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QUARTERLY PROGRESS REPORT NO. 6
ON THE MEASUREMENT OF THE PHYSICAL AND CHEMICAL PROPERTIES OF THE SODIUM-POTASSIUM ALLOY

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NAVAL RESEARCH LABORATORY

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ON THE MEASUREMENT OF THE PHYSICAL AND CHEMICAL PROPERTIES OF THE SODIUM-POTASSIUM ALLOY

C. T. Ewing, Naval Research Laboratory
R. C. Werner, E. C. King, R. A. Tidball,
Mine Safety Appliances Company, Callery, Pennsylvania

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Approved by:

Mr. R. R. Miller, Head, Physical & Inorganic Section
Dr. P. Borgstrom, Superintendent, Chemistry Division

DEPARTMENT OF THE NAVY ★ OFFICE OF NAVAL RESEARCH ★

Problem No. 32C01-06 February 25, 1948

NAVAL RESEARCH LABORATORY
CAPTAIN H. A. SCHADE, USN, DIRECTOR
WASHINGTON, D.C.

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PART I

SUMMARY OF PROPERTY MEASUREMENTS

STATEMENT OF PROBLEM

The physical and chemical properties of liquid metals, together with measurements of heat transfer coefficients on an engineering scale, are being investigated. The investigation to date has been concerned with the alkali metals.

PROPERTY MEASUREMENTS

This quarterly report presents the status of results on the measurements of physical properties of the sodium-potassium alloy. Measurements of some of the properties have been completed and final reports on these will be prepared for the next quarterly report. Two reports from the Mine Safety Appliances Company are included.

VISCOSITY

A portion of the next quarterly report will be devoted to a final presentation and analysis of viscosity measurements made at the Laboratory and elsewhere. There will be included final viscosity values over a range of compositions and over an extensive range of temperatures with an accuracy sufficient for engineering purposes.

DENSITY

The next quarterly report will also contain a similar final reporting on density. All density data, compiled at MSA, at NRL, and elsewhere will be analyzed and presented in final convenient form.

SURFACE TENSION

Surface tension values below 200° C for the pure metals and several alloys will be presented in the next quarterly report.

SPECIFIC HEAT

There are indications that the apparatus for specific heat reported in NRL Report C-3152 will not give results of sufficient

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accuracy for the problem at hand. A re-evaluation of the apparatus is being made and it may be desirable to rebuild some parts to obtain accurate specific heat measurements.

REACTION RATES

A preliminary report will be presented in the next quarterly report on the rate of reaction of liquid sodium-potassium alloys with liquid water. The measurements to date have been made under atmospheric pressure at room temperature.

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PART II

PRELIMINARY REPORT NO. 4 SUPPLEMENT 1

FILM HEAT TRANSFER COEFFICIENTS FOR LIQUID POTASSIUM-SODIUM ALLOYS

by

R. C. Werner and E. C. King

MINE SAFETY APPLIANCES COMPANY
Callery, Penna.

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ABSTRACT

An alloy of 44% potassium and 56% sodium (KNa 44) was tested in a natural circulation apparatus for pressure drop due to friction. Reynolds numbers were in the transition region between 2000 and 10,000. Darcy friction factors were calculated and compared with data on other fluids as published by L. F. Moody.

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INTRODUCTION

A. Authorization.

This project was authorized by Task Order I under Contract N6ori-146, dated June 26, 1946.

B. Statement of Problem.

Task Order I calls for research on the chemical and physical properties of the various potassium-sodium alloys and for determination of methods and procedures for their use in heat transfer.

C. Known Facts Bearing on the Problem.

The flow of fluids inside pipes is governed by the general thermodynamic flow equation which may be written between any two points in the flow system. One of the terms of this equation is the work energy which has been dissipated as friction. The friction term may be predicted from a generalized correlation between the Reynolds number of the flowing fluid and a friction factor when the pipe diameter, length of pipe, viscosity of the fluid, density of the fluid, and fluid velocity are known. When the flow is laminar, only one relationship exists but an added parameter of pipe roughness must be known when flow is turbulent or in the transition region between laminar and turbulent flow. This study was initiated to establish the friction factor--Reynolds number relationship for KNa alloy in natural circulation through pipe caused by density differences accompanying heating and cooling.

The flow equation is an energy balance between any two points in the flow system.

By an energy balance for fluid flowing from Point 1 to Point 2:

$$U_1 + P_1V_1 + \frac{u_1^2}{2g} + X_1 + q = U_2 + P_2V_2 + \frac{u_2^2}{2g} + X_2 + W_S \qquad (1)$$

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in which U = internal energy, ft-lbs. per lb.
P = pressure, lb. per sq. ft.
V = volume, cu. ft. per lb.
u = average linear velocity, ft. per sec.
X = height above datum, ft.
q = heat absorbed by fluid, ft-lb. per lb.
W_S = work done by system, ft-lb. per lb.

An energy balance on the fluid itself gives:

$$dU = \int TdS - \int PdV + \text{etc.} \qquad (2)$$

in which T = temperature, deg. R.
S = entropy, ft-lb. per deg. R. per lb.
etc. = increase in all forms of energy other than heat and compression

If friction losses are defined as W_f, then

$$\int TdS = W_f + q \qquad (3)$$

A combination of Eqs. 1, 2, and 3 gives the general fluid-flow equation:

$$\int VdP + \frac{\Delta u^2}{2g} + \Delta X + W_f + W_s + \text{etc.} = o \qquad (4)$$

The term W_f includes all kinds of friction and may be expressed as follows when using the friction factor to predict the friction between the fluid and the pipe wall:

$$W_f = \frac{u^2 L f}{2gD} \text{ (pipe friction)} + \left(\frac{U_1 - U_2}{2g}\right)^2 \text{ (enlargement)} + \frac{K u_2^2}{2g} \text{ (contraction)} + \text{orifice loss.} \qquad (5)$$

In which
L = length of pipe between (1) and (2), ft.
f = friction factor
D = pipe diameter, ft.
K = factor depending upon ratio of diameters

The integral ($\int VdP$) may be solved formally when V may be assumed to have an average value. For the case of isothermal flow of incompressible fluids, V is constant and

$$\int_{P_1}^{P_2} VdP = V\int_{P_1}^{P_2} dP = V(P_2 - P_1) = \frac{P_2 - P_1}{\rho} \qquad (6)$$

in which ρ = density $\frac{\text{lb.}}{\text{cu. ft.}}$

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A combination of equations 4, 5, and 6 gives:

$$-\int V dP = \frac{P_1 - P_2}{\rho} = \frac{\Delta u^2}{2g} + \Delta X + W_s + \frac{u^2 Lf}{2gD} + \text{enlargement}$$

$$+ \text{contraction} + \text{etc.} \qquad (7)$$

In case the fluid has a variable specific volume, the integral should be used.

In analysing the flow behavior of a natural circulation device shown on Figure 1, there are six segments to the flow system represented by the flow between thermocouple points (TC1, TC2, TC3, etc.). The flow equation may be written for each of the segments and these equations combined to yield one equation with the friction factor the only unknown term. Any term will be omitted when the numerical value is zero, such as for W_s in all equations. The kinetic energy terms will be neglected for the small temperature changes but will be included for the heater and cooler. Also the fluid friction in the 6" diameter heater and separator will be neglected.

$$\frac{P_1 - P_2}{\rho_{1,2}} = \frac{u_2^2 - u_1^2}{2g} + (X_2 - X_1) + \frac{(u_1 - u_0)^2}{2g} + \frac{K u_2^2}{2g} \qquad (1 \text{ to } 2)$$

$$\frac{P_2 - P_3}{\rho_{2,3}} = (X_3 - X_2) + \frac{u_{2,3}^2 \, Lf}{2gD} \qquad (2 \text{ to } 3)$$

$$\frac{P_3 - P_4}{\rho_{3,4}} = \frac{u_{3,4}^2 \, Lf}{2gD} \qquad (3 \text{ to } 4)$$

$$\frac{P_4 - P_5}{\rho_{4,5}} = \frac{u_5^2 - u_4^2}{2g} + (X_5 - X_4) + \frac{u_{4,5}^2 \, Lf}{2gD} \qquad (4 \text{ to } 5)$$

$$\frac{P_5 - P_6}{\rho_{5,6}} = (X_6 - X_5) + \frac{u_{5,6}^2 \, Lf}{2gD} \qquad (5 \text{ to } 6)$$

$$\frac{P_6 - P_1}{\rho_{6,1}} = + \frac{u_{6,1}^2 \, Lf}{2gD} + \frac{(u_6 - u_0)^2}{2g} + \frac{K u_1^2}{2g} \qquad (6 \text{ to } 1)$$

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When multiplying both sides of each equation by the fluid density and adding the equations, the summation of the pressure terms becomes zero. A summation of the six equations with rearrangement gives:

$$\frac{u_{2,3}^{2}\,Lf\rho_{2,3}}{2gD} + \frac{u_{3,4}^{2}\,Lf\rho_{3,4}}{2gD} + \frac{u_{4,5}^{2}\,Lf\rho_{4,5}}{2gD} + \frac{u_{5,6}^{2}\,Lf\rho_{5,6}}{2gD}$$

$$+ \frac{u_{6,1}^{2}\,Lf\rho_{6,1}}{2gD} = (X_1-X_2)\rho_{1,2} + \frac{(u_1{}^2-u_2{}^2)}{2g}\rho_{1,2} - \frac{(u_1-u_0)^2}{2g}\rho_1$$

$$- \frac{Ku_2^{2}}{2g}\rho_2 + (X_2-X_3)\rho_{2,3} + \left(\frac{u_4^2-u_5^2}{2g}\right)\rho_{4,5} + (X_4-X_5)\rho_{4,5}$$

$$+ (X_5-X_6)\rho_{5,6} + \frac{(u_0-u_6)^2}{2g}\rho_{6,1} - \frac{Ku_1^{2}}{2g}\rho_{6,1} \qquad (8)$$

For a given heat input into the system with a corresponding temperature rise of the fluid between points 1 and 2, the mass rate of circulation is established by use of the specific heat of the fluid. The mass rate of flow, the density of the fluids at the several temperatures, and the dimensions of the equipment make it possible to compute each term in equation (8) except the friction factors f. For an exact solution of the equation, it would be necessary to assume that the friction factors all occur on a given roughness line of the friction factor - Reynolds number plot. With this assumption, a trial and error solution will determine the roughness factor for the KNa alloy in stainless steel pipe.

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D. Presentation.

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In this report a method will be presented to determine the pressure drop due to friction in a natural circulation piping system. The apparatus used will be described and methods of calculation explained.

METHODS

A. Apparatus.

Several apparatuses were used before dependable data was collected. The first was constructed with external electrical heaters and high temperatures could not be obtained. The second apparatus was destroyed when electrical power failed on a week-end while the equipment was in the standby condition. The sodium in the apparatus solidified and when power service was resumed, expanded while heating and caused failure in the plates of the heater.

The apparatus finally used is shown in Figure 1. The heater was a 2 ft. section of 6 inch stainless steel pipe containing six 1000 watt immersion heaters, controlled with a variable transformer. The hot leg consisted of an 8 ft. vertical section of 1/2 inch stainless steel pipe welded to the top of the heater. The cold leg was a 10 ft. section of 1/2 inch stainless steel pipe with an 18 inch heat exchange section. Temperatures were measured at the inlet to the heater (Thermocouple 1), at the outlet of the heater (Thermocouple 2), at the top of the hot leg (Thermocouple 3), at the top of the cold leg (Thermocouple 4), below the heat exchanger (Thermocouple 5), and at the bottom of the cold leg (Thermocouple 6). The system was insulated with high temperature pipe lagging and insulating cement. The thermocouples were calibrated against each other in an electrically heated furnace. The voltmeter and ammeter were calibrated against standard instruments supplied by the Pennsylvania Power Co. Heat loss from the heater was determined by measuring the power required to hold the heater at various temperatures while the KNa was solid in the cold leg. The heat loss is plotted against temperature on Figure 2.

B. Operations.

The apparatus was cleaned with 12% sulfuric acid and distilled water, dried under vacuum, and charged with nitrogen. The system was then charged with 30 pounds of KNa 44.

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Tests 1 through 8 were cooled with Dowtherm A in the cooler. Tests 9 through 30 were cooled by removing the insulation from the top horizontal pipe and the cold leg. Radiant cooling was used to reach higher temperatures and higher Reynolds numbers.

C. Method of Calculation.

The exact calculation involves a trial and error procedure for finding the friction factors. It would be a more straight forward calculation if the friction factors and fluid densities were assumed to be the same for each term in equation 8. To evaluate the error which this assumption would make, an exact calculation using equation 8 will be made.

The right hand members of equation 8 may be computed directly from the experimental data on Fig. 1 and 2.

Run No. 5

Circulation Rate

$$w = \frac{q_i - q_r}{(t_2 - t_1) c_{p1,2}} = \frac{14{,}050 - 1160}{175.0 \times 0.3055} = 241.4 \text{ lbs/hr.}$$

$$u = \frac{w}{\rho A} = \frac{.1312w}{\rho} \; .$$

Static Head in Heater.

$$(X_1 - X_2)\rho_{1,2} = (0 - 2)\ 52.30 = -104.6$$

Kinetic energy change in heater.

$$\frac{(u_1^2 - u_2^2)}{2g}\rho_{1,2} = \frac{(\overline{.599}^2 - \overline{.616}^2)\ 52.3}{64.4} = -0.016$$

Enlargement into heater.

$$-\frac{(u_1 - u_0)^2}{2g}\rho_1 = -\frac{(.599 - .006)^2}{64.4}\ 53.0 = -0.289$$

Contraction out of heater.

$$-\frac{Ku_2^2}{2g}\rho_2 = \frac{-0.5 \times .616}{64.4} \times 51{,}6 = -0.152$$

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Static head in cooler section.

$$(X_4 - X_5)\rho_{4,5} = (10 - 7.5)\ 52.29 = +130.7$$

Static head in cold leg.

$$(X_5 - X_6)\rho_{5,6} = (7.5 - 0)\ 52.9 = +397.0$$

Enlargement into separator.

$$\frac{(u_0 - u_6)^2}{64.4}\rho_{6,1} = \frac{(.006 - .599)^2}{64.4} \times 53 = -0.289$$

Contraction out of separator.

$$\frac{-Ku_1^2}{2g}\rho_{6,1} = -0.5 \times .599^2 \times \frac{53.0}{64.4} = -0.152$$

Total driving force = ΔP = +9.115 lbs/sq.ft.

As part of the trial and error, assume on average f, density, velocity and Reynolds Number Equation 8 becames

$$\frac{u^2 f\ L\rho}{2gD} = 9.115 \text{ lbs/sq.ft.}$$

The equivalent length of pipe including only the straight pipe and three turns is given on Table I as 37.75 feet. Solving for an average f by using ρ average and u average.

$$f = \frac{9.115 \times 64.4 \times .622}{37.75 \times .601^2 \times 52.8 \times 12} = .0422$$

The average Reynolds Number is 7470.

A comparison of this point with the friction factor Plot Figure 3 (Reference 4) shows that it corresponds to a roughness of about 0.008. Using this curve for obtaining the friction factors for the individual terms in equation 8 will give a trial to find whether the sum of the following frictional pressure losses are equal to the available pressure (Δ P) shown above.

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$$\frac{\overline{0.612}^{2} \times 9.75 \times .042 \times 51.6}{64.4 \times 0.0518} = 2.388$$

$$\frac{\overline{0.614}^{2} \times 8.5 \times .042 \times 51.7}{64.4 \times 0.0518} = 2.090$$

$$\frac{\overline{0.607}^{2} \times 4.25 \times .0428 \times 52.3}{64.4 \times 0.0518} = 1.052$$

$$\frac{\overline{0.600}^{2} \times 9.25 \times .0433 \times 52.9}{64.4 \times 0.0518} = 2.286$$

$$\frac{\overline{0.599}^{2} \times 6.0 \times 0.433 \times 53.0}{64.4 \times 0.0518} = \underline{1.482}$$

$$\triangle P = 9.308$$

This solution for the left hand side of the equation matches the right hand side within .007 which is satisfactory. Therefore the point as plotted is representative of the apparent roughness of the pipe.

Run 28

The following calculations are Run 28 calculated in the preceding manner to check the method on data collected with radiant cooling.

Circulation Rate.

$$w = \frac{20{,}410 - 2450}{254.5 \times 0.3208} = 220.0 \text{ lbs/hr.}$$

Static head in heater.

$$(X_1 - X_2)\rho_{1,2} = (0-2)49.61 = \qquad -99.22$$

Kinetic energy change in heater.

$$\frac{(u_1{}^2 - u_2{}^2)}{2g}\rho_{1,2} = \frac{(\overline{0.571}^{2} - \overline{0.596}^{2})49.61}{64.4}$$

$$= \frac{-0.030 \times 49.61}{64.4} = -\ 0.023$$

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Enlargement into heater. DECLASSIFIED

$$-\frac{(u_1-u_0)^2\rho_1}{2g} = -\frac{(0.571 - 0.006)^2\ 50.63}{29} = \qquad - 0.251$$

Contraction from heater.

$$-\frac{Ku_2^2\rho_2}{2g} = \frac{-0.5 \times \overline{0.596}^2 \times 48.59}{64.4} = \qquad - 0.134$$

Static head of hot leg.

$$(X_2-X_3)\rho_{2,3} = (2 - 10)\ 48.68 = \qquad -389.44$$

Kinetic energy change in cooler.

$$\frac{(u_4^2 - u_5^2)}{2g}\rho_{4,5} = \frac{\overline{0.586}^2 - \overline{0.579}^2}{64.4} \times 49.64 = + \ 0.007$$

Static head in cooler section.

$$(X_4-X_5)\rho_{4,5} = (10 - 7.5)\ 49.64 = \qquad -124.10$$

Static head in cooler leg.

$$(X_5-X_6)\rho_{5,6} = (7.5 - 0)\ 50.16 = \qquad +376.202$$

Enlargement into separator.

$$\frac{(u_0-u_6)^2\rho_{6,1}}{64.4} = \frac{(0.006 - 0.577)^2\ 50.51}{64.4} = \qquad - 0.256$$

Contraction from separator.

$$-\frac{Ku_1^2\rho_{6,1}}{2g} = \frac{-0.5 \times \overline{0.571}^2 \times 50.51}{64.4} = \qquad - 0.128$$

$$\Delta P = \qquad \overline{10.850}$$

$$\frac{u^2 f L\rho}{2gD} = 10.850$$

$$f = \frac{10.850 \times 2gD}{u^2 L\rho}$$

using av. = 49.61
$u_{av.} = 0.583$
L = 37.75

$$f = \frac{10.850 \times 64.4 \times 0.622}{\overline{0.583}^2 \times 37.75 \times 49.61 \times 12} = 0.0568$$

Average Reynolds Number = 9365

This value compares with the Moody roughness of app. .025

$$\text{Hot Leg} = \frac{0.596^2 \times 9.75 \times 0.0561 \times 48.68}{64.4 \times 0.0518} = 2.839$$

$$\text{Top} = \frac{0.590^2 \times 8.5 \times 0.0562 \times 49.05}{64.4 \times 0.0518} = 2.443$$

$$\text{Exchanger} = \frac{.582 \times 4.25 \times .0565 \times 49.64}{64.4 \times 0.0518} = 1.215$$

$$\text{Cold Leg} = \frac{0.577^2 \times 9.25 \times .0566 \times 50.16}{64.4 \times 0.0518} = 2.622$$

$$\text{Bottom} = \frac{0.572^2 \times 6.0 \times 0.0568 \times 50.51}{64.4 \times 0.0518} = 1.691$$

$$P = 10.810$$

D. Physical Properties.

Viscosity. The viscosities used were taken from NRL report No. C-3105, Quarterly Progress Report No. 3 on the Measurement of the Physical and Chemical Properties of the Sodium-Potassium Alloy, April 1947. These values are shown on Figure 3.

Density. Density values were taken from Preliminary Report No. I, "Density of the System, KNa". Density values are shown on Figure 4.

Specific Heat. Specific heat values were taken from NRl report No. C-3152, Quarterly Progress Report No. 4 on the Measurement of Physical and Chemical Properties of Sodium-Potassium Alloy, Appendix B. Specific heat values are shown on Figure 5.

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RESULTS

The data collected and the calculated results are shown in Table I. The results were plotted in the manner described by L. F. Moody (Reference 4) using the Darcy friction factor as the ordinate and Reynolds number as the abscissa.

Figure 6 is the Moody line for an equivalent roughness of 0.008 plotted with the data from the Dowtherm A tests. Figure 7 is the Moody line for an equivalent roughness of 0.02 plotted with the data from the radiant cooled tests.

The apparatus has been in continuous operation for 112 days. The temperature varied during the fifty-six days when the preceding tests were made. At the conclusion of the tests the temperature at TC-2 was adjusted to approximately 1000°F. It is planned to operate the apparatus at 1000°F. indefinitely.

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CONCLUSIONS

Data has been collected that can be used to determine pressure drop due to friction in natural circulation systems using KNa 44.

The data of Figure 6 should be used when the KNa is cooled rapidly in a short section of the piping.

The data of Figure 7 should be used when the KNa is cooled more uniformly over long sections of the piping. The difference in pressure drop between the two is due to additional turbulence caused by the rapid cooling of the KNa represented by Figure 6.

Results of this experiment will be changed by any future changes in the recommended values of density, specific heat, or viscosity of KNa 44.

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NOMENCLATURE

A	Cross sectional area of pipe, sq. ft.
D	Inside diameter of pipe, ft.
f	Darcy friction factor, dimensionless.
G	Mass flow rate, lbs./hr./sq.ft.
g	Acceleration due to gravity, 32.2 ft./sec./sec.
K	Factor depending on ratio of pipe diameters.
L	Equivalent length of pipe, ft.
N_{Re}	Reynolds number, dimensionless.
P	Pressure, lbs./sq.ft.
ΔP	Frictional pressure drop, lbs./sq.ft.
q	Heat absorbed by fluid, ft.-lbs./lb.
q_i	Heat input to heater, Btu./hr.
q_r	Heat loss to heater, Btu./hr.
S	Entropy, ft.-lbs./°R/lb.
T	Temperature, °R.
t	Temperature, °F.
t_1, t_2, etc.	Temperature of TC-1, TC-2, etc, °F.
U	Internal energy, ft.-lbs./lb.
u	Fluid velocity, ft./sec.
V	Volume, cu.ft./lb.
W_f	Work loss due to friction ft-lbs./lb.
W_s	Work done by system ft-lbs./lb.
w	Circulation rate, lbs./hr.
X	Height above datum, ft.
ρ	Density, lbs./cu.ft.
μ	Viscosity, centipoises.
$\frac{\varepsilon}{D}$	Relative roughness, dimensionless.

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EQUIVALENT LENGTH OF PIPING

3 Tees, side outlet @ 3.5 ft.	10.50 ft.	(Ref. 5)
Hot Leg	8.00 ft.	
Top Section	5.00 ft.	
Cold Leg	10.00 ft.	
Bottom Section	4.25 ft.	
Total	37.75 ft.	

