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WADC TECHNICAL REPORT 54-66

HEAT-TRANSFER FLUIDS FOR AIRCRAFT-EQUIPMENT COOLING SYSTEMS

C. J. GEANKOPLIS
W. B. KAY
A. W. LEMMON
W. ROBINSON

THE OHIO STATE UNIVERSITY RESEARCH FOUNDATION

FEBRUARY 1954

WRIGHT AIR DEVELOPMENT CENTER

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The Ohio State University Research Foundation

February 1954

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Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

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FOREWORD

This report was prepared in the Departments of Chemical and Mechanical Engineering of The Ohio State University. The work was performed between December 1952 and January 1954 as one phase of the activities under Contract No. AF 33(616)-147 with The Ohio State University Research Foundation. It was administered under the direction of the Mechanical Branch, Equipment Laboratory, Directorate of Laboratories, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. Mr. F. R. Ebersbach was the Equipment Laboratory project engineer in charge of the work which was accomplished under RDO No. 664-803F-3, "Centralized versus Individualized Cooling of Aircraft Equipment".

Section V of this report, dealing with the evaluation of the effects of physical properties of heat transfer fluids on cooling system penalty, is the only section prepared in its entirety in the Mechanical Engineering Department. W. E. Krauss and K. G. Hornung who performed the analyses and supervised the calculations are identified as co-authors.

This report is the first of two technical reports to be prepared under this study contract dealing with the evaluation of aircraft equipment cooling systems in general. The second report, WADC TR 54-359, Equipment Cooling Systems for Aircraft, will deal with the evaluation of various types of cooling systems applicable to aircraft equipment, either directly, or by means of a distribution system utilizing a heat transfer fluid.

ABSTRACT

The objective of this study was to tabulate the important physical, chemical, and physiological properties of liquids available for use in aircraft equipment cooling systems. These properties were used as a basis for qualitatively selecting fluids representative of various types and to evaluate their effects on the gross weight increase of aircraft, resulting from the installation of a centralized cooling system. Many physical property values were found to be unknown. This made necessary the collection, development, organization, and use of empirical methods to estimate the physical properties of liquids being studied. These methods are presented herein.

Physical, chemical, and physiological property data are tabulated for 36 fluids. The types of fluids represented are: aqueous solutions, hydrocarbon fuels, hydraulic fluids and lubricants, oxygenated hydrocarbons, fluoro- and chloro-hydrocarbons, organic-inorganic compounds and Silicones. Water is used as a reference fluid since it has the most desirable properties for use as a forced convection heat transfer medium up to 600°F. It is also desirable in terms of corrosiveness, combustibility, toxicity, and stability, but is not suitable because of its high freezing point of 32°F. Among fluids having a freezing point of -65°F, or lower, aqueous solutions are the most desirable group. The methanol-water mixture has the best properties, except for relatively high vapor pressure and potential combustibility of the initial vaporization product. The ethylene glycol-water mixture does not have these drawbacks, but is slightly inferior in other respects.

The gross weight increase of an aircraft, resulting from the installation of a centralized cooling system, is affected by the selection of the type of heat transport fluid to a greater extent, the longer the distribution system, the greater the required fluid circulation rate and the smaller the penalty imposed by the ultimate heat rejection system. Aqueous solutions cause a gross weight increase only slightly greater than does pure water. Other applicable fluids may cause a gross weight increase up to three times that of water. Particularly disadvantageous for large systems are 10-centistoke Silicone fluids because of high viscosity and low specific heat, fluoro-hydrocarbons because of low specific heat and low thermal conductivity and hydrocarbon hydraulic fluids because of high viscosity and relatively low thermal conductivity.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or the conclusions contained therein. It is published only for the exchange and stimulation of ideas.

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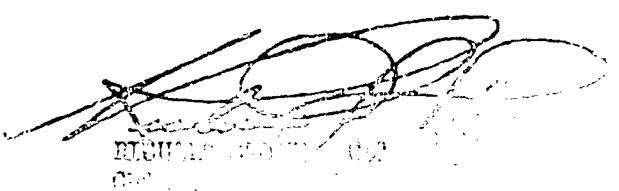


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INTRODUCTION

Equipment cooling imposes performance penalties on aircraft which increase with flight speed and with the complexity of the functions being performed by various types of equipment. With many types of aircraft, a reduction in penalty can be realized by centralization of the cooling system, particularly if a coolant distribution system of small size, weight and pumping power can be designed. This can be accomplished best by use of liquid coolants.

The primary objective of the present study was to determine the significant properties of liquids which would be suitable for application as heat transport fluids in aircraft equipment cooling systems up to 600°F. Among them, liquids normally available on aircraft, such as fuels, lubricants, and hydraulic fluids, were to be considered. The effects of heat transfer fluids on cooling system characteristics were to be evaluated.

The following physical, chemical and physiological properties were selected as being significant in the evaluation of heat transfer fluids:

1. Chemical composition
2. Molecular weight
3. Boiling point
4. Flash point
5. Fire point
6. Freezing point
7. Pour point
8. Vapor pressure
9. Latent heat
10. Density
11. Specific heat
12. Viscosity
13. Thermal conductivity
14. Coefficient of expansion
15. Surface tension
16. Refractive index
17. Dielectric constant
18. Color
19. Odor
20. Combustibility
21. Toxicity
22. Stability
23. Corrosiveness
24. Acidity
25. Solubility
26. Effect on elastomers

Since it was known that experimental data on all of these physical properties would not be available for each fluid considered, it was felt that ways and means of estimating the properties should be found. These empirical estimation methods should be helpful to others in adding new fluids for consideration to the list of those discussed in this report.

The effects of the choice of a heat transport fluid on the overall aircraft penalty imposed by a cooling system may differ considerably, depending on the type of the cooling system. It was not feasible to make the necessary calculations to evaluate all representative fluids as applied to all types of cooling systems and their probable configurations. Therefore, comparative values were established for several fluids in expendable systems and for two fluids in ram air systems. These data were adequate to indicate the relative importance of physical properties, and, therefore, the best fluids, from the systems and aircraft standpoints.

Few fluids stable up to 600°F were found and their properties were determined. The properties of a much larger group of fluids stable to 300°F were studied. However, the data assembled in this report should be adequate for the selection of suitable fluids for operating temperatures as high as 600°F.

SECTION I

ESTIMATION OF PHYSICAL PROPERTIES OF FLUIDS

Before an evaluation can be made of the suitability of a fluid for use in aircraft cooling systems, the physical properties of the fluid must be known. These physical properties are boiling point, vapor pressure, flash point, heat of vaporization, density, specific heat, viscosity, and thermal conductivity.

In many cases these properties have been determined experimentally and are available in the scientific literature, textbooks, and the trade literature. In many other cases the data are completely missing or are incomplete. To determine experimentally all of the missing data would require prohibitive effort, time and expense. Therefore, methods to estimate or calculate these physical properties are believed to be invaluable aids.

A detailed literature search has been performed and has yielded many estimation methods. Some of them were found in standard handbooks, textbooks on heat transfer, physical chemistry reference texts, data books, tables such as the International Critical Tables, and in technical journals.

These empirical and theoretical methods have been evaluated, modified, and sometimes extended to make them more useful. They are discussed in the following pages. Mention is made of all the applicable methods but only those considered important are discussed in detail. Examples are also given in many cases.

In all cases the graphs and correlational representations have not been reproduced along with the descriptions of the estimation methods presented. The limited use anticipated for many of these methods along with the large number of graphs necessary did not seem to make it advantageous to reproduce them here. Difficulties in reproducing copyrighted material is also evident. However, it is not anticipated that the user of this material will suffer too much inconvenience inasmuch as the majority of the graphical representations referred to are contained in three major references, Hougen and Watson (Ref. 10), Maxwell (Ref. 11), and Nelson (Ref. 12), which are readily available in most libraries.

In order to facilitate the transition, for those using the methods, from the material presented in this report to the original sources, the original nomenclature has been preserved. This does invoke some inconsistencies in symbols but the inconvenience of this has been minimized by the frequent definition and redefinition of the terms used. For these reasons, it was not thought to be profitable to include a table of general nomenclature.

It is intended that this section should serve as a manual and guide for estimating physical properties of heat transfer liquids. When new fluids

other than those recorded in this report are to be evaluated, the methods given here can be used to fill in the missing data. In most cases, these methods are sufficiently accurate for engineering purposes. As new methods become available in the literature, those included here can be modified, added to, or extended.

Normal Boiling Point

For any liquid, a certain fraction of its molecules, depending upon the temperature, attain a sufficiently high energy to escape from the liquid phase. This phenomenon is termed vaporization. Until the temperature is at a sufficiently high level, all vaporization takes place at the surface of the liquid. However, at some point in the temperature scale the escaping tendency of the molecules becomes so great that the ambient pressure can be overcome. At this temperature, vapor bubbles form within the liquid, rise to the surface and are dissipated. This is termed boiling. When the ambient pressure is that of standard ground level conditions (760 mm. Hg), the temperature at which boiling occurs is termed the normal boiling point.

Approximately correct boiling points can be determined experimentally by the simple expedient of immersing a calibrated thermometer or thermocouple into the liquid and noting the temperature at which boiling occurs as heat is added to the liquid. Accurate determination of the boiling point of a substance is difficult for many reasons. Some of the more important difficulties are due to, (1) impurities in the liquid, (2) superheating, and (3) insufficient control of ambient pressure.

Experimentally determined values of normal boiling points are available from a number of literature sources. The more important sources are Perry (Ref. 1), Landolt-Bornstein (Ref. 2), Lange (Ref. 3), International Critical Tables (Ref. 4), and Handbook of Chemistry and Physics (Ref. 5).

A great many liquids exist and are proposed for use, as heat transport fluids, however, for which boiling point determinations have not been or can not be made. In those cases where the boiling point should be known for proper evaluation of a possible use of a liquid, it becomes necessary to estimate the value of the boiling point. Many estimation methods are available in the literature. Watson and Nelson (Ref. 6 and 7), Kinney (Ref. 8, 9, and 3, pp. 1525-27), Hougen and Watson (Ref. 10), Maxwell (Ref. 11, p. 16), and many others have shown methods of estimating boiling points. The more important of these methods are summarized in the following discussion.

1. Kinney Method for Estimating Boiling Points of Organic Compounds

The boiling points at atmospheric pressure of organic compounds can be estimated by a set of empirical rules if the structure of the compound is known. Kinney (Ref. 8) has developed this method to a high degree of precision. The method is essentially as follows:

a. The individual boiling point numbers (b.p.n.) of the various atoms and structural groupings are added together to give the molecular boiling point number (B.P.N.).

b. The boiling point (B.P.) in °C is calculated from the B.P.N. by the relation,

$$B.P. = 230.4 \sqrt[3]{B.P.N.} - 543 \qquad (1)$$

The B.P.N. is determined by using values of 0.8 and 1.0 for the b.p.n.'s for each of the carbon and hydrogen atoms, respectively, of the longest aliphatic chain in the molecule. To this sum are added the contributions of each of the other groups or atoms attached to the longest chain. It is essential that the longest aliphatic chain be used as the base because the boiling point is dependent, in part, upon this factor. A portion of the assigned b.p.n.'s are shown in Table 1. A complete table is given by Lange (Ref. 3, pp. 1525-27).

An example of the estimation of the boiling point of 1-methyl-4-(1-methylethyl-1)-1-cyclopentene, $(CH_3)_2{:}CH{\cdot}\underline{CH{\cdot}CH_2{\cdot}C(CH_3){:}CH{\cdot}CH_2}$, is as follows:

Carbon in the longest aliphatic chain (2x0.8)	1.6
Hydrogen in the longest aliphatic chain (4x1.0)	4.0
Methyl radical attached to the aliphatic chain	3.05
Carbon in the cyclopentene ring (5x0.8)	4.0
Hydrogen in the cyclopentene ring (6x1.0)	6.0
Contribution for the five-membered ring	2.5
Contribution for the ethylenic linkage, type $R_2C{:}CHR$	2.3
Methyl attached to the cyclopentene ring	3.05
Calculated B.P.N.	26.50
Calculated B.P. (equation 1)	142.5°C
Observed B.P. (for comparison)	143.1°C

The accuracy of this method is of the order of 2 - 5 percent, which is believed well within the desired accuracy limitations for the present purposes.

Table 1. Individual Boiling Point Numbers (b.p.n.'s)

Carbon, in the main chain	0.8
Hydrogen, attached to the main chain	1.0
Radicals, saturated, attached to the main chain or to cyclic rings	
Methyl	3.05
Ethyl	5.5
Propyl	7.0
Butyl	9.7
2,2 - Dimethyl grouping	-0.4

Table 1, continued

Type of olefinic linkage	
$CH_2:CH_2$	1.2
$RCH:CH_2$	1.5
$RCH:CHR$	1.9
$R_2C:CHR$	2.3
$R_2C:CR_2$	2.8
Radicals, unsaturated, attached to the main chain	
Methylene	4.4
Ethylidene	7.0
Vinyl	5.4
Propylidene	9.0
Butylidene	10.4
Type of acetylenic linkage	
$HC{\equiv}CH$	4.0
$RC{\equiv}H$	4.4
$RC{\equiv}CCH_3$	5.4
$RC{\equiv}CR$	4.8
Cyclic radicals: Add 0.8 for each carbon, 1.0 for each hydrogen, the normal values of any unsaturated linkages, and the following values for the ring:	
Cyclo-propyl, -butyl, -pentyl, -hexyl, respectively	2.1, 2.3, 2.5, 2.7
Cyclo-heptyl, -octyl, etc., (add 0.5 for each additional CH_2 in the ring)	3.4, 3.9, etc.
Alcohol -OH	
RCH_2OH	10.8
Ether -O-	
$RCH_2OCH_3, R_2CHOCH_3, R_3COCH_3$	3.9
Aldehyde =O	
RCH_2CHO	6.2
Ketone =O	
RCH_2COCH_3	8.9
Ester -OO-	
$RCH_2COOCH_3, CH_3COOCH_2R$	8.5
Acid -COOH	
RCH_2COOH	19.3
Amine, primary $-NH_2$	
RCH_2NH_2	7.3

2. Boiling Point of Hydrocarbon Mixtures (Petroleum Fractions)

Because of the fact that petroleum fractions are made up of many compounds with different boiling points, it is necessary to define what is meant by the average boiling point of such a fraction. There are four ways in common use in the petroleum industry of expressing the average boiling point: volumetric, molal, mean, and weight.

a. Volumetric Average Boiling Point

The results of an ASTM distillation* are expressed in °F vs. cc of liquid distilled. Since 100 cc of liquid are charged, the volume of liquid in the receiver plus the loss by evaporation at any time represents the percent of liquid distilled. The volumetric average boiling point is obtained by averaging the temperatures corresponding to 10, 30, 50, 70, and 90 percent distilled.

In working with high-boiling stocks where the vapor temperatures in the ASTM distillation exceed 700°F, it is preferable to use the data from a distillation under reduced pressure in order that the liquid temperature does not enter the range of rapid cracking. Ordinarily a distillation under 10 mm of mercury is satisfactory. Such data are converted to atmospheric pressure by means of a vapor pressure chart. If low-pressure distillation data are not available on high-boiling stocks, the 50-percent-point temperature is taken as the approximate volumetric average boiling point.

b. Molal Average Boiling Point

The molal average boiling point is less than the volumetric average because of the fact that the ratio of specific gravity to molecular weight is higher for the low boiling members of a hydrocarbon series. Thus, in determining the average boiling point from a volumetric distillation curve, the lower boiling fractions should be given increased weighting, in proportion to the variation with boiling point of this ratio of specific gravity to molecular weight.

The molal average boiling point is derived from the volumetric average boiling point by the use of a correction curve, empirically determined, and given by Maxwell (Ref. 11).

c. Mean Average Boiling Point

The mean average boiling point is defined as the boiling point which best correlates the molecular weight of petroleum fractions. Its relation to the volumetric average boiling point is given by the empirically derived curves given by Maxwell (Ref. 11).

---

*See the ASTM procedure as described by Nelson (Ref. 12, p. 26).

d. Weight Average Boiling Point

The weight average boiling point may be calculated directly from the boiling points of the components and their weight fractions or obtained by correcting the volumetric average boiling point using the empirically determined curves given by Maxwell (Ref. 11).

In the estimation of the physical properties of petroleum fractions involving boiling points, the proper average should be used. For various physical properties, these are as follows:

Physical Property	Average Boiling Point
Viscosity and liquid specific heat	Volumetric average
True critical temperature	Weight average
Pseudo-critical temperature and thermal expansion of liquids	Molal average
Molecular weight, specific gravity pseudo-critical pressure, heat of combustion, characterization factor	Mean average

3. Estimation of Boiling Point Using Characterization Factor

For general correlation of the average physical properties of petroleum stocks of different types, paraffin hydrocarbons of maximum hydrogen content may be considered as one extreme and aromatic materials of minimum hydrogen content as the other. To serve as a quantitative index to this property, which may be termed paraffinicity, the U.O.P. (Universal Oil Products) characterization factor (Ref. 7) has been developed. Although this factor is not an exact measure of chemical type and does not show perfect constancy in a homologous series, these disadvantages are, to a considerable extent, offset by its simplicity and convenience of definition and use.

a. Definition and Evaluation of Characterization Factor from Mean Average Boiling Point and Specific Gravity

The definition of the characterization factor arose from the observation that, when a crude oil of supposedly uniform nature is fractionated into narrow cuts, the specific gravity of these cuts is approximately proportional to the cube roots of their absolute boiling points. The proportionality factor is a measure of the paraffinicity of the stock. Thus

$$C = (T_B)^{1/3}/G \qquad (2)$$

where

C = characterization factor.
T_B = mean average boiling point, °R.
G = specific gravity at 60°F.

For the calculation of the mean average boiling point of a petroleum distillate see (2c) above.

b. Range of Values for Characterization Factor

The characterization factor shows fair constancy throughout the boiling range of a number of crude oils and, for others, may either increase or decrease in the higher boiling range. In the paraffin series fair constancy for the average of the reported isomers exists up to a boiling temperature of 700°F. Typical factors for various stocks are as follows:

Paraffin hydrocarbons	12.7
Pennsylvania stocks	12.2 - 12.5
Mid-continent stocks	11.8 - 12.0
Gulf Coast stocks	11.0 - 11.5
Cracked gasolines	11.5 - 11.8
Cracking plant feeds (combined)	10.5 - 11.5
Recycle stocks	10.0 - 11.0
Cracked residuums	9.8 - 11.0
Benzene	9.8

Although not specifically indicated, application of this characterization factor to hydrocarbons, other than those obtained directly from crude oil, follows automatically.

c. Other Methods of Evaluation of Characterization Factor

In addition to the evaluation of the characterization factor of a hydrocarbon from the definition, i.e., from average boiling point and specific gravity, other pairs of properties can be utilized. Watson, et al. (Ref. 6 and 7) have derived empirically and show a series of graphs which permit this. The most convenient pairs of properties, in addition to the above, are: (1) viscosity and specific gravity, (2) viscosity and average boiling point, and (3) specific gravity and molecular weight.

d. Boiling Point

Once the characterization factor has been determined by any of the above described methods not depending on the boiling point, it immediately becomes possible to find the boiling point through the use of the available correlations (Ref. 6 and 7).

4. Summary and Recommended Methods

The Kinney method for estimating boiling points is applicable only to pure organic compounds while the Characterization Factor method is suitable for use with petroleum fractions and some ill-defined organic mixtures. No general method for predicting the boiling point of mixtures has been found, particularly for mixtures containing inorganic compounds. In most cases, with the above exceptions, the value of the boiling point of mixtures must be based upon experimental information. This experimental information

need not be the value of the normal boiling point but could be the vapor pressure at some known temperature. Methods described in the next section on Vapor Pressure could then be used to estimate the temperature when the vapor pressure was 760 mm Hg, i.e., the normal boiling point.

Vapor Pressure

The vapor pressure of a liquid is the pressure exerted on the surroundings by the vapor which results from an evaporation of the liquid. If the liquid is pure (composed of a single compound) it is dependent only on the temperature. If the liquid is composed of more than a single component, it is dependent on both the temperature and the composition of the mixture. When referring to the vapor pressure of a liquid mixture, the initial vapor pressure is meant unless otherwise stated.

Vapor pressure is a property which must be determined experimentally. Its measurement is not difficult at temperatures near the atmospheric boiling point. However, at higher temperatures special methods are employed which require a high degree of skill on the part of the experimentalist in order to get results of the desired accuracy. Fortunately, the general relation between vapor pressure and temperature is well known so that with a minimum of experimental data the vapor pressure of a liquid may be estimated over a range of temperature with an accuracy about equal to the accuracy of the experimental data employed. This is of great practical importance since in many cases the vapor pressure at the desired temperature is not given.

The most practical methods of estimating the vapor pressure of a liquid (either a pure liquid or a mixture) are as follows:

1. Empirical Equations

   a. Standard Vapor Pressure Equation

$$\log P = (A/T) + B \qquad (3)$$

where

P = vapor pressure in absolute units, e.g., atm.
T = temperature in absolute degrees, e.g., °K.
A and B = constants for each compound.

The starting point for the equation is the Clausius-Clapeyron equation. In differential form the Clausius-Clapeyron equation is rigorous, but various assumptions are introduced to integrate it, namely: that the volume of the liquid is insignificant in comparison with that of the vapor; that the vapor is an ideal gas; and that the latent heat is independent of temperature. In spite of the fact that these assumptions hold only at low temperatures, the equation fits the vapor pressure data for practically all substances over wide ranges. Only two experimental values are needed to determine the constants. If the equation is to be used to calculate the pressure over a wide range of temperature, the experimental values used to evaluate the constants should be chosen with as large a temperature differ-

ence as possible. The greatest accuracy is obtained when the standard boiling point and critical point are used for the evaluation and is of the order of 2 per cent.

Example: The standard boiling point of methylcyclohexane is 100.94°C. Its critical point is 299.13°C and 34.32 atm. Calculate the values of the constants A and B in equation (3).

$$\log 1.000 = \frac{A}{100.94 + 273.16} + B = \frac{A}{373.16} + B$$

$$\log 34.32 = \frac{A}{299.13 + 273.16} + B$$

Solving for A and B,

$$A = -1660$$

$$B = 4.435$$

$$\log P\ (\text{atm}) = \frac{-1660}{T} + 4.435$$

b. Antoine Equation

$$\log P = A + B/(t + C) \qquad (4)$$

where

P = absolute pressure in the units desired.
t = °F (or °C as desired).
A, B and C are characteristic constants whose units and values will depend on the units of pressure and temperature.

This equation (Ref. 13) is a modification of the standard vapor pressure equation described above. Three values of the vapor pressure are needed for the calculation of the constants. Its use is recommended when the critical point of the liquid is not known. The accuracy is of the order of 0.5 percent at temperatures in the vicinity of the atmospheric boiling point. If an over-all value of C = 230 (when P = mm and t = °C) is used for all substances the equation can be used to estimate pressures at temperatures approaching the critical with a maximum error of the order of 5 to 10 percent.

c. $\text{Log } P_c/P = a(T_c/T - 1)$ (5)

where

T_c = critical temperature of compound in absolute degrees.
P_c = critical pressure in absolute pressure units.
a = characteristic constant.

This equation gives very good agreement with experimental values but is of limited use because T_c and P_c data are normally not available. This equation is not applicable to mixtures.

d. $$\text{Log } P = (A/T) + B \log T + C \qquad (6)$$

where P and T have the same meaning as in equation (4) and A, B, and C are constants characteristic of the compound.

The accuracy of this equation for interpolation and extrapolation of data is of the same order as that of the Antoine equation. The equation, however, is not as convenient to use.

2. Graphical Methods

a. Dubring's Rule

This rule furnishes a simple and reasonably accurate method of interpolating and extrapolating vapor pressures. The rule is expressed by the equation,

$$(t_{A_1} - t_{A_2})/(t_{B_1} - t_{B_2}) = C \qquad (7)$$

where

t_{A_1} and t_{B_1} are boiling points of substances A and B at the same pressure p_1.
t_{A_2} and t_{B_2} are boiling points at some other pressure p_2.
C is a constant.

Substance A is that of which the vapor pressure is to be determined, and B is a reference substance of which the vapor pressure is known over the desired range. Substance B should, if possible, be chemically similar to A. Two vapor pressures of the substance A are needed to evaluate C.

The above equation can also be put in the form

$$t_A = k_1 t_B + k_2 \qquad (8)$$

where

k_1 and k_2 are constants.
t_A and t_B are any corresponding boiling points of substances A and B.

From this form of the equation it can be seen that t_A plotted against t_B yields a straight line, and the rule is generally used in this graphical form. For most compounds water may be used as the reference substance, so that with the aid of Steam Tables, the vapor pressure of the compound is quickly and easily calculated.

Sample: The vapor pressures of methylcyclohexane are as follows:

100.94°C	1.000 atm.
154.3°C	3.566 atm.
209.4°C	9.894 atm.

Solution: Draw the Duhring line using water as the reference liquid. First, find the temperature at which water has the same vapor pressure as the methylcyclohexane.

methylcyclohexane °C	V.P. atm	water °C
100.94	1.000	100.0
154.3	3.566	140.0
209.4	9.894	180.0

Second, plot the temperature of methylcyclohexane vs. the temperature of water and draw a straight line through the points.

