

HEAT TRANSFER AND SCALE RESISTING PROPERTIES
OF SILICONE RESINS

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I. INTRODUCTION

The process of heat transfer is of utmost importance in chemical engineering. There are few chemical processes which do not require a heating or cooling of gasses or liquids by means of a heat exchanger of some design. The design of heat exchangers vary with the purpose for which they must be used; however, in practically every design, where flowing media are involved, heat is transferred from one medium to another through the wall of a tube. The medium outside the tube may be static or may be flowing.

In the case of heat transfer between flowing liquids, there are three resistances to the heat flow; namely, the film between the heating liquid and the tube wall, the tube wall itself, and the film between the liquid being heated and the tube wall. The equations and calculations for film coefficients, a measure of the resistance to heat flow offered by the film, developed by Nusselt, Grashof, Prandtl, and many others, who worked around the first of the century, are still being used in the design of heat exchangers.

A factor which greatly affects the heat transfer through the wall of a tube is the presence of corrosion or scale on the tube. The corrosion and scale offer an

insulation to the flow of heat and affect the properties of the film between the tube and the liquid. Frequent replacement of equipment because of corrosion and reduction in efficiency due to scale increase the costs of operation of a process. Much work has been done but little accomplished in the prevention of corrosion and scale by the use of special alloys for the construction of heat exchangers, and also by special coatings for the tubes. Coatings on tubes of the recently developed silicone resins have shown some promise in the prevention of corrosion and scale; however very little data of practical value has been obtained in this regard.

The purpose of this investigation is (1) to determine the degree of protection offered by a silicone coated tube against a scale forming liquid in a heat exchanger, and (2) to determine the coefficient of heat transfer across the silicone coating and the liquid film.

II. LITERATURE REVIEW

Heat Transfer

The laws of heat transfer are of controlling importance in the design and operation of many types of chemical engineering equipment. It is known that there are three means by which heat may be transferred; namely, conduction, convection, and radiation.

Conduction (87)(67)(12)(50) is the transfer of heat from one part of a body to another part of the same body, or from one body to another in physical contact with it, without appreciable displacement of the particles of the body.

Convection (87)(67)(12)(50) is the transfer of heat from one point to another within a fluid, gas, or liquid, by the mixing of one portion of the fluid with another. When the motion of the fluid is entirely by differences in density it is called natural convection; whereas, when the motion of the fluid is by mechanical means, it is called forced convection.

Radiation (87)(67)(12)(50) is the transfer of heat from one body to another, not in contact with it, by means of wave motion through space.

In the case of heat transfer from fluid to fluid in a heat exchanger, all three types of transfer take

place at the same time; however, usually only conduction and convection are considered. Therefore for this work it suffices to say that radiant heat emission is proportional to the fourth power of the absolute temperature of the body.

(87)(67)(12)(51)

Conduction

The basic equation for heat transfer by conduction is based on the law of Fourier, ⁽³⁰⁾ which states that the instantaneous rate of heat flow is equal to the product of three factors: the area of the section, taken normal to the direction of the flow of heat; the temperature gradient; and a proportionality factor. Fourier's law may be expressed mathematically as follows:

$$\frac{dQ}{d\theta} = -kA \frac{dt}{dx}$$

Where:

- dQ = the amount of heat flowing, Btu/hr.
- dθ = the differential time, hrs.
- A = the area of the section, sq. ft.
- dt/dx = the temperature gradient; the rate of change of the temperature, t, with respect to the length of the path, x.
- k = a proportionality constant, defined as the thermal conductivity.

Fourier's law as stated above applies specifically to that type of conduction in which the temperature

gradient continually changes and, therefore, the rate of heat transfer varies with respect to time. This is known as the unsteady state. However, if the temperature gradient remains constant, $dq/d\theta$ becomes Q/θ , and is designated by q . This condition is called the steady state and the basic equation, therefore, is as follows:

$$q = -kA \frac{dt}{dx}$$

In the English system the units of k are as follows:

$$\frac{\text{BTU}}{(\text{hr.})(\text{sq.ft.})(^\circ\text{F per ft.})} = \frac{\text{BTU}}{(\text{hr.})(\text{ft.})(^\circ\text{F})}$$

In order for Fourier's law to be of practical use it must be integrated. Upon integration and improvement to take care of variation in cross section path it becomes:

$$q = k_m A_m \Delta t / X$$

Where:

- q = heat transferred, Btu/hr.
- k_m = mean thermal conductivity (Arithmetic mean where k is linear in t)
- A_m = mean area of cross sectional path of conduction, sq. ft.
- Δt = temperature difference between hot and cold side of conducting thickness, $^\circ\text{F}$.
- x = length of conduction path, feet.

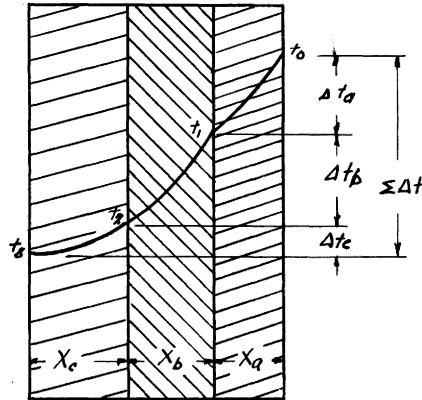


Figure 1

With reference to Fig. 1 (51) it can be shown mathematically that the conduction of heat through a wall composed of three different solids follows the equation:

$$q = \frac{\Sigma (\Delta t)}{\frac{X_a}{k_a A_a} + \frac{X_b}{k_b A_b} + \frac{X_c}{k_c A_c}}$$

Where:

- q = heat transferred, Btu/hr.
- $\Sigma (\Delta t)$ = the sum of the individual temperature differences across each material, °F.
- X_a, X_b, X_c = the thickness of materials a, b, and c, respectively, ft.
- k_a, k_b, k_c = the thermal conductivity of materials a, b, and c, respectively, English hour units.
- A_a, A_b, A_c = the cross sectional area of conduction of materials a, b, and c, respectively, sq. ft.

It should be noted that k_a , k_b , and k_c represent

the mean thermal conductivities of a, b, and c; and A_a , A_b , and A_c the mean areas taken at right angles to the direction of heat flow. Therefore, if the materials a, b, and c, represent concentric cylinders, each average area should be the logarithmic mean of the outer and inner surfaces of that cylinder. This factor must be taken into consideration in heat transfer to fluids moving by forced convection.

(87)(67)(12)(52)

Convection

(65)

The Film Concept. Early investigators as Peclet and Langmuir ⁽⁴⁸⁾ produced evidence that when a fluid flows over the surface of a solid, a stagnant, laminated layer of fluid exists between the main body of the fluid and the solid surface. The stagnant layer or film is caused by friction and by the attractive forces between the fluid and the solid. The film can transfer heat only by conduction and, therefore, offers a restriction to heat flow, since the thermal conductivities of most fluids is low.

Heat Transfer Between Fluids and Solids. In a heat exchanger where heat is being transferred from a fluid to a solid to a fluid the steady state is attained and all mass-flow rates are constant; therefore, the temperature gradation at any point in the

equipment is independent of time. For such conditions Newton found that the rate dq of heat transfer was directly proportional to the overall difference between the temperatures of the warmer and colder fluids, t , and to the heat transfer surface dA :

$$dq = U dA \Delta t$$

The proportionality factor U is called the local overall coefficient of heat transfer. The local overall coefficient may be based on either the area of the heating surface or the cooling surface.

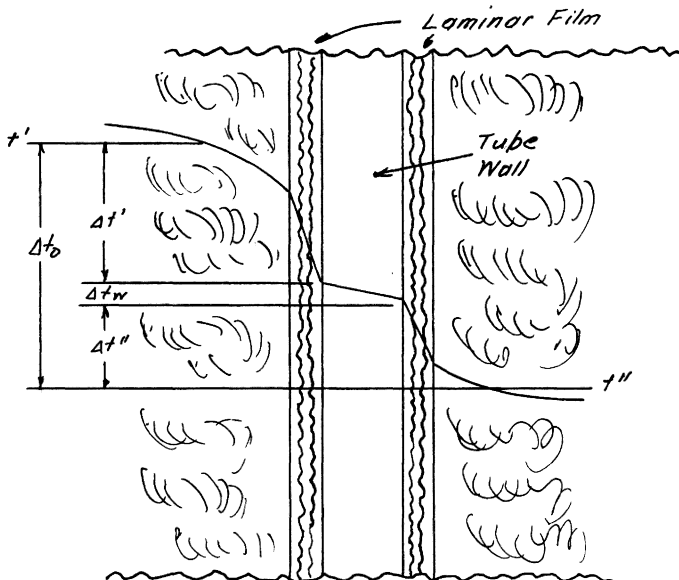


Figure 2

As can be seen from Fig. 2, which represents the temperature gradients in a heat exchanger, the total resistance to the flow of heat consists of two fluid films and the heat exchanger wall.

Because of the difference in temperature $\Delta t'$ between either fluid and the heat exchanger wall, the rate of heat flow dq is proportional to $\Delta t'$ and to the heat transfer surface dA' or:

$$dq = h' dA' \Delta t'$$

The proportionality factor h' is called the local individual coefficient of heat transfer. Since it is a measure of the ability of the stagnant film to conduct heat, it is inversely proportional to the thickness of the film and, therefore, upon the physical properties of the fluid.

If the equations for the overall and the individual heat transfer coefficients and the Fourier equation for conduction are solved for temperature drops, it will be found that the total temperature drop t between the two fluids in a heat exchanger is equal to:

$$\Delta t = dq \left(\frac{1}{h' dA'} + \frac{x_w}{k_w dA_w} + \frac{1}{h'' dA''} \right)$$

Since $dq = U dA \Delta t$ the following equation becomes apparent:

$$\frac{1}{U dA} = \frac{1}{h' dA'} + \frac{x_w}{k_w dA_w} + \frac{1}{h'' dA''}$$

Where the thickness of the wall is small compared with the diameter of the tube, as in a double pipe heat exchanger, a close approximation of the above equation may be written as:

$$\frac{1}{U} = \frac{1}{h^i} + \frac{x_w}{k_w} + \frac{1}{h^o} \quad (52)$$

It has been found that the overall temperature difference between the two fluids in a heat exchanger must be represented by the logarithmic mean difference, between the inlet and outlet temperatures of the two fluids. The logarithmic mean temperature difference is represented by the following equation:

$$\Delta t_m = \frac{\Delta t_2 - \Delta t_1}{\ln \frac{\Delta t_2}{\Delta t_1}}$$

Where:

- Δt_m = the logarithmic mean temperature difference.
 - $\Delta t_1, \Delta t_2$ = the difference in temperature between the two fluids at opposite ends of the heat-exchanger. (39)
- (84)

Jurgensen and Montillon, and Sherwood and Petrie found that the logarithmic mean temperature difference gave the best results in determining local individual heat transfer coefficients. In this case Δt_2 and Δt_1

are the temperature differences between the heat-exchanger tube wall and the fluid. Jurgensen and Montillion also used the arithmetic difference between the average tube wall temperature and the fluid temperature, and found the error to be about two per cent.

The local individual heat transfer coefficient.

Heat transfer to a fluid in turbulent motion is complicated due to the fact that the velocity gradient across the stream of the fluid is not constant, or nearly so, as in natural convection, but apparently involves three velocity zones; namely, the film, the buffer layer, and the turbulent core. In streamline or viscous flow, however, a constant velocity gradient is present and the individual film coefficient has been found to be directly proportional to the cube root of the Reynolds group:

$$\frac{DG}{\mu}$$

Where:

D = diameter
G = mass velocity Consistent units
 μ = viscosity

Reynolds, (70) Prandtl, (69) Taylor, (86) and Hoffman, (35)

as early as 1874, proposed mathematical analogies between heat transfer and fluid friction. The postulation of Reynolds has been found to roughly agree with experimental

data for gases; however, to date, no mathematical derivation has been found to agree for heat transfer to liquids due to the fact that the physical properties of liquids vary over a wide range with relatively small changes in temperature.

The most successful approach to correlating heat transfer and fluid friction has been the experimental. It is generally assumed that the individual heat transfer coefficient is controlled by the important factors entering into both hydrodynamic and heat conduction calculations. Dimensional analysis gives the following equation:

$$\frac{hD}{k} = a \left(\frac{Du\rho}{\mu} \right)^m \left(\frac{C\mu}{k} \right)^n$$

Where:

- h = the local individual heat transfer coefficient.
- D = diameter of the fluid conduit.
- u = velocity of the fluid.
- ρ = density of the fluid.
- μ = viscosity of the fluid.
- C = specific heat of the fluid.
- k = thermal conductivity of the fluid.

The value of the exponent of the Reynolds group is best determined by experimental work on gases because of the fact that the Prandtl group, $C\mu/k$, which relates

the physical properties of the fluid, varies but little.
(58)
Nusselt has no doubt produced more data in this regard than any other investigator. Nusselt in 1909 plotted experimental values for h versus G , the mass velocity ($u\rho$), and obtained straight lines on logarithmic coordinates. The slope of these lines, which mathematically represents the exponent of G , is 0.8. Nusselt used the term mass velocity in his calculations and said it to be equal to both u and W/S , where W is the number of pounds of fluid per hour and S is the cross section area of the fluid conduit in feet.

(29)
Eagle and Ferguson have found the exponent of diameter to be 0.2. Therefore, when the heat transfer coefficient is multiplied by the diameter to the 1.0 power and the diameter is included in the Reynolds group to the 0.8 power, the equation is still mathematically sound.

(54) (33)
Morris and Whitman, Hinton, Dittus and
(28) (84) (21)
Boelter, Sherwood and Petrie, and Colburn
have determined the effect of the Prandtl group on h where liquids were involved, by making experimental tests at a constant Reynolds number. When their values for hD/k are plotted versus C_p/K on logarithmic co-

ordinates a straight line of 0.3 to 0.4 slope results depending upon whether the experimental fluid is being cooled or heated. The slope of 0.3 to 0.4 mathematically represents the exponent of the Prandtl group. It is generally accepted that the exponent of the Prandtl group (41) is higher for heating than for cooling. Kaye and Furnas explain this phenomenon by the difference in the viscosity of the fluid films. When a liquid is being heated the fluid side of the film is cold and of high viscosity; whereas, on heating, the fluid side is hot and of low viscosity and is, therefore, swept away by the turbulent (21) flow. Colburn recommends that it is more logical to use an exponent of $1/3$ for fluids of high viscosity.

Although many investigators have derived constants for the dimensionless equation relating heat transfer to fluid friction, the most widely accepted values are those of Dittus and Boelter. (28) The equation with their values is as follows:

$$\frac{hD}{k} = 0.023 \left(\frac{Du\rho}{\mu} \right)^{0.8} \left(\frac{CA}{k} \right)^{0.4}$$

Where:

- h = local individual coefficient of heat transfer, BTU/hr/ft²/°F.
- D = Diameter of fluid conduit.
- k = Thermal conductivity of fluid.
- u = Velocity through conduit.
- ρ = Density of Fluid.
- μ = Viscosity of fluid.
- C = Specific heat of fluid.

The number of investigators who have attempted to correlate and improve the Dittus-Boelter equation is enormous. Lawrence and Sherwood, (39) Jurgensen and Montillon, (29) Eagle and Ferguson, (85) Sherwood and Petrie, (84) Sieder and Tate, (21) and Colburn are some of the better known investigators, who have worked with both water and hydrocarbon liquids. Each of these investigators found that in the turbulent zone the Dittus-Boelter equation predicted values of h very close to experimental values. Sherwood and Petrie, and Lawrence and Sherwood, who calculated values for h in the transition range between streamline and turbulent flow, which is represented by Reynolds' numbers from 2100 to 10,000, found that the values of h for water are slightly higher than those predicted by the Dittus-Boelter equation. Lawrence and Sherwood also found that for water the exponent of the Reynolds

number was closer to 0.73 and that of the Prandtl number closer to 0.49. These workers carried out an extensive investigation on the effect of the ratio of length to diameter of the heat transfer surface on the film coefficient, and found that the effect is negligible.

Sieder and Tate ⁽⁸⁵⁾ realized that the Dittus-Boelter equation did not contain a factor to take care of the viscosity gradient from the fluid film to the turbulent core, and, as a result of experimental work, proposed the use of a ratio of viscosity of the turbulent core to the film viscosity, all raised to the 0.14 power. This ratio is particularly recommended for fluids of high viscosity at Reynolds' number exceeding 10,000.

Simplified equations, based on the work of Dittus and Boelter, have been derived by several investigators; ⁽⁵²⁾⁽³³⁾ however, their correlation is poor except in the case of specific fluids.

The Dittus-Boelter equation predicts high values of h for hydrocarbon oils in the range of 2100 to 7000 for Reynolds' number. Kaye and Furnas reasoned that this is due to a viscosity factor. The best equation for hydrocarbon oils under these conditions is that of Morris

(54)
and Whitman. Their equation is as follows:

$$\frac{hD/k}{(C_p/k)^{0.4}} = \phi \left(\frac{Dv}{\mu} \right)$$

In their method a value for $\frac{hD/k}{(C_p/k)^{0.4}}$ is read from a graph for a particular Reynolds number.

The circumstances involving heat transfer by convection other than inside tubes are numerous; however, to cover more than involved in this investigation would be a book in itself. It will suffice to mention (53)(67)(12)(87) here that the other most important types of heat transfer by convection involve condensing vapors, evaporation, and fluids flowing outside tubes. McAdams' (53) text on "Heat Transmission" contains the most complete collection of data on all forms of heat transfer published to date.

Fluids in Annular Spaces. The most important problem involved in heat transfer to fluids in annular spaces is that of the proper selection of an equivalent diameter. Otherwise the Dittus-Boelter equation will predict reasonable values. The usual procedure involves substituting an equivalent diameter D_e , equal to four times the hydraulic radius; however, there are two methods (60)(61) of evaluating the hydraulic radius. Nusselt

claims that, if heat is flowing through only one wetted perimeter the hydraulic radius should be based on that perimeter alone. Therefore, Nusselt recommends the formula:

$$D_e = 4r_h = \frac{(\pi)(D_2^2 - D_1^2)}{(\pi) \cdot D_1}$$

Where:

- D_e = equivalent diameter, ft.
- r_h = hydraulic radius, ft.
- D_2 = diameter of outside perimeter, ft.
- D_1 = diameter of inside perimeter, ft.

(52)

McAdams believes that this procedure is too conservative and recommends that the hydraulic radius be based on the total wetted perimeter as in fluid friction calculations; or;

$$D_e = 4r_h = \frac{(\pi)(D_2^2 - D_1^2)}{(\pi)(D_2 + D_1)} = (D_2 - D_1)$$

The Nusselt procedure will predict larger equivalent diameters; however, since for turbulent flow inside pipes, h is inversely proportional to the 0.2 power of diameter, smaller values of h than those based on the total wetted perimeter will be predicted. The fluid friction formula is usually accepted for use in the Dittus-Boelter equation.

(31)

Foust and Christian experimentally obtained values

for h for water flowing in annular spaces and recommended the following equation:

$$\frac{hD_e}{k} = 0.032 \frac{D_2}{D_1} \left(\frac{D_e G}{\mu} \right)^{0.8} \left(\frac{C_p \mu}{k} \right)^{0.4}$$

The value of D_e is based on the total wetted perimeter of the annular space. It can be readily seen that values for $hD_e/k/(C_p\mu/k)^{0.4}$ will be much larger than those predicted in the Dittus-Boelter equation.

Scale Formation. The deposit of corrosion and scale in a heat-exchanger, or the "hot wall" effect, offers a tremendous problem in chemical engineering. Most scale deposits, unless of the sulfate or silicate types, may be removed by means of hydrochloric acid base solvents with a properly selected inhibitor; however, sulfate and silicate scale in a heat-exchanger must be removed by mechanical means, which necessitates dismantling the equipment. The cost of such processes runs into thousands of dollars each year.

According to Perry the formation of scale is always due to the presence of a substance having an inverted solubility curve, i.e., one whose solubility decreases with increasing temperature. A typical example is calcium sulfate whose solubility in water at

20°C is 0.298 parts per 100 parts and 0.162 parts per 100 parts at 100°C. Irving,⁽³⁷⁾ however, claims that ions of calcium sulfate, for example, are adsorbed by the heat-exchanger wall. As steam bubbles leave the metal surface, calcium sulfate is deposited. After deposition of the first layer, ions of calcium sulfate provide nuclei for further crystal growth.

Other common scale-forming materials⁽⁶⁶⁾ are calcium hydroxide, sodium sulfate, sodium carbonate, and the calcium salts of the organic acids found in sugar beet juice and fruit juices. When dissolved in a solution in which the amount of CO₂ is constant, calcium carbonate has a normal solubility curve; however, when the liquid containing calcium carbonate is boiled, the CO₂ is removed and calcium carbonate is precipitated as a true scale.

Perry says that if scale forming substances are present, there is no way of preventing scale formation; however, the rate of scale formation may be decreased by using high velocities or by introducing seed crystals of the scale-forming material in suspension. Scale cannot be entirely prevented by this method. Consequently, the problem is usually the removal of scale or the decrease in the rate of scale formation rather

than in prevention.

Some promise in the reduction of scale formation in boilers has been shown by the use of plastic and (20) silicone coated boiler tubes. The American Iron and Steel Institute has published two progress reports (8)(4) on the inspection of Lithcote coated and lined boiler tubes in service at Montreal, Canada. After the tubes had been in service for four years, the following report was made:

(1). No breakdown of the water side of the coated tubes after four years of service. Slight flaking on the flue gas side.

(2). No scale on the water side that could not be wiped off.

(3). Coated tubes were 7% less efficient than admiralty bronze tubes previously used, but the comparative thermal efficiency of the coated and uncoated tubes would equalize and eventually reverse.

(4). Coating increased the cost of the tubes approximately 100 per cent.

No information is available on coating of heat-exchanger tubes for scale reduction.

Thermal Resistance Due to Scale. As can be clearly seen the presence of scale on a heat-exchanger tube

offers another layer of solid through which heat must be transferred. Therefore, the resistance of the scale or the reciprocal of the heat transfer coefficient for the scale must be added in the equation already given for the overall heat transfer coefficient in terms of its individual resistances. McAdams ⁽⁵²⁾ suggest that the heat transfer coefficient for scale deposits be determined by a condensed form of this equation:

$$\frac{1}{h_d} = \frac{1}{U_d} - \frac{1}{U_c}$$

Where:

- h_d = the heat transfer coefficient for the scale deposit.
- U_d = the overall heat transfer coefficient for the heat-exchanger tube with its scale deposit.
- U_c = the overall heat transfer coefficient for a clean tube.