TABLE I

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TABLE II

No.	Temperatures t_1 F	 t_2 F	 t_3 F	 t_4 F	 t_5 F	 t_6 F	Power Input KW	Circulation Rate w lbs/hr	Frictional Pressure Drop lbs/sqft	Reynolds Number N_{Re}	Friction Factor f
1	314.1	434.7	426.5	424.8	326.4	319.7	2.175	186.2	5.187	4491	0.0403
2	310.0	430.0	425.0	420.0	325.0	315.0	2.175	187.5	5.160	4498	0.0403
3	341.8	471.9	462.2	460.5	355.0	347.0	2.640	210.1	6.768	5389	0.0412
4	377.2	537.0	527.6	526.8	391.4	381.4	3.510	228.4	7.840	6331	0.0405
5	450.0	625.0	615.4	614.1	463.8	454.9	4.120	241.4	9.115	7470	0.4220
6	466.4	658.7	648.2	647.1	482.0	472.4	4.510	240.5	10.180	7700	0.0463
7	492.2	697.9	686.9	685.8	508.3	500.8	5.220	244.5	10.520	8023	0.0472
8	512.0	743.0	732.4	731.1	527.8	520.7	6.240	278.0	11.830	9548	0.0403
9	898.0	1055.8	1028.0	983.2	948.6	926.7	3.630	182.6	6.361	8310	0.0474
10	940.0	1117.3	1090.4	1018.0	988.2	966.7	4.200	189.5	7.859	8895	0.0539
11	400.2	535.2	508.4	479.7	450.0	421.3	2.200	159.8	5.421	4513	0.0574
12	395.0	528.1	502.5	473.5	441.5	418.0	2.170	159.9	5.209	4468	0.0563
13	230.9	307.5	292.4	276.1	258.7	244.6	0.861	109.3	2.977	2103	0.0735
14	293.4	390.3	371.9	351.4	330.7	310.3	1.232	123.6	3.680	2789	0.0662
15	327.5	437.5	416.0	392.1	366.9	346.7	1.565	140.0	4.410	3433	0.0616
16	354.0	474.1	450.8	424.7	397.7	375.7	1.839	150.8	4.440	3843	0.0527
17	406.8	548.9	520.9	492.2	459.4	433.1	2.360	163.8	5.350	4705	0.0535
18	492.0	638.6	623.9	585.2	546.2	510.9	2.665	174.8	6.000	5760	0.0522
19	517.0	674.4	659.6	616.7	569.8	537.6	2.880	175.5	6.840	5831	0.0523
20	546.7	712.7	696.5	653.0	603.6	569.5	3.270	189.5	7.100	6575	0.0528
21	587.0	769.3	751.3	702.1	650.6	613.6	3.640	190.2	4.990	6883	0.0363
22	597.4	789.4	770.9	721.7	665.0	623.9	3.950	196.8	8.130	7260	0.0551
23	644.8	853.4	834.2	776.7	715.4	671.7	4.445	201.5	9.020	7603	0.0539
24	656.3	870.8	850.8	792.6	729.7	685.0	4.730	209.1	9.540	8203	0.0565
25	698.4	929.2	908.0	845.0	775.9	727.6	5.185	211.2	8.690	8616	0.0501
26	717.6	955.4	937.0	867.1	796.7	746.3	5.500	217.3	10.231	9010	0.0554
27	766.3	1035.0	1013.8	935.8	857.5	802.1	6.455	224.8	11.540	9760	0.0576
28	746.3	1000.8	979.2	908.0	831.6	777.6	5.985	220.0	10.850	9365	0.0568
29	445.9	578.1	564.2	530.3	491.4	463.2	2.221	158.9	5.630	4783	0.0600
30	413.6	534.6	521.9	490.5	454.8	425.9	1.951	154.3	5.070	4403	0.0579

DATA AND RESULTS

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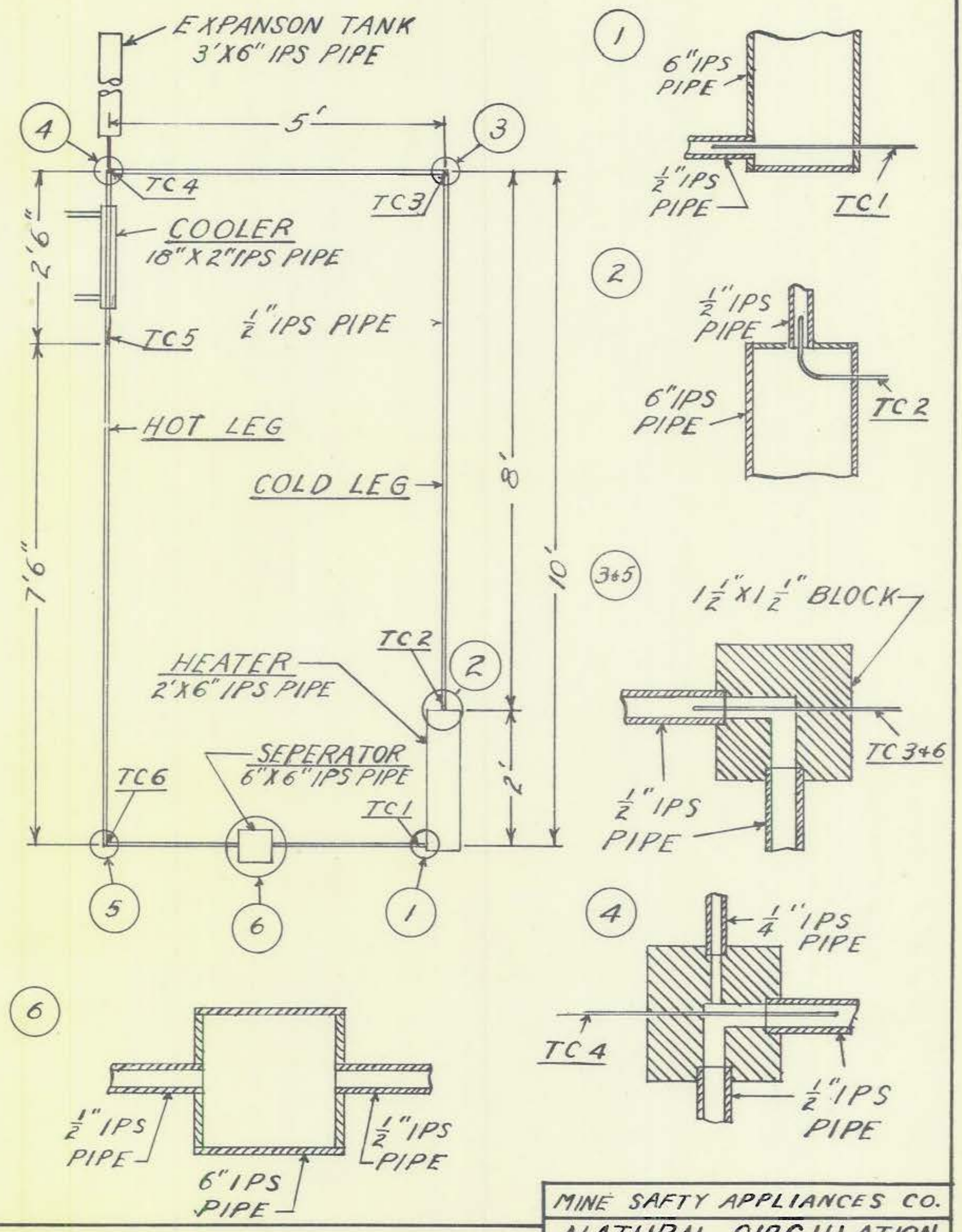
FIGURE 1



MINE SAFTY APPLIANCES CO.

NATURAL CIRCULATION
APPARATUS
1-1-48 R.T.

Note: All parts and pipes made of 18-8 Stainless Steel

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FIGURE 2

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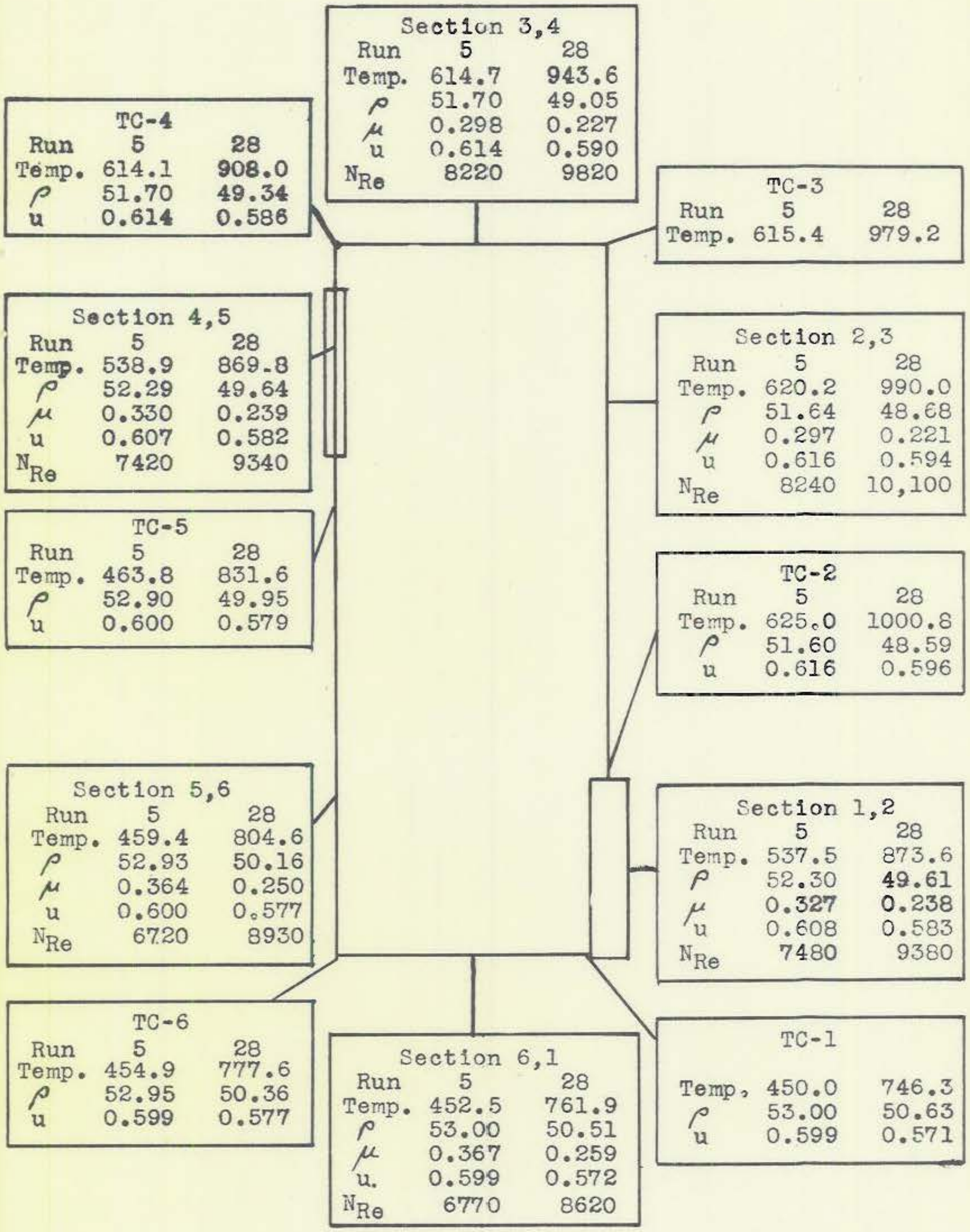

Section 3,4

Run	5	28
Temp.	614.7	943.6
ρ	51.70	49.05
μ	0.298	0.227
u	0.614	0.590
N_{Re}	8220	9820

TC-4

Run	5	28
Temp.	614.1	908.0
ρ	51.70	49.34
u	0.614	0.586

TC-3

Run	5	28
Temp.	615.4	979.2

Section 4,5

Run	5	28
Temp.	538.9	869.8
ρ	52.29	49.64
μ	0.330	0.239
u	0.607	0.582
N_{Re}	7420	9340

Section 2,3

Run	5	28
Temp.	620.2	990.0
ρ	51.64	48.68
μ	0.297	0.221
u	0.616	0.594
N_{Re}	8240	10,100

TC-5

Run	5	28
Temp.	463.8	831.6
ρ	52.90	49.95
u	0.600	0.579

TC-2

Run	5	28
Temp.	625.0	1000.8
ρ	51.60	48.59
u	0.616	0.596

Section 5,6

Run	5	28
Temp.	459.4	804.6
ρ	52.93	50.16
μ	0.364	0.250
u	0.600	0.577
N_{Re}	6720	8930

Section 1,2

Run	5	28
Temp.	537.5	873.6
ρ	52.30	49.61
μ	0.327	0.238
u	0.608	0.583
N_{Re}	7480	9380

TC-6

Run	5	28
Temp.	454.9	777.6
ρ	52.95	50.36
u	0.599	0.577

TC-1

Temp.	450.0	746.3
ρ	53.00	50.63
u	0.599	0.571

Section 6,1

Run	5	28
Temp.	452.5	761.9
ρ	53.00	50.51
μ	0.367	0.259
u.	0.599	0.572
N_{Re}	6770	8620

Run	Circulation lbs/hr	Heat Input Btu./hr
5	241.4	14,060
28	220.0	20,011

Figure 2 Exact Calculation for Runs 5 and 28

[redacted]

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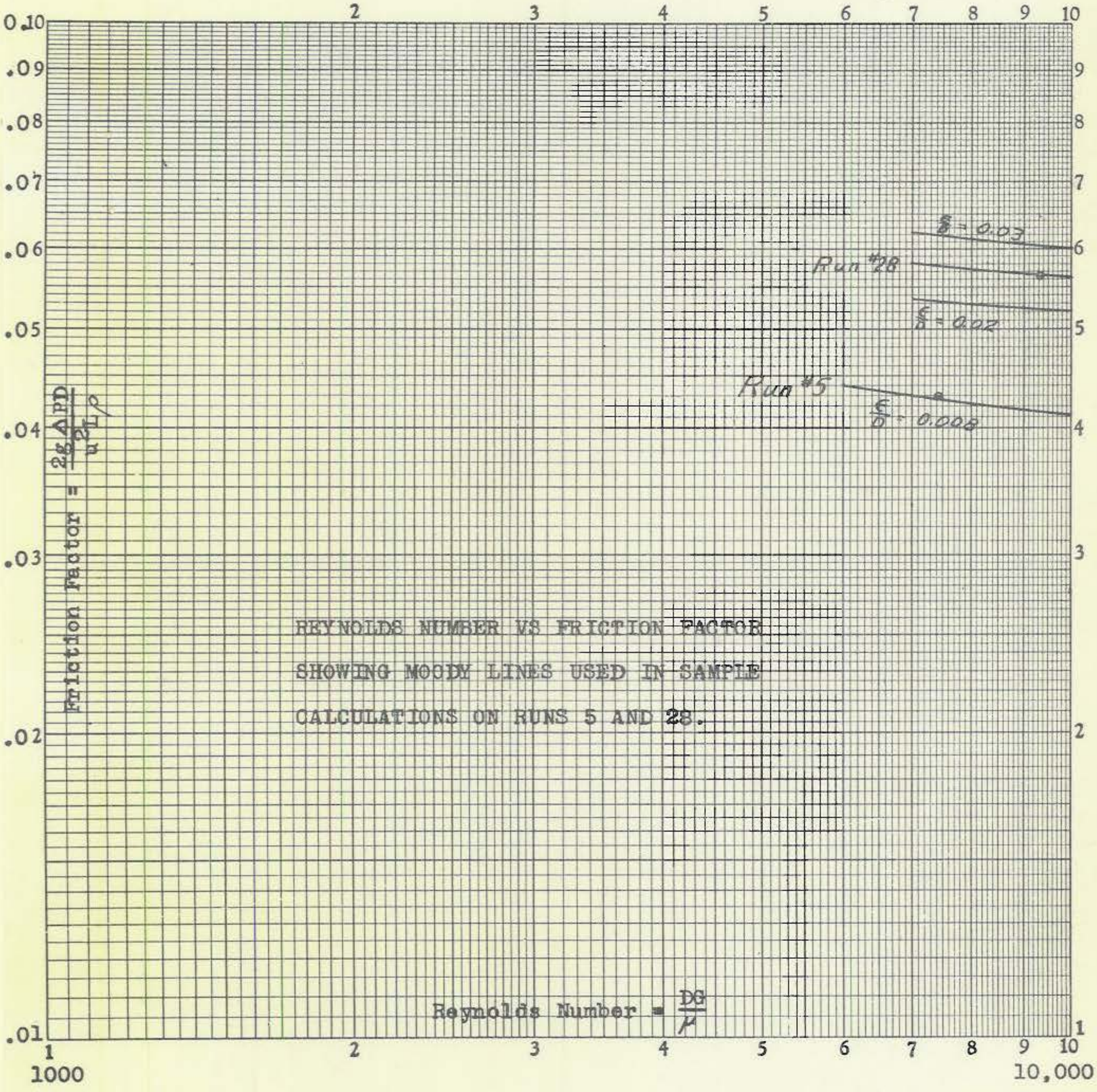
Figure 3



REYNOLDS NUMBER VS FRICTION FACTOR SHOWING MOODY LINES USED IN SAMPLE CALCULATIONS ON RUNS 5 AND 28.

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Figure 4

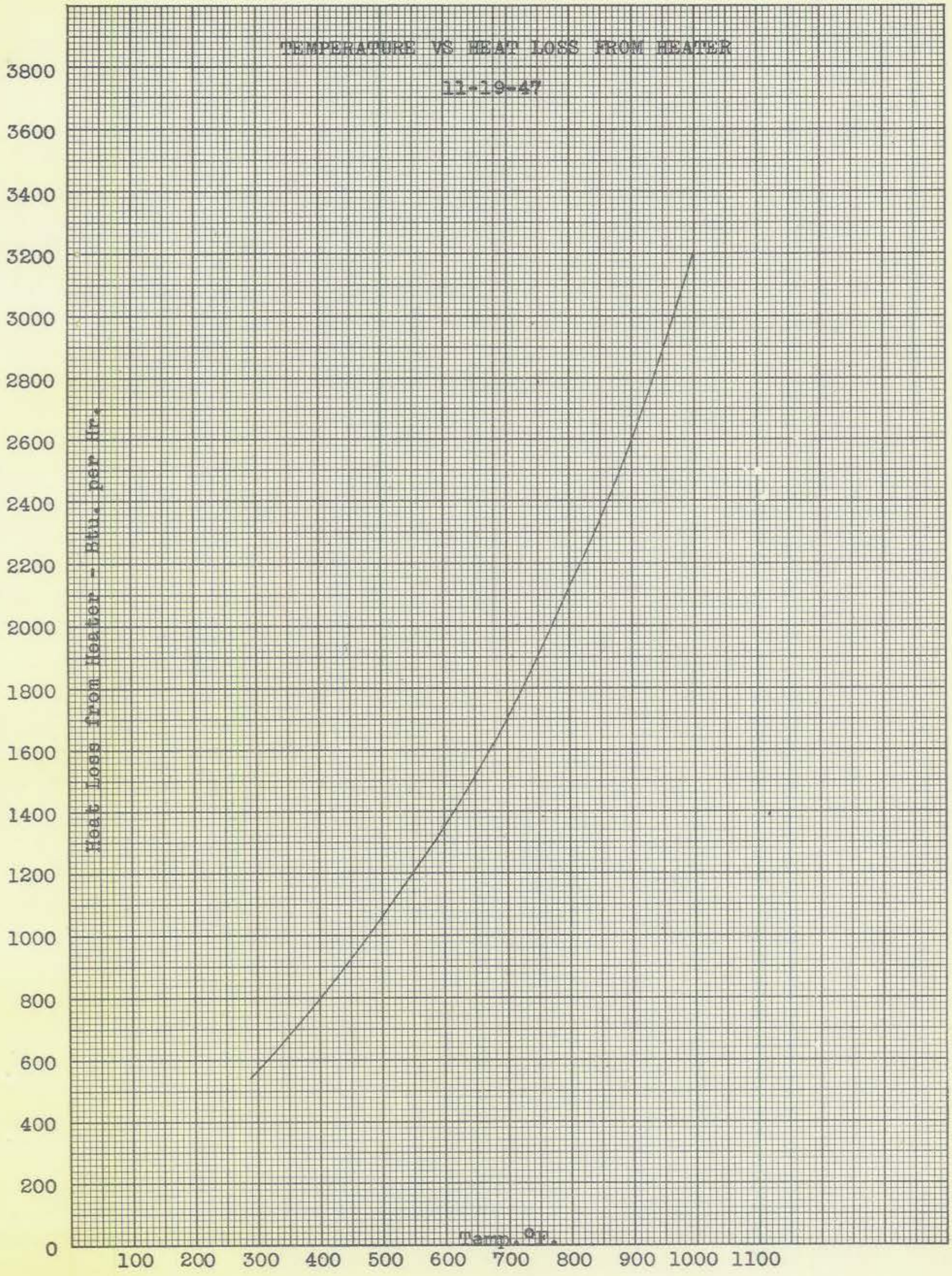

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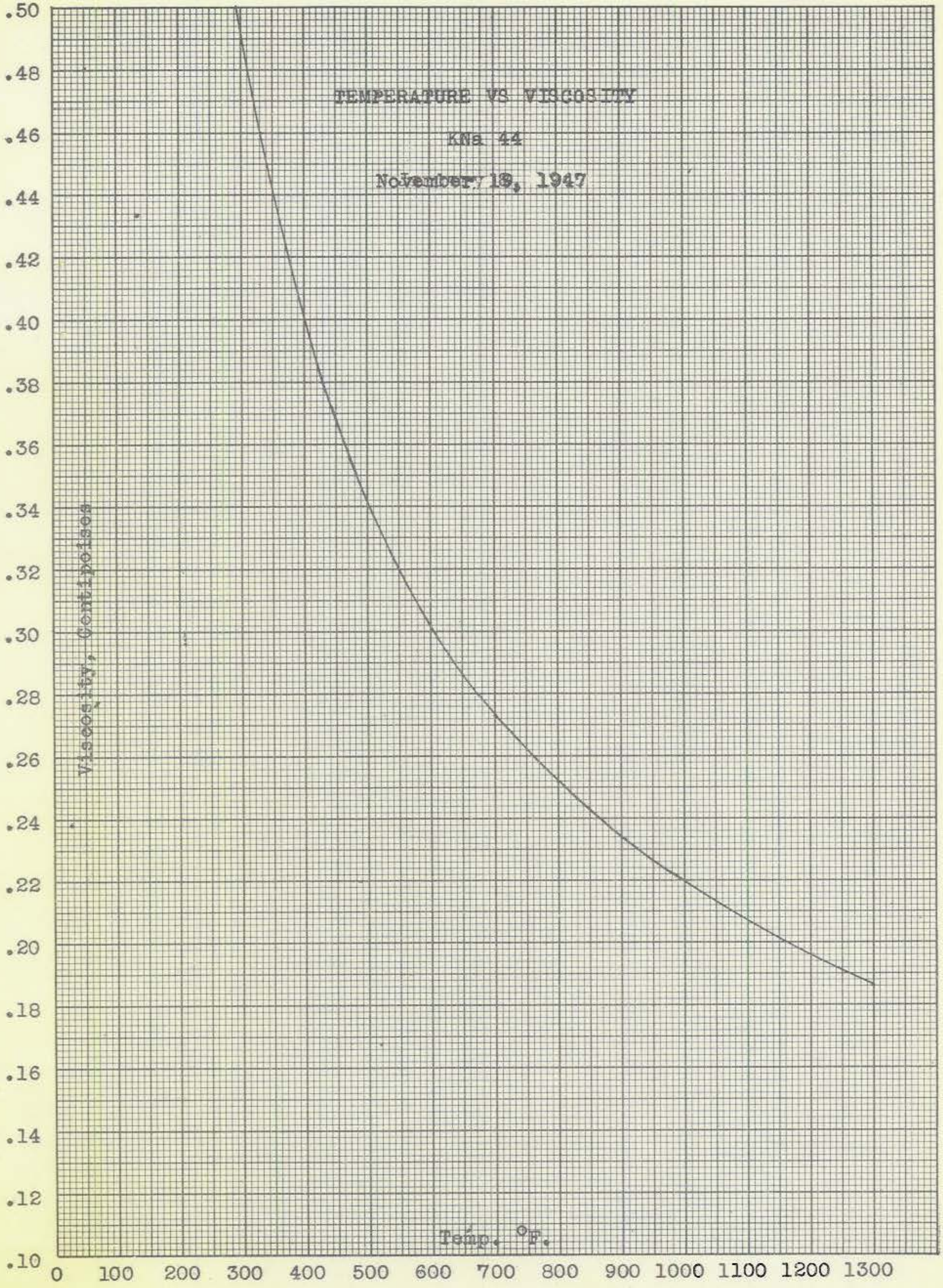
Figure 5


TEMPERATURE VS VISCOSITY

KNa 44

November 18, 1947

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Figure 6

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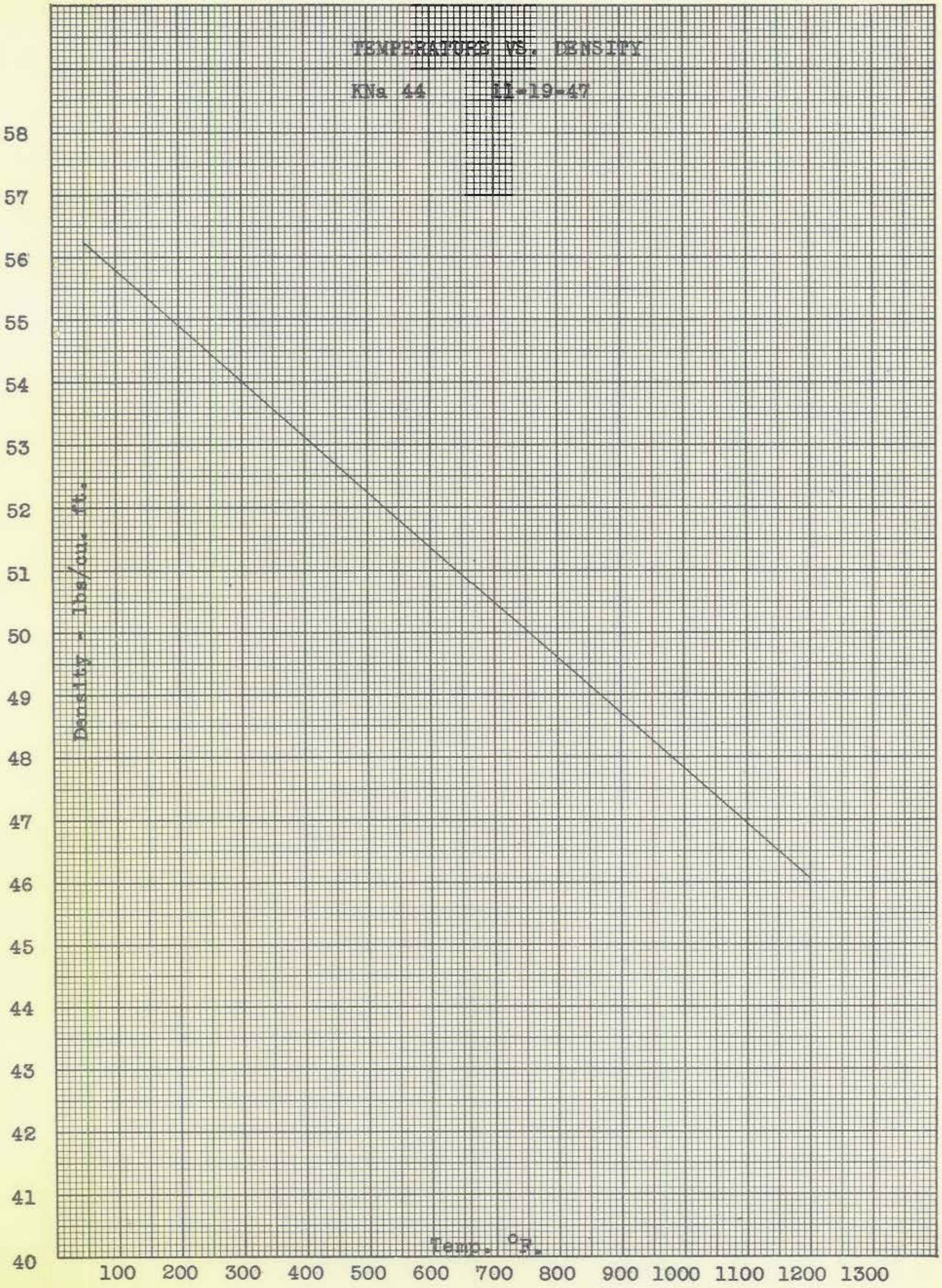

