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SUBJECT: A Method for Evaluating the Heat Transfer Effectiveness of Reactor Coolants

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A METHOD FOR EVALUATING THE HEAT TRANSFER EFFECTIVENESS OF REACTOR COOLANTS

by

M. W. Rosenthal
H. F. Poppendiek
R. M. Burnett

[redacted]

SUMMARY

One of the considerations in the selection of a coolant for a nuclear reactor or any heat exchange system is the amount of flow work required for removal of a unit of heat. This quantity, which is referred to as the "cooling work modulus", varies with the geometry of the system, the fluid velocity (and flow regime), and the properties of the fluid.

In this memorandum equations for calculation of the cooling work modulus are developed for turbulent flow, curves which simplify computation are provided, and the results of the study of a specific reactor are presented for illustration.

INTRODUCTION

A number of factors must be considered when selecting a coolant for a nuclear reactor. For example, the nuclear properties, corrosion characteristics, density, vapor pressure, and the melting temperature of the coolant as well as its heat transfer effectiveness must be evaluated. In this memorandum, only a study of the coolant heat transfer effectiveness in terms of flow work per unit heat removal is conducted. Such a study may be useful in minimizing the pumping power requirements for a given reactor system by properly choosing the coolant and size and number of coolant passages.

An idealized reactor coolant system which is considered to be somewhat representative of actual solid fuel-element reactors is used in the subsequent analyses and is defined by the following postulates:

[redacted]

1. Heat is generated uniformly in the volume of a cylindrical reactor core.

2. Heat is removed by a coolant that is passing through circular, parallel coolant passages which are distributed uniformly through the core. The volume of coolant in the reactor is a constant; thus the number of tubes varies with tube diameter.

3. No heat is generated in the coolant.

4. The coolant passages are presumed to be sufficiently long that thermal and hydrodynamic entrance effects are small and can be neglected.

5. The physical properties are not considered to be temperature dependent; average values are used.

6. Coolant temperature differences (either radially, axially or combinations of the two) are specified for a given amount of heat to be removed from the reactor.

The cooling work modulus, which is developed in the following paragraphs, is a function of the reactor geometry, the heat removal rate, the thermal properties of the coolant, and certain coolant temperature differences which are fixed by such factors as mean coolant temperature, coolant melting and boiling temperatures, tube wall corrosion and mass transfer, and thermal stresses.

DEVELOPMENT OF EQUATIONS

I. Derivation of Cooling Work Modulus

The pressure drop across the reactor is obtained using the Fanning equation.

$$\Delta_p = \frac{2f\rho V^2 L}{g_c D} \tag{1}$$

In the turbulent flow regime the friction factor, f, can be calculated from the following equation.

$$f \equiv \frac{2g_c \tau_w}{\rho V^2} = \frac{0.046}{N_{Re}^{0.2}} \tag{2}$$

The flow work per unit time, P_p, equals the pressure drop multiplied by the total volumetric flow rate through the reactor.

$$P_p = Q\Delta_p = VA_c \Delta_p = V(\pi D^2 n/4)\Delta_p \tag{3}$$

The dimensionless "cooling work modulus" π_p, is obtained by dividing the flow work rate by the total heat removal rate, with the factor J inserted to convert from heat units to work units.

$$\pi_p = \frac{P_p}{Jq_t} \tag{4}$$

If the volume of coolant is held constant at B_c, the number of coolant passages, n, is related to the dimensions of the tubes.

$$n = \frac{4B_c}{\pi D^2 L} \tag{5}$$

Substituting equations (1), (2), (3) and (5) into equation (4), and eliminating velocity by replacement with the Reynolds number, $DV\rho/\mu$

$$\pi_p = \frac{0.092}{g_c J}\left[\frac{\mu^3}{\rho^2}\right]\left[\frac{B_c}{D^4 q_t}\right] N_{Re}^{2.8} \tag{6}$$

If both numerator and denominator are divided by the volume of the reactor, B_R, the coolant volume and heat flow rate can be expressed in terms of a unit volume of reactor

$$\pi_p = \frac{0.092}{g_c J}\left[\frac{\mu^3}{\rho^2}\right]\left[\frac{(B_c/B_R)}{D^4(q_t/B_R)}\right] N_{Re}^{2.8} \tag{6a}$$

II. Heat Transfer Analyses

Two coolant temperature differences arise in the heat transfer analyses. One is the difference between the tube wall and mixed-mean fluid temperatures, Δt_R, and the other is the difference between the inlet and outlet mixed-mean fluid temperatures, Δt_A. Depending on the several design factors such as mean coolant temperature, melting and boiling temperatures, and tube wall corrosion and mass transfer, one or the other of these temperature differences, or a combination of both are parameters that must be considered. One analysis which follows contains a total temperature difference, Δt_t which is equal to $c_1 \Delta t_R + c_2 \Delta t_A$ where c_1 and c_2 are constants which can be selected to emphasize the radial and axial temperature differences as desired.

1. General Case

Including the definitions of the "total temperature difference," Δt_t, and the Nusselt modulus, N_{Nu}, four equations can be written describing

the heat transfer system in the reactor.

$$q_t = hA_H \Delta t_R \tag{7}$$

$$q_t = V\rho A_c c_p \Delta t_A \tag{8}$$

$$h = kN_{Nu}/D \tag{9}$$

$$\Delta t_t = c_1 \Delta t_R + c_2 \Delta t_A \tag{10}$$

Substituting from (7) and (8) into (10).

$$\Delta t_t = \frac{c_1 q_t}{hA_H} + \frac{c_2 q_t}{V\rho A_c c_p} \tag{11}$$

Replacing h using equation (9) and rearranging.

$$\frac{c_1}{N_{Nu}} = \frac{k \Delta t_t A_H}{Dq_t} - \frac{c_2(A_H/A_c)k}{DV\rho c_p} \tag{12}$$

$$\frac{1}{N_{Nu}} = \frac{k \Delta t_t}{c_1 Dq_t/A_H} - \frac{4(A_H/4A_c)(c_2/c_1)k}{DV\rho c_p} \tag{12a}$$

Equation (12a) may be simplified by replacement of terms with dimensionless groups; n is eliminated using equation (5).

$$F \equiv \frac{k \Delta t_t}{c_1 Dq_t/A_H} = \frac{\pi \Delta t_t kLn}{c_1 q_t} = \frac{4 \Delta t_t k(B_c/B_R)}{c_1 D^2(q_t/B_R)} \tag{13}$$

$$X \equiv \left(\frac{A_H}{4A_c}\right)\left(\frac{c_2}{c_1}\right) = \left(\frac{L}{D}\right)\left(\frac{c_2}{c_1}\right) \tag{14}$$

$$\frac{4(A_H/4A_c)(c_2/c_1)k}{DV\rho c_p} = \frac{4Xk}{DV\rho c_p} = \frac{4X}{N_{Re}N_{Pr}} \tag{15}$$

Substituting into equation (12a).

$$\frac{1}{N_{Nu}} = F - \frac{4X}{N_{Re}N_{Pr}} \tag{12b}$$

For fully developed turbulent flow of <u>ordinary fluids</u> the Nusselt modulus can be expressed as a power function of the Reynolds and Prandtl moduli.

$$N_{Nu} = 0.023\ N_{Re}^{0.8}\ N_{Pr}^{0.4} \qquad N_{Pr} \geqq 0.5 \tag{16}$$

For fully developed turbulent flow of <u>liquid metals</u> in pipes a different relationship is employed[1].

$$N_{Nu} = 7 + 0.025\ N_{Re}^{0.8}\ N_{Pr}^{0.8} \qquad N_{Pr} < 0.5 \tag{17}$$

Equation (12b) has been solved simultaneously with equations (16) and (17) by computing machine with F and X as independent dimensionless parameters. The results are presented as a series of curves, Figs. 6 through 22, with N_{Re} as a function of X for various values of F and N_{Pr}. For values of c_1 and c_2 larger than zero, the heat transfer solution for a reactor can be determined from these curves, the Reynolds number thus obtained inserted into equations (6) or (6a), and the cooling work modulus calculated.

Two cases in which particular values of c_1 and c_2 are employed and the special cases of c_1 equal zero and c_2 equal zero are considered in the following sections.

---

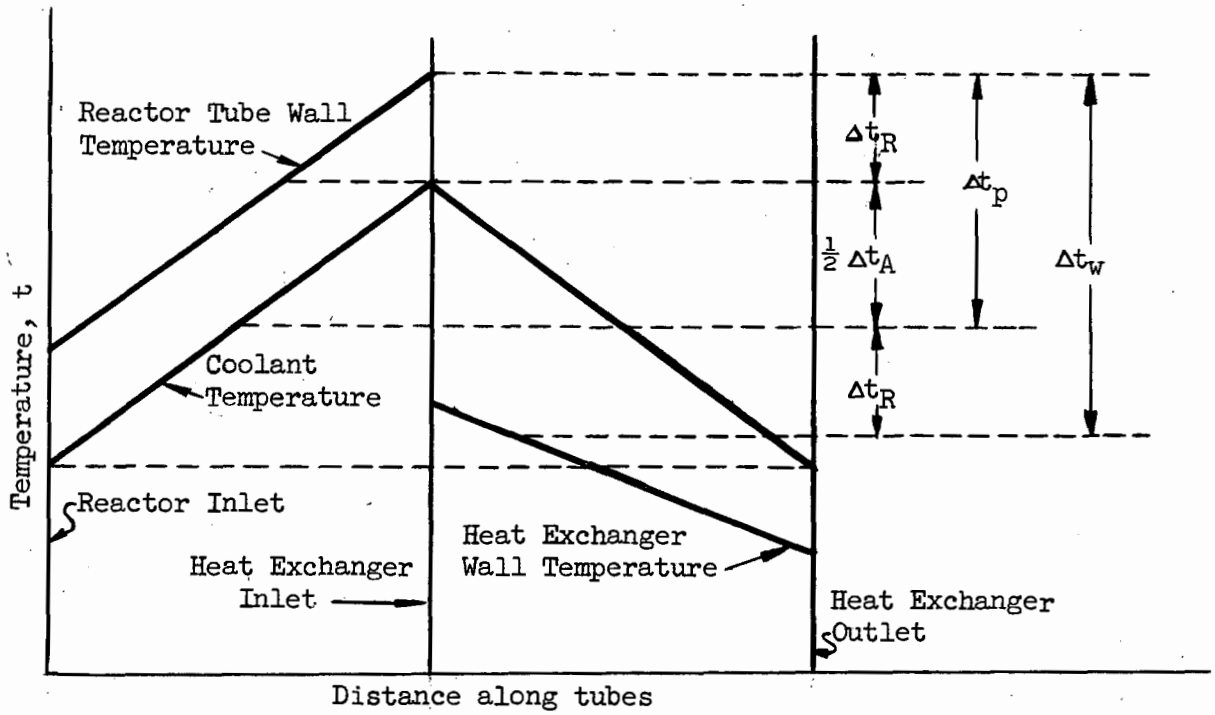
[1] Lyon, R. N., "Liquid-Metals Handbook," 2nd ed., U.S. Government Printing Office, Washington, 1952, p.187.

2. Case where $c_1 = 1$ and $c_2 = 1/2$ (i.e., $\Delta t_t = \Delta t_R + \frac{1}{2}\Delta t_A \equiv \Delta t_p$)

In this case the temperature difference parameter is taken equal to the sum of the radial temperature difference and half the axial temperature rise. For uniform heat generation in the reactor and uniform heat transfer coefficient throughout the coolant tubes, the parameter, Δt_p, is the difference between the hottest point on the tube wall and the mean temperature of the fluid in the reactor. In many systems the mean temperature of the coolant in the reactor is the same as the mean temperature of that fluid in passage through a coupled heat exchanger. Under this condition Δt_p is approximately the difference between the hottest point on the tube wall in the reactor and the mean temperature level available for transferring heat from the coolant to a working fluid or a heat sink. This is illustrated in Figure 1.

[redacted]

FIGURE 1



For $\Delta t_t = \Delta t_R + 1/2\,\Delta t_A \equiv \Delta t_p$

$$F = \frac{k\,\Delta t_p}{D\,q_t/A_H} = \frac{4\,\Delta t_p k(B_c/B_R)}{D^2(q_t/B_R)}$$

$$X = L/2D$$

3. Case where $c_1 = 2$ and $c_2 = 1/2$ (i.e., $\Delta t_t = 2\,\Delta t_R + 1/2\,\Delta t_A \equiv \Delta t_w$)

The temperature difference parameter for this case is selected to apply to a reactor with a symmetrical heat exchanger, that is, a heat exchanger in which the coolant path is geometrically identical with that of the reactor. For this system, except for the effect of temperature on fluid properties, the heat transfer coefficient will be the same in both reactor and exchanger. The mean temperature difference between the heat exchanger tube walls and the coolant will be the same as the temperature drop between the tube wall and coolant in the reactor. Hence Δt_w is approximately the

[redacted]

temperature difference between the hottest point on the tube wall in the reactor and an average temperature of the heat exchanger tube wall. The temperature of this tube wall is the temperature level available for transferring heat from the heat exchanger to the rest of the system. It should be noted that the axial temperature pattern in the heat exchanger tubes depends on how heat is removed from the exchanger and the temperature which is obtained from this analysis is only an intermediate temperature along the length of the wall. This is illustrated in Figure 1.