If the thickness and thermal conductivity of the scale deposit is known, then the same relation used to compute the resistance of the heat-exchanger tube wall may be used, or:

$$\frac{1}{h_d} = \frac{x_d}{k_d}$$

Where:

- h_d, x_d, k_d = the heat transfer coefficient, thickness, and thermal conductivity of the scale deposit respectively.

Apparent thermal conductivities of various scale deposits are given by Partridge⁽⁶⁴⁾ and by Biskamp⁽¹⁸⁾
(56)

Nelson says that with few exceptions the over-all rates computed from the theoretical coefficients can always be reduced by a resistance of 0.0005 (1/2,000). Although this seems small, in certain cases it becomes of great importance. Nelson gives the following example of heating water at a velocity of 3 ft. per sec. within tubes by condensing steam:

hc = 2,500 = steam film coefficient
hw = 800 = water film coefficient

$$U = \frac{1}{\frac{1}{2500} + \frac{1}{800}} = \frac{1}{0.00165} = 605$$

Inserting a scale resistance of 0.0005,

$$U = \frac{1}{0.00165 + 0.0005} = 465.$$

Nelson also says that not infrequently the scale resistance will be 0.005 or even 0.033.

McAdams⁽⁵²⁾ and Perry⁽⁶⁷⁾ give the following table of heat transfer coefficients for scale deposits from heating various waters in a double-pipe heat-exchanger:

Heat-transfer Coefficients h_d for Scale Deposits from Water

Temperature of heating medium.....	Up to 240°F		240-400°F	
Temperature of water	125°F or less		Above 125°F	
Water Velocity, ft/sec	3 and less	Over 3	3 and less	over 3
Distilled	2000	2000	2000	2000
Sea water	2000	2000	1000	1000
Treated boiler feed water	1000	2000	500	1000
Treated make-up for cooling tower	1000	1000	500	500
City, well, Great Lakes	1000	1000	500	500
Brackish, clean river water	500	1000	330	500
River water, muddy ...	330	500	250	330
Hard(over 15 g/gal)...	330	330	200	200
Chicago Sanitary Canal	130	170	100	130

Measurement of Surface Temperature. In order to determine individual coefficients of heat transfer in a heat-exchanger, it is necessary to accurately measure the temperature of the heat-exchanger wall next

to the fluid film in question. From such measurements the individual coefficient may be determined from the following equation:

$$h = \frac{q}{A\Delta t_m}$$

Where:

- h = the individual heat transfer coefficient.
- q = the amount of heat transferred across the fluid film, Btu/hr.
- A = the area of the heat transfer surface, sq. ft.
- Δt_m = the logarithmic mean temperature difference between the fluid and the tube wall, °F.

The most accurate method of determining the tube surface temperature is the use of thermocouples. (52)

However, even this method can introduce serious errors. (22)

Colburn and Hougan say that possible errors from the use of thermocouples are (1) conduction of heat along the thermocouple leads to or from the junction, (2) the location of the couple on the surface may act as an insulator and thus change the normal temperature at that position, and (3) the presence of the couple leads on the surface tends to disturb the flow of fluid and even if correct temperatures are measured the results would be misleading.

(59)
Nusselt has postulated that the conduction of

heat along the wires depends upon the diameter of the wire, the thermal conductivities of the metal surfaces and the wires, the heat transfer coefficients from the wires to the surrounding medium, and the temperature gradient from the surface to the medium. Although Nusselt gives an equation for his theory, no numerical values for the constants involved are available. According to McAdams,⁽⁵²⁾ the errors introduced due to conduction along the leads will be large if the leads are brought out directly into the fluid stream; however, this method is the one most frequently employed.

Jordan,⁽³⁸⁾ and later Webster,⁽⁸⁸⁾ brought the thermocouples out from the surface in small tubes attached to the surface; however, according to Colburn and Hougan, such attachments change the surface temperature since the presence of the tubes changes the flow of heat from the surface. Rietschell⁽⁷¹⁾ obtained very good results by supporting the thermocouples in rather long grooves on the inside of his pipe. The wires near the junctions were kept in good thermal contact with the surface by being packed in the grooves with a litharge-glycerol cement. The wires were then led through a hole in the pipe to the outside. Kreisinger and Barkley⁽⁴⁶⁾ attempted to correct for conduction of heat away from the junction with several thermocouples of different sizes connected

to the same point. Othmer and Coats⁽⁶²⁾ employed one wire of the same metal as the surface being measured and attached directly to it. The other lead was looped around the pipe at the desired position and then covered by an electrodeposited layer of metal the same composition as the wire. By this means they obtained a broad interface for the junction and measured the average temperature around the pipe. Colburn, however, claims that there was too much error due to conduction at the point where the wires entered the electrodeposited layer.

A proposed method of Colburn and also recommended by McAdams is to embed the wires in the surface for approximately one inch back from the junction with good thermal contact and electrical insulation. The thermocouple wire should be placed in a groove 1/32 inch wide and deep around the pipe. The junction should be soldered in place and dressed so as to make the solder flush with the surface of the pipe. The grooves must be filled with a suitable insulating material. McAdams considers a modification of this method and the use of a traveling couple also satisfactory.

Silicones

"Silicone"⁽⁷⁹⁾ is the general term applied to a family of organo-silicon compounds having direct carbon

to silicon linkages, the carbon being one atom of an organic radical. Silicones can be made in various degrees of polymerization to form liquids, greases, rubbers, and resins each characterized by being water repellent, and thermally and chemically stable up to 400°F. The liquids and greases show very little change in viscosity between -40 and 400°F. The dielectric constants of the resins compare favorably with those of the best organic insulations.

The early investigations ⁽³²⁾⁽⁴⁷⁾⁽⁹⁾ into silicones were made in an attempt to make compounds of silicon analogous to those of the organic compounds. Since silicon is the next element after carbon in Group IV of the periodic table, such analogies were thought possible. However, as has been brought out by more recent work, ⁽⁷⁸⁾ silicon is more electropositive than carbon and exhibits a maximum valence of six which under a variety of conditions causes its compounds to take part in vigorous reactions which are unknown to the analogous carbon compounds. Rochow ⁽⁷⁸⁾ explains the differences between silicon and carbon by the fact that the silicon atom is larger in size with a correspondingly greater screening of its nuclear charge.

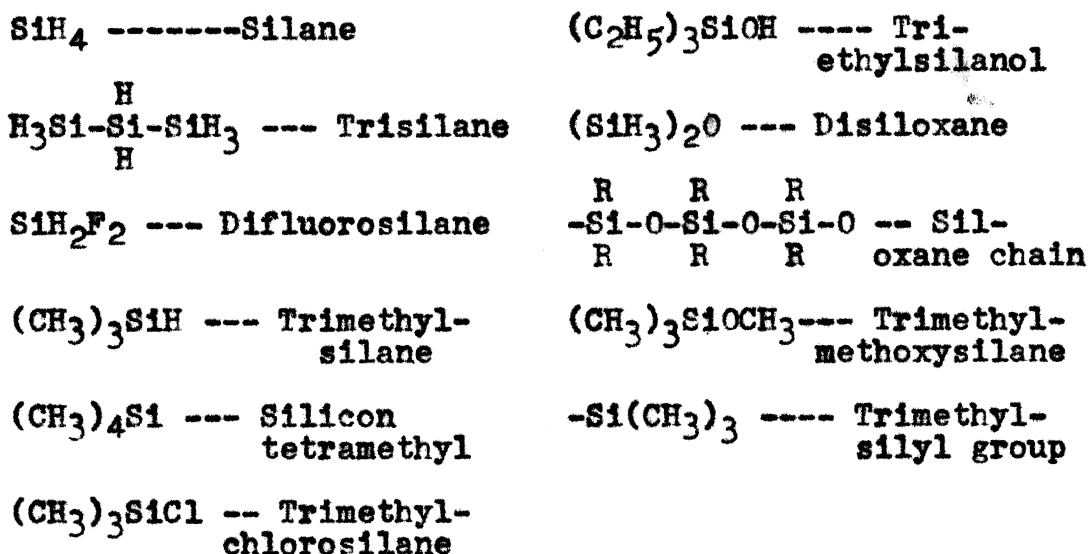
Early investigators of the synthesis of silicones were hindered by the lack of natural occurring silicones; however, in 1863 Friedel and Crafts⁽³²⁾ finally succeeded in producing the first direct C-Si linked compound, silicon tetraethyl, by the reaction of zinc ethyl on silicon tetrachloride. Ladenburg⁽⁴⁷⁾ followed in 1872 with the preparation of silicon tetraethyl by the action of zinc ethyl and sodium on ethyl silicate.

The most notable worker on silicones has been Dr. F. S. Kipping⁽⁷⁷⁾ of the University of Nottingham, England. Dr. Kipping and his students undertook the synthesis of silicones in 1898 in a study on optical rotation. By 1937, Dr. Kipping had completed his study of silicones after producing the majority of the compounds and data available today. However, also in 1937, Kipping⁽⁴²⁾ concluded in a paper in the Proceedings of the Royal Society that there was no immediate prospect for a practical use of silicones.

Just after Dr. Kipping completed his work, Dr. J.F. Hyde,⁽²³⁾⁽³⁶⁾⁽¹¹⁾ of Corning Glass Works, undertook the study of silicone resins as a possible filler for a new fibre glass product. The work expanded to another group under Dr. R. R. McGregor⁽¹¹⁾ at Mellon Institute of Industrial Research. This group worked primarily on

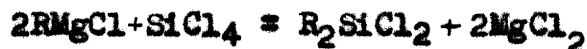
silicone liquid derivatives. As a result of information found by Dr. Hyde and Dr. McGregor, the Dow Corning Corporation ⁽²³⁾⁽¹¹⁾⁽¹⁾⁽¹⁵⁾ was formed and produced the first commercial silicones in May 1944. General Electric Company ⁽¹⁰⁾⁽¹⁾ began to produce silicones in late 1947.

Nomenclature of Organo-Silicon Compounds. In order to better understand an explanation of silicone chemistry it is necessary to be familiar with its nomenclature. The nomenclature of organo-silicon compounds was first proposed by Kipping ⁽⁴³⁾ in 1912 and was modified and condensed by Sauer ⁽³²⁾ in 1944. The system of Sauer is as follows:



Commercial Preparation of Silicones. There are two commercial methods of preparing silicones: (1) sub-

stitution and (2) direct synthesis. Dow-Corning Corporation employs the substitution method which involves the reaction of silicon tetrachloride and a Grignard reagent. The silicon tetrachloride and the Grignard reagent are first prepared from the basic raw materials, sand, brine, and petroleum. The reactions of the synthesis are as follows:

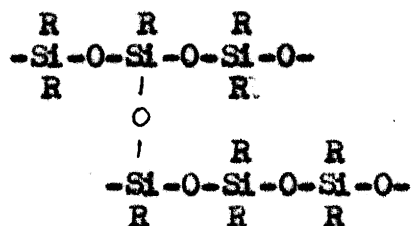


Quantities of $RSiCl_3$ and R_3SiCl will be formed; however, with proper control the desired product will predominate.

The R-chlorosilanes are then hydrolyzed to silanols:



Upon condensation the silanols yield siloxane linkages in the form of chains and networks.

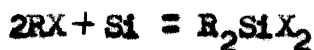


(76)(81)

General Electric employs the direct synthesis method. This method differs from the substitution method in that instead of fully halogenating the silicon and then successively replacing the halogen atoms and organic

groups it attaches both halogen atoms and organic groups to silicon in one operation. The reaction is carried out in the vapor phase with metallic copper as a catalyst.

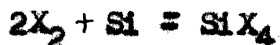
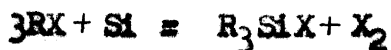
Under optimum conditions the predominant reaction may be represented as:



Several side reactions may occur:



(followed by degradation
of the free radicals.)



Here again no single compound is obtained, but a mixture, from which the predominant product must be separated by fractionation. The yield of R_2SiX_2 in this case has been reported as high as 70 per cent. If compounds of the type R_3SiCl are required predominantly, the corresponding dichlorosilane may first be made and then alkylated further by the Grignard reagent. As before, the organo-silicon halides are hydrolyzed and condensed.

In both processes the physical properties of the

final polymerized product is controlled by the selection of the organic groups, the number of organic groups on the silicon atom, and the degree of polymerization.

Methyl silicone oil. Methyl silicone oil, is a straight chain siloxane polymer produced by the hydrolysis of a mixture of dimethyldichlorosilane and trimethylchlorosilane. Each chain is terminated with the monofunctional trimethylsilyl group. The length of the polymethylsiloxane chain and, therefore, the physical properties of the oil is principally dependent upon the proportion of dimethyldichlorosilane to trimethylchlorosilane employed. The former gives rise to chain building defunctional units, whereas the latter forms chain blocking monofunctional units. Although the actual possible chain length is not known, compounds with from two to ten $(\text{CH}_3)_2\text{SiO}$ units have been isolated by fractional distillation at low pressures.

In addition to the common characteristics of silicones of being able to withstand extremes of temperature and being inert to metals and most chemical reagents, methyl silicone oil is characterized by showing a relatively small change in viscosity over a wide range of temperature. For example, one oil does not have a viscosity-temperature coefficient above

0.67; while those of petroleum oils range from 0.8 to 0.9. In other words, if a typical silicone oil is compared with a standard hydrocarbon oil of viscosity index 100, and the two having the same viscosity at 100°F, it is found that on cooling to -35°F the viscosity of the silicone oil is increased seven times while that of the hydrocarbon oil is increased 1,800 times. Such properties find wide use for silicone oils in hydraulic power transmission systems, ⁽⁷⁵⁾ lubricants, ⁽⁸³⁾ as scientific instrument dampeners, ⁽⁷⁶⁾ and as diffusion pump oils. When used as a lubricant the oils do not suffer loss of viscosity due to shear breakdown under continuous load at high speed.

Due to its excellent dielectric properties ⁽⁷⁵⁾ methyl silicone oil is now being used as the dielectric media in transformers and capacitors. Certain airplane ignition cables were filled with methyl silicone oil during the war to prevent corona discharge at high altitudes. It has also been found ⁽⁷⁵⁾ that the addition of a very small proportion of silicone oil to motor oil greatly reduces the tendency to foam.

Silicone greases, which are especially treated silicone oils are now used as excellent stop cock greases ⁽⁴⁵⁾ and as corrosion preventative coatings which may be

easily removed.

Methyl Silicone Resins. (75) Silicone resins are hydrolysis and condensation products of various organo-chloro silanes in which complex cross-linked siloxane networks are involved.

The degree of cross-linking in a silicone resin is usually designated by the R/Si ratio, (74) the ratio of the number of organic groups in the silicone molecule to that of silicon atoms. Cross-linking is always associated with less than two organic groups per silicon atom; therefore, the R/Si ratio is always something less than two in a silicone resin. If $R/Si = 1.5$, every other silicon atom (on the average) is cross-linked to another ring or chain. If $R/Si = 1.0$, every silicon atom is trifunctional and is bound into a completely cross-linked rigid structure.

Methyl silicone resin may be prepared by three methods: (36)(75)(80)

(1) Dimethyldichlorosilane or its esters may be hydrolyzed and then oxidized with air and a catalyst to attain the desired CH_3/Si ratio.

(2) Dimethyldichlorosilane may be mixed with methyl trichlorosilane or silicon tetrachloride and then hydrolyzed and the products cocondensed.

(3) Silicon tetrachloride may be partially methylated to the desired CH_3/Si ratio and the reaction mixture hydrolyzed directly.

Methyl silicone polymers with CH_3/Si ratios of 1.2, 1.3, 1.4, and 1.5 prepared by the second method are described ⁽⁸⁰⁾ as colorless solids with densities decreasing from 1.20 to 1.06; the time required to harden them at 100°C increases from 2 to 24 hours in the series, and the refractive indices bear a linear relation to the methyl content. Below $\text{CH}_3/\text{Si} = 1.2$, the resins are sticky syrups which cure at room temperature to hard brittle masses; and above 1.5 the products are oily and quite volatile but set to a soft gel after several days or weeks at 200°C .

The methyl silicone resins likewise have the common silicone characteristics of thermal stability and chemical inertness. Samples have been heated to 500°C in vacuo and to 500°C in hydrogen without desintegration, decomposition, or melting. One sample heated in air at 200°C for one year has not undergone any change. However, above 300°C , the resins will slowly oxidize in air. Because of their thermal stability the resins find wide usage as high temperature gasket materials, ⁽¹³⁾ high temperature fibre glass binders, ⁽⁹⁾ and protective coat-

(23)(3) (23)
ings. Dow-Corning has found that the resins offer very good protection to boiler stacks, boiler fronts, engine mufflers and small exhaust gas flues.

Due to the fact that methyl silicone does not decompose to a carbonaceous residue, it is particularly well suited for use as electrical insulation (9)(11)(55)(27)(40)

under elevated temperatures. The dielectric constant for the resins is 3.7, and the power factor 0.008 at 26°C and 0.0045 at 56°C (all measured at 60 cycles per second).

(55)
Moses reports that the output of some electrical machines have been increased as much as one-fourth by the increase in temperature limits, allowable with silicone resin insulation. The weight and bulk of rotating machines have been decreased by 20 per cent. De Kiep, Hill, and Moses (27) have published the results of an accelerated test on an electric motor insulated with silicone resin. The motor was run for 3,376 hours at temperatures between 300 and 500°C, and finally broke down due to bearing failure and melting of the rotor conductors.

(75)
Ethyl Silicone Resins. Ethyl silicone resins are prepared in very much the same way as the methyl resins. The ethyl group attached to silicon in a polymeric siloxane chain renders the composition softer, more soluble, and slower to cure than would a methyl group;

therefore, fewer ethyl than methyl groups are required. The preferable range of ET/Si is, therefore, approximately 0.5 to 1.5. Below 0.5 the resins are very brittle, and shrink and crack as they condense. The compositions are so highly cross-linked that they become insoluble at an early stage and are difficult to store and apply. The resins are usually made to form ET/Si of approximately 1.0.

Due to the difficulty in handling and properly condensing, the ethyl silicone resins are not used so much as the methyl resins; however, their electrical and thermal properties are very much the same.

Silicone Rubber. Methyl silicone rubber (75)(10)

is based on principles entirely different from those of the resins. An elastomeric gum is first prepared by treating the hydrolysis product of very pure dimethyldichlorosilane with one or more reagents which are effective in increasing the molecular weight without resorting to cross-linking. By this method it is possible to build up two thousand or more $(\text{CH}_3)_2\text{SiO}$ units without forming an insoluble gel. The elastomer is then milled with inorganic fillers as in natural and synthetic rubbers. A curing catalyst is added during the mixing, and then the plastic mass is molded to the desired shape, and cured.

The silicone rubber does not melt in air at 300°C nor lose its elasticity in service over long periods of time at 150°C, or when cooled to -55°C. Its electrical properties are similar to those of the resins and liquids. As a result of these properties silicone rubber is put to wide usage as corrosive resisting tubing, electrical insulation, sleeving for wire and cable, and protective coatings.

Application of Silicone Resins. Silicone resins may be applied directly as a resin or may be hydrolyzed and condensed on the surface to be coated in the vapor phase.

The first method (3)(20) simply involves the dipping or spraying of the resin, as received from the manufacturer, on the surface to be coated. However, before dipping or spraying the surface must be prepared in order to eliminate any non-adhering film present or which may form during subsequent curing of the resin to a solid.

(3)
Dow-Corning recommends either Bonderizing or Parkerizing to be the best for iron and steel; however, they have found that a simple acid etch followed by a dichromate treatment can give completely satisfactory results. The adhesion to aluminum can be also greatly

improved by the use of standard treatments for organic coatings, such as a dip in a solution containing alcohol, phosphoric acid, and zinc chromate. On magnesium, the Dow No. 7 treatment is a very effective paint base for the silicone enamels. This consists of a five-minute immersion in 20% HF followed by 45 minutes in 15% sodium dichromate. Castles⁽²⁰⁾ found that 30 minutes degreasing in 15 per cent NaOH followed by etching in 18 per cent HCl for 30-60 minutes was satisfactory for mild steel evaporator tubes.

The vapor phase method⁽⁷³⁾⁽⁵⁷⁾⁽²⁶⁾ has been successfully used to coat ceramics, paper, and cloth, in order to make them water-repellent. Norton⁽⁵⁷⁾ describes the method used by General Electric Company. In this process the clean ceramic pieces are conditioned at 50 to 90 per cent relative humidity and then placed in a cabinet equipped with a fan for circulating air. A measured quantity of methylchlorosilane mixture is vaporized and circulated in the cabinet for a few minutes. The treated pieces are then removed and allowed to stand in air for 20 minutes to allow the hydrogen chloride to dissipate. Measurements on ceramic electrical insulation coated by this method is found to have a resistivity of more than 200,000 megohms at dew point conditions as compared to an untreated-

ed glazed sample which has a resistivity of only 15 to 70 megohms.

(26)
Deane successfully coated dried cotton cloth by the vapor method. In this case, evidence was produced indicating that the reaction was between the methylchlorosilane mixture and the hydroxyl groups of the cellulose fibers.

(73)
Filter paper treated in this manner will not allow water to pass through but will pass hydrocarbon liquids readily.

Curing of Silicone Resins. Curing or polymerization of silicone resins is accomplished by heating the resin usually by infra-red at 140 to 250°C for the necessary length of time. The mechanism of the process is the condensation of the silanols in the liquid resins to form complex, cross-linked siloxane networks. It was originally believed that continued heating was the only requirement for polymerization; however, more recent work by Rochow (72) and Hyde and Delong (36) has shown that air is necessary for complete polymerization. When an insufficient quantity of air is furnished, the resins have a tendency to case harden leaving a semi-polymerized gel beneath the outer shell. This work may explain the action of drying agents on silicone polymerization;

however, Westgate⁽⁸⁹⁾ came to the conclusion that the action was catalytic rather than oxidation.

It was also found in their work that the addition of 3 per cent lead naphthenate (metal basis) reduced the curing time of silicone resins by two-thirds for a specific degree of hardness. The resins were only slightly less heat resistant than non-catalyzed resin.

⁽³⁾
Dow Corning states that lead and also calcium compounds accelerate resin curing; however, they do not recommend these compounds as they tend to gel the solutions. They recommend cobalt, zinc, and manganese compounds. In their available data sheet describing the proper curing procedure for the DC resins, Dow Corning used (Nuodex) cobalt naphthenate as a drier.

Infra-Red Curing. Infra-red heat has been found⁽²⁰⁾ to be best for curing silicone resins as well as organic finishes⁽⁷⁾⁽⁶⁾⁽²⁴⁾ for which it has long been used. Since Ford⁽³⁴⁾ introduced the method in 1932 for baking the finishes on his automobiles, infra-red heating has come into general usage as a fast efficient means of drying and baking.

