M = molecular weight
P_c = critical pressure, atm.
R = gas constant
T = temperature, ° K.
T_c = critical temperature, ° K.
T_R = reduced temperature, T/T_c
v_c = critical volume, cc./gram-mole
z_c = critical compressibility factor, $P_c v_c/RT_c$

Greek

α = constant, Equation 2
β = constant, Equation 3
ϵ = maximum energy of attraction for Lennard-Jones potential, ergs
κ = Boltzmann constant, 1.3805×10^{-16} ergs/° K.
μ^* = viscosity at normal pressures (0.2 to 5 atm.), centipoises
$\mu^*_{T_c}$ = viscosity at normal pressures and critical temperature, centipoises
ξ = $T_c^{1/6}/M^{1/2}P_c^{2/3}$
σ = collision diameter for Lennard-Jones potential, A.

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Heat Transfer Characteristics of Fluorochemical Inert Liquid FC-75

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INERT FLUOROCHEMICAL LIQUIDS, particularly 3M's FC-75, are excellent heat transfer media for cooling electronic components. Chemically, FC-75 (3M) is a fully fluorinated product composed of a mixture of compounds containing eight carbons, principally perfluoroethers (see Table I for typical properties). The unique heat transfer properties of this material have been recognized, but factual data have been lacking.

In this work, variables affecting heat transfer to FC-75 were determined. Comparisons were also made with other commercial dielectric coolants in a forced convection system on the basis of heat transfer properties, not considering other advantages such as high electric strength, nonflammability, thermal stability, low temperature fluidity, chemical inertness, and capability of allowing equipment miniaturization.

The heat transfer properties of inert fluorochemicals have been of interest in the past few years. In 1954, Olyphant and Brice (*6*) recognized that for natural convection liquid cooling, FC-75 had only a modest heat transfer advantage over transformer oil. However, boiling FC-75 transferred ten times as much heat as transformer oil when the oil was under natural convection at the same temperature. This advantage was limited to a factor of 1.5 when applied to experimental transformers, because of steep temperature gradients induced in parts of the cell winding not exposed to the coolant.

Kilham and others (*4, 5*) at Raytheon found that inert fluorochemical liquids were the most effective coolants for miniaturized transformers which operate around 375° F. Cooling, accomplished in these studies by boiling without forced circulation, was 1.5 to 3 times more effective than natural convection using either transformer oil or silicone oil.

Etter at RCA (*2*) studied forced circulation cooling for a high-power transmitting tube. FC-75 was selected as coolant on the basis of heat transfer coefficients calculated by the Dittus-Boelter equation. This calculation indicated a twofold advantage over the next best liquids, transformer and silicone oil. Experimentally, RCA utilized boiling of FC-75 with forced circulation of liquid at 3.5 feet per second over a heated wire. The maximum heat flux obtained was 350 watts per square inch (171,000 B.t.u/hr./sq. ft.)

Fairbanks (*3*) of Raytheon calculated relative heat transfer rates using various liquids and conditions of heat transfer at 185° F. His analysis showed FC-75 to be 20% more effective than commercial silicate ester for natural convection, 80% more effective for forced convection in turbulent flow, but 10% less effective for forced convection in laminar flow. However, he did not compare boiling heat transfer for FC-75 with nonboiling heat transfer for other commercial materials.

From these investigations, it was apparent that the principal advantage of FC-75 as a heat transfer fluid was its ability to transfer heat by boiling. This advantage can be obtained by natural circulation pool boiling, as in Raytheon's transformer, or by forced circulation local boiling as with RCA's transmitting tube.

