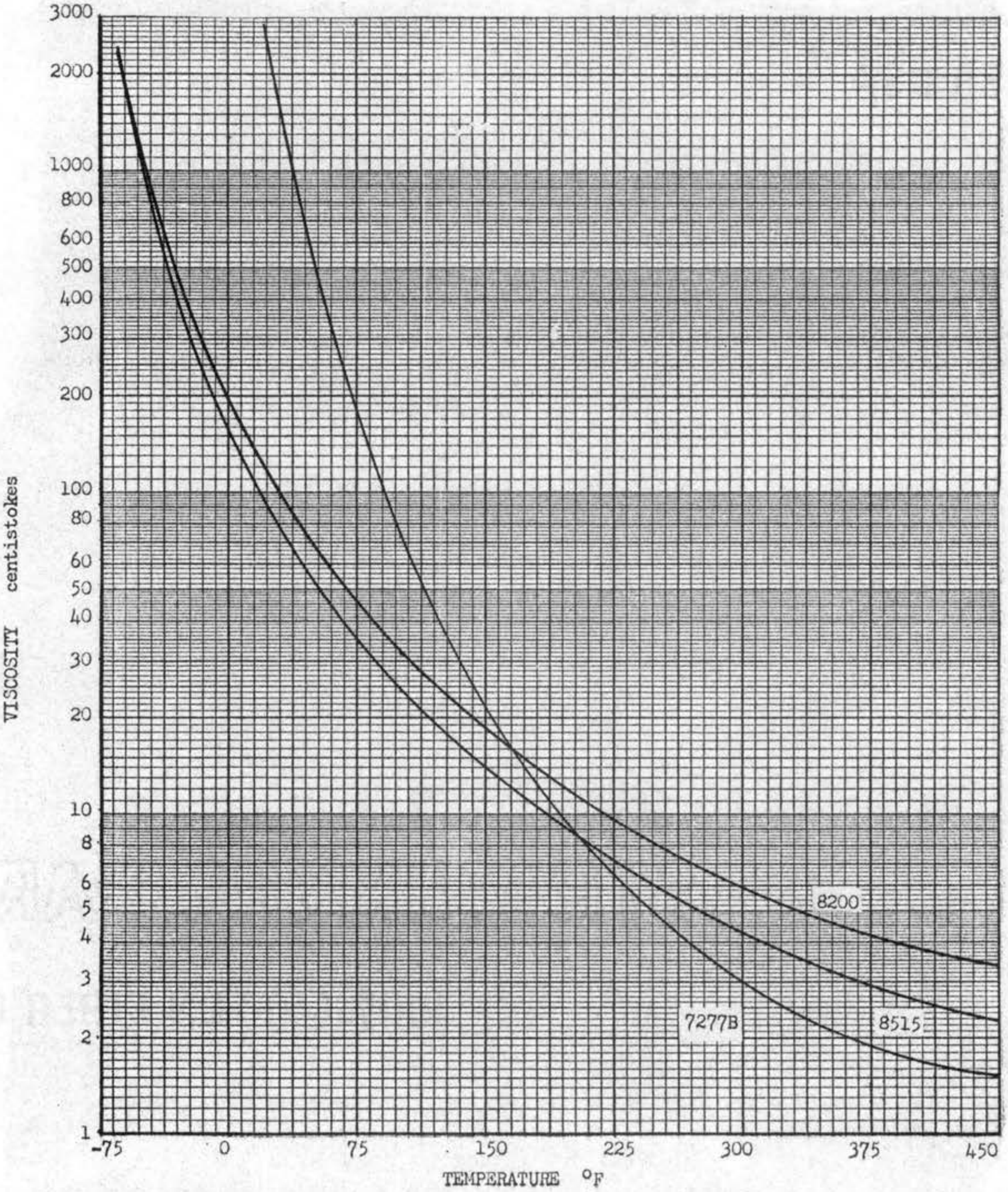

FIGURE 3. VISCOSITY VARIATION WITH TEMPERATURE (8515, 8200, 7277B)

Since the specific heat is considered in heat transfer calculations, it is useful to know the specific heats of hydraulic fluids over wide temperature ranges. In general, the specific heats of hydraulic fluids show an increase with temperature. Typical values for specific heat variation with temperature are represented in Fig. 4.

Thermal conductivity of hydraulic fluids is also a factor considered in the thermal design of hydraulic systems, and this value too needs to be known over the operating temperature range of the fluid. Most hydraulic fluids exhibit a decrease in thermal conductivity with increasing temperature. An exception to this is Skydrol fluid 500A which maintains almost a constant thermal conductivity value over the entire operating range of the fluid. Comparative thermal conductivity values are given in Fig. 5.

Density (therefore specific gravity) is a function of both temperature and pressure, and only in rough calculations should the assumption be made that the specific gravity remains constant. The decrease of specific gravity in a high-temperature aircraft or missile hydraulic system operating between bulk fluid temperatures of -65°F and 500°F may be as much as 35 per cent. Since changes in specific gravity reflect changes in volume, provision must be made in the fluid reservoir to accommodate for the variation. Specific gravity versus temperature is graphically illustrated in Fig. 6.

Although property variation with temperature is often considered more important in hydraulic system design than property variation with

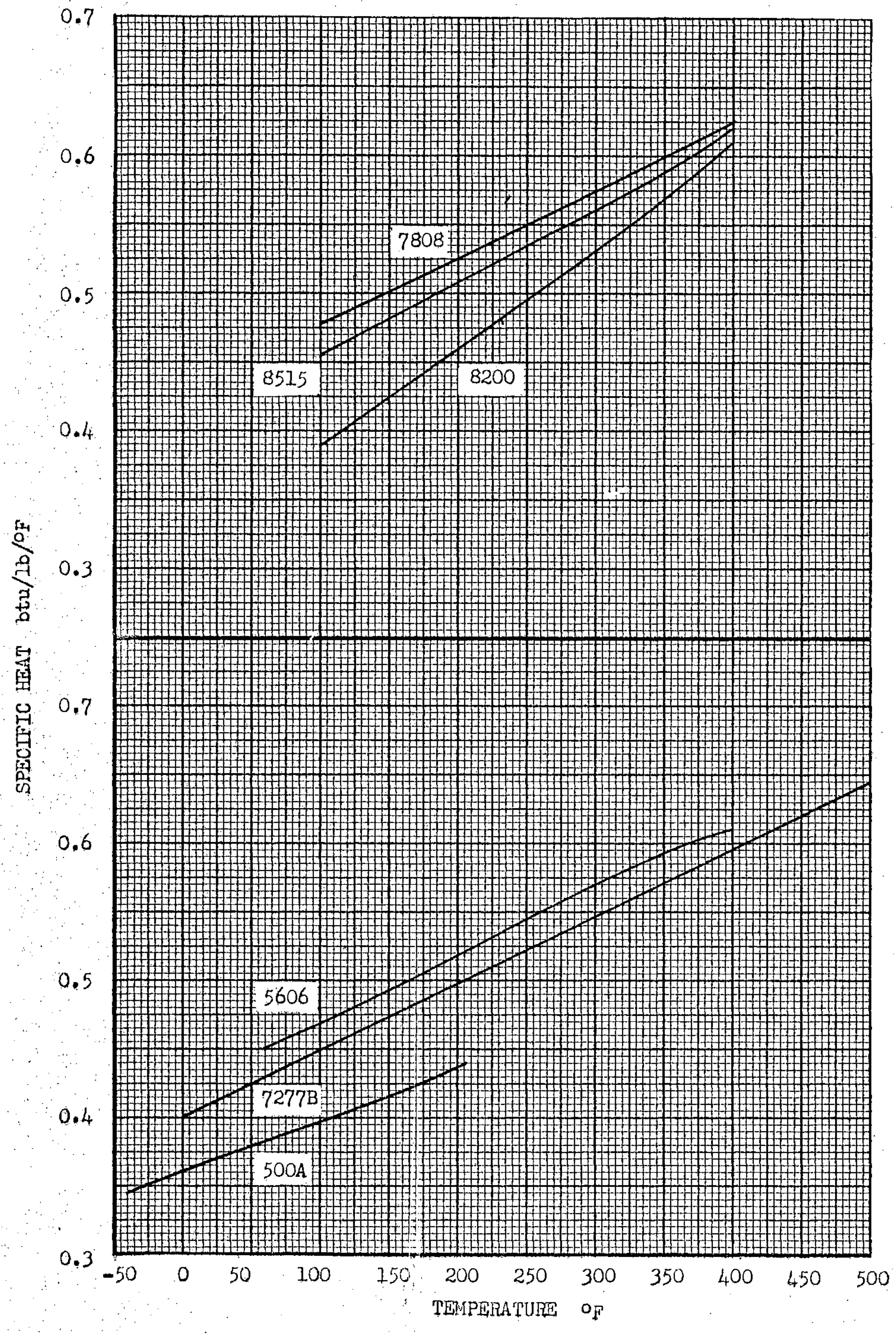

FIGURE 4. SPRCIFIC HEAT VARIATION WITH TEMPERATURE

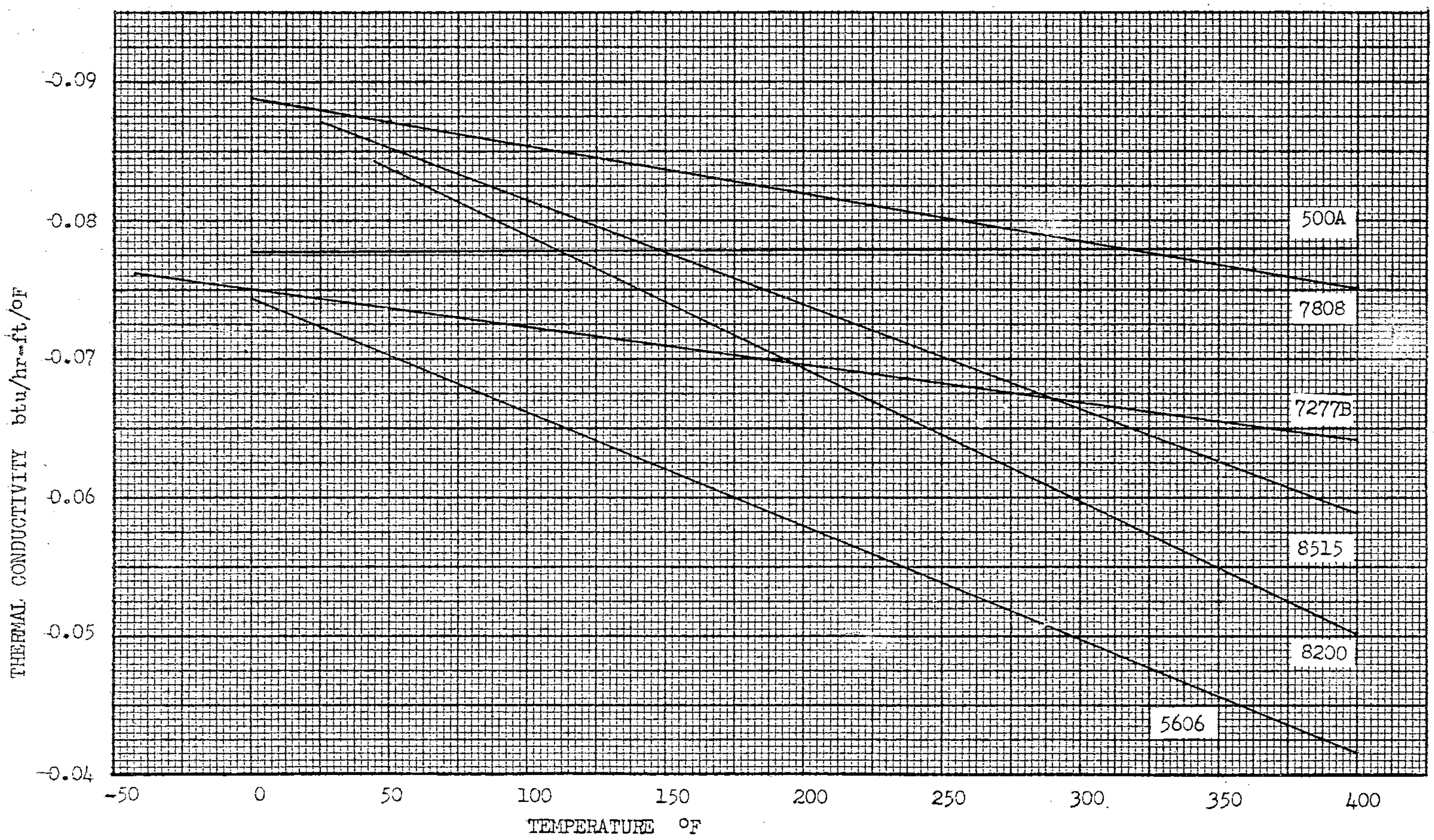

FIGURE 5. THERMAL CONDUCTIVITY VERSUS TEMPERATURE

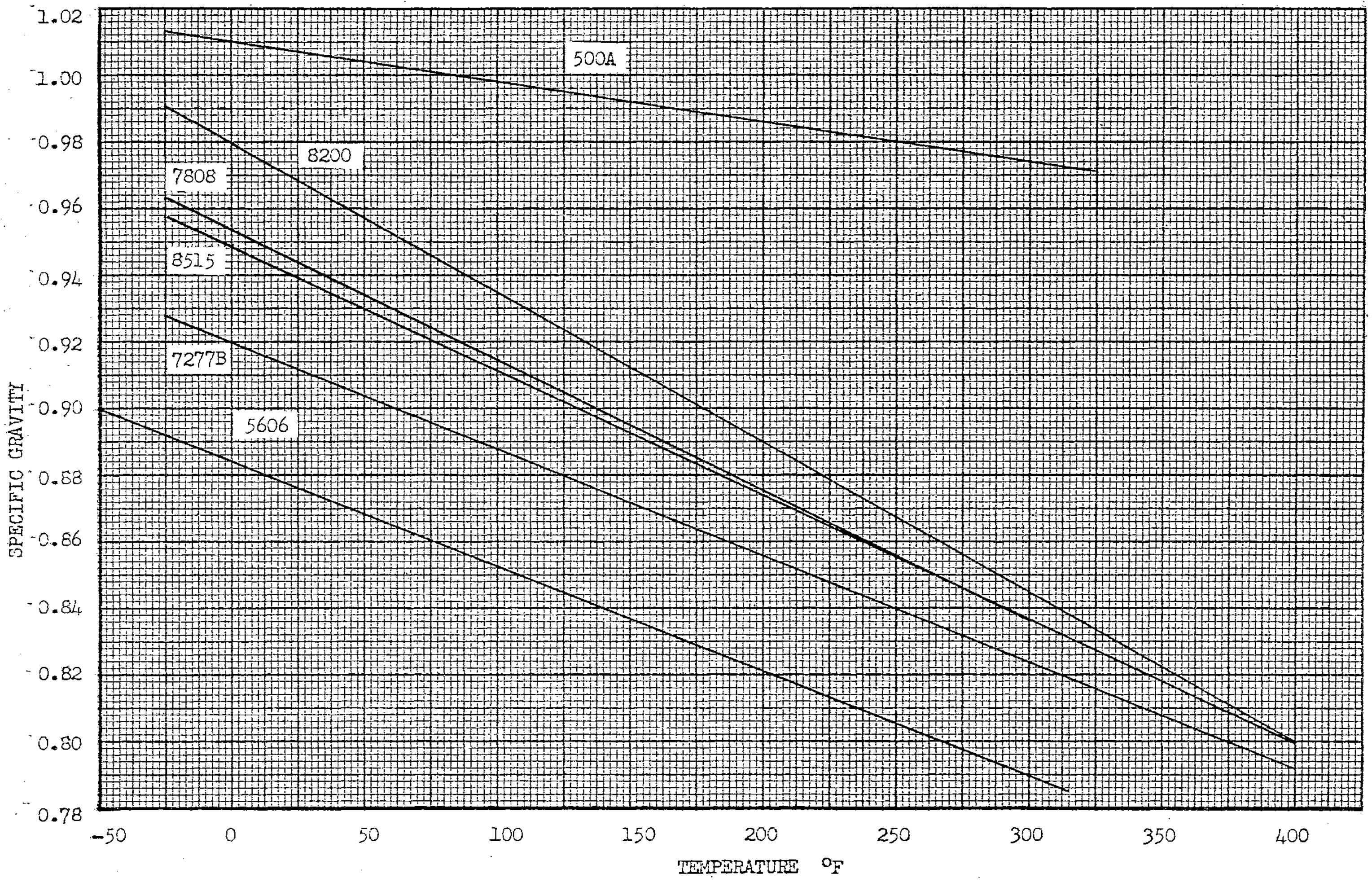

FIGURE 6. SPECIFIC GRAVITY VARIATION WITH TEMPERATURE

pressure, the latter does have its influence upon the physical properties and must be considered.