For $\Delta t_t = 2\,\Delta t_R + 1/2\,\Delta t_A \equiv \Delta t_w$

$$F = \frac{k\,\Delta t_w}{2Dq_t/A_H} = \frac{4\,\Delta t_w k(B_c/B_R)}{2D^2(q_t/B_R)}$$

$$X = L/4D$$

4. Case where $c_1 = 1$ and $c_2 = 0$ (i.e., $\Delta t_t = \Delta t_R$)

The plotted solutions to the general heat transfer equation cannot be used for either $c_1 = 0$ or $c_2 = 0$. However, an explicit solution for either N_{Re} or π_p can be obtained starting from equation (12) or, as shown, from the basic heat transfer relationships

$$q_t = hA_H\,\Delta t_R = h(n\pi DL)\,\Delta t_R \qquad (7)$$

For <u>ordinary fluids</u> the heat transfer coefficient for turbulent flow is given by equation (16a), a rearrangement of equation (16).

$$h = 0.023\,\frac{k}{D}\,N_{Re}^{0.8}\,N_{Pr}^{0.4} \qquad (16a)$$

[redacted]

Substituting equations (5) and (16a) into equation (7) and dividing both sides by B_R.

$$q_t/B_R = 0.092\,\Delta t_R(B_c/B_R)c_p^{0.4}\,\mu^{0.4}\,k^{0.6}\,N_{Re}^{0.8}/D^2 \qquad (18)$$

Solving for the Reynolds number and rearranging yields for <u>ordinary fluids</u>.

$$N_{Re} = \frac{1}{(0.092)^{1.25}}\left[\frac{1}{N_{Pr}^{0.5}\,k^{1.25}}\right]\left[\frac{(q_t/B_R)D^2}{\Delta t_R(B_c/B_R)}\right]^{1.25} \qquad (18a)$$

For <u>liquid metals</u> the heat transfer coefficient for turbulent flow is obtained by solving equation (17) for h.

$$h = \frac{k}{D}\left[7 + 0.025\,N_{Re}^{0.8}\,N_{Pr}^{0.8}\right] \qquad (17a)$$

Substituting equations (5) and (17a) into equation (12), dividing both sides by B_R and solving for the Reynolds number.

$$N_{Re} = \frac{1}{(0.025)^{1.25}}\left[\frac{1}{N_{Pr}}\right]\left[\frac{D^2(q_t/B_R)}{4\,\Delta t_R\,k(B_c/B_R)} - 7\right]^{1.25} \qquad (19)$$

Equations (18a) and (19) can be combined with equation (6a) to yield

<u>For ordinary fluids</u>

$$\pi_p = \frac{1}{(0.092)^{2.5}g_cJ}\left[\frac{\mu^{1.6}}{k^{2.1}\,c_p^{1.4}\rho^2}\right]\left[\frac{D^3(q_t/B_R)^{2.5}}{\Delta t_R^{3.5}(B_c/B_R)^{2.5}}\right] \qquad (20)$$

<u>For liquid metals</u>

$$\pi_p = \frac{0.092}{(0.025)^{3.5}g_cJ}\left[\frac{\mu^{0.2}\,k^{2.8}}{\rho^2\,c_p^{2.8}}\right]\left[\frac{(B_c/B_R)}{D^4(q_t/B_R)}\right]\left[\frac{D^2(q_t/B_R)}{4(B_c/B_R)\,\Delta t_R k} - 7\right]^{3.5} \qquad (21)$$

[redacted]

5. Case where $c_1 = 0$ and $c_2 = 1$ (i.e. $\Delta t_t = \Delta t_A$)

If Δt_A is retained as a parameter, the heat transfer rate is expressed by equation (8), an energy balance on the coolant in passage through the reactor.

$$q_t = V\rho A_c c_p \Delta t_A = V(n\pi D^2/4)\rho c_p \Delta t_A \tag{8}$$

Substituting equation (5) and the definition of the Reynolds number into equation (8)

$$q_t = B_c c_p \mu \Delta t_A N_{Re}/DL \tag{22}$$

Dividing both sides of equation (22) by B_R and solving for the Reynolds number yields the following relationship which applies for <u>all fluids.</u>

$$N_{Re} = \left[\frac{1}{c_p \mu}\right]\left[\frac{LD(q_t/B_R)}{\Delta t_A (B_c/B_R)}\right] \tag{22a}$$

Combining equation (22a) with equation (6a) yields

$$\pi_p = \frac{0.092}{g_c J}\left[\frac{\mu^{0.2}}{\rho^2 c_p^{2.8}}\right]\left[\frac{L^{2.8}\,(q_t/B_R)^{1.8}}{D^{1.2}\,(B_c/B_R)^{1.8}\,\Delta t_A^{2.8}}\right] \tag{23}$$

[redacted]

SOME SPECIFIC REACTOR COOLANT EVALUATIONS

To illustrate the application of the methods of calculation developed in this memorandum, values of the cooling work modulus, π_p, have been calculated and plotted as functions of tube diameter for five possible coolants for an arbitrarily chosen reactor. Calculations were performed for each of four temperature-difference parameters and four plots are presented in Figures 2, 3, 4, and 5.

Reactor Dimensions and Operating Conditions

Length of reactor, L ---------- 2.75 ft.

Diameter of reactor ---------- 3.00 ft.

(Volume of reactor, B_R ---------- 19.44 cu. ft.)

B_c/B_R ---------- 0.30

(Volume of coolant, B_c ---------- 5.83 cu ft.)

Heat removal rate, q_t = 200 MW = ---------- 682.6×10^6 Btu/hr.

(q_t/B_R ---------- 35.1×10^6 Btu/(hr)(cu ft))

Temperature difference parameters (only one can be specified for each case)

Δt_R ---------- 200°F

Δt_A ---------- 200°F

Δt_p ---------- 300°F

Δt_w ---------- 500°F

Mean fluid temperature ---------- 1350°F

[redacted]

[redacted]

Coolant Properties at 1350°F[3]

Coolant	c_p $\frac{Btu}{(lb)(^oF)}$	μ $\frac{lb}{(ft)(hr)}$	k $\frac{Btu}{(hr)(ft)(^oF)}$	ρ $\frac{lb}{cu.ft.}$	N_{Pr}
Bi	0.039	1.98	9.0	593	0.0086
Li	1.0	1.04	22	29.0	0.047
Na	0.30	0.43	34	48.2	0.0038
NaOH	0.49	2.1	0.8	95.0	1.3
NaF-KF-LiF (11.5, 42.0, 46.5 Mole%)	0.45	7.3	2.6	125	1.3

[3] Properties of Liquid Metals from "Liquid-Metals Handbook," 2nd ed., U.S. Government Printing Office, Washington, 1952, p.209.

[redacted]

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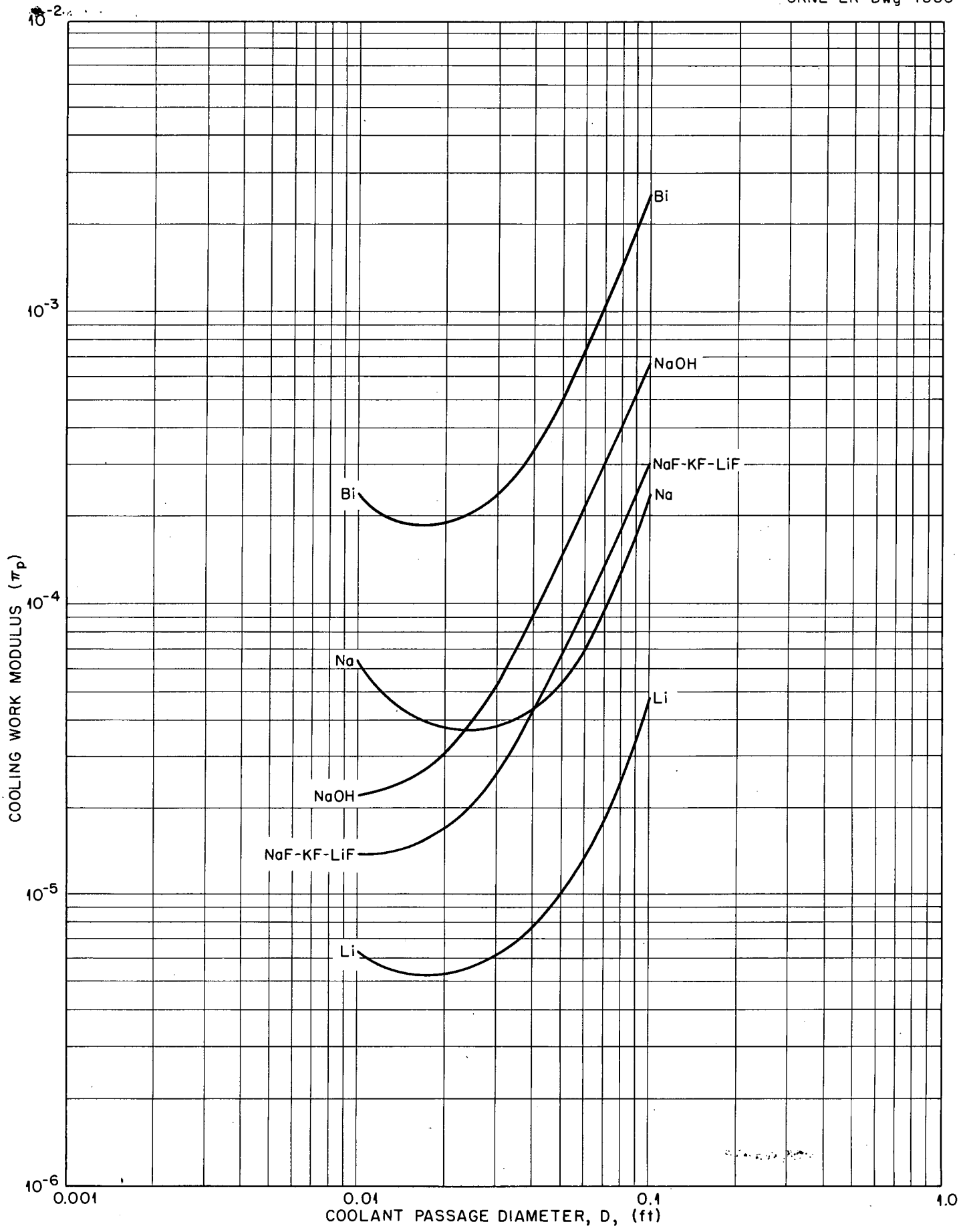

Fig. 2. Case Where $c_1 = 1$ and $c_2 = 1/2$ (i.e., $\Delta t_t = \Delta t_R + 1/2 \Delta t_A \equiv \Delta t_p$) for Reactor Described on Pages 12 and 13.

[redacted]

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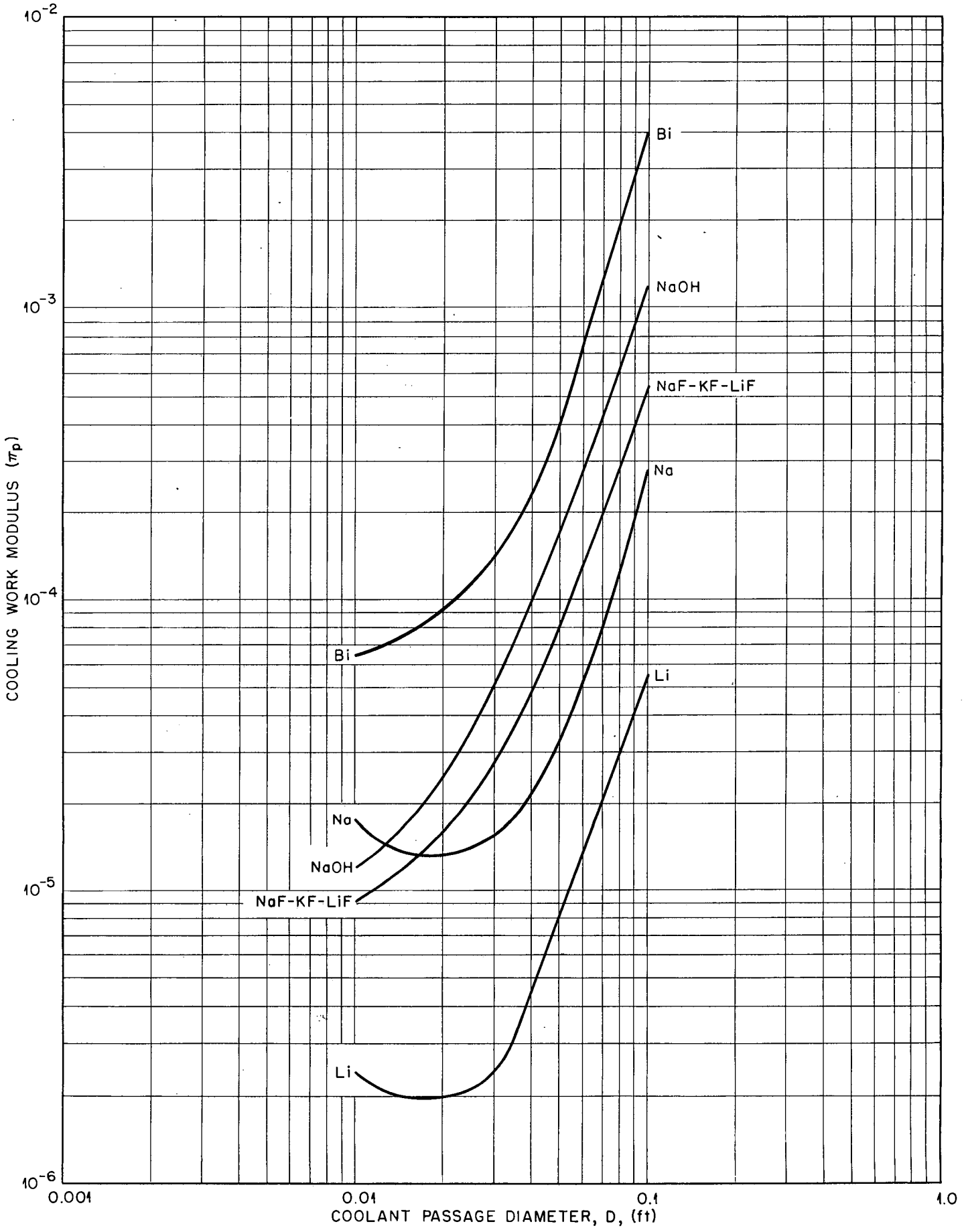

Fig. 3. Case Where $c_1 = 2$ and $c_2 = 1/2$ (i.e., $\Delta t_t = 2\Delta_R + 1/2\ \Delta t_A \equiv \Delta t_w$) for Reactor Described on Pages 12 and 13.