Table I. Typical Properties of Heat Transfer Liquids

Specific gravity (77° F.)	Fluorochemical FC-75	Silicone Oil	Silicate Ester
Pour point, ° F.	1.77	0.97	0.887
Boiling range (760 mm.), ° F.	−80 max.	−67	−85
Maximum temp., ° F.	210 −225	Decomposes	Decomposes
Viscosity, cs. 77° F.	750	400	400
(210° F.)	0.65	100	19
Refractive index (77° F.)	0.33	60	3.8
Surface tension (77° F.), dynes/cm.	1.277	1.403	...
Specific heat (77° F.) B.t.u./lb./° F.	15.1	20.9	26
Electric strength, volts/mil.	0.248	0.33	0.449
Dielectric constant (1kc.)	350	350	250
Dissipation factor (1kc.)	1.86	2.74	2.65
Resistivity, ohm/cc.	0.0005	0.00005	...
Thermal conductivity of liquid, B.t.u./° F. hr. ft.	6×10^{14}	1×10^{14}	9×10^{10}
Thermal conductivity of saturated vapor (1 atm.), B.t.u./° F. hr. ft.	0.081	0.090	0.082
Specific heat of saturated vapor, (230° F.), B.t.u./° F.	0.0080	...	...
Critical pressure, p.s.i.a.	0.236	...	...
	232	..	...

Heat transfer to a boiling liquid must be understood to evaluate the results herein presented and to be used safely. FC-75 and other fluorochemicals boil in the classical manner first described by Nukiyama in 1934, as presented by Westwater (7) and others. As the heat flux to a body raises its surface temperature above the boiling point of the liquid in contact with it, nucleate boiling begins. A very large increase in heat flux may then be tolerated with a moderate increase in surface temperature until the "peak heat flux" is reached. At this point, a transition from nucleate to film boiling occurs at relatively constant heat flux, causing the temperature of the heated surface to increase sharply.

This temperature increase can exceed the melting point of some materials, causing serious damage or "burnout." Thus it is imperative that most heat transfer systems be designed to operate safely below the "peak heat flux."

EXPERIMENTAL PROGRAM

Many types of heat transfer systems can be utilized for cooling electronic components. For preliminary evaluation in this investigation, a forced convection system was chosen, in which a heated wire was cooled by a liquid held at a fixed temperature of 120° F. The following materials were tested (properties given in Table I):

1. FC-75 dielectric-coolant
2. A commercial silicone oil dielectric-coolant
3. A commercial silicate ester dielectric-coolant

The variables affecting heat transfer to FC-75 during local boiling on a heated platinum wire under forced circulation conditions were determined on a second apparatus capable of varying pressure, bulk liquid temperature, heat input, and velocity of fluid flowing.

APPARATUS AND PROCEDURE

First Series. Heat transfer experiments comparing the various coolants were conducted by electrically heating a small stainless steel tube in contact with heat transfer liquids in a reaction flask. Power input to the tube was measured, and the heat transfer surface calculated to give the heat flux.

Figure 1 is a sketch of the experimental equipment. A 1000-ml. reaction flask was placed in a cooling bath to control the liquid temperature. A hot plate under the bath provided supplemental heat when needed. The heated surface within the flask was a 0.040-inch outside diameter stainless steel sheath containing an internal Chromel-Alumel thermocouple, an assembly made to specification by Aero Research Instrument Co. Electric power was applied to a 6-inch section of the sheath submerged in the liquid. The voltage was controlled in the range 0 to 12 volts by measn of a 120-volt variable transformer connected to a 10–1 step-down transformer. Power input to a 4-inch test section centered in the 6-inch heated section was measured by means of an ammeter and a voltmeter with taps clipped to the sheath. A smaller test section was used, to obtain a uniform wire temperature through the test area. This temperature was measured by the internal thermocouple at the center of the test section. A direct-reading potentiometer was used as the thermocouple read-out device.

Forced circulation was provided by a 3-inch paddle at the bottom of the flask connected to a variable-speed stirring motor. The heated sheath was arranged as a semicircle about ¾ inch above the paddle and ¼ inch outside the paddle tip. The paddle rotation caused vortex mixing with the liquid flowing parallel to the heated surface. For low-viscosity liquids, the velocity at the sheath appeared approximately equal to the paddle speed (measured by a tachometer on the stirring motor). However, in the case of higher viscosity fluids, such as the silicone oil, which has a viscosity of 70 centistokes at 120° F. compared to FC-75 at 0.6 centistoke, the fluid velocity was considerably less than the paddle speed. At fixed agitator speeds, therefore, the velocity of the more viscous fluid was reduced, although the power input to the apparatus was greater.