The viscosity increase of hydraulic fluids with pressure is generally not as great as the viscosity decrease with temperature; however, the changes are significant and occur during each cycle of the fluid through the system. The following empirical equation gives an approximate relationship for the viscosity variation with pressure: (10).

$$\mu_p/\mu_o = e^{KP}$$

where

μ_p = viscosity at pressure P

μ_o = viscosity at atmospheric pressure

K = constant determined experimentally for the particular fluid in question

This relationship leads to the common graphic presentation of pressure-viscosity relationship by plotting the pressure versus the log of the viscosity of the fluid for different temperatures. A typical plot is shown in Fig. 7.

Within the pressure ranges encountered in hydraulic systems, the specific gravity shows a slight increase with pressure (Fig. 8), but this variation is generally neglected due to its small change.

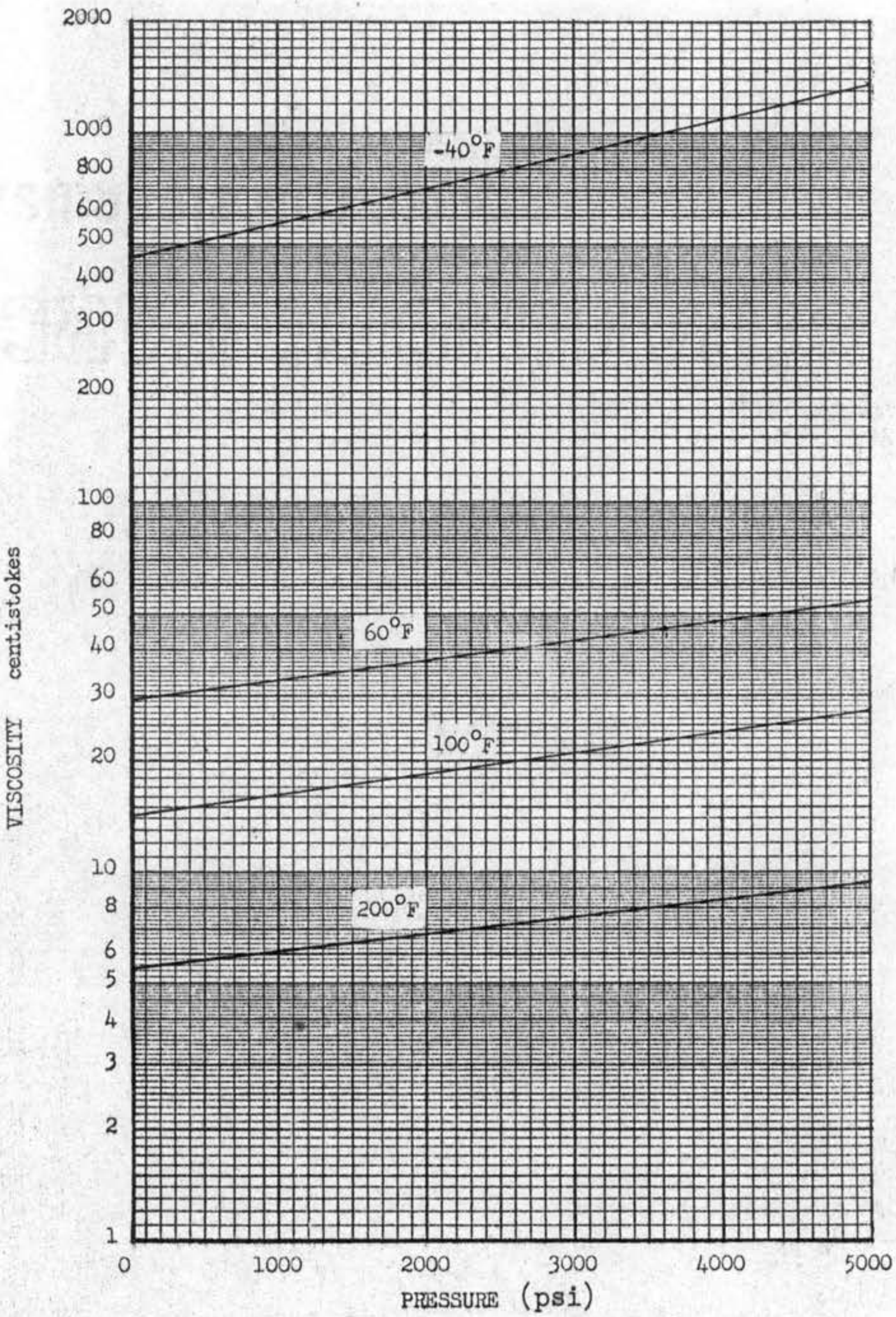

FIGURE 7. VISCOSITY VARIATION WITH PRESSURE (5606)

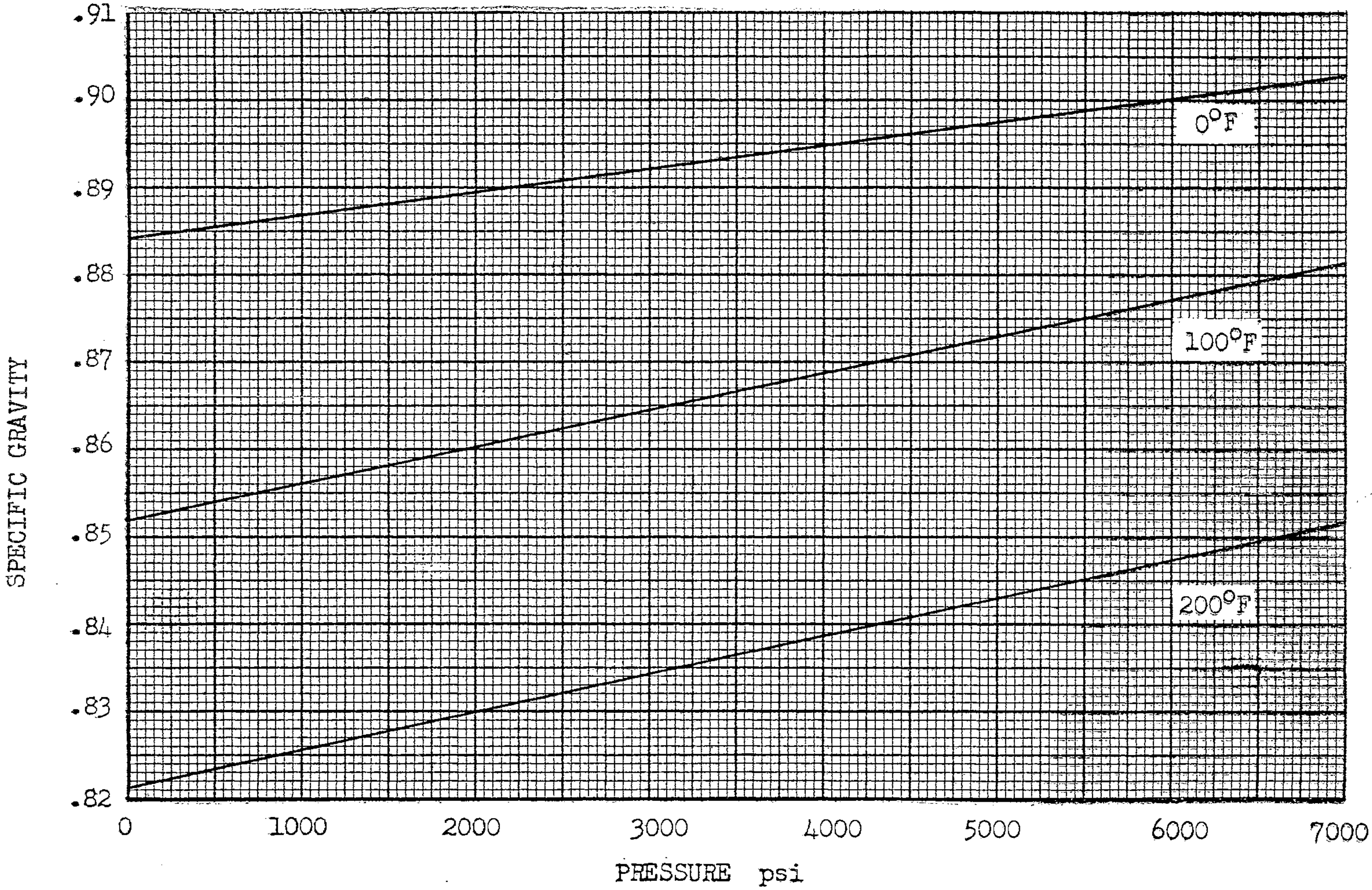

FIGURE 8. SPECIFIC GRAVITY VARIATION WITH PRESSURE (5606)

CHAPTER VI

FLOW PARAMETERS

In the design and analysis of hydraulic circuits, it is often convenient and sometimes necessary to know the numerical value of certain dimensionless parameters and how these parameters are affected by the variables involved. The physical fluid properties and their changes with temperature and pressure are responsible for some of the important variations in the flow parameters.

Many times it is convenient to represent variables in fluid flow as functions of Reynolds Number; i. e., the variation of friction factor versus Reynolds Number. The task undertaken here is one of determining the Reynolds Number at various temperatures and flow conditions, and how the Reynolds Number affects or is affected by fundamental flow parameters.

This chapter considers variations of combinations of Reynolds Number, inside tube diameter, temperature, and flow rate by such techniques as observing lines of constant Reynolds Number on a temperature versus flow rate curve and a temperature versus inside diameter curve, and observing lines of constant flow rate on a temperature versus Reynolds Number curve. Since for a given fluid, a given temperature and pressure determines the viscosity, the variables could also be represented as functions of viscosity, though the large variation of viscosity with temperature pointed to the more convenient representation of the variables with temperature.

Consideration is also given to the Prandtl Number, its variation with temperature, its magnitude, and its place in considering the thermal aspect of hydraulic fluid systems.

Derivation of an Equation

Take the equation of continuity for volume flow rate:[1]

(1) $$Q = V A$$

where Q = flow rate (ft^3/min)

A = area (ft^2)

V = velocity (ft/min)

or for Q to be in gal/min:

(2) $$Q = 7.48 V A$$

For a circular tube, the area is given by:

(3) $$A = \pi d^2/4$$

where d = diameter (ft)

A = area (ft^2)

Substituting (3) into (2) for A gives:

(4) $$Q = 7.48 \pi V d^2/4$$

Solving for V:

(5) $$V = 4 Q/7.48\pi d^2$$

---

[1] One form of this equation is presented in nomographic form in Appendix B. (11).

Now from the definition of Reynolds Number:

(6) $$R = Vd/\nu$$

where R = Reynolds Number

V = velocity (ft/sec)

ν = kinematic viscosity (ft^2/sec)

d = diameter (ft)

Solving (6) for the velocity term:

(7) $$V = R\nu/d$$

Now eliminating the velocity from (5) by (7) and solving for d gives:

(8) $$d = 4Q/7.48\pi R\nu$$

where Q = flow rate (gal/min)

d = diameter (ft)

R = Reynolds Number

ν = kinematic viscosity (ft^2/sec)

Since the kinematic viscosity will generally be given in centistokes, (8) becomes

(9) $$d = 3160\ Q/R\nu$$

or

(10 $$\nu = 3160\ Q/Rd$$

where Q = flow rate (gal/min)

d = diameter (in.)

R = Reynolds Number

ν = kinematic viscosity (centistokes)

Three sets of curves utilizing the above relationship are shown in Figs. 9 to 23. The first group (Figs. 9 to 13) pictures temperature variance with flow rate for various diameters and Reynolds Numbers. The deviation from a linear relationship is a result of the non-linear variation of viscosity with temperature.

The next group (Figs. 14 to 18) shows lines of constant Reynolds Number for various flow rates on temperature versus inside tube diameter plots. This group also illustrates that a linear interpolation for a diameter not given in Figs. 9 to 23 would give a reasonably good approximation, especially for the larger diameters.

The last group (Figs. 19 to 23) shows temperature as a function of Reynolds Number for various flow rates and diameters. Appendix C contains the same information in tabular form as Figs. 9 to 23 with the exception that it is pressure compensated for a pressure of 3000 psi. The pressure compensating process involved the variation of the viscosity with pressure.

Another property of the fluid, the Prandtl Number, certainly requires recognition in considering the thermal aspects of fluid flow through the system. The Prandtl Number ($\mu C_p/k$) appears in the non-dimensional heat transfer relationship in convective heat transfer as shown on page 51 following the figures. (14).