TEMPERATURE VS. DENSITY

KNa 44 11-19-47

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Figure 7

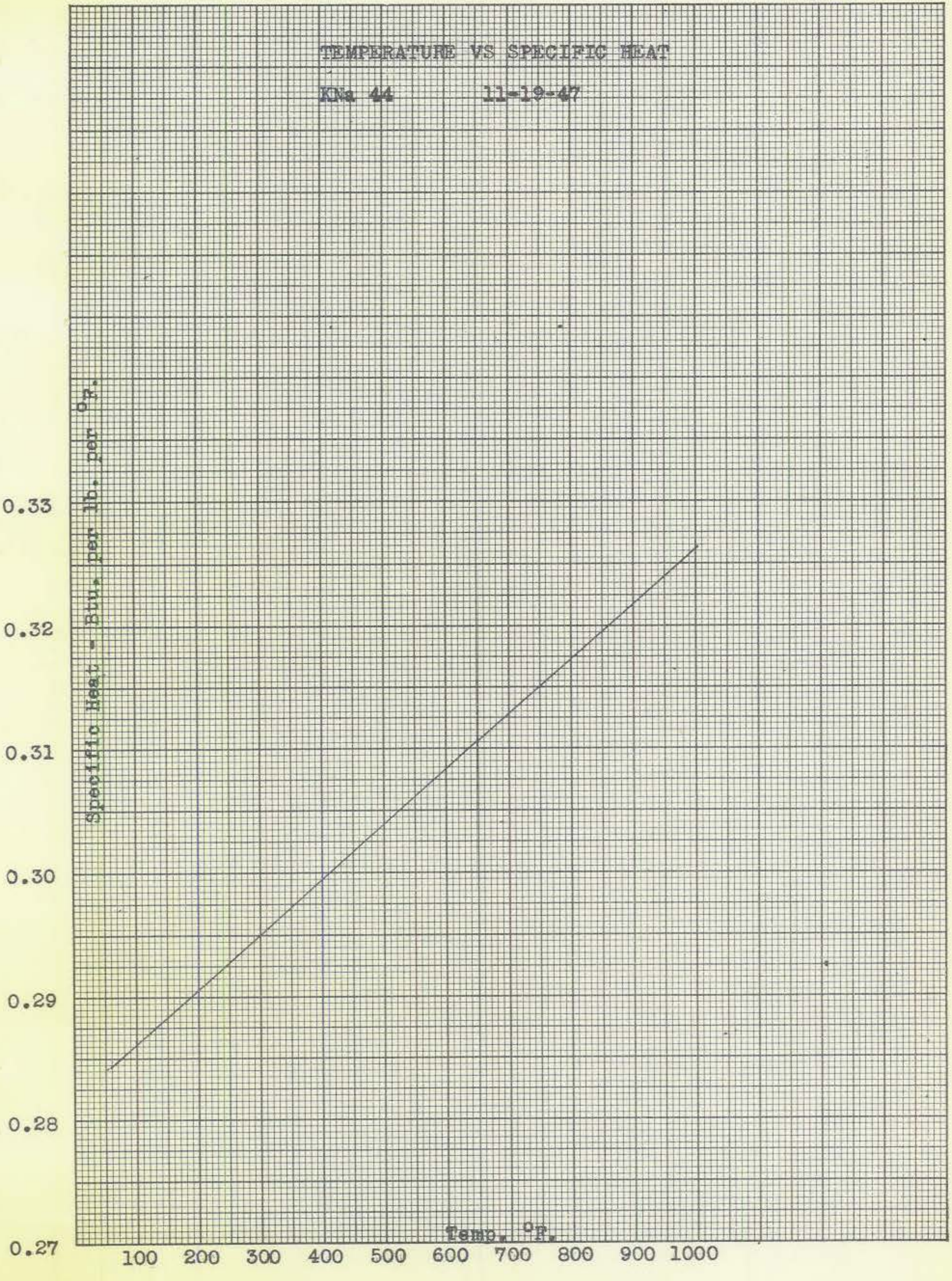

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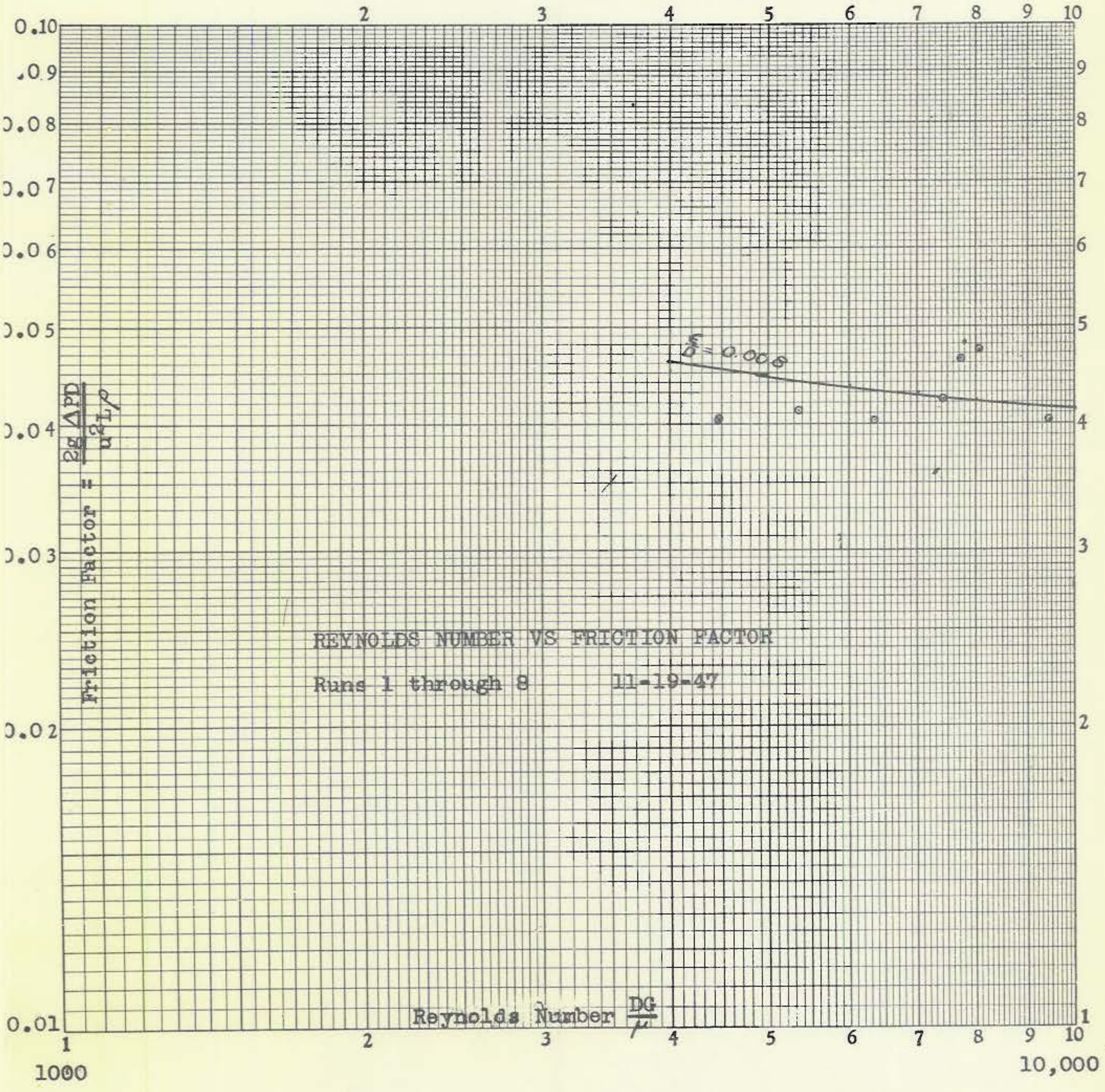
Figure 8



REYNOLDS NUMBER VS FRICTION FACTOR

Runs 1 through 8 11-19-47

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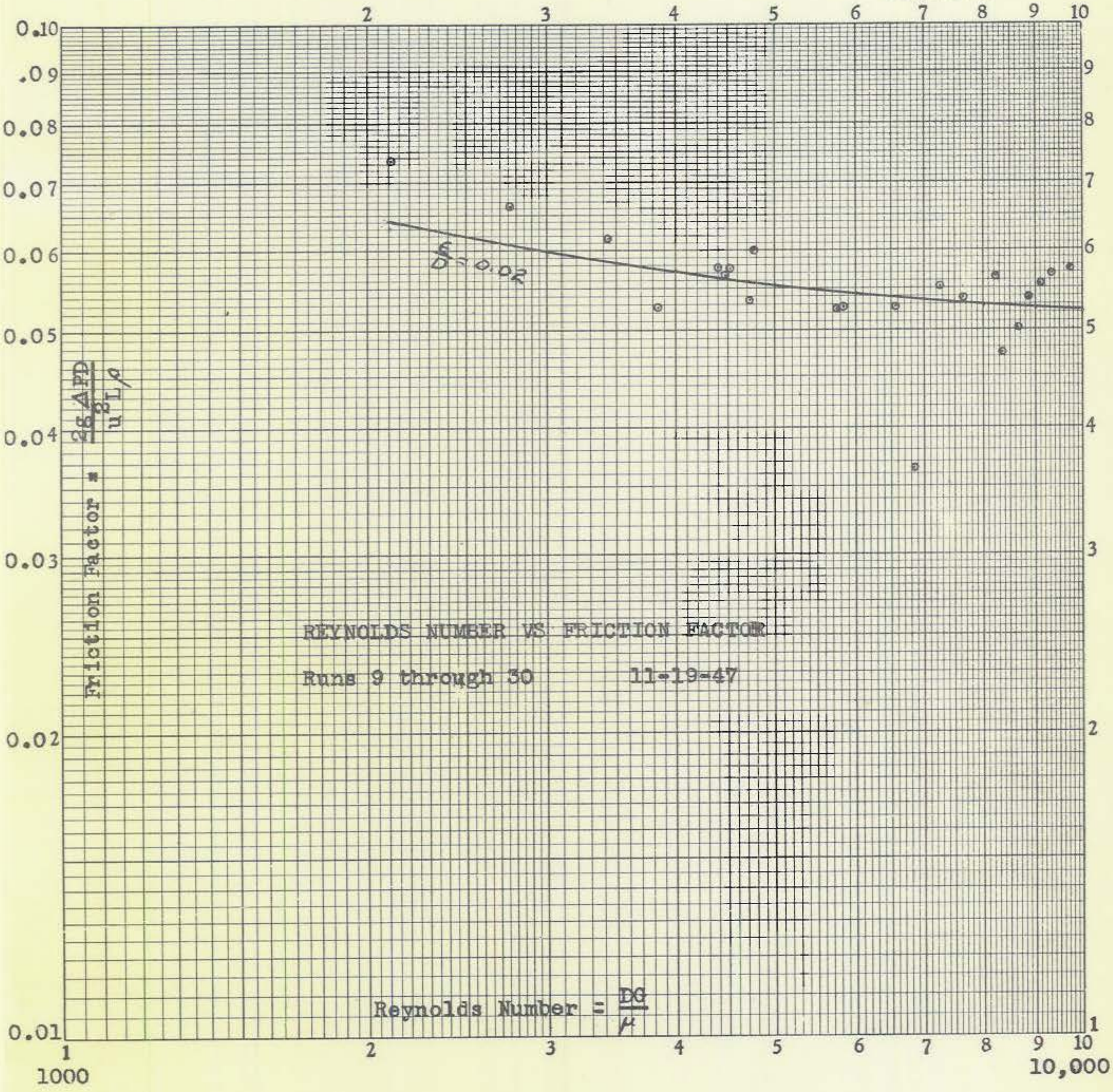
Figure 9



REYNOLDS NUMBER VS FRICTION FACTOR

Runs 9 through 30 11-19-47

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PART III

Preliminary Report No. 6

PRESSURE DROP DUE TO FRICTION IN A NATURAL CIRCULATION SYSTEM OF SODIUM-POTASSIUM ALLOY.

by

Robert A. Tidball

MINE SAFETY APPLIANCES COMPANY
Callery, Penna.

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ABSTRACT

The work on the convection heat transfer properties of sodium-potassium alloys has been extended to 1200°F. and 12 ft./sec. velocity in a nickel double pipe heat exchanger. Overall heat transfer coefficients as high as 3240 B.t.u./(hr.)(sq.ft.) (°F.) were obtained with a 46.8 Wt. % K alloy. The convection heat transfer coefficients could be correlated to a maximum disagreement of + 11% to -10% with a mean deviation of 3.7% by the following formulae:

$$h_i = 0.227\ G_i c_{pi} (G_i D_i/\mu_i)^{-0.5}\ (c_{pi}\mu_i/k_i)^{-0.69}$$

$$h_o = 0.1975\ (D_a/D_o)^{0.53}\ G_o c_{po} (G_o D_e/\mu_o)^{-0.5}\ (c_{po}\mu_o/k_o)^{-0.69}$$

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ABSTRACT

DERIVATION OF THE EQUATIONS FOR CORRELATION

EXPERIMENTAL UNIT

PHYSICAL PROPERTIES OF NaK Alloy

CALCULATIONS

DISCUSSION

APPENDIX

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INTRODUCTION

1. Authorization.

This project was carried out under Task Order I of Contract N6ori-146 dated June 26, 1946.

2. Statement of Problem.

Task Order I calls for research in the chemical and physical properties of various sodium and potassium alloys and for the determination of methods and procedures for their use in heat transfer.

3. Coverage.

This report is a continuation of Preliminary Report No. 4 on "Film Heat Transfer Coefficients for Liquid Potassium-Sodium Alloys".(1) The material to be covered in this report will be the changes made in the experimental unit, changes in the recommended physical properties of NaK alloy, and the data and results from 32 additional runs made on a new nickel heat exchanger with a NaK alloy composition of 46.4 Wt. % K. The problems and difficulties encountered will be discussed.

DERIVATION OF THE EQUATION FOR CORRELATION

In the previous report on "Film Heat Transfer Coefficients for Liquid Potassium-Sodium Alloys" a method was presented for calculating film coefficients from measured overall heat transfer coefficients. This method was presented as being easier than one which would require the measurement of tube wall temperatures due to the difficulty of these temperature measurements under high heat fluxes. However, this method required that the equation for correlating the individual film heat transfer coefficients must first be chosen in order to separate the measured overall heat transfer coefficients into its individual parts. The trouble with this method is that whatever equation is chosen for correlation, that equation will give results which are generally best correlated by that type of equation. It is therefore very important as to which type of equation is chosen.

In the previous report it was assumed that the convection heat transfer coefficients followed the general Nusselt type of equation* in which the Nusselt number is

*Note: See page 168 of Ref. 2

[redacted]

a function of the Reynolds and Prandtl numbers and the value of the exponents were those proposed by Colburn(3) for the center stream i.e. $hD/k = 0.023\,(D_1G_1/\mu_1)^{0.8}(c_{p1}\mu_1/k_1)^{0.33}$ and by Monrad and Pelton(4) for the annulus stream i.e. $hD/k = 0.020\,(D_a/D_o)^{0.53}(G_oD_e/\mu_o)^{0.8}(c_{po}\mu_o/k_o)^{0.33}$. In order to correlate the data by the above method it was found that a so called fouling factor was required. Since this fouling factor did not vary a great deal with temperature or time, during the collection of the data, and since no scale could be found on the heat transfer surface before or after the runs, this fouling factor may only be a mathematical trick which correlated the data without the presence of any actual scale or fouling.

In general, when other investigators worked on heat transfer measurements in clean equipment, they assume no fouling or fouling factor between the fluid and the metal wall. Therefore, it would seem logical, for a beginning, to make this same assumption.

For this report it will be assumed that the convection heat transfer coefficients follow the general Nusselt type of equation in which the Nusselt number is a function of the Reynolds and Prandtl numbers only i.e. $hD/k = \alpha(GD/\mu)^{\beta}(c_p\mu/k)^{\gamma}$ and that there is no scale or fouling. The introduction of new exponents from those obtained by Dittus and Boelter and other investigators* for the Reynolds and Prandtl numbers will be called the "Adjusted Constant Method".

The method used in the previous report will be called the "Resistance Factor Method" instead of "Fouling Factor". This change in names was thought necessary to separate any inference of the title to any actual scaling or fouling. The use of this method does not imply that fouling does exist. It may or may not exist.

The use of new methods or types of equations for correlating convection heat transfer coefficients like those now being introduced into the literature by Martinelli (5,6) and others should also be considered. Since preliminary calculations show that such methods are going to work very well, the next report will deal with this material.

1. Adjusted Constants Method.

The "Adjusted Constants Method" assumes that the convection heat transfer coefficients can be correlated by the general Nusselt type equation and that no scale or fouling

*Note: See page 168 of Ref. 2

[redacted]

exists. Since no data was obtained on the relationship between the convection coefficients for the center stream and the annulus stream, it will also be assumed that these coefficients will differ only by the additional terms of Monrad and Pelton (4) to the Nusselt type equation. The following equations and relationships may then be obtained.

$$h_i = \alpha G_i c_{pi} (G_i D_i/\mu_i)^{\beta} (c_{pi}\mu_i/k_i)^{\gamma} \tag{1}$$

$$h_o = \alpha (0.87) (D_a/D_o)^{0.53} G_o c_{po} (G_o D_e/\mu_o)^{\beta} (c_{po}\mu_o/k_o)^{\gamma} \tag{2}$$

$$\frac{h_o}{h_i} = \frac{0.87 (D_a/D_o)^{0.53} D_i^{(2+\beta)}}{(D_a^2 - D_o^2)^{(1+\beta)} (D_a - D_o)^{-\beta}} \left(\frac{\mu_i}{\mu_o}\right)^{(\beta-\gamma)} \left(\frac{c_{po}}{c_{pi}}\right)^{(1+\gamma)} \left(\frac{k_o}{k_i}\right)^{-\gamma} \tag{3}$$

$$\text{Let } Q = \frac{0.87 (D_a/D_o)^{0.53} (D_i)^{(2+\beta)}}{(D_a^2 - D_o^2)(1+\beta) \quad (D_a - D_o)^{-\beta}} \tag{4}$$

$$\text{and } S = \left(\frac{\mu_i}{\mu_o}\right)^{(\beta-\gamma)} \left(\frac{c_{po}}{c_{pi}}\right)^{(1+\gamma)} \left(\frac{k_o}{k_i}\right)^{-\gamma} \tag{5}$$

$$\text{then } h_o/h_i = SQ \tag{6}$$

The inside convection coefficient (h_i) may be calculated from the overall heat transfer coefficient (U) from the following equation:

$$h_i = \left(1 + \frac{D_i}{D_o S Q}\right) \Big/ \left[\frac{1}{U} - \frac{D_i (D_o - D_i)}{2 D_{av} k_w}\right] \tag{7}$$

$$\text{and } h_o = h_i SQ \tag{8}$$

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For the first approximation, values are chosen for α, β, and γ. The above equations are then applied to the measured overall heat transfer coefficient in order to obtain values of h_i. The value of β is checked by plotting the numerical value of $(h/G\,c_p)$ against the Reynolds number (GD/μ) of the center stream on log-log graph paper. The slope of the line drawn through the data will be β.

The numerical values of α and γ can now be checked by plotting the numerical value of $(h/G\,c_p)(GD/\mu)^{-\beta}$ against the Prandtl number $(c_p\mu/k)$ for the center stream on log-log graph paper. The slope of the line chosen to represent the data will be the value of γ and the intercept of the line with the line $(c_p\mu/k)_i = 1$ will give the value of α.

The new values of α, β, and γ are then used for the second approximation. Only about two approximations will be required. Additional information on the checking of the constants α, β, and γ can be found on page 5 of the previous report.(1)

2. Resistance Factor Method.

The resistance factor method assumes that the convection heat transfer coefficient can be correlated by the Nusselt type equation with the use of the numerical value of the constants proposed by Colburn(3) and that any deviation can be handled by a factor having the same dimensions as resistance to heat transfer.

This method is the one used in the previous report and will not be repeated here. For details the reader is referred to the previous report. (1)

EXPERIMENTAL UNIT

1. Description.

Some changes were made on the experimental unit from that previously reported. Plate 1, in the appendix, will indicate the relocation of the individual parts.

A. The double pipe heat exchanger was constructed entirely of type "A" nickel and then installed as such in the stainless steel experimental unit. The center tube had a wall thickness of 0.025 in. instead of 0.035 in. and was 33.78 in. long instead of 33.81 in. All other dimensions were the same as before.

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B. A second heater was added to the experimental unit just after the cooler. This added heater helped in adjusting the cooling rate when obtaining high temperature conditions.

C. The expansion tank was moved to a position downstream from the second heater. This made it act as a separator for foreign material in the alloy stream since the flow of liquid now passed through the expansion tank.

D. The hole in the orifice plate was increased from 0.400 to 0.600 inches. This enlargemnet decreased the pressure loss through the orifice thus permitting larger flow rates at the same developed pressure head on the pump.

E. A change was made from chromel-alumel thermocouples to 30 gauge iron-constantan thermocouples. The trouble experienced with chromel-alumel thermocouples will be found in the discussion.

F. Two mixers consisting of 6 half moon baffles each were inserted in the two outlet streams between the heat exchanger and the thermocouples. These mixers were necessary to obtain uniform temperature measurements.

G. A three-horsepower motor was installed on the pump to obtain speeds up to 3300 RPM. A "B" Belt drive was used and variable speeds obtained by varying the sheave sizes.

2. Calibration.

The orifice meter was calibrated by weighing the delivery rate of water for different manometer reading. The adapting of this calibration to different liquid flowing through the orifice and for different sealing liquids between the NaK alloy and the mercury manometer may be found in the previous report.(1)

The calibration of the 30 gauge iron-constantan thermocouples was performed by comparing the E.M.F. of the several couples with a 22 gauge thermocouple at different temperatures in an electrical calibrating muffel furnace. Due to the high temperatures involved with iron wire, the life of the couples is short lived and therefore the thermocouples must be recalibrated and replaced often.

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3. Operation.

A. Pretreating: The only difference in the pretreating from that reported in the previous report was the use of a 33% HCl solution for pickling the nickel heat exchanger before it was welded to the stainless steel unit. Short lengths of nickel piping were welded to the exchanger before pickling. Thus the final installation welding took place far enough from the heat exchange surface that no scale was produced from the welding. All other testing was done as before.

B. Operating: The operation of the experimental unit varied only slightly from the operation of the previous unit. The Reeves drive used to regulate the pump speed in the previous unit was replaced by sheaves of different sizes which maintained a constant speed drive during each of the various runs. Except for the high flow rates at low temperatures where the cooling rate was limited by the ambient incoming air. The temperature difference between the inside and annulus stream in the heat exchanger was approximately 30°F. Approximately 30 minutes was required for each run. At the close of each day, the system was cooled to room temperature and then drained into the storage tank. This operation prevented the packing in the pump from becoming impregnated with alloy during the night by a break down in the electric probing circuit. Such additional precautions required about 10 minutes at night and 15 minutes in the morning to be performed.

A different procedure had to be used in connection with the thermocouple. Only 28 or 30 gauge thermocouple wire could be used in the present thermocouple wells. The use of such fine wire in iron-constantan couples for temperature measurements up to 1200 F. required frequent calibration and replacement. The new procedure required calibration of the thermocouples every morning and night at the temperatures of operation with a second set in readiness for replacement. This procedure was an emergency one and will be changed for future work when the thermocouple wells will be changed to accommodate heavier wire or the errors involved with chromel-alumel thermocouples can be eliminated.

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4. Data Collected.

The data collected during an experimental run consisted of reading the manometer and measuring the E.M.F. generated by the four thermocouples located around the double pipe heat exchanger.

New instruments were used to measure the electrical volts and amperes supplied to the main heater. This data was obtained so that the main heater could be used as a flow colorimeter.

PHYSICAL PROPERTIES OF NaK ALLOY

Since the previous report more information on the physical properties has been made available. Each of the four physical properties are, therefore, discussed in order to present which sources of data were used in this report.

1. Density.

No change was made in the density of the 44 Wt. % KNa alloy as previously reported. The density-temperature relationship is reproduced as Figure 1 in the Appendix.

2. Viscosity.

According to report C-3105 of the Naval Research Laboratory, dated April, 1947, a ±5% accuracy in the viscosity of KNa alloy can be obtained by using a simple mixture law and the viscosities of sodium and potassium for alloys of any composition. This procedure was used in obtaining the viscosity of a 44 Wt. % K alloy from the viscosities of Na and K given in the above-mentioned report. Figure 2 in the Appendix shows a plot of the obtained viscosities. These new values are greater than those used in the previous report to the extent of 2.8% at 200°F. and 140% at 1200°F.

3. Thermal Conductivity.

Information on the thermal conductivity of KNa alloy was obtained from report C-3152 of the Naval Research Laboratory, dated July, 1947. This information was worked up for 44 Wt. % K alloy and is plotted in Figure 3 of the Appendix. These new values are greater than those used in the previous report to the extent of 10.5% at 200°F. and 15.3% at 1200°F.