To use the chart to get the vapor pressure of methylcyclohexane proceed as follows: Select a temperature on the ordinate and read a corresponding temperature on the abscissa for water. Look up the vapor pressure of water at this temperature. This will be the vapor pressure of the methylcyclohexane at the first temperature.

b. Cox Method

Cox (Ref. 14) introduced a method of plotting vapor pressure data that gives straight lines and also permits, in some instances, the determination of the entire vapor pressure curve from a single experimental point.

The method consists in laying off on the ordinate of a pair of ordinary coordinate axes a scale of logarithms of pressure and then drawing the horizontal coordinate lines. A straight line is then drawn near the center of the sheet sloping upward to the right at an angle of about 45 degrees with the horizontal. This line is chosen to be the vapor pressure curve of a reference substance, generally water. With the aid of the vapor pressure data on water, a scale of temperatures is then plotted along the abscissa to conform to the arbitrarily chosen vapor pressure line, and the vertical coordinate lines are drawn.

When the vapor pressure of any substance is plotted on this system of coordinates, it is found to yield approximately a straight line. Furthermore, groups of related compounds such as paraffin hydrocarbons, alcohols and metals give lines that converge to a common point. This means that the entire vapor pressure line of a member of such a group for which the point of convergence is known could be determined from a single value of the vapor pressure, such as, for example, the normal boiling point.

Examples of this type of chart are shown by Cox (Ref. 14) and by Perry (Ref. 1, p. 564).

c. Othmer Method

This method (Ref. 15) is somewhat similar to the Dühring method, except that the logarithm of the vapor pressure of the compound is plotted against the logarithm of the vapor pressure of a reference substance, for example water, at the same temperature. Along the axis of the vapor pressure of the reference liquid a temperature scale can be marked off and temperature coordinates superimposed on the pressure coordinates. Vapor pressure data plotted on such a plot are straight lines, so that if two experimental points are known, the line is established.

For the most accurate results, the reference liquid should be as similar as possible to the materials plotted. For example, if the vapor pressures of a series of similar hydrocarbons are to be plotted, then one of the hydrocarbons would make a desirable reference liquid.

Example:

See example worked out for the latent heat of vaporization by the Othmer method on page 18.

3. Special Methods

a. Calculation of the Initial Vapor Pressure of Petroleum Naphthas and Gasolines

The initial vapor pressure of gasoline and petroleum naphthas may be calculated from the ASTM distillation curve using an empirical equation derived by Bridgeman and coworkers (Ref. 16).

$$\log (\pi/14.7) = A \left[1 - (\theta_{10}/\theta)\right] \qquad (9)$$

where

$A = 3.41 + 2.11 \times 10^{-3}\, \theta_{10} - 0.15 \sqrt{S_f}$.
π = vapor pressure in lbs/in^2 abs.
θ_{10} = temperature of 10 percent off on ASTM distillation, °R.
θ = temperature, °R.
S_f = slope of ASTM curve at 10 percent off, °F per unit percent evaporated.

When pressure is expressed in mm mercury and temperature in °C,

$$\log (P/760) = A \left[1 - (T_{10}/T)\right] \qquad (10)$$

where

$A = 3.41 + 3.8 \times 10^{-3}\, T_{10} - 0.6 \sqrt{S}$.
T = temperature, °K.
T_{10} = °K for 10 percent off on ASTM distillation curve.
S = slope of ASTM curve at 10 percent off, °C per unit percent evaporated.

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The accuracy claimed by the authors is 0.2 lbs/in^2 (10 mm mercury). The equation is accurate within this limit for distillates containing propane and lighter constituents.

While the equation is intended only for vapor pressures below atmospheric it can be used to estimate vapor pressures very nearly to the critical region. In such cases the accuracy is probably within 10 percent.

Example: Calculate the initial vapor pressure of kerosene over the temperature range of 50° to 150°F.

ASTM Distillation

Percent Off	In.	10	20	30	40	50	60	70	80	90	Max.
°F		360	388	400	410	418	427	438	448	458	470	500

θ_{10} = 388 + 460 = 848°R.

S_{10} = 1.753°F/unit percent evaporated at 10 percent-off point.

Then,

$$A = 3.41 + 2.11 \times 10^{-3} \times 848 - 0.45 \; 1.753 = 4.6071.$$

$$\log x = 5.7744 - 3907/\theta.$$

From this equation the following vapor pressures are calculated:

°F	lbs/in^2 (abs)	mm Hg
50	0.013	0.7
75	0.030	1.5
100	0.063	3.2
125	0.125	6.4
150	0.234	12.2

4. Summary and Recommended Methods

No method which would permit the estimation of the vapor pressure of liquids without experimental information has been found. All methods presented depend upon at least one experimental determination.

Of the empirical equations presented the standard vapor pressure equation, equation (3), is the most convenient and is sufficiently reliable for most purposes. The Antoine equation, equation (4), is more accurate, particularly when the critical point is not known, but requires three experimental determinations to evaluate the three constants. The accuracy of equations (5) and (6) is similar to that of the Antoine equation but they are not as convenient to use. Equation (5) requires critical data and is not applicable to mixtures.

Duhring's Rule and the Othmer method have about the same accuracy and each requires two experimental points. The Cox method, which requires only one experimental value for a member of a homologous series, is usable as an interpolation and extrapolation method for general purposes when two data points are known. In the latter case it has no significant advantage over the previous graphical methods. The application of the special Bridgeman method for naphthas and gasolines is obvious.

Flash Point

The flash point of a liquid is the temperature at which the vapor above the liquid will ignite. Generally, the flash is short-lived and the momentary burning is extinguished immediately. The observed value of the flash point is materially dependent upon the type of apparatus and experimental procedure employed (Ref. 15).

Types of apparatus used are the Pensky-Martens, Tagliabue Closed Cup, and the Cleveland Open Cup. The different methods yield different answers for the same materials. The higher the flash point (Ref. 4, Vol. II, p. 150), the greater the differences. The flash points differ by as much as 7°C for flash points under 50°C and by as much as 20°C for flash points near 200°C.

1. Available Experimental Data

Actual experimental data are available in the literature on flash points of all types of organic compounds including petroleum oils, acids, esters, ethers, aldehydes, halides, ketones, and nitrogen compounds. The International Critical Tables (Ref. 4, Vol. II, pp. 161-2) present data according to the class of compounds. Lange (Ref. 3, pp. 33-49), Hodgman (Ref. 5, p. 1250) and Perry (Ref. 1, p. 1584) tabulate data according to the name of the compound.

2. Grmandy and Cravens Method

The flash point of an organic liquid or compound has been found by Ormandy and Cravens (Ref. 4, Vol. II, pp. 161-2) to be related to the temperature at which the compound exerts a certain vapor pressure. The absolute value of the vapor pressure at the flash point varies with the chemical nature and structure of the compound but will be approximately the same for compounds in the same homologous series. They found the following relation:

$$\text{Vapor pressure at flash-point (mm Hg)} = B/kN \qquad (11)$$

where

B = barometric pressure, mm Hg
k = constant (generally about 8 but varies with class of compound)
N = number of moles of oxygen required for complete combustion of compound.

The flash point is the temperature at which the vapor pressure of the compound equals the value calculated from equation (11). For many petroleum fractions this flash point generally occurs at the temperature at which the initial vapor pressure is 10 to 15 mm Hg.

3. Dreisbach Method

Dreisbach (Ref. 17, pp. 11, 292) tabulates a characteristic vapor pressure at the flash point for a series of homologous organic compounds. These vapor pressures are 6 to 10 mm Hg for aliphatic hydrocarbons, 40 mm Hg for aliphatic alcohols, up to amyl, and 10 mm Hg for aliphatic ketones. Values for other series are also given. With a knowledge of the characteristic vapor pressure at the flash point and the vapor pressure-temperature relationship of the compound, the Cleveland Open Cup flash point may be estimated to within 5° to 7°C of the experimental value.

4. Lange Method for Petroleum Fractions

The approximate closed-cup flash points of organic compounds composed of only carbon and hydrogen (Ref. 3, pp. 33-49) may be estimated by

$$\text{Flash Point } (^\circ\text{F}) = 0.73\,(\text{I.B.P.}) - 122 \qquad (12)$$

where

I.B.P. = initial boiling point in °F.

This formula is applicable between initial boiling points of -150° and 550°F.

5. Nelson Method for Petroleum Fractions

In the method of Nelson (Ref. 12, p. 125) the flash point is related to the 0 to 10 percent boiling range of the material as follows for distilled steams:

$$\text{Flash Point } (^\circ\text{F}) = 0.64\,T - 100 \qquad (13)$$

where

T = average of the 0 to 10 percent distillation range in °F.

6. Effect of Pressure on Flash Point

The flash point (Ref. 4, Vol. II, p. 150) varies with the barometric pressure at the same rate as the boiling point. If the logarithm of the barometric pressure is plotted against the reciprocal of the flash point in degrees Rankine, a straight line is obtained which should be approximately parallel to the corresponding boiling point line for the same liquid. Hence, as the barometric pressure increases, the flash point increases.

7. Summary and Recommended Methods

The Grumdy and Cravens method is the most general method available for estimating flash points but for reasons of accuracy should not be used if sufficient information is available to permit the use of any of the other methods presented. The Dreisbach method has the best accuracy for organic compounds. For petroleum fractions the Nelson method is preferable to the Lange method but the selection of the best equation will depend in most cases upon the specific experimental information available.

Heat of Vaporization

The amount of heat required to convert 1 gram or 1 pound of a pure liquid (or narrow boiling liquid) into saturated vapor at any given temperature (or pressure, since the pressure of saturated vapor is a function only of temperature) is called the latent heat of vaporization. It is usually understood to apply to vaporization at the normal boiling point (1 atm pressure) and it varies considerably with temperature.

The experimental determination of the latent heat of vaporization is difficult and time-consuming if accurate data are to be obtained. On the other hand, values may be calculated which are more accurate than would normally be obtained experimentally. The most important of these methods are as follows:

1. Clapeyron Equation

$$dP/dt = L/[T(V_v - V_l)] \qquad (14)$$

where

dP/dt = the slope of vapor pressure curve at a given temperature
V_l and V_v = the specific volume of the liquid and vapor, respectively
L = latent heat of vaporization per unit mass.

The method is rigorous and the accuracy will depend on the accuracy of the properties appearing in the equation.

If the pressure is low, it may be assumed that the vapor is an ideal gas and that the liquid volume is negligible. Equation (14), then, becomes

$$dP/dt = MLP/RT^2 \qquad (15)$$

where

M = molecular weight.
P = vapor pressure at temperature T
R = gas constant.

The equation gives results of high accuracy if the slope of the vapor pressure curve is determined carefully by graphical methods. If the slope is obtained by differentiation of a vapor pressure equation, such as

$$\log P = (A/T) + B \qquad (3)$$

where A and B are constants, the accuracy is decreased and is of the order of 5 to 8 percent.

2. Othmer Method

Othmer's method of extrapolating vapor pressure data (Ref. 15) may also be used to estimate the latent heat of vaporization. From the Clapeyron equation, assuming that the volume of the liquid is negligible and that the vapor approaches a perfect gas,

$$dP/dT = PL_M/RT^2 \qquad (16)$$

which may be written

$$dP/PL_M = dT/RT^2 \qquad (17)$$

where

P = vapor pressure
T = temperature
R = gas constant
L_M = molal latent heat.

Then, for any other substance at the same temperature

$$dP'/L_M'P' = dT/RT = dP/L_MP \qquad (18)$$

$$dP'/L_M'P' = dP/L_MP \qquad (19)$$

or

$$(d \log P)/(d \log P') = L_M/L_M' \qquad (20)$$

L/L' may be regarded as a constant over a wide temperature range, though usually not at temperatures near the critical point of either material. The above equation when integrated gives

$$\log P = (L_M/L_M') \log P' + C \qquad (21)$$

where C = integration constant.

According to this equation, if log P of any substance is plotted against log P of any other substance at the same temperature, a straight line results whose slope is equal to the ratio of the molal latent heats.

Example: The following data are available for the vapor pressure of methylcyclohexane:

°C	atm.
120	1.68
140	2.67
180	6.01

Extrapolate the vapor pressure to 220°C and calculate the latent heat of vaporization at 220°C.

Solution:

From a table of the thermodynamic properties of water obtain the following data for water:

°C	atm.
120	1.958
140	3.560
180	9.900

Latent heat of vaporization at 220°C = 802.9 Btu/lb

According to the method outlined on page 12, plot log of vapor pressure of methylcyclohexane as ordinate vs. log of vapor pressure of water as abscissa and draw a straight line through the points. If the vapor pressure of methylcyclohexane is desired at 220°C, look up the vapor pressure of water at 220° (22.90 atm.). Plotting this pressure for water on the curve, the vapor pressure of methylcyclohexane can be read on the ordinate.

The slope of the straight line is found to be 0.795. Then,

$$L'_M/L_{H_2O} = 0.795$$

where L'_M and L_{H_2O} refer to the molal latent heat.

Molecular weight of methylcyclohexane, 98; for water, 18. Then

$$98\ L'/(18)(802.9) = 0.795$$

Latent heat of methylcyclohexane, L' = 147.5 Btu/lb

3. Kistyakowsky Method

Kistyakowsky (Ref. 18) has proposed the following empirical equation for the calculation of the latent heat at the normal boiling point:

$$L/T = 8.75 + 4.571 \log T \qquad (22)$$

where

L = latent heat, gram-calories per gram-mole.
T = normal boiling point, °K.

The accuracy of this equation for non-polar substances is within 3 percent.

4. Watson Method

Watson (Ref. 10, p. 233) plotted $(L/T)f$ versus T_R

where

T_R = the reduced temperature (ratio of the actual temperature to the critical temperature on the absolute scale).
f = a constant characteristic of each substance.

He found the data for all liquids, both polar and non-polar, to fall on one curve. These relations can be expressed by the following empirical equations

$$L/L_1 = \left[(1-T_R)/(1-T_{R_1})\right]^{.38} \qquad (23)$$

where

L_1 = the latent heat at the normal boiling point temperature T_{R_1} which may be obtained by one of the methods described above.

To solve the equation for L requires only a knowledge of the critical temperature to give the complete range of latent heats.

5. Method for Liquid Mixtures

When complete vaporization takes place in a mixture, there are two latent heats of vaporization, one for a constant pressure process, $L_{p,x}$, and the other for constant temperature, $L_{t,x}$. The former is the one usually encountered since most engineering processes occur at constant pressure.

It can be shown (Ref. 19) that $L_{p,x}$ of a solution is approximately equal to the sum of the heats of vaporization of the components plus the integral heat of solution on mixing. For a binary mixture,

$$L_{p,x} = L_{a_0}(x) + L_{B_0}(1-x) + q_s \qquad (24)$$

where

L_{a_0} and L_{B_0} = the latent heats of vaporization of the pure components.
x = mole fraction of component A.
q_s = integral heat of solution of A and B.

The value of q_s is seldom available but is usually small so that its effect on the latent heat is relatively small.

Another procedure is to calculate the enthalpy of the liquid from

some convenient reference state to the bubble-point temperature at the given pressure, and the total enthalpy of the saturated vapor at the dew-point temperature. The difference in the enthalpies, then, is the heat of vaporization at constant pressure of the mixture. To do this, the composition of the mixture must be known as well as the specific heats at constant pressure and latent heats of vaporization of the pure components. If there is a heat of mixing of the liquid components this must be taken into account in calculating the enthalpy of the liquid. The heat of mixing of the vapors may be assumed to be negligible.

6. Summary and Recommended Methods

The Kistyakowsky method is recommended for use in predicting the latent heat of vaporization when experimental vapor pressure data are not available. Actually, the vapor pressure at one temperature, i.e., the normal boiling point, is needed even with this method and sometimes this is sufficient, along with recommended vapor pressure prediction methods such as the Cox chart, to permit the use of the Othmer method. These are about of equivalent accuracy and convenience usually dictates the choice. The Clapeyron equation is recommended above all other methods if sufficient information is available to permit its use.

Liquid Densities

The density of a liquid can be determined easily by weighing the amount of that material which occupies a known volume at a specified temperature, for those substances which are liquid at normal temperatures. The experimental techniques are more difficult for substances which are liquid only at very low or very high temperatures.

Experimental results on liquid densities over a temperature range are usually expressed in the form of a three-constant equation such as

$$V_t = V_0 (1 + at + bt^2 + ct^2) \qquad (25)$$

where

V_t = volume of liquid at t
V_0 = volume of liquid at t = 0
t = temperature, °C.

Reliable and checked values of the constants a, b, and c are listed by Lange (Ref. 3, pp. 1715-7, 1485-98) and in the International Critical Tables (Ref. 4, Vol. II, pp. 22-199) for about 150 organic compounds. Values for about 200 other organic liquids are available in literature and an index appears in the International Critical Tables (Ref. 4, Vol. II, pp. 22-199). These values are only given for temperatures below the normal boiling point.

Values of orthobaric density are listed by Lange (Ref. 3, pp. 1715-7, 1485-98) for a smaller number of compounds and also in Landolt-Bornstein

Tables (Ref. 2, Vol. I, pp. 254, 263, 283; First Suppl., p. 164; Third Suppl., pp. 245, 278, 279, 281, 283).

When experimentally determined values for the liquid density are not available, recourse to empirical methods is the only solution. Some of the more important estimation methods are summarized in the following discussion.

1. Generalized Law of Corresponding States

a. Method of Watson

Watson (Ref. 20) found that compressibility and thermal expansion data for liquids could be correlated by the equation

$$\rho = (\rho_1/\omega_1)\,\omega \qquad (26)$$

where

ρ = density of liquid at p_r and T_r.
ρ_1 = density of liquid at p_{r1} and T_{r1}.
ω = expansion factor of liquid at p_r and T_r.
ω_1 = expansion factor of liquid at p_{r1} and T_{r1}.
p_r = reduced pressure.
T_r = reduced temperature.

The factor ω is a dimensionless quantity termed the expansion factor and when expressed as a function of reduced temperature and pressure is approximately the same for all liquids. Values of ω are listed in Table 2. Watson (Ref. 20) also shows a graphical representation. Thus, from one known value of density, together with the ω-chart or table, the density of that liquid can be estimated at any other temperature and pressure by means of equation (26).

The critical density can sometimes be evaluated from the knowledge of the structural formula alone by the method of Hougen and Watson (Ref. 10, p. 70). In this case, it is possible to estimate densities at all temperatures without any experimental information.

As an example of this method, the following procedure illustrates the steps in determining the critical density and the density at 180°C and 100 atm pressure. It is known that the density of ethyl alcohol at 20°C and 1 atm is 0.789 gm/cc. Also, for ethyl alcohol, T_c (critical temperature) = 243.1°C and p_c (critical pressure) = 63.1 atm.

Temperature, °C	20	243.1	180
Pressure, atm	1.0	63.1	100
T_r	0.568	1.0	0.878
p_r	0.0159	1.0	1.59
ω (from chart, Ref. 20)	0.127	0.044	0.0984

Table 2. Values of Expansion Factor

Reduced Temperature, T_r	Reduced Pressure, p_r							
	0	0.4	0.6	1.0	1.5	2.0	3.0	5.0
0.5	(0.1328)	—	—	0.1332	—	0.1338	—	0.1350
0.6	0.1242	—	—	0.1250	—	0.1258	—	0.1275
0.7	0.1144	0.1150	—	0.1158	—	0.1170	0.1182	0.1202
0.8	0.1028	0.1042	0.1050	0.1056	0.1070	0.1077	0.1098	0.1125
0.9	—	0.0900	0.0915	0.0926	0.0949	0.0968	0.1002	0.1043
0.95	—	—	0.0810	0.0831	0.0872	0.0902	0.0943	0.1006
1.0	—	—	—	0.0440	0.0764	0.0818	0.0875	0.0954

Since

$$\rho = 0.789 \text{ at } 20^{\circ}C \text{ and 1 atm}$$

$$\rho_1/\omega_1 = 0.789/0.127 = 6.21 \text{ (the characteristic constant for ethyl alcohol)}$$

Therefore, at 243.1°C and 63.1 atm,

$$\rho_0 = (6.21)(0.044) = 0.273 \text{ gm/cc}$$

and at 180°C and 100 atm,

$$\rho = (6.21)(0.098) = 0.611 \text{ gm/cc.}$$

For comparison, the value of ρ_0 reported in the International Critical Tables is 0.275 gm/cc.

According to the authors, for most of the substances investigated, deviations from equation (26) and Table 2 were less than 5 percent.

b. Modification of Cawson and Watson

Cawson and Watson (Ref. 21) noted that the values of (ρ_1/ω_1) and $(v_1\omega_1)$ are substantially independent of isomerization. Also, that $v_1\omega_1$ for a number of homologous series could be expressed by the general relation:

$$\rho_1/\omega_1 = a + 2.44\, n_0 + m \log n_a \qquad (27)$$

where

a and m = constants characteristic of the series.
n_c = number of carbon atoms

Thus,

for paraffins	a = 1.88,	m = 0
for mono-olefins	a = 1.1,	m = 0
for monocyclic aromatics	a = -3.0,	m = 0
and for alcohols	a = 2.89,	m = -1.23.

The above equation, with the help of the generalised relationships for estimation of critical temperature, permits the prediction of liquid densities at all conditions without direct experimental density data.

e. Method of Hanson

The relations developed by Watson are based on the principle of corresponding states which is only approximately true. For greater accuracy, Hanson (Ref. 22) introduced certain refinements and grouped the compounds in five groups on the basis of their reduced volumes at T_r of 0.9. He then obtained generalised relations for reduced volumes as a function of reduced temperature for each of these as shown in Table 3. A graphical representation is also possible (Ref. 22). Hanson obtained added confirmation for his method of grouping a homologous series by calculating reduced vapor pressures of liquids as a function of reduced temperatures.

The orthobaric densities (density of a liquid in equilibrium with its saturated vapor) can be calculated at any temperature from T_r = 0.50 to T_r = 0.9 using the relations:

$$\rho = (V_{r1}/V_r)\,\rho_1 \qquad (28)$$

where

V_r = reduced volume at T_r.
V_{r1} = reduced volume at T_{r1}.
ρ = density at T_r, gm/cc
ρ_1 = density at T_{r1}, gm/cc.

The only data required for the use of this relation are the critical temperature and the liquid density at any temperature above T_r = 0.5. In case the critical temperature is not known, it can be calculated by one of several generalised methods (Ref. 10, p. 70).

Table 3. V_r as a Function of T_r for Five Groups of Compounds

T_r	Reduced Volume, V_r				
	I	II	III	IV	V
1.00	1.000	1.000	1.000	1.000	1.000
.97	0.618	0.608	—	0.592	0.587
.95	.572	.561	(0.552)	.546	.536
.90	.505	.494	.484	.478	.467
.85	.465	.455	.444	.440	.425
.80	.436	.426	.415	.413	.395
.75	.413	.403	.393	.391	.372
.70	.395	.384	.375	.376	.355
.60	.365	.355	.347	.356	.324
.50	(.340)	(.330)	.324	.337	.302

Group I. Aliphatic halides, aliphatic mercaptans, mononuclear aromatic hydrocarbons and halides, cycloparaffin hydrocarbons, nitrogen heterocyclics.

Group II. Amines (c_4 and higher), aliphatic ethers (c_4 and higher), esters of monocarboxylic acids, and phenols.

Group III. Aliphatic sulfides (c_4 and higher), fatty acids (c_4 and higher) and ketones.

Group IV. Alcohols (c_2 and higher).

Group V. Nitrites.

It is to be noted that paraffin hydrocarbons could not be included in any of the above groupings and hence their densities should be estimated by the method of Watson indicated previously.

The average deviation for 28 compounds tested at $T_r = 0.50$ was 0.006 units in V_r which corresponds to an error of about one percent in density.

As an example of this method, the calculation of the orthobaric density of n-butyl alcohol at 200°C is shown.

Data: Liquid density at 20°C = 0.810 gm/cc
Critical temperature, T_r = 287°C = 560°K

Calculations:

At 20°C, $T_r = \frac{20 + 273}{560} = 0.523$; $V_r = 0.341$ (Table 3, Group IV)

At 200°C, $T_r = \frac{200 + 273}{560} = 0.845$; $V_r = 0.437$

At 200°C, $\rho = \frac{0.341}{0.437}(0.810) = 0.631$ gm/cc.

2. Estimation of Temperature Effect on Liquid Densities

The density of a liquid at a series of temperatures is frequently desired when the value at only one or two temperatures is known. The following method has been found for extrapolating and/or interpolating the data (Ref. 17, p. 268).

The law of Cailletet and Mathias, usually known as the law of rectilinear diameters, states that the mean density of any substance in the state of liquid and saturated vapor at the same temperature (from low temperatures up to the critical point) is a linear function of the temperature. This may be expressed mathematically as

$$d_v + d_l = a + bt \qquad (29)$$

where

d_l = the density of the liquid in g/cc at a temperature of t °C
d_v = the density of the vapor in the same units and at the same temperature
a and b = constants.

To obtain the values of a and b it is necessary to know accurately the liquid densities of a substance at only two temperatures. Suitable temperatures for these determinations are 20° and 25°C. In ordinary work, densities above 30°C are not as accurate as those between 20° and 30°C. Except in cases where special equipment is used, the densities obtained at the lower temperatures would probably give better values for calculating the parameters. The values of a and b are easily obtained by first calculating the vapor density and then substituting this value along with the value for liquid density in equation (29). When the values of a and b are known, the density at any temperature up to the critical point may be calculated.