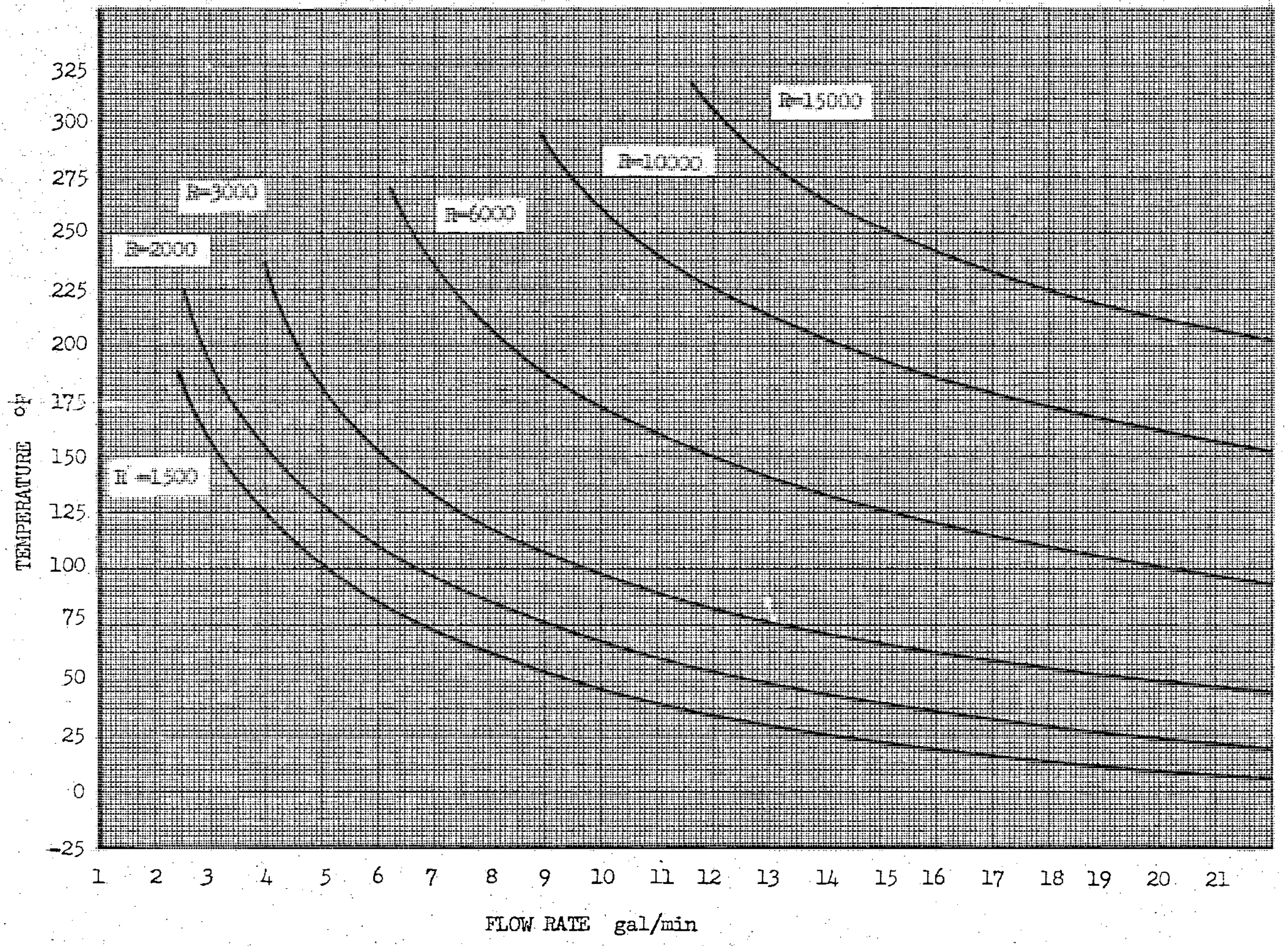

FIGURE 9. TEMPERATURE VERSUS FLOW RATE FOR FLUID 5606 (DIAMETER = 1 INCH)

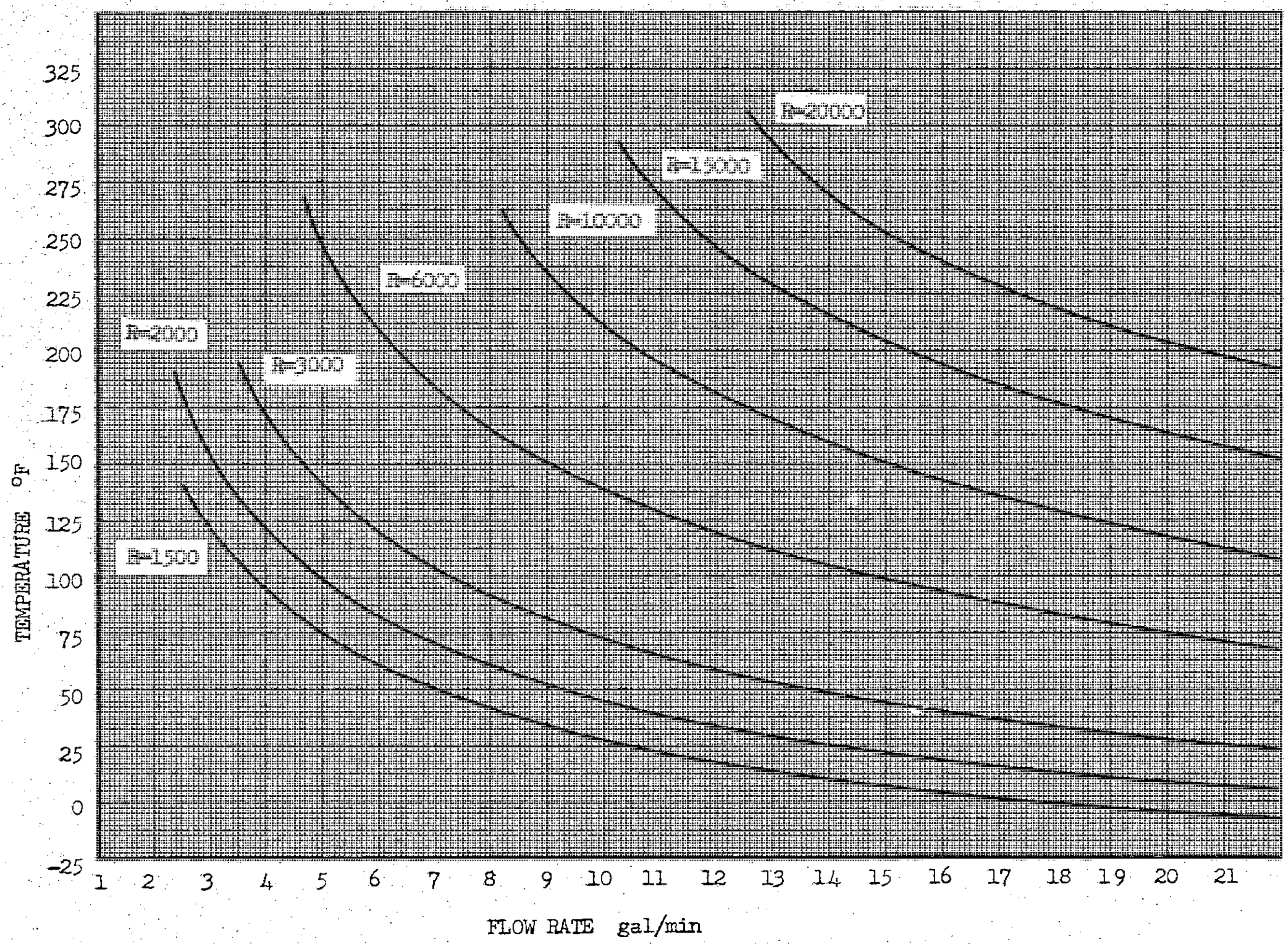

FIGURE 10. TEMPERATURE VERSUS FLOW RATE FOR FLUID 5606 (DIAMETER = 3/4 INCH)

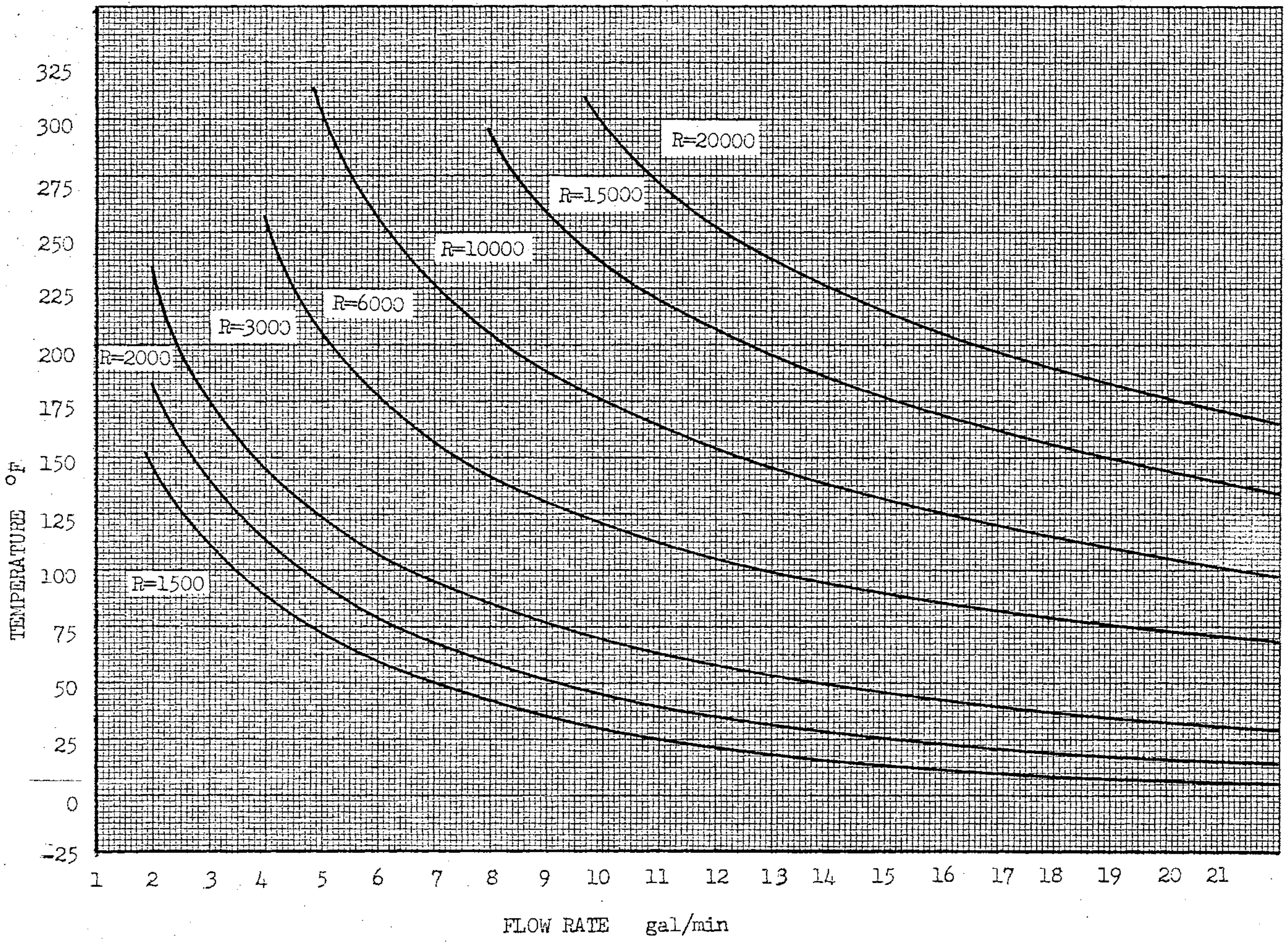

FIGURE 11. TEMPERATURE VERSUS FLOW RATE FOR FLUID 5606 (DIAMETER = 1/2 INCH)

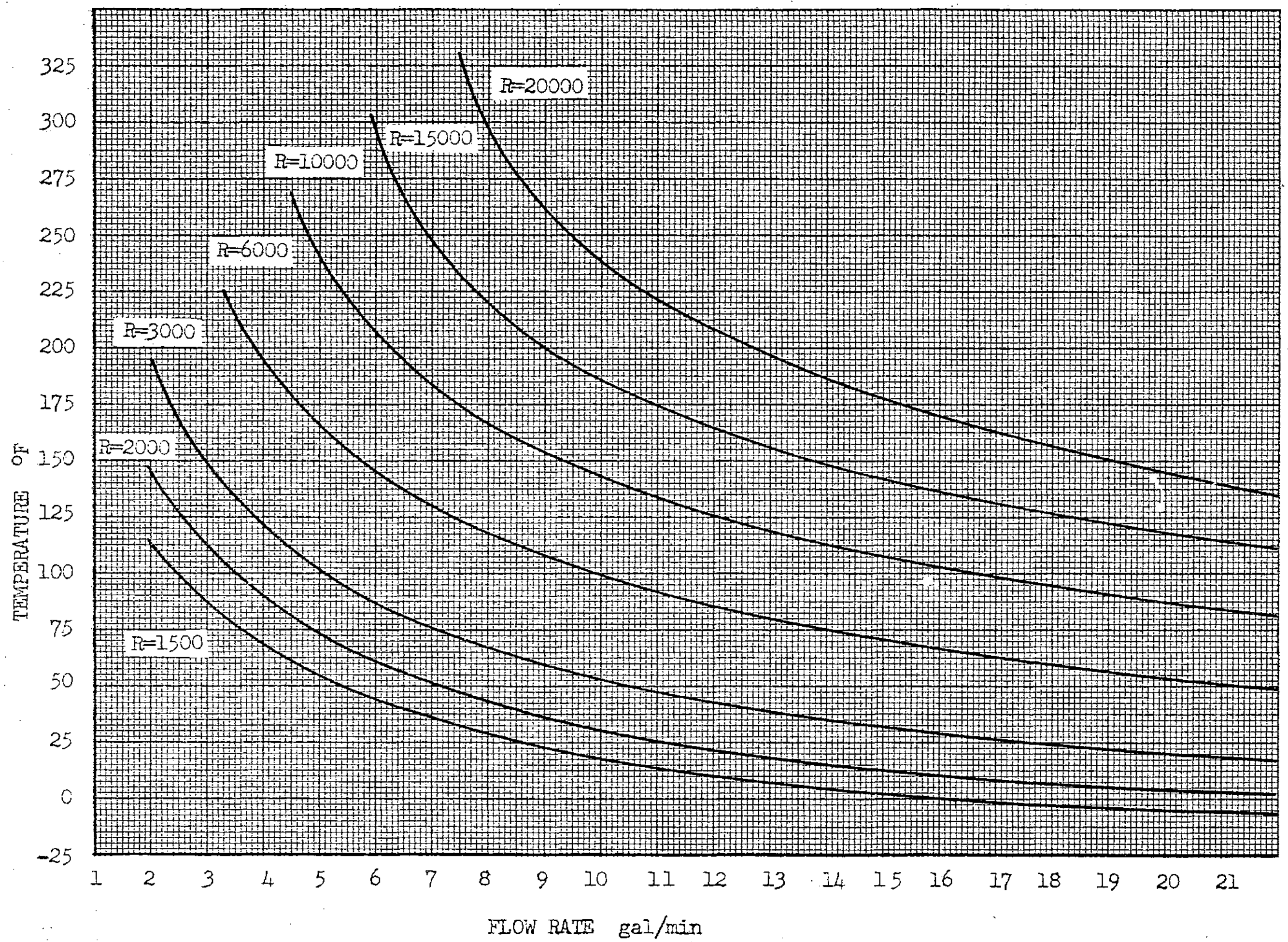

FIGURE 12. TEMPERATURE VERSUS FLOW RATE FOR FLUID 5606 (DIAMETER = 3/8 INCH)