[redacted]

4. Specific Heat.

The only information of specific heat used in this report was obtained from report C-3152 of the Naval Research Laboratory, dated July, 1947. This information was worked up for 44 Wt. % K alloy and the results are shown in Figure 4 of the Appendix. These new values are also greater than the ones previously used to the extent of 1% at 200°F. and 24.1% at 1200°F.

A check was attempted through use of the data collected on the main heater of the experimental unit using it as a flow calorimeter. The specific heats calculated from this data was approximately 20-30% low. Further work is needed to explain this discrepancy.

CALCULATIONS

In this section of the report, all calculations, plottings, and correlations will be reported for the 32 runs which were made on the new nickel double pipe heat exchanger.

The composition of the NaK alloy used in this set of experimental runs was found to be 46.4 Wt. % K by chemical analysis. This composition was assumed near enough to the 44 Wt. % K alloy for which this study was proposed that no corrections were made for the difference in analysis. All calculations are based as though the actual composition of the alloy had been 44 Wt. % K.

1. Dimensional Constants for Experimental Unit.

Tube diameters:

	Symbols	Inches
Inside diameter of outer tube	D_a	1.37
Outside diameter of center tube	D_o	0.75
Inside diamter of center tube	D_i	0.70

Tube diameter ratios:

$$\frac{D_a}{D_o} = \frac{1.37}{0.75} = 1.827$$

$$\frac{D_a}{D_i} = \frac{1.37}{0.70} = 1.956$$

$$\frac{D_o}{D_i} = \frac{0.75}{0.70} = 1.071$$

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The area used for heat transfer was again based only on the inside area of the center tube through which heat was being transferred.

Actual area = $\pi(0.70/12)(33.78/12)$

$A_1 = 0.516$ sq. ft.

No correction was introduced at this time to correct for changes in area due to thermal expansion.

2. Calculations Applying to Both Methods.

The method of calculating the following items is identical with the previous report:(1)

Average Temperature
Mass Flow Rate
Temperature Differentials
Hot and Cold Stream Conditions
Overall Heat Transfer Coefficients

In Figure 5 in the appendix the overall heat transfer coefficients obtained from the 32 runs on the nickel double pipe heat exchanger were plotted against the flow rate in lbs./hr. A cross plot was made by plotting the overall heat transfer coefficients against the temperature for three constants flow rates. Figure 6 shows these results.

All other calculations required different mumerical values for the constants compared to the previous report due to change in the dimension and material of construction of the heat exchanger and so each item will be considered individually.

A. Metal wall resistance to heat transfer: The metal wall resistance to heat transfer was calculated from the thermal conductivity values for nickel reported by Van Dusen and Schelton(7). These values were converted to Btu/(sq.ft.)(°F./ft.) and are reported in Figure 7 in the Appendix. Since the Thermal Conductivity was practically a straight line relationship with temperature on both sides of the Curie temperature, the wall resistance to heat transfer was calculated at 100°F., 680°F., and 1400°F. and a straight line relationship was used between points.

[redacted]

Wall resistance at 100°F.

$$= \frac{(0.70/12)(0.75/12 - 0.70/12)}{39.4\ (0.75/12 + 0.70/12)}$$

$$= 0.511 \times 10^{-4}\ ^{\circ}\mathrm{F.}/\left[(\mathrm{B.t.u.})/(\mathrm{hr.})(\mathrm{sq.ft.})\right]$$

Wall resistance at 680°F.

$$= \frac{(0.70/12)(0.75/12 - 0.70/12)}{29.7\ (0.75/12 + 0.70/12)}$$

$$= 0.675 \times 10^{-4}\ ^{\circ}\mathrm{F.}/\left[(\mathrm{B.t.u.})/(\mathrm{hr.})(\mathrm{sq.ft.})\right]$$

Wall resistance at 1400°F.

$$= \frac{(0.70/12)(0.75/12 - 0.70/12)}{35.1\ (0.75/12 + 0.70/12)}$$

$$0.573 \times 10^{-4}\ ^{\circ}\mathrm{F.}/\left[(\mathrm{B.t.u.})/(\mathrm{hr.})(\mathrm{sq.ft.})\right]$$

These results are shown in graphic form in Figure 8.

B. Mass Velocity: The mass velocity is given in lb./(hr.)(sq.ft.) and was calculated from the mass flow rate and the cross sectional area of the stream.

For the center stream.

$$G_1 = \frac{4\ w}{\pi (D_1)^2}$$

$$= \frac{4\ w\ (144)}{\pi (0.70)^2}$$

$$= 374\ w$$

[redacted]

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For the annulus stream.

$$G_o = \frac{G_1(D_1)^2}{(D_a{}^2 - D_o{}^2)}$$

$$= \frac{w\ (0.70)^2}{(1.37)^2 - (0.75)^2}$$

$$= \frac{w\ (0.49)}{1.877 - 0.562}$$

$$= 139.2\ w$$

The values of mass velocity for the center and annulus streams are reported as G_1 and G_o for each run in Table 1.

C. Reynolds number: The Reynolds number for the two streams was calculated from the mass velocity, the diameter or equivalent diameter of the stream, and the viscosity at the average temperature of the stream.

For the center stream.

$$N_{Re_1} = G_1\ D_1/\mu_1$$

$$= \frac{374\ w\ (0.70)}{12\ (2.42\ \mu_1)}$$

$$= \frac{9.02\ w}{\mu_1}$$

where the viscosity is given in centipoise instead of English units.

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For the annulus stream.

$$N_{Re_o} = G_o D_e / \mu_o$$

where $D_e = D_a - D_o$

$$N_{Re_o} = \frac{139.2\ w\ (1.37 - 0.75)}{(2.42 \mu)\quad 12}$$

$$= \frac{2.97\ w}{\mu_o}$$

where the viscosity is given in centipoise instead of English units.

D. Values of Prandtl Number: The values of the Prandtl number or $c_p \mu / k$ were obtained from the physical properties of 44 Wt. % K alloy at the desired temperatures. The values are presented in graphic form in Figure 9 in the Appendix. These values of the Prandtl number are 7.6% at 200°F. and 175% at 1200°F. higher than the values given in the previous report.

3. Correlation by Adjusted Constants Method.

In order to make the first approximation with the adjusted constants method the numberical value of the constants in the Nusselt type of equation were chosen equal to those proposed by Colburn.(3) The values of these constants in the form in which they are used are $\alpha = 0.023$, $\beta = -0.2$, and $\gamma = -0.67$.

A. Value of Q: By introducing the values of the above constants and the necessary pipe diameters in equation 4, the value of Q was obtained.

$$Q = \frac{0.87\ (1.827)^{0.53}}{(1.956 + 1.071)^{0.8}\ (1.956 - 1.071)}$$

$$= 0.558$$

This constant can be used so long as the value of $\beta = -0.2$ for the present heat exchanger.

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B. Value of S: Values of S may be obtained by introducing the above constants in equation 5.

$$S = \left(\frac{\mu_i}{\mu_o}\right)^{0.47} \left(\frac{c_{po}}{c_{pi}}\right)^{0.33} \left(\frac{k_o}{k_i}\right)^{0.67}$$

Value of the above expression may be found in Figure 10 of the Appendix.

C. Values of the convection heat transfer coefficients: The values of the convection heat transfer coefficients were calculated from equations 7 and 8 with the corresponding constants introduced.

$$h_i = \left(1 + \frac{1.672}{S}\right) \Big/ (1/U - \text{Wall Resistance})$$

$$h_o = h_i\, S\, (0.558)$$

These numerical values for the first approximation of the convection heat transfer coefficients are not reported.

D. Checking the assumed values of α, β, and γ: The value of β was checked by plotting the expression (h/Gc_p) against the Reynolds number for the center stream on log-log graph paper. Five lines were drawn through the points obtained at the five different temperatures. The average slope was -0.5. This was quite a change from the assumed value of $\beta = -0.2$. Figure 11 in the Appendix shows the results of this plotting.

The value of α and γ were checked by plotting the value of the expression $(h/Gc_p)\ (GD/\mu)^{0.5}$ against the Prandtl number for the inside stream. Figure 12 in the Appendix shows this data plotted on log-log paper. The slope of the line chosen to represent the data was -0.69 (the value of γ). The intercept at $(c_p \mu/k)_i = 1$ was 0.027 (the value of α).

These new values were used for the second approximation.

[redacted]

E. Second Approximation: The values of the constants were now $\alpha = 0.027$, $\beta = -0.5$ and $\gamma = -0.69$. A new value and a graph had to be prepared for Q and for S. Figures 13 in the Appendix show the new value for S. Q now equals 0.778.

At this point an attempt was made to see if any resistance factor could be obtained. A graph, which is Figure 14, had to be prepared giving the values of the function J*. The attempt at a resistance factor is shown in Figure 15 in the Appendix. The data indicated that no resistance factor could be obtained.

The values of h_1 and h_o for the second approximation were determined from the following formulae:

$$h_1 = \left(1 + \frac{1.200}{S}\right) \Big/ \left(\frac{1}{U} - \text{Wall Resistance}\right)$$

$$h_o = h_1 S\ (0.778)$$

These values of h_1 and h_o are reported in Table 1 of the Appendix.

A recheck on the values of the constants by the method above gave $\alpha = 0.227$, $\beta = 0.5$, and $\gamma = 0.69$. Figure 16 and 17 in the Appendix show the graphs use in the second approximation. A third approximation will not be needed since there were only slight changes in the value of the constants.

The correlation formulae for h_1 and h_o are as follows:

$$h_1 = 0.227\ G_1 cp_1\ (G_1 D_1/\mu_1)^{-0.5}\ (cp_1 \mu/k_1)^{-0.69}$$

$$h_o = 0.1975\ (D_a/D_o)^{0.53}\ G_o cp_o (G_o D_e/\mu_o)^{-0.5} cp_o \mu_o/k_o)^{-0,69}$$

---

*Note: This function J is described in the previous report and in the calculations on the resistance factor method in this report on a latter page.

[redacted]

The equation for h_1 with slight rearranging was checked by plotting the experimental points and comparing them with the equation. Figure 18 shows the results of this plotting and gives a maximum disagreement of +11% to -10% with a mean deviation of 3.7%.

4. Correlation by Resistance Factor Method.

The resistance factor method is included in this report as a comparison and because it was the method used in the previous report. The values of the constants in the Nusselt type of equation were also chosen equal to those proposed by Colburn(3) for the first approximation. In the form used in this report $\alpha = 0.023$, $\beta = 0.2$, and $\gamma = 0.67$.

A. Values of S and Q: Since the same values for the constants were chosen as in the first approximation by the adjusted constants method there will be no change in S or Q. Figure 10 shows the value of S and Q = 0.558. These values will hold as long as there is no change in the assumed values of the constants.

B. Value of J: The value of J can be found from the following formula by definition:

$$J = \frac{\left(\frac{c_{p_1} \mu_1}{k_1}\right)^{0.67} \left(1 - \frac{D_1}{D_o S Q}\right)}{0.023\ c_{p_1}}$$

Figure 19 in the appendix shows the value of J in graphic form.

C. Value of the "Resistance Factor": Figure 20 shows a resistance factor graph constructed by plotting $1/U - D_1 (D_o - D_1)/2 D_{av} k_w$ against $J (G_1 D_1/\mu_1)^{0.2}/G_1$. The intercept along the Y - axis gave a value of resistance factor i.e. $R = 0.000125$°F./$\left[(\text{B.t.u.})/(\text{hr.})(\text{sq.ft.})\right]$.

[redacted]

D. Values of film heat transfer coefficients. The values of the film heat transfer coefficients were obtained by introducing the values of S, the overall coefficients, and the wall resistance into Equations 7 and 8, which are rewritten below with the numerical constants.

$$h_i = 1 + \frac{1.672}{S} \quad 1/U - \text{Wall Resistance} - 0.000125)$$

$$h_o = h_i S(0.558)$$

These values are reported in Table 1 of the Appendix.

E. Checking the assumed values of α, β, and γ. The value of β was checked by plotting the values of (h/Gc_p) against the Reynolds number for the center stream on log-log graph paper. The slope of the lines drawn through the points for each temperature was measured and the values averaged. The average slope was found to be -0.2 which was the assumed value. Figure 21 in the appendix shows the results of this plotting.

The values of α and γ were found from Figure 22 in the Appendix where $(h/Gc_p)(GD/\mu)^{0.2}$ was plotted against $(cp\mu/k)$ for the center stream on log-log graph paper. The data was quite scattered but a line was finally decided upon which gave a slope of -0.55 (the value of γ) and an intercept of 0.023 (the value of α) at the value of $(cp\mu/k) = 1$.

Since the value of α and β checked the assumed values, a second approximation was not needed as the same values of the resistance factor would have been obtained.

The equations now have the following form:

$$h_i = 0.023\, G_i c_{pi} (G_i D_i/\mu_i)^{-0.2}$$

$$(cp_i\, \mu_i/k_i)^{-0.55}$$

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$$h_o = 0.020\, G_o c_{po} (G_o D_e/\mu_o)^{-0.2}$$

$$\cdot\ (c_{po}\,\mu_o/k_o)^{-0.55}\ (D_a/D_o)^{0.53}$$

The equation for h_i is plotted in Figure 23 in the Appendix in a different form along with the experimental data. A maximum disagreement of +20% to -16% was obtained with a mean deviation of 6.4% when all but one run was included. This one run was eliminated because it was made at a much lower flow rate than the others.

DISCUSSION

The operations of and the results obtained from the nickel heat exchanger suggest several items on which further comments should be made.

1. Fluid Mixers.

The addition of six half-moon baffles to each of the two pipe lines leaving the double pipe heat exchanger and located before the thermocouples contributed greatly to smoothing out temperature fluxuations. The heat balance around the double pipe heat exchanger was thereby greatly improved.

Mixing by the pump was sufficient for smoothing out the temperature reading at one of the two entrance lines. On the other it was thought that approximately two feet of piping between the heater and thermocouple would be sufficient to give good mixing. However, this was not as good as expected and a mixer will be added for future work.

2. Thermocouples.

A great deal of trouble was experienced in the use of chromel-alumel thermocouples. It was found that at 800°F. if the thermocouples were slowly withdrawn from the thermocouple wells the temperature equivalent of the couples rose 11°F. on three couples and rose 14°F. on the 4th couple before the temperature equivalent started falling. The thermocouple wells consisted of 1/8 inch O.D. nickel tubing with an immersion of approximately 4 inches inside the piping. The last two inches were located along the center line of the pipe. It was felt that no such temperature

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gradient could possibly exist especially on runs where no heat transfer took place. The manufacture of the thermocouple wire is now in the process of running similar experiments with the hope of removing such errors.

The experiment was repeated with iron-constantan thermocouple wire with the results that only a 1/2°F. variation occurred before the temperature dropped. Iron-constantan thermocouples appeared to be satisfactory, however, heavier wire will be required for work above 1000°F.

3. 500 - 800°F. Anomaly.

An inspection of either Figure 5 or 6 in the Appendix indicates that some sort of phenomenon occurred between 500 and 800°F. in respect to the heat transfer rates. The change in the overall heat transfer coefficient with temperature is less predominate between 500 and 800°F. than for any other temperature range. This phenomenon was first thought to be due to physical change in the properties of the system such as wetting. Reference to the history of the experimental runs indicate there was a lapse of time between runs at the two lower temperatures and the three higher temperatures at which time the equipment stood idle. This lapse of time may have allowed a slight fouling to take place. Further runs will have to be made before any definite explanation will be attempted to explain this 500 - 800°F. anomaly.

4. Anomaly in Correlation by Reynolds Number.

Reference to Figure 21 on the correlation of convection heat transfer coefficients with Reynolds number by the resistance factor method indicates a break occurs at each temperature towards the low Reynolds number end of the graph. Dotted lines were used to indicate this anomaly. This same break occurs in the data correlated by the adjusted constants method (Figure 16) but only to the extent of the spread in the data.

This anomaly could not be the break between viscous and turbulent flow as measured by friction in pipes since it occurs at too high a Reynolds number.

It would appear from this break that the convection heat transfer coefficient does not decrease as rapidly as predicted by the present correlation when operating at lower Reynolds number, thus indicating that at low flows

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the heat transfer rate is increased due to the high thermal conductivity of the liquid. This conclusion is substantiated by the work of Martinelli (5,6) and others, and since preliminary calculations using their methods show close agreement with the data it has been decided that the next report will be devoted to this type of correlation.

CONCLUSIONS

The work on the convection heat transfer coefficients for liquid sodium-potassium alloys has been extended to 1200°F. and 12 ft./sec. velocity in a nickel double pipe heat exchanger. The results obtained can be correlated by the Nusselt type of equation with new numerical constants called the "Adjusted Constant Method" over the range of temperatures and velocities covered in this report. The recommended equations are as follows:

$$h_i = 0.227\, G_i\, c_{pi}\, (G_i D_i/\mu_i)^{-0.5}\, (c_{pi}\mu_i/k_i)^{-0.69}$$

$$h_o = 0.1975\, (D_a/D_o)^{0.53} G_o c_{po}\, (G_o D_e/\mu_o)^{-0.5}\, (c_{po}\mu/k_o)^{-0.69}$$

The above equations had a maximum disagreement of +11% to -10% with a mean deviation of 3.7% for the data reported.

Since the above equations can correlate the data without the use of a resistance factor it can be concluded that there was no or very little scaling or fouling during the experimental runs.

Preliminary calculations indicate that the data can be correlated by the method or type of equations being introduced into the literature by such investigators as Martinelli and others. The next report will deal with this correlation.

Future experimental work will deal with other sodium-potassium compositions, heat exchangers which will use two separate flowing streams and attempts to run longer periods of time to study actual fouling or scaling conditions.

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APPENDIX

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LETTER SYMBOLS

DRAWINGS

1. Double Pipe Heat Exchanger No. 3.

TABLES

1. Data and Results - Double Pipe Heat Exchanger No. 3 - KNa Alloy 44 Wt. % K.

FIGURES

1. Density of KNa Alloy - Alloy No. 5 - 44 Wt. % K.
2. Viscosity of KNa Alloy - Alloy No. 5 - 43.5 Wt. % K.
3. Thermal Conductivity of KNa Alloy - 44 Wt. % K.
4. Specific Heat of KNa Alloy - Alloy No. 5 - 44 Wt. % K.
5. Plot of Flow Rate with Overall Heat Transfer Coefficient in Figure of Eight Heat Exchanger No. 3 - 44 Wt. % K Alloy.
6. Cross Plot of Temperature with Overall Heat Transfer Coefficients holding Flow Rate Constant in Figure 5.
7. Thermal Conductivity - Type "A" Nickel.
8. Wall Resistance to Heat Transfer.
9. Prandtl Number for KNa Alloy - 44 Wt. % K.
10. Value of S = $\left(\frac{\mu_i}{\mu_o}\right)^{0.47} \left(\frac{c_{po}}{c_{pi}}\right)^{1/3} \left(\frac{k_o}{k_i}\right)^{2/3}$ for 44 Wt. % Alloy.
11. Effect of Reynolds Number of Heat Transfer Coefficient for KNa Alloy in Figure of Eight Double Pipe Heat Exchanger - 1st Approximation - Adjusted Constants Method.
12. Effect of Prandtl Number on Heat Transfer Coefficients for KNa Alloy in Figure of Eight Double Pipe Heat Exchanger. Center Stream Data - 1st Approximation - Adjusted Constants Method.
13. Value of S = $(\mu_i/\mu_o)^{0.19} (cp_o/cp_i)^{0.31} (k_o/k_i)^{0.69}$ For 44 Wt. % K Alloy.

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14. Value for the Expression $J = (cp_1 \mu_1/k_1)^{0.69}$

$$\left[1 + D_1 \Big/ D_o(\mu_1/\mu_o)^{0.19}(cp_o/cp_1)^{0.31}(k_o/k_1)^{0.69}(0.778)\right]$$

$$x \frac{1}{0.227}\ cp_1$$

15. Attempt to Determine Resistance When Using Adjusted Constants Method in Figure of Eight Heat Exchanger No. 3 - 44 Wt. % K Alloy.
16. Effect of Reynolds Number on Heat Transfer Coefficient for KNa Alloy in Figure of Eight Double Pipe Heat Exchanger - 44 Wt. % K Alloy. 2nd Approximation - Adjusted Constants Method.
17. Effect of Prandtl Number on Heat Transfer Coefficient for KNa Alloy in Figure of Eight Double Pipe Heat Exchanger. Center Stream Data - 44 Wt. % K Alloy - 2nd Approximation - Adjusted Constants Method.
18. Heat Transfer Data - 44 Wt. % K Alloy in Nickel Double Pipe Heat Exchanger - 2nd Approximation - Adjusted Constants Method.
19. Value for the Expression $J = (c_{p1}\mu_1/k_1)^{2/3}$

$$1 + \frac{D_1}{D_o(\mu_1/\mu_o)^{0.47}(cp_1/cp_o)^{1/3}(k_o/k_1)^{2/3}\ (0.558)}$$

$$x \quad \frac{1}{0.023\ cp_1}$$

20. Plot for Determining Resistance Factor in Figure of Eight Heat Exchanger No. 3 - 44 Wt. % K Alloy.
21. Effect of Reynolds Number on Heat Transfer Coefficient for KNa Alloy in Figure of Eight Double Pipe Heat Exchanger - 44 Wt. % K - Resistance Factor Method.
22. Effect of Prandtl Number on Heat Transfer Coefficients for KNa Alloy in Figure of Eight Double Pipe Heat Exchanger. Center Stream Data 44 Wt. % K Alloy - Resistance Factor Method.
23. Heat Transfer Data - 44 Wt. % K Alloy - Nickel Double Pipe Heat Exchanger - Resistance Factor Method.

REFERENCES

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LETTER SYMBOLS

A	- Area	sq. ft.
c_p	- Specific heat at constant pressure	B.t.u./(lb.)(°F.)
D	- Diameter of pipe or tube	ft.
G	- Mass velocity	lb./(hr.)(sq.ft.)
h	- Coefficient of heat transfer, individual	B.t.u./(hr.)(sq.ft)(°F.)
J	- Numerical function	
k	- Thermal conductivity	B.t.u./(hr.)(sq.ft.)(°F./ft.)
N_{Nu}	- Nusselt number	(hD/k)
P_{Pr}	- Prandtl number	(cp /k)
N_{Re}	- Reynolds number	(GD/)
q	- Rate of heat transfer	B.t.u./(hr.)(sq.ft.)
Q	- Numerical constant	
R	- Resistance factor	
S	- Numerical function	
t	- temperature	°F.
Δt	- temperature differential	°F.
U	- Heat transfer coefficient, overall	B.t.u./(hr.)(sq.ft.)(°F.)
w	- Mass flow rate	lb./hr.
ρ	- Density	lb./cu.ft.
μ	- Viscosity	lb./(sec.)(ft.) or centipoise

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Subscripts

a - Refers to inside diameter of outer tube of pipe.

av - Refers to average diameter of metal tube wall.

c - Refers to cool stream in double pipe heat exchanger.

e - Refers to equivalent diameter.

h - Refers to hot stream in double pipe heat exchanger.

i - Refers to inside surface of center tube.

m - Refers to mean condition.

o - Refers to outside surface of center tube.

w - Refers to water.