An Improved Series. New experimentalapparatus (Figure

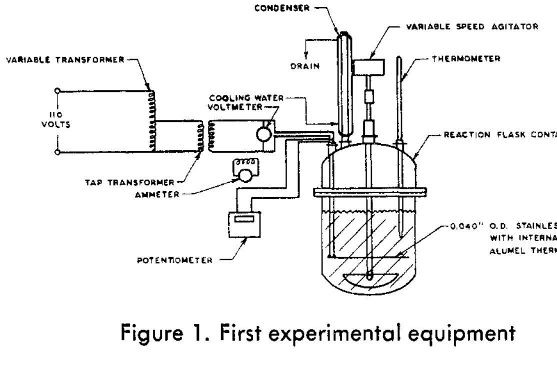

Figure 1. First experimental equipment

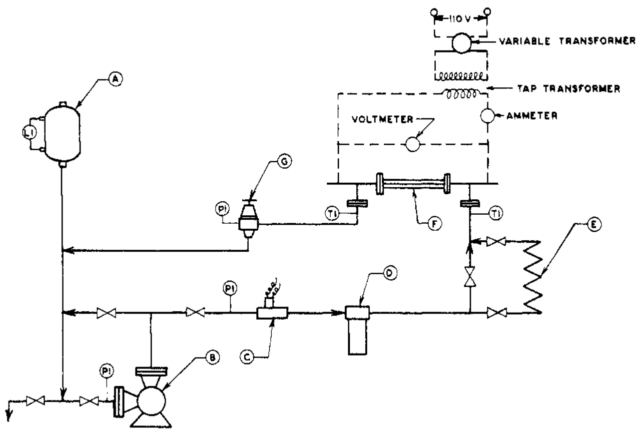

Figure 2. Improved experimental apparatus

A. Surge tank
B. Turbine pump
C. Turbine flowmeter
D. 50-micron filter
E. Cooling coils
F. Flow tube
G. Pressure regulator

2) was assembled to accomplish the main objective of the study because the initial apparatus (Figure 1) was incapable of pressure variation and accurate determination of liquid velocity.

The liquid to be tested was pumped from a reservoir through a flow tube by a self-lubricated turbine pump. Flow rate was regulated by means of a bypass valve and measured with a Fischer-Porter turbine flowmeter, which performed exceptionally well throughout the experimentation. Recalibration of the unit at the end of the study was in complete agreement with original calibration conducted prior to the initiation of tests. The liquid flow also passed through a 50-micron filter to eliminate foreign material.

The temperature of the flowing liquid was regulated by passing a portion of the flow through a ¾-inch outside diameter copper coil approximately 25 feet long immersed in a 55-gallon drum. Hot water, cold water, and dry ice-cooled ethylene glycol were used in the 55-gallon drum as heat sinks, depending upon the liquid temperature desired. The bulk liquid temperature was measured with standard dial thermometers, one prior to the flow tube and one directly following.

The flow tube was a ¾-inch inside diameter borosilicate glass pipe 12 inches long, held in place by steel back-up flanges attached to mating flanges at either end. The heated surface was a 0.028-inch platinum wire mounted at the center line of the flow tube. Figure 3 is a detail of the flow tube assembly, showing the method used to hold the wire in place. Copper tubing ¼ inch in inside diameter served as power leads to the test wire. At the point of attachment between the wire and copper tube, a streamlined surface was provided so that flow pattern disturbances would be held to a minimum.

Directly following the flow tube assembly, a back-pressure regulator maintained the desired system pressure.