As stated above, it is necessary to estimate the vapor density before the liquid density can be calculated. Because the vapor deviates from an ideal gas the equation of state for an ideal gas cannot be used for the calculation of its density much above atmospheric pressure without introducing large errors. Dreisbach (Ref. 17, p. 70) has overcome this limitation by making use of the relation

$$\log d_v = A - B/(t + 230). \qquad (30)$$

According to this equation a plot of the vapor density versus the reciprocal of ($t^{\circ}C + 230$) gives a straight line. The equation has the same form as the Antoine equation (4) for vapor pressure (Ref. 13). Since the equation is based on experimental data it eliminates the errors due to the deviation from the gas law. This relation shows excellent agreement with experimental data up to about 4 atmospheres. Above this pressure and up to about 10 atmospheres there is decreasing agreement, although even near 10 atmospheres the agreement may often be very good.

When d_v's at higher temperatures corresponding to pressures greater than 4 atmospheres are desired, the values of A and B are obtained by a different method. The method given by Dreisbach (Ref. 17, p. 70) may best be described by considering a specific problem using the tables prepared by Dreisbach in this reference.

Consider the calculation of the values of A and B for isopropylbenzene which has a boiling point of 152.393°C at 760 mm pressure.

1. From the structural formula the compound is classified as a benzene derivative with a saturated side chain (Ref. 17, p. 70).

2. $$A = \log M - E \qquad (31)$$

   where M is the molecular weight and E is a quantity which is a function of temperature and the structure of the compound.

3. From the appropriate table and for the given boiling point temperature, the value of E is obtained.

   For isopropyl benzene the value of E at 152.393°C is 0.43835 (Ref. 17, p. 70). The molecular weight is 120.19. Therefore, A = log 120.19 - 0.43835 = 1.64151.

   The value of B is obtained from the same table, for the same temperature as A. This is found to be equal to 1562.7.

   The values of A and B are then substituted in equation (30) and the equation is used to calculate the density of the saturated vapor at any temperature t.

3. Calculation of the Thermal Coefficient of Expansion of a Liquid

The coefficient of volume expansion, α, of a liquid is the ratio of the change in volume per degree to the volume at 0°C (or at some other specified temperature).

$$\alpha = (1/V_0)(\partial V/\partial t)_p \qquad (32)$$

The coefficient varies with temperature. For liquids far removed from their critical temperature the specific volume is little affected by pressure and the pressure need not be taken into account in the calculation of the coefficient of expansion.

For finite temperature changes, equation (32) may be written

$$e_{av} = (1/V_0)(V_2 - V_1)/(t_2 - t_1) \qquad (33)$$

where e_{av} is the average value of the coefficient over the temperature range t_1 to t_2 and V_2, V_1 and V_0 refer to the specific volume of the liquid at temperatures t_2, t_1, and t_0, the latter being the temperature of the reference state.

Maxwell (Ref. 11, p. 140) shows a chart based on the characterization factor previously described which permits the empirical determination of an expansion factor for hydrocarbons. In many cases this is also applicable to organic compounds. The accuracy obtainable is unknown but the error in the expansion factor is certainly not more than 10 percent for any normal extrapolation, i.e., for reasonable temperature ranges.

4. Summary and Recommended Methods

The method of Hansen is recommended as being the most accurate and the most generally applicable for the calculation of liquid densities. When sufficient experimental data are available, the method of Dreisbach is preferable for predicting the variation of liquid density with temperature. Otherwise, the characterization factor technique provides the only semi-empirical method which can be applied through the use of the coefficient of expansion definition.

Specific Heat of Liquids

While considerable progress has been made in the theory and calculation of heat capacities of the solid and vapor states little has been accomplished for the liquid state. The methods for estimating specific heats of liquids are based, therefore, on correlations of experimental data and are empirical in nature. The following general rules (Ref. 23) serve as a guide in the estimation of specific heats of liquids.

1. Pure Liquids

a. The specific heat, c_{p-l}, of a liquid is usually greater than that of the solid, c_{p-s}, but less than that of the vapor c_{p-v}; and the values of c_{p-l} and c_{p-v} run parallel. This generalization applies principally to organic compounds.

b. The specific heat of a liquid increases with rise of tempera-

ture (except mercury and some alkali metals). The relation is, approximately, a linear one.

c. The differences between the molal heat capacities (Mc_p) of successive members of certain homologous series of organic compounds are nearly constant and approximately equal to 8.0, except for the alcohols which are higher.

d. The product (specific heat x density) at the same reduced temperature of $T/T_c = 0.6$, is constant so that equal volumes of organic liquids at this reduced temperature have the same heat capacity.

e. Isomeric liquid organic compounds of similar chemical constitution have approximately the same molal heat capacity (Mc_p).

f. As a general rule, an unsaturated compound has a lower specific heat than a saturated substance which differs from it by H_2 but the effect depends on constitution.

g. A number of liquid elements and compounds containing up to five atoms in the molecule have molal heat capacities which are approximately additively composed of atomic heats of about 6 gram-calories, agreeing with Dulong and Petit's law and Joule's law for solids. Kopp's law gives values which are usually too high.

2. Liquid Mixtures

The accuracy with which the heat capacity of liquid mixtures can be calculated by the mixing rule on the basis of weight fraction of components depends on whether heat is evolved or absorbed on mixing of the components. This depends on the molecular structure and the kinds of atoms in the molecule. For example, molecules containing atoms of oxygen, nitrogen and fluorine along with hydrogen are strongly associated whereas hydrocarbon molecules are not. The specific heats of liquid mixtures of the latter can be calculated by the mixing rule with fair accuracy but the specific heats of aqueous solutions can not.

3. Empirical Equations

a. Eckart's Equation

Eckart (Ref. 24) has examined a mass of specific heat data from the literature. He found that the liquid specific heat at 60°F can be represented by the equation

$$c_{p-60^\circ F} = 0.7125 - 0.3105\ G \qquad (4)$$

where

c_p = specific heat, Btu/lb
G = specific gravity at 60°F.

According to Eckart, 91 percent of the data fell within 5 percent of this relationship.

b. Forsch and Whitman's Equation

Forsch and Whitman (Ref. 25) determined the specific heats of 15 petroleum oils over temperature intervals varying from 50° to 430°F. The results were in general agreement with Eckart's equation but could be better correlated by the equation

$$c_p = \frac{(t + 670)(2.10 - 0 \text{ at } 60^\circ F)}{2030} \qquad (36)$$

where t is in °F.

This equation was found to fit the data with an average deviation of 2.3 percent at 240°F and represents petroleum oils whose specific gravity at 60°F varies from 0.75 to 1.00. This equation relates specifically to petroleum oils from the Mid-continent field (characterization factor, 11.8).

c. Fallon and Watson's Equation

Fallon and Watson (Ref. 26) have derived the following equation for the liquid specific heats of hydrocarbons and petroleum fractions at temperatures between 0°F and reduced temperatures $(T/T_c) = 0.85$:

$$c_p = 0.355 + 0.128 \times 10^{-2} (\text{API gravity}) + \left[0.503 + 0.117 \times 10^{-2} (\text{API gravity})\right] \cdot \left[0.05\,C + 0.41\right]\left[10^{-3}\right](t) \qquad (36)$$

where

t = °F

C = characterization factor, see equation (2), page 6

$$= \frac{\sqrt[3]{T_B}}{G}$$

d. Chow and Bright's Method

In a recent paper by Chow and Bright (Ref. 27) an empirical correlation is presented for predicting the heat capacity of organic liquids from their structural parachor and molar refraction. The parachor, P, is defined as

$$P = M\sigma^{1/4}/(\rho_l - \rho_v) \qquad (37)$$

Molar refraction, R, is calculated from the Lorentz-Lorenz equation

$$R = (M/\rho_l)(n^2 - 1)/(n^2 + 2) \qquad (38)$$

where

M = molecular weight
ρ_l = density of the saturated liquid
ρ_v = density of the saturated vapor
n = refractive index of the liquid
σ = surface tension.

According to the authors, the liquid specific heat, c_p, is related to the parachor and molar refraction as shown by the equation

$$c_p = (P + B)/AR \qquad (39)$$

where A and B are constants characteristic of a given homologous series of compounds.

While both the parachor and molar refraction are virtually independent of temperature, heat capacities are not, so that the equation holds only for a given temperature which the authors chose as 20°C.

In the calculation of the heat capacity of a given organic compound at 20°C by equation (39), the appropriate values of the constants A and B are selected from Table 4 and the parachor and molar refraction are calculated by means of equations (37) and (38). If data necessary for the application of these equations are not available, the parachor and molar refraction may be calculated from the atomic and structural values given in Table 5.

Table 4. Values of A and B at 20°C

Class	A	B
Paraffinic hydrocarbons	18.5	24
Acids	19.5	- 5.8
Alcohols	15.9	- 5.8
Esters	20.25	- 5.8
Ketones	15.8	-18
Nitriles	16.5	-20
Amines	17.8	45
Monochlorides	17.5	-37
Dichlorides	26	-21
Trichlorides	20	-89

Table 4, continued

Class	A	B
Chloroacetates	18	-58
Dichloroacetates	20.6	-76
Trichloroacetates	22.6	-94
Lucalcohols	21.5	76
Aromatic hydrocarbons	17.3	-49
Benzoates	15.75	-97
Phenyl ethers	16.75	-41
p-Cresyl ethers	14.6	-88

Table 5. Atomic and Structural Values of Parachors and Molar Refractions

	Parachor	Refraction Sodium D Line
C	9.2	2.418
H	15.4(1)	1.100
$-CH_2-$	40.0	4.618
O (hydroxyl)	20	1.525
O (ether)	20	1.643
O (carbonyl)	20(2)	2.211(2)
F	25.5	— (4)
Cl	55	5.967
Br	69	8.865
I	90	13.90
N (primary amine)	17.5	2.322
N (secondary amine)	17.5	2.502

Table 5, continued

	Parachor	Refraction Sodium D Line
N (tertiary amine)	17.5	2.840
N (nitrile)	55.5(3)	5.516(3)
S	50	—(4)
P	40.5	—(4)
3 - membered ring	12.5	0
4 - membered ring	6	0
5 - membered ring	3	0
6 - membered ring	0.8	0
7 - membered ring	-4.0	0
Double bond	19.0	1.733
Semipolar double bond	0	1.733
Triple bond	38	2.398
Singlet linkage	-9.5	

(1) For hydrogen on carbon. Hydrogen on bromine has a parachor of 16.4; on chlorine 12.8; on oxygen and on nitrogen 12.5.
(2) Includes allowance for double bond.
(3) Includes allowance for triple bond.
(4) Value depends on type of compound.

Parachor strain constants

(R = hydrocarbon radical, X = negative group)

Constant

3 carbonyl in ring

0 RCH_2X; R·CHO; R·CO·R; RCH_2R; RNH_2; No·R; NOOR; R_2SeO

-3 $RCHX_2$; RCOOH; R·CO·OR; R·CO Cl; R_2CHX; R_2CH·R; $RCONH_2$; RO·CO·OR; RO·CO·Cl; R·SO·OR; RO·SO·OR; R_2NH; NO Cl; NO_2R; NO_2CR; H_2O, asides; R SeOOH

Table 5, continued

Constant	
-6	$R \cdot CX_3$; R_3CX; $Cl \cdot CO \cdot Cl$; $R \cdot SO_2 \cdot Cl$; R_3CR; $R \cdot SO_2 \cdot R$; $RO \cdot SO_2 \cdot R$; $RO \cdot SO_2 \cdot OR$; R_2N; NCl_3; NO_2Cl; PX_3; R_3P; $PO(OR)_3$; BX_3; AsX_3; SbX_3
-9	CX_4; R_4C; SCl_4; SO_2Cl_2; $NOCl_3$; $POCl_3$; SiX_4; SnX_4
-12	$SOCl_4$; NCl; PC_3; $SbCl_5$
-15	SCl_6

Sample Calculation:

The method is illustrated by the calculation of the specific heat of diphenylamine, $C_6H_5NHC_6H_5$.

From Table 5

12 Carbon atoms	(12)(9.2) = 110.4	(12)(2.148) = 29.016	
10 Hydrogen (to carbon)	(10)(15.4) = 154.0	(10)(1.100) = 11.000	
1 Hydrogen (to nitrogen)	12.5	1.100	
1 Nitrogen (secondary amine)	17.5	2.502	
2 6-membered ring	(2)(0.8) = 1.6	0	
Strain constant (R_2NH)	- 3	—	
	P = 293.00	B = 43.618	

From Table 4

$$A = 17.8; \quad B = 45$$

Equation (39)

$$C = (293 + 45)/(17.8 \times 43.618) = 0.435$$

The nearest experimental data are reported to be 0.437 at 54°C.

Accuracy:

A comparison of calculated values with experimental for a great variety of liquids shows that the mean deviation of the calculated values is about 2 percent with the maximum not exceeding 5 percent.

The correlation gives no information on the temperature coefficient of specific heat.

4. Summary and Recommended Methods

The method of Chen and Wright provides the most generally applicable and accurate method for the prediction of specific heats of liquids. The Forsch and Whitman, and Fallon and Watson methods are applicable to hydrocarbons and petroleum fractions, as specifically mentioned, while the Eckart method presumably can be applied to any liquid, including mixtures.

Viscosity of Liquids

Any fluid in motion which has its flow constrained in any fashion is subject to shear stresses. The resistance of the fluid to shear is commonly termed viscosity. Viscosity is actually a measure of the force required to cause the slippage of one layer of molecules past an adjacent layer. The measurement of the viscosity of a liquid is difficult to perform accurately because of its dependence on temperature. Pressure has a minor effect. In some cases, viscosity is dependent also upon the rate of shear. Viscosity values can sometimes be correlated by considering the molecular weight and molecular structure.

Experimentally determined values for the viscosity of a large number of common compounds are available in the usual standard reference texts of Perry (Ref. 1), Landolt-Bornstein (Ref. 2), Lange (Ref. 3), International Critical Tables (Ref. 4), and the Handbook of Chemistry and Physics (Ref. 5). Where no information whatsoever is available, or for extending information where only one or a few experimental data points are available, the following estimation techniques are recommended.

1. Method of Hougen and Watson

The method of Hougen and Watson (Ref. 10, pp. 869-74) is based on the theorem of corresponding states and the prediction depends upon a generalized graphical relationship between reduced viscosity and reduced temperature and pressure. A consideration of all available data on the variation of viscosity with temperature and pressure in both the liquid and gaseous states led to the construction of the generalized chart.

If no direct viscosity measurements are available, an approximation to the entire viscosity curve for the fluid may be estimated from

$$\mu_c = 61.6 \sqrt{MT_c}/(V_c)^{2/3} \qquad (40)$$

where

μ_c = critical viscosity, micropoises
M = molecular weight

T_c = critical temperature, °K
V_c = critical volume, cc/gm.mole.

Once a value for μ_c is known, the generalised correlation curves can be entered for known values of reduced temperature T_r and reduced pressure P_r and a value for the reduced viscosity μ_r may be obtained. The viscosity at the known values of T_r and P_r is then,

$$\mu = \mu_r \mu_c \qquad (41)$$

When one experimental point is known the generalised correlation can be used to obtain μ_c so that the former approximation is not necessary.

When a number of experimental points are available, this method, or the plotting of the experimental points as the logμ vs. the log T as recommended by the ASTM can be used for interpolation or extrapolation.

2. Estimation of Viscosities of Liquid Mixtures

a. ASTM Method

The ASTM procedure proposes that, for blends of two liquid petroleum fractions, the standard ASTM viscosity graphical representation be used but with substitution of a composition scale for the temperature scale. Specifically, 0°F should represent 100 percent of the light component and 100°F should represent 100 percent of the heavy component. This is limited in the number of cases to which it applies.

The viscosity of petroleum fractions over a temperature range may be estimated accurately and quickly if the viscosity at two temperatures or the viscosity at one temperature and the characterisation factor are known. These data are plotted on ASTM viscosity-temperature plotting paper (Charts D341-43) and a straight line drawn between the two points and extrapolated to higher and lower temperatures. In the case that only one value of the viscosity is known, a straight line is drawn through the point and parallel with the viscosity-temperature curve of a hydrocarbon liquid of approximately the same characterisation factor (see discussion of characterisation factor on page 6). Examples of the ASTM charts are shown by Maxwell (Ref. 11, pp. 155-77).

b. Mole Fraction Method

The second method is a rather obvious and simple technique of using the mole fraction average of the viscosities of the pure components to represent the viscosity of the mixture. This may be used for rough approximations in cases where the components making up the mixture are similar and have approximately the same viscosity.

c. Method of Hougen and Watson

Unfortunately, neither of the above two methods is satisfactory for systems such as, for example, the methyl alcohol-water system which, according to the meager data available, has a viscosity composition curve which goes through a maximum. We are forced to agree with Hougen and Watson (Ref. 10, pp. 869-74) who state, "No entirely satisfactory method is available for estimating the viscosities of mixtures." However, they present the following method which, although not completely tested, shows more promise than either of the other two methods.

This method is similar to that described above for single liquids. Uyehara and Watson (Ref. 10, pp. 869-74) recommend that the reduced values of pressure, temperature, and viscosity for mixtures be based on the pseudocritical properties. The pseudocritical temperature, pressure, and viscosity are taken as equal to the molal average of the true critical properties of the components of the mixture. Thus, for a binary mixture

$$\mu'_c = N_1 \mu_{c1} + N_2 \mu_{c2} \qquad (42)$$

where

μ'_c = pseudocritical viscosity of mixture, micropoises
N_1 = mole fraction of component 1
μ_{c1} = critical viscosity of component 1, micropoises
N_2 = mole fraction of component 2
μ_{c2} = critical viscosity of component 2, micropoises

Values calculated by this method show fair agreement with data on the viscosities of gaseous mixtures. This method is believed to be simpler than others involving use of the viscosities of the pure components at the conditions of the mixture. Little is known concerning the accuracy of this method with liquid mixtures.

d. Arrhenius Method

This method (Ref. 28) can be represented by the following equation for a binary mixture:

$$\log \nu = N_1 \log \nu_1 + N_2 \log \nu_2 \qquad (43)$$

where

ν = kinematic viscosity of mixture
N_1 = mole fraction of component 1
ν_1 = kinematic viscosity of component 1
N_2 = mole fraction of component 2
ν_2 = kinematic viscosity of component 2.

This equation is derived thermodynamically on the assumption that every molecule of the various components of a mixture has an equal chance to contribute activated molecules. A similar equation has been used for years in the petroleum industry but the mole fraction is replaced by

weight or volume fractions. Such a replacement would be valid only as long as the components do not differ widely in molecular size.

e. Effect of Molecular Weight

When a liquid of high molecular weight is in solution with a liquid of low molecular weight, a different situation arises. The thermodynamics of this case can be treated on the assumption that the large molecule consists of several smaller segments which act independently of each other and are able to occupy all available sites in the solution with the same freedom as the molecules of the solvent.

Powell and Eyring propose using an effective mole fraction, N_2^e, for the segmental large molecule instead of the actual mole fraction, N_2. The N_2^e is defined by

$$N_2^e = n_2^e/(n_1 + n_2) \tag{44}$$

$$n_2^e = n_2\left[1 + (Q-1)\phi\right] \tag{45}$$

where

N_2^e = effective mole fraction for the large-molecular weight molecule or liquid
n_1 = number of molecules of low-molecular-weight liquid
n_2^e = effective number of molecules of large-molecular-weight molecule
Q = effective number of segments per molecule
ϕ = volume fraction of the low-molecular-weight liquid.

Using the effective mole fractions in equations (44) and (45), better agreement is obtained in many cases between observed and calculated viscosities of mixtures. Calculated results using four different mixtures deviated on the average by 21 percent from the experimental.

f. Effect of Structure

In mixtures of highly cyclic (very rigid) compounds with those in long chains (very flexible), the latter act as if they were present in a higher concentration than represented by the mole fraction. This is why the more paraffinic oils always dominate the viscosity of the blend.

It seems that the method of equation (43) is readily applicable to mixtures of compounds having similar molecular weights. Equation (42) has limited use because of the difficulty in calculating the effective mole fraction.

g. Characterization Factor

Determination of the viscosity-temperature relationship is also possible through the use of the characterization factor, defined on page 6. Watson and Nelson (Ref. 6 and 7) and Hougen and Watson (Ref. 10, pp. 869-74)

give empirical charts which relate the viscosity at 100°C and 210°F. with the characterization factor and some other property such as boiling point or molecular weight. Extrapolation can be made by means of the ASTM charts previously mentioned. Maxwell (Ref. 11, pp. 155-77) also shows much of this same type of information.

3. Summary and Recommended Methods

The method of Hougen and Watson is considered to be the best available for predicting viscosities of pure substances or of simple mixtures when little or no experimental data are available. For mixtures of two petroleum fractions for each of which a significant amount of information is available, the ASTM method is readily applicable. Also, in some cases the characterization factor technique provides a convenient tool for hydrocarbon mixtures, petroleum fractions and, in a limited way, to some types of pure organic compounds.

Thermal Conductivity of Liquids

There is a scarcity of experimental thermal conductivity data of liquids in the literature. Only several hundred experimental values are reported. Many difficulties are encountered in obtaining accurate experimental data. The chief cause of inaccuracy is the presence of convection effects which tend to increase measured values of thermal conductivity. It is quite probably that many of the experimental values deviate from the true values by as much as 10 percent. A recent compilation of experimental values by Sakiadis and Coates (Ref. 29) is available.

Since experimental data are not available for many of the newer chemicals, the values must be estimated by empirical and theoretical means. Some of the less important methods found which have little utility or accuracy are those of Denbigh (Ref. 30), Smith (Ref. 31) and Riedel (Ref. 32). The best methods so far available are discussed in the following.

1. Palmer Method for Organic Liquids

The equation derived by Palmer (Ref. 33), for a temperature of 30°C (86°F), is as follows:

$$k = 0.0947 \left[(\rho\, c_p)/(\lambda/T) \right] \sqrt[3]{\rho/M} \qquad (46)$$

where

k = thermal conductivity, cal/sec-cm^2(°C/cm)(at 30°C)
ρ = density, gm/cc
c_p = specific heat, gm-cal/gm-°C
M = molecular weight
λ/T = ratio of latent heat divided by boiling point at 1 atm, cal/gm-mole-°K

To convert the above k to Btu/hr-ft^2($^\circ$F/ft), multiply by 242.

For 48 liquids this equation checks the experimental values with an average deviation of ± 8.8 percent. The liquids tested include water and alcohols (associated liquids), ether, some chlorinated hydrocarbons, and hydrocarbons. This equation appears promising and has been checked extensively using available data.

A sample calculation is shown for cyclohexane liquid:

ρ = 0.771 gms/cc
λ/T = 20.0
c_p = 0.465, gm-cal/gm-$^\circ$C
M = 84.16 (molecular weight)

$$k = (0.0947 \times 0.771 \times 0.465/20)\sqrt[3]{0.771/84.16}$$

$$= 3.56 \times 10^{-4} \text{ cal/sec-cm}^2(^\circ\text{C/cm})$$

$$= 0.0860 \text{ Btu/hr-ft}^2(^\circ\text{F/ft})$$

2. Cragoe Method for Hydrocarbons

Cragoe (Ref. 34) investigated the thermal conductivity of petroleum oils. He correlated the data of seven different observers, using 18 different oils, and obtained the equation

$$k = (0.0678/Q)\left[1 - 0.0003(t - 32)\right] \qquad (47)$$

where

k = thermal conductivity, Btu/hr-ft^2($^\circ$F/ft)
Q = specific gravity, 60°/60°F
t = temperature, $^\circ$F

This equation correlated the experimental data with an average deviation of ± 7 percent and a maximum of ±27 percent at 1 atmosphere pressure. The data covered the range from 32° to 400°F and 0.78 to 0.95 specific gravity. For hydrocarbon liquids this equation is recommended.

3. Temperature Effect on Organic Liquids

The thermal conductivity of most liquids generally varies in a linear manner with temperature as follows (Ref. 29).

$$k = a\left[1 + b(t - 32)\right] \qquad (48)$$

where

k = thermal conductivity
a = constant
b = constant
t = temperature, $^\circ$F.

There is no way to predict the temperature coefficient b and constant a. A method which sometimes can be used is to use the value of b obtained from similar compounds or compounds in a homologous series and determine a from a prediction or one experimental point.

4. Summary and Recommended Methods

As stated, the Palmer method is recommended for organic liquids while the Cragoe method is specifically applicable to petroleum oils. The change in the thermal conductivity with temperature can usually be expressed by equation (48).

SECTION II

GENERAL EFFECTS OF FLUID PROPERTIES ON OPERATION OF AIRCRAFT COOLING SYSTEMS AND PERSONNEL

In the design and operation of aircraft cooling or heat transfer systems for auxiliary equipment the physical properties of the heat transfer fluids utilized will have large effects. It is, of course, desirable to use, in any such application, the most efficient fluid, consistent with the requirements for personnel safety, reliability, and dependability, convenience of use, and others. Therefore, in the evaluation of the desirability of any particular fluid, knowledge of its properties is important, not only to help evaluate the cooling system's penalty on aircraft performance, but also to help evaluate the fringe effects of personnel safety, etc., mentioned above, which may become overriding in the final selection of the best fluid.