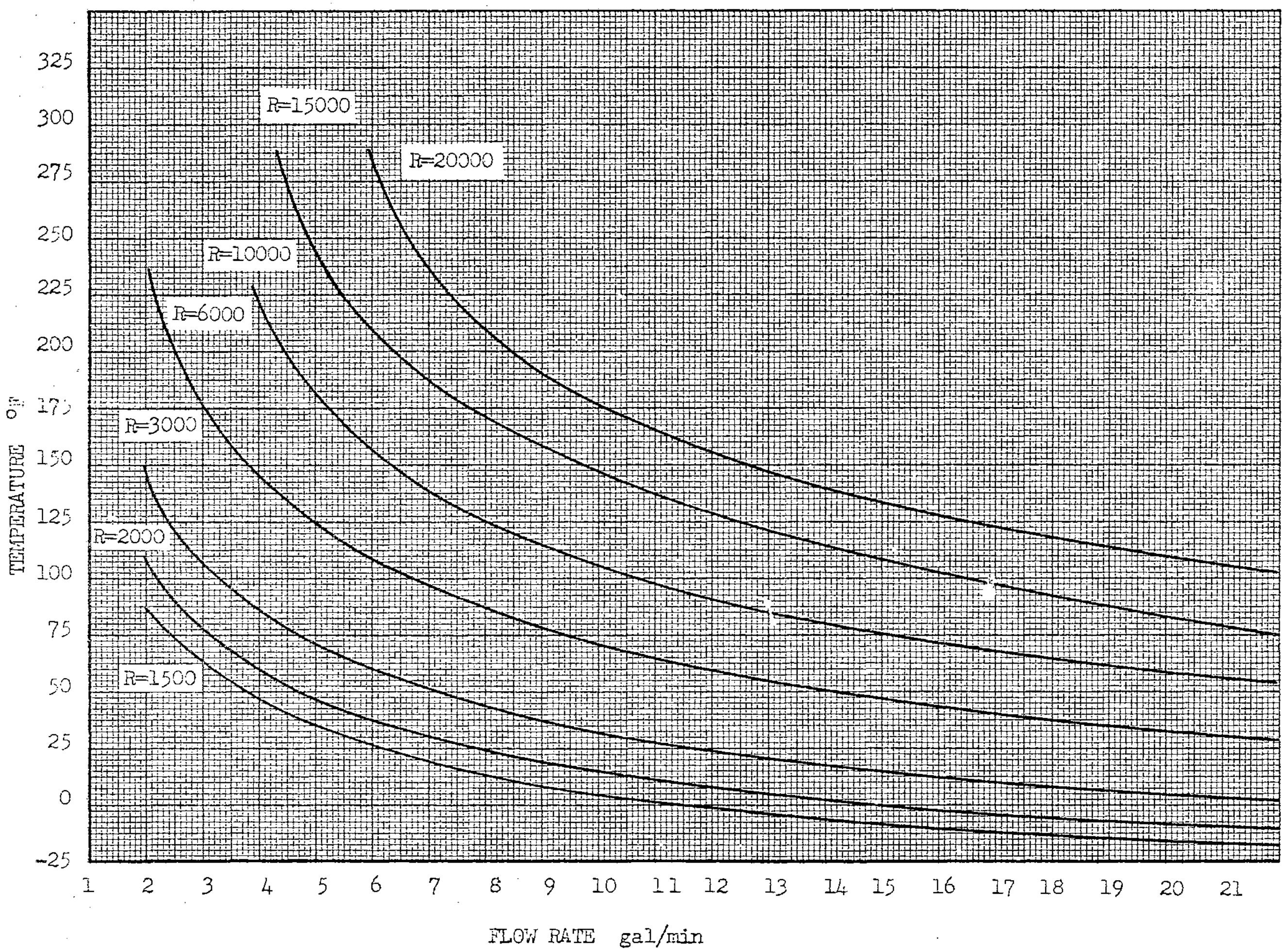

FIGURE 13. TEMPERATURE VERSUS FLOW RATE FOR FLUID 5606 (DIAMETER = 1/4 INCH)

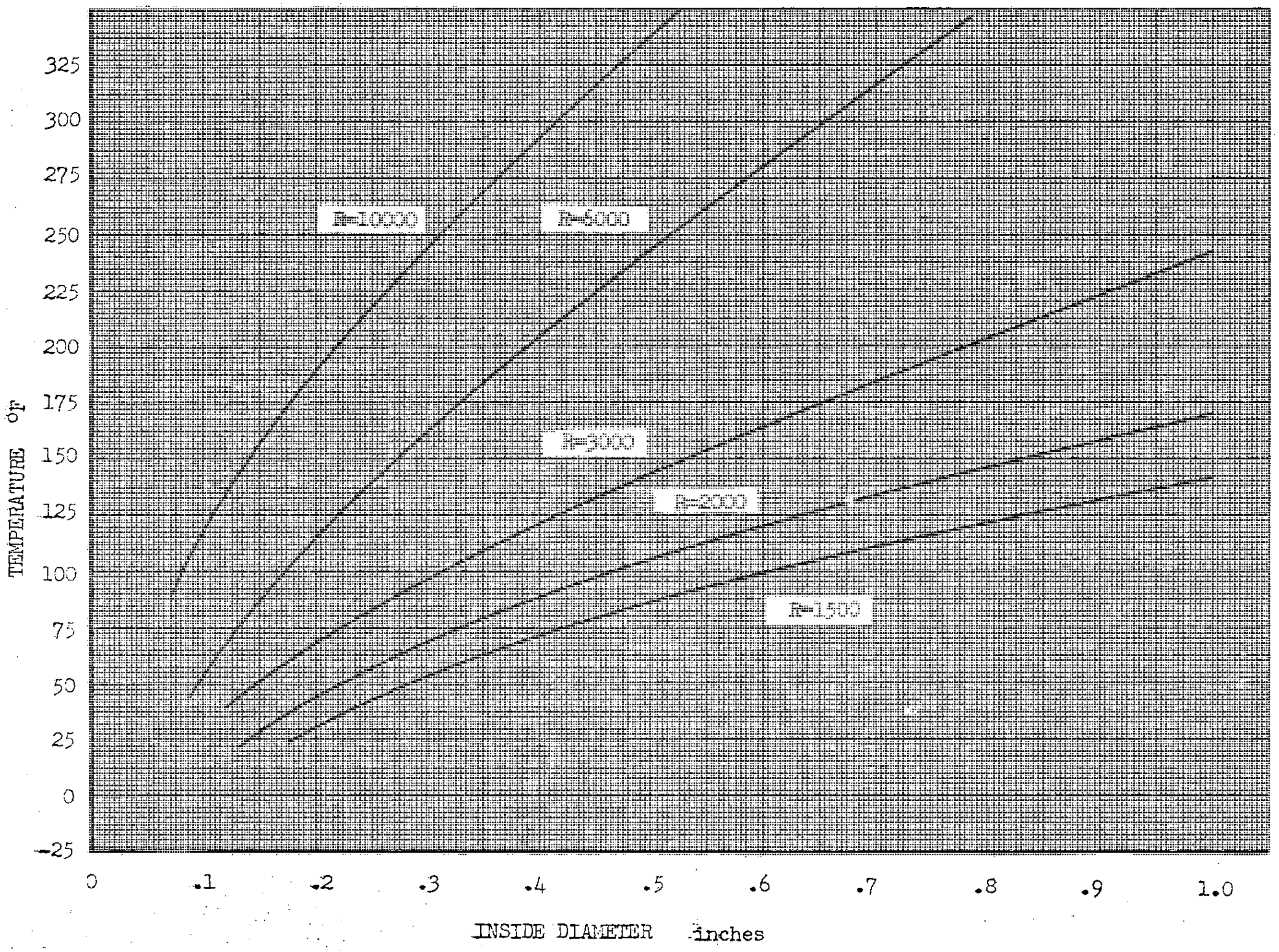

FIGURE 14. TEMPERATURE VERSUS INSIDE DIAMETER FOR FLUID 5606 (FLOW RATE = 4 GAL/MIN)

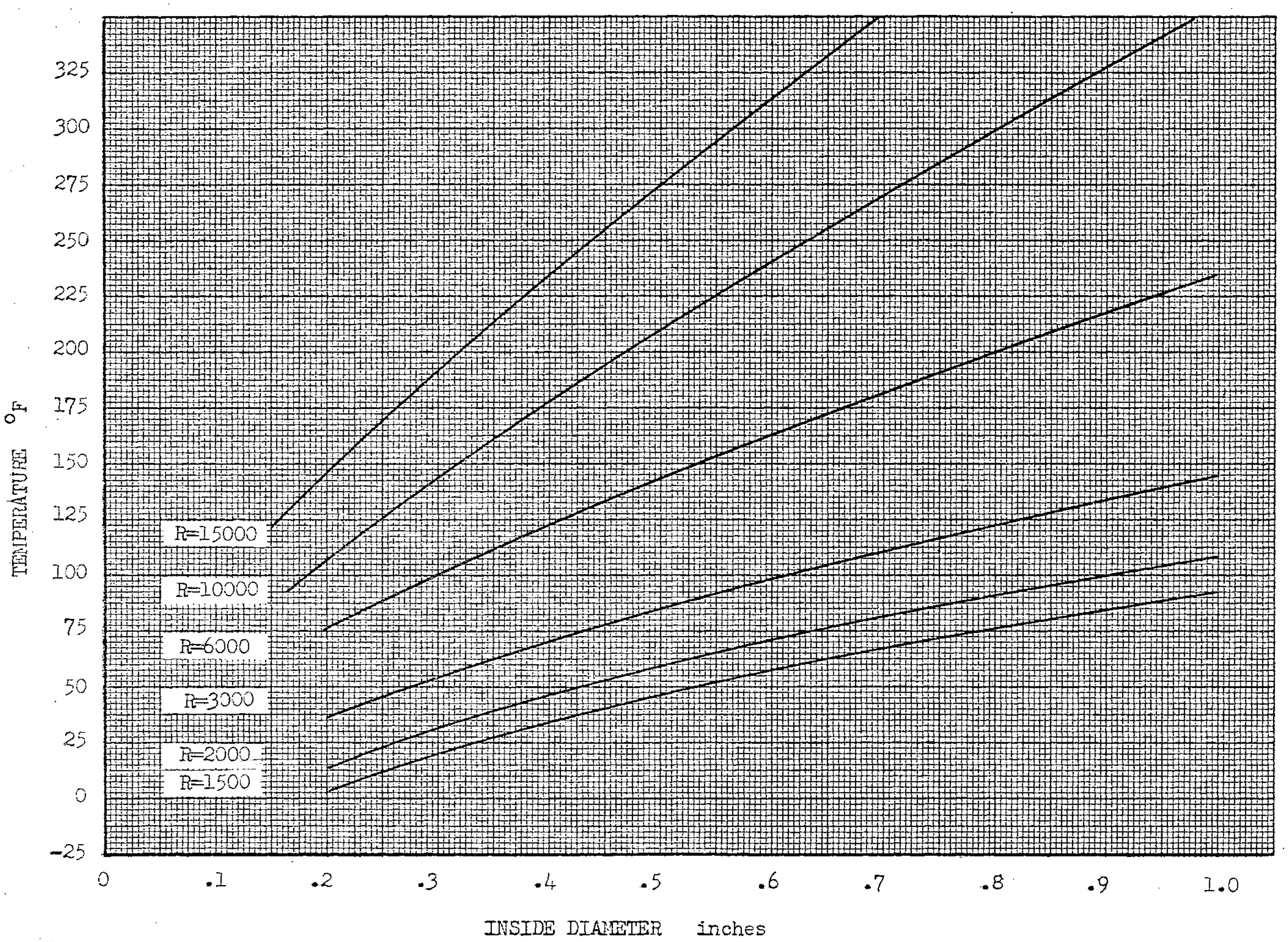

FIGURE 15. TEMPERATURE VERSUS INSIDE DIAMETER FOR FLUID 5606 (FLOW RATE = 8 GAL/MIN)

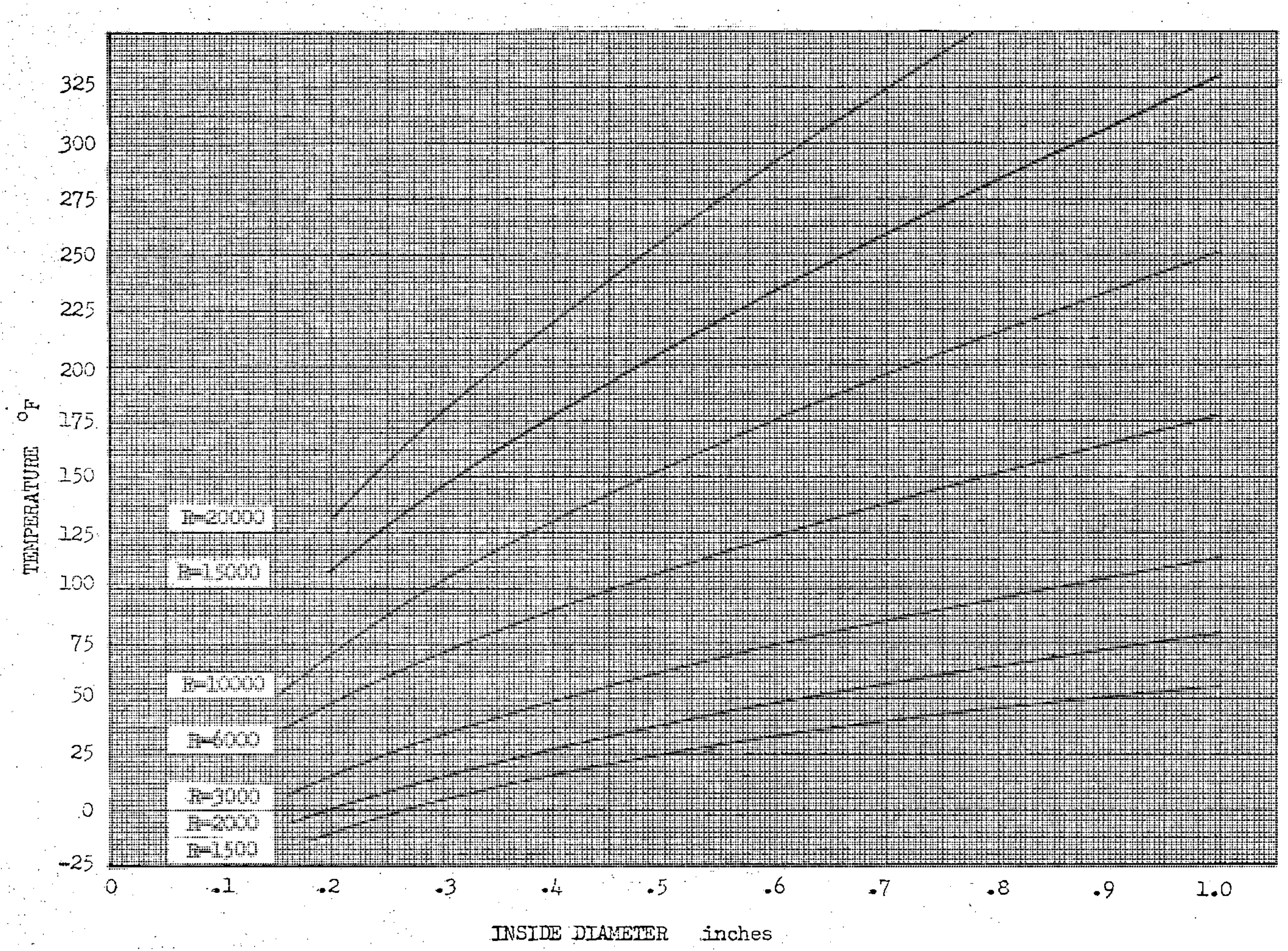

FIGURE 16. TEMPERATURE VERSUS INSIDE DIAMETER FOR FLUID 5606 (FLOW RATE = 12 GAL/MIN)