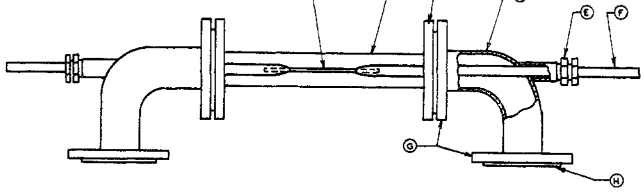

Figure 3. Detail of flow tube assembly

A. 22-gage platinum wire
B. ¾-inch borosilicate glass pipe, flow tube
C. ¾ × 4 inch reducing flange
D. 1-inch 90° steel elbow
E. ¼-inch bulk head fitting
F. ¼-inch o.d. copper tubing, power lead
G. 1-inch slip-on flange
H. ⅛-inch Teflon gasket

The liquid was returned to the pump suction following the regulator, thus completing the flow circuit.

Power at 0 to 6 volts was provided by passing line voltage of 110 volts alternating current through a voltage regulator, a variable transformer, and a 20-1 step-down transformer all connected in series. An ammeter and voltmeter were used to measure the power input to the heated surface. The surface temperature of the wire was determined from the resistance-temperature relationship of platinum. Initial attempts to use a stainless steel-sheathed thermocouple for the heated surface, as in the reaction flask tests, were unsuccessful because of burn-out problems at peak heat flux. Evidently temperatures above 2000° F. were reached in shifting to film boiling, which destroyed the stainless steel sheath. Since supply of these special units was limited, platinum wire heating units were substituted.

At the start of each run, the bulk liquid temperature, pressure, and velocity were regulated as desired. Then the power to the test wire was increased slowly. At each power level, voltage and amperage were read. Bulk temperature was maintained constant throughout the run.

Upon reaching the peak heat flux, power was turned off, the velocity changed, and power reapplied while pressure and bulk temperature were maintained constant. After completion of runs with the three velocities the pressure was changed. Bulk liquid temperature was held constant until runs at all pressures had been concluded. Then the temperature was adjusted to another value, and the above sequence repeated.

DISCUSSION OF RESULTS

The heat transfer properties of FC-75 are unique because of its low boiling point (214° F.) and high upper temperature limit (750° F.), permitting a high heat transfer rate by evaporative cooling. In a forced convection system, FC-75 can cool at a higher heat flux by local boiling, whereas other materials with higher boiling points are limited to pure convective cooling.

Comparison Tests. Initial tests provided data comparing FC-75 with the other common dielectric coolants listed previously. A maximum heat flux—that is, heat per unit area— was determined for each liquid using, as an end point for FC-75, 90% of the peak heat flux obtained in the nucleate boiling region. Maximum values for the commercial silicate ester and silicone oil were taken when the heated surface reached 400° F., which is the maximum operating temperature recommended by the manufactures.

The results obtained for a heated surface temperature of 400° F. are:

	Maximum Heat Flux, Watts/Sq. In.	
Liquid (120° F.)	250 r.p.m.	450 r.p.m.
FC-75 (90% of peak heat flux)	338	420
Silicone oil	118	232
Silicate ester	212	232

If comparisons are made at a lower heated surface temperature, the advantage of FC-75 is increased—for example, 325° F., at 250 r.p.m., gave the following results:

Liquid (120° F.)	Heat Flux, Watts/Sq. In., 250 R.P.M.
FC-75	320
Silicone oil	90
Silicate ester	145

Figure 4, a plot of heat flux *vs* temperature difference between the heated surface and bulk liquid, shows the results obtained in this initial investigation conducted at atmospheric pressure.

Heat Transfer Variables. During the second phase of the study on FC-75, using the flow apparatus described, heat