It is the purpose of this section of the report to present a discussion of each of the important physical, chemical, and physiological properties associated with heat transfer fluids, in a general way.

Vapor Pressure and Boiling Point

The vapor pressure has been previously described as the quantitative statement of the escape tendency of the molecules in a liquid expressed in terms of pressure, while the boiling point is the temperature at which this escape tendency becomes sufficient to overcome the ambient pressure. The normal boiling point, i.e., the boiling point at standard ground-level pressure, is important in this application only in the fact that it defines the temperature at which the vapor pressure is one atmosphere.

A consideration of the formation of vapor in this type of system is important for four reasons. First, the formation of vapor at the heat transfer surfaces (when forced convection heat transfer is being used) will have a deleterious effect upon the heat transfer coefficient. Second, the formation of vapor in the circulating pumps might cause vapor lock and consequent loss of circulation. Third, the escape of vapor formed would cause depletion of the heat transfer fluid with subsequent failure of the system. Fourth, the escape of the vapor, in the case of a toxic or inflammable substance, would expose the air and ground crews of the aircraft to a safety hazard.

For all fluids, with but few exceptions, a pressurized system is necessary to counteract at least one of the above possible difficulties, particularly for aircraft operation at high altitudes. All these considerations lead one to conclude that an ideal liquid is one with a low vapor pressure. This would mean that the system could be operated safely and efficiently at a low pressure. Low pressure means (1) less metal or plastic weight, cost, and volume required in the containing system, (2) less danger of vapor binding at heat transfer surfaces or in pumps, and (3) less danger of fluid or vapor escape through leakage at flanges, connections, joints, etc.

Flash Point, Fire Point, and Combustibility

Obviously, for safety reasons, a non-combustible, heat transfer fluid is most desirable for the present purpose. Lacking this, a liquid having high flash and fire points is next in order of desirability. The higher the flash and fire points, the less danger and the fewer precautions that need to be taken in handling the material. Also, higher flash and fire points mean less need for safety features designed in the aircraft and ground handling equipment to combat fires caused by accidental leakage of vapor or spillage of fluid.

Freezing Point and Pour Point

In the present application, low freezing and pour points are extremely desirable. Fluids having freezing or pour points above -65°F will be undesirable because of the need for providing auxiliary heating units for maintaining the liquid in a fluid condition in all parts of the system and/or providing extremely overdesigned pumps and prime movers in terms of normal operating conditions to force the fluid through the system. Higher pressures in parts of the system with higher strength requirements in the containing system would also be a result. The increase in cost, weight, and complexity of the aircraft, which would result, is apparent.

Density

On the basis of all criteria which can be established, a high fluid density is desirable in the present application. First, and probably foremost, a high fluid density, all other properties being equal, means a smaller system since the volume flow rate would be reduced.

Other considerations lead one to conclude also that high density means higher heat transfer coefficients and more heat transferred in forced convection per unit of power expended in pumping the fluid. The size of the heat exchangers themselves will not change noticeably, particularly if air is used as the ultimate coolant, since it would have a controlling effect upon the overall heat transfer coefficient. Consequently, the major saving which can be accomplished with a high-density heat transfer fluid will be in pumping power and in the size of the fluid lines. The density range of fluids known and available for this type of use is small, being only about 0.7 to 1.4 gms/cc. This maximum factor of 2 would have some effect upon the pumping power requirements but the saving in available horsepower and cost which could be achieved is probably not significant.

Specific Heat

The specific heat of a heat transfer fluid can affect the design and operation of a cooling system in two ways. First, a higher heat transfer coefficient can be obtained in practice with a fluid having a higher specific heat, all other things being equal. Second, the heat storage capacity of a

fluid is higher if it has a higher specific heat. This latter effect would result in (1) a lower temperature increase in absorbing the same amount of heat (and a larger temperature difference and heat transfer rate or a lower hot-side temperature) with the same amount of fluid circulating in the system or (2) a lower requirement on the fluid circulation rate if the hot-side temperature and heat load were to be maintained.

The effect of high specific heat on the cost, weight, volume, and power requirement of the cooling system is one of decreasing all of these items. Therefore, it is likely to be the most important property affecting the system's penalty on the aircraft.

Viscosity

The viscosity of the heat transfer fluid has a substantial effect upon the heat transfer coefficient and upon the frictional pressure drop through the system. In both cases a low value for the viscosity is desirable. As discussed previously, a higher heat transfer coefficient for the fluid side may have relatively little effect upon the size of the heat exchanger because of the probable controlling effect of the ultimate fluid. However, the decrease in the pumping power requirement with low viscosity can be highly significant, in this case, because of the large range of viscosities of fluids available and considered for this application. Effects of lower pumping power requirements on the aircraft are obvious.

Another important consideration is that of the increase in viscosity of a fluid at the extremely low temperatures at which it is necessary to guarantee performance of the system. An increase in viscosity between 100° and -50°F by a factor of 100 to 1000 is not unusual. A system temperature of -50°F at start-up is not unusual in some regions. Consequently, a fluid which has a relatively minor viscosity increase in this temperature range, perhaps by a factor of 10 to 50, must be chosen. Otherwise, the pumps and prime movers for this system must be tremendously overdesigned for their normal operating temperature or else the complexity of an auxiliary heating system for the fluid must be permitted. In most cases, neither of these latter solutions can be tolerated.

Thermal Conductivity

Of relatively minor importance in the selection of a heat transfer fluid is its thermal conductivity. Although the heat transfer coefficient for the fluid is, in part, dependent upon its thermal conductivity, in most cases, and particularly with air as the ultimate coolant, this property is of minor importance. However, with another liquid as the ultimate coolant, the thermal conductivity of the transfer fluid may become more important.

High thermal conductivity will tend to reduce heat exchanger size and pressure drop. This may be of significance in short systems of appreciable cooling capacity where the heat exchanger would account for an appreciable portion of the system weight and pumping power. However, thermal conduc-

tivity should have little effect on the penalty or aircraft performance imposed by large centralised systems.

Coefficient of Expansion

Fluids having a small coefficient of expansion are most desirable, particularly for use in large systems containing an appreciable quantity of liquid. The weight of liquid to be contained must be sufficient to fill all transfer lines and heat exchangers under the lowest temperature conditions on the ground. Under operating conditions, the temperature of the fluid may be increased by 200° to 300°F which, if accompanied by a considerable volume change, necessitates the installation of one or several expansion tanks. While larger density at the system operating temperature may reduce the aircraft penalty, as discussed before, a substantial increase of density at minimum starting temperature is only disadvantageous since it increases the weight and total volume of the cooling system.

Dielectric Strength

Dielectric strength of the heat transfer fluid is not important in normal applications except as accidental leakage or spillage causes the fluid to come into contact with electrical or electronic parts. The prevention of this particular possibility, however, seems to be easily solvable by other techniques.

On the other hand, if the technique of cooling electrical and electronic components by submerging them in the cooling medium becomes prevalent, then a high value for the dielectric strength will be necessary. This trend should become more prevalent for individualised systems because of the many advantages that can be realised in respect to heat transfer and equipment size.

Toxicity

The dangers of toxic liquids and vapors to personnel is by definition and probably needs no further discussion here. However, the degree of toxicity is important since many fluids, otherwise desirable, are mildly toxic. The use of any fluid having bad toxicological properties should not be considered.

Stability

The stability of a fluid selected for a use of this type is of prime importance. The gum-forming tendencies of hydrocarbons are well known and can be guarded against by proper design of equipment and by judicious use of additives or anti-oxidents. Other compounds polymerize under certain conditions forming plastic-like materials while still others decompose to form gases and carbonaceous deposits.

Two possible difficulties are immediately apparent when unstable compounds are utilized. First, gums, plastic-like materials, and other deposits can clog lines, jam pumps, or coat heat transfer surfaces. Second, the formation of gases can cause gas binding of pumps and heat transfer surfaces. In addition, extensive decomposition could cause serious depletion of the heat transfer fluid. All of these possible effects are undesirable and any one could lead to failure of the cooling system.

In some cases, the gaseous decomposition products are extremely toxic. The possible effects of this on personnel are immediately apparent.

Corrosiveness

It is important that the corrosive properties of each fluid be known, not only for materials within the system, but also for those outside which might be exposed because of leakage, spillage, etc. If the corrosive properties of a fluid on many materials are well known, it is usually a straightforward process to design properly a system for its use. However, the corrosive properties of many fluids are not well known and the designer thereby has a serious problem.

When properties are known, it becomes a relatively simple problem to determine the effect on weight, cost, and performance of the cooling system which is imposed by the requirement that certain metals or plastics be used with a particular fluid. Again, it is obvious that a non-corrosive fluid for which the designer has wide leeway in his selection of proper materials is the most desirable.

SECTION III

HEAT TRANSFER FLUIDS SUITABLE BELOW 300°F

In this section the fluids are discussed which have been investigated and which can be used for the approximate range from near the freezing point to 300°F. The discussions and comparisons are mainly on a qualitative basis.

The fluids have been classified into seven main groups. The principal basis for classification has been differences in the chemical compositions and not physical properties. The main groups are as follows:

1) Water (reference fluid)
2) Aqueous solutions
3) Hydrocarbons
   a. Fuels
   b. Lubricants and hydraulic fluids
4) Fluoro-and chloro-hydrocarbons
5) Oxygenated hydrocarbons
6) Organic-inorganic compounds
7) Silicones

In each group the most promising fluid was selected and is discussed in detail. The density, specific heat, viscosity, and thermal conductivity were the main properties considered in evaluating the heat transfer properties of the fluid. Other properties such as boiling point, vapor pressure, flash point, and toxicity were used in considering the overall suitability of the fluid for use in aircraft cooling systems.

For the present application of heat transfer fluids, a high density is desirable to obtain small system volumes and low pumping power. A high specific heat is needed for a small circulation rate, small system weight, small pumping power, and a large heat transfer coefficient. A large thermal conductivity gives better heat transfer coefficients. Small values of viscosity are desired for greatest heat transfer coefficients and lowest pumping power.

Boiling point and vapor pressures were not considered in the selections in most cases since it was assumed that the heat transfer system would operate under pressure. Differences in flash and fire points were also not used in the selections as long as these values were high enough for safe operation. Differences in freezing points were not appraised as long as the freezing point was below -50°F except in the case of water which was used as a reference fluid. Fluids which are highly toxic or extremely corrosive were disregarded. Combustibility was not evaluated since the majority of the fluids are combustible to some extent. Only those fluids which are reasonably stable were considered in the selection.

To make a final choice of a fluid all the above physical properties would have to be examined in addition to such physical properties as pour

point, dielectric constant, effect on elastomers, and solubility in water. The chemical effects such as reaction with impurities, water, air, gasoline, and corrosion products should also be considered.

The properties which are tabulated for each fluid were obtained from commercial trade literature, journal references, textbooks, or reference books. Where data did not exist the important physical properties were estimated using the methods of Section I. These properties are boiling point, vapor pressure, flash point, fire point, freezing point, pour point, latent heat, density, specific heat, viscosity, thermal conductivity, combustibility, toxicity, stability, corrosiveness, and effect on elastomers. Where data on these important properties are not given in the tables contained in this report, either the data were not available or they could not be estimated.

Data on the less important properties were not estimated when not available. These are molecular weight, surface tension, refractive index, dielectric constant, color, odor, acidity, solubility, and foaming tendencies.

Data on stability of fluids are very difficult to estimate. The accuracy and uniformity of the data on stability in the tables is not as good as desired. This is due to the inherent difficulties in estimating or determining experimentally the stability of a fluid. In many cases the stability is determined by simply heating the liquid in an open beaker for several hours and then examining the liquid for decomposition. In this test the decomposition gases escape and may hasten the breakdown of the liquid. A fluid which is unstable in open air may be relatively stable in a closed system where little air is present. Hence, it is difficult to translate the results of stability tests in an open system to a closed system or vice versa.

In many cases the stability data were obtained from commercial sources and the experimental methods were not given. Where detailed stability statements are listed, these data were obtained from commercial sources without any experimental verification.

In the property tables presented in this report, a designation of good or excellent for stability means that there is relatively no decomposition over the temperature range indicated. Very unstable fluids were not considered in this study.

The data on toxicity of fluids are very difficult to obtain experimentally and also very difficult to interpret. A substance may be toxic because of several reasons. For example, the material may be toxic when in the air and breathed, or the absorption of the liquid or gas through the skin may cause toxic effects.

It is important to note that the concentration of the substance, the duration of exposure, and the frequency of exposure to the substance are the prime factors in determining if a substance has toxic effects. In most cases, a direct determination of the toxicity of a substance on humans has not been made. Most of the data are obtained by experimentation on animals. Extrapolations are then made as to the effect on humans. At other times, data have been obtained because of accidental exposure of humans to toxic materials.

Good qualitative toxicity data depend on so many variables that it is difficult to make definite statements. In the property tables contained in this report, the designation non-toxic indicates that the liquid can be used as a heat transfer fluid with little danger to humans if the liquids spill or fumes arise.

Data on corrosion are in the same category as data on stability and toxicity. Good experimental data obtained under a variety of conditions are scarce. In many cases the corrosiveness of a liquid is tested by inserting a test metal specimen into a heated beaker of the liquid. The results may be entirely different from the case where the liquid and metal are tested under flow conditions. Also, small amounts of impurities often greatly affect results. In open systems, gaseous decomposition products escape which may cause corrosion in closed systems.

Hence, it can be seen that it is difficult to state quantitatively the corrosiveness of liquids. In the tables contained in this report the statement non-corrosive indicates that the fluid is probably non-corrosive to ordinary metals such as steel and aluminum over the temperature range indicated.

For the seven groups of fluids established, the properties of the most promising fluid in each group are tabulated and discussed in this section. The properties of the other fluids in each group which were studied are given in Appendix I.

Group 1. Water (Reference Fluid)

Water is placed in a separate group by itself because of its physical properties which differ so widely from those of other fluids. Water is not entirely suitable as an aircraft heat transfer fluid because of its high freezing point of 32°F.

Water is a good reference fluid to be used as a basis of judging the suitability of other fluids as heat transfer media. It has many desirable properties such as a very high thermal conductivity of 0.361 Btu/hr-ft²-(°F/ft) at 100°F, a low viscosity of 0.684 centipoises (100°F), a high density of 0.993 gms/cc (100°F), and a very high specific heat of 1.00 Btu/lb-°F (100°F). Its corrosiveness is not significant since many inhibitors are available to reduce its corrosive action on metals.

Figure 1 shows a plot of what is believed to be the most reliable data for thermal conductivity of five different investigators. The data of Timrot appear to be quite inconsistent with those of other investigators. The other properties of water are listed in Table 6.

Water is the superior heat transfer fluid, except for its high freezing point. Additives presently used to lower the freezing point are discussed in this report under the classification of aqueous solutions. Their properties are substantially inferior to those of water since their densities, specific heats and thermal conductivities are lower and their viscosities are greater.

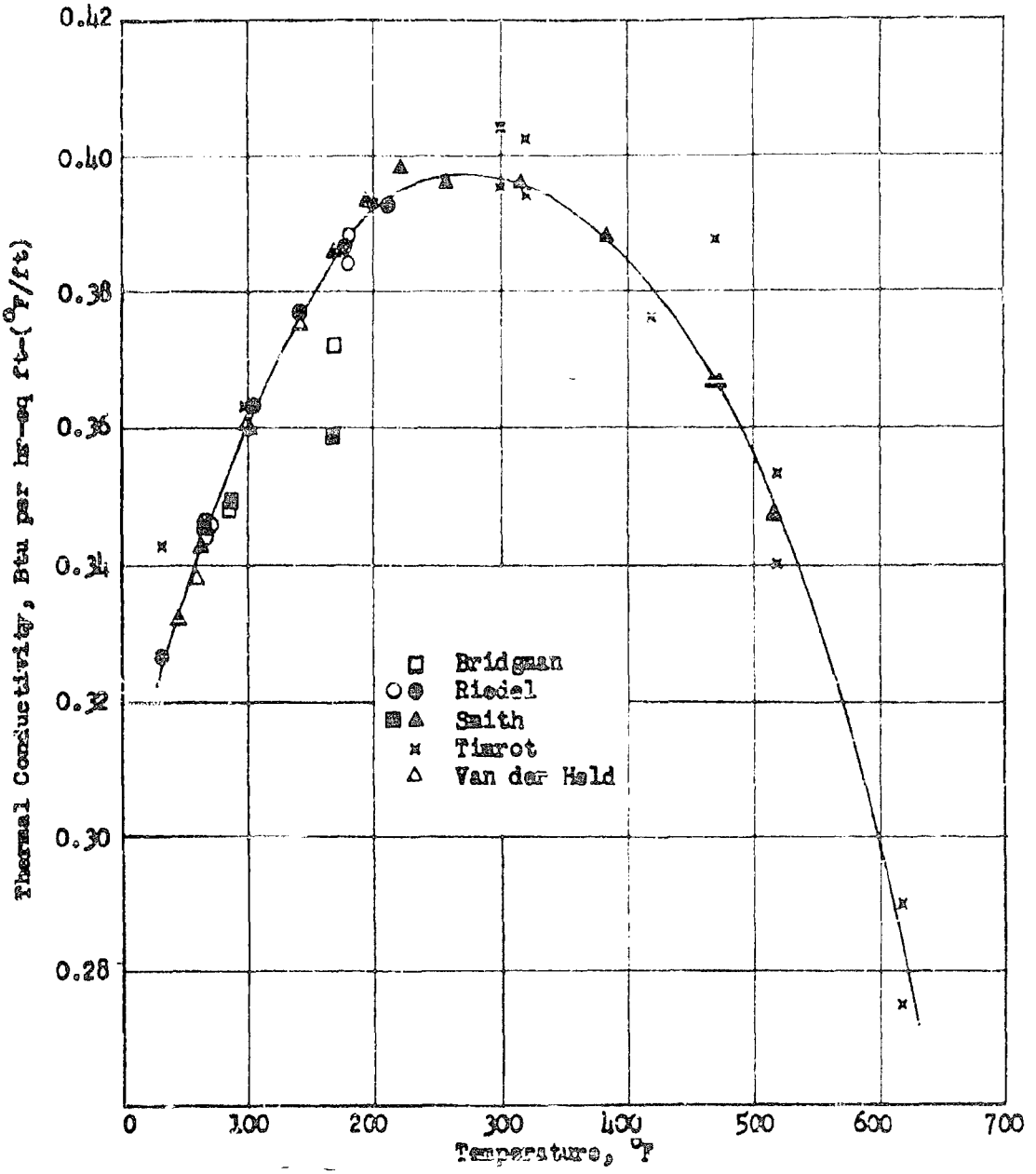


Figure 1. Thermal Conductivity of Water

Table 6. Properties of Water as a Reference Fluid

1. Molecular weight, 18.0

2. Boiling point, 212°F at 760 mm Hg

3. Flash point, none

4. Fire point, none

5. Freezing point, 32°F

6. Pour point, 32°F

Temp. °F	7. Vapor pressure (1)* mm Hg	8. Latent heat (1) Btu/lb	9. Density (1) Gms/cc	10. Specific heat (1) Btu/lb-°F	11. Viscosity (2) Centi-poises	12. Thermal conductivity (3) Btu/hr - ft²(°F/ft)
32					1.792	0.326
50	9.3	1066	0.999	1.00	1.308	0.334
100	49	1037	0.993	1.00	0.684	0.361
150	193	1008	0.980	1.00	0.432	0.379
200	597	978	0.963	1.00	0.305	0.393
250	1542	946	0.942	1.01	0.229	0.397
300	3470	910	0.918	1.03	0.185	0.397

13. Dielectric constant (4), 80 at 1×10^8 cycles/sec, 20°C

14. Combustibility, non-combustible

15. Toxicity, non-toxic

16. Stability, excellent over 600°F

17. Corrosiveness, corrosive to many metals

18. Effect on elastomers, little or no effect

19. Specific references for this fluid:

(1) Keenan, J. H. and Keyes, F. G., Thermodynamic Properties of Steam, John Wiley and Sons, Inc., New York, 1948.

(2) Goldstein, W. H., Heat Transmission, McGraw-Hill Book Co., New York, 1942, p. 407.

*Number in parentheses refers to specific reference for fluid given in item 19 of this table.

(3) Riedel, L., Chem. Ing. Tech., Vol. 23, 1951, pp. 321, 465;
Smith, J. F., Trans. Am. Soc. Mech. Engrs., Vol. 58, 1936, p. 719;
Smith, J. F., Ind. Eng. Chem., Vol. 22, 1930, p. 1246;
Timrot, D. L. and Vargaftik, W. B., J. Tech. Phys. (USSR), Vol. 10, 1940, p. 1063;
Van Der Held, E. F. M. and Van Drunen, F. G., Physica, Vol. 15, 1949, p. 865;
Bridgman, P. W., Am. Acad. Arts and Sci., Vol. 49, 1923, p. 341.
(4) Lange, N. A., Handbook of Chemistry, Handbook Publishers, Inc., Sandusky, Ohio, 1952, p. 1254.

20. Specific comments on physical properties:

a. Very high specific heat.
b. Freezing point very high.
c. Very high thermal conductivity.
d. Values of thermal conductivity obtained by plotting data of five investigators. Data of Timrot at 32°F appear to be erroneously high. Do not extrapolate data in table beyond 300°F since data reach a peak. See Figure 1.
e. Low viscosity.
f. High density.

Group 2. Aqueous Solutions

The fluids listed in this group are mixtures each of which consists of a solution of water and a soluble organic liquid. These are:

1) Water-methyl alcohol (-65°F fr. pt.)
2) Water-methyl alcohol (-85°F fr. pt.)
3) Water-ethyl alcohol (-65°F fr. pt.)
4) Water-ethyl alcohol (-85°F fr. pt.)
5) Hollingshead Corp. water-base fluid H-2
6) Water-ethylene glycol (-65°F fr. pt.)
7) Water-propylene glycol (-65°F fr. pt.)
8) Water-cellusolve (-65°F fr. pt.)
9) Water-glycerine (-52°F fr. pt.)

The data in Table 7 and in Appendix I show that in all cases the specific heat and the thermal conductivity are reduced markedly from that of pure water by the addition of the organic liquid to the water. The viscosity is always increased and in some cases by a large percentage. In some solutions the density is slightly greater than that of water and in other solutions the density is less.

The most promising fluid in this class is the water-methyl alcohol solution freezing at -65°F. In this solution the density and the specific heat are about 10 to 15 percent less, the viscosity about 50 percent greater, and the thermal conductivity about 50 percent less than that of pure water.

The water-cellusolve solution freezing at -65°F has physical properties for heat transfer fluids which are just as suitable as those of water-methyl alcohol. However, cellusolve (ethylene-glycol mono-ethyl ether) is not as chemically stable as methyl alcohol and may form peroxides especially with prolonged use or at high temperatures. Consequently, the methyl alcohol-water solution is the one presented as optimum for this group when only the heat transfer properties are considered. The properties of this solution are listed in Table 7.

The water-methyl alcohol solution has a high vapor pressure, a very low flash point of about 60°F, and is flammable. If safety and non-flammability are of paramount importance, then the water-ethylene glycol solution (Table 22) is recommended. It is doubtful that this solution will flash, but if it does, it should occur considerably above 250°F. Also, it is quite likely that this solution is non-combustible. The main drawback of this solution when compared to water-methyl alcohol is its high viscosity of 3.14 centipoises at 100°F and over 500 at -50°F. This shows a poor viscosity-temperature index which might make it unsuitable for use in extremely cold climates, due to poor start-up characteristics.

Table 7. Properties of Water-Methyl Alcohol Solution Freezing at -65°F

At 100°F the density of this solution is 10 percent less than that of pure water, the specific heat is 16 percent less, the viscosity is 49 percent greater, and the thermal conductivity is 43 percent less.

1. Chemical composition, solution of 57 weight-percent methyl alcohol and 43 percent water

2. Average molecular weight, 24.0

3. Initial boiling point, 167°F at 760 mm Hg

4. Flash point (1), about 60°F

5. Freezing point, -65°F

Temp. °F	6. Vapor pressure (7)* mm Hg	7. Approx. latent heat (2) Btu/lb	8. Density Gm/cc	9. Specific heat (3) Btu/lb-°F	10. Viscosity (4) Centipoises	11. Thermal conductivity (5) Btu/hr - ft²(°F/ft)
-50					7.40	0.180
0			0.928	0.700	3.50	0.182
50	33.5	615	0.908	0.806	1.95	0.185
100	155	590	0.888	0.844	1.02	0.188
150	516	574	0.863	0.861**	0.58	0.190
200	1500	560	0.841	0.877**	0.36	0.193**
250	3560	548	0.811	0.890**	0.23**	0.195**
300	7250	538	0.777	0.897**	0.15**	0.198**

12. Color, colorless

13. Combustibility (5), combustible

14. Toxicity (5), toxic

15. Stability, stable to 300°F, no data above 300°F

16. Corrosiveness, corrosive but can be inhibited

17. Solubility, soluble in water

18. Effect on elastomers (6), some elastomers such as rubber swell

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*Number in parentheses refers to specific reference for fluid given in item 19 of this table.