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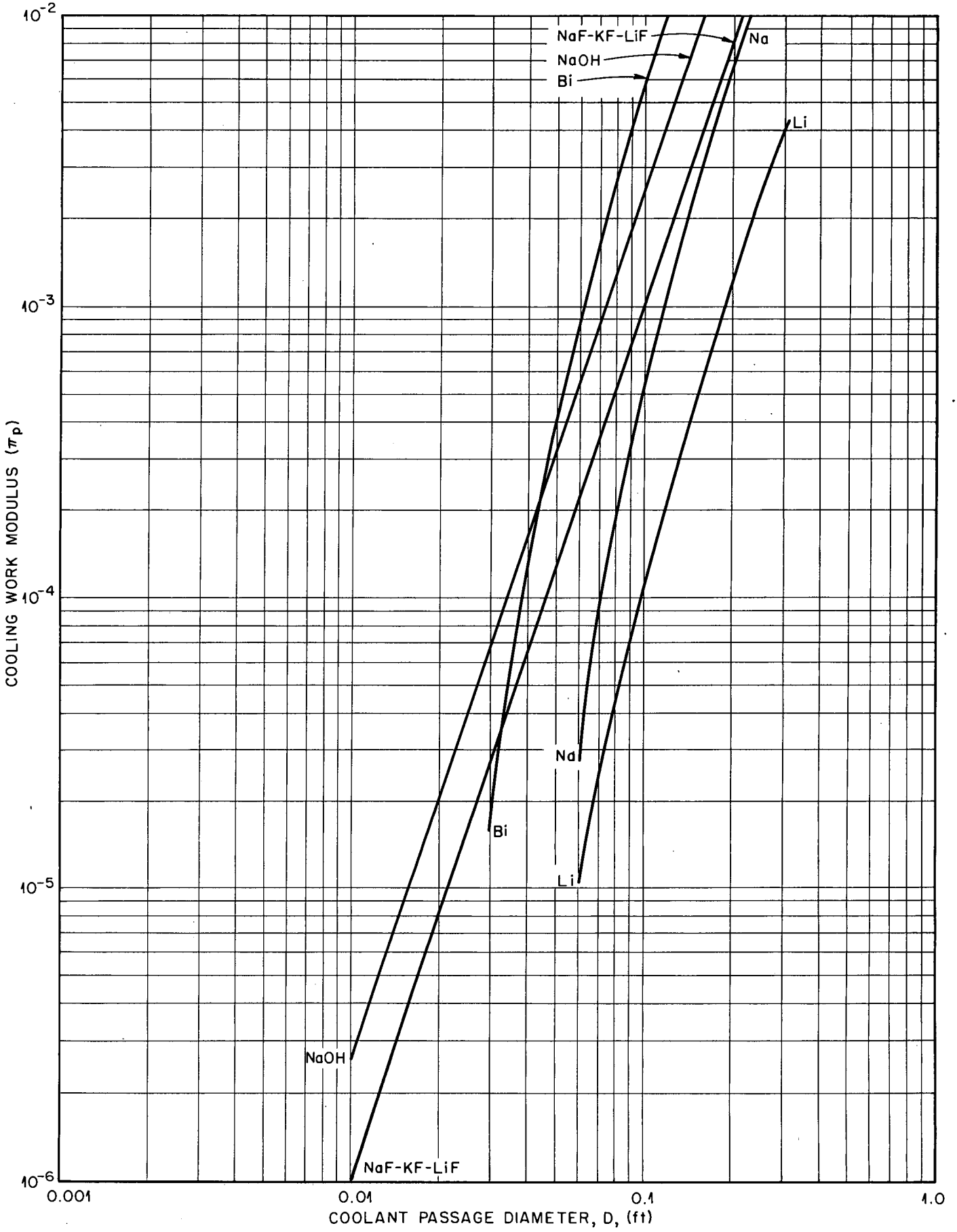

Fig. 4. Case Where $c_1 = 1$ and $c_2 = 0$ (i.e., $\Delta t_f = \Delta t_R$) for Reactor Described on Pages 12 and 13.

[redacted]

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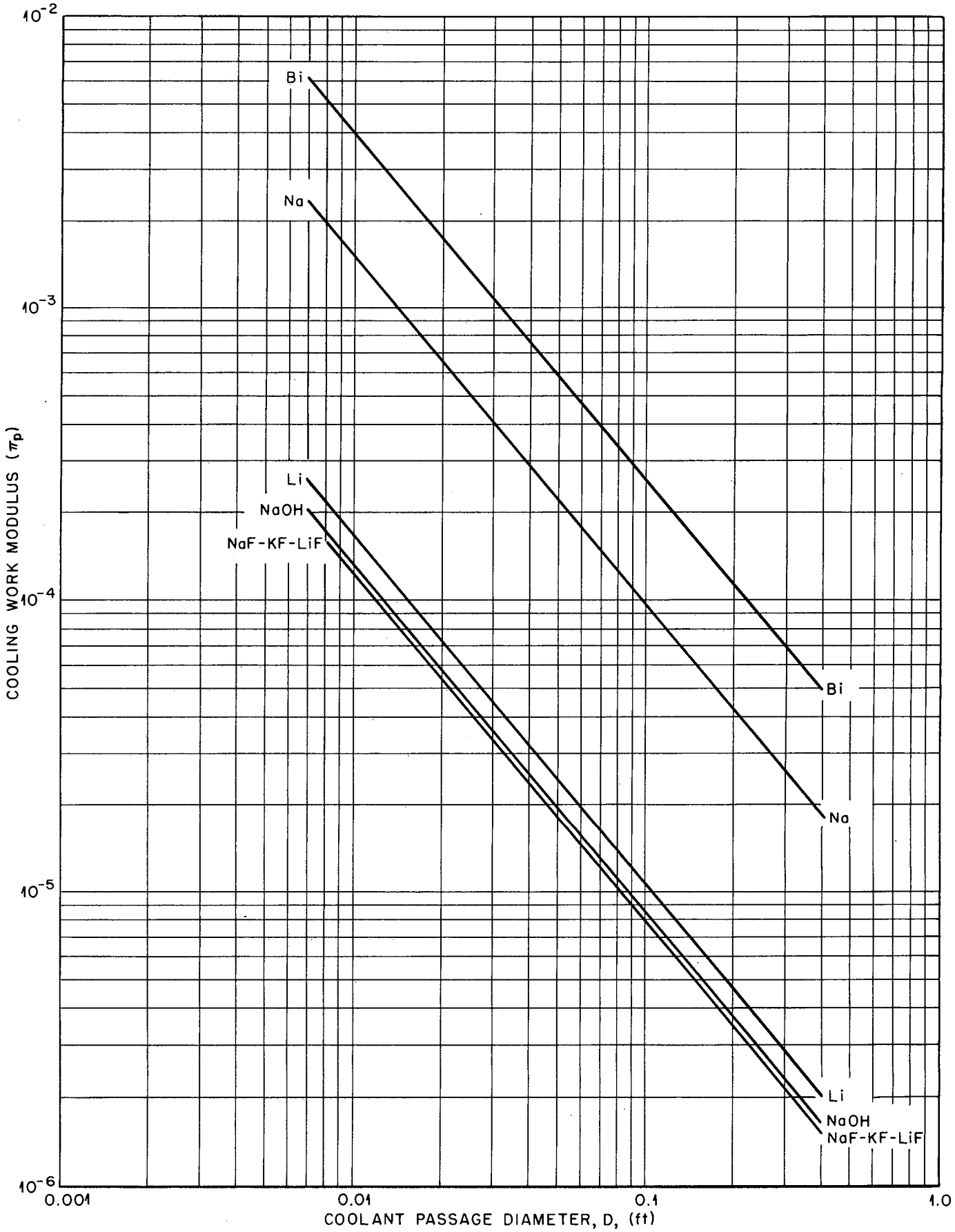

Fig. 5. Case Where $c_1 = 0$ and $c_2 = 1$ (i.e., $\Delta t_f = \Delta t_A$) for Reactor Described on Pages 12 and 13.

DISCUSSION

The cooling work moduli for five different reactor coolants are plotted in Figures 2, 3, 4, and 5 for four specific temperature difference parameters and over a range of pipe diameters. The following observations are based on these curves and on the equations from which they were obtained:

Δt_R Constant. If the radial temperature difference, Δ_R, is set equal to a constant as in Figure 4, π_p increases with increase in pipe diameter and viscosity and decreases with increase in thermal conductivity, density and heat capacity (see equations 20 and 21). For this case the light liquid metals are better coolants than ordinary fluids because these metals have low viscosities and high thermal conductivities.

Δt_A Constant. If the axial temperature difference, Δt_A, is set equal to a constant as in Figure 5, π_p decreases with increase in pipe diameter, density and heat capacity and increases slowly with viscosity (see equation 23). For this case those ordinary fluids having high thermal capacities per unit volume (the product of specific heat and density) are better coolants than the liquid metals because the metals have low thermal capacities per unit volume.

General Case. The case where a total temperature difference, $\Delta t_t (= c_1 \Delta t_R + c_2 \Delta t_A)$, is fixed is a composite of the two specific cases discussed above; the radial and axial temperature-difference

solutions represent the asymptotic solutions for the general case in the large and small cooling passage diameter regions, respectively. Note that minima exist in the π_p vs. D. curves for the general case. Figures 2 and 3 are examples of cases for which neither c_1 nor c_2 equals zero.

For the specific examples considered here the cooling work moduli fell in the range $10^{-6} < \pi_p < 10^{-1}$, meaning that the amount of flow work per unit time (pumping power) required to extract the heat generated in the reactor ranged from 0.0001% to 10% depending on the type of coolant, pipe diameter, and temperature difference parameter stipulated. All of the physical properties of a coolant influence its effectiveness in transferring heat from the reactor. An ideal coolant would be one that had a high thermal conductivity, heat capacity, and density and a low viscosity.

Because of their low densities and thermal conductivities gases yield very high values of the cooling work modulus. Calculations performed for helium reveal that for the reactor discussed above the cooling work moduli are of the order of 10^3 to 10^7, much higher than for any liquid considered.

The analysis presented in this memorandum is limited to the conditions of the postulates stated on page 4. The same type of derivation can be performed for different postulates by changing the basic equations. For example, if it were desirable to maintain the weight of coolant constant rather than the volume, allowance could be made for this by alteration of equation 5, and the rest of the analysis carried out as before. Other changes can likewise be made in this manner.

Figs. 6-22

The following curves are solutions to the pair of simultaneous equations 12b and 16 for ordinary fluids ($N_{Pr} \geqq 0.5$), and the pair 12b and 17 for liquid metals ($N_{Pr} < 0.5$).

$$F \equiv \frac{k\,\Delta t_t}{c_1 D q_t / A_H} = \frac{4\,\Delta t_t\; k(B_c/B_R)}{c_1 D^2 (q_t/B_R)}$$

$$X \equiv \frac{c_2}{c_1}\left(\frac{L}{D}\right)$$

$$N_{Re} \equiv \frac{DV\rho}{\mu}$$

$$P \equiv \frac{c_p \mu}{k}$$

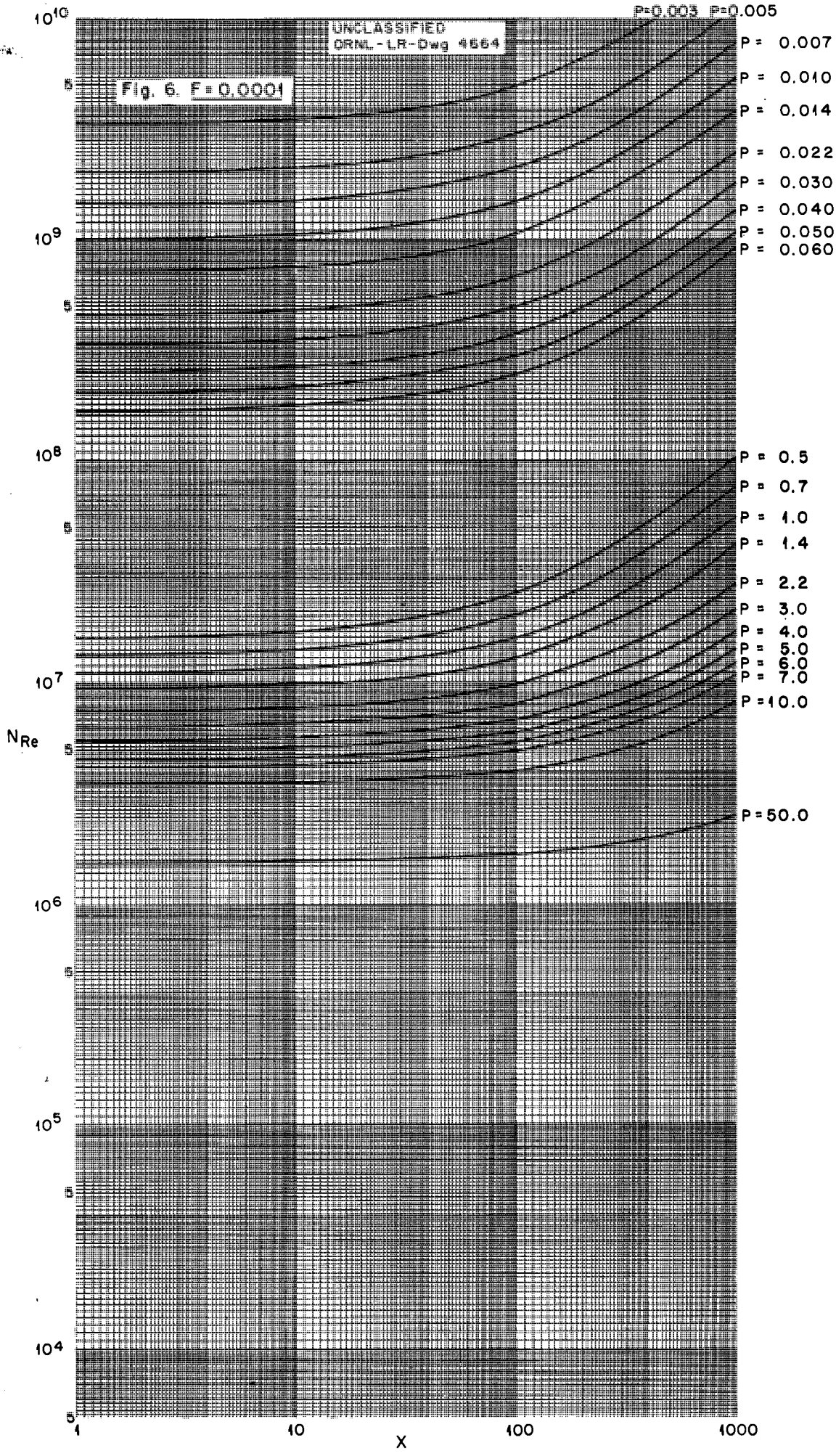
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Fig. 6. F = 0.0001
P=0.003
P=0.005
P = 0.007
P = 0.010
P = 0.014
P = 0.022
P = 0.030
P = 0.040
P = 0.050
P = 0.060
P = 0.5
P = 0.7
P = 1.0
P = 1.4
P = 2.2
P = 3.0
P = 4.0
P = 5.0
P = 6.0
P = 7.0
P = 10.0
P = 50.0
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
N_{Re}
1
10
100
1000
X