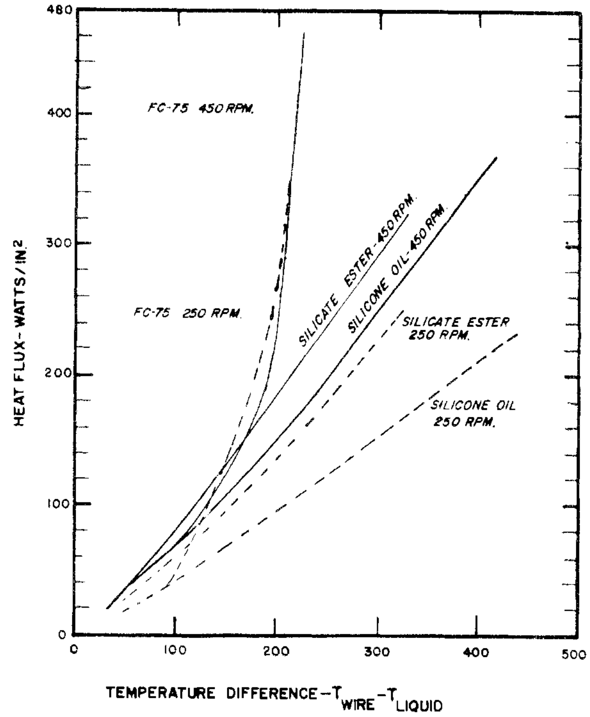

Figure 4. Comparison of heat transfer properties of commercial dielectric coolants

Liquid temperature, 120° F.; two levels of agitations

flux data were obtained for various conditions of pressure, velocity, and bulk liquid temperature:

Pressure, Pressure, Atm.	Velocity, Ft./Sec.	Bulk Liquid Temp. ° F.
2	3	5
4	5	45
6	7	120
8		170

Graphs of heat flux *vs.* wire temperature were prepared from the experimental data (Figures 5 through 8). Each figure represents the effect of velocity and pressure variation on heat flux at a constant subcooled liquid temperature. Data on heat transferred in both the liquid convection and nucleate boiling regions are included.

In all cases, as expected, an increase in velocity produced a proportional increase in heat flux throughout the liquid convection range.

In the nucleate boiling region, increased velocity did not significantly affect the rate of change of heat flux; but it did increase the peak heat flux obtainable. This indicates that in boiling, the growth and collapse of bubbles on or near the heated surface have more effect on heat transfer than does the fluid velocity until the peak flux is reached. Higher velocities extend the peak heat flux by more rapid removal of bubbles.

Pressure increase during nucleate boiling, with other factors held constant, produced an increased wire temperature equal to the increase in boiling point with pressure. There was a constant difference of approximately 15° F. between the boiling point of the liquid and the wire temperature at the initiation of boiling.

The effect of pressure on peak heat flux at constant velocity varied with fluid temperature. At higher fluid temperatures (120° and 170° F.) increasing pressure produced increased peak heat flux up to a maximum at approximately 6 atm. This was in close agreement with a prediction of 5.4 atm. based on correlations developed for other materials (*1*) which were studied at their normal boiling temperatures. Additional pressure increase above the 6-atm. value caused a decreased peak flux. As the liquid temperature was decreased, the maximum flux value was reached at lower pressure—with a liquid temperature of 45° F., the maximum occurred at 4 atm.; at 5° F., it occurred at 2 atm.

The peak heat flux curves given on Figures 5 through 8 were obtained by empirical correlation of the data using a digital computer. A statistical study indicated that the variables of liquid temperature, pressure, and velocity accounted for 91% of the variation of peak heat flux within the range of experimentation for a particular specimen of platinum wire. Some tests with a different platinum wire specimen produced peak fluxes approximately 20% higher. The more conservative set of data was used to develop the correlation expressed by the equation:

$$\begin{aligned} F = {} & 301.1 + 34.6V - 0.267P - 0.1935BLT \\ & + 0.101(V)(P) + 0.0155(V)(BLT) + 0.00809(P)(BLT) \\ & - 1.012V^2 - 0.00915P^2 - 0.003705BLT^2 \end{aligned}$$

where

F = peak heat flux, watts/per sq. inch
V = velocity, feet per second
P = pressure, p.s.i.g.
BLT = bulk liquid temperature, ° F.

Extrapolation of this equation beyond the experimental limits and geometry is not recommended.

Accuracy of Data. The accuracy of the voltmeter and ammeter used for this work was to ± 1% of full scale. Allowing for mid-scale accuracy, the determination of power input is accurate to about ± 4%.

Temperature data, allowing for measurement errors and temperature gradient to the outside surface, have an accuracy to approximately ± 10° F.