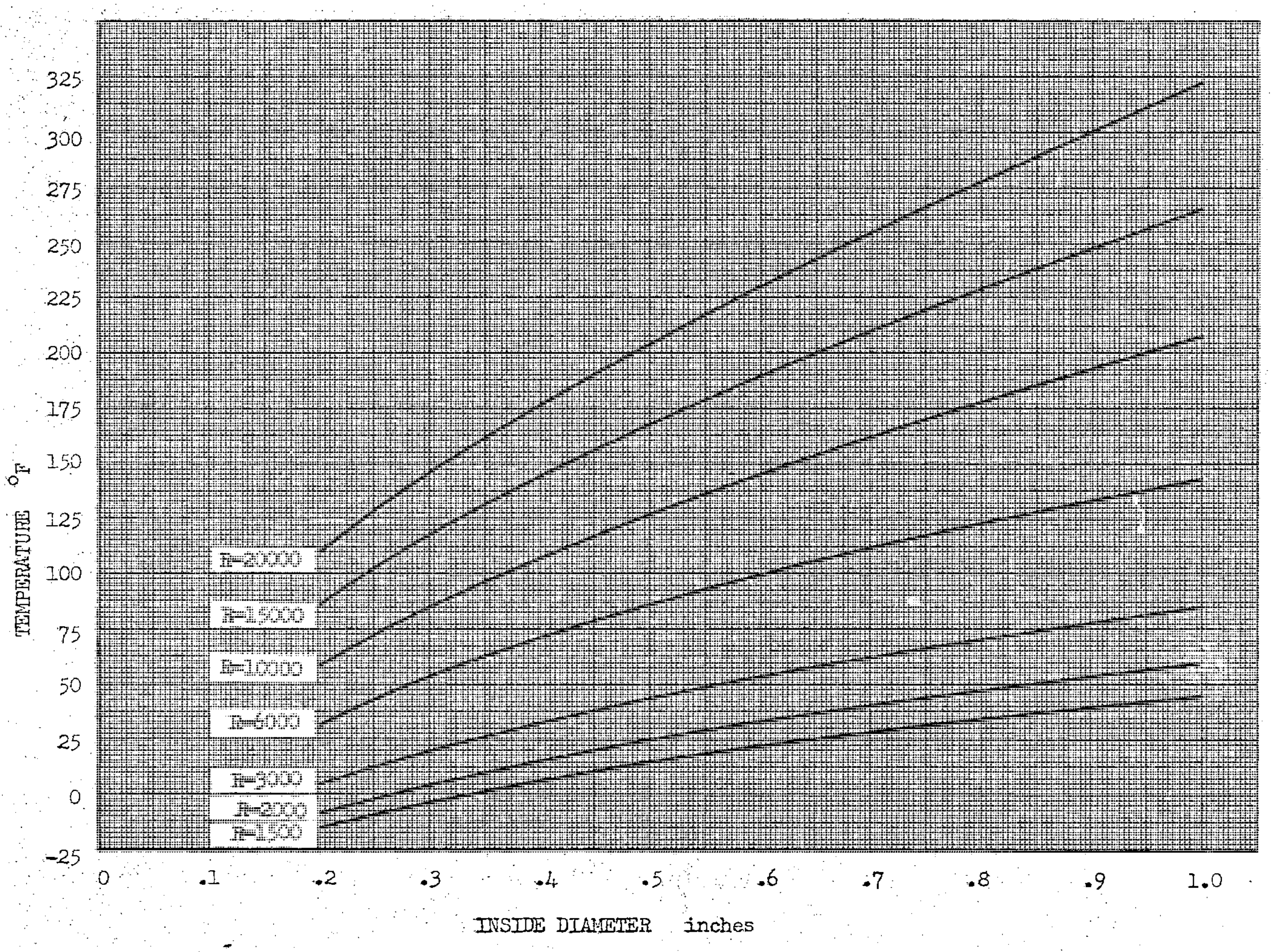

FIGURE 17. TEMPERATURE VERSUS INSIDE DIAMETER FOR FLUID 5606 (FLOW RATE = 16 GAL/MIN)

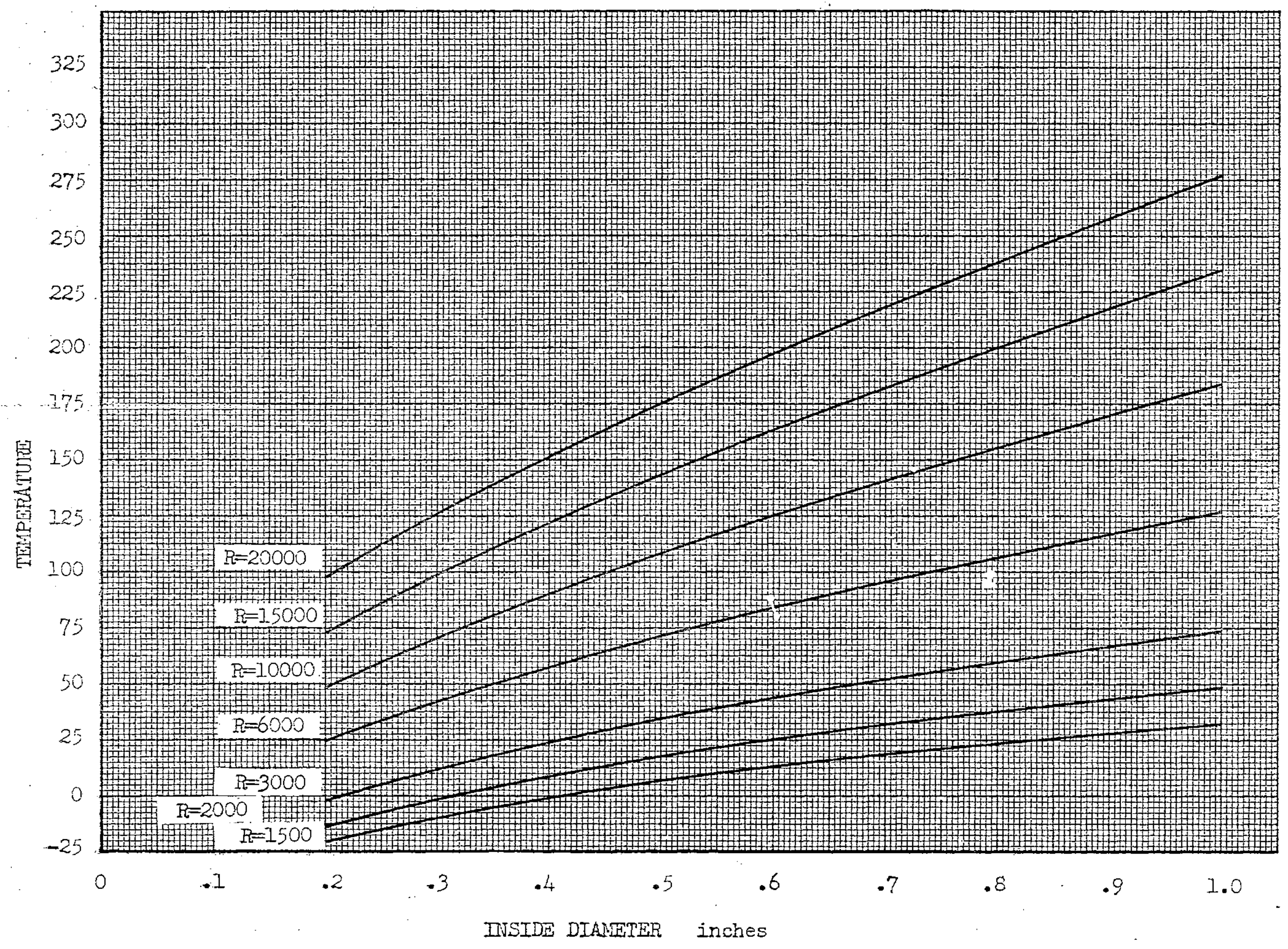

FIGURE 18. TEMPERATURE VERSUS INSIDE DIAMETER FOR FLUID 5606 (FLOW RATE = 20 GAL/MIN)

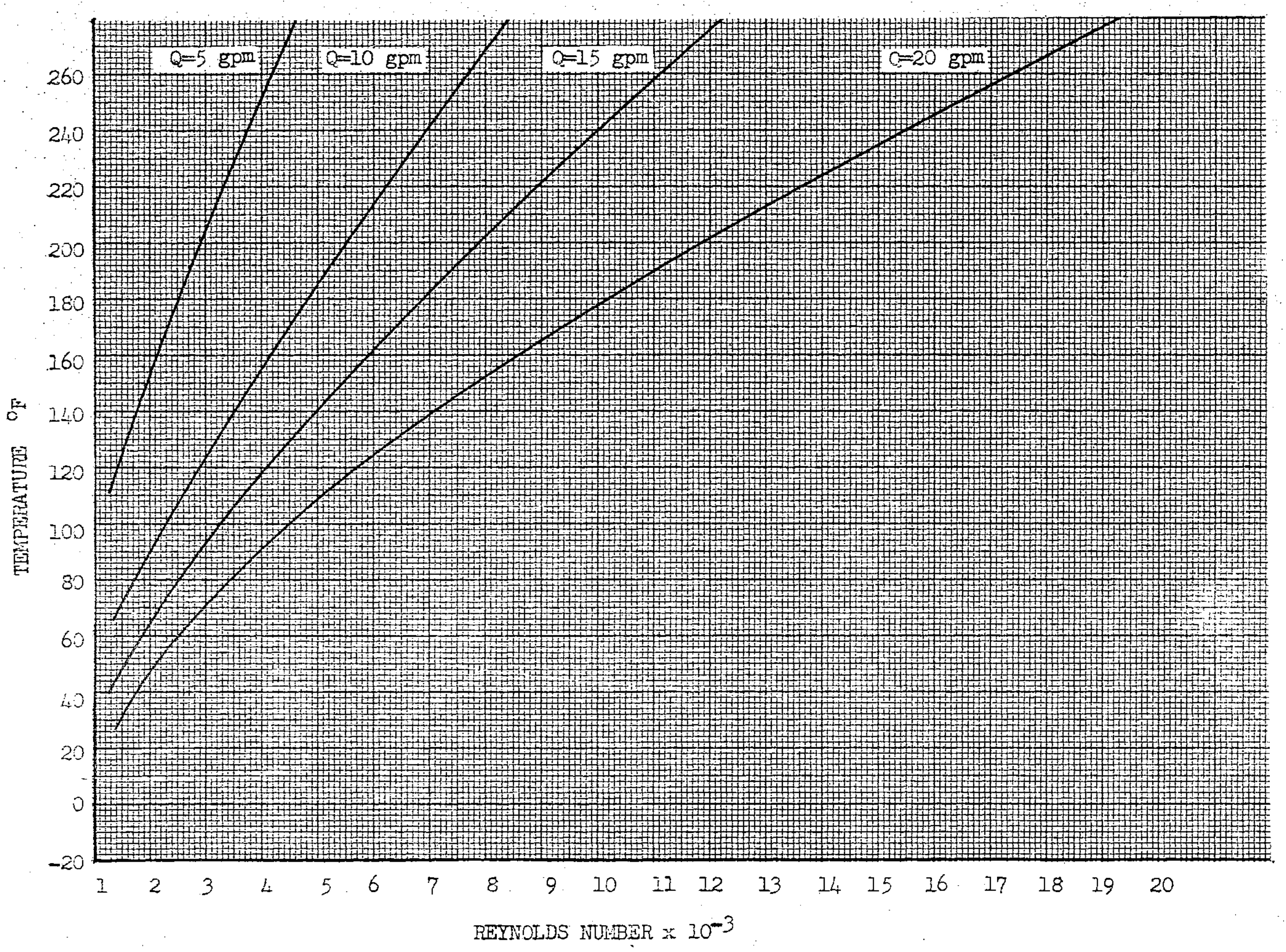

FIGURE 19. TEMPERATURE VERSUS REYNOLDS NUMBER FOR FLUID 5606 (DIAMETER = 1 INCH)