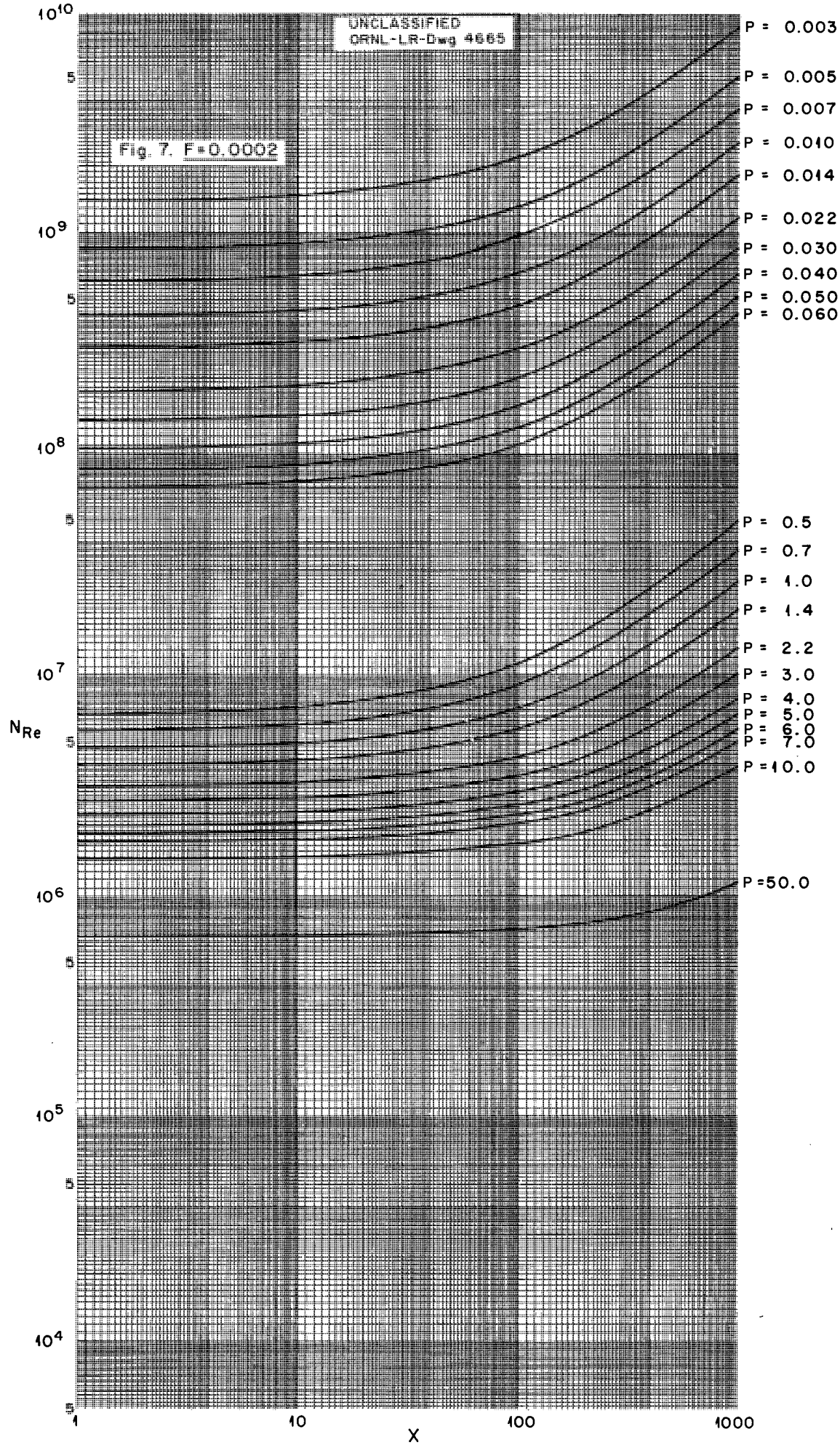
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Fig. 7. F=0.0002
P = 0.003
P = 0.005
P = 0.007
P = 0.010
P = 0.014
P = 0.022
P = 0.030
P = 0.040
P = 0.050
P = 0.060
P = 0.5
P = 0.7
P = 1.0
P = 1.4
P = 2.2
P = 3.0
P = 4.0
P = 5.0
P = 6.0
P = 7.0
P =10.0
P =50.0
10^{10}
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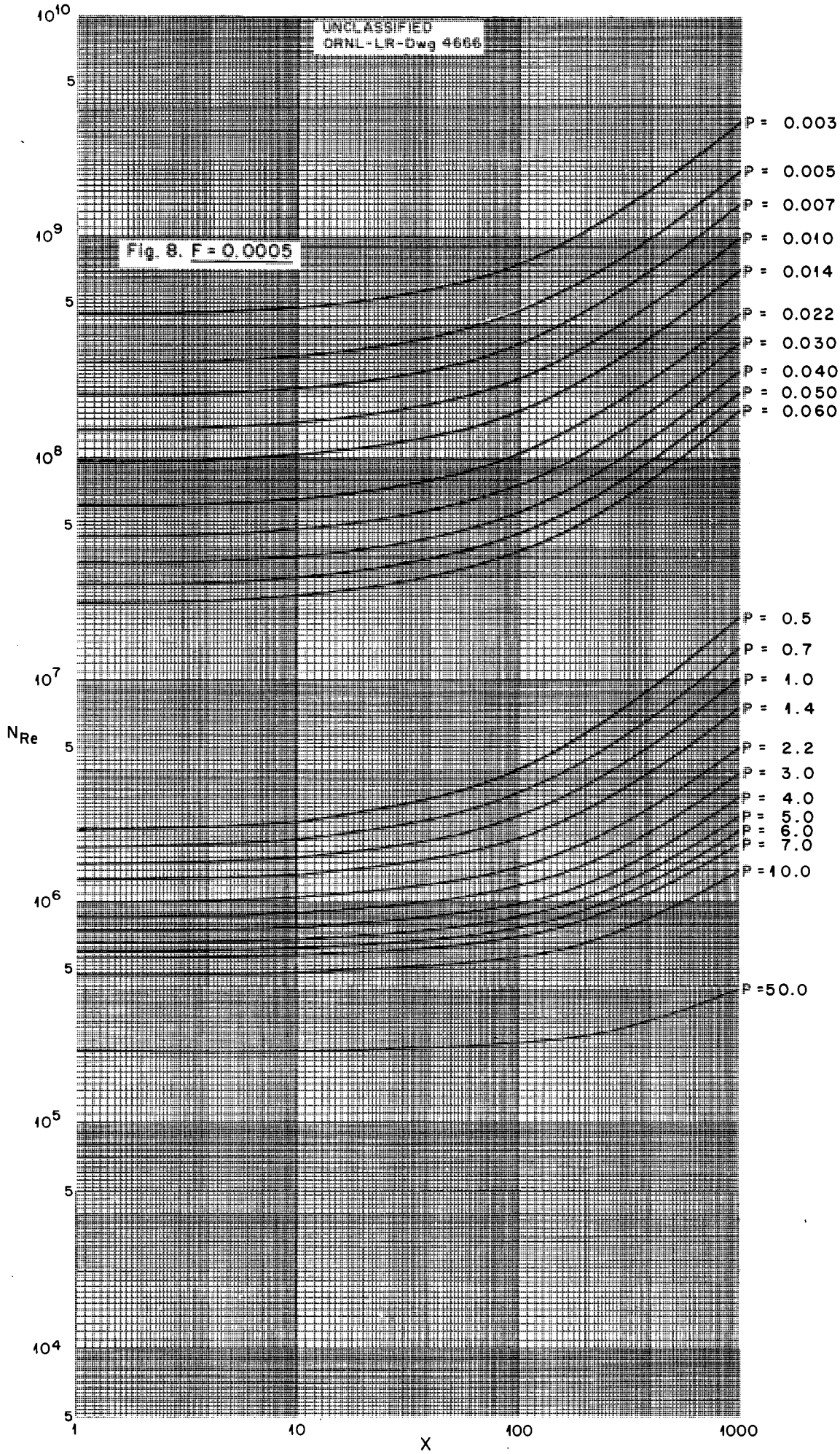
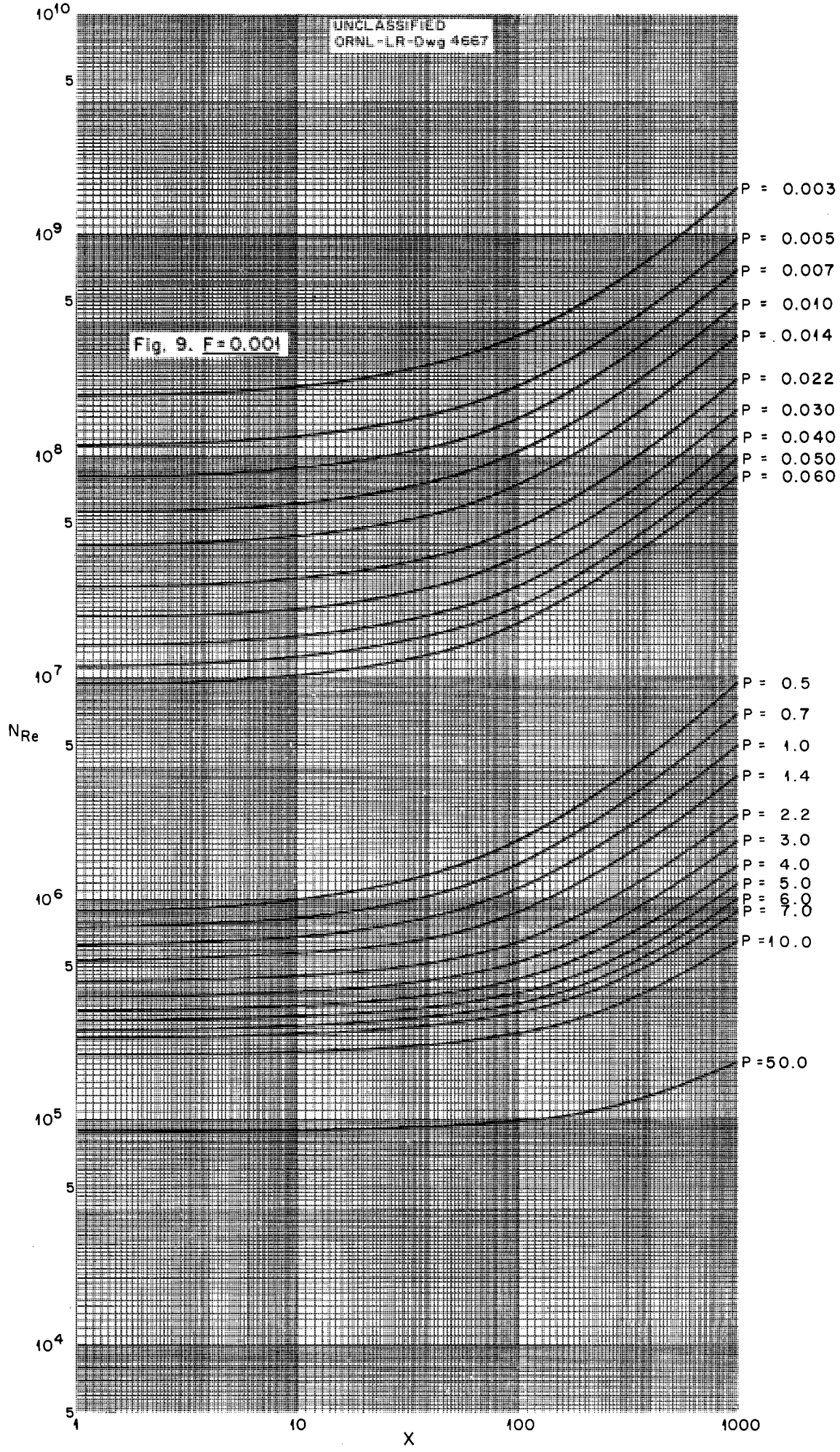
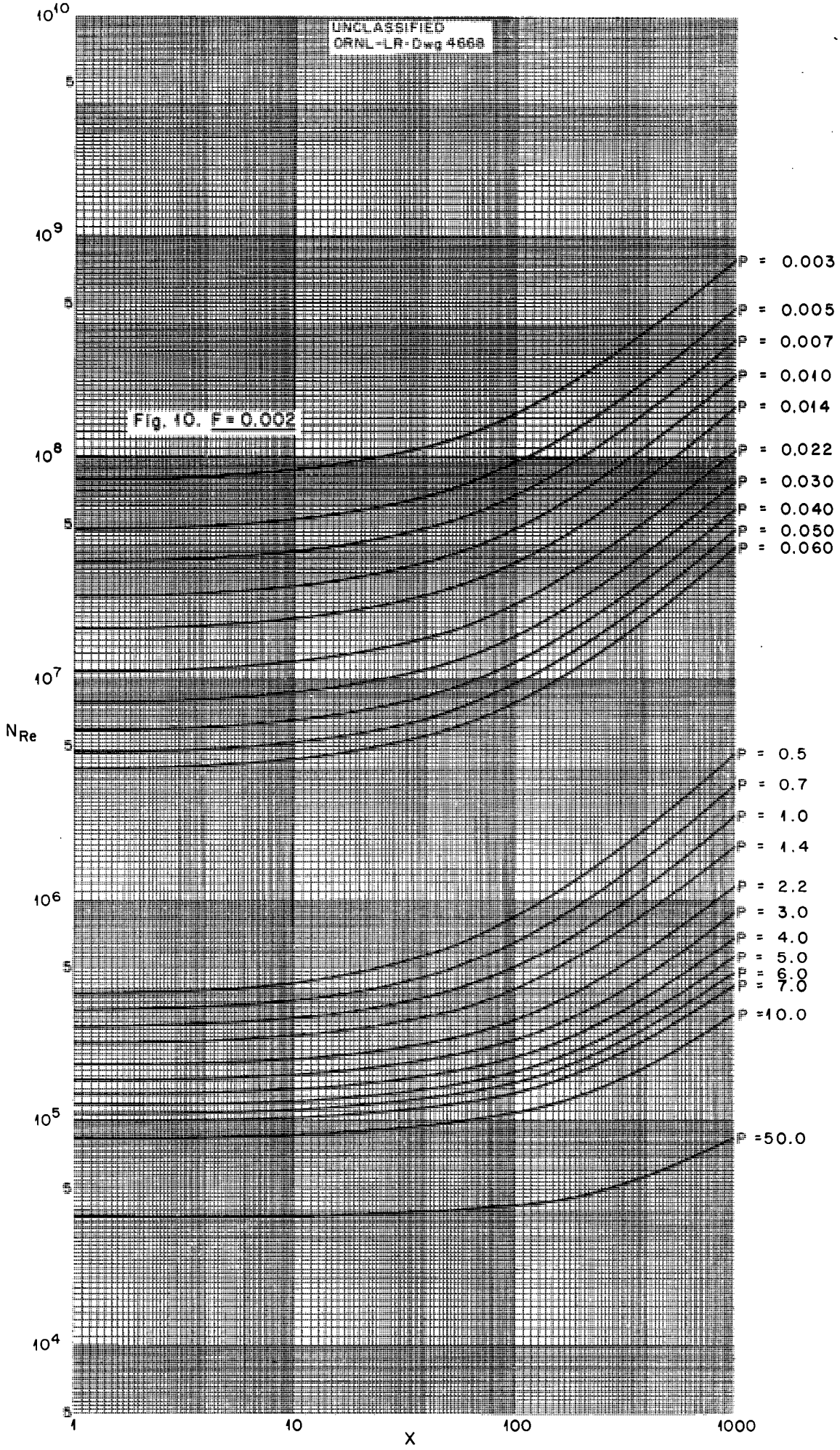
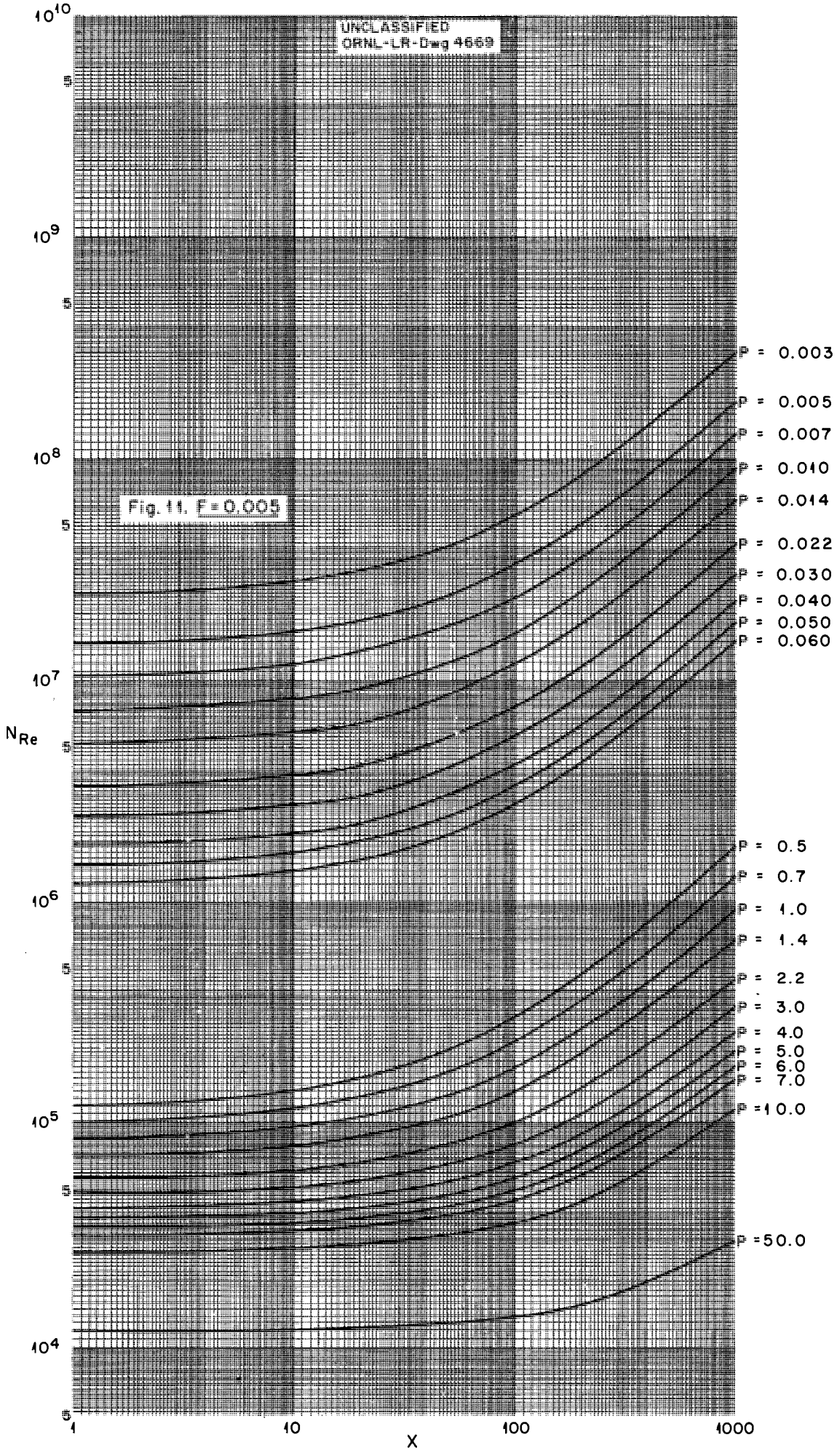
10^{5}
10^{4}
N_{Re}
1
10
100
1000
X