⁽⁴⁴⁾
Klinkenstein has given the following reasons for using infra-red heat:

- (1) The process is visible and can be carefully

controlled.

(2) Proper arranging of lamps, insures uniform baking.

(3) "Case hardening" does not occur. No film is formed which prevents escape of the solvent.

(4) There is less danger of "chilling" which may cause wrinkling or crystallization.

Industrial infra-red lamps are manufactured in 250, 500, and 1000 watt sizes without reflectors. New type 250 watt lamps are available with self contained vaporized aluminum reflectors.

The major considerations in the construction of an infra-red oven are efficiency, ⁽¹⁷⁾ even heating, ⁽¹⁵⁾ and ventillation. ⁽⁴⁴⁾ Most authors agree that the most effective distance from the lamps to the work is from 8 to 14 inches and that natural draft ventillation is sufficient. Bennett and Haynes ⁽¹⁵⁾ state the lamps should be placed at the vertices of an equilateral triangle whose sides are from 8 to 12 inches in length. They found that 15 per cent more concentration of energy is obtained in this manner than if the lamps are placed at the corners of a square.

Bennett and Haynes also found that infra-red is the most efficient method of baking varnishes on me-

tallic surfaces, due to the fact that the metal attains the same temperature as the outside surface of the varnish; therefore, baking takes place on both sides at the same time.

(68)

Petty gives the design calculations and construction procedure of a small infra-red oven.

III. EXPERIMENTAL

Purpose of Study

The investigation was undertaken with a three-fold purpose:

1. The construction and installation of a double pipe heat-exchanger and other equipment necessary for conducting the experimental tests.
2. The determination of individual coefficients of heat transfer across a silicone coating on a heat-exchanger tube and a water film at various Reynolds numbers.
3. The determination of the effect of a silicone resin, when applied to the surface of a heat-exchanger tube, on the water film coefficient of heat transfer, and the rate of scale formation.

Plan of Investigation

The plan of investigation was as follows:

Construction: Cleaning Bath for Precoating Treatment of Tubes. A V-type trough was constructed of 24-ga. galvanized sheet iron to accommodate one $7\frac{1}{2}$ -in. standard 1-in. I.D. iron pipe. The sheet iron was coated with Tygon paint to prevent corrosion due to the cleaning baths. A suitable support was provided for the trough.

Infra-red Oven. An infra-red oven was constructed for the purpose of polymerizing the silicone coating on the heat-exchanger tubes. Infra-red lamps were placed on four sides of the oven so as to apply an even, efficient heat to one coated tube. The infra-red lamps were standard industrial 250 watt self-contained reflector type and were mounted on the apexes of equilateral triangles. The oven was capable of attaining a temperature of 440^oF.

Spraying and Drying Rack. A simple rack was constructed of angle iron capable of suspending the 74¹/₂-in. tubes in a vertical position for the purpose of spraying and air drying. The tubes were held in the rack by a wire wrapped around the threads on one end so as not to damage that portion of the silicone coating which was under investigation.

Experimental Horizontal Double-Pipe Heat-Exchanger. An experimental horizontal double-pipe heat-exchanger was constructed for the experimental tests. The outside pipe of the heat-exchanger was a 5-ft. section of standard 2-in. I.D. Pyrex glass pipe. Glass was used in order that the progress of the experiment could be visible at all times. The inside pipe under test was a 1-in. standard iron pipe coated with silicone resin. The ends of the heat-exchanger were provided with openings to the annular space and also with packing glands to facilitate installation and removal

of the tubes under test. One end contained an opening through which the thermocouple wires, mounted in the experimental tube wall, could be withdrawn. A feed solution tank fitted with an agitator was used to store and maintain a saturated gypsum scaling medium. A constant head tank was constructed to insure a constant flow of solution through the heat-exchanger. A steam separator and steam reduction valve insured a constant flow of dry steam through the inside of the tube under test. Necessary temperature and flow measuring equipment were provided.

Tube Processing: The experimental tubes were cut in lengths of 74½-in. from a standard 20 ft. section of 1-in. I.D. standard iron pipe and threaded on each end before being processed.

Cleaning and Priming. Two methods of cleaning and priming were investigated. The first method included degreasing in 15 per cent NaOH solution for 45 minutes at 100-200°F followed by etching in 15 per cent HCl for 45 minutes. The second method was etching in 15 per cent HCl until corrosion products disappeared, followed by priming in 15 per cent sodium dichromate for 45 minutes. The best method was used to prime the experimental tubes.

Coating. The tubes were spray-coated. The resins were used undiluted and diluted with toluene to give the desired thickness of coating. A maximum of 0.3 per cent

(Nuodex) Cobalt Naphthenate on the dry resin basis was used as a drying agent. After coating, the tubes were air dried for 16 hours before being placed in the infra-red oven.

Curing. The silicone resins on the tubes were polymerized by baking in an infra-red oven at 440°F for the time required to produce the desired hardness. The final hardness was measured by a "pencil hardness" test.

Installation of Thermocouples. Copper-constantan thermocouples were mounted in the tube wall before coating. The couples were fused, and then inserted in the tube wall in small grooves cut in the surface of the tube at right angles to the axis. The grooves extended half-way around the tube. The junction of the couples were soldered in, the leads peened in, and brought out on the opposite side of the pipe from the junction. Six thermocouples were placed at equal intervals along the tube wall and at angles of 72° around the tube.

Experimental Tests: The tests listed in Table I are divided into "Heat Transfer Tests" and "Accelerated Scaling Tests". The "Heat Transfer Tests" were made by passing water through the heat-exchanger at various Reynolds numbers while the "Accelerated Scaling Tests" were made by passing a saturated gypsum solution through the heat-exchanger at a constant Reynolds number. The non-

coated tubes were run for comparison with the coated tubes. An attempt was also made to correlate the data of other workers in the heat transfer runs on the non-coated tubes.

Collection of Data. The following data in regard to the heat-exchanger was collected in both the "Heat Transfer Tests" and the "Accelerated Scaling Tests".

- (1) Inlet and Outlet solution or water temperatures.
- (2) E.M.F. produced by each of the six thermocouples installed in the heat-exchanger tube wall.
- (3) Inlet and Outlet steam temperatures.
- (4) Flow of solution or water.

Table I

Planned Tests on Non-Coated and Silicone Coated Tubes in
an Experimental Heat-Exchanger

Heat Transfer Tests

Test No.	Tube	Reynolds Number
1a	Non-coated	2,000 - 10,000
2a	One spray coat of undiluted resin	2,000 - 10,000
3a	One spray coat of diluted resin	2,000 - 10,000
4a	Non-coated	10,000 - 15,000
5a	Two spray coats of diluted resin	2,000 - 10,000

Accelerated Scaling Tests

Test No.	Tube	Reynolds Number	Time of Test, hrs.
1b	Non-coated	15,000	10-24
2b	One spray coat of undiluted resin	15,000	10-24
3b	One spray coat of diluted resin	15,000	10-24
4b	Non-coated	4,000	10-24
5b	Two spray coats of diluted resin	4,000	10-24

Materials

Silicone Resin D.C. 801 (1 gal.). Composition, 60.0% solids, 40.0% aromatic solvent by weight. Viscosity, not given. Lot No. P-2. Used in flexibility tests. Purchased from the Dow Corning Corporation, Midland, Mich.

Silicone Resin, D.C. 802 (1 gal.). Composition, 50.0% solids, 50% Toluene by weight. Viscosity, 1.74 poises at 25°C. Lot No. MWB-3. Used for coating heat-exchanger tubes. Purchased from Dow Corning Corporation, Midland, Mich.

Silicone Resin, D.C. 803 (1 gal.). Composition, 50% solids, 50% Toluene by weight. Viscosity, not given. Lot No. M-13. Used in flexibility tests. Purchased from the Dow Corning Corporation, Midland, Mich.

Silicone Resin, D.C. 804 (1 gal.). Composition, 60.0% solids, 40% Toluene by weight. Viscosity, 0.23 poises at 25°C. Lot No. 0.12. Used for coating heat-exchanger tubes. Purchased from the Dow Corning Corporation, Midland, Mich.

Nuodex Cobalt, 6%. (1 gal.). Composition, cobalt naphthenate solution containing 6.00% cobalt. Used as a drying agent in the curing of the silicone resins. Manufactured by the Nuodex Products Company, Inc., Elizabeth, New Jersey.

Toluene (5 gal.). Grade, purified commercial. Lot No. 111846. Used to dilute silicone resins to desired spraying consistency. Obtained from J.T. Baker Chemical

Company, Phillipsburg, N. J.

Caustic Soda (20 lbs.). Grade, commercial flake. Lot No. C108J. Used in degreasing bath for tube preparation. Obtained from The General Chemical Company, New York, New York.

Hydrochloric Acid (6 lbs.). Grade, C.P. Composition, 37.0% HCl by weight. Specific gravity, 1.878. Used in etching bath for tube preparation. Manufactured by E. I. DuPont de Nemours and Company, Wilmington, Del.

Sodium Dichromate (25 lbs.). Grade, Cryst., technical.. Used in priming bath for tube preparation. Obtained from The General Chemical Co., New York, New York.

Tygon Paint (1 gal.). Code No. TP-61 White. Used to coat tube preparation trough. Manufactured by U. S. Stoneware, Akron, Ohio.

Tygon Tubing (35 ft.). Inside diameter, 3 mm. Used as a protection for thermocouple leads. Manufactured by U. S. Stoneware, Akron, Ohio.

Copper Wire (300 ft.). Size, No. 24 B. & S. ga. Insulation, enamel. Calibration, 1938. Used to make copper-constantan thermocouples. Purchased from Leeds and Northrup Company, Philadelphia, Penn.

Constantan Wire (300 ft.). Size, No. 24 B. & S. ga. Insulation, enamel. Calibration, 1938. Used to make copper-

constantan thermocouples. Purchased from Leeds and Northrup Company, Philadelphia, Penn.

Gypsum (100 lbs.). Grade, as mined. 90-95% purity. Used to make scaling medium. Donated by United States Gypsum Company, Plasterco, Virginia.

Pyrex Pipe (15 ft.). Straight length Pyrex flanged pipe, 2-in. I.D., 60-in. long. Used to construct heat-exchanger. Purchased from Corning Glass Works, Corning, N. Y.

Air (40 psig.). Used for spraying and drying tubes. Obtained from the Nash Hytor Compressor: Size AL-574; RPM 3500; 75 psi. Manufactured by Nash Engineering Co., South Norwalk, Conn.

Angle Iron (94 ft.). 1" x 1" x 1/8". Used as infra-red oven frame and drying rack. Purchased from Tidewater Supply Company, Roanoke, Virginia.

Angle Iron (28 ft.). 1 1/2" x 1 1/2" x 3/16". Used as lamp supports for infra-red oven. Purchased from Tidewater Supply Company, Roanoke, Virginia.

Porcelain Sockets (25). Medium base, baseboard mounting. Used for infra-red lamps and fuses in infra-red oven. Purchased from Frees, Beale, and Sharpe Hardware Company, Washington, D. C.

Switches (6), toggle, 125v, 12 amp. Used for control circuit on infra-red oven.

Lamps, Infra-red (22), internal reflector, industrial, 110-125 volts, medium base. Used as source of heat in infra-red oven. Manufactured by General Electric Lamp Works, Warren, Ohio. Purchased from Tidewater Supply Company, Roanoke, Virginia.

Wire (100 ft.), insulated, electrical, 12 gauge. Used to wire infra-red oven.

Wire (300 ft.), rubber insulated, single conductor, electrical, 12 gauge. Used to supply 3 phase current to equipment.

Fuses, (3), 30 amp, screw type, medium base. Used in fuse box on infra-red oven.

Wire, (75 ft.), rubber insulated, double conductor, lamp cord size, stranded, electrical. Used to wire Brown Resistance Thermometer. Purchased from Blacksburg Hardware Company, Blacksburg, Virginia

Asbestos Board (67 sq. ft.), $\frac{1}{4}$ " thick. Used as insulation for infra-red oven.

Belts (3), V-type, Gates Tru-flex, No. 2370. Used as pump drive from electric motor. Purchased from Blacksburg Hardware Company, Blacksburg, Virginia.

Apparatus

Infra-red Oven. (Drawing 1.) The oven was used to cure the silicone coated heat-exchanger tubes. The frame was constructed from 1" x 1" x 1/8" angle iron with welded permanent joints. The frame is so constructed that it may be quickly dismantled into four sections to facilitate moving. The walls of the oven were made from 1/2-in. asbestos board through which five inch holes were drilled to accommodate the infra-red lamps. The walls were attached to the frame by means of 3/16" round head stove bolts. Twenty-two infra-red lamps were used as a source of radiation, six being placed on top and bottom, and five on each of the two sides. The lamps were so placed that any three adjacent lamps formed an equilateral triangle whose sides were approximately 12-in. in length. This arrangement, together with the fact that the coated metal tube wall approached a uniform temperature, insured even baking of the silicone resins. The baking temperature was measured by means of the thermocouples inserted in the wall of the tube being baked. The tubes were supported during baking by means of extensions of 1" I.D. standard iron pipe passed through 1-3/8" diameter holes drilled in the end walls of the oven.

Double-Pipe Heat-Exchanger. (Item 2, Drawing 2). The horizontal double-pipe heat-exchanger was constructed from

a 5-ft. section of 2-in. I.D. Pyrex glass pipe as the outside pipe and a $74\frac{1}{2}$ -in. length of 1-in. I.D. standard iron pipe, the experimental tube, as the inside pipe. The inlet end-section consisted of a standard cast-iron, 2-in. to 1-in. reducing cross to which a standard A.S.M.E., 2-in. cast iron flange was brazed. A packing gland for the inside pipe was formed by brazing a $2\frac{1}{4}$ -in. O.D. x $1\frac{3}{8}$ -in. I.D. washer inside the cross at the termination of the threads. The gland was completed by screwing a 2-in. standard cast iron plug, which had a $1\frac{3}{8}$ -in. diameter hole drilled through the center into the threaded end of the cross. One 1-in. nominal diameter threaded opening of the cross was an inlet to the annular space of the heat-exchanger; the other was to provide for an outlet for the thermocouple leads. The entire end section was fitted to the Pyrex pipe by means of a standard cast iron Pyrex pipe connection flange and gasket which bolted directly to the standard A.S.M.E. flange on the end section by means of four $\frac{5}{8}$ -in. x 3-in. machine bolts.

The outlet end-section was constructed identical to the inlet section except that a 2-in. to 1-in. standard cast iron reducing tee was used rather than the cross. Also, opposite the 1-in. threaded side outlet of the tee, a $\frac{1}{4}$ -in. brass petcock was tapped to provide an air vent to the heat-exchanger.

Cooler (Item 3, Drawing 2). The cooler which was used to cool the scaling medium after passing through the experimental heat-exchanger was available in the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia. It was a counter-current, water cooled type and was constructed from a 41-in. section of 4-in. nominal diameter black iron pipe. The hot scaling medium passed inside four $\frac{1}{2}$ -in. nominal diameter black iron tubes, the total cooling area of which was 2.22 sq. ft. The tubes were welded into tube sheets of $\frac{1}{8}$ -in. sheet steel on the ends of the 41-in. section. Caps provided with 1-in. nominal diameter nipples were welded to the ends of the 41-in. section to form the inlet and outlet for the cooling water.

Feed Tank (Item 9, Drawing 2). The feed tank for the scaling medium consisted of one half of a standard 55-gallon drum. A hole was cut in the bottom and provided with a 1-in. fitting as a drain.

Feed Pump (Item 10, Drawing 2), centrifugal type, Fig. 201, Size 1. Used to pump the scaling medium from the feed tank to the constant head tank. Manufactured by the Ramsey Pump Company, Ltd., Senecal Falls, N.Y.

Constant Head Tank (Item 5, Drawing 2). The constant head tank consisted of a steel drum, 14-in. in diameter and 23-in. high. It was fitted with a $\frac{1}{2}$ -in. overflow pipe

four inches from the top of the tank. A 1-in fitting was provided in the bottom as an outlet.

Pump Drive Motor, induction type, model 5K204 A2, 220/440 volts, 3 phase, speed, 1720 rpm fully loaded, one horse-power. Manufactured by General Electric Company, Schenectady, N. Y.

Steam Separator (Item 6, Drawing 2). The steam separator was constructed from a 18-in. section of 4-in. nominal diameter standard black iron pipe. A 4-in. A.S.M.E flange was screwed on each end of the 18-in. section. Solid flanges, provided with suitable inlets and outlets, were cut and drilled from $\frac{1}{4}$ -in. steel plate for the top and bottom of the separator.

Steam Reduction Valve (Item 13, Drawing 2), Body-Br, Trim-304, Max. body press. 200, Temp. 388, Range 50-100 lbs., Fig. 33. Used to control flow of steam into experimental heat-exchanger. Manufactured by Mason-Nielan Regulator Company, Boston, Mass.

Steam Trap (Item 12, Drawing 2), Type 81, high pressure, $\frac{3}{4}$ -in. size, pressure seat no. 80. Used on exhaust steam line from experimental heat-exchanger. Manufactured by C. A. Dunham Company, Chicago, Ill.

Thermocouples. The copper constantan thermocouples were constructed by twisting the cleaned ends of copper and a constantan wire, cut to the proper length, for ap-

proximately 3/8-in. and fusing the joint by means of an oxy-acetylene torch.

Thermocouple Cold Junction. The thermocouple cold junction bath consisted of a 1-qt. metal can placed on the inside of a larger can, 5½-in. high x 5½-in. diameter, and the space between the two containers filled with asbestos lagging. Each of the six thermocouple cold junctions, which were constructed in the same manner as the hot junction, described above, were inserted into a 4-in. length of 3-mm. I.D. glass tubing half-filled with mercury. Each glass tube was inserted through a No. 1 rubber one-hole stopper which, in turn, was fitted into a metal top, containing space for six such stoppers, made to fit the 1-qt. container. The bath was completed by fitting the top, containing the six stoppers and glass tubes, on the container, and by filling the container with tap water, below 80°F, above the mercury level in the glass tubes. The temperature of the bath was obtained with a glass mercury thermometer with two degree graduations from 40 to 300°F.

Resistance Thermometers, bulb type A, range 0-300°F, complete with galvanometer indicator Model No. 9003, standardization panel Model No. 9001, and twelve point rotary switch Model No. 70814. Used to make all fluid temperature measurements. Manufactured by Brown Instrument Company, Philadelphia, Penn.

Air Regulator, 80 lb. capacity. Used to control flow of air for spraying and drying tubes. Manufactured by the DeVilbiss Company, Toledo, Ohio.

Tube Preparation Trough. The V-type tube preparation trough was 75-in. long, 9-in. wide, and $4\frac{1}{2}$ -in. deep; and constructed of 24-ga. sheet iron coated with five coats of Tygon paint. The support for the trough consisted of two boards, 6-in. x $\frac{3}{4}$ -in. x 75-in., nailed together, edge to edge, and at right angles to also form a V. Four legs, 24-in. in length, constructed of 1-in. x 1-in. x $\frac{1}{8}$ -in. angle iron were attached to the wooden support by means of wood screws.

Spraying and Drying Rack. The spraying and drying rack consisted of two vertical, 86-in. lengths of 1-in. x 1-in. x $\frac{1}{8}$ -in. angle iron spaced at the top and bottom by a $31\frac{1}{2}$ -in. length of angle iron. Two 48-in. angle iron members were welded to the bottoms of the vertical members as a base.

Manometers. Two 23-in. standard differential manometers employing carbon tetrachloride as the indicating liquid were used to measure the flow of fluid to the constant head tank and through the experimental heat-exchanger. The manometers were constructed in the Chemical Engineering Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

Balance, Ohaus, double-beam, sliding scale, 21.1 kilogram capacity, one gram accuracy. Used to weigh chemicals for preparing tube priming solutions and scaling medium. Manufactured by the Newark Scale Works, Newark, N. J.

Pencil Hardness Tester. The pencil hardness tester consisted of a 4-in. length of 3/8-in. I.D. glass tubing held in a vertical position by a clamp which was, in turn, attached to a ringstand. The pencil fitted loosely in the glass tube and a 200 gram weight placed on top the pencil provided the correct pressure.

Batteries, (3), dry cell, Eveready No. 6. Used as the source of E.M.F. for Brown Resistance thermometer and Leeds-Northrup Potentiometer. Manufactured by the National Carbon Company, Inc. Purchased from Blacksburg Hardware Company, Blacksburg, Virginia.

Pencils, drawing, 6B through 9H. Used in pencil hardness test. Manufactured by Eberhard Faber. Purchased from The College Book Store, Blacksburg, Virginia.

Microscope, 100X and 430X, graduated focusing scale. Used to examine and measure thickness of silicone coatings. Manufactured by Baush and Lomb Optical Company, Rochester, N.Y. Loaned by Professor J. B. Lucas, Chemistry Department, Virginia Polytechnic Institute, Blacksburg, Virginia.