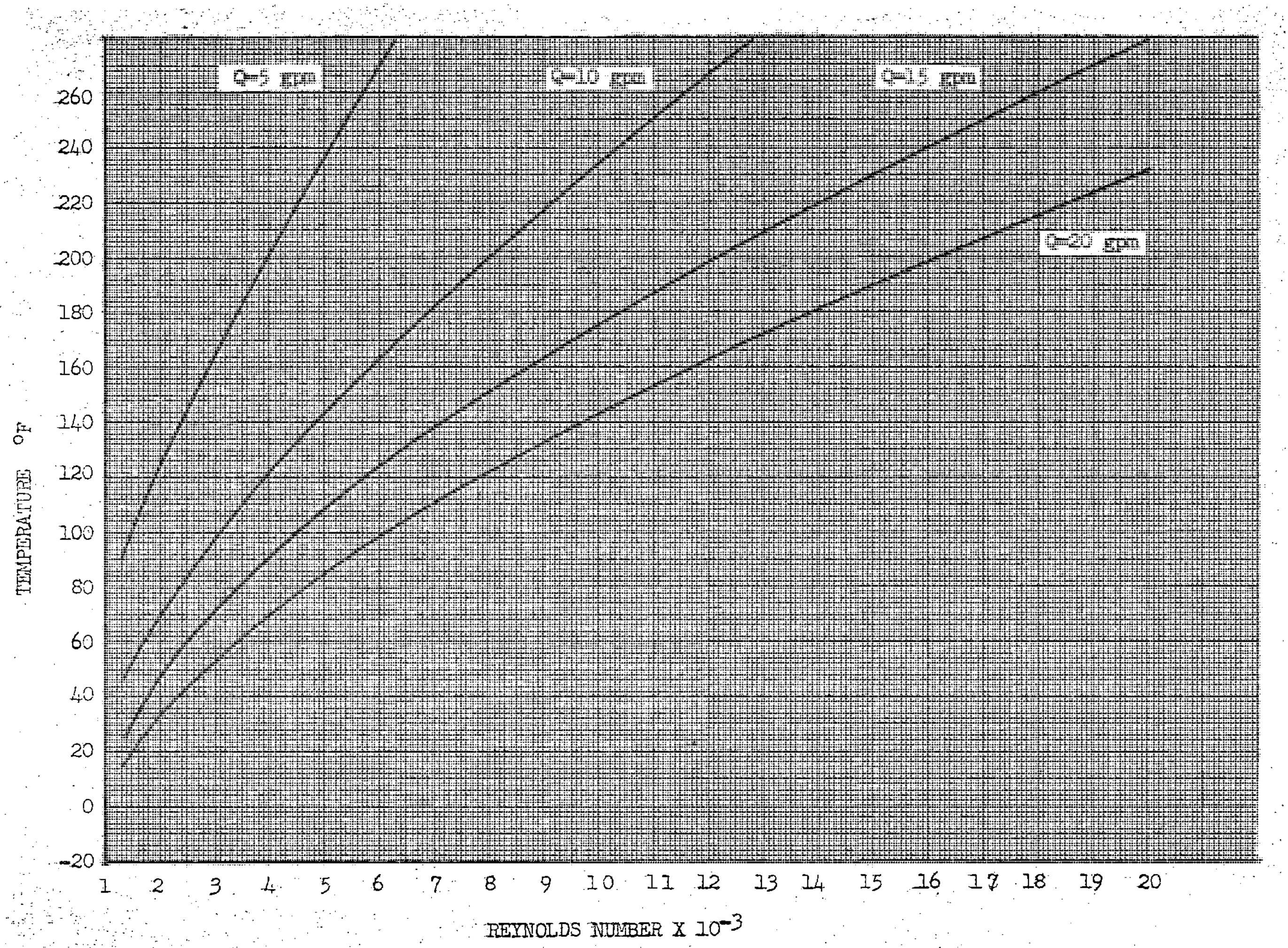

FIGURE 20. TEMPERATURE VERSUS REYNOLDS NUMBER FOR FLUID 5606 (DIAMETER = 3/4 INCH)

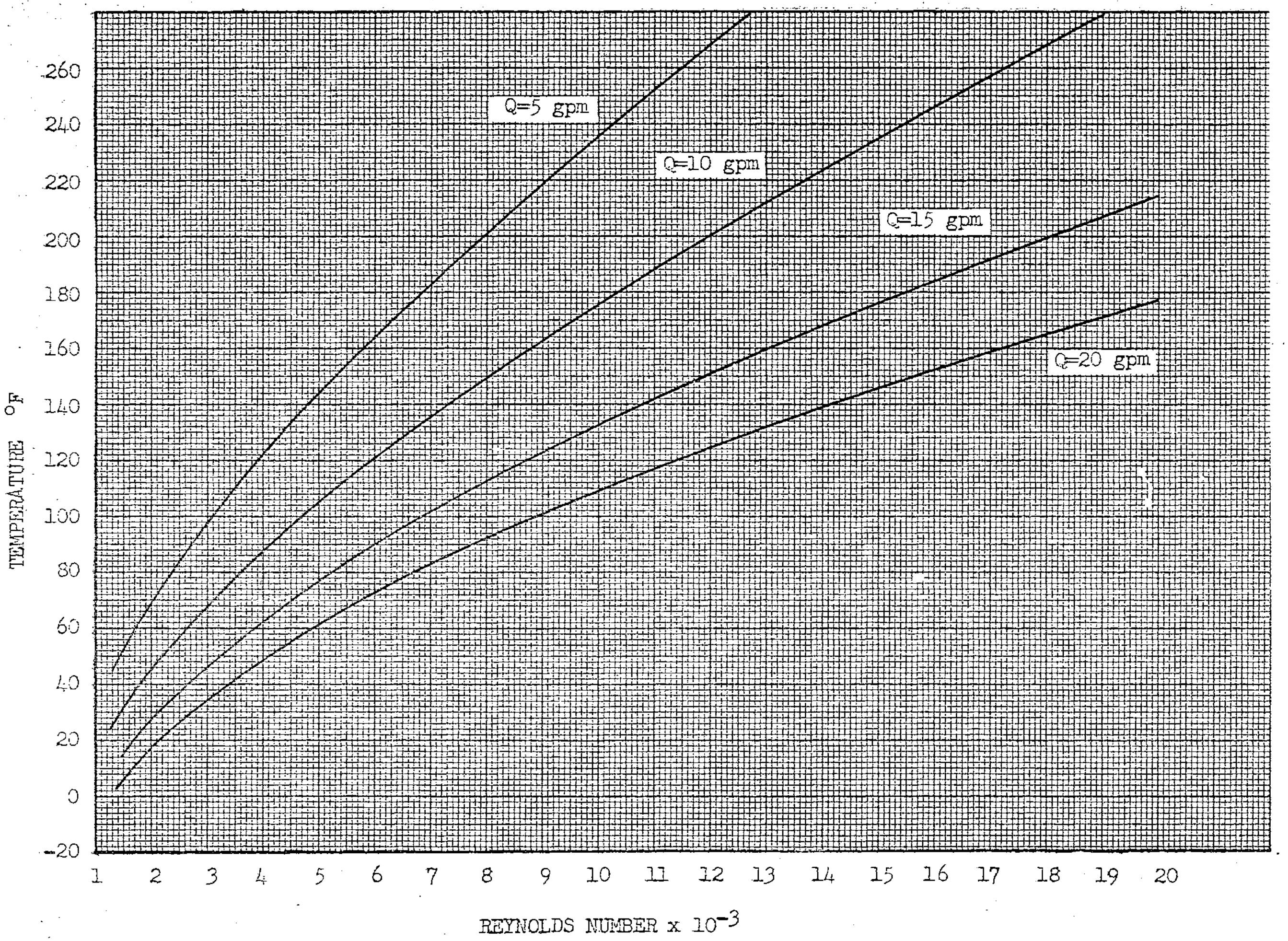

FIGURE 21. TEMPERATURE VERSUS REYNOLDS NUMBER FOR FLUID 5606 (DIAMETER = 1/2 INCH)

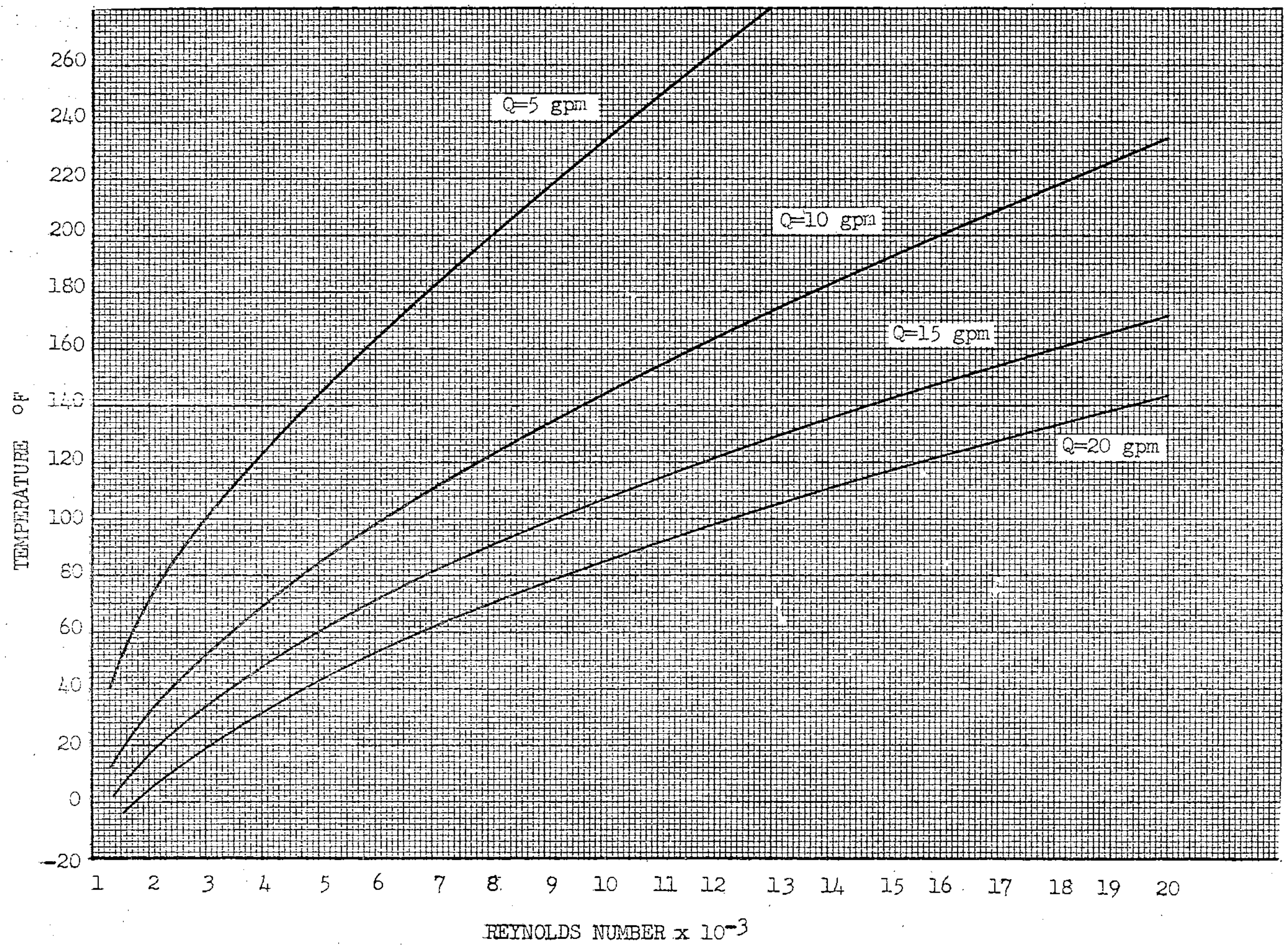

FIGURE 22. TEMPERATURE VERSUS REYNOLDS NUMBER FOR FLUID 5606 (DIAMETER = 3/8 INCH)

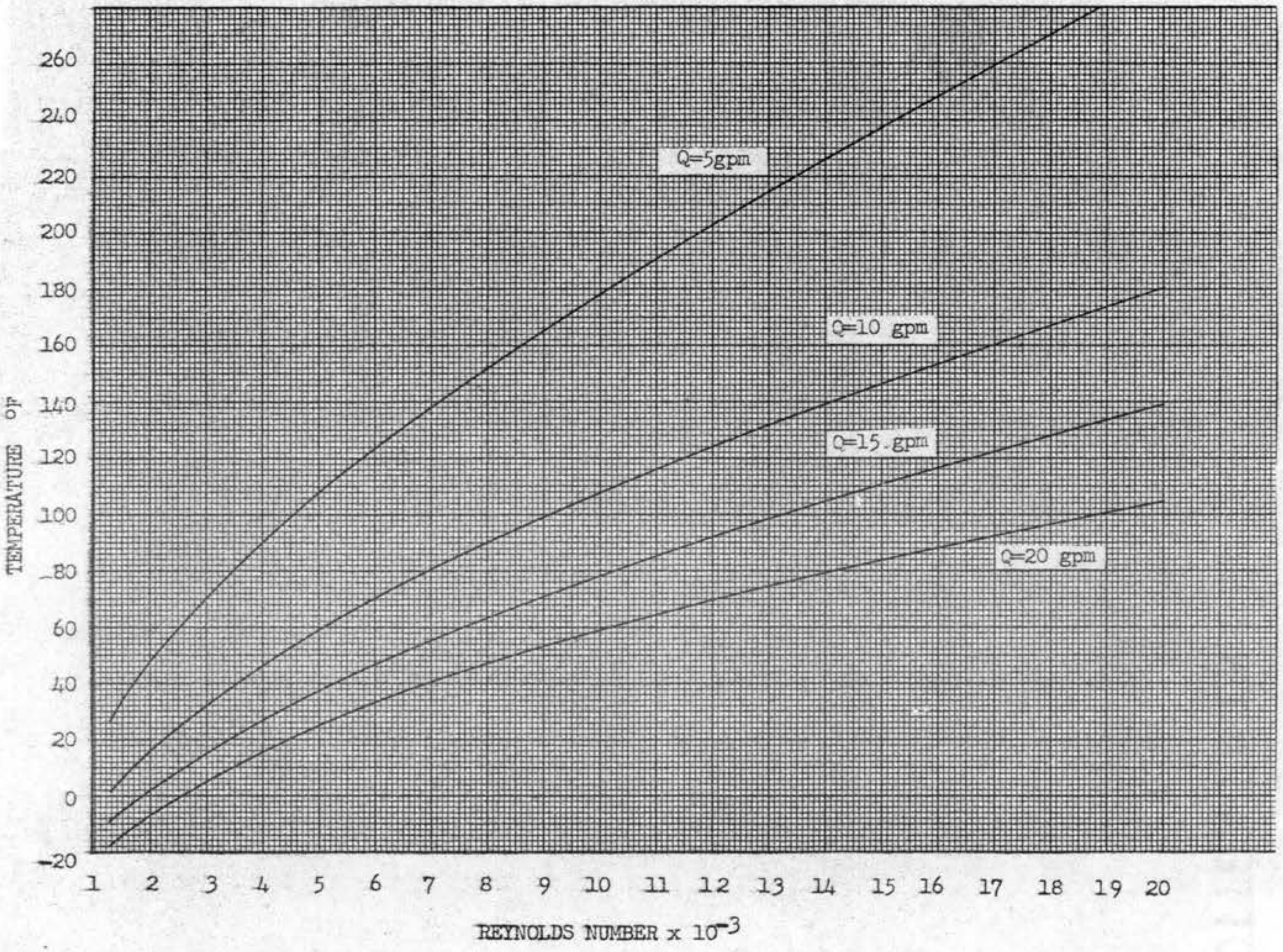

FIGURE 23. TEMPERATURE VERSUS REYNOLDS NUMBER FOR FLUID 5606 (DIAMETER = 1/4 INCH)

$$N_u = f(R, P_r)$$

where N_u = Nusselt Number

$f(R, P_r)$ = some function of the Reynolds Number and Prandtl Number

The Nusselt Number is a dimensionless quantity that is a convenient measure of the convective heat transfer coefficient because, once its value is known, the convective heat transfer coefficient can be calculated from the relation:

$$h = N_u \, k/L$$

where h = convective heat transfer coefficient

N_u = Nusselt Number

k = thermal conductivity

L = characteristic length dimension describing the geometry (L = inside diameter for circular tubes)