UNCLASSIFIED
ORNL-LR-Dwg 4666
Fig. 8. F = 0.0005
P = 0.003
P = 0.005
P = 0.007
P = 0.010
P = 0.014
P = 0.022
P = 0.030
P = 0.040
P = 0.050
P = 0.060
P = 0.5
P = 0.7
P = 1.0
P = 1.4
P = 2.2
P = 3.0
P = 4.0
P = 5.0
P = 6.0
P = 7.0
P = 10.0
P = 50.0
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
5
N_{Re}
1
10
100
1000
X


UNCLASSIFIED
ORNL-LR-Dwg 4667
Fig. 9. F = 0.001
P = 0.003
P = 0.005
P = 0.007
P = 0.010
P = 0.014
P = 0.022
P = 0.030
P = 0.040
P = 0.050
P = 0.060
P = 0.5
P = 0.7
P = 1.0
P = 1.4
P = 2.2
P = 3.0
P = 4.0
P = 5.0
P = 6.0
P = 7.0
P = 10.0
P = 50.0
N_{Re}
X
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
5
1
10
100
1000


UNCLASSIFIED
ORNL-LR-Dwg 4668
Fig. 10. F = 0.002
P = 0.003
P = 0.005
P = 0.007
P = 0.010
P = 0.014
P = 0.022
P = 0.030
P = 0.040
P = 0.050
P = 0.060
P = 0.5
P = 0.7
P = 1.0
P = 1.4
P = 2.2
P = 3.0
P = 4.0
P = 5.0
P = 6.0
P = 7.0
P = 10.0
P = 50.0
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
N_{Re}
1
10
100
1000
X


UNCLASSIFIED
ORNL-LR-Dwg 4669
Fig. 11. F = 0.005
N_{Re}
X
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
1
10
100
1000
P = 0.003
P = 0.005
P = 0.007
P = 0.010
P = 0.014
P = 0.022
P = 0.030
P = 0.040
P = 0.050
P = 0.060
P = 0.5
P = 0.7
P = 1.0
P = 1.4
P = 2.2
P = 3.0
P = 4.0
P = 5.0
P = 6.0
P = 7.0
P = 10.0
P = 50.0

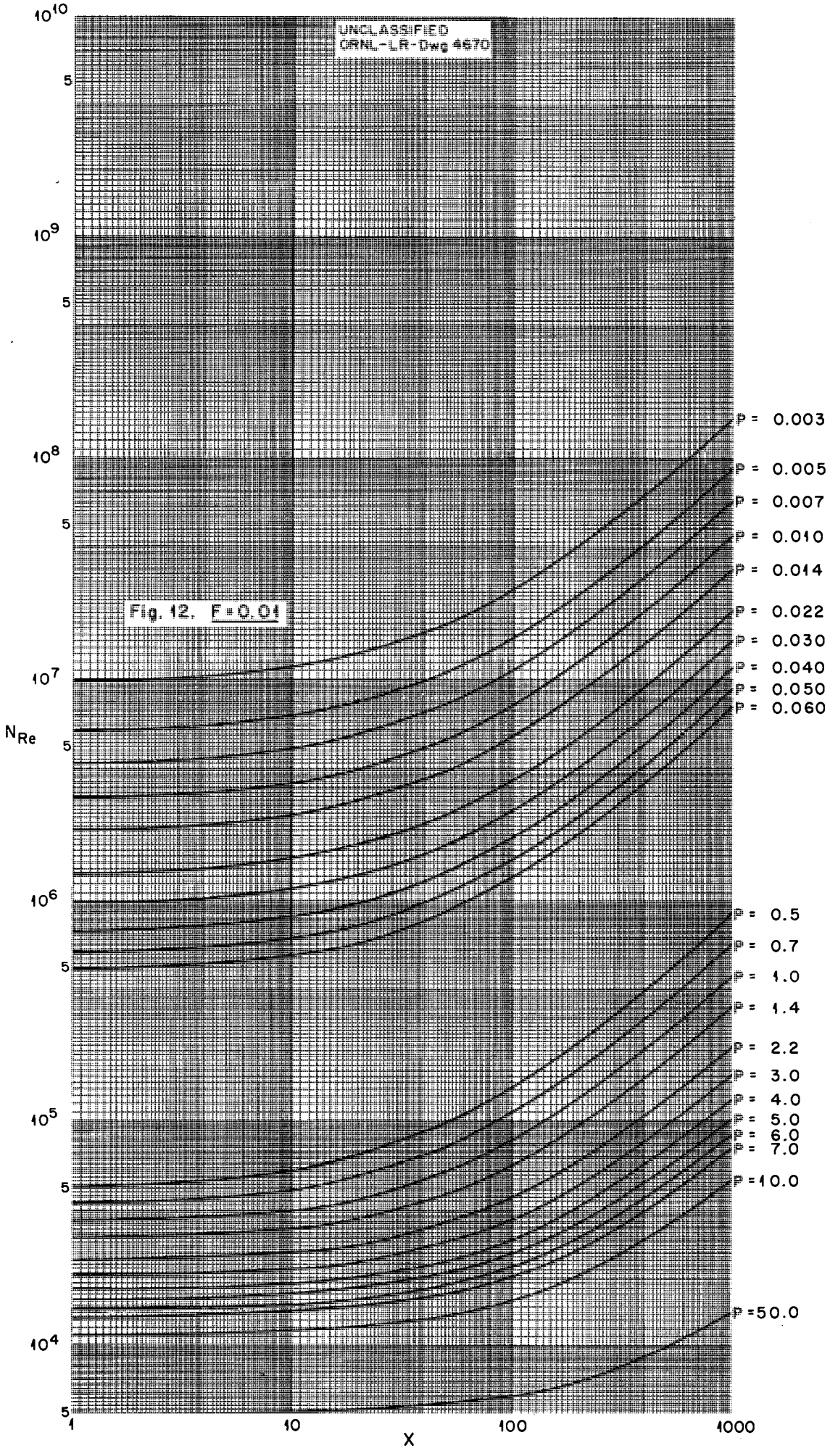

UNCLASSIFIED
ORNL-LR-Dwg 4670
10^{10}
5
10^9
5
10^8
5
10^7
5
10^6
5
10^5
5
10^4
5
N_{Re}
1
10
100
1000
X
P = 0.003
P = 0.005
P = 0.007
P = 0.010
P = 0.014
P = 0.022
P = 0.030
P = 0.040
P = 0.050
P = 0.060
P = 0.5
P = 0.7
P = 1.0
P = 1.4
P = 2.2
P = 3.0
P = 4.0
P = 5.0
P = 6.0
P = 7.0
P = 10.0
P = 50.0