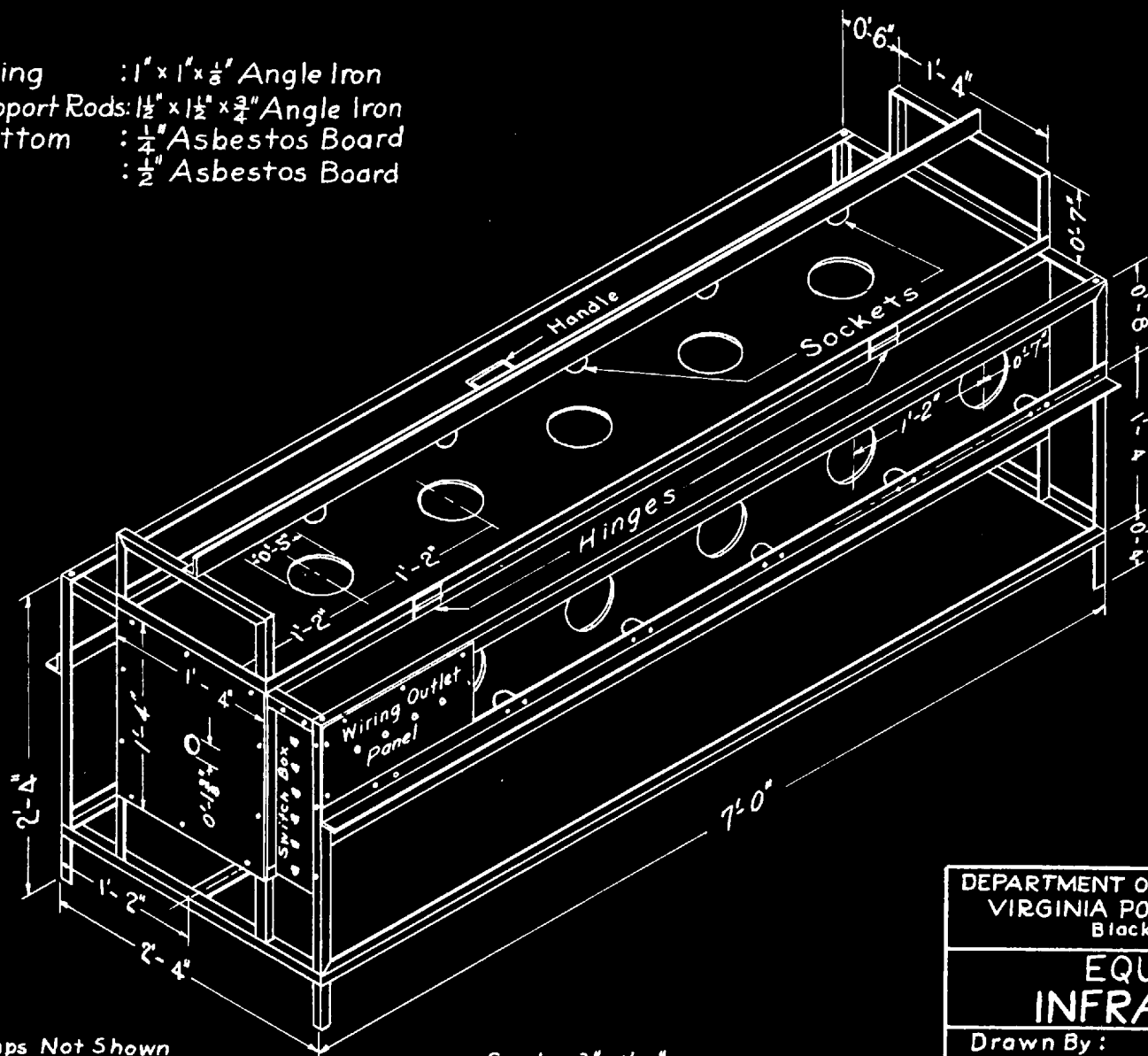
Potentiometer, Model K, compensating cold junction type, No. 89571. Used to measure E.M.F. produced by thermocouples. Manufactured by Leeds & Northrup Company, Philadelphia, Penn.

Agitator, portable, Lightnin Mixer, Model C-3, No. 38533. Used to agitate feed solution. Manufactured by Mixing Equipment Company, Inc., Rochester, N. Y.

Spray Gun, type-MV. Used to spray heat-exchanger tubes. Manufactured by the DeVilbiss Company, Toledo, Ohio.

NOTE:

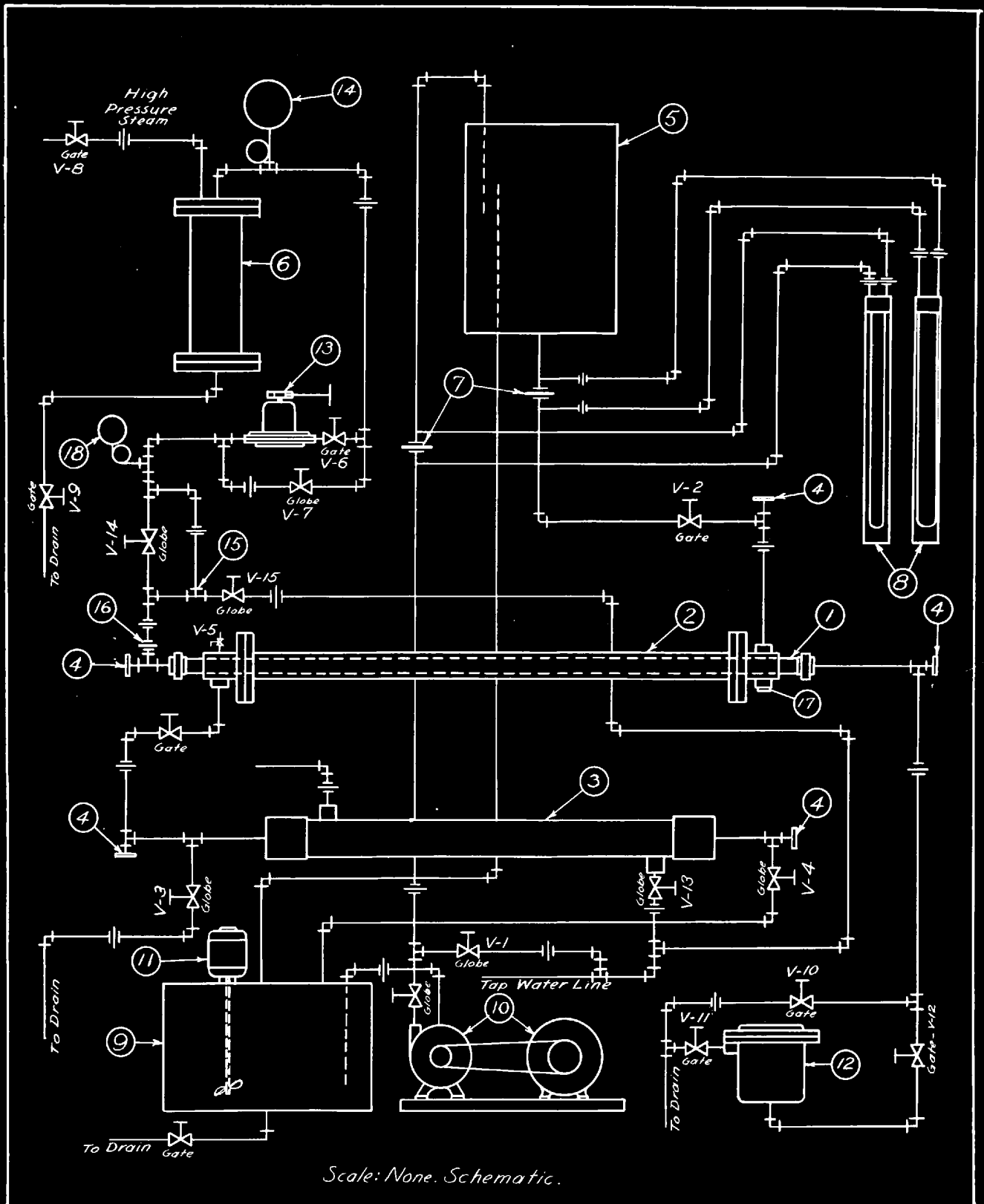
- All Framing : 1" x 1" x 1/8" Angle Iron
- Lamp Support Rods: 1 1/2" x 1 1/2" x 3/4" Angle Iron
- Top & Bottom : 1/4" Asbestos Board
- Sides : 1/2" Asbestos Board



Infra-Red Lamps Not Shown

Scale: 3/4" = 1'-0"

DEPARTMENT OF CHEMICAL ENGINEERING VIRGINIA POLYTECHNIC INSTITUTE Blacksburg, Virginia	
EQUIPMENT INFRA-RED OVEN	
Drawn By: _____	Date: _____
Checked By: <i>OTW</i>	Date: <i>9/29/47</i>
Approved By: <i>Jwb</i>	Date: <i>9/29/47</i>
DRAWING No. 1	



Scale: None. Schematic.

LEGEND

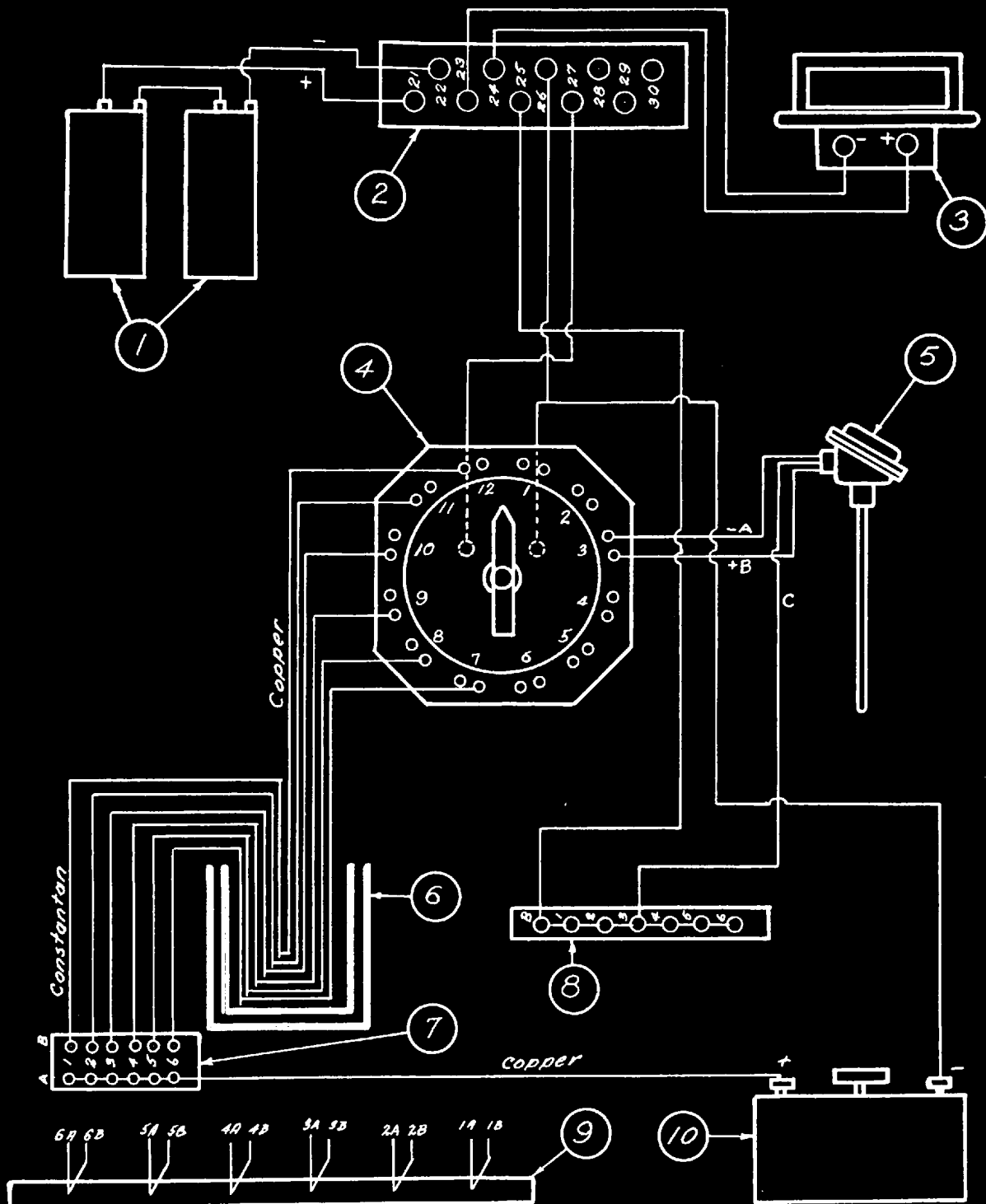
- | | |
|-----------------------------|--------------------------------|
| (1) Experimental Tube | (10) Feed Pump and Motor |
| (2) Test Heat-Exchanger | (11) Agitator |
| (3) Feed Cooler | (12) Steam Trap |
| (4) Resistance Thermometers | (13) Steam Reduction Valve |
| (5) Constant Head Tank | (14) High Pressure Steam Gauge |
| (6) Steam Separator | (15) Steam Injector |
| (7) Orifices | (16) Flexible Joint |
| (8) Manometers | (17) Thermocouple Outlet |
| (9) Feed Tank | (18) Low Pressure Steam Gauge |

DEPARTMENT OF CHEMICAL ENGINEERING
 VIRGINIA POLYTECHNIC INSTITUTE
 Blacksburg, Virginia

EQUIPMENT HEAT EXCHANGER & ACCESSORIES

Drawn By: *eds* Date: 2/2/46
 Checked By: *zwb* Date: 9/9/47
 Approved By: *zwb* Date: 9/29/47

DRAWING
 NO. 2



Note: Resistance Thermometers No. 1 thru No. 5
Connected to Switch Points No. 1 thru No. 5

LEGEND

- (1) No. 6 Dry Cell Batteries
- (2) Connection Block in Standardization Box
- (3) Brown Temperature Indicator
- (4) Brown 12-Point Rotary Switch
- (5) Brown Resistance Thermometer Bulb
- (6) Thermocouple Cold Junction & Bath
- (7) Thermocouple Connection Block
- (8) Common Connection Strip in Rotary Switch
- (9) Heat-Exchanger Tube & Thermocouples
- (10) Leads & Northrup Potentiometer

DEPARTMENT OF CHEMICAL ENGINEERING
VIRGINIA POLYTECHNIC INSTITUTE
Blacksburg, Virginia

EQUIPMENT WIRING DIAGRAM

Drawn By: *24*, Date: *20/1/47*
Checked By: *Date:*
Approved By: *20*, Date: *9/2/47*

DRAWING
NO. 3

Method of Procedure

Preliminary Preparation of Tubes. The 74½-in. heat-exchanger tubes (Item 1, Drawing 2) were cut from a 20-ft. section of 1-in. nominal diameter standard black iron pipe, and threaded on each end for a distance of one inch to accommodate 1-in. nominal diameter unions which coupled the tube to the inlet and exhaust steam lines. Six slots, 1/32-in. wide and 1/32-in. deep and extending half-way around the tube, were cut in the outer surface of the tube. The first and last slots were placed 5¼-in. from the ends of the tube and the remaining four equally spaced between the first and last, and 72° from each other around the tube. The point for inserting the thermocouple junction was marked with a small chisel.

When the slots had been satisfactorily cut, the tube was placed in the preparation trough and covered with 15 per cent NaOH solution at room temperature. The NaOH solution was allowed to react for 45 minutes, during which time, an organic rust preventative which coated the tube was effectively loosened. The NaOH solution was drained from the trough by means of a drain spout located at one end, and the tube was washed thoroughly, both inside and out, with a strong stream of tap water. Any of the loosened organic coating which remained on the tube, after the NaOH solution was drained, was washed off by the water stream.

The trough was next filled with enough 15 per cent hydrochloric acid to cover the tube, and the reaction was also allowed to take place for 45 minutes. The hydrochloric acid removed any traces of rust and corrosion present. The tube was again washed thoroughly and wiped with a clean cotton cloth to remove a black film which formed during etching. The tubes which were not to be coated were given no further chemical treatment.

The tubes to be coated were next treated with a 15 per cent sodium dichromate solution for 45 minutes to put a dichromate prime on the surface. This procedure was found necessary to prevent a thin film of rust from forming while the thermocouples were being installed. The dichromate solution was then drained and the tubes washed thoroughly as before. The tube was removed from the trough, suspended in a vertical position, and dried with a stream of air under 20 psig pressure. With the dichromate prime, it was not necessary to install the thermocouples immediately.

Installation of Thermocouples. A copper and a constantan wire were cut to the proper length, i.e., the distance from its slot to the outlet steam end of the pipe plus 18-inches, and twisted together by holding one set of ends in a vise and manipulating the loose ends. The ends which were in the vise were cleaned for $\frac{1}{4}$ -in., twisted tighter, and fused with an acetylene torch. Care was taken not to make the fused

junction larger than 1/16-in in diameter. The thermocouple junction was placed over its proper position in the tube wall and driven into the slot with a light hammer. The twisted leads were then peened into the remainder of the slot and brought out on the opposite side of the pipe from the junction. Solder was peened into the slot around the junction for a distance of $\frac{1}{2}$ -in. on each side, and filed smooth. It was necessary to peen the solder in the tubes to be coated because the application of heat caused rusting which could not be removed completely. However, the solder was applied with heat to the tubes not to be coated. The slots in all cases were filled with silicone resin DC 803.

This method of attaching the thermocouples was checked in two ways:

(1) One couple was installed in a two inch section of 1-in. nominal diameter pipe and placed in a breaker of water with a mercury glass thermometer. The temperature of the water was gradually raised from 70 to 208°F. The readings of the mercury thermometer and the thermocouple were taken simultaneously for approximately each 10 degree of temperature rise. After the water had reached the boiling point, the heat source was removed and the water allowed to cool. During cooling, the temperature was recorded in the same manner as for heating.

(2) After each tube had been installed in the heat-

exchanger, tap water was passed through the heat-exchanger at approximately 1.5 feet per second. The temperature of the tap water was measured by the inlet resistance thermometer (Item 4, Drawing 2), the outlet resistance thermometer, and the six thermocouples. This temperature was usually about 60°F. The water was then circulated through the system by means of the feed pump (Item 10, Drawing 2) and steam at about 250°F was passed through the inside of the experimental tube. The water in the system was allowed to reach a temperature of 200°F; the steam was turned off and bled from the system. The water was allowed to circulate for ten minutes after the steam was shut off and the temperatures again read as above. This data was used only to check the operation of the thermocouples in each tube at a low temperature and at a high temperature, and was not recorded. For the five tubes tested, in only one instance did a thermocouple read the incorrect value. In this case its reading was not used in the experimental test.

Coating of Heat-Exchanger Tubes. When the thermocouples had been installed, the tube was suspended in the spraying and drying rack and the thermocouple wires tied to a vertical member of the rack to prevent them from touching the tube. The proper silicone resin was placed in the suction cup of the spray gun and 40 psig air pressure applied. The spray gun used was not equipped with a graduated air valve; therefore,

the air valve was adjusted until a fine spray was emitted from the gun. Insufficient air would not force the resin from the gun, and too much air caused droplets in the spray. The tube was coated by making a slow, even pass at the tube from end to end from a distance of about 18 inches. The tube was then rotated to expose an uncoated surface and another pass made. This procedure was continued until the tube was coated with a smooth even coat of silicone resin.

The tube was air dried for 16 hours before applying a second coat or before placing the tube in the infra-red oven for curing.

Tube Curing. The silicone coated tubes were cured in a infra-red oven (Drawing 1) at 440°F for the time required to give the desired pencil hardness. An extension tube was screwed to one end of the heat-exchanger tube and passed through the hole in one end wall of the oven. The tube was then lowered into the oven and the other extension tube, already in the hole in the opposite end wall, was attached. Due to the fact that the couplings which joined the extension tubes and the heat-exchanger tube could not pass through the end wall holes, it was impossible for the tube to fall on the infra-red lamps in the bottom of the oven. The thermocouple wires were brought out through one end hole, and care was taken to make sure that they did not rest against the silicone coating at any point. The oven was turned on full heat, and the time was meas-

ured from that point.

Pencil Hardness Test. The silicone coated tubes were given the hardness test before and after the experimental test in the heat-exchanger. In all cases the hardness was the same for both times. The tube being tested was supported horizontally under the tester by two wooden supports located at each end. A pencil, lower than the suspected hardness of the coating, was sharpened in a Little Giant pencil sharpener and further sharpened by rubbing the point lightly on a piece of 2/0 emery cloth while holding the pencil at a 45° angle. The pencil, was then placed in the tester and the 200 gram weight placed on its top. The mounting clamp was moved back and forth for a distance of approximately one-half inch. The hardness of the pencils were progressively increased until one was found which would tear the film. The coating was rated as the hardness of this pencil.

Coating Thickness Measurement. When the pencil hardness test was completed, the microscope was placed over the tube, while the tube remained stationary. The thickness was measured by counting the number of focusing knob integrations difference between a focus on the surface of the tube, and a focus on the surface of the silicone. One integration represented 0.0025 mm. or 0.0000984-inch. Measurements were taken in three different places and the results averaged.

Installation of Heat-Exchanger Tube. The heat-exchanger inlet end section was removed from the Pyrex glass pipe by removing the flange connecting bolts and disconnecting the inlet pipe union, and placed on the coated heat-exchanger tube, laying horizontally between two end supports, in its correct position. Thermocouple junction No. 1 was positioned on top of the tube. Each thermocouple was tagged, passed into the end section and withdrawn through the 1-in. nominal diameter opening in the end section provided for this purpose. A No. 7 rubber stopper having six slits in its periphery was dipped in silicone resin D.C. 803. The thermocouple wires were inserted in the six slits and the stopper drawn up to the 1-in. nominal diameter opening. When it was sure that the thermocouple wires were securely sealed in these slits, the stopper was again coated with silicone resin D.C. 803 and inserted tightly into the 1-in. nominal diameter opening.

The heat-exchanger tube with the end section attached was then inserted through the Pyrex pipe and out of the outlet end section until approximately 4-in. protruded. The bolts in the inlet end section flange were replaced and the inlet pipe union reassembled. The steam lines were connected, the packing glands tightened, and the thermocouples connected to the thermocouple connection block (Item 4, Drawing 3). After the equipment had been checked for leaks, the thermocouples were checked as previously described.

Experimental Tests. (Valve designations refer to Drawing 2). For the "Heat Transfer Tests" valve V-1 was opened and the constant head tank was allowed to fill with water. When the constant head tank had filled to the overflow, valve V-1 was closed, and heat-exchanger inlet valve, V-2 was opened after making sure control valves V-3 and V-4 were closed. This precaution was taken to prevent taking air into the main flow manometer line. Pet-cock V-5 was then opened slowly to allow the heat-exchanger to fill. The pet-cock was closed and tap water valve V-1 was again opened, until the manometer in that line read 15-in. of carbon tetrachloride. Control valve V-3 was immediately opened wide, which represented maximum velocity through the heat-exchanger.

After checking to make sure that inlet steam valves V-6 and V-7 were closed, main steam valve V-8 was opened. Separator drain valve V-9 was opened until all water had drained from the steam line. During subsequent operation valve V-9 was cracked to provide a continuous drain on the steam separator. Steam trap by-pass valve V-10 and steam pressure regulator by-pass valve V-7 were opened to heat the steam lines. When a steady blast of steam was being emitted from the steam exhaust pipe, valves V-10 and V-7 were closed and valves V-6, V-11, and V-12 were opened. The steam pressure regulator was adjusted to approximately 40 psig so as to

cause a rise in water temperature through the heat-exchanger of approximately 30°F. The equipment was allowed to come to equilibrium for one-half hour. While the equipment was reaching equilibrium, the Brown Resistance thermometer was standardized and the thermocouple cold junction bath changed.

After each set of data was taken the velocity through the heat-exchanger was changed by manipulating control valve V-3. The steam pressure also had to be reduced by changing the setting of the steam regulator (Item 13, Drawing 2), in order to maintain a rise in water temperature of approximately 30°F. In general, this change amounted to about 5 psig for each two inch change in the main flow manometer reading.

At Reynolds numbers below 2500 it was necessary to use hot water inside the experimental heat-exchanger tube. This was accomplished by closing steam valve V-14 and opening tap water valve V-15, thereby, injecting steam into the tap water.