**Extrapolated from data on water-methyl alcohol solutions of different compositions.

Table 7, continued

19. Specific references for this fluid:

(1) Sax, I. N., Handbook of Dangerous Materials, Reinhold Publishing Corp., New York, 1951, p. 242.
(2) Othmer, D. F., Ind. Eng. Chem., Vol. 32, 1940, p. 841.
(3) International Critical Tables, McGraw-Hill Book Co., New York, Vol. II, p. 116.
(4) Perry, J. H., Chemical Engineers Handbook, McGraw-Hill Book Co., New York, 1950, p. 373.
(5) Riedel, L., Chem. Ing. Tech., Vol. 23, 1951, p. 465.
(6) Dunkle, H. H. and Potter, E. C., Chem. Eng., Vol. 43, 1946, p. 108.
(7) Chin Chu, J., Distillation Equilibrium Data, Reinhold Publishing Corp., New York, 1950, pp. 143-6.

20. Specific comments on physical properties:

a. Specific heat data extrapolated above 104°F and accuracy uncertain.
b. Flash point given is flash point of pure alcohol. Flash point of solution should be slightly higher.

Group 3. Hydrocarbons

In this group, a distinction is made between those hydrocarbons used as aircraft fuels and those used as hydraulic or lubricating oils.

1. Fuels

A total of three hydrocarbon liquid fuels were studied in this sub-group. These fluids are:

1) Aviation fuel AN-F-58
2) Jet fuel JP-4
3) Jet fuel JP-3

In all cases the data in Table 8 and Appendix I show that for these hydrocarbon fuels the density is much less than that of water, the specific heat markedly less, the thermal conductivity very much less, and the viscosity slightly less.

The most promising heat transfer fluid of the fuels is the aviation fuel. Its properties are given in the following table. The differences between the aviation fuel and the JP-3 and 4 fuels are not significant. The chief difference is in the viscosity. A major disadvantage of the aviation fuel is its low flash point of near 0°F. Lower vapor pressure, and higher flash point make the JP-4 (Table 26) or JP-3 (Table 25) somewhat safer. However, their flash point of 65°F is still relatively low.

Table 8. Properties of Aviation Fuel AN-F-58

At 100°F the density of this liquid is 32 percent less than that of water, the specific heat is 50 percent less, the viscosity is 39 percent less and the thermal conductivity is 76 percent less.

1. Chemical composition, mixture of hydrocarbons ranging from 5 to 12 carbon atoms

2. Molecular weight (5)*, 134

3. Initial boiling point (1), 143°F at 760 mm Hg

4. Flash point (7), greater than 0°F

5. Freezing point (1), -76°F

Temp. °F	6. Vapor pressure (4) mm Hg	7. Latent heat (3) Btu/lb	8. Density (2) (1) Gm/cc	9. Specific heat (1) Btu/lb-°F	10. Viscosity (6) Centi-poises	11. Thermal conductivity (1) Btu/hr - ft²(°F/ft)
-50			0.824		1.36	0.0901
0	35		0.803	0.439	0.820	0.0887
50	123	155	0.781	0.472	0.562	0.0874
100	350	151	0.760	0.505	0.415	0.0861
150	850	145	0.739	0.538	0.330	0.0848
200	1800	140	0.712	0.571	0.276	0.0835
250	3450	136	0.685	0.604	0.235	0.0822
300	6050	131	0.647	0.637	0.198	0.0808

12. Color, clear, water-white

13. Odor, pleasant

14. Combustibility, highly combustible

15. Toxicity, non-toxic when breathed in small amounts

16. Stability, stable to 300°F. In the presence of oxygen gum is formed at most temperatures unless stabilized by an antioxidant.

17. Corrosiveness, non-corrosive

18. Solubility, insoluble in water

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*Number in parentheses refers to specific reference for fluid given in item 20 of this table.

Table 8, continued

19. Effect on elastomers, natural rubber unsuitable. Neoprene and some synthetics are suitable.

20. Specific references for this liquid:

(1) Properties of Specification AN-F-58 Fuel. WADC, Memo MCREXP-539-28 dated 12/29/48.
(2) Maxwell, J. B., Data Book on Hydrocarbons, D. Van Nostrand Co., New York, 1950, p. 143.
(3) Ibid., p. 116.
(4) Ibid., p. 44.
(5) Ibid., p. 21.
(6) Letter to W. Robinson, 5/26/53, from WADC, WCLEM-2.
(7) Dreisbach, R. R., P-V-T Relationships of Organic Compounds, Handbook Publishers, Inc., Sandusky, Ohio, 1952, p. 292.

2. Lubricants and Hydraulic Fluids

The hydrocarbon fluids studied in this sub-group are as follows:

1) Shell Tellus 15 hydraulic fluid
2) Texas Co. Aircraft hydraulic oil AA
3) Penn State MIL-O-5606
4) MIL-O-6081 Grade 1010 jet engine lubricating oil
5) Standard Oil of Ohio Univis J-43 hydraulic fluid
6) Socony-Vacuum Mobil Aero hydraulic oil HFA

The properties of these fluids are very similar to those of the hydrocarbon fuels except that the viscosities of the lubricants and hydraulic fluids are several times greater.

The most promising fluid in this sub-group is the Penn State MIL-O-5606 fluid (Table 9). However, the MIL-O-6081 grade 1010 jet engine lubricating oil and the Shell Tellus 15 hydraulic fluid have heat transfer properties which are quite similar to the Penn State fluid. The much lower viscosities of hydrocarbon fuels makes them more desirable heat transfer fluids than the lubricants and hydraulic fluids. The latter's large viscosities at very low temperature are particularly objectionable. The flash point of the Penn State MIL-O-5606 fluid is 230°F which is considered to be high enough to make this fluid relatively safe, in addition to its low vapor pressure.

Table 9. Properties of Penn State MIL-O-5606 Mineral Oil

At 100°F the density of this fluid is 17 percent less than that of pure water, the specific heat is 50 percent less, the viscosity is 1730 percent greater, and the thermal conductivity is 78 percent less.

1. Chemical composition, a hydrocarbon mixture

2. Molecular weight (see comments), 226

3. Boiling point (see comments), 490°F at 760 mm Hg

4. Flash point (1), 230°F

5. Fire point (1), 255°F

6. Freezing point (1), Below -75°F

7. Pour point (1), Below -75°F

Temp. °F	8. Vapor pressure (1)* mm Hg	9. Latent heat (4) Btu/lb	10. Density (1) Gms/cc	11. Specific heat (1) Btu/lb-°F	12. Viscosity (1) Centi-poises	13. Thermal conductivity (1) Btu/hr - ft²(°F/ft)
-50			0.88	0.425***	616	0.082***
0	Insignificant		0.86	0.450	112	0.081
50	Insignificant	95.0	0.84	0.475	27.3	0.080
100	0.23**	92.5	0.83	0.500	11.8	0.079
150	0.84**	89.9	0.81	0.525	6.4	0.0775
200	3.0	87.2	0.79	0.550	4.27	0.076
250	11.3	84.2	0.77	0.575	3.19	0.075
300	36.2	81.2	0.75	0.600	2.55	0.074

14. Color, no data

15. Odor, no data

16. Combustibility (2), slight combustibility (see comments)

17. Toxicity (2), relatively non-toxic

18. Stability, stable to 300°F, no data above 300°F but probably will form gums

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*Number in parentheses refers to specific reference for fluid given in item 23 of this table.
**Extrapolated by Cox chart.
***Extrapolated linearly.

Table 9, continued

19. Corrosiveness (2), no data but believed to be non-corrosive

20. Solubility (2), insoluble in water

21. Effect on elastomers (3), natural rubber generally not resistant. A very few synthetic rubbers acceptable.

22. Foaming tendencies (1), has foaming tendency. Silicone additive cuts down tendency to foam.

23. Specific references for this fluid:

(1) Letter to W. Robinson, 7/17/52, from M. R. Fenske, Penn. State College.
(2) Sax, I. N., Handbook of Dangerous Materials, Reinhold Publishing Corp., New York, 1951.
(3) Perry, J. H., Chemical Engineers' Handbook, McGraw-Hill Book Co., New York, p. 1192.
(4) Othmer, D. F., Ind. Eng. Chem., Vol. 32, 1940, p. 841.

24. Specific comments on physical properties:

a. Molecular weight assumed to be that of mineral oil.
b. Boiling point extrapolated from vapor pressure data.
c. Combustibility, toxicity, corrosiveness, and solubility assumed to be that of a mineral oil.

Group 4. Fluoro- and Chloro-Hydrocarbons

The compounds in this group are basically hydrocarbons in which chlorine or fluorine has been substituted for some of the hydrogens. Some of the compounds also contain some oxygen or nitrogen. Some of these chemicals have been synthesized recently and are relatively new. Some are also quite expensive at present but future large-scale production should reduce prices considerably.

The majority of the fluids are characterized by their high stability and non-inflammability. Fluids in this group, covered in this study, are:

1) Minnesota Mining and Manufacturing Co. fluorochemical O-75
2) Minnesota Mining and Manufacturing Co. fluorochemical N-43
3) Freon-113
4) Freon-11
5) Hexachlorobutadiene

All of the fluids have unusually high densities from 50 to 85 percent greater than water and very low specific heats of about one-fourth that of water. The densities are almost double those of hydrocarbons and the specific heats are about one-half those of hydrocarbons. The thermal conductivities are much less than that of water and slightly less than those of hydrocarbons. The viscosities of some of these fluids are less than that of water and some have viscosities greater than water.

The most promising heat transfer fluid in this group is the O-75 fluorochemical (Table 10). The Freon-11 fluid has similar heat transfer properties but was not considered desirable because of its very low boiling point of 74.7°F. The O-75 fluid is non-flammable and should be quite safe as a heat transfer fluid in the present application. The low specific heat of the fluid should prove objectionable from the system's standpoint.

Table 10. Properties of Minnesota Mining and Manufacturing Co. Fluorochemical O-75

This fluid is unique in that it is thermally stable to 1100°F and non-combustible. The fluid is also characterized by a high density of 1.71 gms/cc at 100°F and a very low pour point of -148°F.

At 100°F the density of this liquid is 72 percent greater than that of pure water, the specific heat is 74 percent less, the viscosity is 61 percent greater, and the thermal conductivity is 82 percent less.

1. Chemical composition, completely fluorinated cyclic ether with the empirical formula $C_8F_{16}O$.

2. Average molecular weight (1), 416

3. Boiling point (1), 214°F at 760 mm Hg

4. Flash point (1), non-flammable

5. Fire point (1), non-flammable

6. Freezing point (1), -171°F

7. Pour point (1), -148°F

Temp. °F	8. Vapor pressure (1)* mm Hg	9. Latent heat (1)(2) Btu/lb	10. Density (1) Gms/cc	11. Specific heat (1) Btu/lb-°F	12. Viscosity (1) Centi-poises	13. Thermal conductivity (1) Btu/hr - ft²(°F/ft)
-50			1.98		9.90	0.105***
0			1.87	0.248**	3.74	0.092***
50	10	41.6	1.79	0.254	1.88	0.078
100	61	40.4	1.71	0.260	1.10	0.065
150	232	39.2	1.64	0.266**	0.721	0.051
200	620	38.1	1.58	0.271**	0.511	0.038***
250	1500	36.8	1.53	0.277**	0.388	0.024***
300	3160	35.4	1.48	0.283**	0.306	0.02 ***

14. Coefficient of expansion (1),

°F	Coefficient
77-104	0.89×10^{-3}/°F
104-176	1.11×10^{-3}/°F

*Number in parentheses refers to specific reference for fluid given in item 26 of this table.
**Estimated, see comments.
***Extrapolated linearly.

Table 10, continued

15. Surface tension (1),

°F	Dynes/cm
77	15.2

16. Refractive index (1),

°F	Value
77	1.276

17. Dielectric constant at 100 cycles/sec (1),

°F	Value
77	1.85

18. Color (1), colorless

19. Odor (1), odorless

20. Combustibility (1), non-combustible

21. Toxicity (1), no toxic effects observed as yet

22. Stability (1), thermally stable to 1100°F

23. Corrosiveness (1), does not corrode metals up to 575°to 925°F

24. Solubility (1), insoluble in water

25. Effect on elastomers (1), does not appear to have much effect at ordinary temperatures

26. Specific references for this fluid:

(1) Bulletin from Minnesota Mining and Manufacturing Company, St. Paul, Minnesota.
(2) Othmer, D. F., Ind. Eng. Chem., Vol. 32, 1940, p. 841.

27. Specific comments on physical properties:

a. The thermal conductivity has a very large temperature coefficient. This should be investigated further.
b. The temperature coefficient of the specific heat was assumed the same as fluorochemical N-43 of Minnesota Mining and Manufacturing Company. This temperature coefficient of N-43 was obtained experimentally by J. Fisher, The Ohio State University, Chemical Engineering Laboratories, Columbus, Ohio. Experimental data should be obtained for fluid O-75.

Group 5. Oxygenated Hydrocarbons

In this group the compounds are also basically hydrocarbons but contain oxygen as a hydroxyl linkage, ester linkage, ether linkage, or some similar type of linkage.

The fluids are characterized by quite high boiling points (all over 365°F) and densities near that of water. The specific heats and thermal conductivities are very much less than that of water but similar to those of hydrocarbons. The viscosities are quite high and range from 14 to 63 times that of water. The flash points are quite high, being over 220°F.

The fluids which were considered in this group are:

1) Rohm and Haas Co. aliphatic diester Flexol 201
2) Penn State MIL-L-6387 synthetic ester base
3) Propylene glycol
4) Carbide and Carbon Corp. Ucon 50-HB-280-X
5) Carbide and Carbon Corp. Ucon LB-30-X

Pure propylene glycol (Table 11) is the most promising fluid in this group. It has a very high specific heat of 0.624 Btu/lb-°F at 100°F, compared to that of the other oxygenated hydrocarbons of about 0.45 Btu/lb-°F. The viscosity of 20.3 centipoises (100°F) is quite high. The viscosity also increases to a very large value of 480 centipoises at 0°F which might cause start-up difficulties. The flash point of 225°F appears adequate for safety purposes. The low vapor pressure of the fluid is desirable also.

Table 11. Properties of Propylene Glycol

At 100°F the density of this liquid is 4 percent greater than that of water, the specific heat is 38 percent less, the viscosity is 3000 percent greater and the thermal conductivity is 66 percent less.

1. Chemical composition (1), $C_3H_6(OH)_2$

2. Molecular weight, 76.1

3. Boiling point (1)*, 369°F at 760 mm Hg

4. Flash point (3), 225°F

5. Freezing point (4) (estimated), approximately -126°F

Temp. °F	6. Vapor pressure (1) mm Hg	7. Latent heat (2)*** Btu/lb	8. Density (1) Gms/cc	9. Specific heat (1) Btu/lb-°F	10. Viscosity (1) Centi-poises	11. Thermal conductivity (1) Btu/hr - ft²(°F/ft)
-50			1.087**	0.513		0.143**
0	0.005		1.056**	0.550	480**	0.135**
50	0.07	362	1.045	0.587	75.5	0.129
100	0.63	352	1.024	0.624	20.3	0.121
150	3.8	342	1.003**	0.661	8.8	0.114
200	19.5	333	0.982**	0.698	5.2	0.106
250	66	322	0.961**	0.735	3.6**	0.098**
300	225	310	0.940**	0.772	2.84**	0.090**

12. Color (3), clear, water white

13. Odor (3), no odor

14. Combustibility (5), a flammable liquid and a moderate fire hazard

15. Toxicity (3), non-toxic

16. Stability (3), stable to 300°F, no data above 300°F

17. Corrosiveness (3), practically non-corrosive

18. Solubility (3), completely soluble in water and alcohol

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*Number in parentheses refers to specific reference for fluid given in item 20 of this table.
**Extrapolated.
***Estimated by method of Othmer.

Table 11, continued

19. Effect on elastomers (3), rubber suitable

20. Specific references for this fluid:

(1) Booklet on Glycols, published by Carbide and Carbon Chemicals Corporation, 1947.
(2) Othmer, D. F., Ind. Eng. Chem., Vol. 32, 1940, p. 891.
(3) Booklet on Celanese Organic Chemicals, Celanese Corporation of America, N. Y.
(4) Parks, G. F. and Huffman, H., J. Phys. Chem., Vol. 31, 1927, p. 1842.
(5) Sax, N. I., Handbook of Dangerous Materials, Reinhold Publishing Company, New York, 1951, p. 327.

21. Specific comments on physical properties:

a. There is no definite freezing point since a glass is formed, the transition region being between -184°F and -163°F. The softening temperature is -126°F. The value of -126°F which is considered safe is well below the minimum temperature (-65°F) set in this study.
b. Latent heat estimated by method of Othmer.

Group 6. Organic-Inorganic Compounds

The compounds in this group are combinations of hydrocarbons and inorganic compounds. They are either aliphatic silicates or phosphates combined with hydrocarbons.

The fluids are quite similar to the hydrocarbons in many of their physical properties. However, the boiling points are all over 400°F. The fluids in this group are:

1) John B. Pierce Foundation amyl silicate HF-140
2) John B. Pierce Foundation isobutyl-isopropyl silicate
3) Oronite Chemicals Co. aliphatic silicate ester Orsil HF-1
4) Celanese Corp. tricresyl phosphate Lindol HF

The fluid selected as one of the most promising in this group is the isobutyl-isopropyl silicate (Table 12). Its properties are very close to those of hydrocarbons. The properties of the amyl silicate are similar to those of the isobutyl-isopropyl silicate.

The flash point of the isobutyl-isopropyl silicate is 170°F which is slightly low for safety purposes, although its vapor pressure is low. If a fluid is required with a higher flash point and very low vapor pressure, then the Orsil HF-1 fluid (Table 42) should be used. This fluid flashes at 395°F and has a fire point of 450°F which is quite safe. However, the viscosity of this fluid of 380 centipoises at -50°F is quite high and its specific heat and thermal conductivity are lower.

Table 12. Properties of John B. Pierce Foundation Isobutyl-Isopropyl Silicate

At 100°F the density of this liquid is 13 percent less than that of water, the specific heat is 53 percent less, the viscosity is 97 percent greater, and the thermal conductivity is 83 percent less.

1. Chemical composition (1)*, isobutyl-isopropyl silicate

2. Molecular weight (1), 287

3. Boiling point (1), 425°F at 760 mm Hg

4. Flash point (1), 170°F

5. Fire point (1), 180°F

6. Pour point (1), less than -100°F

Temp. °F	7. Vapor pressure (1) mm Hg	8. Latent heat (2) Btu/lb	9. Density (1) Gms/cc	10. Specific heat (1) Btu/lb-°F	11. Viscosity (1) Centipoises	12. Thermal conductivity(1)** Btu/hr - ft²(°F/ft)
-50			0.942	0.456***	15.1	
0	Less than 1 mm	See	0.917	0.460	4.60	0.0655
50	Less than 1 mm	See	0.892	0.463	2.26	0.0639
100	2.4	Com-	0.867	0.473	1.34	0.0624
150	3.5	ments	0.842	0.491	0.91	0.0629
200	11.5		0.817	0.522	0.67	0.0633
250	42		0.792	0.565	0.515	0.0656
300	99		0.767	0.607	0.414	0.0680

13. Coefficient of expansion,

°F	Coefficient
0-100	5.88×10^{-4}/°F

14. Refractive index,

°F	Value
77	1.392

15. Color (1), colorless

16. Odor (1), mild and pleasant

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*Number in parentheses refers to specific reference for fluid given in item 24 of this table.
**See comments.
***Extrapolated linearly.

Table 12, continued

17. Combustibility (1), combustible

18. Toxicity (1), non-toxic on exposure to fumes

19. Stability, no data but believed stable to 300°F

20. Corrosiveness (1), not corrosive to ferrous metals, copper, and copper alloys, slightly corrosive to aluminum

21. Acidity (1), none

22. Solubility (1), insoluble in water, soluble in hydrocarbons

23. Effect on elastomers, no data

24. Specific references for this fluid:

    (1) Letter to W. Robinson, 8/8/52, from John B. Pierce Foundation, Raritan, N. J.
    (2) Othmer, D. F., Ind. Eng. Chem., Vol. 32, 1940, p. 841.

25. Specific comments on physical properties:

    a. Very low pour point.
    b. Temperature effect on thermal conductivity very odd since it appears to reach a minimum at 100°F. More data should be obtained.
    c. Latent heat data as estimated by Othmer method are very high and appear incorrect. Data should be obtained on this.

Group 7. Silicones

The compounds known as the silicones are similar to hydrocarbons. The densities are near that of water but the specific heats are quite low, being even less than those of hydrocarbons. The thermal conductivities are similar to the values for hydrocarbons.

The viscosities of these compounds are much greater than that of water, but the fluids are essentially non-volatile, and the flash points are over 320°F. The fluids in this group, covered in this study, are:

1) Dow-Corning Silicone DC-200
2) Dow-Corning Silicone DC-510
3) Dow-Corning Silicone DC-550

The most promising fluid is the silicone DC-200 (Table 13) because of its low viscosity compared to the other silicones. The fluid is relatively non-hazardous since its flash point is 325°F.

The DC-200 fluid having a viscosity of 10 centistokes was selected for this study. Other DC-200 fluids having viscosities much lower (down to 1 centistoke at 25°C) are available. However, these fluids have much lower flash points which may be unsuitable for use in the present case. Also, the boiling points are considerably lower. If these lower viscosity fluids are considered, they compare favorably with the fluoro- and chloro-hydrocarbons, Group 4. However, they are considerably less stable than the fluorocarbons.

Table 13. Properties of Dow Corning Co. DC-200 Silicone Fluid (10 Centistokes Viscosity at 25°C)

At 100°F the density of this fluid is 7 percent lower than that of pure water, the specific heat is 66 percent less, the viscosity is 965 percent greater, and the thermal conductivity is 79 percent less.

1. Chemical composition, dimethylpolysiloxane

2. Molecular weight (1)*, unknown

3. Boiling point (1), greater than 509°F at 760 mm Hg

4. Flash point (1), 325°F

5. Freezing point (1), -85°F

Temp. °F	6. Vapor pressure (1)** mm Hg	7. Latent heat Btu/lb	8. Density (2) Gms/cc	9. Specific heat (2) Btu/lb-°F	10. Viscosity (2) Centi-poises	11. Thermal conductivity(1)**** Btu/hr - ft²(°F/ft)
-50			1.020***	0.326***	74.5***	0.0820
0	0.011	See	0.987***	0.330	28.6	0.0804
50	0.026	com-	0.955***	0.335	13.4	0.0789
100	0.064	ments	0.928***	0.340	7.23	0.0773
150	0.140		0.900***	0.344	4.68	0.0757
200	0.280		0.871***	0.349	3.27	0.0741
250	0.850		0.854***	0.353***	2.47	0.0725
300	2.15		0.816***	0.358***	1.96	0.0709

12. Color (2), water-white

13. Odor, no data

14. Combustibility (2), slight combustibility

15. Toxicity (2), non-toxic

16. Stability (2), good stability to 400°F, many times more stable than that of most organic fluids. May gel in air after 30 days at 200°C.

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*Number in parentheses refers to specific reference for fluid given in item 20 of this table.
**Extrapolated by using Cox chart and boiling point at 1 atmosphere.
***Extrapolated linearly.
****See comments.

Table 13, continued

17. Corrosiveness (2), non-corrosive to metals

18. Solubility (2), insoluble in water, soluble in benzene, gasoline, kerosene, chloroform, etc.

19. Effect on elastomers (1), tends to leach plasticiser from rubber stocks causing them to shrink

20. Specific references for this fluid:

    (1) Letter to Christie J. Geankoplis, 3/24/53, from Dow Corning Corporation, Cleveland, Ohio.
    (2) Dow Corning Silicone Notebook, Reference No. 2003, issued June 1952.

21. Specific comments on physical properties:

    a. This fluid is practically non-volatile and has no true boiling point. Due to lack of molecular weight and boiling point data, values cannot be estimated. Latent heat at boiling point is 32.4 Btu/lb.
    b. Thermal conductivity calculated from equation where

$$K_t = .000328 - 2.22 \times 10^{-7} \, T \, {}^{\circ}C$$

$$K_t = \frac{\text{Btu - cal}}{\text{hr-sec-cm}} \, ({}^{\circ}C/cm)$$

Overall Comparison of Groups 1 to 7

In Table 14 the ranges of the values of the more important physical properties in each group are given to illustrate the variation within a group and the variation between groups.

Table 14. Ranges of Physical Properties of Seven Groups of Fluids at 100°F

Group	Density Gms/cc	Specific heat Btu/lb-°F	Thermal conductivity Btu/hr-ft²-(°F/ft)	Viscosity Centipoises
1. Water	0.993	1.00	0.361	0.684
2. Aqueous solutions	0.82-1.17	0.71-0.84	0.119-0.232	0.88-14.9
3. Hydrocarbons				
a. Fuels	0.75-0.76	0.50-0.51	0.086-0.087	0.42-0.68
b. Lubricants and hydraulic fluids	0.83-0.86	0.46-0.50	0.078-0.079	8.5-12.7
4. Fluoro- and chloro-hydrocarbons	1.45-1.85	0.20-0.28	0.051-0.069	0.38-3.6
5. Oxygenated hydro-carbons	0.90-1.02	0.42-0.62	0.082-0.121	14.1-63.5
6. Organic-inorganic compounds	0.87-1.15	0.39-0.47	0.062-0.073	1.3-32.3
7. Silicones*	0.93-1.07	0.34-0.38	0.077-0.090	7.2-80

*DC-200 Silicone fluids are available having viscosities comparable to Group 4 but their flash points are relatively low.