Fig. 12. F = 0.01

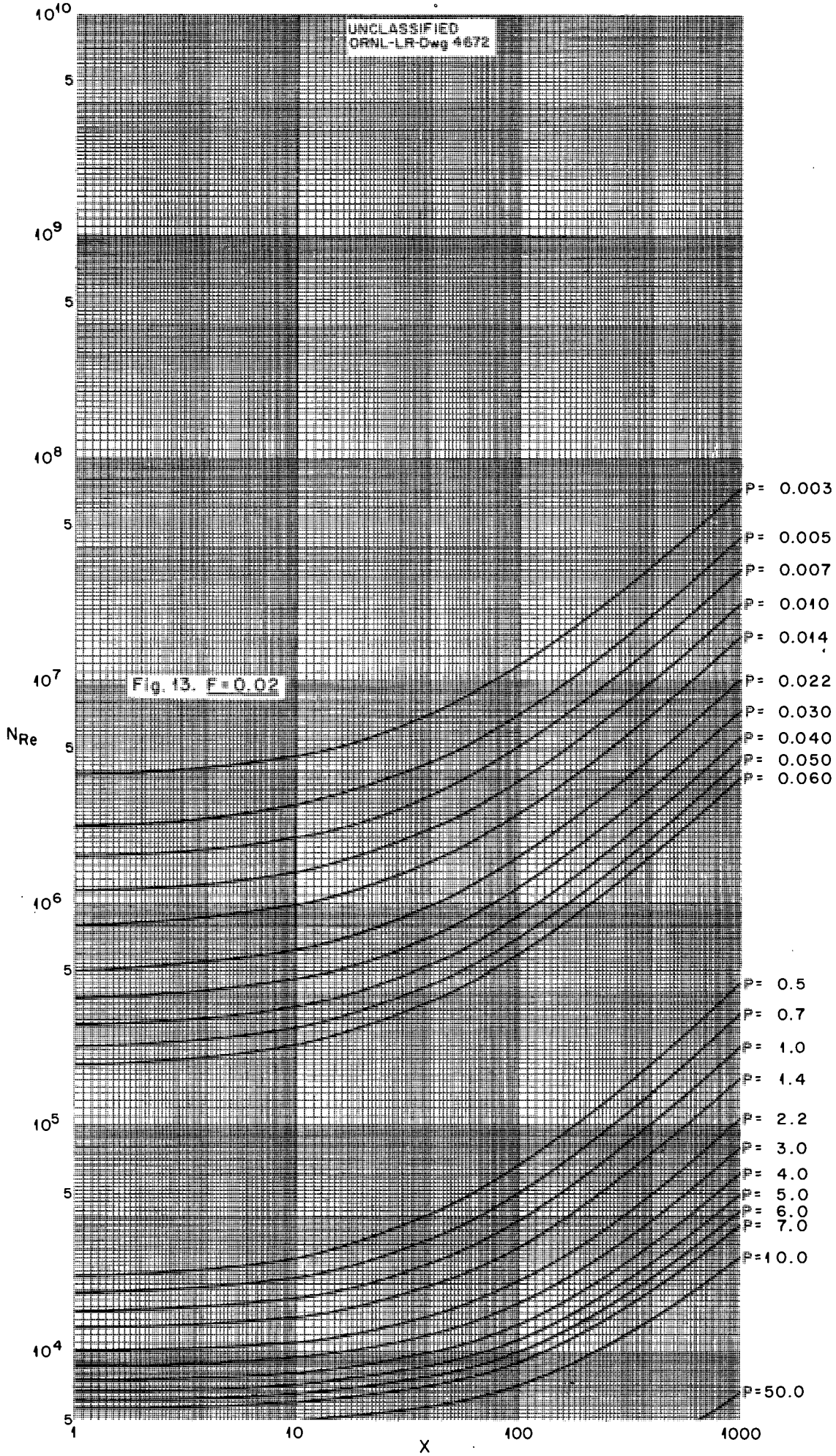

UNCLASSIFIED
ORNL-LR-Dwg 4672
10^{10}
5
10^9
5
10^8
5
10^7
5
10^6
5
10^5
5
10^4
5
N_{Re}
1
10
100
1000
X
P= 0.003
P= 0.005
P= 0.007
P= 0.010
P= 0.014
P= 0.022
P= 0.030
P= 0.040
P= 0.050
P= 0.060
P= 0.5
P= 0.7
P= 1.0
P= 1.4
P= 2.2
P= 3.0
P= 4.0
P= 5.0
P= 6.0
P= 7.0
P=10.0
P=50.0

Fig. 13. F = 0.02

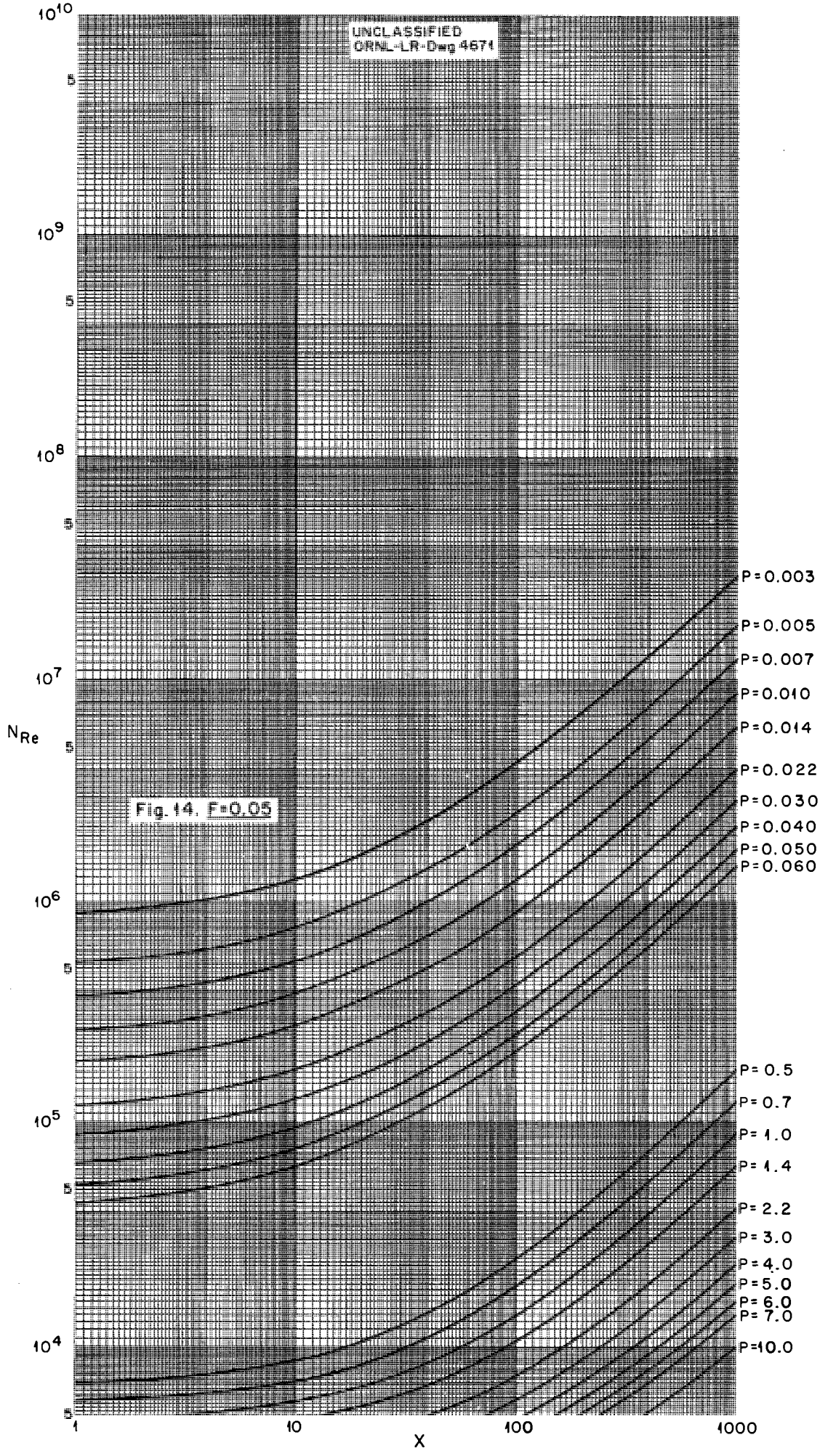

UNCLASSIFIED
ORNL-LR-Dwg 4671
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
N_{Re}
1
10
100
1000
X
P=0.003
P=0.005
P=0.007
P=0.010
P=0.014
P=0.022
P=0.030
P=0.040
P=0.050
P=0.060
P= 0.5
P= 0.7
P= 1.0
P= 1.4
P= 2.2
P= 3.0
P= 4.0
P= 5.0
P= 6.0
P= 7.0
P=10.0

Fig. 14. F=0.05

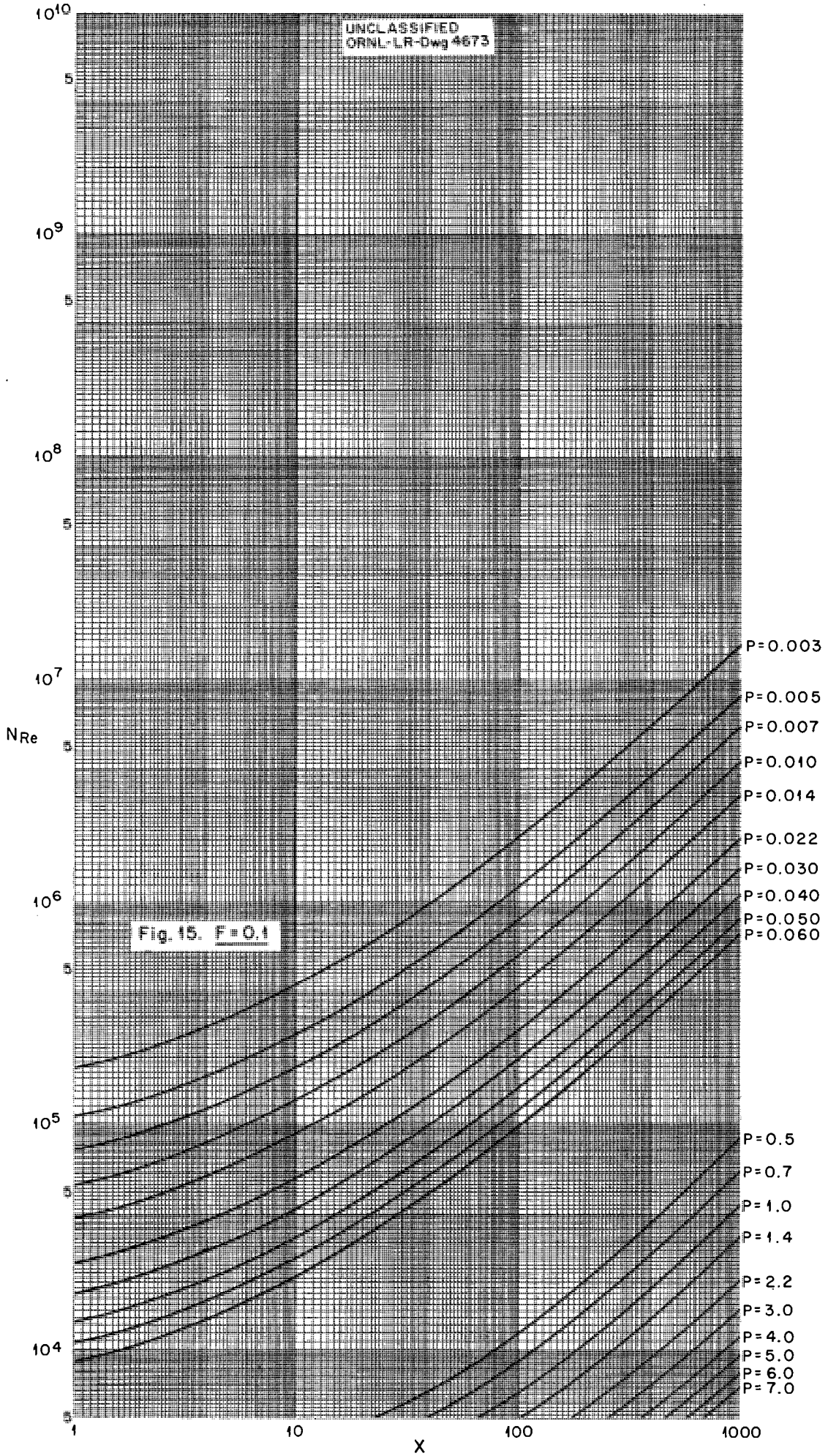

UNCLASSIFIED
ORNL-LR-Dwg 4673
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
N_{Re}
1
10
100
1000
X
P=0.003
P=0.005
P=0.007
P=0.010
P=0.014
P=0.022
P=0.030
P=0.040
P=0.050
P=0.060
P=0.5
P=0.7
P=1.0
P=1.4
P=2.2
P=3.0
P=4.0
P=5.0
P=6.0
P=7.0

Fig. 15. F = 0.1

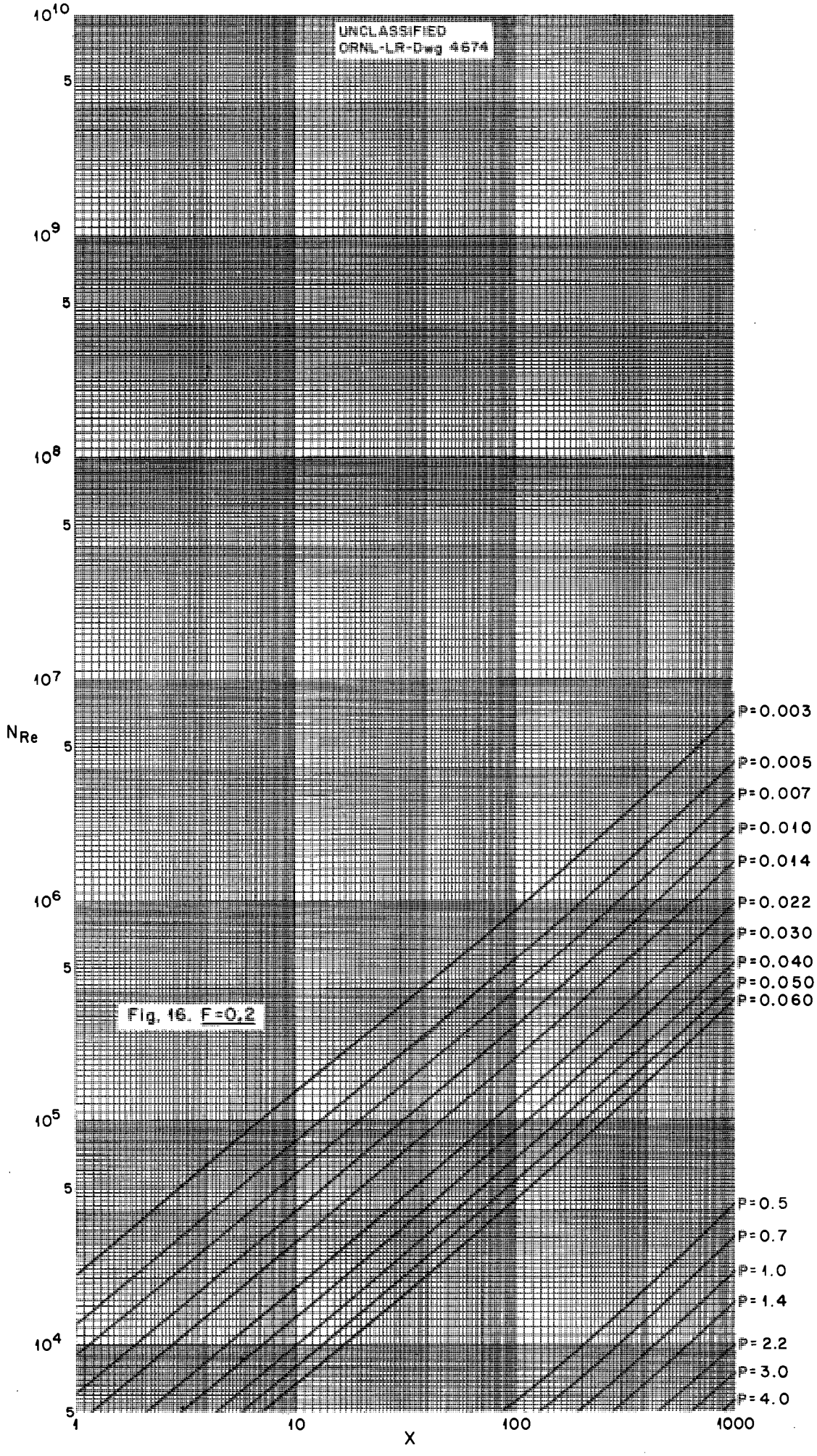

UNCLASSIFIED
ORNL-LR-Dwg 4674
10^{10}
5
10^9
5
10^8
5
10^7
5
10^6
5
10^5
5
10^4
5
N_{Re}
1
10
100
1000
X
P = 0.003
P = 0.005
P = 0.007
P = 0.010
P = 0.014
P = 0.022
P = 0.030
P = 0.040
P = 0.050
P = 0.060
P = 0.5
P = 0.7
P = 1.0
P = 1.4
P = 2.2
P = 3.0
P = 4.0