For the "Accelerated Scale Tests" the equipment was put into operation in the same manner as for the "Heat Transfer Tests", except that the feed pump (Item 10, Drawing 2) was used to carry fluid to the constant head tank and the fluid was allowed to return to the feed tank rather than pass out to the drain. The flow of fluid through the

heat-exchanger was controlled by valve V-4 and the inlet solution temperature was allowed to reach 155°F before data was taken. Also at this point, cooling water valve V-13 was opened to maintain the heat-exchanger inlet temperature at approximately 155°F.

Immediately after the first data was taken, which represented zero time for the scale test, 0.4 lbs. of gypsum was added to the water in the feed tank to make a saturated solution, and the agitator started. The agitator was run for five minutes for the first time and for one minute after each set of data was taken. When the scale had ceased to form, as indicated by a constant heat transfer coefficient, another 0.4 lbs. of gypsum was added to insure a saturated solution.

Data and Results

The data and results of the experiments are given on the following pages in the form of tables and graphs.

Table II gives the properties of water at various temperatures used in calculating the results of the experiment.

Table III is a sample data sheet for "Heat Transfer Test" No. 2a. The data sheets for the "Accelerated Scale Tests" were identical except that "Time" was substituted for "Reading No." and "Manometer Reading-Ins. CCl₄" remained constant throughout the tests.

Tables IV through XIII give the data and results of experiments 1 through 5. The "a" section of the experiments in all cases was the "Heat Transfer Test"; while the "b" section was the "Accelerated Scale Tests". In all cases the average thermocouple readings have been converted to temperature, and the manometer readings to flow through the heat-exchanger in lbs/hr and ft/sec. The results were calculated as shown below under "Sample Calculations".

Table XIV gives the values of thermal conductivity for silicone resin DC 802, and the water film coefficient between tap water and resin DC 802. These values were calculated from the data and results of Experiments 2a and 5a.

Figure I is a sample of the E.M.F.-Temperature curves used to convert the thermocouple readings as read by the potentiometer to temperature in degrees Fahrenheit.

Figure II depicts the data of Experiment 1a and 4a in graphical form. This method of graphically representing the change in the heat-transfer coefficient with change in Reynolds numbers is usually employed because the slope of the data mathematically represents the power to which the Reynolds number should be raised in the demensionless equation $\frac{hd}{k} = \phi \left(\frac{Du\rho}{\mu} \right)^m \left(\frac{C\mu}{k} \right)^n$ and the y- intercept represents the numerical value of the constant ϕ . The

Dittus-Boelter equation is plotted for comparison. The line drawn through the data is not intended to represent the true equation. It was drawn to show that the data, in general, follows a slope of 0.8.

Figure III depicts the same for the silicone coated tubes as Figure II does for the non-coated tube in Experiments 2b, 3b, and 5b. The same line drawn through the data in Figure I is redrawn here for comparison.

Figure IV represents in graphical form the rate of scale formation on the coated and non-coated tubes in Experiments 1b, 2b, 3b, 4b, and 5b.

Sample Calculations. The following method, illustrated by Reading No. 1 of Experiment 2a, was used in calculating the results of all experiments:

(a) Arithmetic average values for the inlet and outlet annulus water temperatures and the EMF readings of the six thermocouples were obtained for the three sets of readings shown in Table III. An average of the six average values for the thermocouples was then made thereby giving the arithmetic average for the eighteen thermocouple readings. The values obtained above were:

Inlet annulus water temperature:	62.5°F
Outlet annulus water temperature:	82.0°F
Thermocouple reading	: 3.768 Mv.

(b) The manometer reading of 13.6 ins.- CCl_4 was converted to rate of flow and velocity through the heat-exchanger by means of a calibration curve for the manometer. The values obtained here were:

Rate of flow, W : 5320 lbs/hr.

Velocity, u : 1.905 ft/sec.

(c) Arithmetic average water temperature:

$$\frac{62.5 + 82.0}{2} = 72.2^\circ\text{F}$$

(d) Heat transferred to annulus water, q :

$$q = wc \, dt$$

$$dt = 82.0 - 62.5 = 19.5^\circ\text{F}$$

C = specific heat of water. Taken as 1.0 throughout investigation.

$$q = 5320 \times 1.0 \times 19.5 = 103,500 \text{ Btu/hr.}$$

(e) The average thermocouple reading (3.768 Mv) was converted to degrees from an EMF - temperature chart (Fig. I) to give the average pipe wall temperature.

3.768 Mv corresponds to 192.1°F .

(f) Logarithmic mean temperature difference, Δt_m :

$$\Delta t_m = \frac{\Delta t_2 - \Delta t_1}{\log_e \frac{t_2}{t_1}}$$

$$\Delta t_2 = 192.1 - 62.5 = 129.6^\circ\text{F}$$

$$\Delta t_1 = 192.1 - 82.0 = 110.1^\circ\text{F}$$

$$\Delta t_m = \frac{129.6 - 110.1}{\log_e \frac{129.6}{110.1}}$$

$$= \frac{19.5}{\log_e 1.175} = \frac{19.5}{0.1610}$$

$$\Delta t_m = 120.8^\circ\text{F}$$

(g) Film Coefficient, h:

$$h = \frac{q}{A \Delta t_m}$$

A = 1.92 sq. ft. effective heating area of heat-exchanger.

$$h = \frac{103,500}{1.92 \times 120.8} = 447 \frac{\text{Btu}}{\text{sq.ft./hr./}^\circ\text{F}}$$

(h) Reynolds number, $D_e G/\mu$ or $D_e u/\mu$:

$$D_e = 0.0571 \text{ ft. based on } D_e = D_2 - D_1$$

$$u = 1.905 \text{ ft/sec. (From manometer calibration chart)}$$

$$\mu = 0.000641 \text{ Eng. Sec. Units = viscosity at } 72.2^\circ\text{F (Table II)}$$

$$\rho = 62.29 \text{ lbs/ft}^3 = \text{Density of water at } 72.2^\circ\text{F. (Table II)}$$

$$\frac{D_e u \rho}{\mu} = \frac{0.0571 \times 1.905 \times 62.29}{0.000641}$$

$$= 10,550 \text{ (dimensionless)}$$

(i) Prandtl number, C_p/k :

$$C_p = 1.0$$

$$\mu = 2.31 \text{ Eng. Hour-Units = Viscosity of water at } 72.2^\circ\text{F. (Table II)}$$

$$k = 0.347 \text{ hr. units = thermal conductivity of water at } 72.2^\circ\text{F.}$$

$$\frac{C_p}{k} = \frac{1.0 \times 2.31}{0.347} = 6.66 \text{ (dimensionless)}$$

$$\left(\frac{C_p}{k}\right)^{0.4} = 2.13$$

(j) Nusselt number, hd/k :

$$\frac{hd}{k} = \frac{447 \times 0.0571}{0.347} = 73.6$$

(k) $\frac{hd/k}{(C\mu/k)^{0.4}} = \frac{73.6}{2.13} = 34.5$

(1) In order to determine the thermal conductivity of the silicone resin (Table XIV) and values for the water film between the silicone resin and the annulus water, a value of $hd/k/(C\mu/k)^{0.4}$ was taken from Figure III for Experiments 3a and 5a at a particular Reynolds number, for instance 5100.

Exp. No. 3a: $hd/k/(C\mu/k)^{0.4} = 57.6$

Exp. No. 5a: $hd/k/(C\mu/k)^{0.4} = 33.3$

The nearest value of $D/k/(C\mu/k)^{0.4}$ for Experiment 3a and 5a to a Reynolds number of 5100 was taken from Tables VIII and XII. These values were calculated as follows:

Exp. No. 3a: 0.0776

Exp. No. 5a: 0.0794

The value for h at the Reynolds number of 5100 was therefore:

Exp. No. 3a: $h = 57.6/0.0076 = 742$

Exp. No. 5a: $h = 33.3/0.0794 = 419$

These values represent the coefficient of heat transfer for the silicone film and the water film and will hereafter be called h_t . Since h_t is made up of the silicone film and the water film, it may be broken down as:

$$\frac{1}{h_t} = \frac{1}{h_s} + \frac{1}{h_w}$$

Where:

h_s = the heat transfer coefficient
for the silicone film

h_w = the water film coefficient

But: $h_s = \frac{k_s}{l_s}$

Where: k_s = the thermal conductivity of the
silicone film, Btu/ft²/ft/hr/°F.

l_s = the thickness of the silicone
film, ft.

Therefore: $\frac{1}{h_t} = \frac{l_s}{k_s} + \frac{1}{h_w}$

Where: $l_s = 0.0006\text{-in.} = 0.00005\text{-ft.}$ for
Exp. No. 3a.

$l_s = 0.0018\text{-in.} = 0.00015\text{-ft.}$ for
Exp. No. 5a.

Two unknowns, k_s and h_w , are involved; however, with
the above two sets of values the equation may be solved
simultaneously as follows.

$$\begin{cases} \frac{1}{419} = \frac{0.00015}{k_s} + \frac{1}{h_w} \\ \frac{1}{742} = \frac{0.00005}{k_s} + \frac{1}{h_w} \end{cases}$$

$$\begin{cases} 0.00238 = \frac{0.00015}{k_s} + \frac{1}{h_w} \\ 0.00135 = \frac{0.00005}{k_s} + \frac{1}{h_w} \end{cases}$$

$$0.00103 = \frac{0.00010}{k_s}$$

Subtraction

$$k_s = 0.098$$

On substitution of $k_s = 0.098$ back into the equation:

$$h_w = 1,200$$

TABLE II

PROPERTIES OF WATER AT VARYING TEMPERATURES

Temp. (°F)	Viscosity		Thermal Cond. hr. Units	Density lbs./ft.
	Eng. sec. units	Eng. hour units		
65	0.000706	2.55	0.343	62.34
66	697	2.52	0.343	62.34
67	688	2.48	0.344	62.33
68	678	2.45	0.344	62.32
69	669	2.41	0.345	62.31
70	0.000660	2.38	0.346	62.30
71	651	2.35	0.346	62.30
72	643	2.32	0.347	62.29
73	634	2.28	0.347	62.28
74	626	2.25	0.348	62.27
75	0.000617	2.22	0.349	62.26
76	609	2.19	0.349	62.26
77	602	2.16	0.350	62.25
78	594	2.14	0.351	62.24
79	587	2.11	0.351	62.23
80	0.000579	2.08	0.352	62.22
81	572	2.06	0.352	62.21
82	565	2.03	0.353	62.20
83	558	2.01	0.353	62.19
84	551	1.98	0.354	62.18
85	0.000544	1.96	0.355	62.17
86	0.000538	1.94	0.355	62.16
87	532	1.92	0.356	62.14
88	526	1.89	0.357	62.13
89	520	1.87	0.357	62.12
90	0.000514	1.85	0.358	62.11
91	508	1.83	0.358	62.10
92	502	1.81	0.359	62.09
93	497	1.79	0.359	62.08
94	491	1.77	0.359	62.07
95	0.000485	1.75	0.360	62.06
96	479	1.73	0.360	62.05
97	474	1.71	0.361	62.04
98	468	1.69	0.361	62.03
99	463	1.67	0.362	62.01
100	0.000458	1.65	0.362	62.00

FIGURE I

E.M.F. vs. Temperature

Calibration Curves for Copper-
Constantan Thermocouples.
(1938 Calibration)

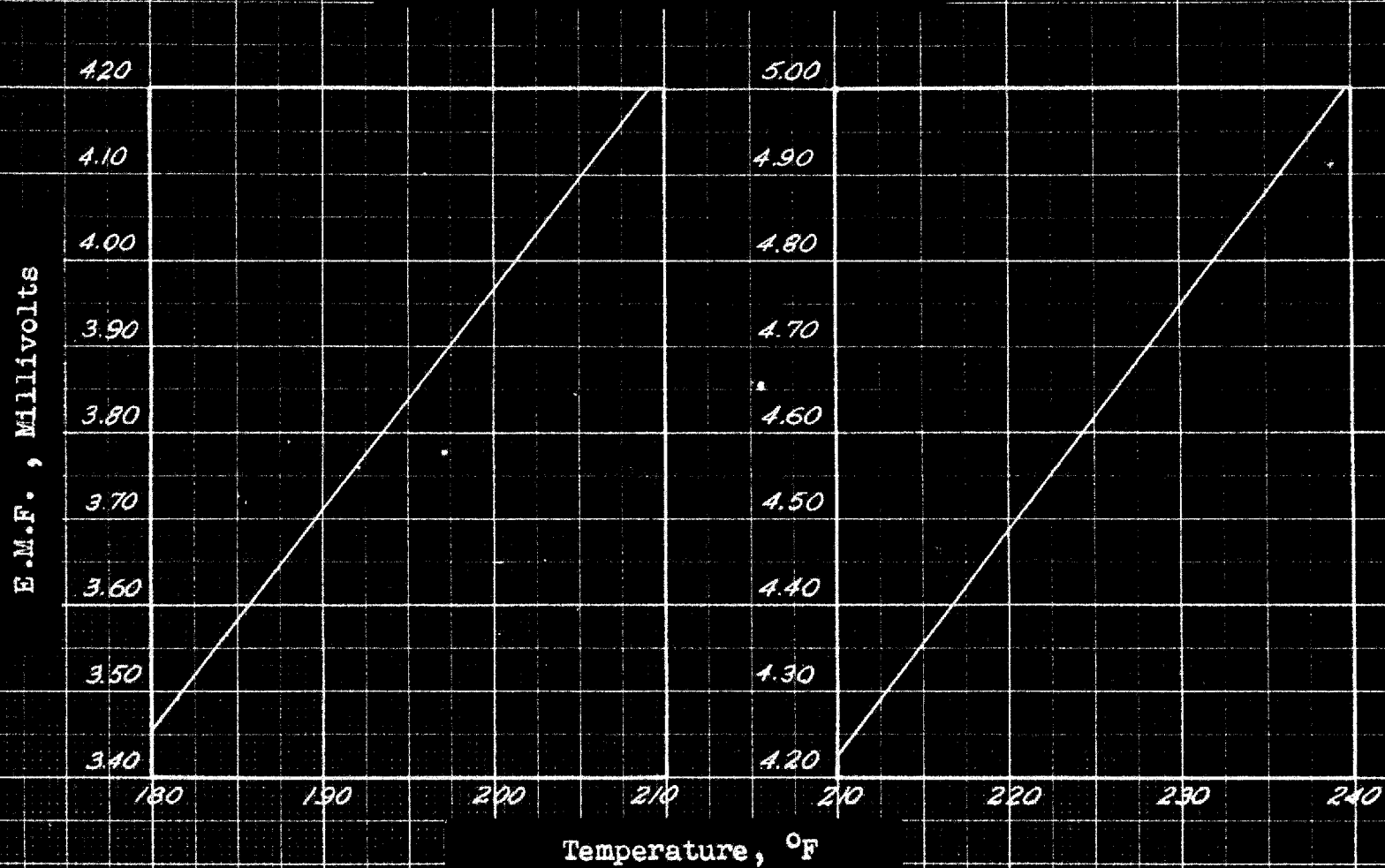


TABLE III

Sample Data Sheet Showing Data Recorded in Experiment 2a.

Reading No.	Annulus Water Temp.		Mano- meter Read., ins. CCl ₄	Steam Temp.		Reading of Pipe Wall Thermocouples, E.M.F., MV.						Av. Thermo- couple E.M.F., MV.
	Inlet, OF	Outlet, OF		Inlet, OF	Outlet, OF	#1	#2	#3	#4	#5	#6	
1	62.5	82.0		280	276	3.76	3.76	3.94	3.30	3.86	4.01	3.771
	63.0	82.0		280	276	3.80	3.68	3.98	3.30	3.83	4.08	3.778
	62.0	82.0		280	276	3.81	3.66	3.94	3.30	3.82	4.00	3.755
Av.	62.5	82.0	13.6	280	276							3.768
2	62.5	82.5		265	262	3.55	3.53	3.83	3.21	3.73	3.75	3.600
	62.5	83.0		265	262	3.55	3.53	3.78	3.21	3.64	3.82	3.588
	62.5	83.0		265	262	3.53	3.50	3.73	3.20	3.70	3.75	3.568
Av.	62.5	83.0	10.6	265	262							3.585
3	62.5	86.0		266	263	3.61	3.51	3.82	3.24	3.70	3.95	3.638
	62.5	86.0		266	263	3.60	3.50	3.83	3.29	3.70	3.94	3.626
	62.5	86.0		267	263	3.60	3.60	3.85	3.25	3.73	3.86	3.648
Av.	62.5	86.0	8.0	266	263							3.637
4	63.0	89.5		263	261	3.55	3.48	3.86	3.33	3.80	3.88	3.650
	63.0	89.5		264	261	3.54	3.38	3.84	3.36	3.79	4.02	3.655
	63.0	89.5		263	261	3.53	3.47	3.82	3.32	3.75	3.88	3.628
Av.	63.0	89.5	5.9	263	261							3.644
5	62.5	94.0		263	262	3.33	3.40	3.97	3.38	3.97	4.18	3.705
	62.5	94.0		264	263	3.36	3.41	4.02	3.41	4.01	4.20	3.735
	62.5	94.0		266	264	3.35	3.44	4.03	3.43	3.99	4.23	3.745
Av.	62.5	94.0	4.15	264	263							3.728
6	62.5	100.0		258	255	3.34	3.43	4.00	3.49	3.93	4.16	3.725
	62.0	100.0		256	255	3.33	3.37	3.99	3.50	3.97	4.24	3.733
	62.0	100.0		257	255	3.34	3.45	4.05	3.55	3.96	4.13	3.746
Av.	62.2	100.0	2.4	257	255							3.734
7	62.5	111.0		260	258	3.30	3.48	4.19	3.72	4.08	4.53	3.883
	62.5	112.0		260	258	3.32	3.46	4.20	3.70	4.09	4.53	3.883
	62.5	112.0		260	258	3.26	3.47	4.20	3.77	4.12	4.45	3.878
Av.	62.5	111.7	1.30	260	258							3.881

TABLE IV

Experimental Test No. 1a

Data and Results on Heat Transfer between Tap water and a 1-in. Standard Iron Pipe in an
Experimental Heat-Exchanger.

Reading No.	av. annulus water temp.			Flow of Water, (lbs/hr)	Heat Transferred, (Btu/hr)	av. Pipe Wall Temp., (°F)	Log. Mean t, (°F)	Water* Film Coef. h, $\frac{\text{Btu}}{\text{hr/ft}^2 \text{ } ^\circ\text{F}}$	Water Velocity, (ft/sec)	DG/u, ** Units	Cu/k, Consistent Units	hd/k, ** Consistent Units	$\frac{\text{hd/k}}{(\text{Cu/k})^{0.4}}$ Consistent Units
	Inlet, (°F)	Outlet, (°F)	Average, (°F)										
1	59.7	89.7	74.7	4940	148,100	190.7	116.2	664	1.765	10,100	6.39	108.6	51.7
2	60.0	90.0	75.0	4690	140,800	190.0	114.5	640	1.680	9,650	6.36	104.5	49.8
3	60.0	92.7	76.3	4200	136,500	190.7	110.5	643	1.510	8,840	6.24	105.1	50.7
4	60.3	97.0	78.6	3710	136,000	192.0	112.7	628	1.340	8,070	6.04	102.1	49.8
5	60.0	101.0	80.5	3160	129,500	192.3	110.3	611	1.140	7,020	5.88	99.0	48.7
6	60.0	103.3	81.6	2460	106,500	189.4	106.2	522	0.835	5,520	5.78	84.4	41.8
7	60.0	100.0	80.0	1930	77,100	167.5	86.2	465	0.695	4,270	5.91	75.4	37.0
8	58.3	83.3	70.8	5540	138,500	179.6	108.3	666	1.985	10,800	6.82	109.8	51.1
9	58.7	86.3	72.5	4450	122,800	177.0	103.8	616	1.595	8,880	6.63	101.5	47.7
10	59.0	89.7	74.3	3980	121,700	181.5	107.0	592	1.435	8,190	6.43	97.0	46.0
11	59.0	92.0	75.5	3480	115,000	182.4	106.2	563	1.255	7,280	6.30	92.0	44.1
12	59.3	97.3	78.3	2840	108,000	184.4	105.2	534	1.020	6,120	6.06	86.8	42.3
13	59.7	78.0	67.8	1410	23,000	117.5	49.0	244	0.510	2,660	7.15	40.4	18.4
14	60.0	80.7	70.3	980	20,200	117.5	46.4	226	0.365	1,973	6.86	37.3	17.3
15	61.6	96.7	79.1	2400	84,200	172.7	92.5	474	0.865	5,240	6.01	77.1	37.6
16	62.0	101.6	81.8	2030	80,400	180.0	97.0	432	0.730	4,580	5.75	69.9	34.7
17	60.6	104.0	82.3	1520	66,000	175.1	91.3	377	0.550	3,470	5.72	61.0	30.3
18	61.0	81.0	71.0	1480	29,600	130.8	59.3	260	0.540	2,950	6.79	42.9	20.0
19	61.0	86.0	73.5	1200	30,000	128.6	54.2	288	0.440	2,480	6.52	47.2	22.3
20	57.5	81.5	69.5	5290	129,500	170.3	100.5	670	1.930	10,300	6.91	110.5	51.0
21	58.0	82.3	70.0	5200	126,200	168.8	98.6	666	1.860	10,000	6.88	110.0	50.9
22	60.0	81.8	71.0	5390	117,500	169.5	97.6	626	1.930	10,500	6.79	103.2	48.0
23	60.0	85.0	72.5	4890	122,100	170.6	98.0	649	1.750	9,750	6.63	106.8	50.1
24	60.0	86.7	73.3	4420	118,000	169.1	95.0	592	1.585	8,910	6.57	97.4	46.0

* Based on effective heat transfer surface of 1.92 sq. ft.

** Based on 0.0571 ft. equivalent diameter of annular space.

Tube degreased with 15% NaOH solution for 45 min., and
etched in 15% HCl solution for 45 min.

TABLE V

Experiment No.1b

Data and Results on the Effect of a Saturated Gypsum Solution as a Scaling Medium on a clean 1-in. Standard Iron Pipe in an Experimental Heat-Exchanger.