Effect of Materials. The preliminary data taken with stainless steel at atmospheric pressure and 120° F. liquid temperature indicated a surface temperature at peak heat flux of 345° F., which is 130° F. above the saturation boiling temperature. Correspondingly, data with a platinum wire in the forced convection apparatus at 15 p.s.i.g. and 120° F. liquid temperature indicated a surface temperature of 350° F. at peak heat flux, or 90° F. above the saturation boiling temperature at this pressure. This limited comparison indicates that, under the same conditions, platinum operates at a lower temperature than stainless steel. Westwater (*7*) indicates that copper should also operate at a lower temperature than stainless steel at the same heat flux.

Effect of Geometry. Although this work was conducted on wires of relatively small diameter, geometrical variations probably do not cause major differences in peak heat flux or surface temperature, except for wires of much smaller diameter than that used in this work (*7*). However, further investigation of geometry would be profitable, especially a flat surface facing up and facing down with forced convection at various velocities.

CONCLUSIONS

At constant pressure and heat flux, the temperature of the heated surface remains constant with variation in bulk liquid temperature.

At constant bulk liquid temperature and heat flux, the temperature of the heated surface varies directly with the change in boiling points of the liquid caused by varying the system pressure.

The peak heat flux for FC-75, with a 22-gage platinum wire as the heated surface, varies with pressure, velocity, and bulk liquid temperature.

Increase in velocity increases peak heat flux in the nucleate boiling region, but does not affect the rate of change of flux with temperature.

Maximum heat flux obtained with FC-75 was 508 watts per sq. inch, (255,000 B.t.u./hr. sq. ft.) at a fluid temperature of 5° F., velocity of 7 feet per second., and 2, atm. pressure.

Variation of heat flux with surface temperature for FC-75 in convective and nucleate boiling heat transfer to the peak heat flux at various liquid velocities, pressures, and temperatures

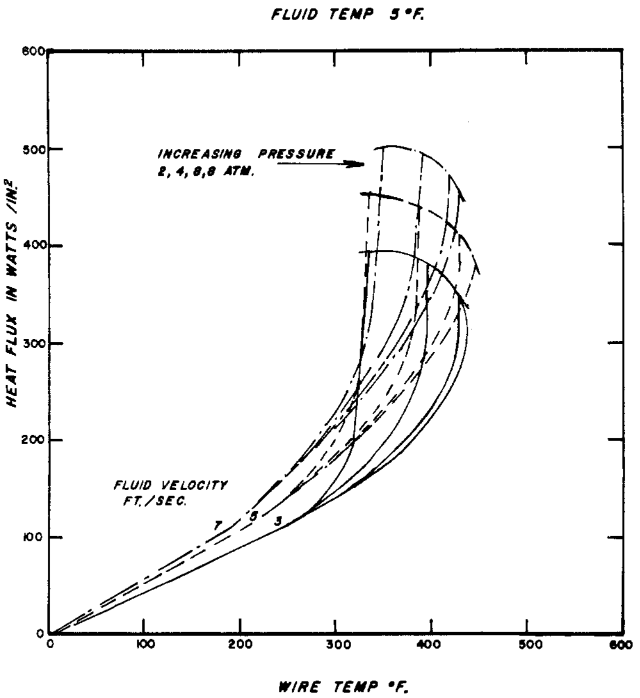

Figure 5. At 5° F.