Table 14 shows that the variations within a group are generally quite small except for viscosity. However, the variation of thermal conductivity in the aqueous solutions is over 100 percent. This is expected since the thermal conductivity of an aqueous solution depends almost directly on the percentage of the organic liquid added to the water.

The viscosity range within each group is quite large. Additions of small amounts of blending agents often have marked effects on the viscosity of the resultant solution.

In studying the variations between groups it is very evident that water is markedly superior to all the other six groups. The extremely high thermal

conductivity and high specific heat are mainly responsible.

It is difficult to rate the other groups in an exact order after water because of the combined effects of the various properties. However, when primary importance is assigned first to high specific heat and then also to low viscosity, it is evident that Group 2, aqueous solutions, is more desirable for heat transfer systems than the remaining five. On the same basis, Group 3a, hydrocarbon fuels, appears next best. Then, Group 6, inorganic-organic compounds and Group 3b, hydrocarbon lubricants and hydraulic fluids, should rank similarly, the former having slightly lower specific heats, but appreciably lower minimum viscosities. Next best should be Groups 5 and 4, with the latter somewhat inferior because of the very low specific heat, although compensated for partly by very low viscosity. The least desirable should be Group 7, having next to the lowest specific heats, and also very appreciable viscosities.

Other Fluids Considered Unsuitable

The properties of a number of other fluids were examined. For various reasons these fluids were deemed unsuitable for use as heat transfer fluids. These fluids are discussed below.

1. Monsanto Chemical Company Arcolors

There are a number of chlorinated bi-phenyl and chlorinated polyphenyls called Arcolor compounds. Although suitable from a safety standpoint, they have other undesirable features which eliminate them from further consideration. Arcolor 1248 has a flash point of 380°F but is non-flammable. Arcolor 1254 is inflammable. Arcolor 1242 flashes at 350°F and has a fire point of 633°F. The objectionable characteristic of these fluids is their high pour point which is 20°F for the 1248 fluid and 50°F for the 1254 fluid. These fluids also attack rubber and neoprene.

2. Dowtherm A

The fluid is quite suitable in many respects but has a freezing point of 54°F.

3. Other Mineral Oils or Hydrocarbon Oils

Many other mineral or hydrocarbon oils are available but their properties are so similar to the fluids presented in Group 3 (Tables 9, 28-38) that they were not studied in detail for this reason.

4. Freon-21, Freon-12, Freon-22, and Freon-114

Other Freons such as Freon-21, -12, -22, and -114 have properties similar to Freon-113 and -11 whose properties are given in Tables 34 and 35.

respectively. However, the higher vapor pressures and lower boiling points of the other Freons make them less desirable for the present use. Freon-21 boils at the low temperature of 48°F. Freon-12 and -22 both boil at a temperature considerably below 0°F. Freon-114 boils at 38°F.

5. Trichlorobenzene

This liquid has no flash point but it freezes at the high temperature of 50°F. Hence, it is unsuitable as are a number of the other chlorinated aromatics.

6. Ethers

The ethers generally have heat transfer properties similar to the oxygenated hydrocarbons of Group 5. However, these compounds have a strong tendency to react to form peroxides which may create an explosion hazard.

SECTION IV

HEAT TRANSFER FLUIDS FOR HIGH TEMPERATURES (300° to 600°F)

The presentation in the preceding Section III is concerned with fluids which can be used primarily below 300°F. If it is desired to operate the heat transfer system even for relatively short intervals at temperatures above 300° and possibly even up to 600°F, the number of fluids available is severely limited.

Most of the fluids become chemically unstable at temperatures above 300°F and below 600°F. The following nine fluids have been found to be stable and useful above 300°F.

1) Water (reference fluid), stable well over 600°F
2) Minnesota Mining and Manufacturing fluorochemical O-75, stable up to 1100°F
3) Minnesota Mining and Manufacturing fluorochemical N-43, stable up to 900°F
4) Dow-Corning Silicone DC-550 fluid, stable up to 500°F
5) Dow-Corning Silicone DC-200 fluid, stable up to 400°F
6) Dow-Corning Silicone DC-510 fluid, stable up to 400°F
7) Carbide and Carbon Ucon 50-HB-280-X fluid, stable up to 500°F
8) Carbide and Carbon Ucon LB-30-X fluid, stable up to 500°F
9) Cronite Chemicals Aliphatic Orthosilicate Ester Orsil HF-1 fluid, stable up to 500°F.

Physical properties for these high-temperature fluids are tabulated and considered in detail only for the most useful and important of the above nine fluids. These are water, fluorochemical O-75, fluorochemical N-43, Ucon 50-HB-280-X, and Silicone DC-550. The Silicones DC-200 and DC-510 were not considered in detail since they are only useful up to about 400°F. Data for the Ucon LB-30-X were not obtained in detail since its properties are very similar to the Ucon 50-HB-280-X. The data for Orsil HF-1 fluid were not considered since there is not sufficient information to insure that the fluid is stable up to the 500°F limit stated.

Most of the physical properties were estimated or extrapolated for temperatures above 300°F. These physical property values are only very approximate and should be used only in a qualitative and not quantitative manner. However, the values for water are quite accurate.

As in the low temperature studies, water (Table 15) is the most promising fluid for temperatures over 300°F and is shown mainly for reference purposes. The main disadvantage of water is its high vapor pressure, reaching 1543 lbs/sq in.abs. at 600°F. Its specific heat increases to 1.45 Btu/lb-°F at 600°F and its thermal conductivity drops only slightly. It is still undesirable because of its high freezing point.

If a low-vapor-pressure liquid is required at high temperatures, the Silicone fluid DC-550 or the Ucon 50-HB-280-X fluid would have to be used. Fluids in this classification other than water have their properties tabulated in Appendix II.

Table 15. Water at High Temperatures

1. Chemical composition, H_2O

2. Boiling point, 212°F at 760 mm Hg

3. Flash point, non-flammable

Temp. °F	4. Vapor pressure (1) psia	5. Density (1) gm/cc	6. Specific heat (1) Btu/lb-°F	7. Viscosity (1) Centi-poises	8. Thermal conductivity (2) Btu/hr - ft²(°F/ft)
300	67.0	0.9179	1.03	0.185	0.397
400	247.3	0.860	1.08	0.139	0.384
500	680.8	0.785	1.29	0.108	0.354
600	1542.9	0.679	1.45	0.086	0.298

9. Stability, very stable at least to 600°F and probably higher

10. Specific references for this fluid:

(1) Keenan, J. H. and Keyes, F. G., Thermodynamic Properties of Steam, John Wiley and Sons, Inc., New York, 1948.
(2) Figure 1.

SECTION V

EFFECT OF HEAT TRANSFER FLUIDS ON COOLING SYSTEM PENALTY

by

W. Robinson, W. E. Krause and K. G. Hornung

The purpose of this section is to present quantitative information on how the choice of the heat transfer fluid may affect the aircraft gross weight attributable to an equipment cooling system containing a liquid distribution system. This information is intended to provide the basis for a more definitive preferential classification of the various groups of fluids set forth in Section III.

The choice of the heat transfer fluid should affect the aircraft penalty caused by a cooling system in different degrees, depending on the type of the ultimate heat rejection process employed. If a system imposes an appreciable penalty in providing the ultimate heat sink, little relative change in total system penalty should result by designing for different heat transfer fluids, even if their physical properties differ appreciably. For example, this should be the case for systems which utilize engine bleed air and for systems which utilize an expendable ultimate coolant and operate for several hours. Systems imposing an inherently small penalty in providing an ultimate heat sink should be more appreciably affected by the choice of the heat transfer fluid. This should apply, for example, to ram air systems operating at subsonic or low supersonic flight speed, fuel cooling systems, and expendable cooling systems designed for very short operating time. For the comparison of fluids in respect to aircraft penalty, it is desirable to determine the greatest differences that are likely to occur. A means to do so is to determine the characteristics of expendable cooling systems, designed for minimum penalty and containing practically no expendable fluid, i.e., the operating time is extremely short.

Nomenclature

The following symbols are used in this section for the abbreviation of concepts used in the discussion and the illustrations.

Symbol	Concept
ϵ_E	heat exchange effectiveness of equipment, dimensionless
ϵ_{It}	heat exchange effectiveness of transfer-fluid side of intermediate heat exchanger, dimensionless
kw	cooling capacity, kilowatts
L_D	length of distribution line, feet
M_∞	flight Mach number, dimensionless
T_{Es}	temperature of equipment surface, ^oF
T_U	temperature of expendable coolant, ^oF
T^o_∞	total ram air temperature, ^oF

Symbol	Concept
W_U	weight of expendable coolant, pounds
X_{ref}	reference fuel-to-gross weight ratio of aircraft, dimensionless
ΔT_{IU}	temperature difference between heat exchanger surface and boiling expendable coolant, °F
ΔW_g	gross weight increase of aircraft due to installation of cooling system, pounds

Expendable Cooling System

Maximal effects of heat transfer fluid properties on characteristics of distribution and intermediate heat exchange components can be indicated by comparing the optimum base weights of expendable cooling systems designed for different transfer fluids. The base weight of an expendable cooling system includes (1) the weight of the fluid distribution lines, (2) the weight of the intermediate heat exchanger between the transfer fluid and the expendable coolant, (3) the weight of the transfer fluid circulating pump and its power supply system, and (4) the effect of the increase in fuel flow to the powerplant required to maintain a constant thrust, while shaft power is extracted for conversion into transfer fluid pumping power. When the weight of the ultimate component of the system, i.e., the weight of the expendable coolant, its container, etc., are added to the base weight, and the sum is divided by $(1 - X_{ref})$, where X_{ref} is the ratio of the fuel load to the gross weight of the aircraft before installation of the cooling system, the gross weight increase of the aircraft due to the entire cooling system is determined. Obviously, the greatest effect of the heat transfer fluid is obtained if the weight of the ultimate component is negligible, i.e., if the operating time of the system is very short. Then, the fluid comparison can be made on the basis of the base weights alone.

Another feature of the expendable cooling system which emphasizes the effect of heat transfer fluid properties is that the heat transfer coefficient on the side of the heat exchanger surface in contact with the expendable coolant is very high since boiling occurs. Therefore, the predominant resistance to heat transfer would be on the transfer fluid side and would control the optimum size of the heat exchanger.

The optimum design of the system for any transfer fluid, at given operating conditions, cooling capacity and system length, is obtained when the system base weight is a minimum. As the surface of the heat exchanger is increased, its temperature rise above the boiling point of the expendable coolant is decreased. Therefore, the heat transfer fluid circulation rate may be reduced in order that a desired equipment temperature be maintained. Thus, with an increase in heat exchanger weight goes a decrease in distribution line weight and pumping power requirements. For optimum design, the respective rates of increase and decrease of gross weight resulting from these variations must be equal and balance each other. The minimum system base weight can be defined in terms of the optimum temperature difference, ΔT_{IU}, between the evaporating ultimate coolant and the heat transfer surfaces,

since, for a given evaporation temperature, the heat transfer coefficient for submerged boiling is also a function of ΔT_{IU}.

The characteristics of a system of known length can be determined for a given evaporation temperature, T_U, and equipment temperature, T_{Es}, by specifying the ultimate temperature difference, ΔT_{IU}, the heat exchange effectiveness on the transfer fluid side of the heat exchanger, ϵ_{Tt}, and the heat exchange effectiveness of the equipment, ϵ_E. The weight of the heat exchanger is defined solely by ΔT_{IU}. The transfer fluid flow rate depends on all specified quantities and is inversely proportional to the specific heat of the transfer fluid. The diameter of the transfer fluid line is optimized by minimizing the combined aircraft gross weight increase due to (1) the weight of the transfer line and (2) the weight of the power supply system and the gross weight effect due to increase in fuel consumption resulting from shaft power extraction from the powerplant, required to supply the pumping power for conveying the transfer fluid through the distribution system. The total pumping power, power supply system weight and increase in fuel consumption of the powerplant are determined by the flow rate and the sum of the fluid pressure drops through the transfer line and the heat exchanger. Thus, together with the weight of the heat exchanger, the system base weight is defined for the specified ΔT_{IU}. For any set of design conditions, the system of least base weight can be found by designing for different values of ΔT_{IU}. As previously mentioned, the weight of the heat exchanger decreases with increasing ΔT_{IU} while the fluid flow rate increases. The pumping power, the weight of the distribution system and the weight of the power supply system also increase with the fluid flow rate. Consequently, an optimum ΔT_{IU} and a corresponding optimum size of the heat exchanger can always be found. However, in boiling heat transfer from submerged surfaces there is for every fluid at a given pressure a value of ΔT_{IU} at which maximum heat flux from the heat exchanger surface would be obtained. Greater temperature differences would reduce the heat flux and, therefore, this temperature difference should be considered as a limiting value. At greater temperature differences, not only the flow rate, pumping power, etc. would increase but also the weight of the heat exchanger.

1. Methods of Analysis and Range of Data

Details of the methods of analysis for the calculation of the base weight of expendable cooling systems will be presented in a future report* dealing with the characteristics of various types of aircraft equipment cooling systems. It is felt that the purposes of the present report would be served best by the presentation of a summary of results obtained in the evaluation of the effects of transfer fluid properties in general and of specific fluids, representative of the groups distinguished in Section III, when utilized in this system.

In the following, are presented typical data for optimum system designs using water boiling at 100°F (62,000 feet altitude) as the expendable

*Contract No. AF 33(616)-147

fluid. The calculated results are based on a system cooling capacity of 25 kilowatts. On a unit basis, they should be considered representative of a range of cooling capacities from 15 to 40 kilowatts. The effectiveness of heat exchange of the equipment, e_E, as well as of the transfer fluid side of the intermediate heat exchanger, e_{It}, is taken as 90 percent.

Aircraft penalty is evaluated on the basis of added gross weight, maintaining range and performance of the aircraft the same as without installation of the cooling system. The extraction of shaft horsepower from the powerplant, for the purpose of generating the power required for circulating the heat transfer fluid in the distribution system, results in increased fuel consumption of the powerplant. The additional fuel load is evaluated on the basis of average representative aircraft characteristics. For a specific aircraft, this effect may be from one-third to 3 times as great as here considered. However, this would not change materially the base weight of the system since the additional fuel consumption contributes only a small part of the system base weight.

2. Effects of Individual Fluid Properties

The effects of individual fluid properties are illustrated in Figures 2, 3 and 4 on the basis of optimum design calculations made for a system with a 300-foot distribution component, i.e., the distance between the heat exchanger and the most remote equipment item is 150 feet. The trends indicated apply also to systems with shorter distribution lines, but not less than 50 feet long. For very short line lengths the effect of thermal conductivity would become pronounced since then the heat exchanger weight would become an important portion of the system base weight. For systems with long distribution lines, the thermal conductivity of the fluid, in the range of possible variation among the various fluids, i.e., in the ratio of about 5 to 1, is of minor importance and, therefore, has not been considered.

In the design calculations for Figures 2, 3 and 4, the properties of water as a transfer fluid at 115°F are taken as base values. Holding other properties constant, the values of viscosity, specific heat and density are each varied individually over a range representative of the groups of fluids identified in Section III. The results are presented as the ratios of system base weight with one property varied to the system base weight with water as transfer fluid, as functions of the ratio of the value of each individually varied property to that of water.

Figure 2 represents the effect of increased fluid viscosity. Curve A, for all properties other than viscosity the same as those of water, indicates an initial increase in relative base weight in proportion with the viscosity to the 0.05 power, and at 25 times the viscosity of water, an increase in proportion to the viscosity to the 0.2 power. Thus an initial fivefold increase in viscosity raises the base weight about 11 percent, while a further fivefold increase raises the base weight an additional 28 percent of the reference value.

The trends shown by the other curves in Figure 2 are similar to

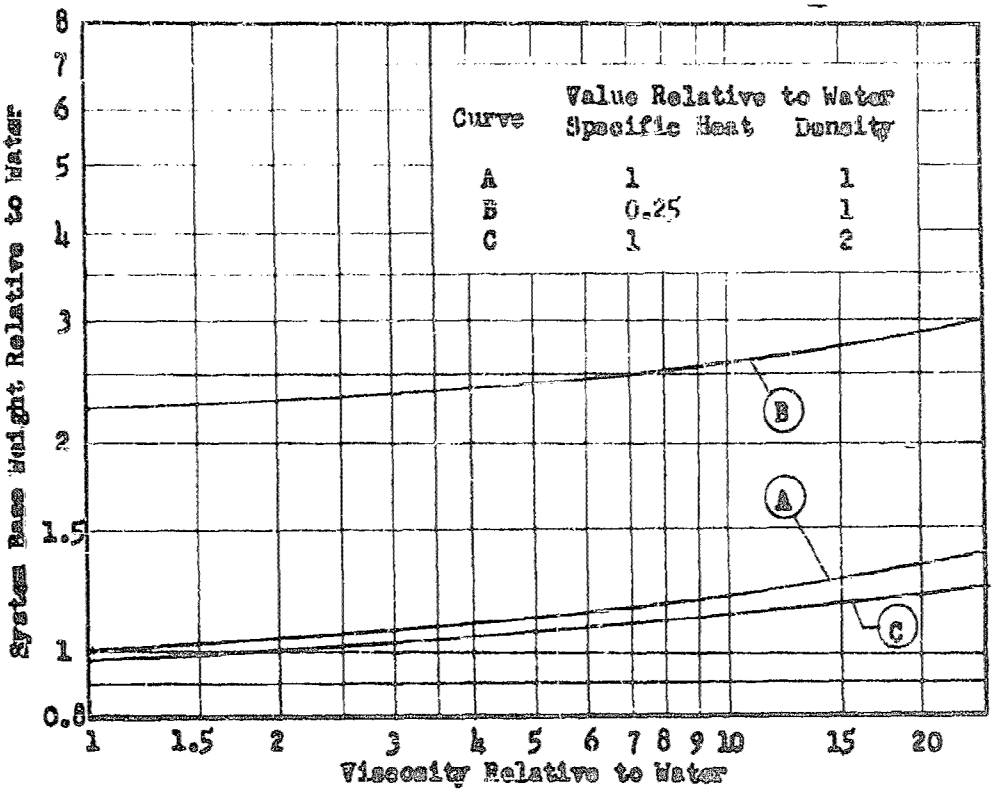


Figure 2. Effect of Viscosity of Transfer Fluid on Base Weight of Expendable Cooling System

those of curve A. The values of curve B are based on a fluid having a specific heat one-fourth that of water. For such a fluid with low specific heat the initial effect of viscosity increase is very small, the exponent of the curve being less than 0.05, but the rate of base weight increase at high viscosity is the same as shown by curve A. The values of curve C are based on a fluid having a density twice that of water. The rate of system base weight increase with viscosity for such a fluid is somewhat more uniform. The initial rate is almost the same as for curve A, but at high viscosity the slope of curve C is appreciably smaller.

By comparison of curves A, B and C in Figure 2 it is apparent that the effect of increased viscosity can be compensated by greater fluid density. For example, the viscosity can be increased about twice but will not affect the base weight if the density is also increased about twice and the other properties are the same as those of water. Extrapolation of curve A also shows that the viscosity would have to be increased more than 100 times to have the same effect as reducing the specific heat to one-fourth, if all other properties are the same as those of water.

Figure 3 represents the effect of specific heat of the transfer fluid on the system base weight. Curve A, for all properties other than specific heat the same as those of water, indicates the relative base weight

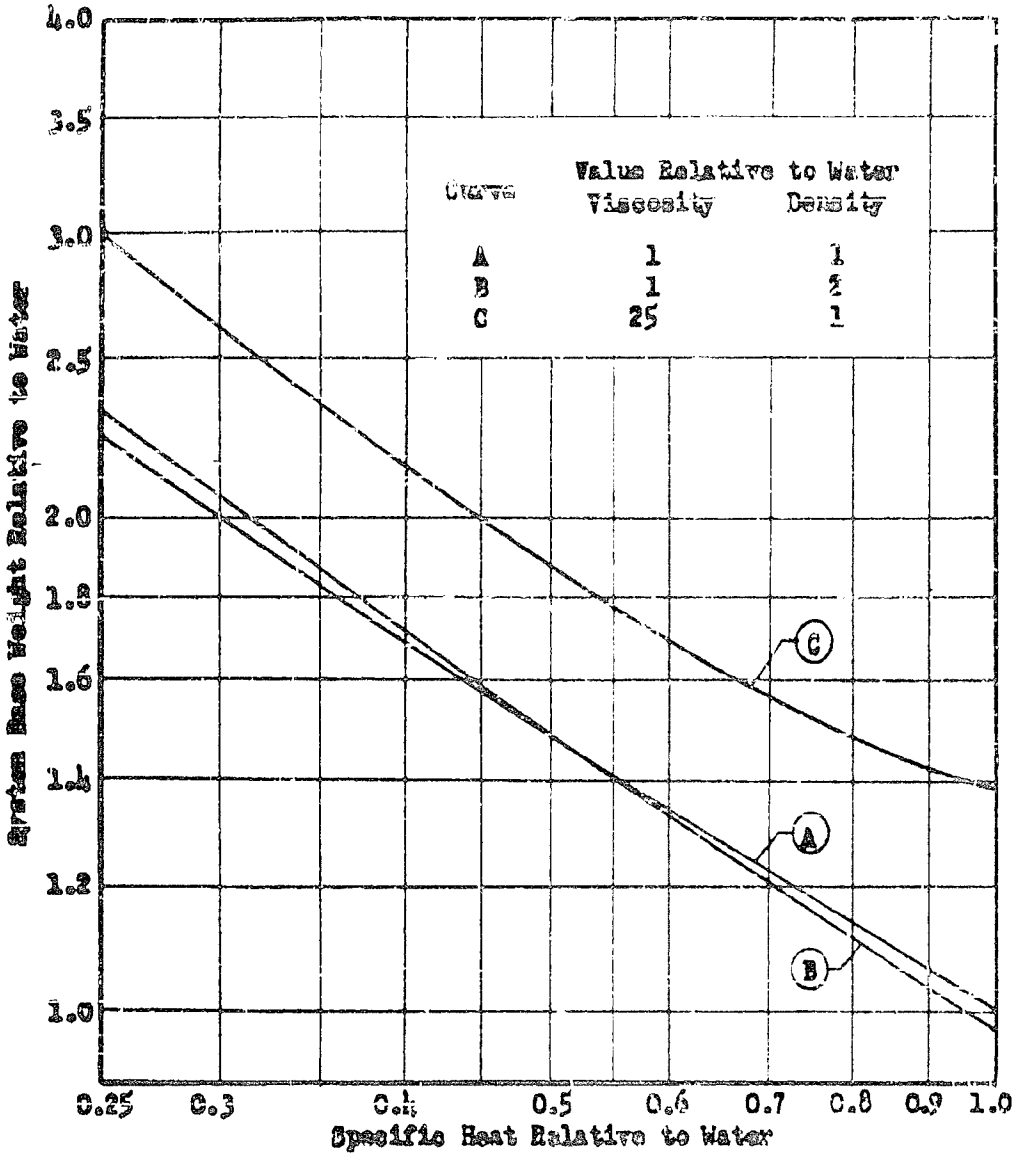


Figure 3. Effect of Specific Heat of Transfer Fluid on Base Weight of Expendable Cooling System

to change in inverse proportion to specific heat raised to a power varying from 0.55 at high specific heat to 0.64 at low specific heat. Thus, a fluid having a specific heat only half as large and all properties equal to those of water causes the system base weight to be somewhat less than 50 percent greater. If its specific heat should be only one-fourth that of water the system base weight would be increased by more than 125 percent.

The trends of the other curves in Figure 3 are similar to those of curve A. Curve B for a fluid having a density twice that of water is almost identical. The slope of the curve is almost constant and varies from -0.62

to ~0.64. Curve C for a fluid having a viscosity 25 times that of water has a greater slope than the other two curves at low specific heat. However, with an initial decrease of specific heat from that of water, the base weight increases not as rapidly for the high-viscosity fluid, being inversely proportional to the specific heat to the 0.2 power.

Comparison of curves A, B and C in Figure 3 discloses that the effect of decreased specific heat can be compensated to a limited extent by increased density when the specific heat is great. But at low specific heat, increased density also increases the base weight. Reducing the specific heat alone by about 34 percent has the same effect on the base weight as increasing the viscosity alone 25 times, if all other properties are the same as those of water. The effect of reducing the specific heat alone by 75 percent is the same as increasing the viscosity 25 times and simultaneously reducing the specific heat by about 63 percent.

Figure 4 represents the effect of transfer fluid density on the system base weight. Curve A, for all properties other than density the same as those of water, indicates the relative base weight to change in inverse proportion to the density raised to the 0.05 power. Thus, use of a fluid having a density 50 percent greater and all other properties the same as water results in a system base weight only 2 percent smaller. A further increase of density to twice that of water causes a total reduction of base weight of a little more than 3 percent.