Fig. 16. F=0.2

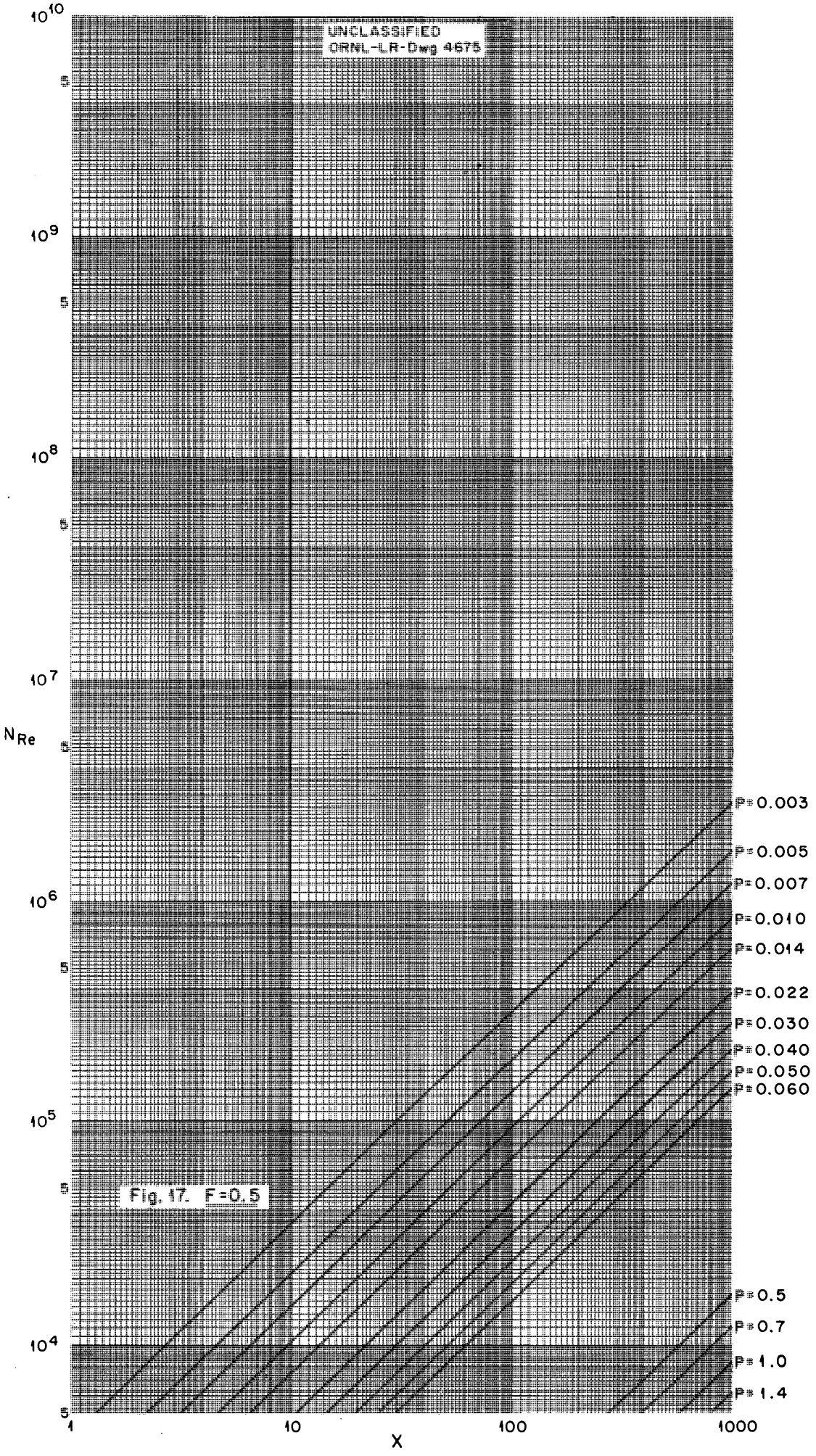

UNCLASSIFIED
ORNL-LR-Dwg 4675
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
N_{Re}
P=0.003
P=0.005
P=0.007
P=0.010
P=0.014
P=0.022
P=0.030
P=0.040
P=0.050
P=0.060
P=0.5
P=0.7
P=1.0
P=1.4
1
10
100
1000
X

Fig. 17. F=0.5

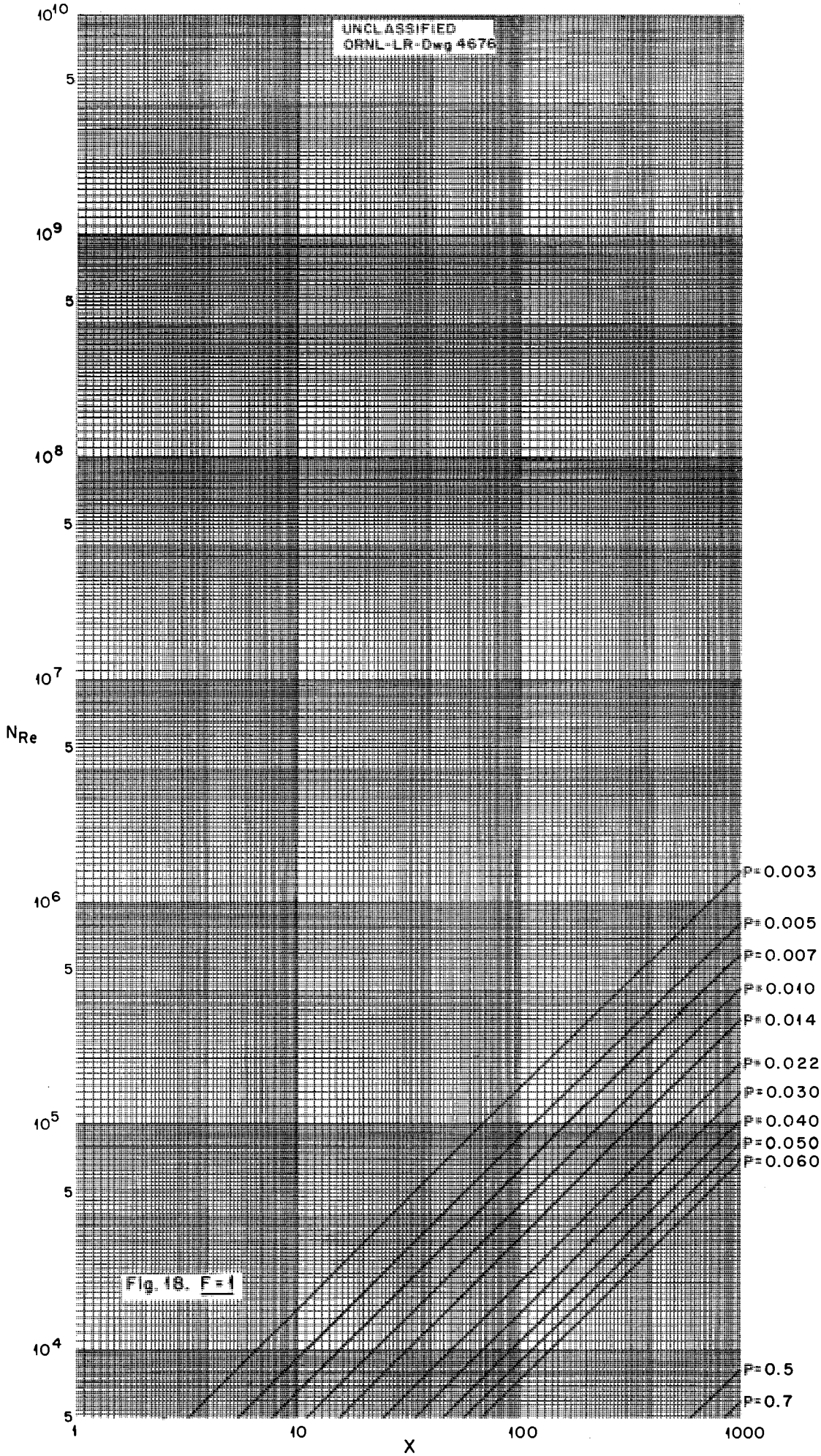

UNCLASSIFIED
ORNL-LR-Dwg 4676
10^{10}
5
10^9
5
10^8
5
10^7
N_{Re}
5
10^6
5
10^5
5
10^4
5
1
10
100
1000
X
P=0.003
P=0.005
P=0.007
P=0.010
P=0.014
P=0.022
P=0.030
P=0.040
P=0.050
P=0.060
P=0.5
P=0.7

Fig. 18. F=1

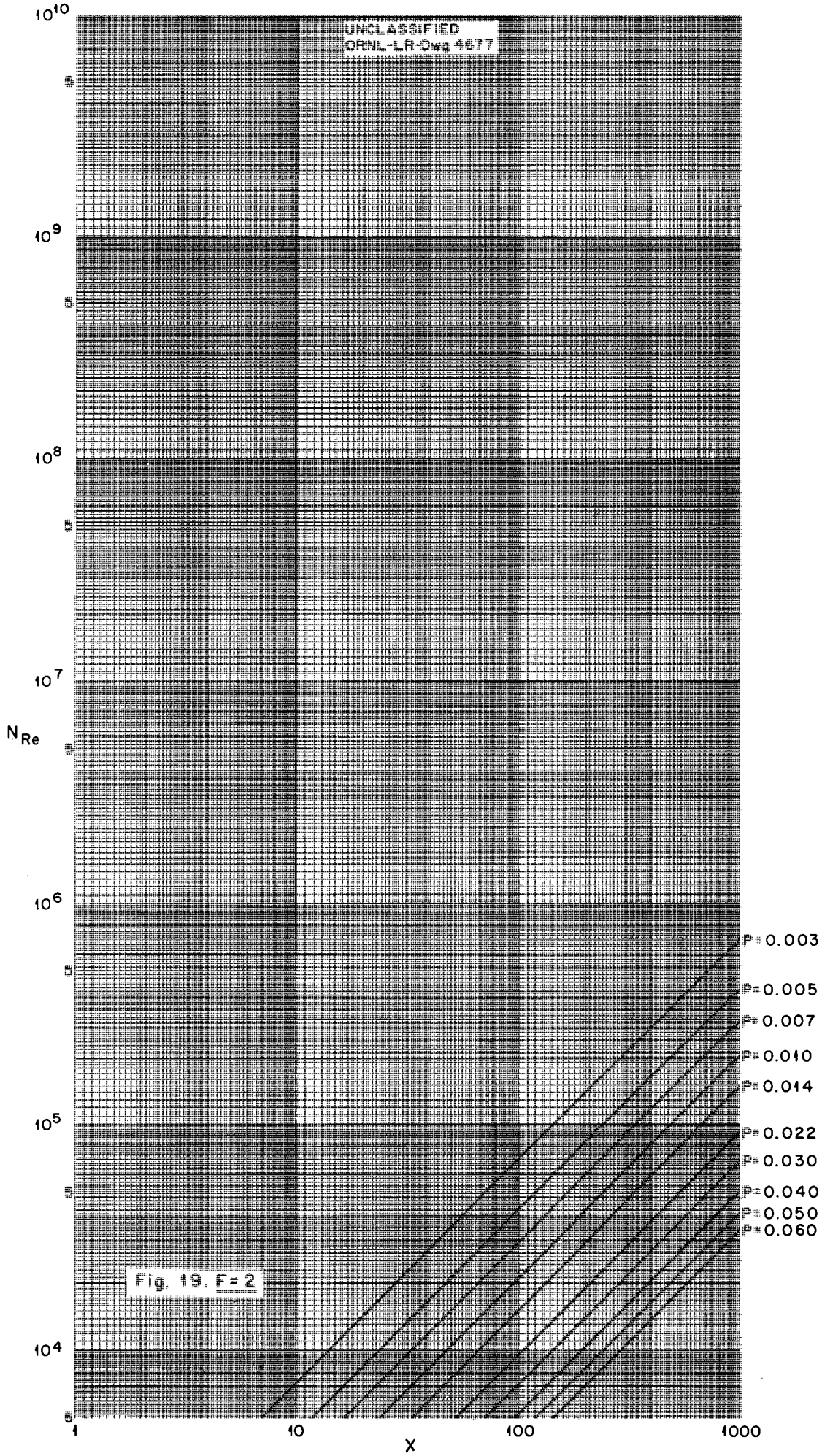

UNCLASSIFIED
ORNL-LR-Dwg 4677
10^{10}
10^{9}
10^{8}
10^{7}
N_{Re}
10^{6}
10^{5}
10^{4}
1
10
100
1000
X
P=0.003
P=0.005
P=0.007
P=0.010
P=0.014
P=0.022
P=0.030
P=0.040
P=0.050
P=0.060