Time, (hrs)	Av. Annulus Solution Temp.		Av. Rise in Sol. Temp., dt, (°F)	Av. Pipe Wall Temp., (°F)	Log. Mean Δt , (°F)	Flow of Solu- tion, (lbs/hr)	Heat Trans- ferred, (Btu/hr)	Water * Film Coef., h, $\left(\frac{\text{Btu}}{\text{hr/ft}^2/\text{°F}}\right)$
	Inlet (°F)	Outlet (°F)						
0.00	156.3	177.5	21.2	212.0	44.2	3110	66,000	778
1.42	152.8	173.8	21.0	220.0	56.0	3110	65,300	608
2.75	148.6	164.0	15.4	224.9	68.2	3110	47,900	366
4.00	152.5	168.0	15.5	228.0	67.5	3110	48,200	372
4.83	153.1	168.7	15.6	228.7	67.4	3110	48,500	375
5.75	153.3	169.8	16.5	228.7	67.0	3110	51,300	400
6.83	151.0	167.5	16.5	228.3	69.1	3110	51,300	387

*Based on effective heat transfer surface of 1.92 sq. ft. $\frac{D_{eff}}{\mu} = \text{Approx. } 15,000$

Tube degreased with 15% NaOH solution for 45 min., and etched in 15% HCl solution for 45 min.

TABLE VI
Experimental Test No. 2a.

Data and Results on Heat Transfer between Tap Water and a 1-in Standard Iron Pipe Coated with
Silicone Resin DC 804 in an Experimental Heat-Exchanger.

Reading No.	Av. Annulus Water Temp.			Flow of Water,	Heat *	Av. Pipe wall Temp.,	Log. Mean Δt ,	Water Film Coef. h , ($\frac{\text{Btu}}{\text{hr/ft}^2/\text{°F}}$)	Water Velocity,	DG/ μ ,**	Qu/k,	hD/k,**	$\frac{hD/k}{(Qu/k)^{0.4}}$
	Inlet, (°F)	Outlet, (°F)	Average, (°F)	(lbs/hr)	Transferred, (Btu/hr)	(°F)	(°F)		(ft/sec)	Consistent Units	Consistent units	Consistent units	Consistent units
1	62.5	82.0	72.2	5320	103,500	192.1	120.8	447	1.905	10,550	6.60	73.6	34.5
2	62.5	83.0	72.7	4590	94,200	185.0	112.2	437	1.645	9,160	6.60	71.8	33.7
3	62.5	86.0	74.2	3960	93,000	187.0	111.2	436	1.425	8,110	6.44	71.4	33.8
4	63.0	89.5	76.2	3420	90,500	187.5	101.5	464	1.235	7,210	6.24	76.0	36.5
5	62.5	94.0	78.2	2900	91,200	190.6	111.9	425	1.140	6,830	6.07	69.0	33.5
6	62.2	100.0	81.1	2210	84,000	191.0	108.9	402	0.795	4,940	5.85	65.2	32.1
7	62.5	111.7	87.1	1630	80,000	196.6	107.5	388	0.550	3,940	5.40	62.2	31.8
Coating began to flake at this point.													

* Based on effective heat transfer surface of 1.92 sq. ft.

** Based on 0.0571 ft. equivalent diameter of annular space.

Tube Coating: Resin used: One spray coat of DC 804 Containing 60% resin.

Drier used: 0.15% (Duodex) cobalt naphthenate on dry resin basis.

Air Drying: Conditions: 16 hrs. at 75-80°F.

Curing Conditions: Baked under infra-red for 16 hrs. at 440°F.

Pencil Hardness: 7H

Thickness: 0.002-in.

TABLE VII

Experiment No. 2b

Data and Results on the Effect of a Saturated Gypsum Solution as a Scaling Medium on a 1-in. Standard Iron Pipe Coated with Silicone Resin DC-804 in an Experimental Heat-Exchanger.

Time, (hrs)	Av. Annulus Solution Temp.		Av. Rise in Sol. Temp., dt, (°F)	Av. Pipe Wall Temp., (°F)	Log. Mean Δt , (°F)	Flow of Solution, (lbs/hr)	Heat Transferred, (Btu/hr)	Water * Film Coef., h, Btu hr/ft ² /°F
	Inlet (°F)	Outlet (°F)						
0.00	158.0	173.5	15.5	229.5	63.1	3110	48,200	398
0.50	158.0	173.0	15.0	235.5	69.6	3110	46,700	350
1.25	156.5	171.0	14.5	237.5	72.9	3110	45,100	322
1.92	156.0	170.0	14.0	238.2	75.0	3110	43,500	302
5.17	158.0	171.5	13.5	243.5	76.2	3110	42,000	280
7.17	160.0	174.0	14.0	246.5	79.6	3110	43,500	284
9.33	157.0	171.0	14.0	246.7	82.3	3110	43,500	285
11.83	Data taken; however, inlet soln. temp. had dropped to low for constant $\frac{D_{ue}}{\mu}$							

*Based on effective heat transfer surface of 1.92 sq. ft. $\frac{D_{ue}}{\mu}$ = Approx. 15,000

Tube Coating

Resin Used: One spray coat of DC 804 containing 60% resin.

Curing Conditions: Baked under infra-red for 16 hrs. at 440°F.

Drier Used: 0.15% (Nuodex) cobalt naphthenate on dry resin basis.

Pencil Hardness: 7H

Air Drying Conditions: 16 hrs. at 75-80°F.

Thickness: 0.0020-in.

TABLE VIII

Experimental Test No. 3a

Data and Results on Heat Transfer between Tap Water and a 1-in. Standard Iron Pipe Coated with
Silicone Resin DC 802 in an Experimental Heat-Exchanger

Reading No.	Av. Annulus Water Temp.			Flow of Water, (lbs/hr)	Heat* Trans- ferred, (Btu/hr)	Av. Pipe Wall Temp., (°F)	Log. Mean Δt , (°F)	Water Film Coef. h, $\left(\frac{\text{Btu}}{\text{hr/ft}^2\text{°F}}\right)$	Water Velocity, (ft/sec)	DG/ μ , ** Consistent Units	Cp/k, Consistent Units	hD/k,** Consistent Units	$\frac{hD/k}{(Cp/k)^{0.4}}$ Consistent Units
	Inlet, (°F)	Outlet, (°F)	Average, (°F)										
1	62.5	90.0	76.2	5320	146,300	165.7	88.5	902	1.905	11,120	6.24	147.5	71.0
2	62.5	92.5	77.5	4570	137,000	165.7	87.4	816	1.640	9,760	6.14	133.0	64.3
3	62.5	95.5	79.0	3930	129,700	163.0	83.0	814	1.415	8,650	6.01	132.5	64.6
4	62.0	96.5	79.2	3400	117,200	161.6	81.0	754	1.225	7,450	5.98	122.5	60.0
5	61.0	100.0	80.5	2800	109,100	161.0	79.0	720	1.005	6,200	5.88	116.9	57.6
6	60.0	101.5	80.7	2280	94,600	156.3	73.6	671	0.820	5,070	5.88	108.8	53.6
7	58.5	117.0	87.7	1560	91,300	166.8	75.4	631	0.565	3,790	5.32	101.0	51.7
8	57.5	116.0	86.7	1320	77,200	162.2	70.4	572	0.485	3,210	5.42	91.8	46.6

*Based on effective heat transfer surface of 1.92 sq. ft.

**Based on 0.0571 ft. equivalent diameter of annular space.

Tube Coating: Resin Used: One spray coat of DC 802 diluted to 40% resin content.

Drier Used: 0.3% (Nuodex) cobalt naphthenate on dry resin basis.

Air Drying Conditions: 16 hrs. at 75-80°F.

Curing Conditions: Baked under infra-red for 12 hrs. at 440°F.

Pencil Hardness: 2H.

Thickness: 0.0006-in.

TABLE IX

Experiment No. 3b

Data and Results on the Effect of a Saturated Gypsum Solution as a Scaling Medium on a 1-in. Standard Iron Pipe Coated with Silicone Resin DC 802 in an Experimental Heat-Exchanger.

Time, (hrs)	Av. Annulus Solution Temp.		Av. Rise in Soln. Temp., $\frac{dt}{dt}$, (°F)	Av. Pipe Wall Temp., (°F)	Log. Mean Δt , (°F)	Flow of Solu- tion, (lbs/hr)	Heat Trans- ferred, (Btu/hr)	Water * Film Coef., h, Btu $\left(\frac{h}{hr/ft^2/°F}\right)$
	Inlet (°F)	Outlet (°F)						
0.00	159.5	175.0	15.5	214.3	46.5	3110	48,200	540
0.50	159.0	173.0	14.0	217.8	51.5	3110	43,500	440
0.92	155.0	168.5	13.5	219.0	56.8	3110	42,000	385
2.08	158.0	170.0	12.0	224.2	60.1	3110	37,300	323
2.83	157.0	169.0	12.0	225.3	62.3	3110	37,300	312
4.00	157.0	168.5	11.5	225.5	63.0	3110	35,800	296
5.08	157.5	168.5	11.0	227.4	64.1	3110	34,200	278
6.92	157.5	166.5	11.0	227.3	64.1	3110	34,200	278
8.75	157.0	168.0	11.0	226.8	64.3	3110	34,200	277
10.00	158.0	169.0	11.0	227.2	63.2	3110	34,200	282

*Based on effective heat transfer surface of 1.92 sq. ft. $\frac{DM^2}{\mu} = \text{Approx. } 15,000$

Tube Coating

Resin Used: One spray coat of DC 802
diluted to 40% resin content.

Curing Conditions: Baked under infra-red for
12 hrs. at 440°F.

Drier Used: 0.3% (Nuodex) cobalt naphthenate
on dry resin basis.

Pencil Hardness: 2H.

Air Drying Conditions: 16 hrs. at 75-80°F.

Thickness: 0.0006-in.

TABLE X

Experimental Test No. 4a.

Data and Results on Heat Transfer between Water and a 1-in. Standard Iron Pipe in
an Experimental Heat-Exchanger.

Reading No.	Av. Annulus Water Temp.			Flow of Water, (lbs/hr)	Heat Trans- ferred, (Btu/hr)	Av. Pipe Wall Temp., (°F)	Log. Mean Δt , (°F)	Water * Film Coef. h, $\frac{\text{Btu}}{\text{hr/ft/°F}}$
	Inlet, (°F)	Outlet, (°F)	Average, (°F)					
1	161.0	180.2	170.6	2840	54,500	219.0	47.8	593
2	160.0	180.7	170.3	2460	50,900	219.5	48.4	548
3	157.8	181.8	169.8	2080	49,900	219.9	49.2	528
4	139.5	170.5	155.0	930	28,900	214.0	57.8	260

Water Velocity, (ft/sec)	DG/ μ , ** Consistent Units	C_p/k , Consist- ent Units	hD/k ,** Consist- ent Units	$\frac{hD/k}{(C_p/k)^{0.4}}$
1.020	14,150	2.33	87.9	62.6
0.885	12,300	2.33	81.0	57.7
0.745	10,350	2.33	78.2	55.7
0.340	4,240	2.65	38.9	26.3

* Based on effective heat transfer surface of 1.92 sq. ft.

** Based on 0.0571 ft. equivalent diameter of annular space.

Tube degreased with 15% NaOH solution for 45 min., and
etched in 15% HCl solution for 45 min.

TABLE XI

Experiment No. 4b

Data and Results on the Effect of a Saturated Gypsum Solution as a Scaling Medium on a clean 1-in. standard Iron Pipe in an Experimental Heat-Exchanger.

Time, (hrs)	Av. Annulus Solution Temp.		Av. Rise in Soln. Temp., dt, (°F)	Av. Pipe Wall Temp., (°F)	Log. Mean Δt, (°F)	Flow of Solu- tion, (lbs/hr)	Heat Trans- ferred, (Btu/hr)	Water * Film Coef., h, Btu (hr/ft ² /°F)
	Inlet (°F)	Outlet (°F)						
0.00	139.5	170.5	31.0	214.0	57.8	930	28,900	260
0.58	140.5	171.5	31.0	221.0	63.6	930	28,900	237
1.25	136.0	166.5	30.5	220.5	66.3	930	28,400	216
2.33	137.0	169.0	32.0	219.4	65.2	930	29,800	238
3.00	140.0	170.0	30.0	220.6	64.5	930	27,900	225
4.00	140.0	170.0	30.0	221.2	65.2	930	27,900	223
5.00	140.0	170.5	30.5	220.0	63.7	930	28,300	231
7.25	140.6	171.0	30.4	220.4	60.8	930	28,200	241
8.92	140.3	171.5	31.2	219.6	62.4	930	29,000	241
10.00	141.0	172.0	31.0	219.7	62.0	930	28,800	241

*Based on effective heat transfer surface of 1.92 sq. ft. $\frac{Du\rho}{\mu} = \text{Approx. } 4100$

Tube degreased with 15% NaOH solution for 45 min., and etched in 15% HCl solution for 45 min.

TABLE XII

Experimental Test No. 5a

Data and Results on Heat Transfer between Tap Water and a 1-in. Standard Iron Pipe Coated with
Silicone Resin DC 802 in an Experimental Heat-Exchanger.

Reading No.	Av. Annulus Water Temp.			Flow of Water, (lbs/hr)	Heat Trans- ferred, (Btu/hr)	Av. Pipe Wall Temp., (°F)	Log. mean t, (°F)	Water * Film Coef. h, Btu hr/ft ² /°F	Water Velocity, (ft/sec)	DG/u,** Consistent Units	Cu/k, Consistent Units	hD/k,** Consistent Units	$\frac{hD}{k}$ (Cu/k) ^{0.4} Consistent Units
	Inlet, (°F)	Outlet, (°F)	Average, (°F)										
1	62.1	84.3	73.2	5340	118,500	209.8	136.2	453	1.913	10,760	6.54	74.6	35.2
2	62.1	86.3	74.2	4545	110,000	204.2	128.8	445	1.630	9,280	6.43	72.9	34.5
3	62.3	90.8	76.5	3730	106,300	207.2	131.8	421	1.350	7,930	6.22	68.8	33.1
4	62.5	92.0	77.2	3340	98,500	197.7	119.8	428	1.205	7,130	6.17	69.9	33.8
5	62.5	95.5	79.0	2840	93,600	195.0	114.8	425	1.020	6,180	6.00	69.1	33.7
6	62.6	99.6	81.1	2260	83,500	189.0	106.7	408	0.810	5,040	5.85	66.2	32.7
7	63.6	119.1	91.3	1230	68,200	191.6	97.9	363	0.455	3,180	5.08	57.9	30.2
8	64.0	122.0	93.0	930	53,900	184.3	88.4	317	0.340	2,420	4.98	51.8	27.3

* Based on effective heat transfer surface of 1.92 sq. ft.

** Based on 0.0571 ft. equivalent diameter of annular space.

Tube Coating: Resin Used: Two spray coats of DC 802 containing 40% resin.

Drier Used: 0.15% (Muodex) cobalt naphthenate on dry resin basis.

Air Drying Conditions: 16 hrs. at 75-80°F.

Curing Conditions: Baked under infra-red for 16 hrs. at 440°F.

Pencil Hardness: 2H.

Thickness: 0.0018-in.

TABLE XIII

Experiment No. 5b

Data and Results on the Effect of a Saturated Gypsum Solution as a Scaling Medium on a 1-in. Standard Iron pipe Coated with Silicone Resin DC 802 in an Experimental Heat-Exchanger.

Time, (hrs)	Av. Annulus Solution Temp.		Av. Rise in Soln. Temp., dt, (°F)	Av. Pipe Wall Temp., (°F)	Log. Mean Δt , (°F)	Flow of Solu- tion, (lbs/hr)	Heat Trans- ferred, (Btu/hr)	Water * Film Coef., h, Btu (hr/ft ² /°F)
	Inlet (°F)	Outlet (°F)						
0.00	139.0	167.3	28.3	221.0	64.3	930	26,300	213
0.50	139.5	165.5	26.0	231.0	78.1	930	24,200	161
1.00	137.0	161.8	24.8	231.6	81.6	930	23,000	147
1.50	140.8	162.8	22.0	234.0	81.6	930	20,400	130
2.00	144.0	166.8	22.8	235.6	80.0	930	21,200	139
3.83	139.0	159.3	20.3	235.0	85.0	930	18,900	116
4.83	137.6	159.5	21.9	236.0	87.1	930	20,300	121
5.83	139.3	160.3	21.0	236.4	86.5	930	19,500	117
7.58	136.8	157.1	20.3	235.0	86.4	930	18,900	114
10.00	139.0	160.1	21.1	236.3	86.5	930	19,600	118

* Based on effective heat transfer surface of 1.92 sq. ft. $\frac{D_{eff}}{\mu} = \text{Approx. } 4100$

Tube Coating

Resin Used: Two spray coats of DC 802
diluted to 40% resin content.

Curing Conditions: Baked under infra-red for
12 hrs. at 440°F.

Drier Used: 0.15% (Nuodex) cobalt naphthenate
on dry resin basis.

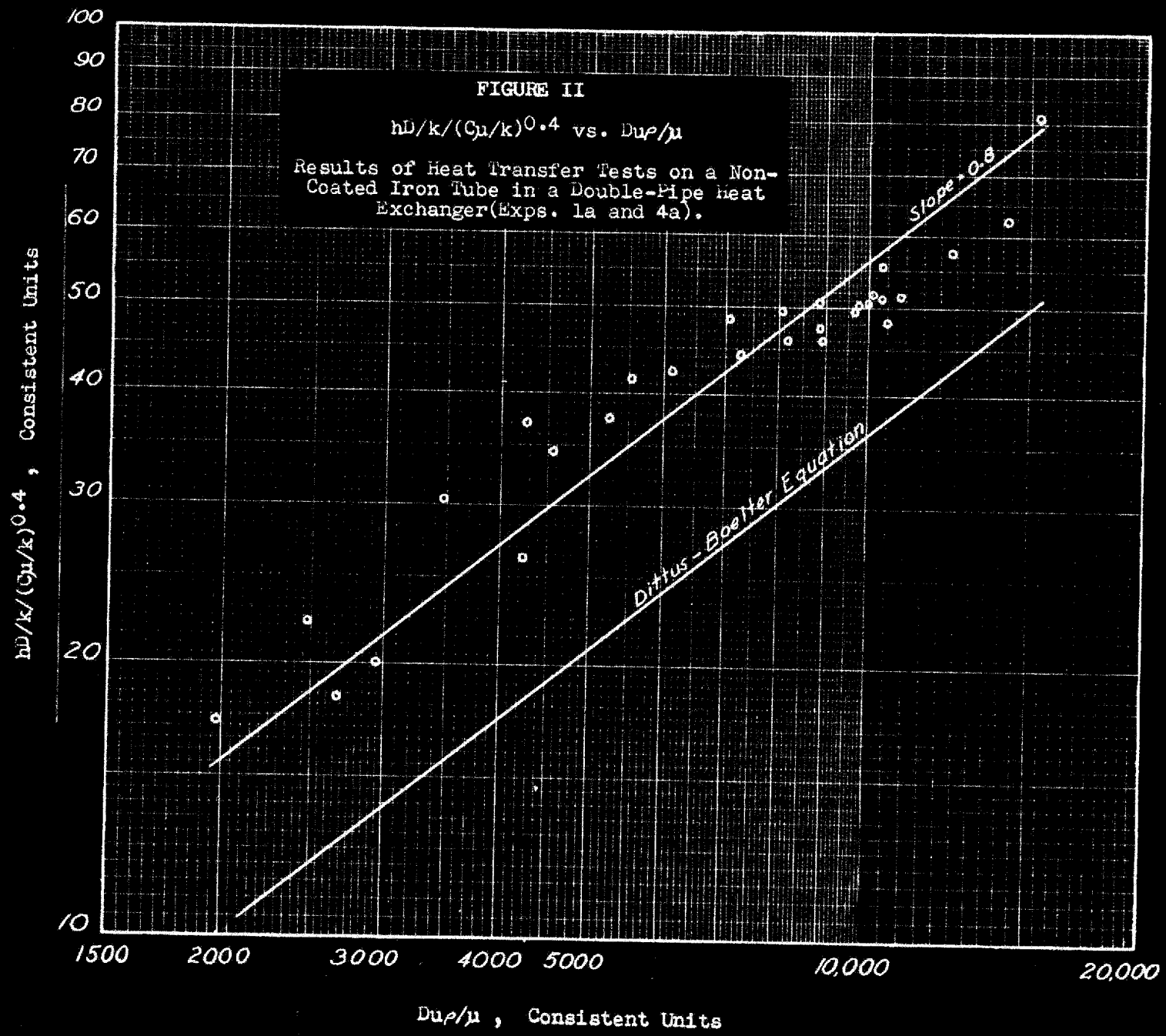
Pencil Hardness: 2H.

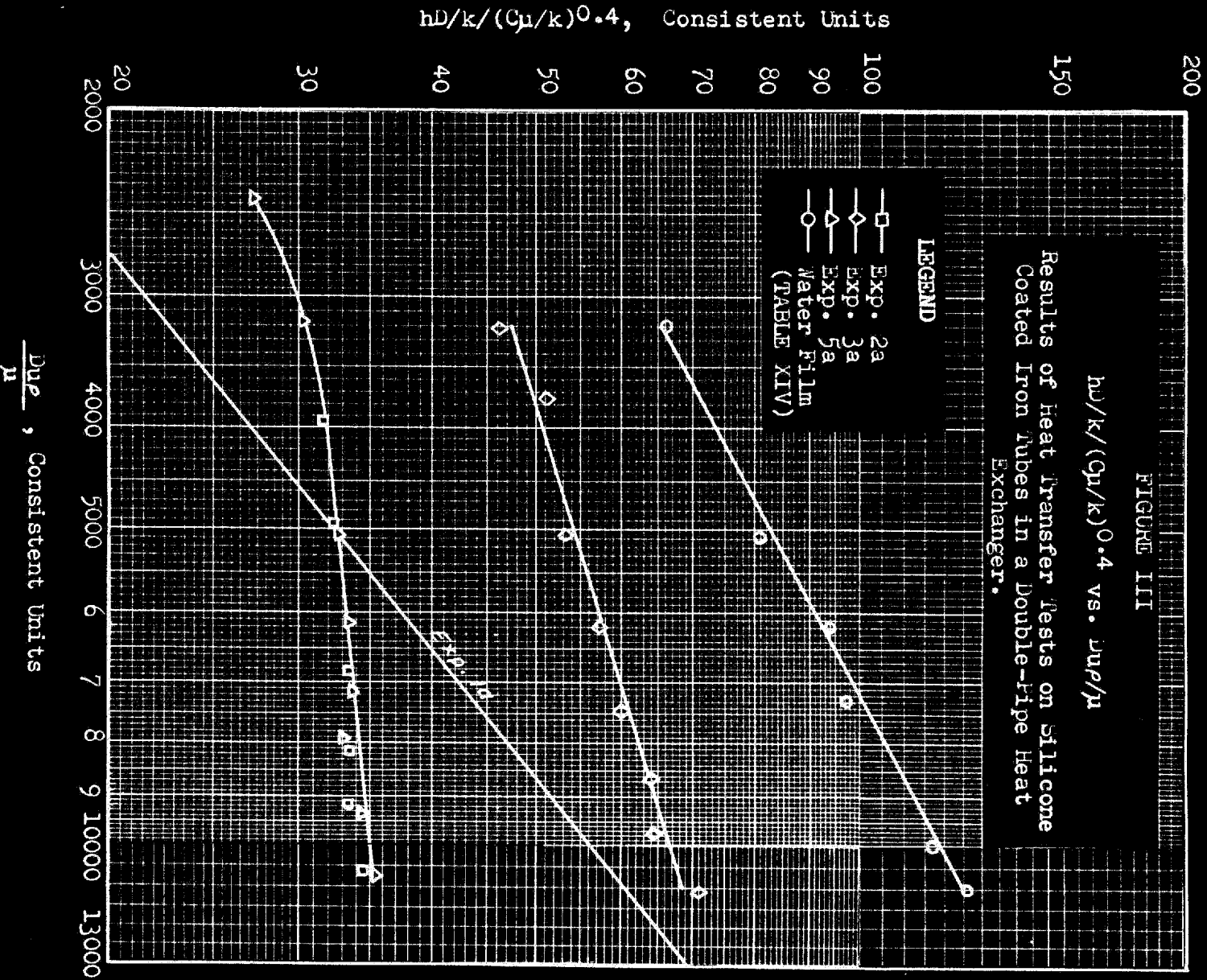
Air Drying: (1) 10 hrs. (2) 16 hrs. at 75-80°F. Thickness: 0.0018-in.