Unknowns

α - Unknown numerical constant

β - Unknown numerical exponent

γ - Unknown numerical exponent

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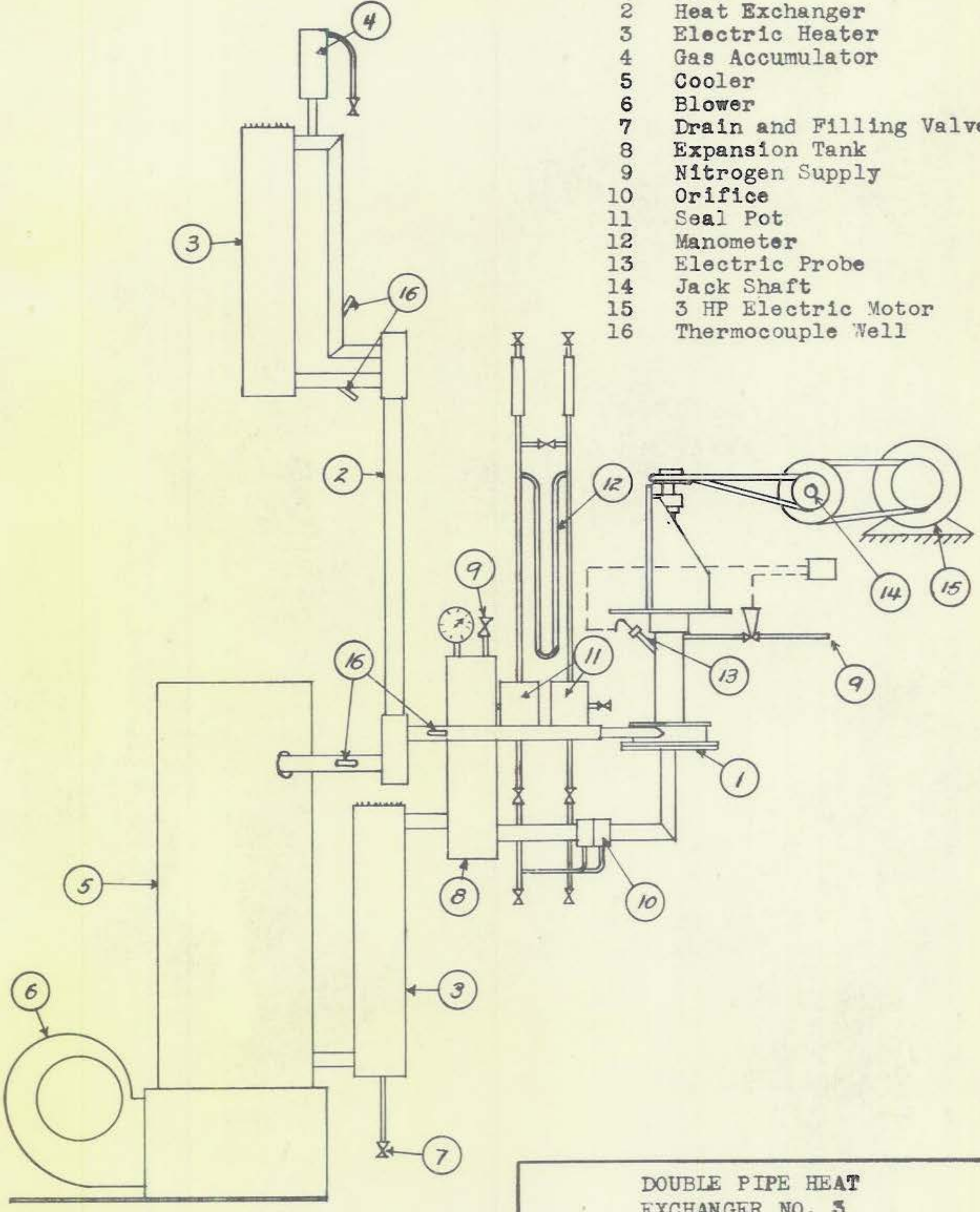

Item	Discription
1	Pump
2	Heat Exchanger
3	Electric Heater
4	Gas Accumulator
5	Cooler
6	Blower
7	Drain and Filling Valve
8	Expansion Tank
9	Nitrogen Supply
10	Orifice
11	Seal Pot
12	Manometer
13	Electric Probe
14	Jack Shaft
15	3 HP Electric Motor
16	Thermocouple Well

DOUBLE PIPE HEAT
EXCHANGER NO. 3

Scale 1" = 12"	Date 12-1-47
D'n by - E. King	Plate No. 1

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DATA AND RESULTS

DOUBLE PIPE HEAT EXCHANGER NO. 3

KNa ALLOY 44 Wgt. % K

CE FACTOR		USING ADJUSTED CONSTANTS				
$\left(\frac{h}{Gc_p}\right)\left(\frac{GD}{\mu}\right)_i^{0.2}$ inside	$\left(\frac{hD}{k}\right)_i\left(\frac{cp}{k}\right)_i^{-.45}$	Film Coefficients inside h_i	Film Coefficients outside h_o	Factor $\left(\frac{h}{Gc_p}\right)_i$	$\left(\frac{h}{Gc_p}\right)\left(\frac{GD}{\mu}\right)_i^{0.5}$	$\left(\frac{hD}{k}\right)\left(\frac{cp}{k}\right)_i^{-.31}$
.1977	260.0	6560	5040	.00983	3.34	76.7
.203	239.0	6220	4770	.01072	3.41	72.9
.1980	194.7	5450	4160	.01165	3.36	64.0
.203	172.0	4960	3780	.01310	3.38	58.0
.201	130.0	3990	3040	.01457	3.20	46.8
.204	127.3	3970	3020	.01507	3.25	46.6
.222	115.0	3640	2770	.01795	3.38	42.7
.303	78.0	2650	2020	.0305	3.78	31.0
.246	356.0	7380	5680	.01053	4.30	92.8
.253	312.0	6820	5250	.01189	4.40	85.7
.242	260.0	6070	4660	.01263	4.28	76.3
.250	230.0	5600	4310	.01406	4.32	70.3
.249	177.3	4650	3580	.01606	4.20	58.4
.286	159.5	4280	3290	.0202	4.53	55.3
.270	402.0	7570	5830	.01077	5.01	99.5
.265	340.0	6840	5270	.01176	4.99	89.9
.259	286.0	6130	4720	.01277	4.90	80.7
.272	256.0	5700	4390	.01450	5.05	74.6
.276	206.0	4910	3780	.01708	5.08	64.6
.306	172.5	4290	3320	.0207	5.22	56.1
.322	496.0	8340	6430	.01158	5.80	110.5
.312	394.0	7370	5680	.01311	5.75	97.8
.321	345.0	6780	5230	.01480	5.86	90.0
.318	285.0	5830	4630	.01638	5.80	79.7
.316	224.0	5090	3930	.01920	5.87	67.7
.360	192.5	4560	3520	.02390	6.11	60.5
.392	570.0	8880	6850	.01358	6.78	117.8
.392	430.0	7650	5900	.01410	6.38	101.6
.384	400.0	7320	5650	.01670	6.76	97.4
.303	271.0	5740	4430	.01572	5.84	76.4
.292	203.0	4670	3600	.01726	5.59	62.1
.381	205.0	4720	3640	.0244	6.59	62.8

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						USING RESISTA		
Mass Velocity		Reynolds No.		Prandtl No.		Film Coefficients		Factor
inside G_i	outside G_o	inside N_{Re_i}	outside N_{Re_o}	inside N_{Pr_i}	outside N_{Pr_o}	inside	outside	$\left(\frac{h}{Gc_p}\right)_i$
2,260,000	840,000	116,700	36,400	.020	.0212	12,850	6,910	.01920
1,945,000	725,000	101,000	31,500	.0198	.0210	11,770	6,330	.02030
1,570,000	585,000	82,700	25,400	.0197	.0211	9,630	5,180	.02060
1,270,000	472,000	66,700	20,600	.0198	.0211	8,460	4,550	.02200
920,000	342,000	48,500	15,100	.0196	.0209	6,370	3,420	.02330
884,000	329,000	46,400	14,300	.0197	.0210	6,290	3,380	.02390
681,000	254,000	35,600	11,030	.0198	.0212	5,670	3,050	.02790
292,000	108,500	15,100	4,720	.0198	.0212	3,840	2,060	.04420
2,280,000	848,000	166,700	53,000	.0139	.0145	15,550	8,460	.02220
1,870,000	695,000	136,500	43,400	.0139	.0145	13,650	7,430	.02380
1,570,000	583,000	114,700	36,400	.0140	.0145	11,370	6,190	.02360
,297,000	482,000	94,800	30,100	.0140	.0145	10,050	5,470	.02530
943,000	351,000	69,000	21,900	.0139	.0145	7,750	4,220	.02680
692,000	256,000	50,600	16,100	.0139	.0144	6,960	3,790	.03280
,210,000	820,000	216,000	69,600	.0103	.0106	16,200	8,870	.02310
,830,000	681,000	180,000	57,800	.0103	.0106	13,700	7,500	.02360
,510,000	561,000	147,800	50,700	.0103	.0106	11,520	6,300	.02400
,235,000	458,000	121,000	38,900	.0104	.0106	10,300	5,640	.02620
905,000	337,000	88,700	28,500	.0103	.0106	8,320	4,560	.02900
651,000	242,000	66,300	20,500	.0104	.0106	6,950	3,810	.03360
,200,000	820,000	249,000	79,700	.0090	.0091	19,300	10,600	.02680
,720,000	639,000	193,000	62,100	.0090	.0090	15,430	8,470	.02740
,402,000	521,000	157,200	50,700	.0090	.0090	13,430	7,370	.02930
,121,000	417,000	125,500	40,500	.0090	.0091	11,100	6,100	.03030
812,000	311,000	93,600	30,100	.0090	.0090	8,730	4,800	.03200
583,000	217,000	65,500	21,000	.0090	.0090	7,500	4,120	.03930
,955,000	741,000	250,000	81,200	.0080	.0081	21,800	11,980	.03260
1,620,000	602,000	202,000	66,000	.0080	.0081	16,450	9,030	.03400
1,310,000	487,000	164,000	54,300	.0080	.0081	15,230	8,360	.0348
1,090,000	406,000	137,200	44,500	.0080	.0081	10,380	5,700	.0284
809,000	301,000	101,300	31,900	.0080	.0081	7,760	4,270	.0286
576,000	214,000	72,700	23,500	.0080	.0081	7,870	4,320	.0407

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DATA

Run No.	Av. Temp. °F.	Flow Rate lbs/hr	Temp. Drop t_h °F.	Temp. Diff. t_m °F.	Av. Temp. inside t_i °F.	outside t_o °F.	Over-all U	1/U	Wall Resist.
1	301	6030	14.9	20.5	314	288	2530	.000395	.0000569
2	305	5200	21.5	26.7	318	292	2420	.000415	.000057
3	306	4200	27.6	31.2	322	290	2150	.000465	.000057
4	305	3400	30.1	29.9	320	290	1975	.000506	.000057
5	308	2460	35.8	31.1	323	296	1633	.000612	.000057
6	306	2360	35.1	29.7	322	292	1617	.000618	.000057
7	304	1820	44.7	31.1	319	288	1505	.000665	.000057
8	304	780	74.0	29.8	318	289	1117	.000895	.000057
9	516	6100	21.2	27.9	531	502	2760	.000362	.000062
10	516	5000	25.2	28.9	531	502	2590	.000386	.000062
11	515	4200	28.4	30.2	530	500	2350	.000426	.000062
12	515	3470	29.6	28.0	530	501	2190	.000457	.000062
13	517	2520	35.8	28.9	531	502	1855	.000538	.000062
14	518	1850	47.4	30.2	533	503	1730	.000578	.000062
15	802	5900	22.4	29.2	814	787	2790	.000358	.000066
16	800	4900	24.0	28.2	814	786	2570	.000389	.000066
17	797	4030	28.7	30.3	813	784	2350	.000426	.000066
18	798	3300	30.3	28.0	812	785	2200	.000454	.000066
19	797	2420	38.0	29.5	814	786	1925	.000517	.000066
20	798	1740	45.0	28.0	812	785	1720	.000581	.000066
21	1003	5800	22.7	27.3	1016	989	3050	.000328	.000063
22	1002	4600	26.2	27.8	1016	988	2750	.000363	.000063
23	1004	3750	27.4	25.4	1016	990	2570	.000389	.000063
24	1002	3000	34.8	28.5	1016	988	2320	.000431	.000063
25	1003	2230	39.2	27.5	1016	989	2010	.000497	.000063
26	1004	1560	52.5	28.5	1016	990	1822	.000548	.000063
27	1203	5330	26.0	27.8	1215	1189	3240	.000309	.000060
28	1202	4330	28.6	28.1	1216	1188	2860	.000349	.000060
29	1202	3500	30.8	25.3	1216	1189	2760	.000362	.000060
30	1202	2920	29.6	25.0	1215	1189	2240	.000445	.000060
31	1202	2160	34.0	23.5	1213	1189	1875	.000533	.000060
32	1206	1540	49.1	25.9	1219	1192	1893	.000528	.000060

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Figure 1

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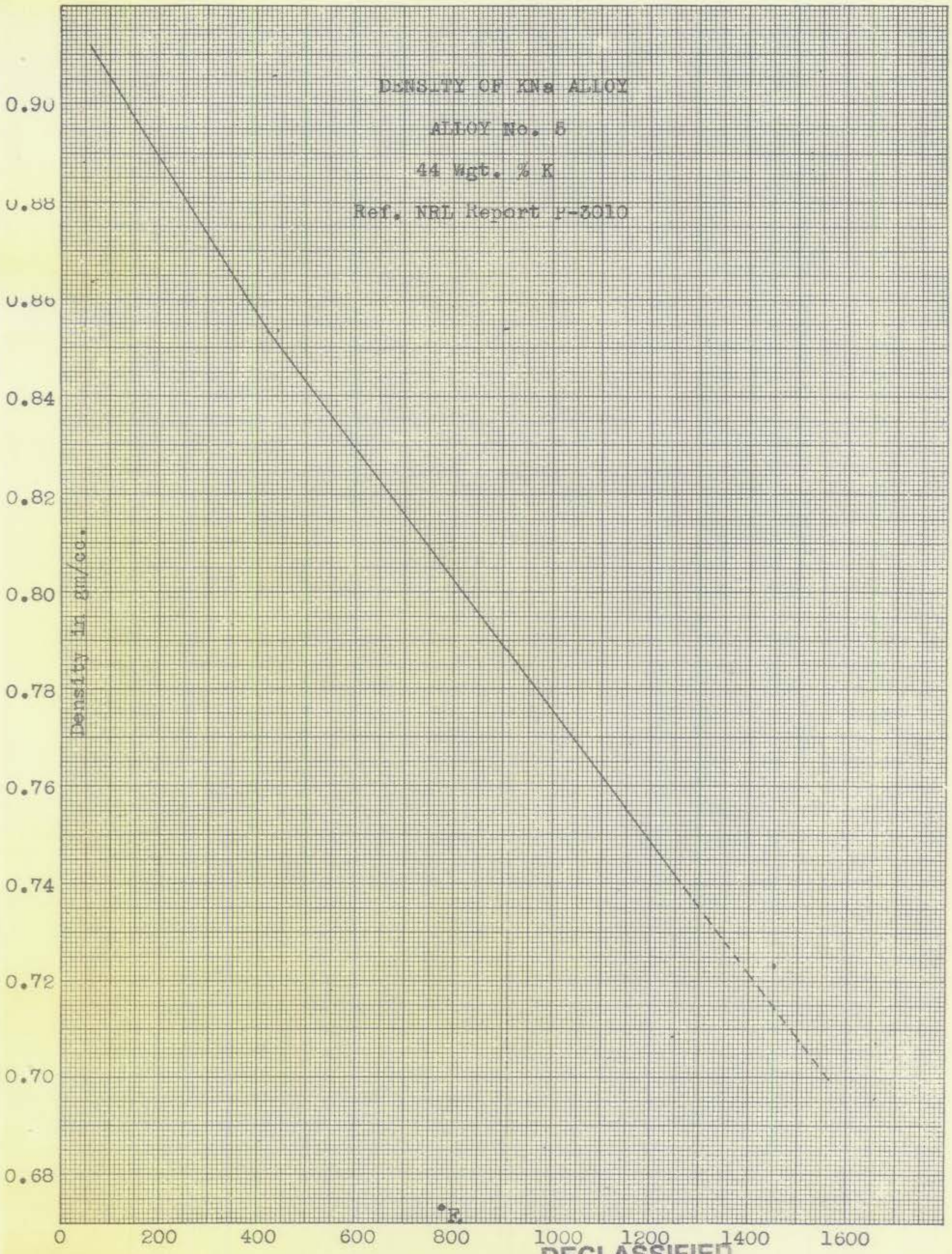

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Figure 2

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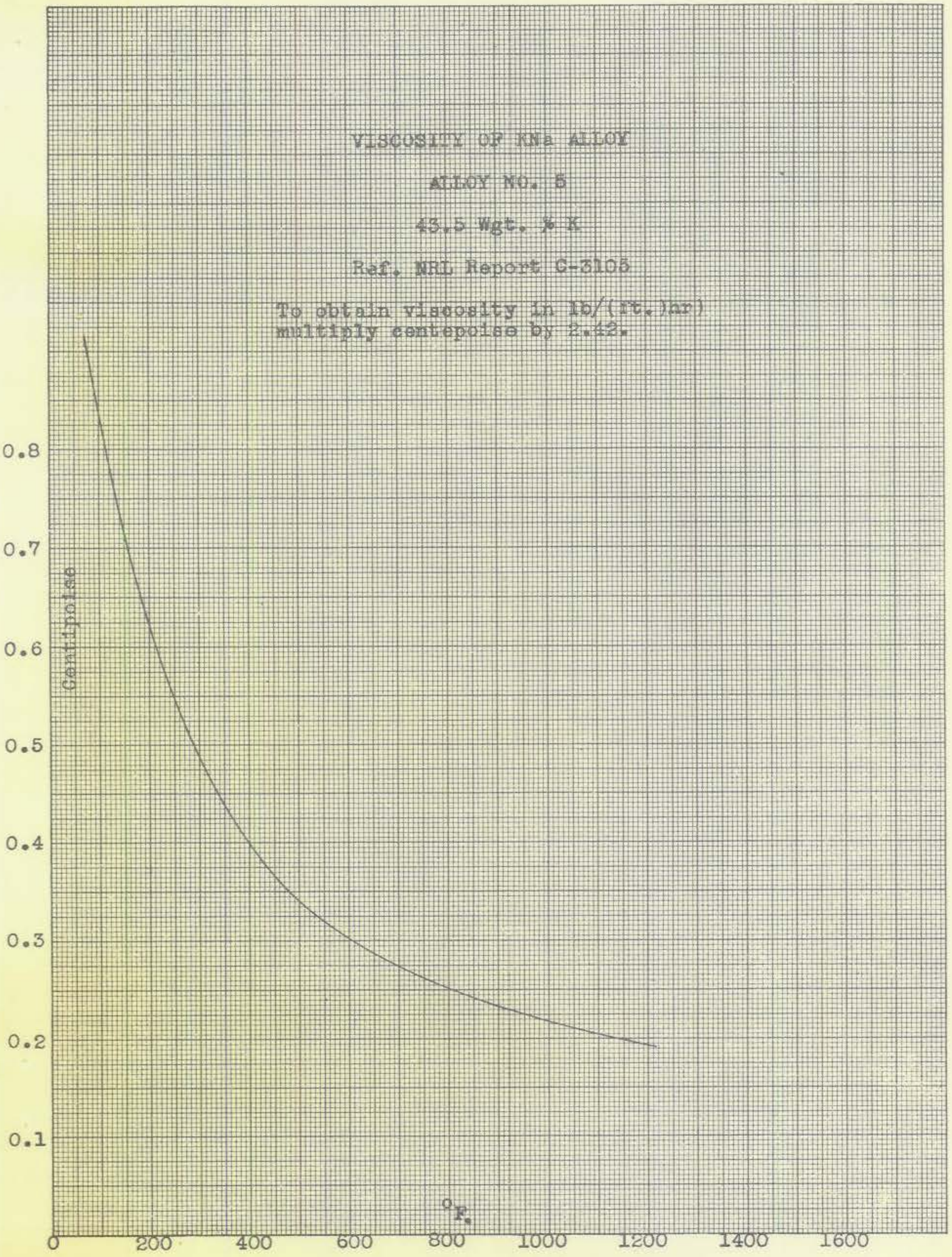

VISCOSITY OF KNa ALLOY

ALLOY NO. 5

43.5 Wgt. % K

Ref. NRL Report C-3105

To obtain viscosity in lb/(ft.)hr)
multiply centepoise by 2.42.

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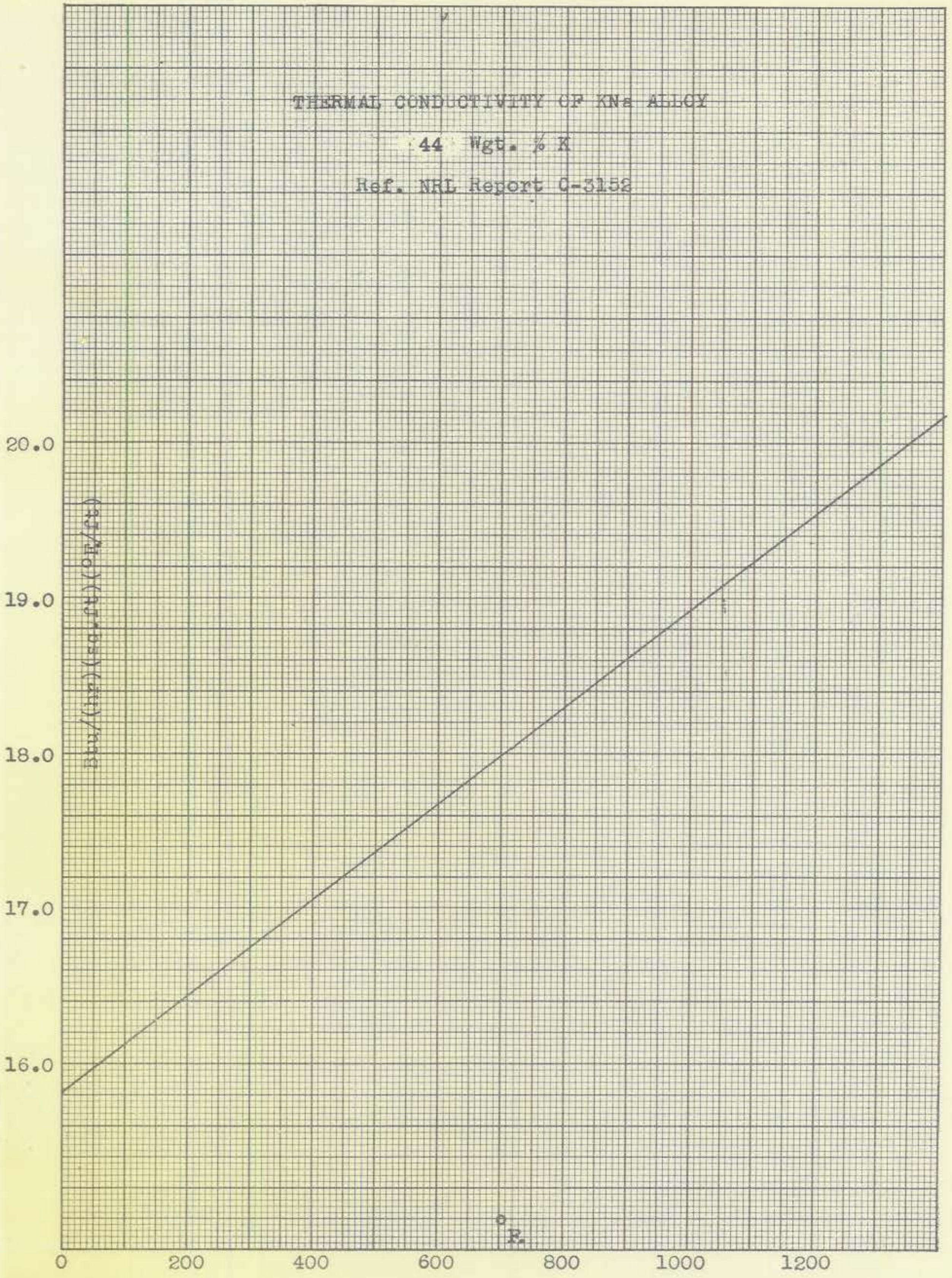
Figure 3



THERMAL CONDUCTIVITY OF KNa ALLOY

44 Wgt. % K

Ref. NRL Report C-3152

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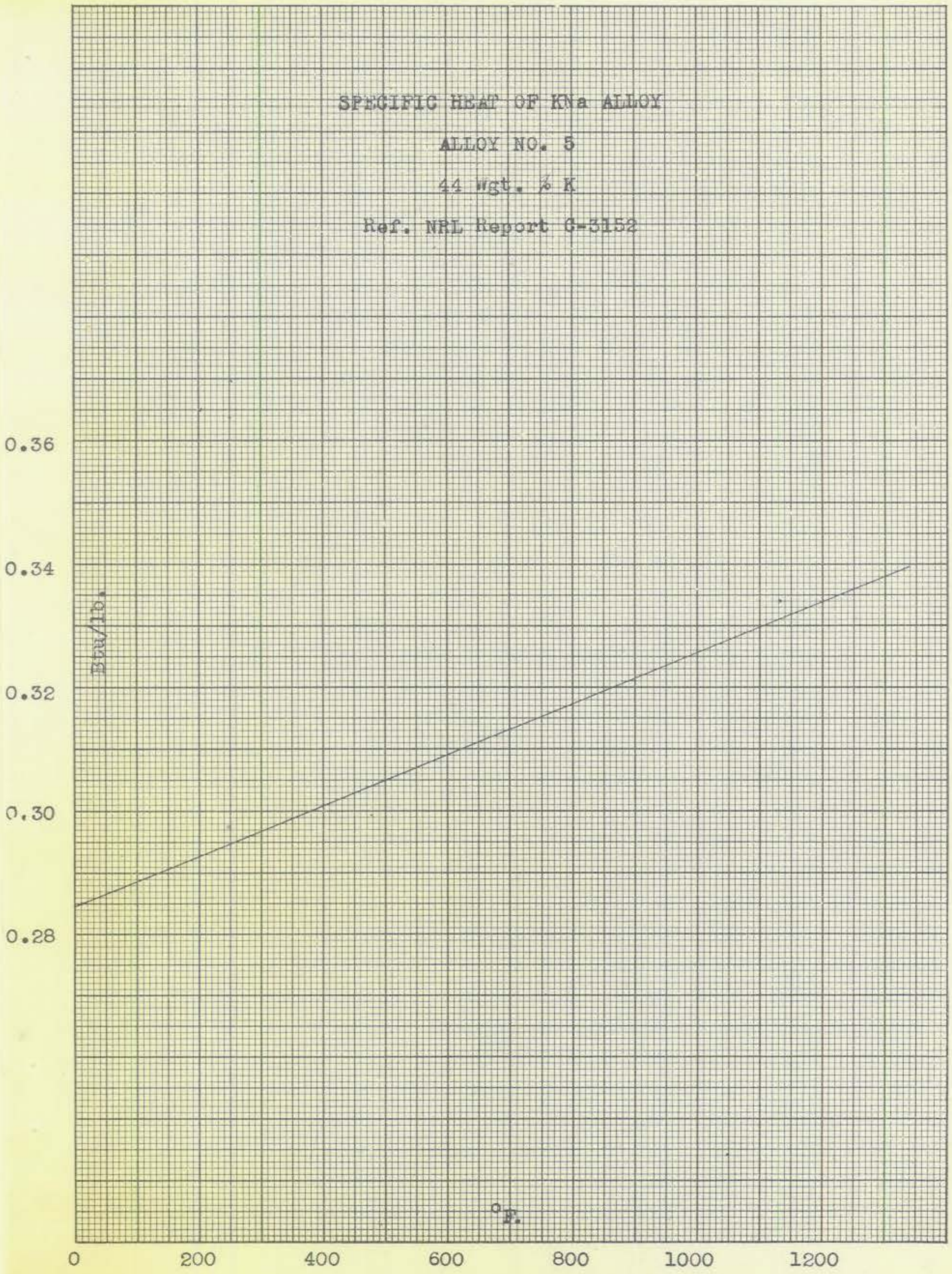
Figure 4