Fig. 19. F=2

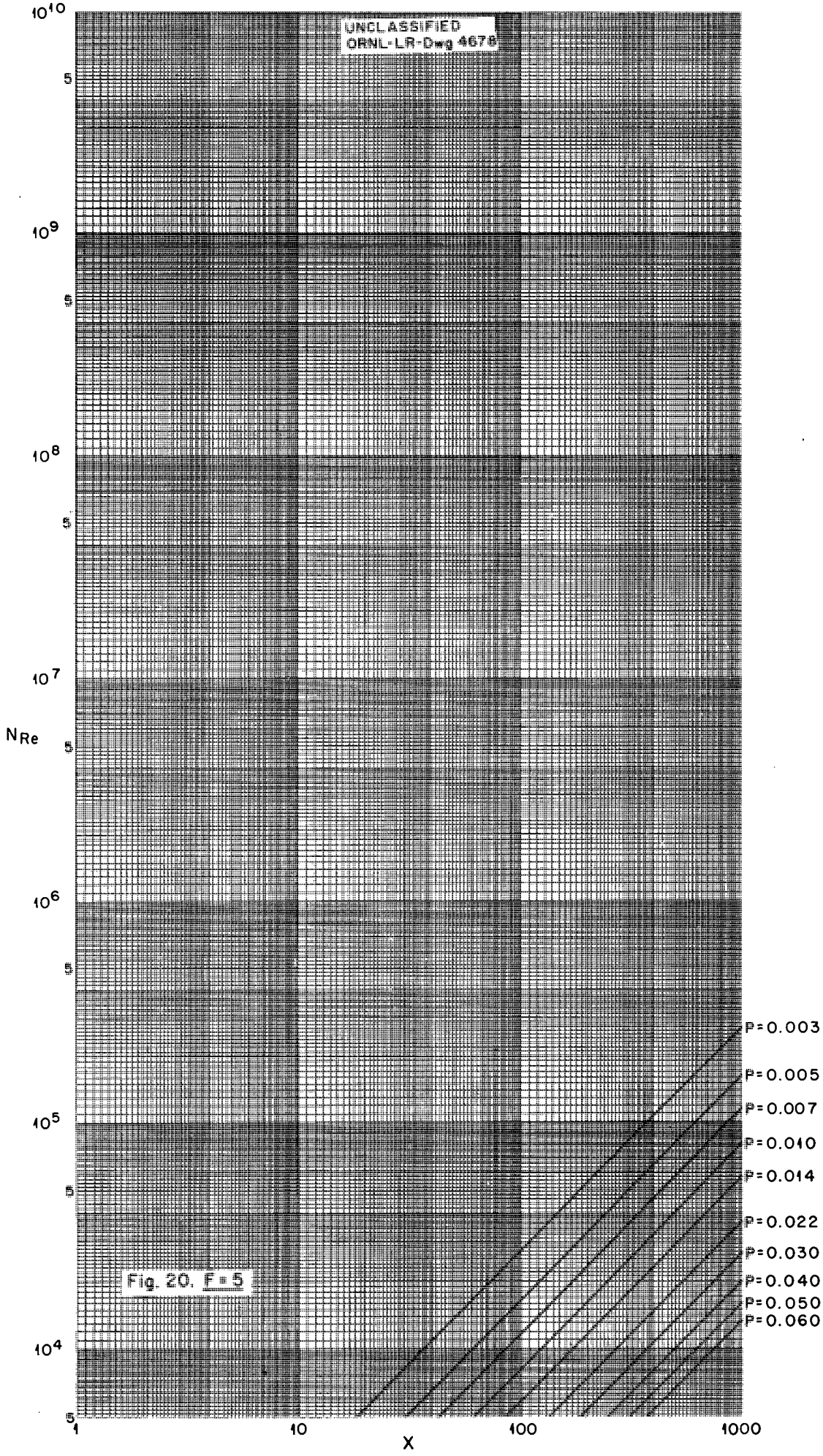

UNCLASSIFIED
ORNL-LR-Dwg 4678
10^{10}
5
10^9
5
10^8
5
10^7
N_{Re}
5
10^6
5
10^5
5
10^4
5
1
10
100
1000
X
P=0.003
P=0.005
P=0.007
P=0.010
P=0.014
P=0.022
P=0.030
P=0.040
P=0.050
P=0.060

Fig. 20. F=5

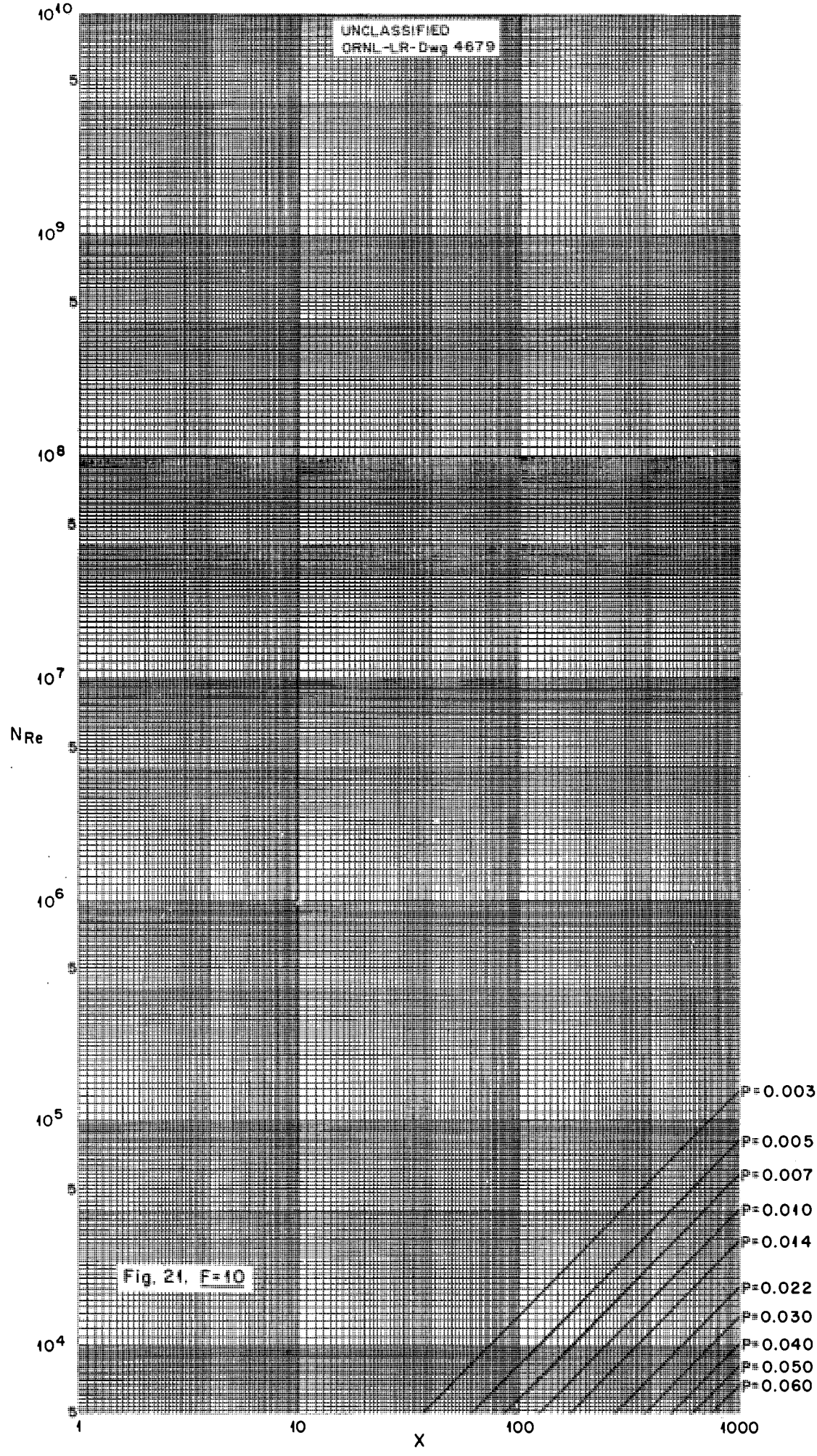

UNCLASSIFIED
ORNL-LR-Dwg 4679
10^{10}
5
10^9
5
10^8
5
10^7
N_{Re}
5
10^6
5
10^5
5
10^4
5
1
10
100
1000
X
P=0.003
P=0.005
P=0.007
P=0.010
P=0.014
P=0.022
P=0.030
P=0.040
P=0.050
P=0.060

Fig. 21. F=10

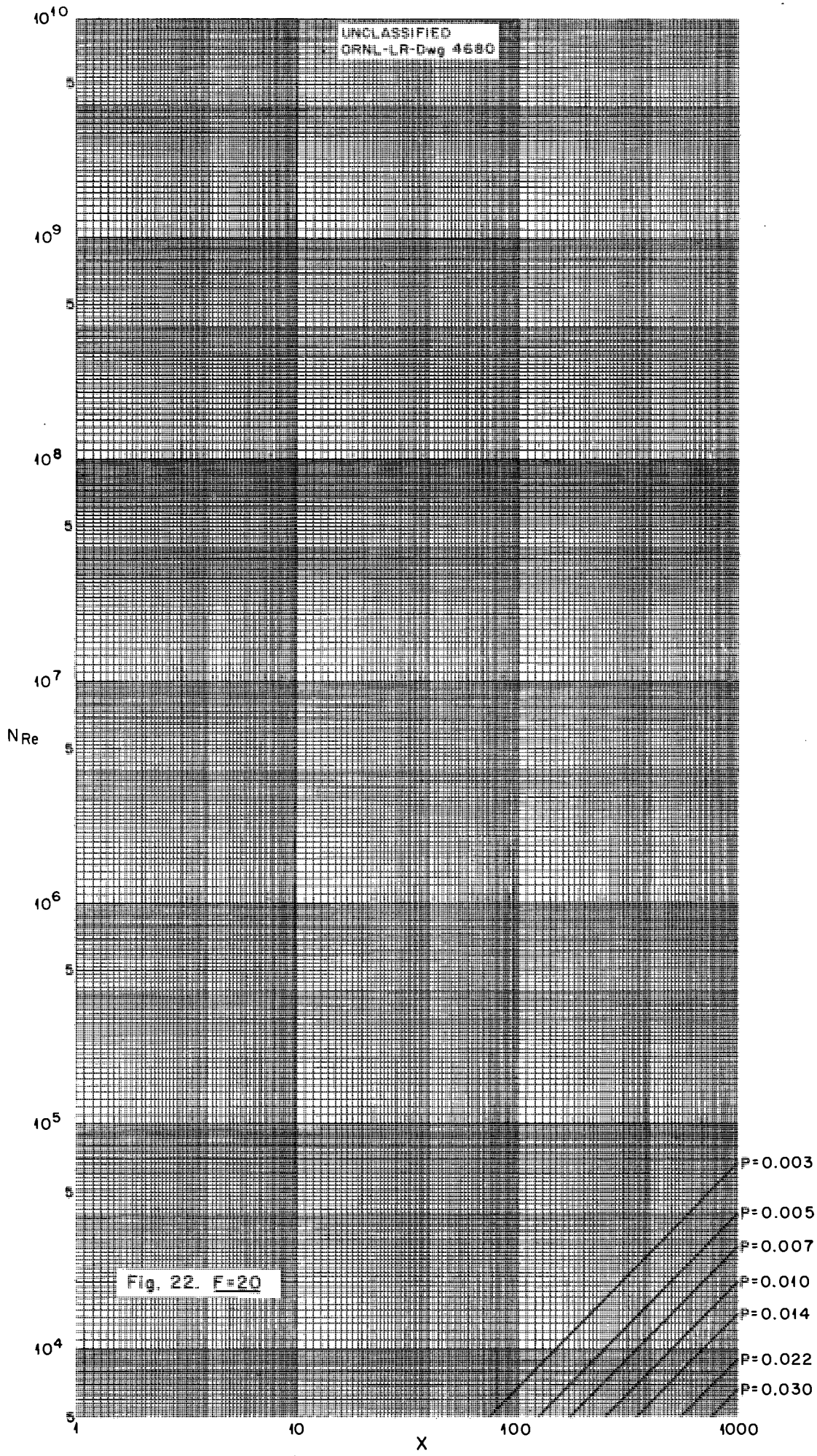

UNCLASSIFIED
ORNL-LR-Dwg 4680
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
N_{Re}
1
10
100
1000
X
P=0.003
P=0.005
P=0.007
P=0.010
P=0.014
P=0.022
P=0.030

Fig. 22. F=20

NOMENCLATURE

A_c	Total cross-sectional area of flow passages through reactor, square feet.
A_H	Total heat transfer surface in reactor, square feet.
B_c	Volume of coolant in reactor, cubic feet.
B_R	Volume of reactor (including coolant), cubic feet.
c_1, c_2	Constants in equation 10.
c_p	Specific heat of fluid, Btu/(lb)(^oF).
D	Diameter of coolant passages in reactor, feet.
F	Dimensionless parameter defined by equation 13.
f	Friction factor defined in equation 2.
g_c	Conversion factor, 4.17×10^8 (lb mass)(ft)/(hr)^2 (lb force).
h	Heat transfer coefficient, Btu/(hr)(sq ft)(^oF)
J	Conversion factor, 778.2 ft-lb/Btu.
k	Thermal conductivity of fluid, Btu/(hr)(sq ft)(^oF/ft).
L	Length of a coolant passage in reactor, feet.
N_{Nu}	Dimensionless Nusselt modulus, hD/k.
N_{Pr}	Dimensionless Prandtl modulus, $c_p \mu/k$.
N_{Re}	Dimensionless Reynolds modulus, $DV\rho/\mu$
n	Number of coolant passages in reactor
P_p	Flow work per unit time, based on pressure drop of fluid in passage through reactor, ft-lb/hr.
P	Prandtl modulus in Figures 6-22.
q_t	Rate of heat generation in reactor, Btu/hr.

Q	Total volumetric rate of coolant flow, cu ft/hr.
V	Mean velocity of coolant in reactor, ft/hr.
X	Dimensionless parameter defined by equation 14.
Δp	Pressure drop of coolant across reactor, lb/sq ft.
Δt_A	Rise in bulk temperature of coolant (axial temperature difference) between entrance and exit of reactor, ^{o}F.
Δt_p	Temperature difference parameter, $\Delta t_R + 1/2\,\Delta t_A$
Δt_R	Temperature difference between tube wall and bulk fluid (radial temperature difference), ^{o}F
Δt_t	Temperature difference parameter, $c_1 \Delta t_R + c_2 \Delta t_A$
Δt_w	Temperature difference parameter, $2\,\Delta t_R + 1/2\,\Delta t_A$
μ	Viscosity of fluid, lb mass/(ft)(hr)
ρ	Density of fluid, lb/cu ft.
π_p	Dimensionless "cooling work modulus" defined by equation (4); equals flow work per unit heat removal.
τ_w	Shear force at wall due to fluid friction, lb force/sq ft.