Curve B in Figure 4 for a fluid having a viscosity 25 times that of water shows that the density of a high-viscosity fluid is more important. The base weight varies then in inverse proportion to the density raised to a power between 0.12 and 0.24. This is due to the fact that the high pumping power at high viscosity is reduced appreciably by increased density and its effect is not materially offset by the increase in the weight of the transfer lines with increased density. At the low viscosity, represented by curve A, these effects are almost in balance. In contrast, at low viscosity and low specific heat, i.e., one-fourth that of water, as shown by curve C, the base weight increases with density. The slope of the curve varies from about 0.01 to 0.06. The great circulation rate (required because of the low specific heat) also necessitates the use of larger distribution lines which causes the weight increase of the lines (due to larger density) to exceed any possible reduction in base weight due to reduced pumping power. This relationship also causes the intersection of curves A and B in Figure 3.

The greatly different magnitudes of base weight, represented by curves A, B and C in Figure 4, indicate that the effect of fluid density is minor in comparison to specific heat and viscosity. As indicated by the average slopes of curves A in Figures 2, 3 and 4, the most important property by far is specific heat, the second is viscosity and the third is density. Disregarding the effect of thermal conductivity, the curves in Figures 2, 3 and 4 should be useful in estimating the relative system base weight resulting from the use of a transfer fluid of known physical properties.

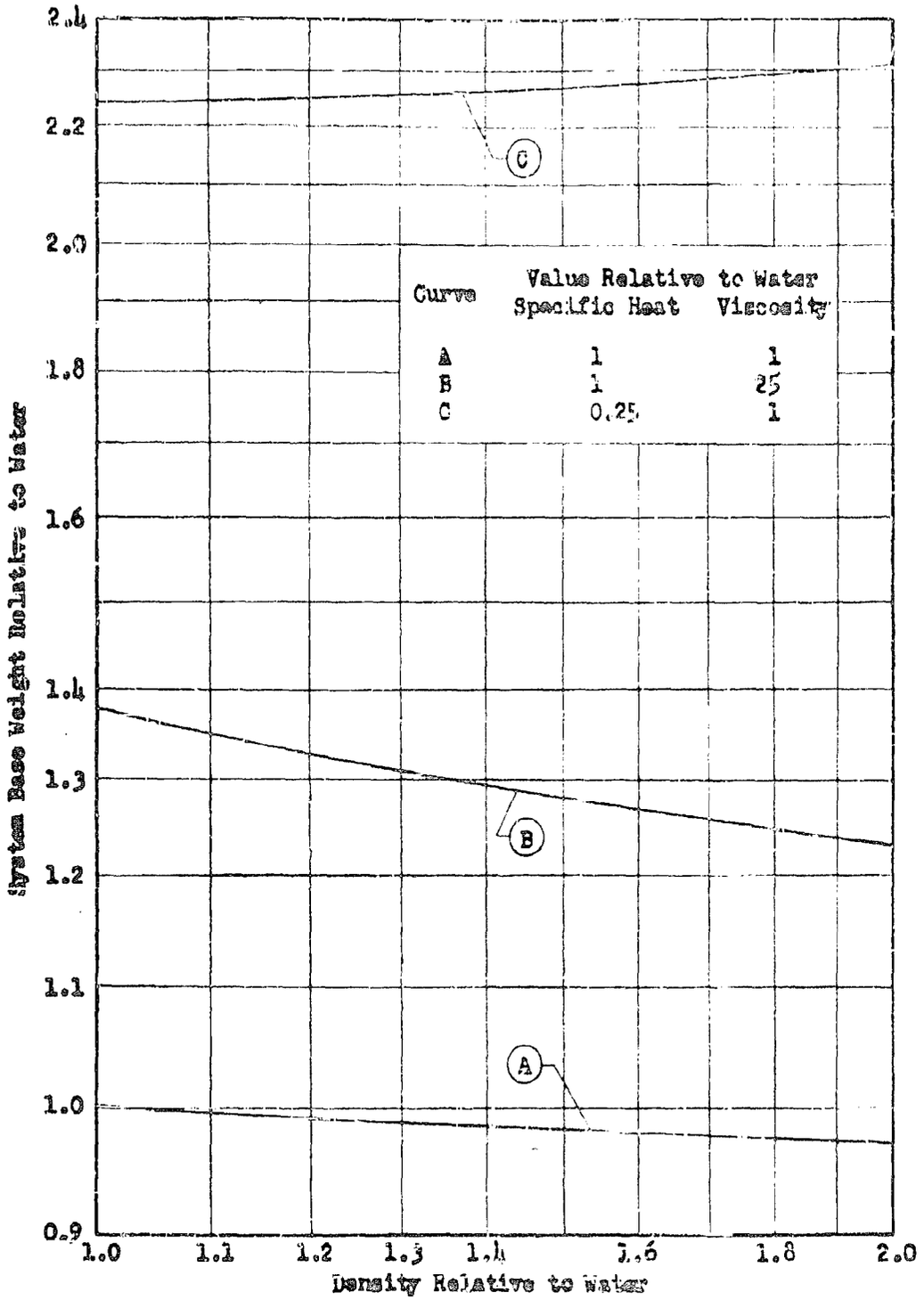


Figure 4. Effect of Density of Transfer Fluid on Base Weight of Expendable Cooling System

For example, Fluorochemical O-75 at 115°F has the following properties, relative to water, density 1.71, viscosity 1.6, specific heat 0.26, and thermal conductivity 0.165. The estimate can be made from curve B in Figure 3 which indicates a relative base weight of about 2.25 at a relative specific heat of 0.26. According to curve C in Figure 4, the base weight should be reduced about 1 percent for the change of relative density from 2 to 1.71. According to curve B in Figure 2, the base weight should be increased about 1 percent for the change in relative viscosity from 1 to 1.6. Thus 2.25 is the final estimate. This is a fair approximation of the calculated value of 2.42 shown in Table 17 for the O-75 fluid. The difference of 7.5 percent between the estimated and calculated relative base weight of the O-75 fluid occurs because the appreciable deviation of the thermal conductivity from that of water has been disregarded.

As another example, a MIL-O-5606 hydraulic fluid has the following relative properties: density 0.835, viscosity 15.7, specific heat 0.509 and thermal conductivity 0.214. Curve A in Figure 3 indicates a relative base weight of 1.46 for a relative specific heat of 0.509, but for relative density and viscosity each at unity. Curve A in Figure 2 indicates a relative base weight of 1.35 for a relative viscosity of 15.7, but for relative density and specific heat each at unity. An interpolation of the slopes of curves A and B in Figure 4 at the relative density of 1.0 may be used to estimate the density effect. The estimated exponent is -0.20. Therefore the density factor is estimated to be $(0.835)^{-0.20} = 1.04$. The estimated relative base weight is $(1.46)(1.35)(1.04) = 2.05$. A calculated value of 2.53 is shown in Table 17 for the same fluid. This is not in good agreement. Neglecting the effect of thermal conductivity is here of much greater consequence.

The difference between calculated and estimated base weights is actually not the effect of the thermal conductivity alone but of the Prandtl number, i.e., the ratio of the product of specific heat and viscosity to thermal conductivity. The relative Prandtl number of the O-75 fluid is 2.52, that of the MIL-O-5606 fluid 37.2. Over this range, the inaccuracy of the estimate is changed from 7.5 to 23 percent when the Prandtl number variation is neglected completely. Therefore, the base weight appears to be proportional to the Prandtl number to a power somewhat less than 0.06, when the line length is great.

Estimates made on basis of Figures 2, 3 and 4 are compared above with calculated values for the same system length, cooling capacity and temperature level. Greater inaccuracies must be expected in particular when the line length is considerably shorter. The Prandtl number effect becomes more pronounced when the heat exchanger represents an appreciable percentage of the total system weight, as it does in short systems.

3. System Characteristics for Representative Fluids

Combined effects of fluid properties and comparative merits of the various groups of fluids classified in Section III are illustrated by the results of design calculations for optimum systems using fluids representative of each group.

Table 16. Properties of Representative Heat Transfer Fluids

Group No.	Fluid	Temp. °F	Density lbs per cu ft	Viscosity lbs per ft-hr	Specific heat Btu per lb-°F	Thermal conductivity Btu per hr-ft-°F	Prandtl number
1	Water	115	61.6	1.450	1.0	0.366	3.96
		175	60.5	0.864	1.0	0.386	2.24
2.a	Methanol-water solution, 53-47 weight percent	115	54.9	2.080	0.85	0.1895	9.33
		175	53.6	1.094	0.87	0.1920	4.94
2.b	Ethylene glycol-water solution, 62.5-31.5 weight percent	115	54.8	6.35	0.773	0.2165	22.07
		175	54.5	3.14	0.811	0.2105	12.07
3.1	JP-3 Aircraft fuel	115	46.1	1.210	0.515	0.0864	7.21
		175	44.2	0.895	0.524	0.0848	5.72
3.2	MIL-O-5606 Hydrocarbon hydraulic fluid	115	51.4	22.75	0.509	0.0785	147.5
		175	49.9	12.60	0.538	0.0772	87.8
4	Fluorochemical O-75	115	105.5	2.320	0.260	0.0605	10.0
		175	100.5	1.453	0.269	0.0445	8.8
5	Propylene glycol	115	63.4	33.9	0.635	0.1190	180.5
		175	61.9	16.0	0.680	0.1100	99.0
6	Isobutyl-isopropyl Silicate	115	53.6	2.859	0.478	0.0625	21.8
		175	51.8	1.380	0.550	0.0631	12.0
7	DC-200 Silicone fluid, 10 centistoke grade	115	57.2	14.78	0.340	0.0772	65.0
		175	55.4	8.20	0.345	0.0748	42.5

Table 17. Characteristics of Distribution System and Heat Exchanger of Indirect Expendable Water System for Various Heat Transfer Fluids

Fluid No. (See Table 16)	Temp. potential equip.-ult. sink, °F	Distribution line length, ft	Optimum boiling temp. difference, °F	Fluid flow rate, lbs per hr	Optimum line diameter, inches	Delta p, line pressure drop, lbs per sq in.	Heat exchanger pressure drop, lbs per sq in.	Pumping power, horsepower	Distribution line weight		Power supply system weight		Added fuel weight		Heat exchanger weight		Specific system weight	
									lbs per 25 hp	Percent system base weight	lbs per 25 hp	Percent system base weight	lbs per 25 hp	Percent system base weight	lbs per 25 hp	Percent system base weight	$\frac{\Delta W_E(1-K_{ref})+W_U}{hp}$	Percent water system base wt.
1	30	300	12.5	6,200	.630	133.0	2.4	0.968	75.0	61.5	19.4	15.9	3.9	3.2	23.7	19.4	4.88	100
1	150	300	30.0	886	.266	24.0	1.5	0.262	23.0	71.9	5.2	16.4	1.1	3.3	2.7	8.4	1.28	100
1	150	50	30.0	886	.266	41.8	1.5	0.046	3.6	31.4	5.0	43.5	0.19	1.6	2.7	23.5	0.46	133
2a	30	300	12.0	6,920	.698	128.5	12.8	1.30	82.4	59.0	26.0	18.6	5.3	3.7	26.3	18.7	5.56	114
2a	150	300	30.0	1,020	.297	24.0	9.1	0.322	25.0	70.6	6.4	18.1	1.3	3.7	2.7	7.6	1.42	111
2a	150	50	30.0	1,020	.297	37.3	9.1	0.084	4.2	34.6	5.0	41.1	0.25	2.1	2.7	22.2	0.49	104
2b	30	300	10.5	6,830	.717	135.1	37.5	1.58	85.7	53.5	31.5	19.6	6.4	4.0	36.7	22.9	6.41	138
2b	150	300	24.6	1,081	.315	25.0	16.3	0.384	27.3	68.1	7.0	17.4	1.4	3.5	4.4	11.0	1.60	125
2b	150	50	24.6	1,081	.315	39.5	16.3	0.084	4.2	34.6	5.0	41.1	0.25	2.1	4.7	23.9	0.49	104
3.1	30	300	10.6	10,550	.871	100.8	12.1	1.88	105.0	56.4	37.6	20.2	7.6	4.1	35.9	19.3	7.43	152
3.1	150	300	24.0	1,530	.372	176.1	9.9	0.444	31.4	67.2	8.9	19.0	1.8	3.8	4.7	10.0	1.87	146
3.2	30	300	6.6	8,800	.851	130.0	150.0	3.48	108.0	35.0	69.6	22.5	14.1	4.5	117.0	37.9	12.36	251
3.2	150	300	15.5	1,450	.382	217.7	118.5	0.709	34.0	52.4	14.2	21.9	2.9	4.5	13.3	21.2	2.59	202
3.2	150	50	16.1	1,456	.383	36.2	144.0	0.383	5.7	20.7	7.7	27.9	1.5	5.8	12.5	45.6	1.10	241
4	30	300	9.6	19,850	.905	129.0	20.2	2.41	190.8	64.7	48.2	16.4	9.8	3.3	45.8	15.6	11.80	242
4	150	300	21.3	3,040	.398	218.5	21.0	0.526	48.8	72.1	10.5	15.5	2.1	3.1	5.3	9.3	2.70	212
5	30	300	7.5	7,350	.748	156.7	235.0	3.30	99.4	37.6	66.1	25.1	13.4	5.1	85.1	32.2	10.55	215
5	150	300	17.6	1,169	.382	262.0	144.1	0.558	30.1	56.1	11.2	20.8	2.3	4.3	10.1	18.8	2.11	168
6	30	300	9.5	10,700	.863	113.0	44.0	2.28	112.2	52.4	45.6	21.3	9.2	4.3	47.2	22.0	8.56	176
6	150	300	22.4	1,505	.359	196.0	22.6	0.462	31.7	65.6	9.2	19.1	1.9	3.9	5.5	11.4	1.94	151
6	150	50	23.9	1,522	.361	32.6	32.0	0.138	5.3	34.1	5.0	32.1	0.55	3.6	4.7	30.2	0.82	135
7	30	300	6.0	12,840	.964	115.0	128.5	3.66	138.3	36.9	73.2	19.5	14.8	3.9	149.0	39.7	15.03	308
7	150	300	12.0	2,205	.411	176.9	94.6	0.785	42.8	48.7	15.7	17.8	3.2	3.6	26.3	29.9	3.52	274

Equipment temperatures of 130° and 250°F are considered, corresponding to temperature potentials of 30° and 150°F between the equipment and the ultimate water coolant evaporating, as mentioned previously, at 100°F. The fluid properties at an intermediate temperature of 115°F, respectively 175°F, are assumed as the bases for the design calculations. These properties of the selected representative fluids are given in Table 16. The characteristics of the distribution system and heat exchanger for these temperature potentials of 30° and 150°F and line lengths of 300 and 50 feet are presented in Table 17.

The wide variation of optimum boiling temperature difference, to which the heat exchanger surface is inversely proportional, is the result of the available temperature potential, the greatly different fluid properties and the distribution line length. For the design temperature potential of 30°F, from 20 to 55 percent of the available temperature difference is utilized on the expendable-fluid-side of the heat exchanger. However, at the higher temperature potential of 150°F between the equipment and the expendable fluid only 8 to 20 percent is utilized in this manner. The generally larger fluid flow rates required at the small temperature potential result in much larger optimum heat exchanger surfaces (smaller ΔT_{IU}) so as to hold down the flow rate, the pumping power, and the weight of the distribution line. When the distribution line is shorter and the overall temperature potential is the same, the optimum heat exchanger surface is smaller (larger ΔT_{IU}) since this reduces the heat exchanger weight which represents a larger percentage of the system weight. The temperature difference ΔT_{IU} of 30°F shown in Table 17 for water and the methanol-water solution at 150°F temperature potential is the assumed temperature difference of maximum heat flux in boiling heat transfer from a submerged surface.

The optimum fluid flow rates for any given temperature potential and line length increase, as shown in Table 17, in the same order as the values of specific heat of the various fluids decrease (Table 16). In some instances of small differences of specific heat the order may be reversed because of the effect of another property on the total system weight. At the smaller overall temperature potential, the flow rates are greatly increased since they are inversely proportional to the difference between the temperature potential ($T_{EU} - T_U$), and the boiling temperature difference ΔT_{IU} and, as pointed out above, the optimum value of ΔT_{IU}, constitutes a bigger percentage of ($T_{EU} - T_U$), the smaller the latter. The effect of line length is insignificant. The range of relative flow rates between water and Fluorochemical O-75 is greater than 1 to 3 and somewhat less than the range of specific heats which approaches 4 to 1.

The optimum distribution line diameters follow essentially the same order as the flow rates, but are also affected by the fluid density and viscosity. This is apparent in that the line diameter for the Fluorochemical O-75 is smaller than that for the Silicone fluid DC-200, although the flow rate of the former is 40 to 50 percent greater. However, the Fluorochemical's density is approximately 80 percent greater. The effect of viscosity is indicated by the line diameters for the JP-4 fuel and the MIL-O-5606 hydraulic oil. At 30°F temperature potential, the flow rate for the latter is appreciably smaller, but its line diameter is only slightly smaller since its

viscosity is almost 19 times greater. Obviously, the effect of viscosity on optimum line diameter is opposite to that of density, but is not as great. The line diameters increase between water and the Silicone fluid DC-200 by 50 to 65 percent, but are always less than 1 inch (25 kw cooling capacity), even at the low temperature potential and for the fluids requiring the highest flow rates. It is apparent that the weight of the distribution lines is more critical than pumping power requirements so that the optimum line diameters are held small at the expense of increased pressure drop. The effect of line length is insignificant.

The distribution line pressure drops are affected by the flow rate, viscosity and density. The values shown in Table 17 represent the combined effects and, therefore, are difficult to analyse by numerical comparison. It is apparent that the pressure drop decreases with increased flow rate, but increases with viscosity and density. Thus, the JP-3 fuel having the lowest viscosity and density and an average flow rate has the smallest distribution line pressure drop. Water has a relatively high pressure drop because of the low flow rate which results in a small optimum line diameter. For the same line length the pressure drops are almost doubled at the higher overall temperature potential since the line sizes are greatly reduced for optimum system characteristics. Since the optimum flow rate and line diameter are practically independent of line length, the pressure drops are in direct proportion to the line length when the temperature potential is the same. The minimum line pressure drop among the long systems is 101 pounds per square inch at the low temperature potential and 176 pounds per square inch at the high temperature potential. The range of relative values for all the fluids is about from 1 to 1.5.

The pressure drops of the transfer fluids in the heat exchanger are principally affected by the Prandtl number and are generally in the same order. Thus, for optimum boiling temperature differential, a high-Prandtl-number fluid such as, for example, propylene glycol, would have a large pressure drop. The range of relative pressure drops at both temperature potentials is almost 100 to 1. The pressure drop in the heat exchanger of a system with shorter distribution line length is greater since the heat exchanger size is reduced to optimize the total system weight.

The pumping power of the entire distribution system is directly proportional to the total pressure drop through the lines and the heat exchanger and to the flow rate, but inversely proportional to the density. Thus, there are compensating effects which hold the pumping power in the range from 1 to 3.8 for the lower temperature potential and from 1 to 3 for the higher temperature potential. Considering the system's cooling capacity of 25 kilowatts, the pumping powers are small.

For a given length of transfer system, the percentages of the total base weight contributed by various parts of the system are not greatly affected by the temperature potential. Among the long systems, the largest percentage of the weight is in the distribution lines, except for high-Prandtl-number fluids for which the weight of the heat exchanger may well be equal or somewhat greater than that of the distribution lines when the temperature potential is small. The more favorable fluids have less than

20 percent of their weight in the heat exchanger at low temperature potential and less than 10 percent at high temperature potential. Thus with increased temperature potential, the relative weight of the distribution lines increases and that of the heat exchanger decreases. The sum of the percentages of distribution line weight and heat exchanger weight of the long system is between 70 and 80 percent, irrespective of temperature potential and transfer fluid. The weight of the power supply system for long fluid lines constitutes from 16 to 25 percent of the system weight and the weight due to added fuel consumption to compensate for power extraction from the power plant is less than 5 percent.

Among the short systems a more appreciable percentage of the total weight is in the heat exchanger and the power supply system. In particular, the latter becomes relatively heavy if it is assumed that its minimum weight is 5 pounds, irrespective of pumping power, as has been done here for all fluids other than the hydraulic oil which requires a heavier power supply system. The 5-pound minimum weight is believed to be a realistic assumption. Thus, the percentage weight distributions shown in Table 17 for three of the four fluids used in the short system would differ in favor of a lower power supply system weight at cooling capacities much larger than 25 kilowatts.

4. Comparison of Overall Weight Effects of Representative Fluids

Comparing the specific base weights resulting from the various fluids on an absolute basis indicates a very critical effect at low temperature potential. Between water and the Silicone fluid the difference in specific base weight of the long system is more than 10 pounds. At the high temperature potential the difference is 2-1/4 pounds. Consequently, the choice of the fluid would be much more important when only a small temperature potential is available between the equipment and the ultimate fluid. Similarly, when the distribution system is short, the absolute differences do not represent large weights and, therefore, the choice of fluid appears to be less important.

The specific base weights relative to water in systems of the same length and temperature potential differ appreciably for the various fluids. The relative values are lower at the higher temperature potential because the water system operates at the limiting ultimate temperature differential of 30°F. In the order of increasing system base weight (shown in Table 17), the fluids may be given the following classifications.

1) Water (Group 1)

2) Methanol-water solution (Group 2)

3) Ethylene glycol-water solution (Group 2)

4) JP-3 Aircraft fuel (Group 3.1)

5) Isobutyl-isopropyl silicate (Group 6)

6) Propylene glycol (Group 5)

7) MIL-O-5606 Hydraulic fluid (Group 3.2)

8) Fluorochemical O-75 (Group 4)

9) DC-200 Silicone fluid (Group 7).

The aqueous solutions (Group 2) come closest in relative aircraft penalty to water because their specific heats are high compared to the other fluids. The ethylene glycol-water solution is inferior to the methanol-water solution because of lower specific heat and appreciably greater viscosity, the latter particularly at the low fluid temperature corresponding to the smaller temperature potential. Although the specific heat of the JP-3 fuel is more than 30 percent smaller than that of the ethylene glycol-water solution, its relative system base weight is not greatly different because its low viscosity has a compensating effect.

The worst fluid, causing a specific system base weight 3 times that for water, appears to be the DC-200 Silicone fluid. It has the unfortunate combination of the second lowest specific heat, the second highest viscosity and fourth lowest thermal conductivity. The other Silicone fluids of much reduced viscosity should show somewhat better characteristics which would be more comparable to the O-75 Fluorochemical. The O-75 fluid is the next poorest fluid. It has an effect not appreciably different from the MIL-O-5606 hydraulic fluid which also causes a high penalty that is 2 to 2-1/2 times that of water. The Fluorochemical having the lowest specific heat and thermal conductivity of all fluids does not appear as the worst fluid only because it has a low viscosity which has some compensating effect. In contrast, the MIL-O-5606, which results in practically the same system base weight as the O-75 fluid, has a fairly high specific heat, but it has the highest viscosity of all fluids and relatively low thermal conductivity. Its properties, other than viscosity, are generally similar to those of the JP-3 fuel which is also a hydrocarbon. However, the hydraulic fluid's viscosity is 14 to 19 times larger. This is the principal cause for a 38 to 66 percent greater system base weight.

The relative magnitudes of the system base weights due to the different transfer fluids do not define completely the effects of the various fluids on the aircraft, since the weight of the ultimate component is not included. Only at very short operating times of the expendable fluid systems would the relative base weights be almost representative of the relative aircraft penalties. However, the significance of the larger base weights is apparent when they are compared with the base weight of the water system and the added consumption of the expendable coolant giving the same total weight and a measurable operating time. This is particularly significant at small temperature potential when the base weight is appreciable. It is illustrated in Figure 5 which is a plot of the system gross weight parameter versus system operating time. The gross weight increase of the aircraft for a water distribution system and the following operating times would correspond to the following fluids at zero operating time: 16 minutes - methanol-water solution, 25 minutes - ethylene glycol-water solution, 43 minutes - JP-3 fuel, 1 hour - isobutyl-isopropyl silicate, 1 hour 24 minutes - propylene glycol, 1 hour 55 minutes - O-75 Fluorochemical, 2 hours 4 minutes - MIL-O-5606 hydraulic fluid.