The energy equation implies that for the conduction terms to approach the order of the convection terms, the temperature gradient must be large near the surface, and as the Prandtl Number increases, the temperature gradient too must increase; thus, for fluids of high Prandtl Numbers, a very large temperature gradient is required in the thermal boundary layer for the conduction terms to approach the order of magnitude of the convection terms. Further for the convection and conduction terms to become of the same order of magnitude, the thickness of the thermal boundary layer is determined by: (15)

$$(\delta_t/L)^2 \sim 1/R\ P_r$$

where δ_t = thickness of thermal boundary layer

R = Reynolds Number

P_r = Prandtl Number

L = characteristic length describing geometry

Now the velocity boundary layer thickness is established by:

$$\delta_s/L \sim 1/\sqrt{R}$$

Therefore the following ratio is established:

$$\delta_t/\delta_s \sim 1/\sqrt{P_r}$$

where δ_t = thermal boundary thickness

δ_s = velocity boundary thickness

P_r = Prandtl Number

The above relationship illustrates that the Prandtl Number is instrumental in defining the ratio of the thermal boundary thickness to the velocity boundary layer thickness, and that in high Prandtl Number fluids such as hydraulic fluids, the thermal boundary layer will be much smaller than the velocity boundary layer. Also from this relation it can be seen that the Prandtl Number relates the temperature distribution to the velocity distribution and that these distributions become identical at a P_r equal to one. A very interesting relationship known as Reynolds analogy, has been formulated on the assumed similarity of the thermal and velocity distribution and it relates heat transfer and skin friction: (4)

$$N_u = \frac{1}{2} R f$$

where R = Reynolds Number

N_u = Nusselt Number

f = skin friction coefficient which equals the shear stress divided by the dynamic velocity head

The convective heat transfer coefficient is then calculated as shown on page 51. But since this simple analogy is based on the case for a Prandtl Number equal to one, it ceases to be valid for hydraulic fluids which have Prandtl numbers much greater than one. For a Prandtl Number different than one, the Nusselt Number remains proportional to the coefficient of skin friction (f) except that the factor of proportionality depends both on the Reynolds Number and the Prandtl Number. For the case of forced convection in tubes, Kreith (5) suggests the following relationship be used:[2]

$$h = 0.023 \frac{k}{d} R^{0.8} P_r^{0.33}$$

where h = convective heat transfer coefficient

k = thermal conductivity

d = diameter

R = Reynolds Number

P_r = Prandtl Number

Another relationship helps to compensate for viscosity variation with temperature and it has been mentioned previously on page 9.

---

[2] All properties except C_p are evaluated at the average film temperature, t_f, where t_f equals the average of the bulk temperature and the wall temperature. C_p is evaluated at the bulk fluid temperature.

Since Prandtl Number varies considerably with temperature, it needs to be defined at various temperatures. This information is shown in Figs. 24 and 25.

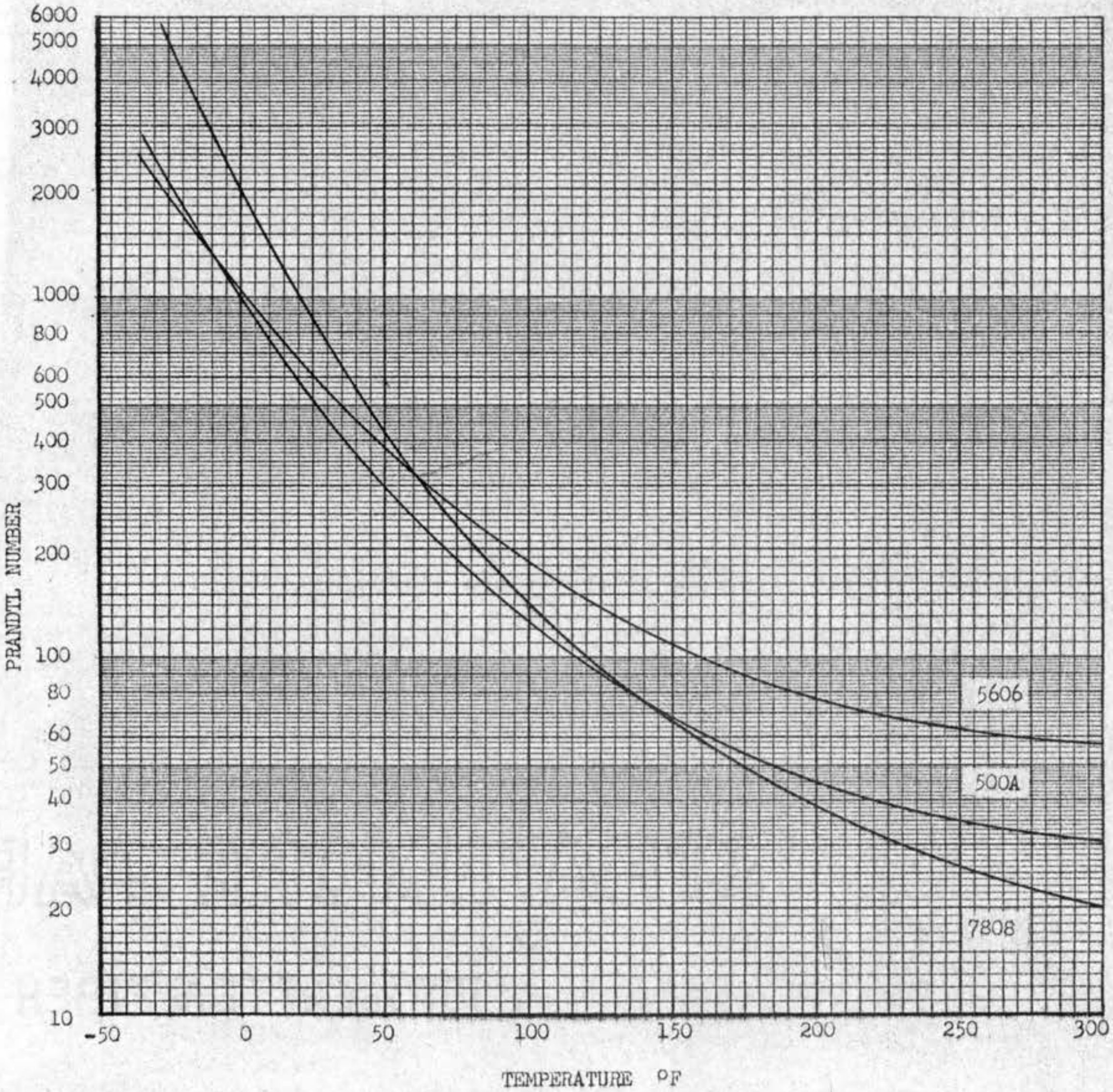

FIGURE 24. PRANDTL NUMBER VARIATION WITH TEMPERATURE (5606, 7808, 500A)

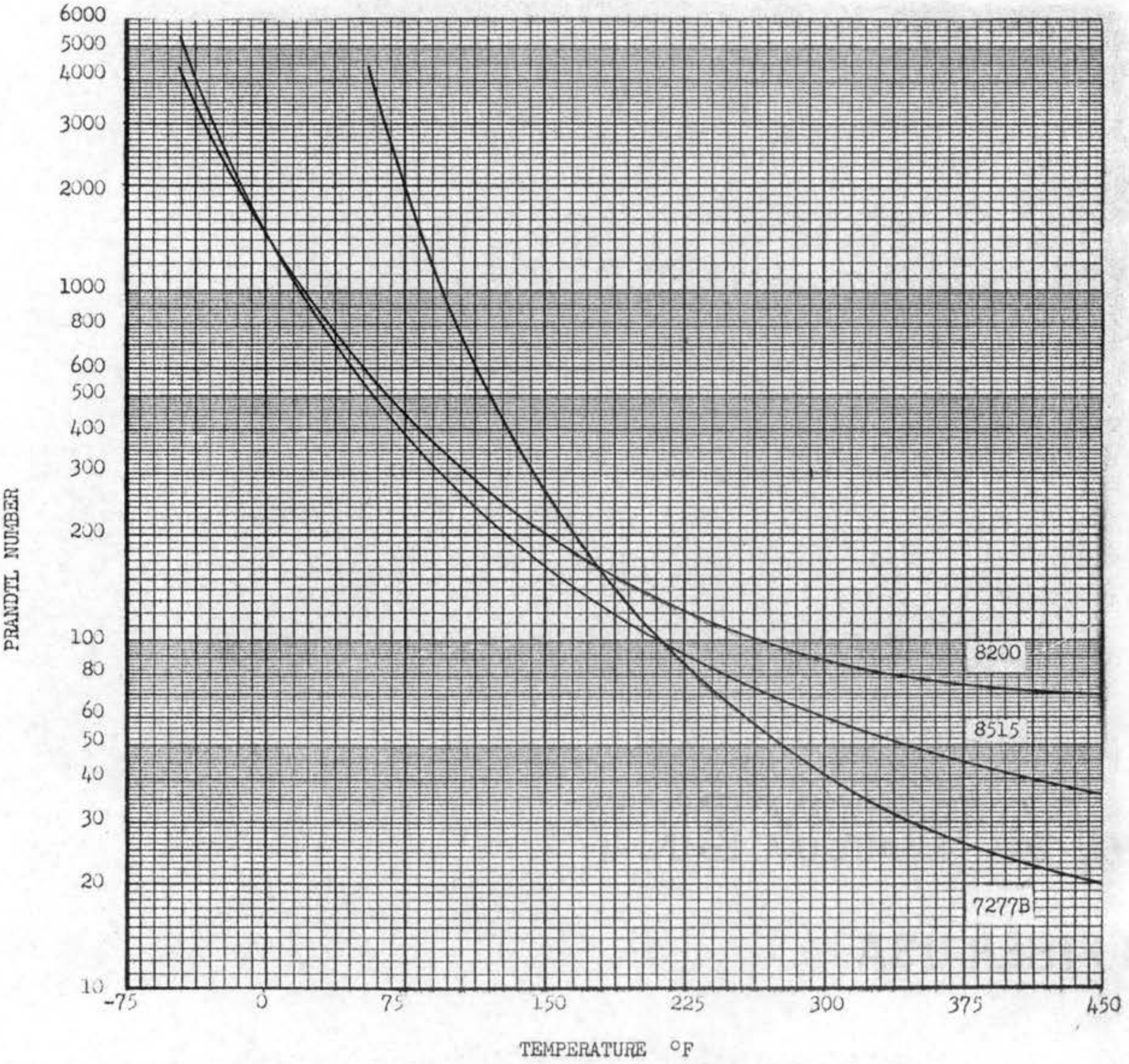

FIGURE 25. PRANDTL NUMBER VARIATION WITH TEMPERATURE (8515, 8200, 7277B)

CHAPTER VII

DISCUSSION

The purpose of this investigation was to collect, organize, and analyze the physical properties used in thermal considerations of hydraulic fluids and the design of hydraulic fluid systems. Since this information was viewed from more or less a thermal standpoint, the author feels his comments would be of help in the thermal design of hydraulic circuits. With these ideas in mind, the following discussion, conclusions, and recommendations are presented.

Although the pressure ranges in newly proposed hydraulic systems remain relatively unchanged from present designs, fluids have to meet the added requirement of being thermally stable at increased temperatures within the system pressure range. Factors other than high-temperature environments such as low temperatures and fire resistance should also be considered in new fluid development.

In the course of the study, one of the main hindrances stemmed from the difficulty in obtaining a complete set of information about the hydraulic fluids. For example, in the task of finding the properties of 7277B, the viscosity from 20°F to 400°F was obtained from a one-page data sheet published by the Oronite Chemical Company. A visit to the Boeing Company failed to yield any additional information. Finally, a second letter to the Oronite Chemical Company requesting specific information about specific properties fulfilled the list of needed information about the fluid. The problem connected with obtaining a complete set of data for fluid 7808 was similar. The viscosity was obtained from Reference (12), the specific heat and thermal conductivity were obtained from the Boeing Company, and the specific gravity information was obtained from Reference (9). Information about the other fluids took an equal amount of searching to locate. The scope of the problem of finding a complete set of physical properties cannot be realized by merely stating where the information was obtained. Numerous reports, textbooks, technical articles, and hydraulic manuals were scanned in search of the desired information.

It was found that the two best methods for getting property information were (a) to visit a consumer, and (b) to write letters requesting specific information from the companies who manufacture the product.

One obvious conclusion from the preceding discussion was that nowhere was there available in fingertip form, a complete list of information about any single fluid. This now leads to the recommendation that a complete list of information be compiled about hydraulic fluids, put into suitable form, and made available for use to interested parties. Of course, this information need not be limited to the properties considered in this thesis, but fluid property information such as is found in this study for only a few of the hydraulic fluids should have its place in any hydraulic-system, thermal-design manual.

The point is that engineers who might need this information for heat-transfer or thermal-design work should have it readily available and should not have to make an intense investigation simply to determine a couple of needed properties about a fluid.

It was felt that certain important information about hydraulic fluids had not received adequate attention in considering hydraulic systems. A variable such as viscosity change with pressure is considered as one item that needs to be better defined. For the most part, viscosity versus temperature data is invariably presented only at atmospheric pressure. Indeed this shows the relative comparison of variation among hydraulic fluids, but since hydraulic systems do not operate at zero gage pressure (an impossibility), it would be both logical and convenient to have available the viscosity variation with temperature for the pressures normally encountered in hydraulic circuits. An example will help to illustrate the point.

At a temperature of 100°F and for fluid 5606, the viscosity increases from 14.1 centistokes at atmospheric pressure to 21 centistokes at 3000 psi, or an increase of approximately 30 per cent. For a diameter of one-half inch and a flow rate of ten gallons per minute, the two Reynolds Numbers are 4800 and 3100 respectively, or a decrease of approximately 35 per cent due to the increase in pressure. Similarly, the Prandtl Numbers are 182 and 263 for respective pressures of atmospheric and 3000 psig, or an increase of approximately 44 per cent. Now using the equation of page 53 and calculating the convective heat transfer coefficients for the two pressure levels yields respective values of 90 and 68 BTU/hr ft^2-°F, which represents a decrease of 25 per cent for the convective heat transfer coefficient due only to the increased pressure effect on viscosity.