SPECIFIC HEAT OF KNa ALLOY

ALLOY NO. 5

44 Wgt. % K

Ref. NRL Report C-3152

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[redacted]

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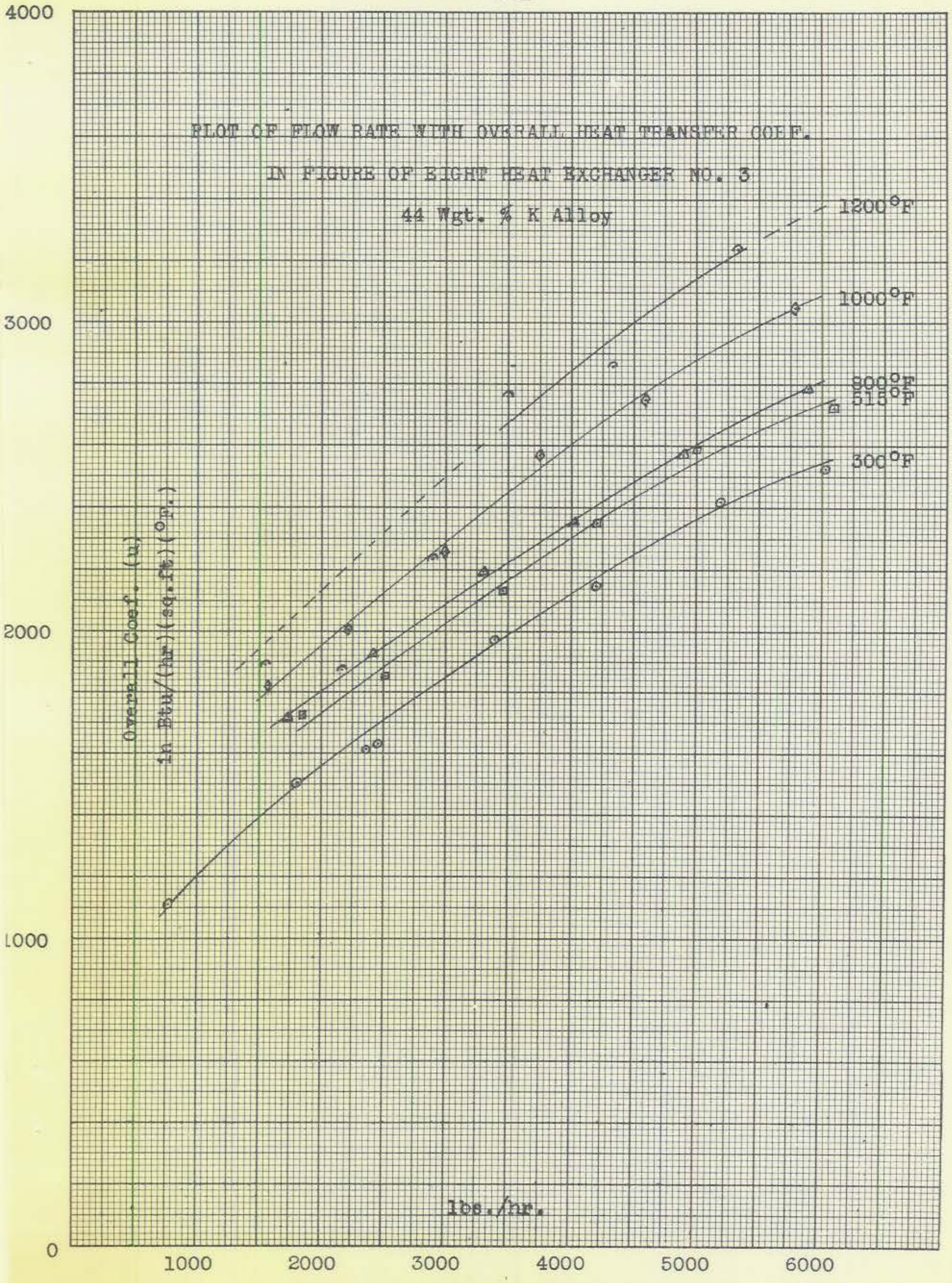
Figure 5



PLOT OF FLOW RATE WITH OVERALL HEAT TRANSFER COEF.

IN FIGURE OF EIGHT HEAT EXCHANGER NO. 3

44 Wgt. % K Alloy

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[redacted]

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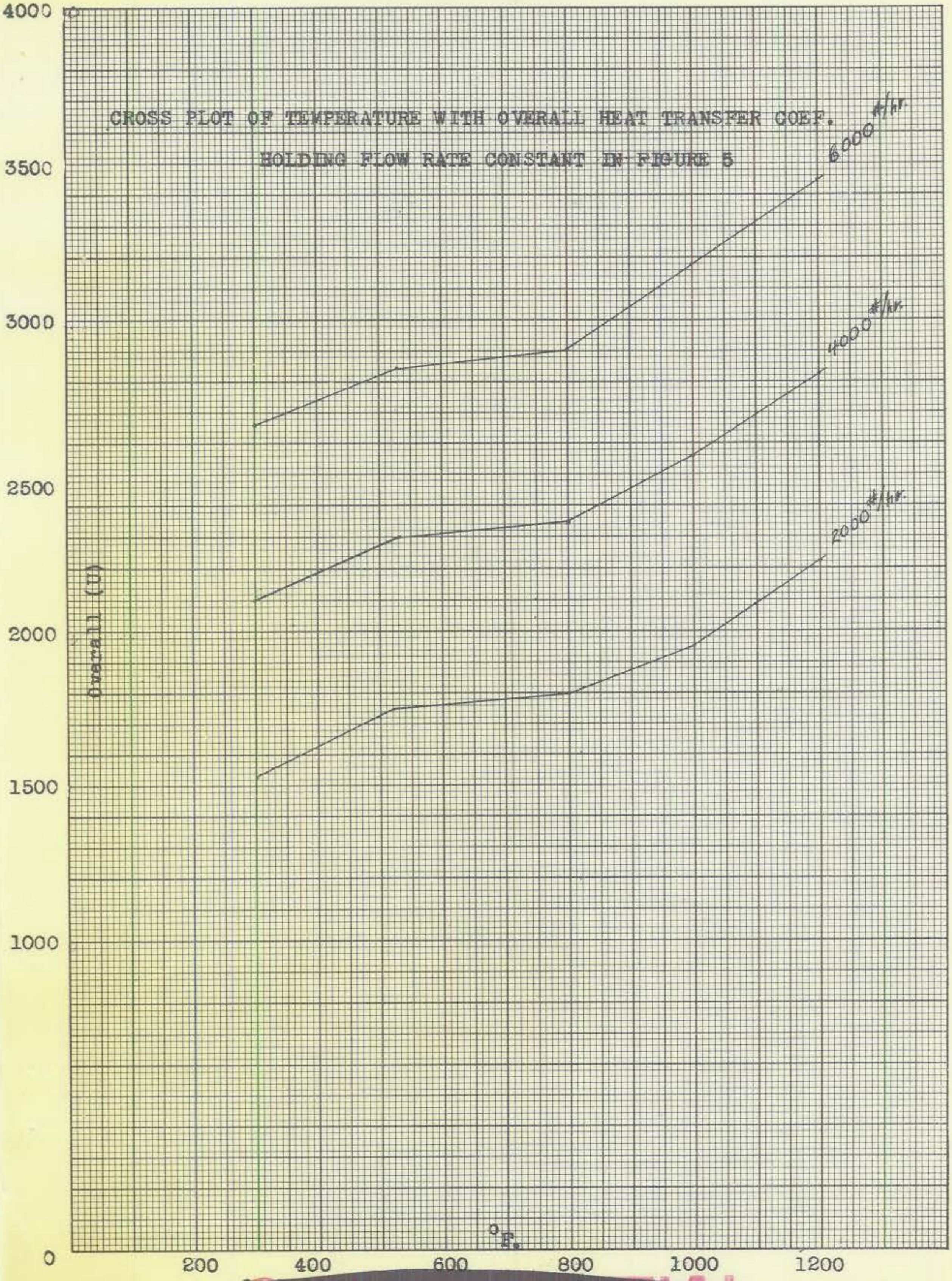
Figure 6



CROSS PLOT OF TEMPERATURE WITH OVERALL HEAT TRANSFER COEF.
HOLDING FLOW RATE CONSTANT IN FIGURE 5

[redacted]

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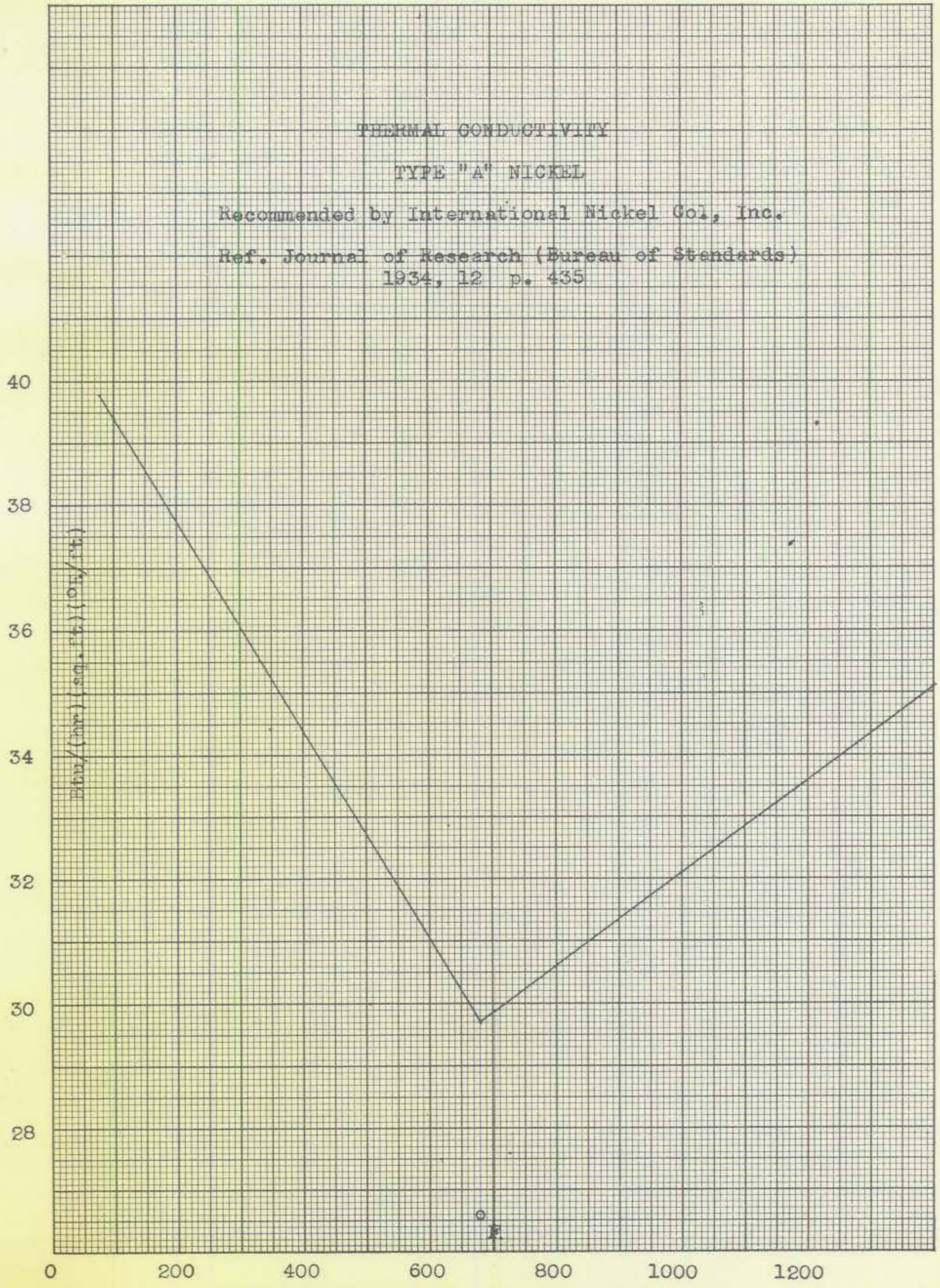
Figure 7



THERMAL CONDUCTIVITY

TYPE "A" NICKEL

Recommended by International Nickel Co., Inc.

Ref. Journal of Research (Bureau of Standards)
1934, 12 p. 435

[redacted]

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Figure 8

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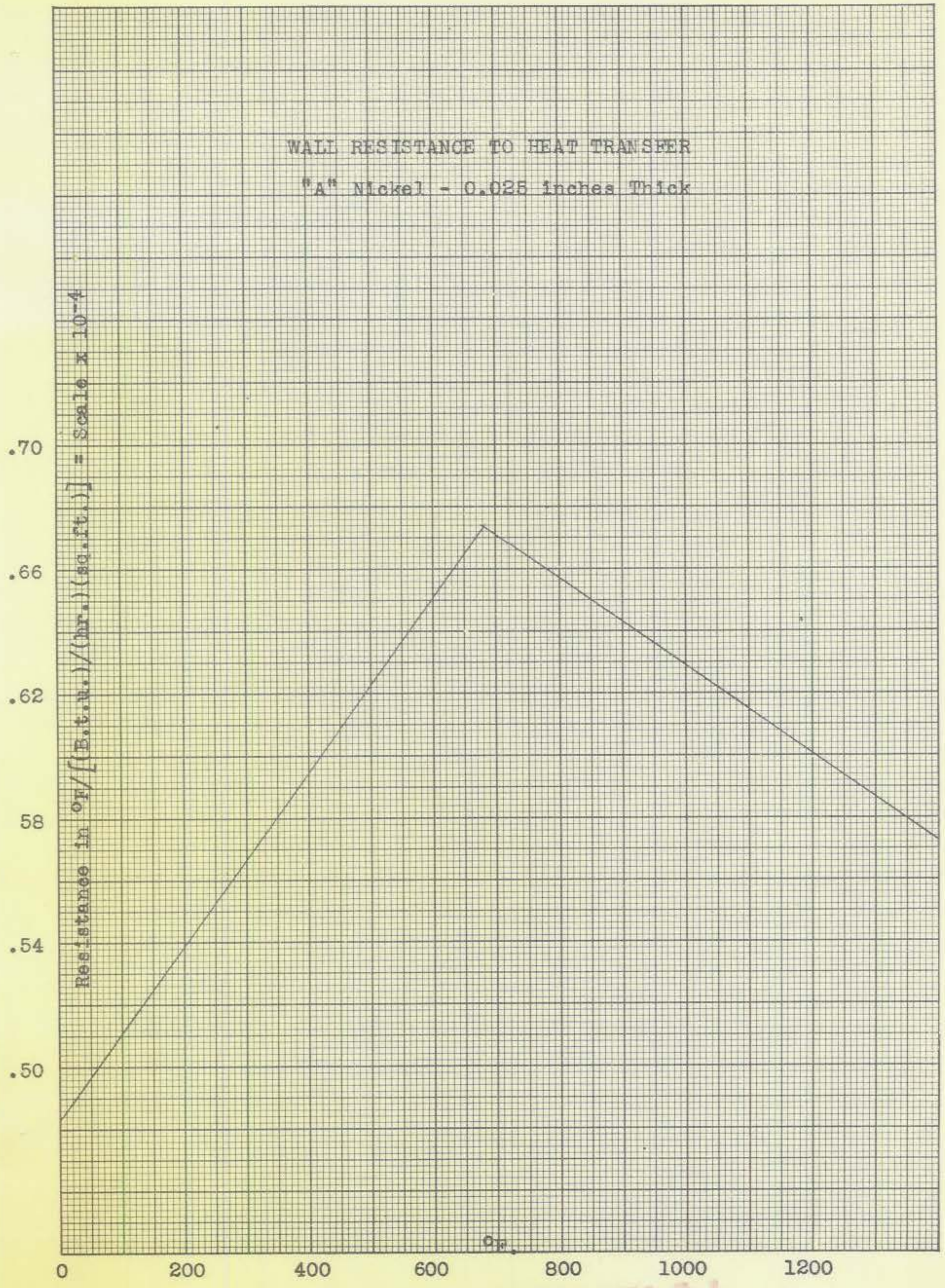
WALL RESISTANCE TO HEAT TRANSFER

"A" Nickel - 0.025 inches Thick

[redacted]

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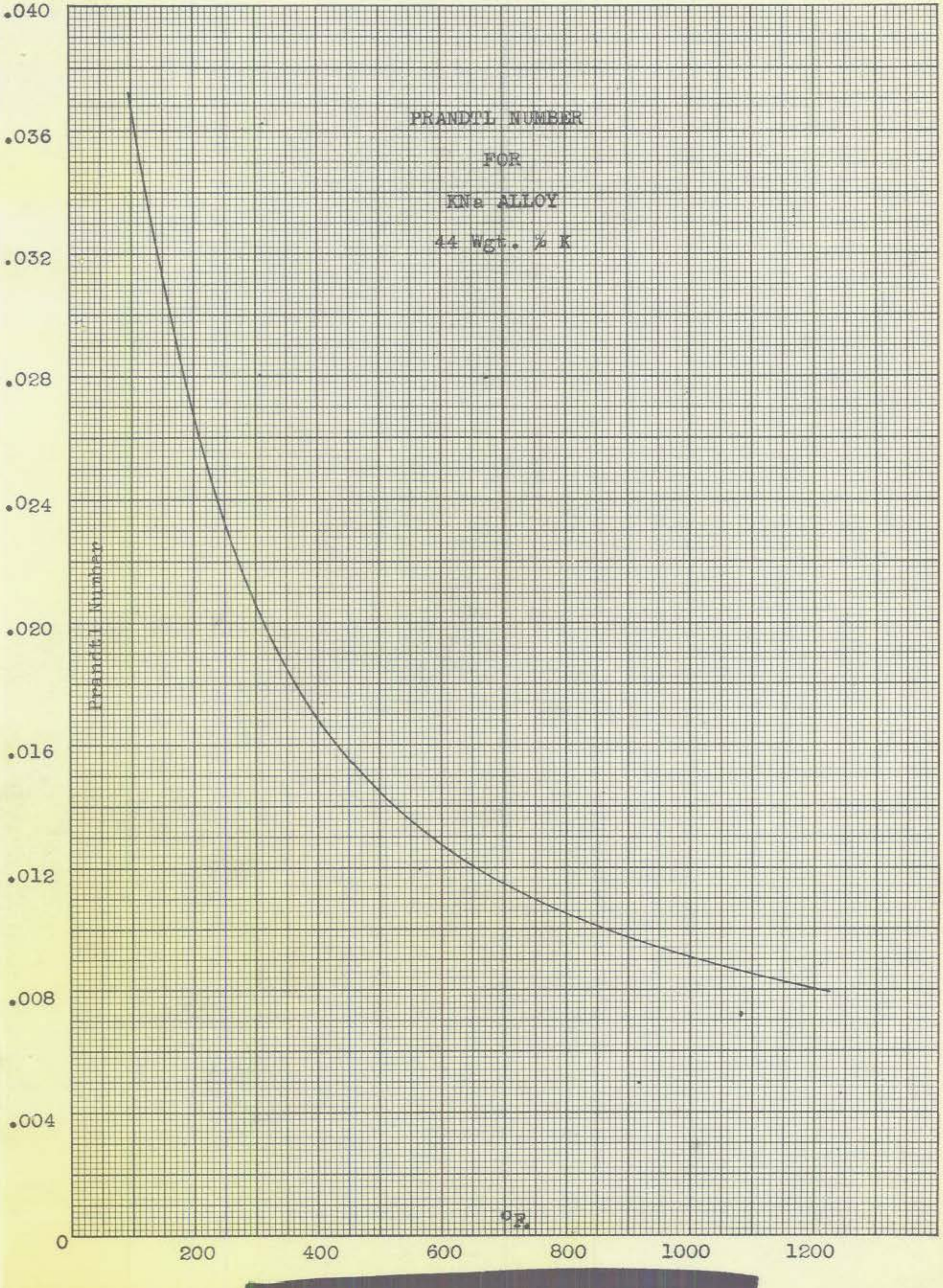
Figure 9



[redacted]

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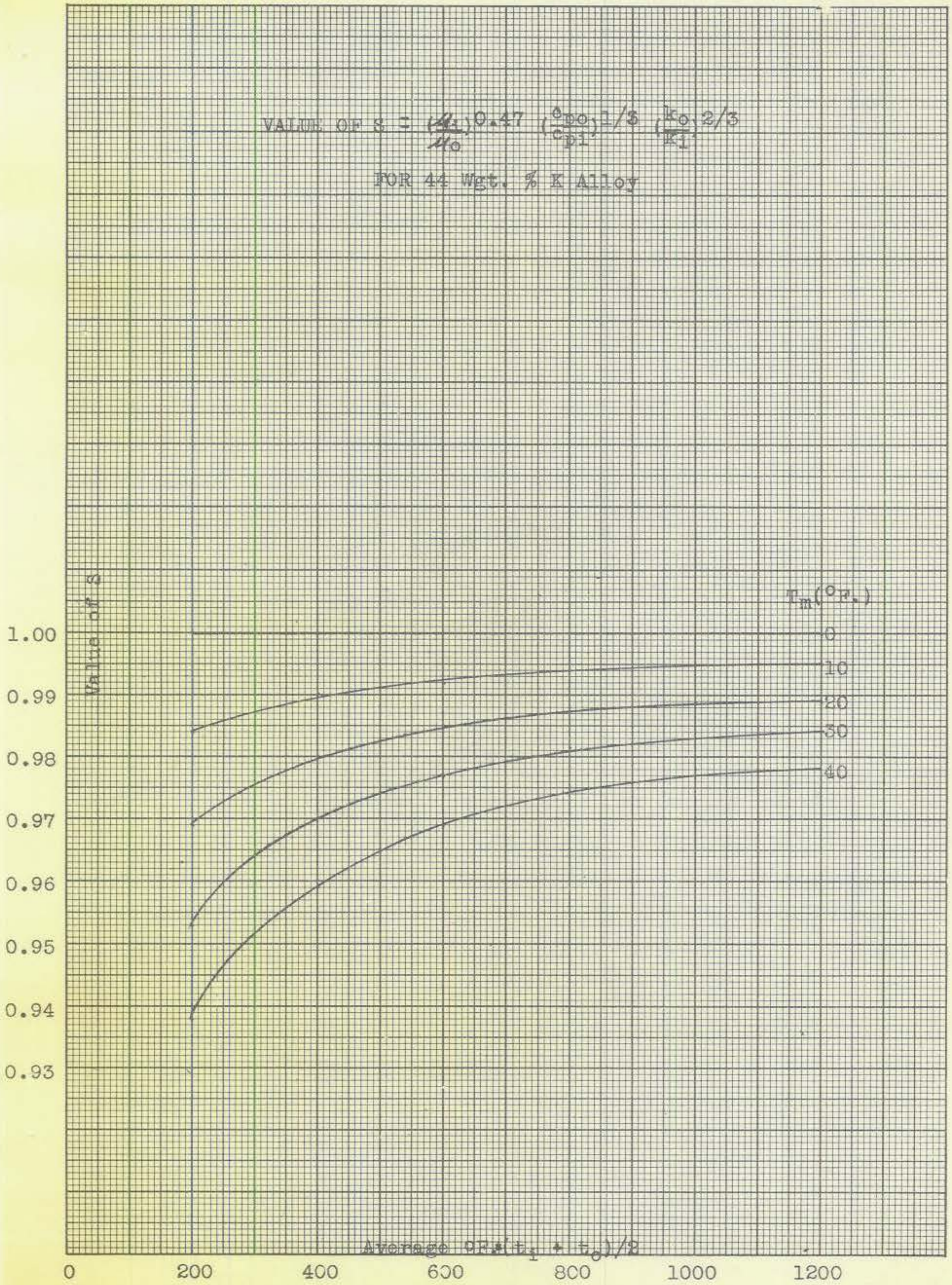
Figure 10



VALUE OF S = $(\frac{\mu_i}{\mu_o})^{0.47} (\frac{c_{po}}{c_{pi}})^{1/3} (\frac{k_o}{k_i})^{2/3}$

FOR 44 Wgt. % K Alloy

[redacted]