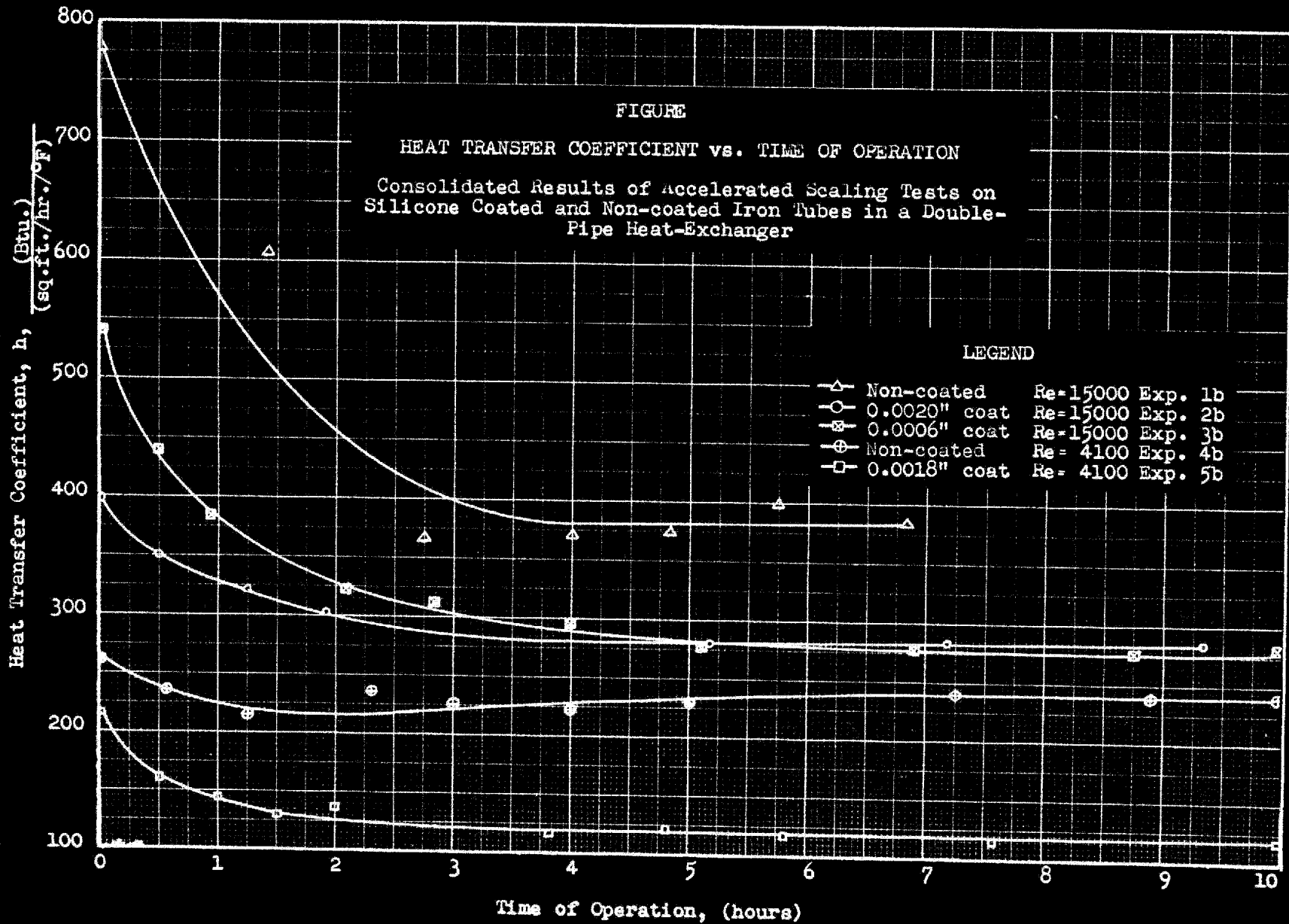
TABLE XIV

Calculated Thermal Conductivities of Silicone Resin DC 802 and Coefficients of Heat Transfer for a Water Film between Annulus Water and a Silicone Surface in a Double-Pipe Heat-Exchanger

Exp. No.	$\frac{hD/k}{(Cu/k)^{0.4}}$ From Graph (Figure III)	Nearest Av. $\frac{D/k}{(Cu/k)^{0.4}}$ (Calc. from Data)	DG/u From Graph	h_t , $\frac{\text{Btu}}{\text{hr/ft } ^\circ\text{F}}$	Calc. Therm. Cond. Silicone, k_s , $\frac{\text{Btu}}{\text{hr/ft } ^\circ\text{F}}$	h_w $\frac{\text{Btu}}{\text{hr/ft } ^\circ\text{F}}$	$\frac{h_w D/k}{(Cu/k)^{0.4}}$ Const. Units
5a 3a	33.7 57.6	0.0794 0.0776	6200 6200	419 742	0.098	1180	93.7
5a 3a	32.6 54.0	0.0798 0.0799	5100 5100	408 675	0.103	1010	80.6
5a 3a	30.5 46.5	0.0830 0.0814	3200 3200	368 571	0.103	810	66.1
5a 3a	33.9 60.3	0.0788 0.0794	7300 7300	430 758	0.099	1220	96.7
5a 3a	35.0 66.0	0.0776 0.0787	10000 10000	451 838	0.097	1480	116.3
5a 3a	35.3 68.0	0.0776 0.0787	11000 11000	455 864	0.096	1590	125.2







IV. DISCUSSION

Coating of Heat-Exchanger Tubes. The most important consideration in getting proper adhesion between the silicone resin and the iron tubes was the chemical preparation of the tubes. Although it was found that degreasing in 15 per cent NaOH for 45 minutes followed by etching in 15 per cent HCl for 45 minutes removed all traces of corrosion, a dichromate priming was necessary to prevent rusting while installing the thermocouples. If silicone coated tubes were used commercially, no doubt, the dichromate treatment would not be necessary since any delay between cleaning and coating could be eliminated.

Drying after the chemical cleaning was also important. An attempt was made to dry one of the heat-exchanger tubes, which had not been treated with dichromate, in the infra-red oven; however, it was found that rusting took place immediately upon application of heat. The same tube was reprocessed and dried at room temperature in a stream of compressed air without any visible traces of rust formation. Drying with cotton rags was also tried; however, it was found that traces of lint, which were difficult to remove, were left on the tube.

It was also necessary to handle the dried tubes which had not been treated with dichromate with clean cotton

raggs to prevent rust formation. This procedure was not necessary with the primed tubes; nevertheless, the same precautions in handling were taken in case any grease film from the hand might cause poor adherence of the resin. When the tubes were degreased in 15 per cent NaOH for 45 minutes, etched in 15 per cent HCl for 45 minutes, and primed in 15 per cent sodium dichromate for 45 minutes, the silicone coating adhered firmly and was completely satisfactory in every respect.

Infra-red Curing of the Silicone Resins. In every case infra-red curing of the silicone resins produced a hard film and, as well as could be determined, was well polymerized. No effort was made to force air into the drier during curing; however, it is believed that the natural draft of the oven furnished the necessary air. The air temperature in the oven never exceeded 410°F; however, the tube wall temperature, as measured by thermocouples, was 440-450°F. This temperature was assumed to be the temperature of the resin coating. The assumption was supported by the fact that the proper curing time at 440-450°F for a desired resin hardness could be accurately interpolated from information furnished by Dow Corning Corporation. ⁽³⁾ The placement of the lamps in the infra-red oven was considered satisfactory, because all thermocouples along the heat-exchanger tube being cured read the

same temperature when the oven was on "full heat". However, when the oven was set for "low heat", i.e., when every other lamp was on, the thermocouples indicated temperature differences up to 30°F. Therefore, all tubes were cured at 440-450°F to insure even curing.

It was noted that the resins remained soft for the entire curing period as long as heat was applied, and, upon cooling to room temperature, they set to a hard film. Although no tests were carried out to obtain specific data on this observation, it is obvious that at elevated temperatures the resins are thermo-plastic.

The Pencil Hardness Test. It was realized early in the investigation that the pencil hardness test would be of little value unless a method was developed to provide a constant pressure on the pencils for each test. The choice of the 200 gram weight in the simple tester constructed for the investigation was not arbitrary. Several weights were tested until one was found which would give the same degree of hardness as that indicated by Dow Corning for a particular set of curing conditions. By using a constant pressure, the sharpness of the pencil was not too critical as long as a reasonable attempt was made to produce a sharp point by rubbing it on fine sand paper. The accuracy of the test was considered to be to the nearest unit hardness.

Accuracy of Thermocouples. As can be seen from the consistency of the thermocouple readings given in Table III, the thermocouples mounted in the tube walls were sufficiently accurate for this investigation. In the thermocouple checks described under Method of Procedure no variation between the readings of the thermocouples, the glass thermometer, and the resistance thermometers could be detected. In fact the thermocouples in these checks could be read to the nearest 0.1 degree Fahrenheit; whereas, the resistance thermometers and the glass thermometer could be only estimated to the nearest 0.5 degree Fahrenheit. No doubt there was some lead loss in the thermocouples due to radiation and conduction of heat away from the junctions by the annulus fluids; however, such errors could not be detected due to the inaccuracy of the glass and resistance thermometers. It can be therefore assumed that the variations in the thermocouple readings during the experimental tests were due to actual changes in temperature rather than to errors in the thermocouples. This assumption was supported by the fact that the variations were less for the coated tubes than for the non-coated tubes. In the case of the non-coated tubes, the thermocouples were closer to the fluid film and, therefore, at a point where the temperature is apt to change rapidly

with variations in the fluid film thickness; whereas, in the coated tubes, the couples were located under the resin, which acted as an insulator, and was therefore, more affected by the steam film temperature.

No attempt was made to check the temperature measuring equipment against a known temperature, because temperature differentials were the most important considerations. The physical properties of the annulus fluid only were dependent upon the actual temperature, and one degree Fahrenheit variation in the average temperature of the annulus fluid would not have been sufficient to change the results of the investigation appreciably.

Choice of Silicone Resin. Since the purpose of this investigation dealt with the surface conditions of silicone resins, no investigation was conducted to determine specifically which resin was most suitable for coating heat-exchanger tubes. A flexibility-adherence test was conducted on several metal strips coated with DC 801, DC 802, DC 803, and DC 804, and cured for 12 hours at 440° F. Each of these strips was bent over a $\frac{1}{2}$ -in. bar and observed carefully for traces of cracks and poor adhesion. The only resin which would crack was DC 803; therefore, the test was considered a failure except for the fact that DC 803 should not be used to coat the tubes. The next hardest cured resin was DC 804; therefore, it was chosen

for the first experimental test. The results of this test are shown in Tables VI and VII, and in Figures III and IV. When steam was passed through the inside of the tube at the beginning of the test, the coating on the tube could be seen to craze as the tube expanded. After approximately four hours of operation the coating began to flake off the tube. This occurrence was believed to have been due to the low thermal coefficient of expansion of the DC 804 as compared to the iron tube. However, since the coating crazed, rather than split in long cracks, indications were that its adhesion to the tube was good. The subsequent tests were conducted on resin DC 802 and no further trouble due to thermal stress was encountered. DC 802 was used in preference to DC 801 because of its faster curing time. DC 801 and DC 802 are classed by Dow Corning as more flexible resins.

Heat Transfer Tests on Non-Coated Tubes. The heat transfer tests were conducted on the non-coated tubes in Experiments 1a and 4a in order to have a basis of comparison for similar tests on the coated tubes, and to attempt to correlate the data of other investigators especially Dittus and Boelter. ⁽²⁸⁾ The use of equivalent diameters for annuli suggested by Nusselt and by McAdams ⁽⁵³⁾ were also investigated in this test to determine which would most nearly correlate the Dittus-Boelter equation. It was found

that the Nusselt procedure indicated values for $hd/k/(C\mu/k)^{0.4}$ approximately 100% too low. The results of the McAdams procedure were shown in Figure II. As a result of this finding all heat transfer tests were calculated on the basis of the McAdams procedure. The values of $hd/k/(C\mu/k)^{0.4}$ in Figure II are approximately 50 per cent higher than the Dittus-Boelter equation; however, they are approximately 50% lower than the values obtained by Faust and Christian⁽³¹⁾ for water flowing in annuli. The data agrees very closely with that of Sherwood and Petrie,⁽⁸⁴⁾ and Jurgensen and Montillon⁽³⁹⁾ when their calculations are based on the average temperature of the water. It must also be noted that these workers investigated water flowing inside pipes and not in annuli. The McAdams procedure for the equivalent diameter of an annulus, therefore, gave excellent results in this investigation. Even though the Dittus-Boelter equation is the most widely accepted means of predicting heat transfer coefficients in heat-exchangers, it was derived for a wide variety of liquids. In general, it can be seen from the compilation of data given by McAdams⁽⁵³⁾ for heating water that the heat transfer coefficients for water at Reynolds numbers below 2,000 are considerably higher than those values indicated by the Dittus-Boelter equation.

The line of 0.8 slope drawn through the data in Figure II was not intended to represent the true equation of the

plot. It was drawn to show that the data does, in general, follow a slope of 0.8. It was decided that the data was too scattered to be represented by an equation derived by empirical means. Also, it was not the purpose of this investigation to propose an additional equation for the prediction of heat transfer coefficients for water flowing in pipes. Had it been possible to have taken the data over a range of Reynolds numbers from 2,000 to 50,000, an empirical equation would have been of some value.

Heat Transfer Test on Coated Tubes. The results of the heat transfer test on the coated tubes are shown in graphical form in Figure III. The curves showing the combined water film and silicone film seem to be of little value except to indicate that below a certain critical Reynolds number the combined silicone and water film resistance is less than the water film resistance alone on the non-coated tubes. This definitely indicates a higher water film coefficient on the surface of the silicone than would ordinarily be expected. The water film coefficient on the silicone surface is also shown in Figure III. The value for $hd/k/(C\mu/k)^{0.4}$ for the silicone surface is 300 per cent higher than the clean iron surface at a Reynolds number of 3,000 and 200% higher at 10,000. If the theory of film coefficients holds true, the film on a non-wetting silicone surface must be, therefore, thinner than on a wetted iron tube. The slope of

the data of 0.504 is also peculiar. It may possibly be due to the difference in fluid friction between liquids and wetted surfaces, and liquids and non-wetted surfaces. Such a difference would be most apparent in the Reynolds group since it is the controlling factor in relating heat transfer to fluid friction. Unfortunately, no literature is available on heat transfer and fluid friction involving non-wetted surfaces.

The actual values of the heat transfer coefficients given in Table XIV were, of course, dependent upon the calculated value for the thermal conductivity of the silicone resin. In this calculation it was assumed that for a given Reynolds number the film coefficient remained the same on the 0.0018-in. coating and on the 0.0006-in. coating. It appears to the investigator that this is a reasonable assumption; if so, the film coefficient values are accurate. The thermal conductivity of the silicone resin, on the other hand, takes into account the resistance of the interface between the silicone and the pipe wall as well as the resistance of the resin. However, it is believed that this resistance was negligible due to the good adhesion and therefore close contact obtained at the interface. The value of approximately 0.1 obtained for the thermal conductivity is not unreasonable. The thermal conductivities of most organic materials varies between 0.06 and 0.3

Btu/(hr.)(sq.ft)(°F per ft.), while silicates vary between 0.2 and 0.6. Since silicones might be considered a combination of the two, its thermal conductivity should lie within their range.

Scaling Tests on the Non-Coated Tubes. The results of the scaling tests on the non-coated tubes are shown in Figure IV in graphical form. In Test No. 1b, which was conducted at a Reynolds number of 15,000 the water film coefficient was reduced from 778 to an average value of 385 in $3\frac{1}{2}$ hours. Had the investigator realized that the scale would form so fast, more data would have been taken in the first three hours of operation. In Test No. 4b which was conducted at a Reynolds number of 4100, the film coefficient dropped from 260 to an average value of 230, or a drop of only 11.5 per cent as compared to 51 per cent for Test No. 1b. However, the drop in Test No. 4b should have also been close to 50 per cent. In order to reach the low Reynolds number of 4100 while operating at an average scaling solution temperature of approximately 155°F, it was necessary to reduce the velocity through the heat-exchanger to 0.34 ft/sec. This velocity was not sufficient to force the gases formed in the heat-exchanger out of the vent cock at the outlet end. As a consequence, the gases had to be removed by increasing the velocity periodically. This procedure resulted in washing away a large part of the scale formed on the heat-

exchanger tube. This trouble was corrected in the following test on the coated tube at the same Reynolds number, by reconstructing the vent so as to cause a continuous drain of liquid and gas from the top of the heat-exchanger.

The scale which formed on the tubes was a cream colored mud as long as the tubes remained immersed in the scaling medium; however, upon drying the scale became a hard, white solid which could not be removed without resorting to abrasion with a stiff wire brush. In general, the thickness of the scale was approximately 1/16-in.

It was not considered necessary to run the tests longer than 10 hours. In every case the heat transfer coefficient leveled off to an average value at the end of $3\frac{1}{2}$ to $4\frac{1}{2}$ hours. As can be seen from the curves of Figure IV, the addition of the extra gypsum to the system after the coefficients had leveled off also had no effect. Therefore, all possible scale formation had occurred.

Scaling Tests on the Coated Tubes. The results of the scaling tests on the coated tubes are also shown in graphical form in Figure IV. The overall result of these tests was that silicone coated heat-exchanger tubes do not prevent the formation of gypsum scale under the conditions of these tests. In Test No. 3b the heat transfer coefficient dropped from 540 to 285, or 47 per cent and in Test No. 5b the drop was from 215 to 115, or 47 per cent. In both cases

the heat transfer coefficient reached a minimum in approximately $3\frac{1}{2}$ hours. These results indicate that the rate of scale formation on the silicone coated tubes is the same as for the non-coated tubes.

The results of Test No. 2b are not considered accurate due to the flaking off of the silicone coating. Just enough coating had flaked off at the end of 5 hours operation to cause the heat transfer coefficients of Tests No. 2b and 3b to be equal; whereas the thickness of the coatings in these tests were 0.002-in. and 0.0006-in. respectively.

In physical appearance the scale formation on the coated and non-coated tubes was identical. However, the adherence of the scale to the coated tubes was considerably less. Although the adhesion was not slight enough to cause the scale to flake off when dried, it could be easily removed by rubbing briskly with the finger or a cotton rag. In the main body of the heat-exchanger there was no apparent change in the silicone coating at the conclusion of the scaling tests; however, on the 0.0006-in. coating it was noted that the resin had worn down to the point that it was barely visible at the inlet and outlet sections of the tube. This occurrence was no doubt due to abrasion and added turbulence at those sections.

Practibility of Silicone Coated Heat-Exchanger Tubes.

It is not believed by the investigator that there would be any advantage in using silicone coated heat-exchanger tubes where scale forming liquids similar to that used in this investigation are involved. In all probability, the cost of coating the tubes would increase the total cost by 100 per cent. Any saving in operating costs due to the fact that the scale may be easily removed would most likely be cancelled by the added cost due to reduction in heat transfer except in cases where Reynolds numbers in the range of 2000 to 4000 are involved. Such low rates of flow are not usually used in heating water; however, the fact that the silicone resin has a tendency to wear off must also be considered.

It does seem possible, from the results of this investigation that silicone coatings might be used to increase heat transfer by as much as 50% at Reynolds numbers between 2000 and 4000 if clean soft water is used.

Recommendations

Additional Tests. It is recommended that further tests be conducted on the heat transfer properties of silicone surfaces in the viscous flow range of Reynolds numbers to determine what further phenomena might occur due to its non-wetting properties. These tests could be made on equipment similar to that used in this investigation; however, more accurate water flow measuring equipment will have to be employed.

A study of non-wetted surfaces should be made at higher Reynolds numbers to determine whether or not the film coefficient on such surfaces remains higher than that for non-wetted surfaces throughout the practical turbulent range. In this work chromium plated tubes similar to those used to promote drop-wise condensation of steam could be employed.

Further investigation should also be made on the thermal conductivity of silicone resins at various temperatures, in view of the fact that the resins have possibilities of becoming an insulation binder. However, the measurements should be made in a standard type of tester.

Equipment Modification. If further investigation is to be conducted on the present equipment it must be made more flexible. The heat transfer surface area of the feed solution

cooler should be increased so that the inlet solution to the heat-exchanger may be maintained at any desired temperature; thereby, the Prandtl group may be controlled to any desired value.

Thermocouples with protective tubing should be installed to measure the inlet and outlet annulus water temperatures in order to bring the accuracy of the pipe wall temperature and the water temperature to the same degree. Thermocouples will respond more quickly to small changes in temperature, than will the resistance thermometers used in this investigation.

In order to obtain better results on heat transfer tests at Reynolds numbers below 2500, it was necessary to use heated tap water instead of steam on the inside of the heat-exchanger tubes. A constant head tank should be provided for this water in order to maintain a constant rate of flow. In this study it was necessary to discard much data taken below Reynolds numbers of 2500 because of changes in the tap water pressure while recording the data.

The constant head tank for the feed water and solution to the heat-exchanger should be raised so as to furnish a head of at least 40 feet to provide for higher velocities through the heat-exchanger. The use of higher velocities will necessitate using a mercury manometer in conjunction

with the carbon tetrachloride manometer. If a scaling or corrosive liquid is to be circulated through the system after the constant head tank has been raised, a pump of higher head capacity must be also installed.