It is felt that four properties of a hydraulic fluid are sufficient to make an adequate thermal study of a hydraulic fluid system:

1. Viscosity
2. Thermal conductivity
3. Specific heat
4. Specific gravity or density

The above properties are instrumental in the determination of the dimensionless Reynolds Number and Prandtl Number which are in turn the basis of estimating the coefficient of heat transfer in problems of forced convection. The heat transfer problem in hydraulic systems is certainly a convection problem and due to the very small coefficient of expansion for normal liquids and the temperature differences encountered, the problem becomes one of forced convection. Clarification of this point is established by reference to the equation of motion which implies that for the buoyant forces to approach the order of the viscous forces, the following approximation must hold: (4)

$$G \approx R^2$$

where G = Grashof Number

R = Reynolds Number

But the Grashof Number is given by:

$$G = g\beta\theta L^3/\nu^2$$

where

g = gravitational constant

β = coefficient of expansion

θ = difference between bulk fluid temperature and wall temperature

L = characteristic length dimension (L = inside diameter for tubes)

ν = kinematic viscosity

Simplification of the approximation gives a ridiculously large temperature difference even for a low Reynolds Number of 1500, thus eliminating the possibility of the Grashof Number even approaching the magnitude of the square of the Reynolds Number and consequently, eliminating the possibility of the existence of free convection except for very small Reynolds Numbers.

Attention is directed toward certain desirable properties of a hydraulic fluid. Although larger values of viscosity increase viscous heating, it is necessary that a fluid have a relatively large viscosity to insure proper pump lubrication and to minimize system leakage. As pointed out in Chapter V, one of the limiting factors governing the use of a fluid in high temperature applications is its decrease in viscosity at elevated temperatures. It is also desirable to have a large convective heat transfer coefficient to transfer heat adequately from a heated fluid and larger values of specific heat, thermal conductivity, and specific gravity help increase this coefficient. More needs to be said about specific gravity, especially as applied to airborne systems where it is desired to keep the total weight as low as possible; therefore, fluids with smaller specific gravities are generally used in aircraft and missile systems as compared with those used in commercial plant systems.

Of the six fluids contained in the previous chapters, it is felt that adequate information for a complete thermal investigation is available only for fluid 5606. For 5606, there is available viscosity variation with temperature and pressure, specific heat and thermal conductivity variation with temperature, and specific gravity variation with temperature and pressure. The other fluids do not have such a detailed set of information because one important property was not obtained about them. The importance of this property, variation of viscosity with pressure, has been discussed previously. Also not available for the other fluids is specific gravity variation with pressure, but the small effect of the normal operating pressures (1500-3000 psi) in hydraulic systems on the specific gravity of 5606 indicates that this information has little effect on the consideration in this text and can for the present be neglected.

It can be concluded from the information contained in Chapter VI that the physical properties do have an important influence on the fluid flow parameters and the nature of this data suggests the extension of the information to include a wider scope of the variables, a broader selection of fluids, and possibly the development of other methods of representation. It should be pointed out that the variation of viscosity with temperature was instrumental in determining the general shape of curves since it constituted the largest variable in determining values for the dimensionless parameters, the Reynolds Number and the Prandtl Number.

This information contained in graphic form in Chapter VI certainly has room for extension. Further investigation might well include line pressure drop as one of the variables in the flow parameters, especially if experimental data could be obtained that would in some way relate the temperature rise of a system to the pressure drop. It is believed that information of this type would be very valuable to the designer of a hydraulic system for (a) he would be able to predict the temperature rise of a system by relating it to a pressure drop, (b) he could eliminate high localized temperature rises thus eliminating so-called "hot spots", and (c) he could design into a bypass system, pressure drops that would heat the fluid quickly. A quick heating of the fluid could be useful in polar climates where the problem is to get the fluid up to an operating temperature quickly. After the desired temperature had been reached the hydraulic system could then be switched to the main operating system.

Another possibility of extension of the information in Chapter VI could include the convective heat transfer coefficient. This could be done by plotting the Nusselt Number versus functions of the Reynolds Number and Prandtl Number for different temperatures such as by using the equation on page 53. Of course, curves would differ for different fluids, but if viscosity were used as a parameter instead of temperature, the data might not be exact but it would give a good approximation of the temperature of any of the fluids since the variation of the other fluid properties is small when compared with the viscosity variation.

Finally, one last word about the Prandtl Number. Hydraulic fluids have high Prandtl Numbers that vary considerably with temperature (see Figs. 24 and 25), and therefore, the simplifying assumption that is often made that the Prandtl Number is constant and of the order of unity cannot be justified.

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APPENDICES

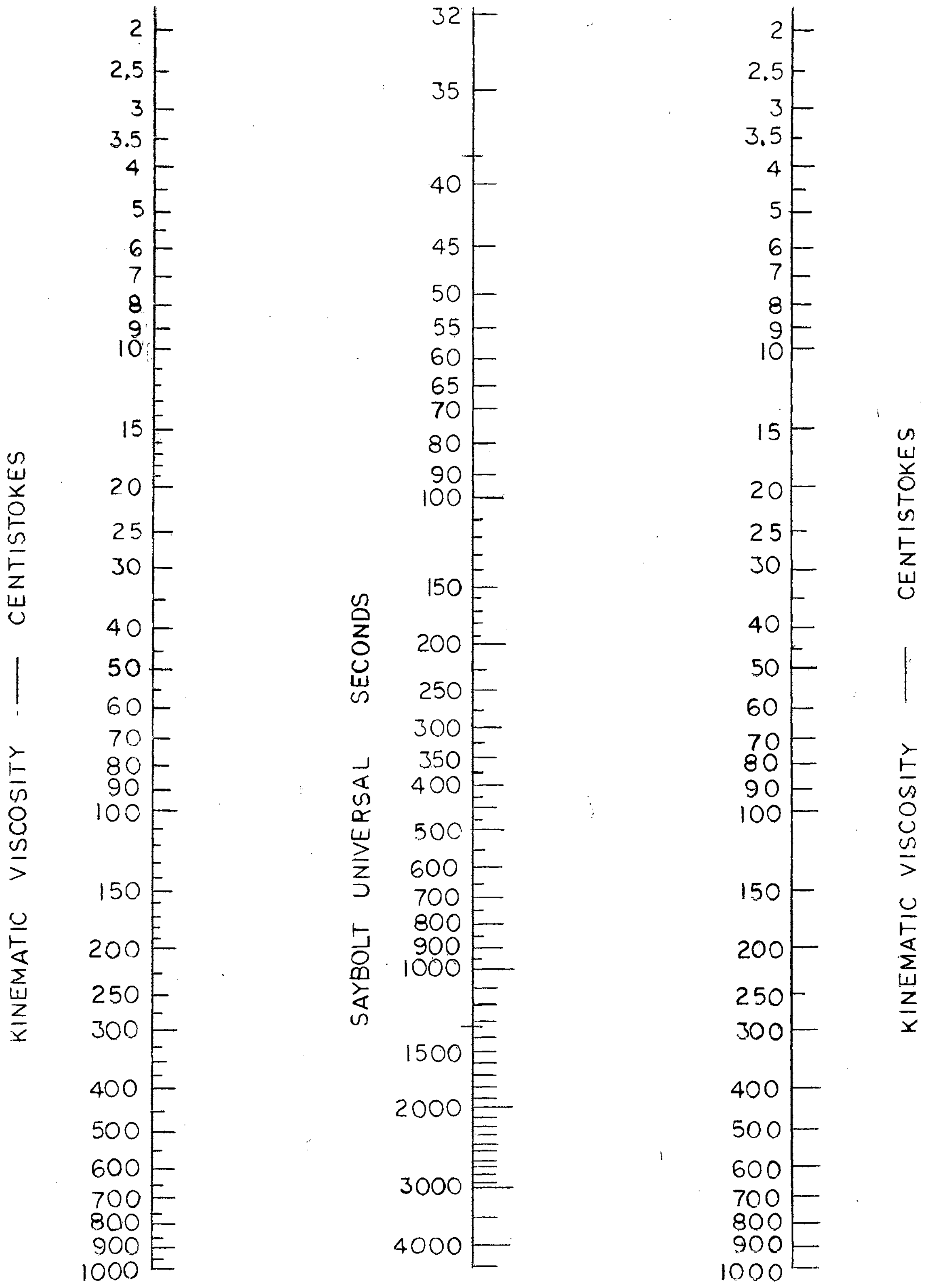

Figure 26. Viscosity Nomograph

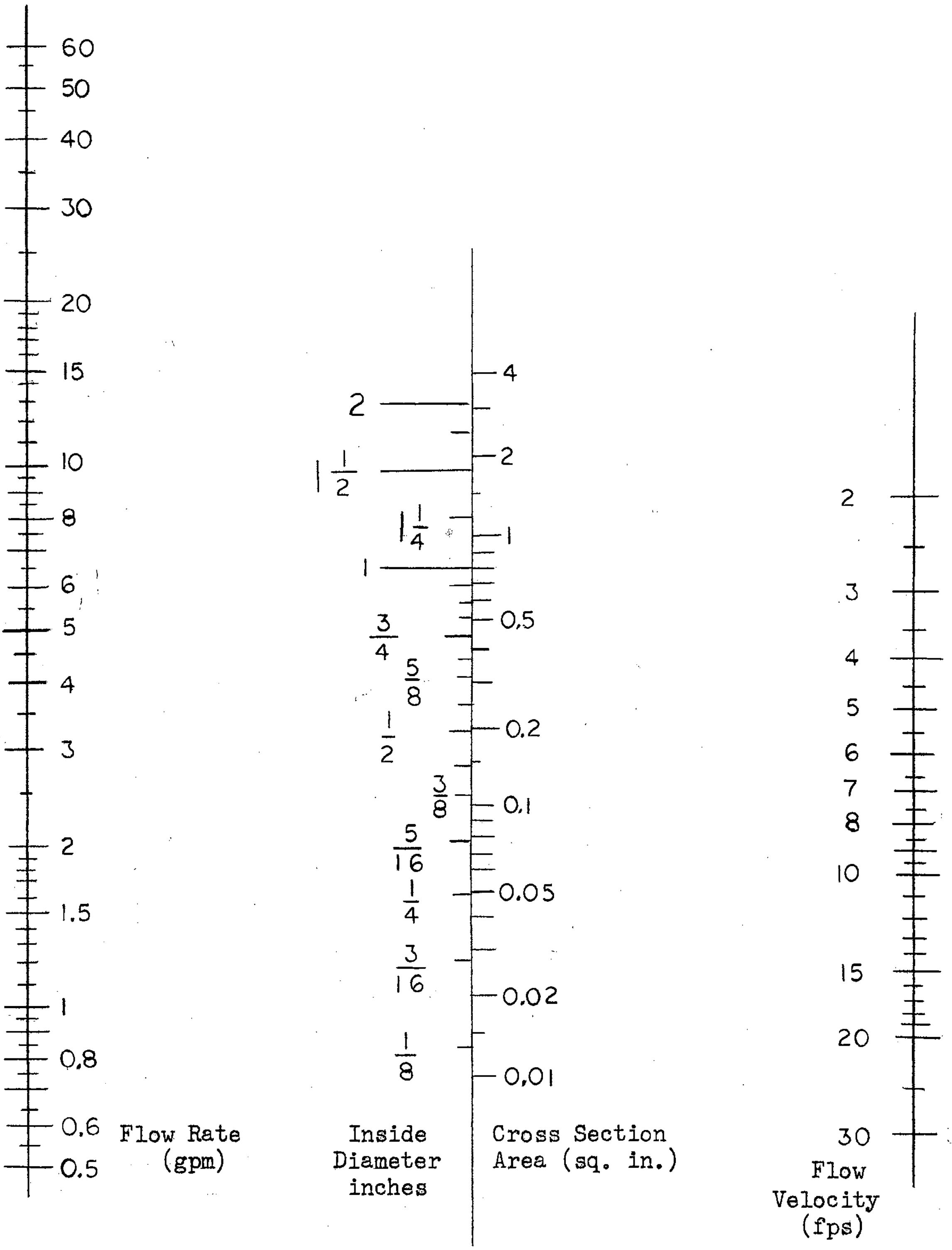

Figure 27. Nomograph for Continuity Equation

TABLE II

COMPENSATED FLOW PARAMETER DATA FOR FLUID 5606

Values are temperatures °F for given diameters
Pressure = 3000 psi

DIAMETER = 1 inch

Flow Rate (gpm)	Reynolds Number x 10^{-5} 1.5	2	3	6	10	15	20
2.5	---	---	---	---	---	---	---
5	156	190	---	---	---	---	---
7	127	150	202	---	---	---	---
10	100	120	155	---	---	---	---
12	89	106	139	233	---	---	---
15	75	92	120	192	---	---	---
20	59	75	98	155	233	---	---
25	49	63	85	135	192	---	---

DIAMETER = 3/4 inch

Flow Rate (gpm)	Reynolds Number x 10^{-3} 1.5	2	3	6	10	15	20
2	---	---	---	---	---	---	---
5	130	156	210	---	---	---	---
7	104	125	164	---	---	---	---
10	82	94	129	210	---	---	---
12	70	89	115	187	---	---	---
15	60	76	98	155	230	---	---
20	46	61	80	129	188	270	---
25	37	50	69	112	155	210	---

TABLE II (Continued)

DIAMETER = 1/2 inch

Flow Rate (gpm)	Reynolds Number x 10^{-3} 1.5	2	3	6	10	15	20
2	185	237	---	---	---	---	---
5	98	119	155	---	---	---	---
7	80	98	126	201	---	---	---
10	62	74	98	155	233	---	---
12	52	64	87	138	197	---	---
15	41	54	73	120	167	233	---
20	30	43	59	98	138	182	233
25	14	33	49	84	125	155	192

DIAMETER = 3/8 inch

Flow Rate (gpm)	Reynolds Number x 10^{-3} 1.5	2	3	6	10	15	20
2	148	183	265	---	---	---	---
5	80	99	128	210	---	---	---
7	64	78	104	164	250	---	---
10	46	60	80	123	182	265	---
12	39	51	72	114	157	218	---
15	30	42	60	98	137	183	233
20	18	29	47	80	115	150	182
25	11	22	37	68	98	129	155

TABLE II (Continued)

DIAMETER = 1/4 inch

Flow Rate	Reynolds Number x 10^{-3}						
(gpm)	1.5	2	3	6	10	15	20
2	113	135	182	---	---	---	---
5	59	74	98	155	233	---	---
7	44	58	79	125	176	252	---
10	30	41	60	98	137	182	235
12	23	34	51	87	122	160	200
15	15	24	42	74	105	140	167
20	5	17	30	60	87	115	140
25	-2	5	22	49	54	99	120

VITA

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