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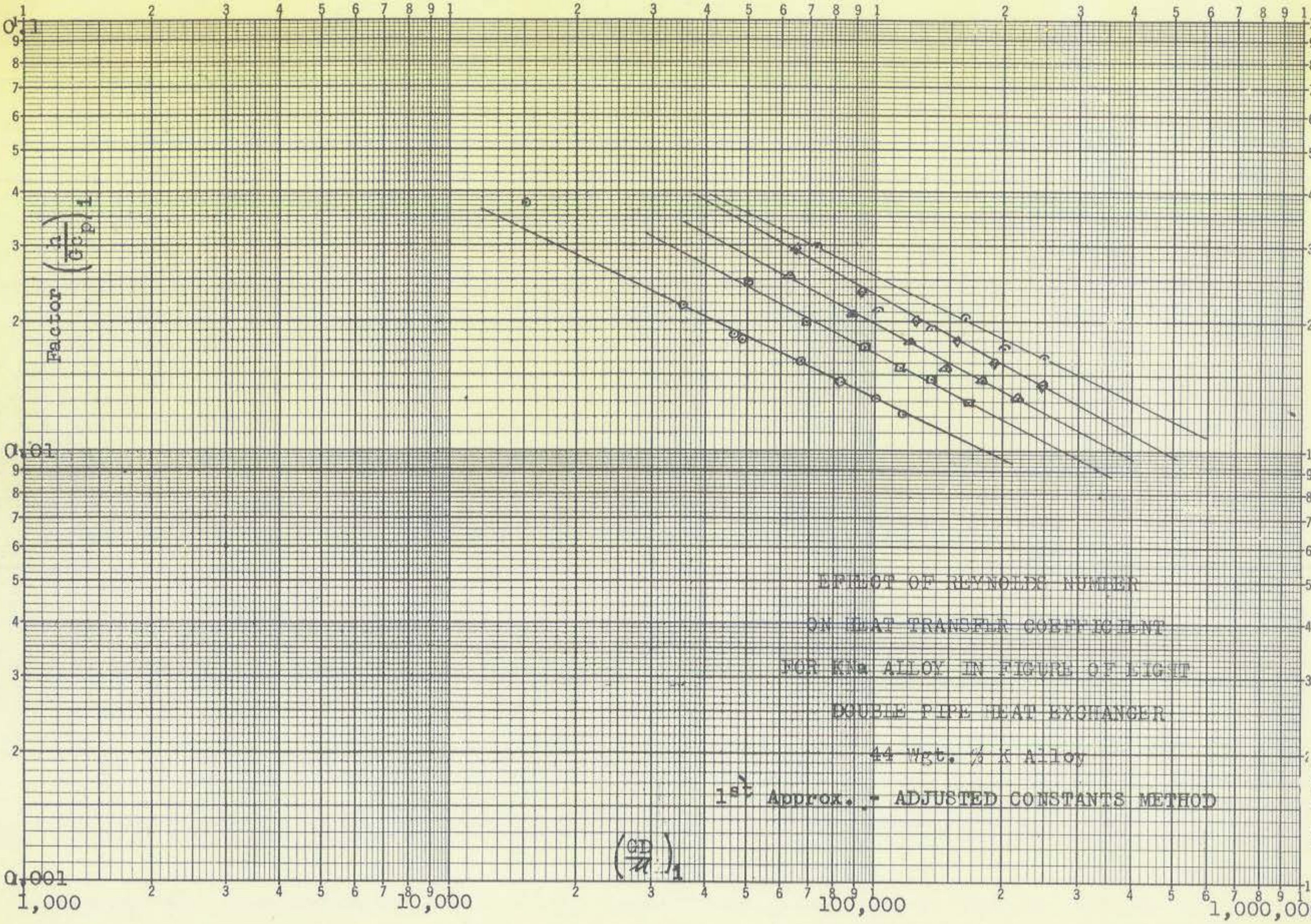
[redacted]

Figure 11



EFFECT OF REYNOLDS NUMBER
ON HEAT TRANSFER COEFFICIENT
FOR KNa ALLOY IN FIGURE OF EIGHT
DOUBLE PIPE HEAT EXCHANGER
44 Wgt. % K Alloy
1st Approx. - ADJUSTED CONSTANTS METHOD

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[redacted]

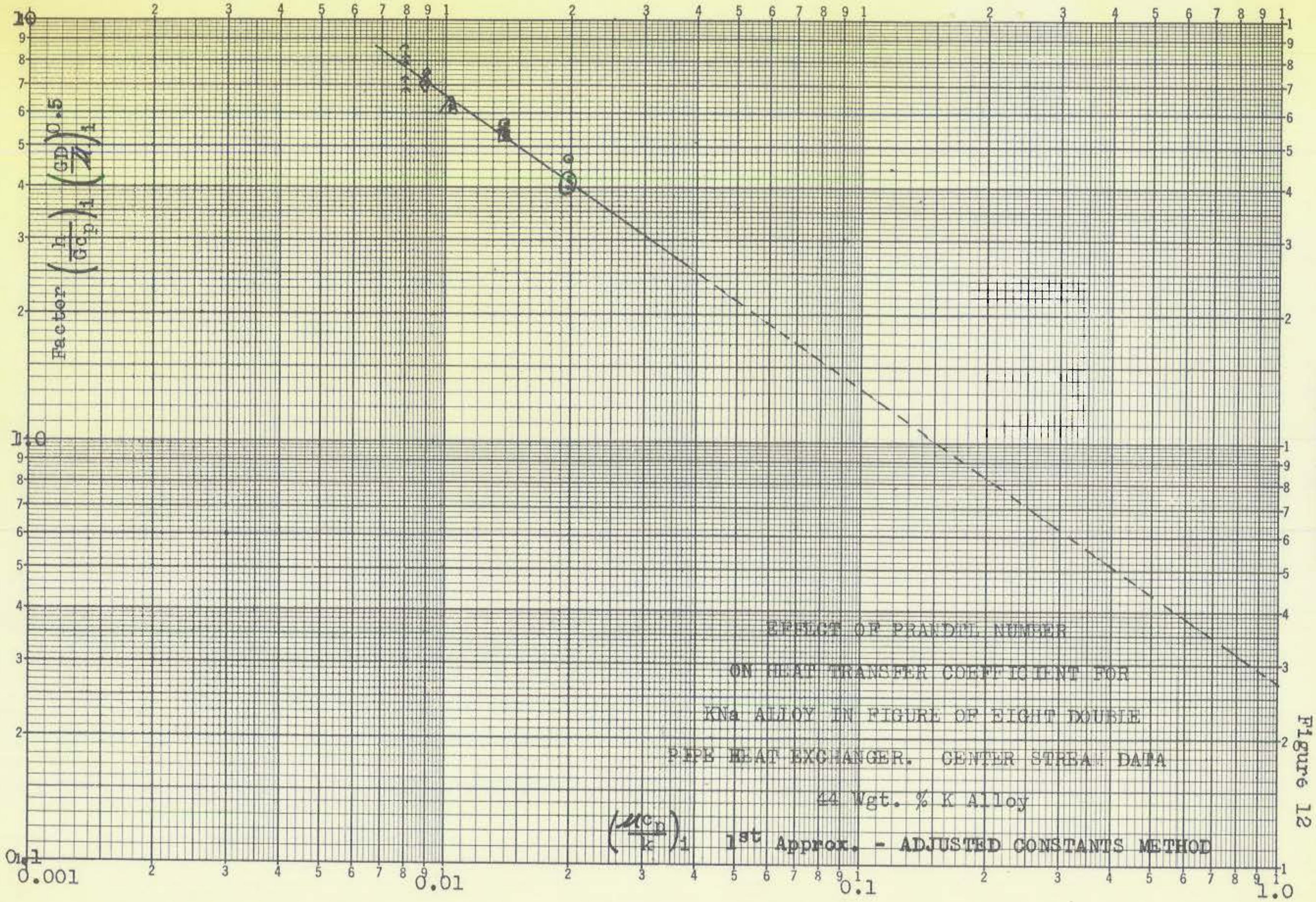

Figure 12

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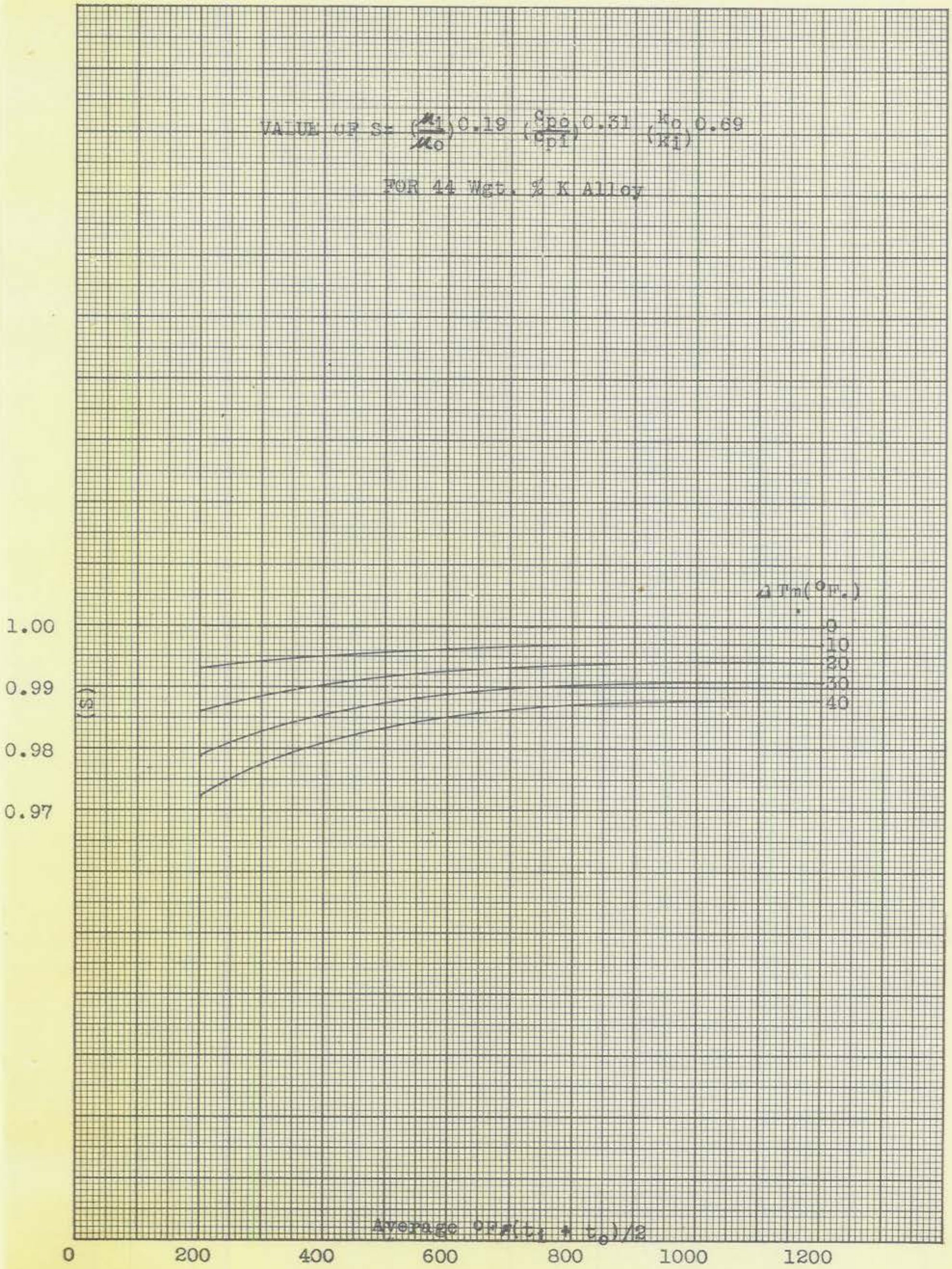
Figure 13



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[redacted]

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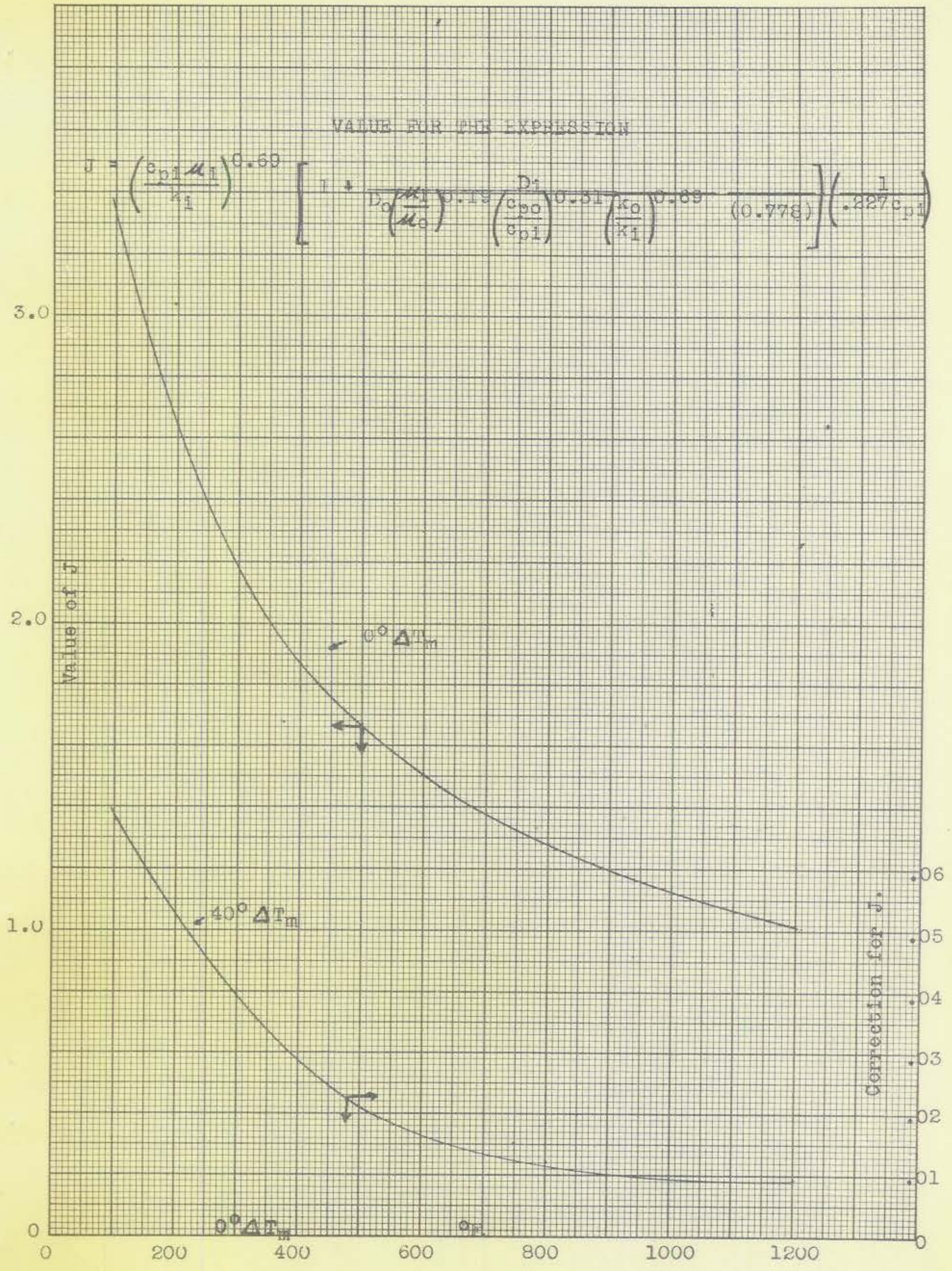
Figure 14



VALUE FOR THE EXPRESSION

$$J = \left(\frac{c_{pi}\mu_i}{k_i}\right)^{0.69}\left[1 + \frac{D_i}{D_o\left(\frac{\mu_i}{\mu_o}\right)^{0.19}\left(\frac{c_{po}}{c_{pi}}\right)^{0.31}\left(\frac{k_o}{k_i}\right)^{0.69}(0.778)}\right]\left(\frac{1}{.227c_{pi}}\right)$$

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[redacted]

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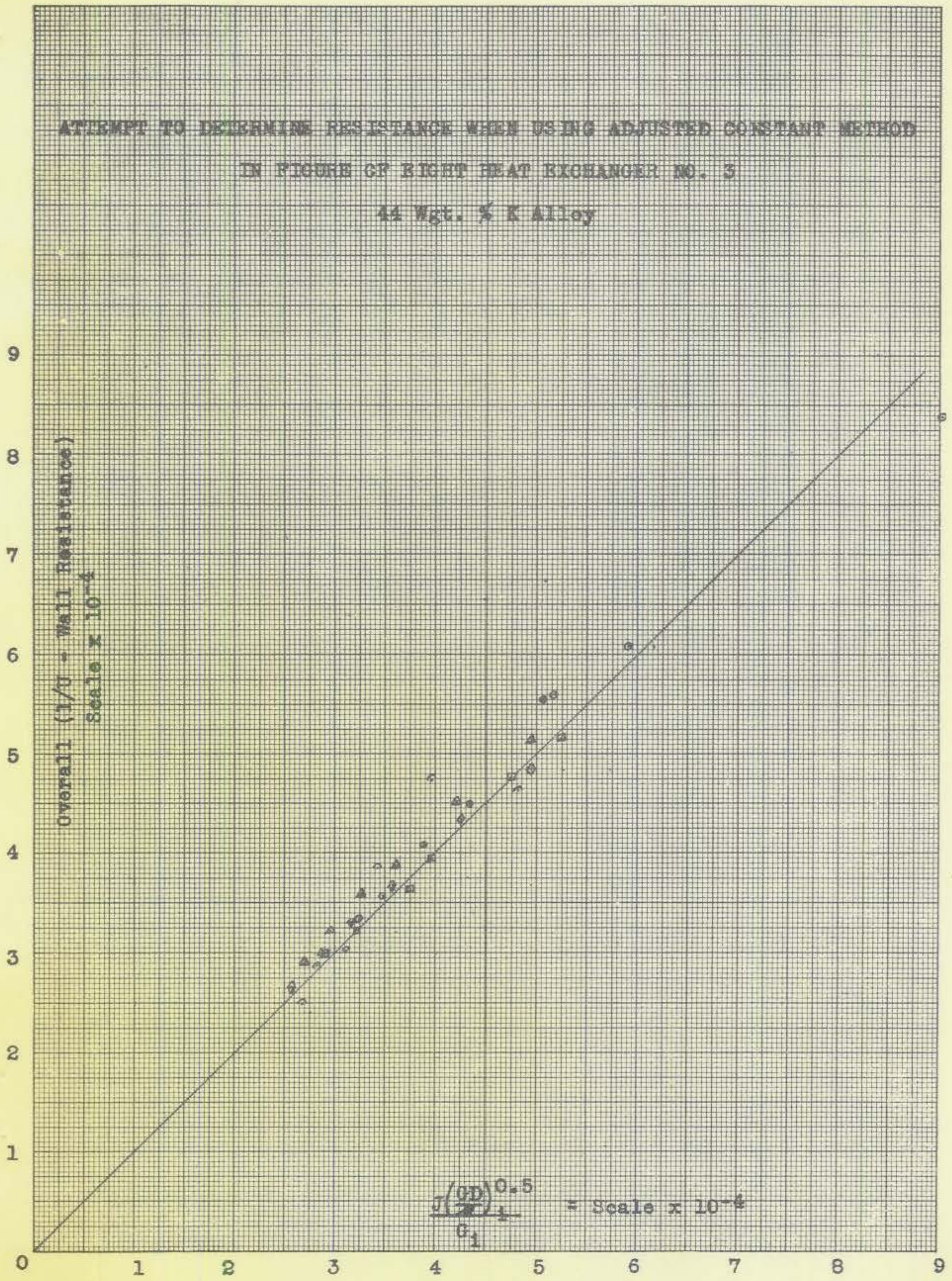
Figure 15



ATTEMPT TO DETERMINE RESISTANCE WHEN USING ADJUSTED CONSTANT METHOD
IN FIGURE OF EIGHT HEAT EXCHANGER NO. 3
44 Wgt. % K Alloy

[redacted]

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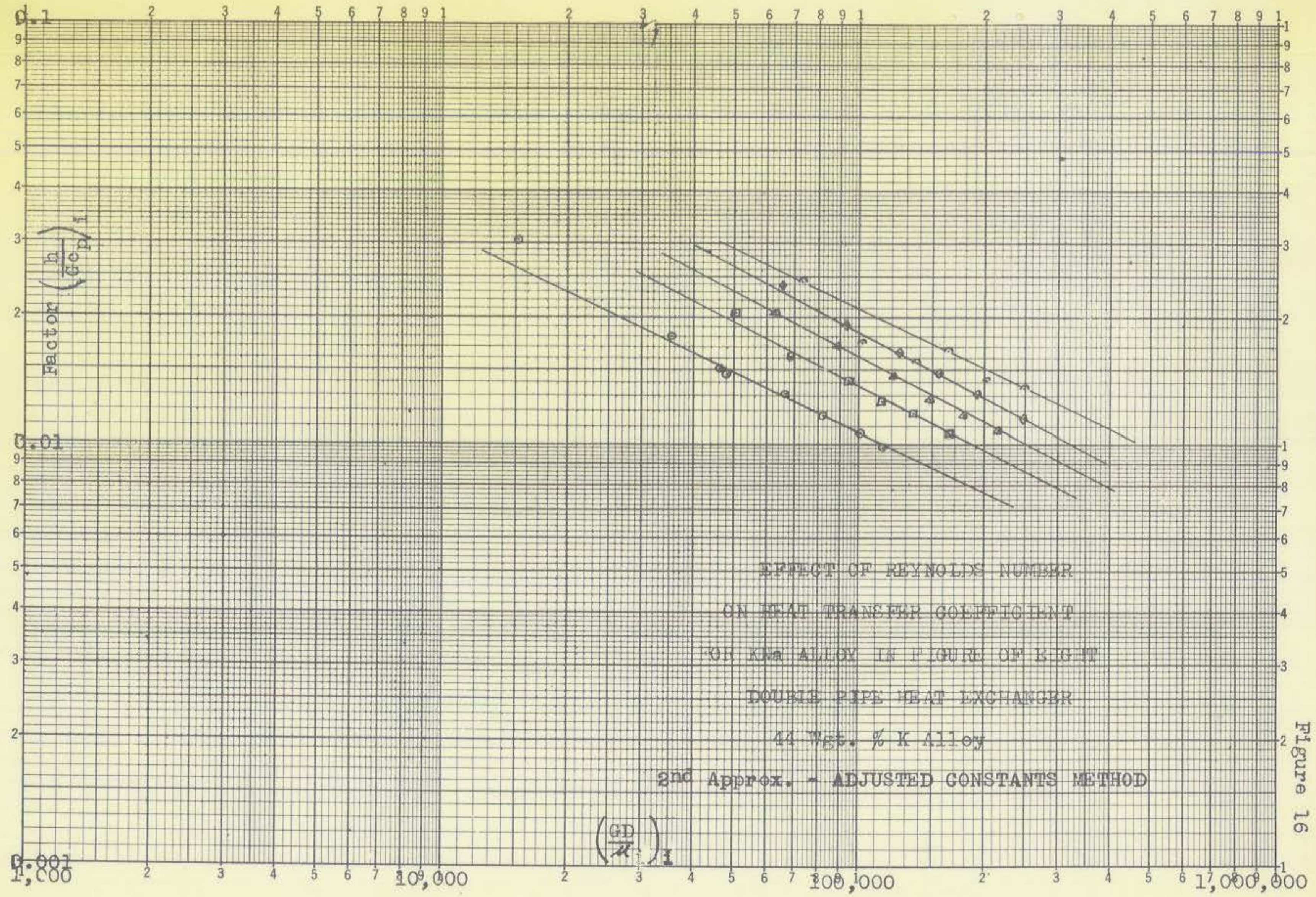

EFFECT OF REYNOLDS NUMBER
ON HEAT TRANSFER COEFFICIENT
FOR KNa ALLOY IN FIGURE OF EIGHT
DOUBLE PIPE HEAT EXCHANGER
44 Wgt. % K Alloy
2nd Approx. - ADJUSTED CONSTANTS METHOD

Figure 16

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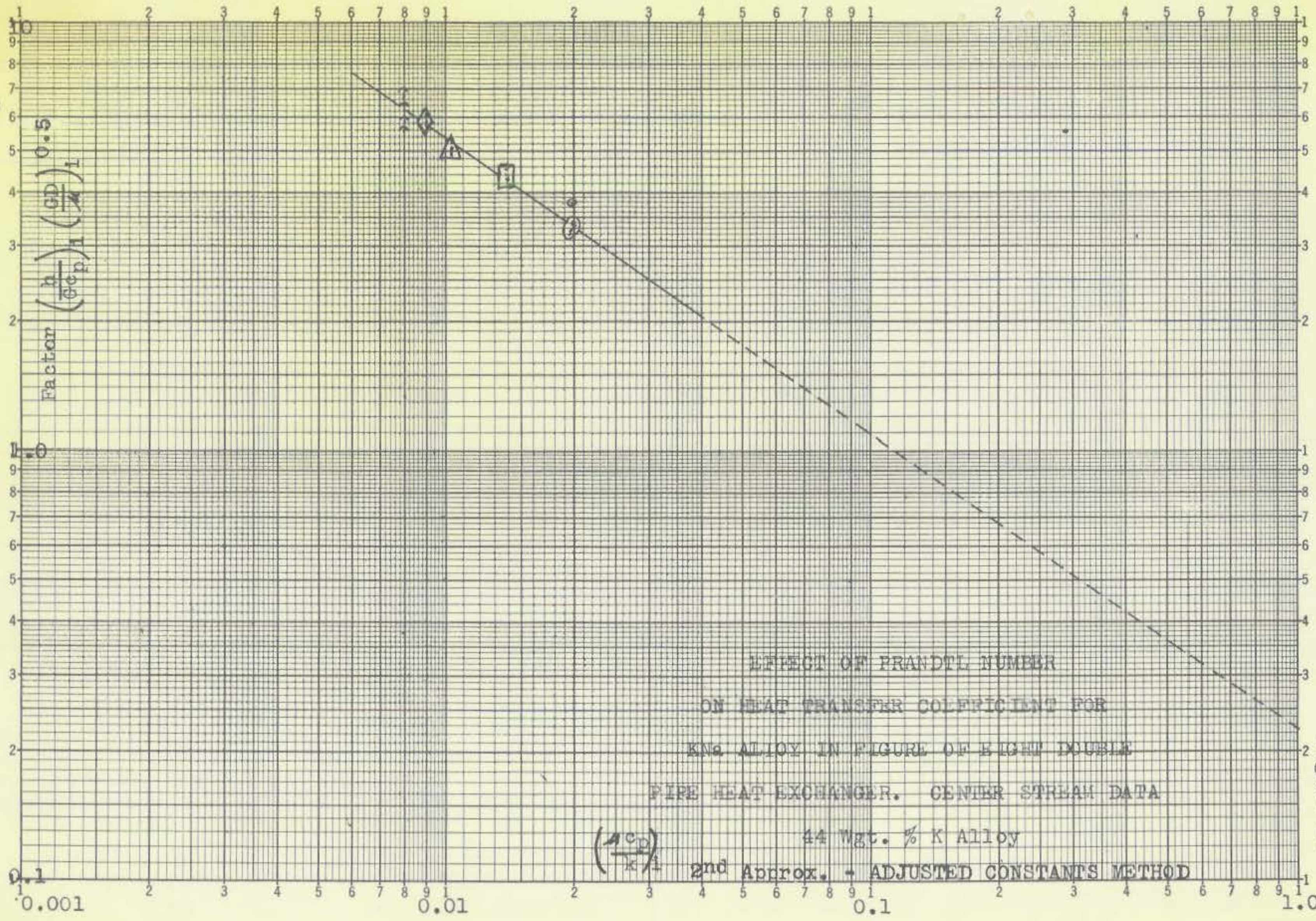
[redacted]