Limitations

The tests in this investigation were limited mainly by the inflexibility of the equipment. Due to the fact that the constant head tank for the feed water and solution could not be raised higher than 15 ft. above the drain level, the velocity through the heat-exchanger was limited to 1.9 ft. per sec. When using tap water, which could not be heated, at 60°F, the maximum possible Reynolds number was 10,500. A Reynolds number of 15,300 could be attained by circulating water at 155°F through the system by means of the feed pump; however, in this case the velocity through the heat-exchanger was limited to 1.2 ft. per sec. by the capacity of the pump.

The lower limit of the Reynolds number was controlled by erratic heating water velocities, inaccuracy of the main flow manometer, and the feed cooler. It was not possible to read the main flow manometer below 0.5-in. of carbon tetrachloride. This value represented a velocity of 0.34 ft. per sec. or a Reynold number of approximately 1800 when heating tap water entering the heat-exchanger at 60°F. However, it was practically impossible to control the equipment at these conditions. Steam could not be used on the inside of the heat-exchanger tubes because it caused boiling of the annulus fluid. Water at 200°F could be used; however,

it was practically impossible to take data due to the erratic velocities of the hot water. As a consequence the lower practical Reynolds number limit was considered to be 2500. Scaling Test No. 5b was conducted at 0.34 ft. per sec. velocity; however, in this case the average annulus feed temperature was about 155°F; therefore, boiling did not take place because of the low heat transfer rate at the lowered Δt . It was impossible to maintain a lower average feed temperature below 155°F for the scaling tests due to the low efficiency of the feed cooler. The lower Reynolds number limit for the scaling tests was therefore 4100.

V. CONCLUSIONS

Heat Transfer Tests. In tests on the determination of heat transfer coefficients for heating water by iron and silicone surfaces, and on the determination of combined coefficients for silicone resins and water films on standard 1-in. nominal diameter iron pipes, conducted in an experimental horizontal tube heat-exchanger having an effective heat transfer surface of 1.92 sq. ft., the following conclusions were reached:

1. The equipment was satisfactory as a means of determining water film coefficients between Reynolds numbers of 2000 to 15,000 due to the fact that data taken thereon for water film coefficients between a clean 1-in. nominal diameter standard iron pipe and tap water flowing in the annulus space between the 1-in. standard iron pipe and a 2-in. I.D. Pyrex pipe, correlated the data of previous investigations. Values of $hd/k/(C_p/k)^{0.4}$ as the ordinate plotted versus corresponding values of $Du\rho/\mu$ as the abscissa on logarithmic coordinates varied linearly with a slope of 0.8 from 17 to 81 for Reynolds numbers from 2000 to 15,300.

2. The equivalent diameter that should be used for heat transfer calculations for annuli between a 1-in. nominal diameter standard iron pipe and a 2-in. I.D. Pyrex glass pipe is the arithmetic difference between the inside

diameter of the Pyrex pipe and the outside diameter of the standard iron pipe.

3. The application of one 0.002-in. spray coat of silicone resin DC 804 to the outside surface of a 1-in. nominal diameter standard iron pipe caused the dimensionless group $hd/k/(C_p/k)^{0.4}$ to vary linearly on logarithmic coordinates from 31.6 to 34.5 for values of $Du\rho/\mu$ from 3950 to 10,600.

4. The application of one 0.0006-in. spray coat of silicone resin DC 802 to the surface of a 1-in. nominal diameter standard iron pipe caused the dimensionless group $hd/k/(C_p/k)^{0.4}$ to vary linearly on logarithmic coordinates from 46.5 to 71.0 for values of $Du\rho/\mu$ from 3200 to 11,100.

5. The application of two spray coats, 0.0018-in. total thickness, of silicone resins DC 802 to the surface of a 1-in. nominal diameter standard iron pipe, caused the dimensionless group $hd/k/(C_p/k)^{0.4}$ to vary linearly on logarithmic coordinates from 32.0 to 35.5 for values of $Du\rho/\mu$ from 4000 to 10,700, and to vary in a convex curve from 27.3 to 32.0 for values of $Du\rho/\mu$ from 2400 to 4000.

6. For heat transfer between silicone resin DC 802 and water, values of $hd/k/(C_p/k)^{0.4}$ varied linearly with a slope of 0.504 on logarithmic coordinates from 66.3 to 125.0 for values of $Du\rho/\mu$ from 3200 to 11,000.

7. The thermal conductivity of silicone resin DC 802 cured for 12 hours under infra-red heat at 440-450°F to a pencil hardness of 2H is from 0.096 to 0.103 Btu/(hr.) (sq.ft.)(°F per ft.) at approximately 150°F.

Accelerated Scaling Tests. In accelerated scaling tests conducted on clean non-coated and silicone coated 1-in. nominal diameter standard iron pipe heat-exchanger tubes with a saturated gypsum solution at an average temperature of 155°F in an experimental horizontal tube double-pipe heat-exchanger, the following conclusions were reached:

1. In a 7 hour test on a clean non-coated tube at a Reynolds number of 15,000, the water film coefficient of heat transfer decreased from 778 to constant average value of 385 in 3½ hours. Also in this time the tube became completely covered with gypsum scale which, when dried, could be removed only by means of abrasion with a stiff wire brush.

2. In a 10 hour test on a clean non-coated tube at a Reynolds number of 4100, the water film coefficient of heat transfer decreased from 260 to a constant average value of 240 in 3½ hours. The tube became completely covered with scale in this time, and could be removed only by abrasion from a stiff wire brush.

3. In a 10 hour test conducted at a Reynolds number of 4100 on a tube coated with two coats, 0.0018-in. total thick-

ness, of silicone resin DC 802 cured for 12 hours under infra-red heat at a temperature of 440-450°F to a pencil hardness of 2H, the water film coefficient decreased from 245 to a constant average value of 115 in 3½ hours. The tube was completely covered with gypsum scale which could be removed by rubbing with the hand and which caused no apparent change in the resin coating.

4. In a 10 hour test conducted at a Reynolds number of 15,000 on a tube coated with one 0.0006-in. spray coat of silicone resin DC 802 cured for 12 hours under infra-red heat at 440-450°F to a pencil hardness of 2H, the water film coefficient decreased from 540 to a constant average value of 275 in 4½ hours. The tube was completely covered with scale which could be easily removed by rubbing with the hand.

VI. SUMMARY

The effects of silicone coated heat-exchanger tubes on the water film coefficient of heat transfer and on the formation of gypsum scale were studied. The heat-exchanger tubes consisted of $74\frac{1}{2}$ -in. sections of 1-in. nominal diameter standard iron pipe into whose surface were installed six copper-constantan thermocouples for measuring the temperature of the tube wall.

Silicone resins DC 804 and DC 802 were used for coating the tubes. Silicone resin DC 804 was cured for 16 hours under infra-red heat at $440-450^{\circ}\text{F}$ to a pencil hardness of 7H; however, due to the fact that it would not withstand the thermal stresses encountered in the heat-exchanger, its use was abandoned. Silicone resin DC 802 was cured for 12 hours under infra-red heat at $440-450^{\circ}\text{F}$ to a pencil hardness of 2H.

The horizontal tube double-pipe heat-exchanger consisted of a 5-ft. section of 2-in. I.D. Pyrex pipe fitted with a reducing tee and a reducing cross as the end-sections. Heat was applied to the heat-exchanger by steam from 15 to 40 psig.

In the "Heat Transfer Tests", which were conducted with water at 60°F and at Reynolds numbers from 2500 to 11,000, it was found that the water film coefficients on the sili-

cone surface varied from 810 to 1590 Btu/(hr.)(sq.ft.)(°F); while those on non-coated iron tubes varied from 244 to 670 under the same conditions.

In "Accelerated Scaling Tests", which were conducted at Reynolds numbers of 15,000 and 4,100 using a saturated gypsum solution at 155°F as the scaling medium, it was found that scale formation on the coated and non-coated tubes reduced the film coefficient approximately 50 per cent in 3½ to 4½ hours. A coating of 0.0006-in. thickness caused the initial water film coefficient to be 70 per cent of the coefficient for a non-coated tube at a Reynolds number of 15,000. A coating of 0.0018-in. thickness caused the initial water film coefficient to be 83 per cent of the initial coefficient for a non-coated tube at a Reynolds number of 4,100.

The thermal conductivity of silicone resin DC 802 was found to be 0.096-0.103 Btu/(hr.)(sq.ft.)(°F per ft.) at 150°F.

VII. BIBLIOGRAPHY

1. Anon. Chemical Engineering Progress for Peace-silicones. Chem. Met. Eng. 53, 2, 132, (1946).
2. Alquist, F. N., Groom, C. H., and Williams, G. F., Chemical Removal of Scale. Power Plant Eng. 47, 71-2, (1943).
3. Anon. Dow-Corning Silicone Resins for use as Vehicles in Formulating Protective Coatings. Dow-Corning Corporation. Feb. 5, 1946.
4. Anon. Fourth Year Inspection of Plastic Coated and Lined Boiler Tubes. Montreal, Canada. Progress Report-PR101-C, American Iron and Steel Institute, August 14, 1944.
5. Anon. Heat Resisting Resins Have Wide Applications. Iron Age, 154, 10, 81, (1944).
6. Anon. Infra-Red Drying. Elec. Engr. and Merchandiser. 21, 4, 101-4, (1945).
7. Anon. Infra-Red Lamps Speed Finish Baking. Aero Digest, 51, 1, 80, (1945).
8. Anon. Inspection Plastic Coated and Lined Boiler Tubes. Montreal, Canada. Preliminary Report-PR101B, American Iron and Steel Institute. July 14, 1943.
9. Anon. Silicones. Westinghouse Engineer. 5, 130, (1945).

10. Anon. Silicone Rubber. General Electric Div.
Rubber Age (NY), 56, 2, 173-5, (1944).
11. Anon. Silicone Summary. Chem. Ind. 57, 4, 638-40, (1945).
12. Badger, W. L. and McCabe, W. L. "Elements of Chemical Engineering". Chapter IV. McGraw-Hill Book Co., New York. 1936. 2nd ed.
13. Bass, S. L. and Kauppi, T. A. New Class of High Polymers of Interest to Radio Industry. Inst. Radio Engrs. Proc. 33, 7, 441-7, (1945).
14. Benedicks, C. Hot-Wall Effect. Am. Inst. Mining and Met. Engrs. 71, 599, (1925).
15. Bennett, H. J. and Haynes, H. Paint Baking with Near Infra-Red. Chem. Met. Eng. 47, 2, 106-7, (1940).
16. Beoddy, J. H. The Effect of Heat Transfer on Corrosion. p. 11. Unpublished Thesis. Library, Virginia Polytechnic Institute, Blacksburg, Virginia. 1939.
17. Birdsall, G. W. How to Get Most from Infra-Red Heating-Drying-Baking. Steel. 117, 6, 116-19, (1945).
18. Biskamp, H. Z. Tech. Physik. 12, 30-3, (1931);
McAdams, W. H. "Heat Transmission". p. 137.
McGraw-Hill Book Co., New York. 1942. 2nd ed.

19. Brown, S. P. Use of Silicones as Diffusion Pump Oils. Rev. Sci. Instr. 16, 11, 316-18, (1945).
20. Castles, J. T. The Use of Silicone Resins as Non-Wetting Films on Heating Surfaces. p. 97. Unpublished Thesis. Library, Virginia Polytechnic Institute, Blacksburg, Virginia. 1946.
21. Colburn, A. P. A Method of Correlating Forced Convection Heat Transfer Data and a Comparison with Fluid Friction. Trans. A. I. Ch. E. 29, 174-210, (1933).
22. Colburn, A. P. and Hougan, O. A. Studies in Heat Transmission-I-Measurement of Fluid and Surface Temperatures. Ind. Eng. Chem. 22, 5, 522-24, (1930).
23. Collings, W. R. New Dow Corning Plant Produces Silicones at Midland. Chem. Eng. News. 23, 18, 1616-19, (1945).
24. Cusack, T. P. Infra-Red Baking of Ordnance Finishes. Prod. Finishing. 6, 10-22, (1942).
25. Davis, Elbert. The Silicones-New Heat Resistant Plastics. Pacific Plastics. 3, 6, 28-9, (1945).
26. Deane, T. S. The Water-Repellent Treatment of Cotton Fabrics with Organo Chlorosilanes. p. 66. Unpublished Thesis. Library, Virginia Polytechnic Institute. Blacksburg, Virginia. 1947.

27. De Kiep J., Hill, L. R. and Moses, G. S. The Application of Silicone Resin Insulation for Electric Machinery. Elec. Engr. 64, 3, 94-8, (1945).
28. Dittus, F. W. and Boelter, L. K. M. Univ. Calif. Pub. in Eng. 2, 443, (1930); McAdams, W. H. "Heat Transmission". p. 166. McGraw-Hill Book Co., New York. 1942. 2nd ed.
29. Eagle, A. and Ferguson, R. M. Coefficients of Heat Transfer from the Internal Surface of Tube Walls. Engineering. 130, 691, (1930).
30. Fourier, J. B. "Theorie Analytique de la Chaleur". Oeuvres de Fourier, Gauthier-Villors et Fils, Paris, 1862; McAdams, W. H. "Heat Transmission". p. 7. McGraw-Hill Book Co., New York. 1942. 2nd ed.
31. Foust, A. S. and Christian, G. A. Non-Boiling Heat Transfer Coefficients in Annuli. Trans. A.I.Ch.E. 36, 541-54, (1940).
32. Friedel, C. and Crafts, J. H. Ann. 127, 31, (1863); Rochow, E. G. "Chemistry of Silicones". p. 30. John Wiley and Sons, Inc., New York. 1946.

33. Hinton, A. G. "World Power Conference, London, 1928, Technical Data on Fuel", p. 101-3.
World Power Conference, London, 1928; McAdams, W. H. "Heat Transmission". p. 166. McGraw-Hill Book Co., New York. 1942. 2nd ed.
34. Hoffman, A. M. Infra-Red Lamps Eliminate a Bottleneck in Industry. *Comp. Air.* 46, 8, 6514-5, (1941).
35. Hoffman, E. Z. *gez. Kalte. Ind.* 44, 99-107, (1937);
McAdams, W. H. "Heat Transmission". p. 163. McGraw-Hill Book Co., New York. 1942. 2nd ed.
36. Hyde, F. S. and DeLong, R. C. Condensation Products of Organo-Silanedriols. *J. Amer. Chem. Soc.* 63, 1194, (1941).
37. Irving, G. S. Why Does Scale Stick to Metal? *Steam Engr.* 12, 258-60, (1943).
38. Jordan, H. P. Measurement of Surface and Fluid Temperatures. *Proc. Inst. Mech. Eng. (London)*. 4, 1317, (1909); Colburn, A. P. and Hougan, O. A. Studies in Heat Transmission-I-Measurement of Fluid and Surface Temperatures. *Ind. Eng. Chem.* 22, 522, (1930).
39. Jurgensen, D. F. and Montillion, G. H. Heat Transfer Coefficients on Incline Tubes. *Ind. Eng. Chem.* 27, 1466-75, (1935).

40. Kauppi, T. A. and Moses, G. L. Organo-Silicon Compounds for Insulating Electric Machines. Trans. A.I.E.E. 90-3, (1945).
41. Kaye, W. A. and Furnas, C. C. Heat Transfer Involving Turbulent Fluids. Ind. Eng. Chem. 26, 7, 783-6, (1934).
42. Kipping, F. S. Organic Derivatives of Silicon. Proc. Roy. Soc. (London). A159, 139, (1937).
43. Kipping, F. S. Organic Derivatives of Silicon: The Nomenclature of Organo-Silicon Compounds. J. Chem. Soc. 101, 2106, (1912).
44. Klinkenstein, G. The Uses and Limitations of Radiant Heat for Baking Organic Finishes. Proc. Amer. Electroplaters Soc. 93-8, (1941).
45. Kolderman, R. W. Silicones, New Class of High Polymers. Can. Chem. and Proc. Ind. 29, 3, 147-52, (1945).
46. Kreisinger, H. and Barkley, J. F. Bur. Mines. Tech. Paper. 114, (1915); Colburn, A. P. and Hougan, O. A. Studies in Heat Transmission-I Measurement of Fluid and Surface Temperatures. Ind. Eng. Chem. 22, 522, (1930).
47. Ladenburg. Ann. 164, 302, (1872); Rochow, E. G. "Chemistry of Silicones". p. 30. John Wiley and Sons, Inc., New York. 1946.

48. Langmuir, I. Relationship Between Air Velocity and Heat Transfer from Solids. *Phy. Rev.* 34, 401, (1912).
49. Lawrence, A. E. and Sherwood, T. K. Heat Transmission to Water Flowing in Pipes. *Ind. Eng. Chem.* 23, 301-9, (1931).
50. McAdams, W. H. "Heat Transmission". p.l. McGraw-Hill Book Co., New York. 1942. 2nd ed.
51. *ibid.* p. 6-26.
52. *ibid.* p. 133-253.
53. *ibid.* p. 210-339.
54. Morris, F. H. and Whitman, W. G. Heat Transfer for Oils and Water in Pipes. *Ind. Eng. Chem.* 20, 234-40, (1928).
55. Moses, G. L. New Silicone Resins Boost Insulation Temperature Limits. *West. Eng.* 4, 5, 138-41, (1944).
56. Nelson, W. L. "Petroleum Refinery Engineering". p. 218. McGraw-Hill Book Co., New York. 1941. 2nd ed.
57. Norton, F. J. "Organo-Silicon Films". CDR-5, General Electric Co. 1944.
58. Nusselt, W. Der Wärmeübergang in Rohrleitungen. *Z. ver Deut. Ing.* 53, 1750, (1909); McAdams, W. H. "Heat Transmission". p. 165. McGraw-Hill Book Co., New York. 1942. 2nd. ed.

59. Nusselt, W. Measurement of Fluid and Surface Temperature. Mitt. Forsch. arb., Heft, 63, 26, (1909); Colburn, A. P. and Hougan, O. A. Studies in Heat Transmission. Ind. Eng. Chem. 22, 522-24, (1930).
60. Nusselt, W. Z. Ver. deut. Ing. 61, 685, (1917); McAdams, W. H. "Heat Transmission". p. 200. McGraw-Hill Book Co., New York. 1942 2nd ed.
61. Nusselt, W. Z. Ver. deut. Ing. 57, 199, (1913); McAdams, W. H. "Heat Transmission". p. 200. McGraw-Hill Book Co., New York. 1942. 2nd ed.
62. Othmer, D. F. and Coats, H. B. Measurement of Surface Temperatures, Ind. Eng. Chem. 20, 2, 124-8, (1928).
63. Partridge, E. P. and White, A. H. Mechanism of Formation of Calcium Sulfate Boiler Scale, Ind. Eng. Chem. 21, 9, 834-43, (1929).
64. Partridge, E. P. Engineering Research Bull. 15, Univ. Michigan. 1930; McAdams, W. H. "Heat Transmission." p. 137. McGraw-Hill Book Co., New York. 1942. 2nd ed.

65. Peclet, J. C. E. "Traite de la Chaleur, Consideree dans ses Applications". Masson, Paris. 1860;
McAdams, W. H. "Heat Transmission". p. 241.
McGraw-Hill Book Co., New York. 1942. 2nd ed.
66. Perry, J. H. "Chemical Engineer's Handbook". p. 1057.
McGraw-Hill Book Co., New York. 1941. 2nd ed.
67. *ibid.* p. 948-1000.
68. Petty, W. L. The Construction and Capacity of an Infra-Red Drying Oven. p. 45. Unpublished Thesis, Library, Virginia Polytechnic Institute. Blacksburg, Virginia. 1943.
69. Prandtl, L. Physik Z. 11, 1072, (1910); McAdams, W. H. "Heat Transmission". p. 163. McGraw-Hill Book Co., New York. 1942. 2nd ed.
70. Reynolds, O. Trans. Roy. Soc. (London). A186, 123, (1894); McAdams, W. H. "Heat Transmission". p. 162. McGraw-Hill Book Co., New York. 1942. 2nd ed.
71. Rietschell, H. Measurement of Fluid and Surface Temperature. Heft. 3, (1910); Colburn, A. P. and Hougan, O. A. Studies in Heat Transmission-I-Measurement of Fluid and Surface Temperatures. Ind. Eng. Chem. 22, 522, (1930).

72. Rochow, E. G. Personal Communication. 1947.
73. Rochow, E. G. "Chemistry of Silicones". p. 83-88.
John Wiley and Sons, Inc., New York. 1946.
74. *ibid.* p. 53
75. *ibid.* p. 60-82.
76. *ibid.* p. 18-30.
77. *ibid.* p. 60.
78. *ibid.* p. 3.
79. *ibid.* p. 122.
80. Rochow, E. G. and Gilliam, W. F. Polymeric Methyl
Silicon Oxides. J. Amer. Chem. Soc. 63, 798,
(1941).
81. Rochow, E. G. The Direct Synthesis of Organo-
Silicon Compounds. J. Amer. Chem. Soc. 67, 963,
(1945).
82. Sauer, R. O. Nomenclature of Organosilicon Com-
pounds. J. Chem. Ed. 21, 303, (1944).
83. Scarlott, C. A. Silicones-Miracle of Molecule
Engineering. Plastics and Resins. 5, 2, 7-12,
(1946).
84. Sherwood, T. K. and Petrie, J. M. Heat Transmission
to Liquids Flowing in Pipes. Ind. Eng. Chem. 24,
736-45, (1932).

85. Sieder, E. N. and Tate, G. E. Heat Transfer and Pressure Drop of Liquids in Tubes. Ind. Eng. Chem. 28, 1429-35, (1936).
86. Taylor, G. I. Brit. Advisory Comm. Aeronaut, Rept. and Memo. 272, 31, 423-429, (1916); McAdams, W. H. "Heat Transmission". p. 163. McGraw-Hill Book Co., New York. 1942. 2nd ed.
87. Walker, W. H. et al. "Principles of Chemical Engineering". p. 100-165. McGraw-Hill Book Co., New York. 1937. 3rd ed.
88. Webster, G. C. Measurement of Fluid and Surface Temperatures. Trans. Inst. Eng. Shipbuilders, Scotland, 57, 58, (1913); Colburn, A. P. and Hougan, O. A. Studies in Heat Transmission-I-Measurement of Fluid and Surface Temperatures. Ind. Eng. Chem. 22, 522, (1930).
89. Westgate, M.W. Catalytic Curing of Silicone Resins- Chem. Eng. News. 23, 1082, (1945).
90. Williams, G. F. Chemical Removal of Scale from Heat-Exchanger Surfaces. Power. 87, 20-2, (1943).

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