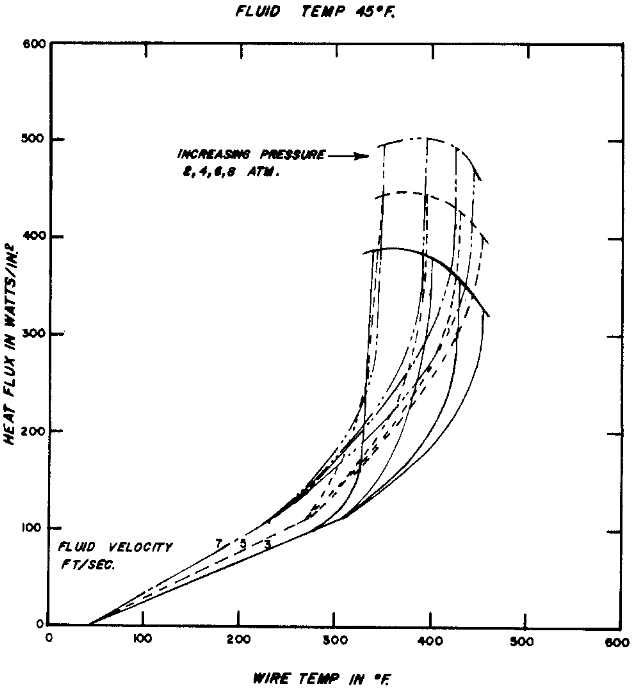

Figure 6. At 45° F.

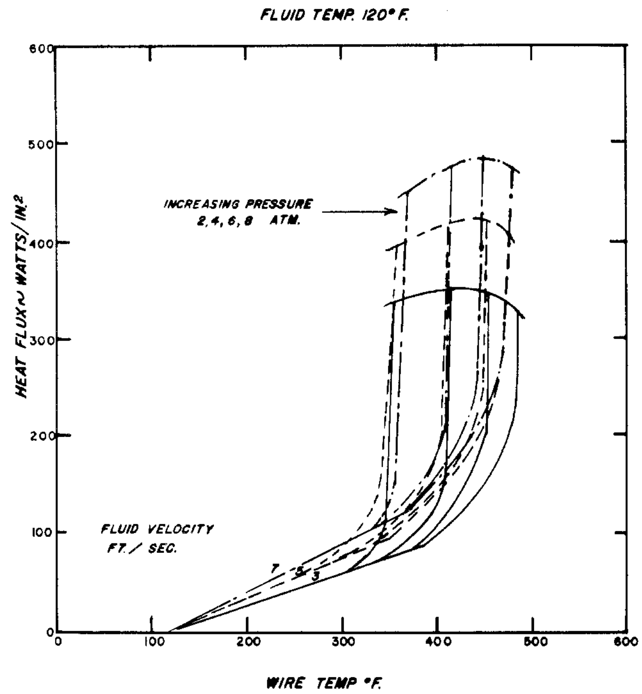

Figure 7. At 120° F.

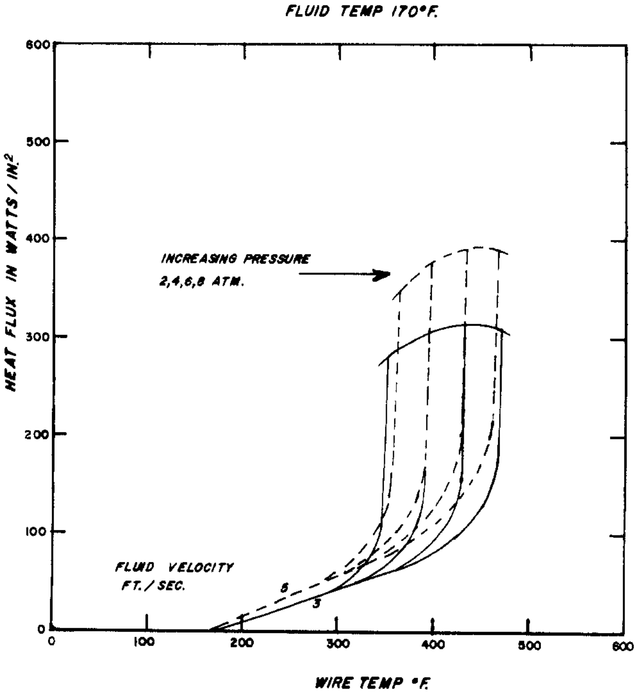

Figure 8. At 170° F.

In the nucleate boiling region at high velocity and low pressure, a 150 to 200% increase (minimum to maximum) in heat flux can be obtained with a variation in heated surface temperature of only 15° to 20° F.

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