[redacted]



EFFECT OF PRANDTL NUMBER
ON HEAT TRANSFER COEFFICIENT FOR
KNa ALLOY IN FIGURE OF EIGHT DOUBLE
PIPE HEAT EXCHANGER. CENTER STREAM DATA
44 Wgt. % K Alloy
2nd Approx. - ADJUSTED CONSTANTS METHOD

Figure 17

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[redacted]

Figure 18

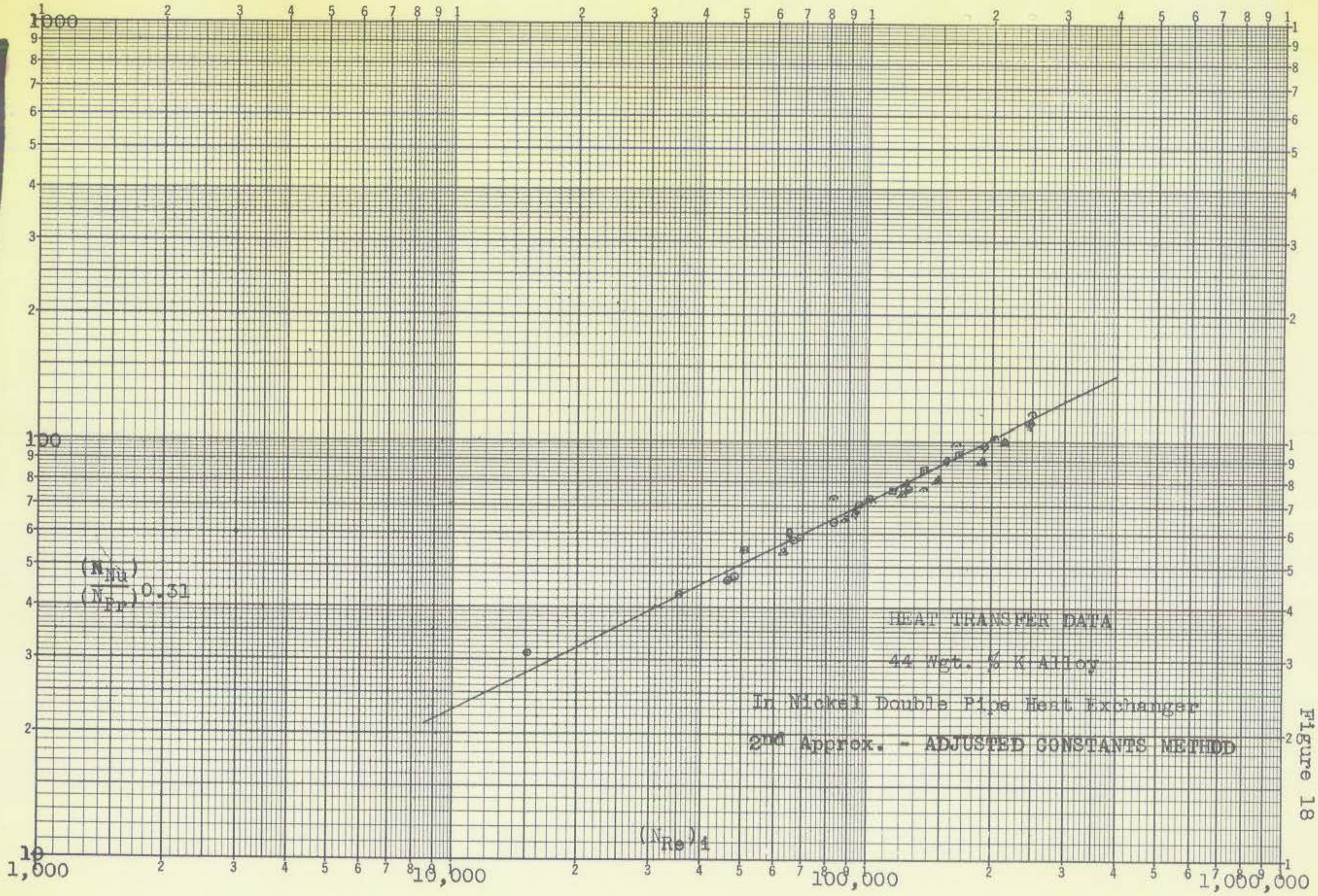

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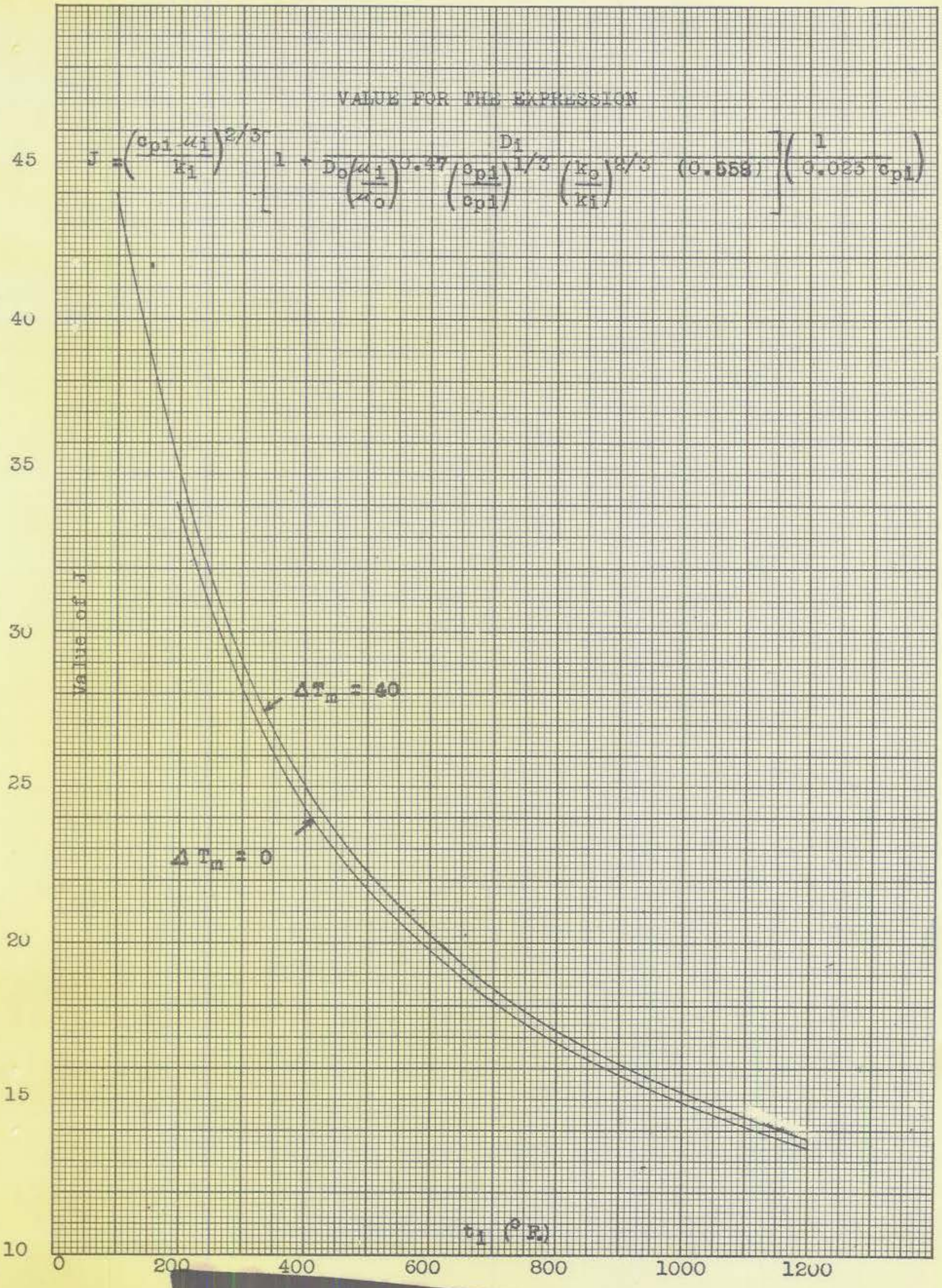
Figure 19



VALUE FOR THE EXPRESSION

$$J = \left(\frac{c_{pi}\,\mu_i}{k_i}\right)^{2/3}\left[1 + \frac{D_i}{D_o\left(\frac{\mu_i}{\mu_o}\right)^{0.47}\left(\frac{c_{pi}}{c_{pi}}\right)^{1/3}\left(\frac{k_o}{k_i}\right)^{2/3}(0.558)}\right]\left(\frac{1}{0.023\,c_{pi}}\right)$$

[redacted]

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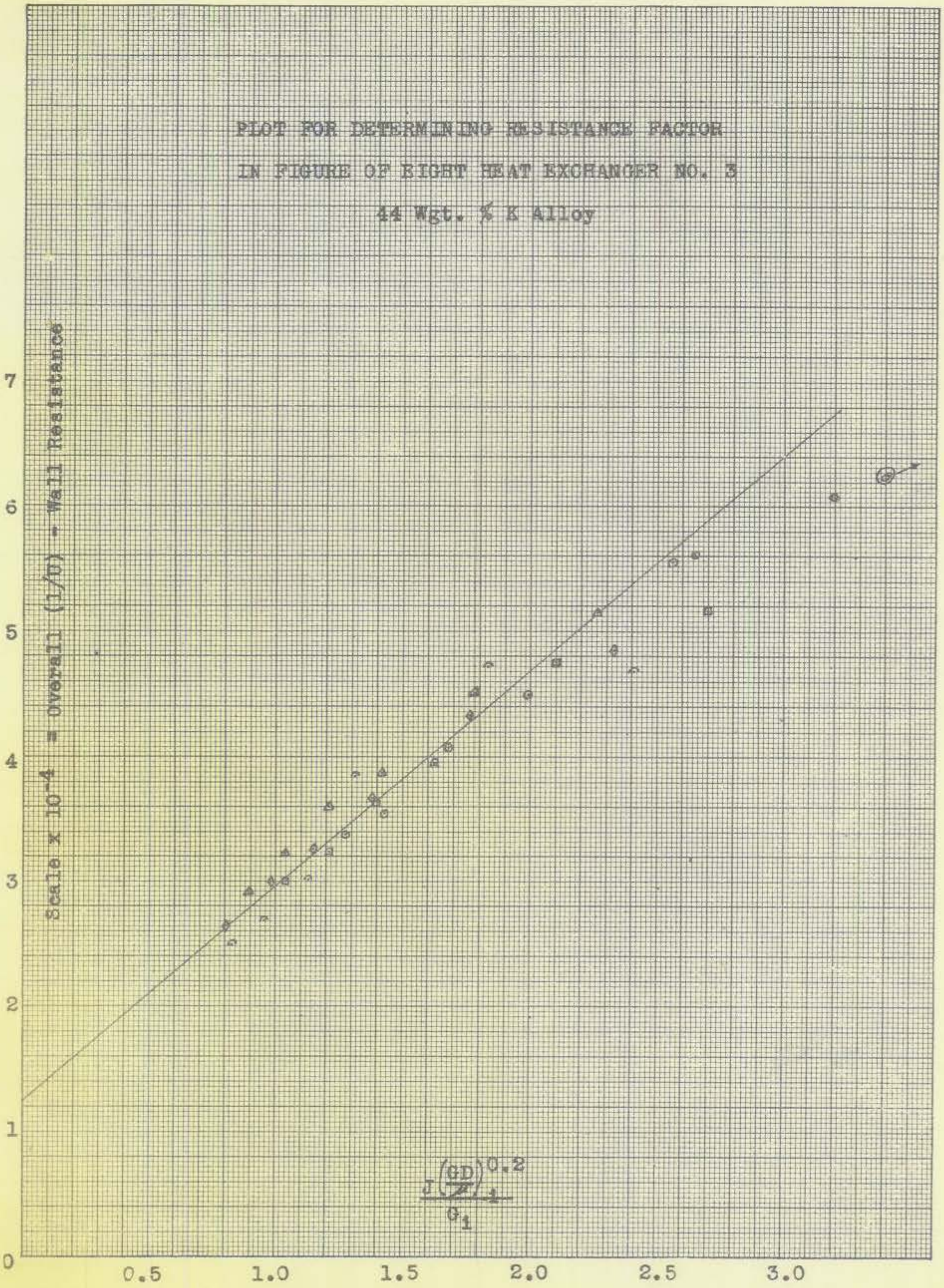
Figure 20

UNCLASSIFIED



PLOT FOR DETERMINING RESISTANCE FACTOR
IN FIGURE OF EIGHT HEAT EXCHANGER NO. 3
44 Wgt. % K Alloy

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[redacted]

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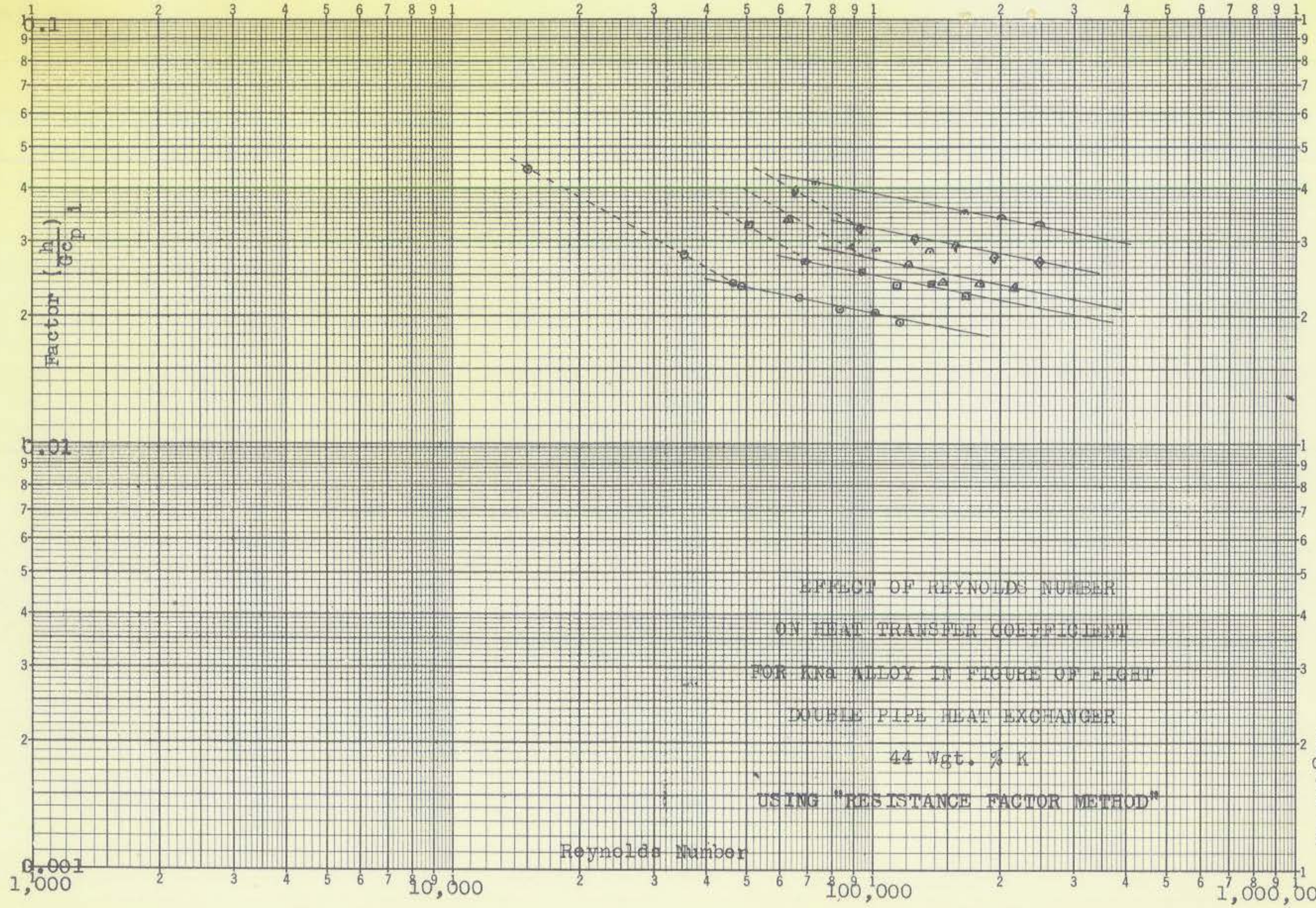
Figure 21



EFFECT OF REYNOLDS NUMBER

ON HEAT TRANSFER COEFFICIENT

FOR KNa ALLOY IN FIGURE OF EIGHT

DOUBLE PIPE HEAT EXCHANGER

44 Wgt. % K

USING "RESISTANCE FACTOR METHOD"

[redacted]

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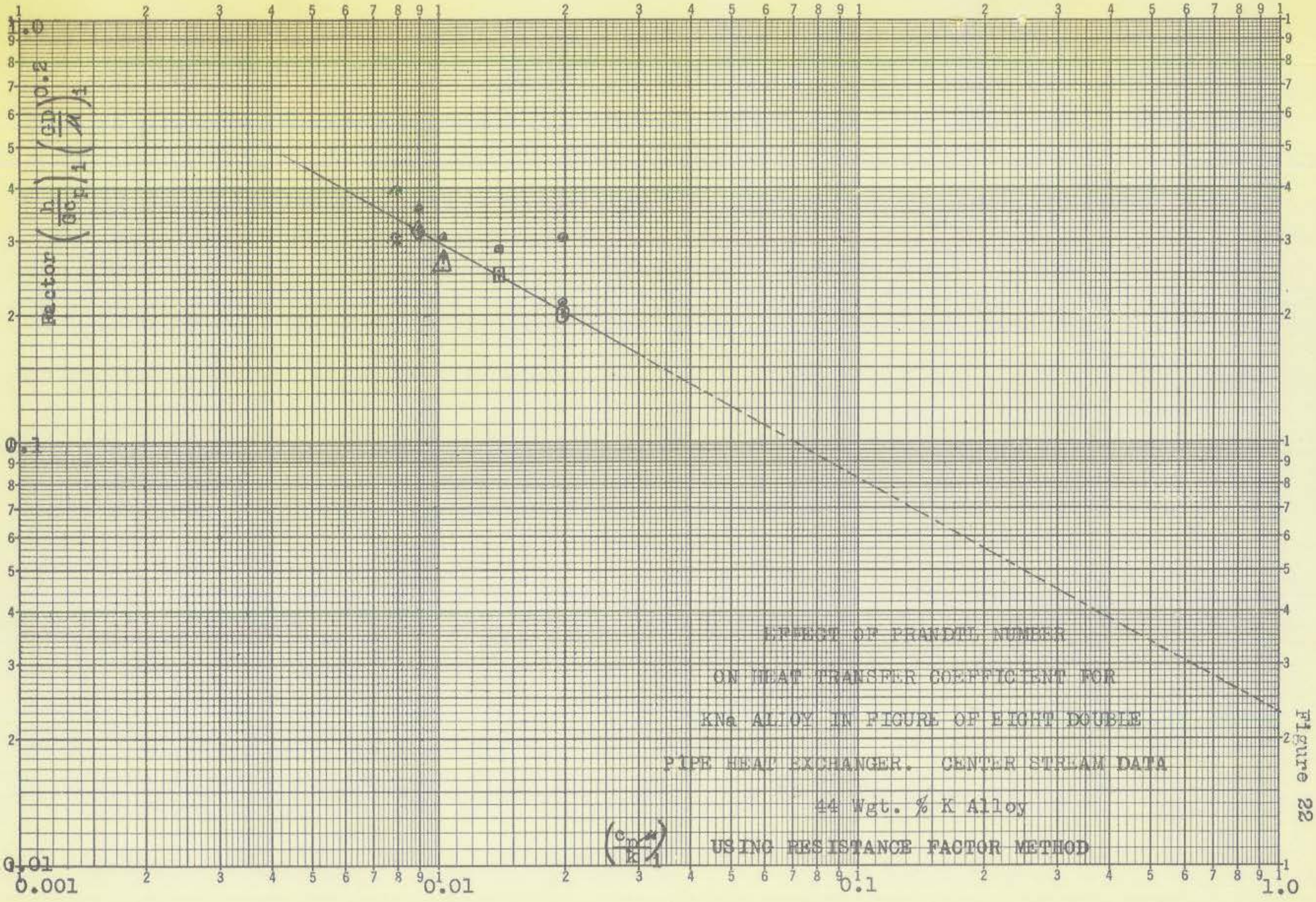
Figure 22



EFFECT OF PRANDTL NUMBER ON HEAT TRANSFER COEFFICIENT FOR KNa ALLOY IN FIGURE OF EIGHT DOUBLE PIPE HEAT EXCHANGER. CENTER STREAM DATA

44 Wgt. % K Alloy

USING RESISTANCE FACTOR METHOD

[redacted]

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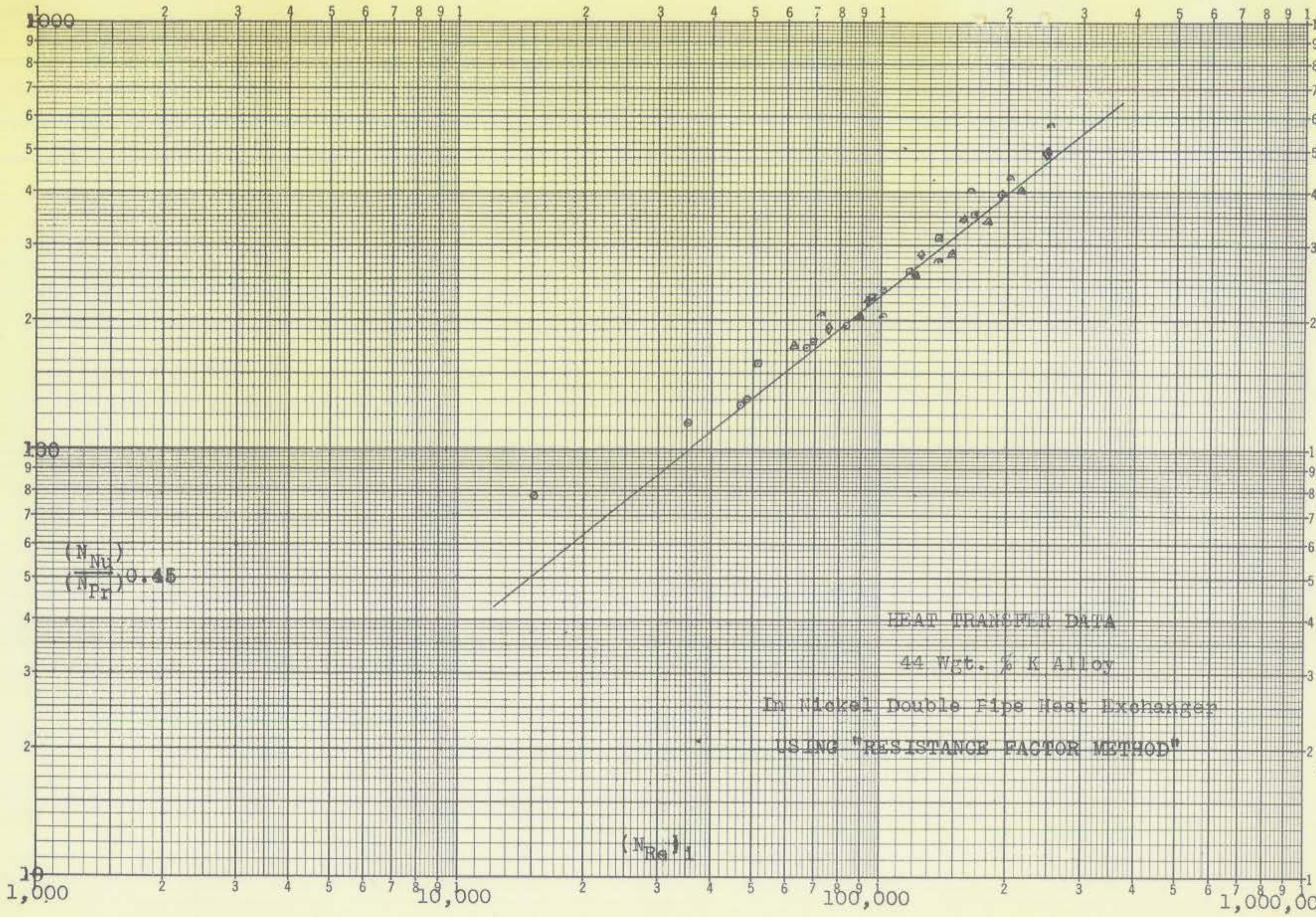
[redacted]



HEAT TRANSFER DATA

44 Wgt. % K Alloy

In Nickel Double Pipe Heat Exchanger

USING "RESISTANCE FACTOR METHOD"

Figure 23

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