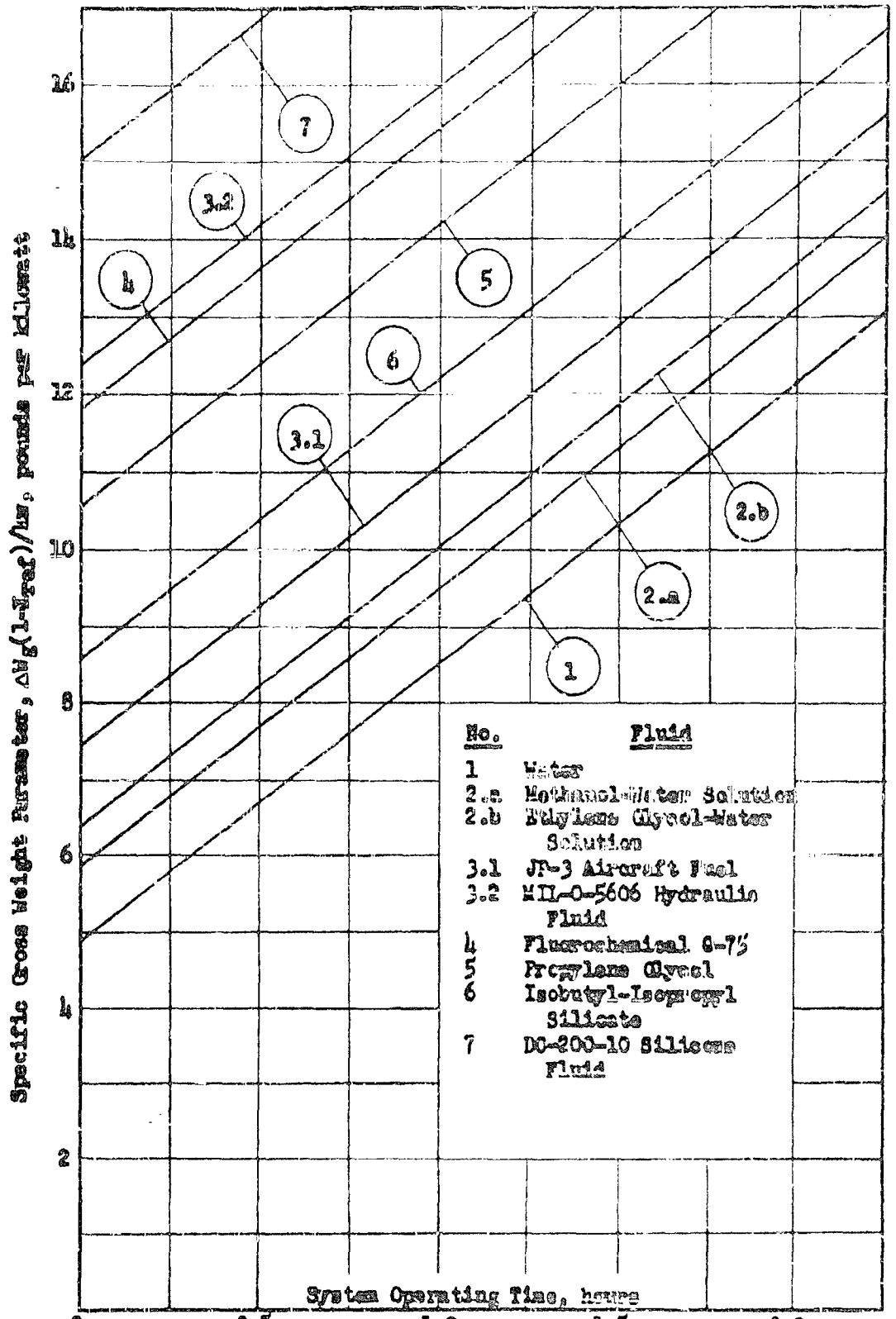


Figure 5. Variation of System Gross Weight Parameter with Operating Time of Expendable Cooling System for Various Transfer Fluids. Temperature Potential $(T_{g_{in}}-T_{ti})=30°F$. Distribution Line Length $L_D=200$ feet

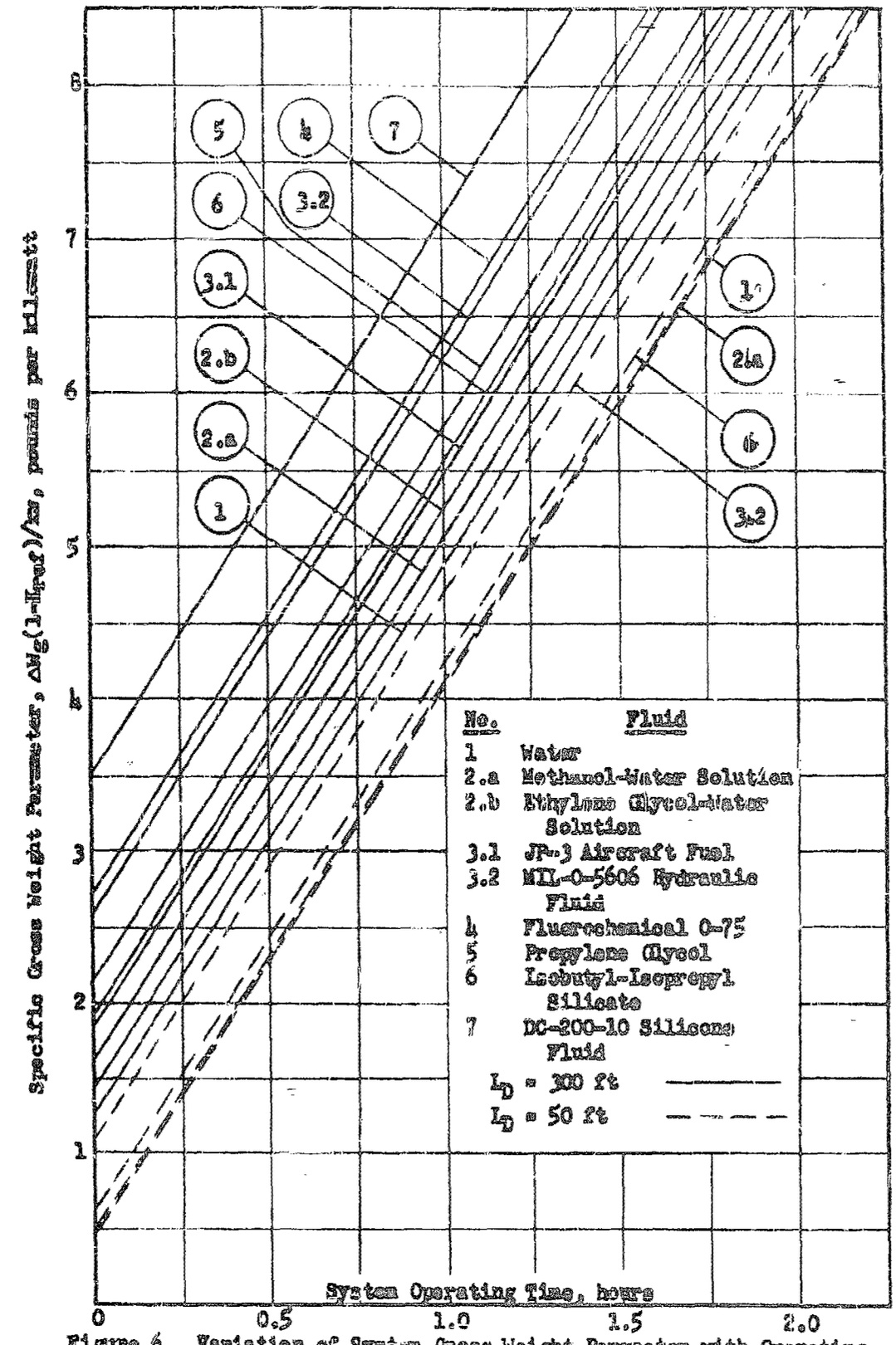


Figure 6. Variation of System Gross Weight Parameter with Operating Time of Expendable Cooling System for Various Transfer Fluids. Temperature Potential, $(T_{Es}-T_U)$ = 50°F

A similar effect exists at higher temperature potential, but of less significance since the system base weights are smaller. The equivalent operating times of the water system, indicated in Figure 6 to correspond to the base weight of the other systems, are shorter than those indicated in Figure 5. These times and corresponding fluids are, for example: 2.5 minutes - methanol-water solution, 10 minutes - JP-3 fuel, 14 minutes - propylene glycol, 24 minutes - 0-75 Fluorochemical and 37 minutes - DC-200 Silicone fluid. The transfer fluid is of still smaller significance when the distribution lines are short because, then, the system base weight is very small. As shown in Figure 6, even the MIL-O-5606 fluid has a small enough base weight that the equivalent operating time of the water distribution system is only 10 minutes.

The relative gross weight increase of the aircraft compared to that caused by a water distribution system decreases with operating time of the expendable system, i.e., with increasing weight of the ultimate system. This is illustrated in Figures 7, 8 and 9. Because of large base weight at small temperature potential, the curves in Figure 7 do not converge as rapidly as those in Figures 8 and 9. In Figure 8 are included several lines for constant percentages of total weight represented by the base weight. Figures 8 and 9 each contain only two constant-percentage base weight lines. In comparison, the range of relative gross weight shown in each of the figures at the same percentage of gross weight represented by the base weight is about the same, but decreases with greater temperature potential and shorter line length. For the short system at high temperature potential, the base weight becomes a small percentage of the total gross weight increase already at relatively short operating time. Obviously, as the base weight becomes a smaller percentage of the total, the relative gross weights do not differ as greatly for the various fluids. Thus, as shown in Figure 8, when the base weight constituted 20 percent of the total, the maximum difference in total gross weight is 15 percent, using the least desirable fluid rather than water. However, when the base weight constitutes 80 percent of the total, there is a difference of 96 percent in the total gross weight.

Comparison on the basis of constant-percentage base weight favors the fluid with the less desirable properties since it would, for the same system design and operating conditions, actually be responsible for a greater percentage of the gross weight in the form of distribution system base weight. This, however, would depend on the type of ultimate system employed. For example, for expendable water systems operating for one hour, Figure 8 indicates that the water distribution system would constitute 27 percent of the gross weight while the DC-200 fluid system would represent 50 percent. The relative gross weight due to the latter fluid would be 47 percent greater than that due to the use of water as a transfer fluid.

Some of the trends, demonstrated by Figures 7, 8 and 9, in the relative effects of different transfer fluids on the aircraft gross weight increase due to an expendable water system should be applicable to other ultimate cooling systems as well. The relative base weights of the expendable system should be considered as the maximum relative values of gross weight increase, resulting from the choice of transfer fluid, that could be approached with any cooling system, no matter how low the penalty of its ultimate component. The significance of the expendable cooling system's

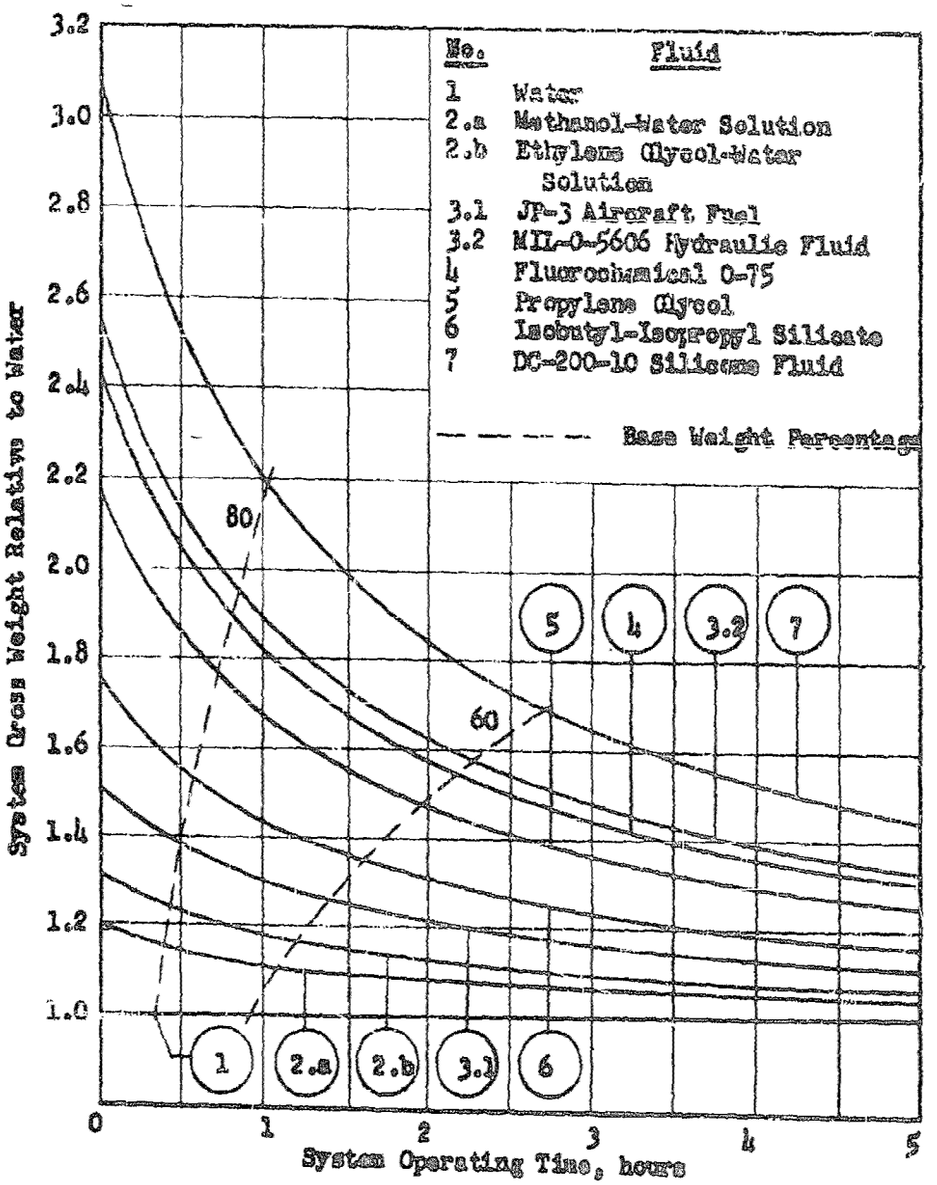


Figure 7. Variation of Relative Gross Weight of Expendable Cooling System with Operating Time for Various Transfer Fluids. Temperature Potential, $(T_w - T_f) = 20°F$. Distribution Line Length, L_D = 300 feet

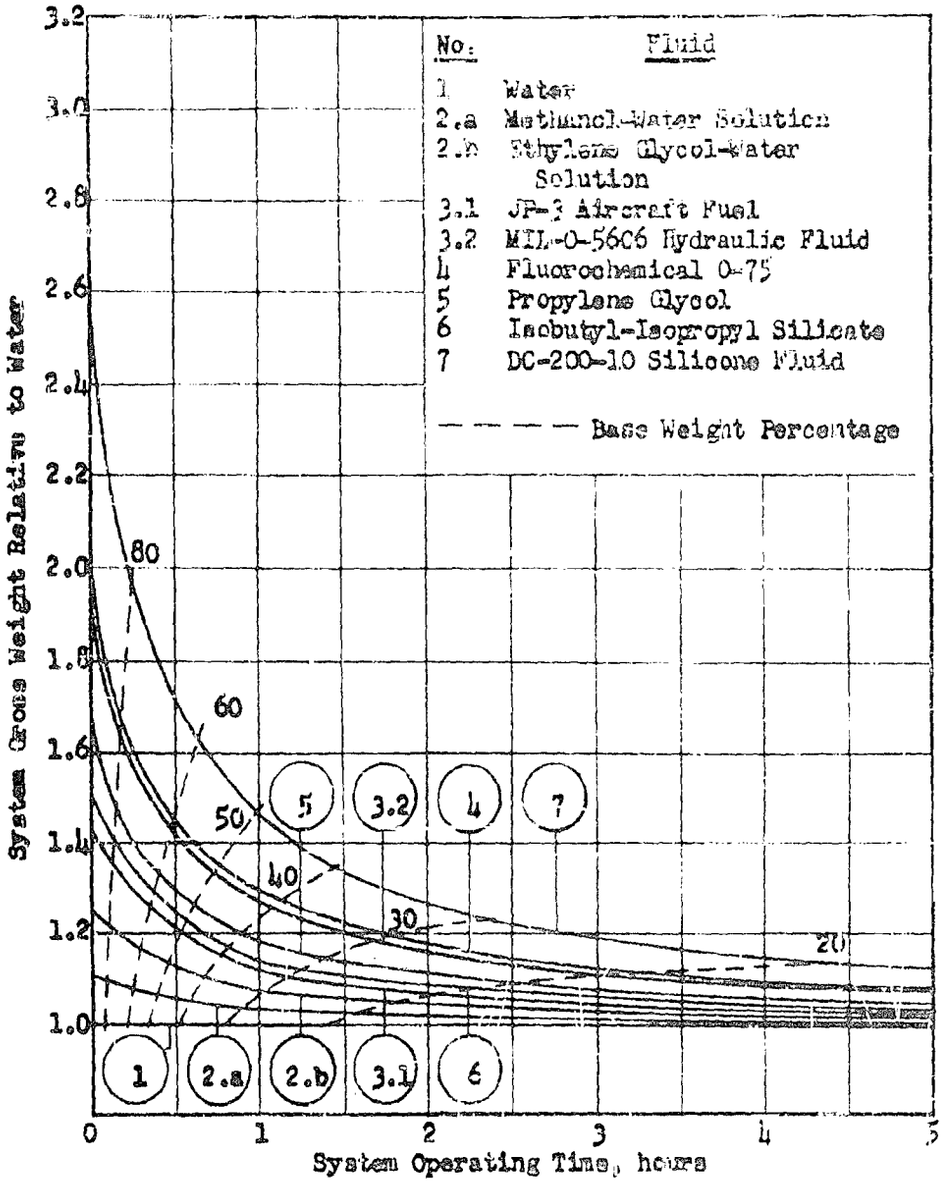


Figure 8. Variation of Relative Gross Weight of Expendable Cooling System with Operating Time for Various Transfer Fluids. Temperature Potential, (T_{E_S}-TU) = 150°F. Distribution Line Length, L_D = 300 feet

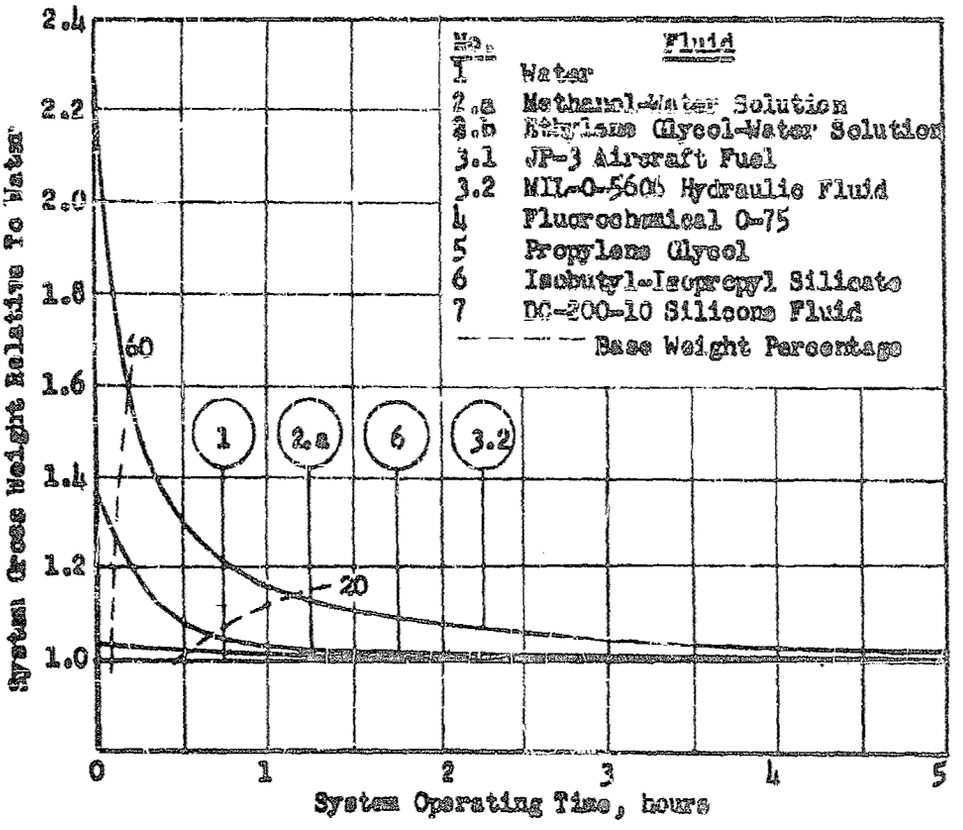


Figure 9. Variation of Relative Gross Weight of Expendable Cooling System with Operating Time for Various Transfer Fluids. Temperature Potential, $(T_{Eq}-T_U) = 150^{\circ}F$. Distribution Line Length L_D = 50 feet.

operating time is the same as that of the operating condition of the ultimate component of any other cooling system. For example, the operating condition of a ram air system may be defined by the flight speed, altitude and air temperature.

Systems having small ultimate component penalty, corresponding to short operating times of the expendable system or base weight percentages from 60 to 90 percent, incur appreciable increase in gross weight percentagewise when a transfer fluid of less desirable physical properties is used. When the length of the distribution line is short, the percentage increase may be greater, but the absolute increase would be small since the entire system gross weight would be small. For any given operating condition of the ultimate cooling system, the relative effect of the transfer fluid is greatest, the smaller the temperature potential between the equipment and the ultimate coolant.

When the ultimate component penalty of a system is great, corresponding to long operating times of the expendable system or base weight percentages of less than 20 percent, the choice of transfer fluid should have percentage-

wise a less appreciable affect on the total gross weight of the entire cooling system, providing the temperature potential is not marginal. However, the absolute increase in system gross weight due to the choice of another fluid may be quite appreciable because of great system weight in general. This is not fully appreciated from the analysis of the indirect expendable system because for it the ultimate-side penalty is essentially fixed, being represented by the weight of fluid required to be evaporated to supply the necessary cooling capacity for a specified length of time. Therefore, the system base weight alone can be optimized. Other systems, such as those using air originating in the flight atmosphere as coolant, are optimized by the combined effect of the distribution system, the intermediate heat exchanger and the ultimate system, since the latter's penalty can be modified appreciably by changing the characteristics of the distribution system and heat exchanger. Thus, when the penalty level of the ultimate cooling system is high, such as it is, for example, for a bleed air system, a transfer system of relatively great base weight would be desirable to hold the combined gross weight to a minimum. Consequently, the use of a transfer fluid of poorer properties, while not changing the gross weight of the entire system by an appreciable percentage, may result in a considerable absolute weight increase, since it must allow only little change of the ultimate component's gross weight.

The evaluation of the effects of various transfer fluids in the expendable cooling system on the basis of equal operating time, to correspond to a specified operating condition of another cooling system having the same percentage base weight for a reference fluid, should provide a general means for determining the desirability of using a specific fluid with any cooling system.

In the following sub-section are presented results of the comparison of the use of two transfer fluids in an indirect ram air system which indicate the general applicability of Figures 7, 8 and 9, and illustrate some of the preceding observations.

Ram Air Cooling Systems

The indirect ram air system has a ram air duct supplying cooling air from the atmosphere to an intermediate heat exchanger and an exhaust duct discharging the heated air to the atmosphere. The heat exchanger is linked to the equipment items by a distribution system in which a heat transfer fluid is circulated by means of a pump. The aircraft gross weight increase resulting from this system may be considered to consist of a base weight and the weight of the ducts and the weight increase due to the external and momentum drag caused by the supply of cooling air. The base weight includes the same quantities as that of the expendable system, listed on page 80. The conversion of drag into gross weight includes considerations of the ratio of fuel weight to gross weight and of the lift-drag ratio of the aircraft.

For a given flight speed altitude and atmospheric air temperature, an optimum design constitutes minimization of the entire gross weight of the system. Considering the heat exchanger size constant, a large circulation

rate of the same transfer fluid will increase the gross weight that may be ascribed to the transfer system, because of greater pumping power, weight of distribution lines and power supply system. Simultaneously, the gross weight penalty due to the ultimate cooling system decreases because of smaller duct sizes and drag. These result from the reduction in cooling air rate which is permissible because a higher mean surface temperature of the intermediate heat exchanger is produced by the increase in transfer fluid flow rate. Increasing the transfer fluid flow rate at constant heat exchanger size will also increase the transfer fluid pumping power requirement of the intermediate heat exchanger so that its size should be increased in order that the total penalty ascribable to the heat exchanger, i.e., its weight plus the system weight resulting from its power requirement, be minimized. This is of significance principally when the transfer fluid has a high Prandtl number so that the penalty due to pumping power required by the heat exchanger is an appreciable part of the total base weight of the system.

Use of a transfer fluid with lower specific heat results in an increase of flow rate which would cause the base weight of the system to increase considerably if the cooling air rate would be maintained constant. Therefore, an increase in cooling air rate and heat exchanger size is required to minimize the total gross weight of the system. Thus, the heat exchanger will have a higher heat transfer effectiveness on the liquid side and a lower effectiveness on the air side. Then, the optimum temperature rise of the cooling air is equivalent to a smaller percentage of the total available temperature potential between the equipment and the total inlet temperature of the cooling air.

1. Methods of Analysis

Like for the expendable system, the methods of analysis for the ram air system will be presented in a future report dealing with characteristics of various types of aircraft equipment cooling systems. The results of design calculations made for the optimum use of the methanol-water solution (freezing at -65°F, Table 16) and the MIL-O-5606 hydraulic fluid (Table 16) are presented in the following.

The calculated results are based on a cooling capacity of 25 kilowatts. The effectiveness of the equipment is taken as 90 percent. The effects of increased fuel consumption of the power plant due to extraction of pumping power are evaluated on the same basis as for the expendable system (see page 82) and the same considerations apply. Similarly, for the conversion of drag to gross weight representative aircraft characteristics are assumed which are within ± 50 percent of any value that is likely to be encountered. However, the effect of drag on the gross weight is relatively small because, for the conditions analyzed, the drag contributes only on the order of 20 percent of the total gross weight.

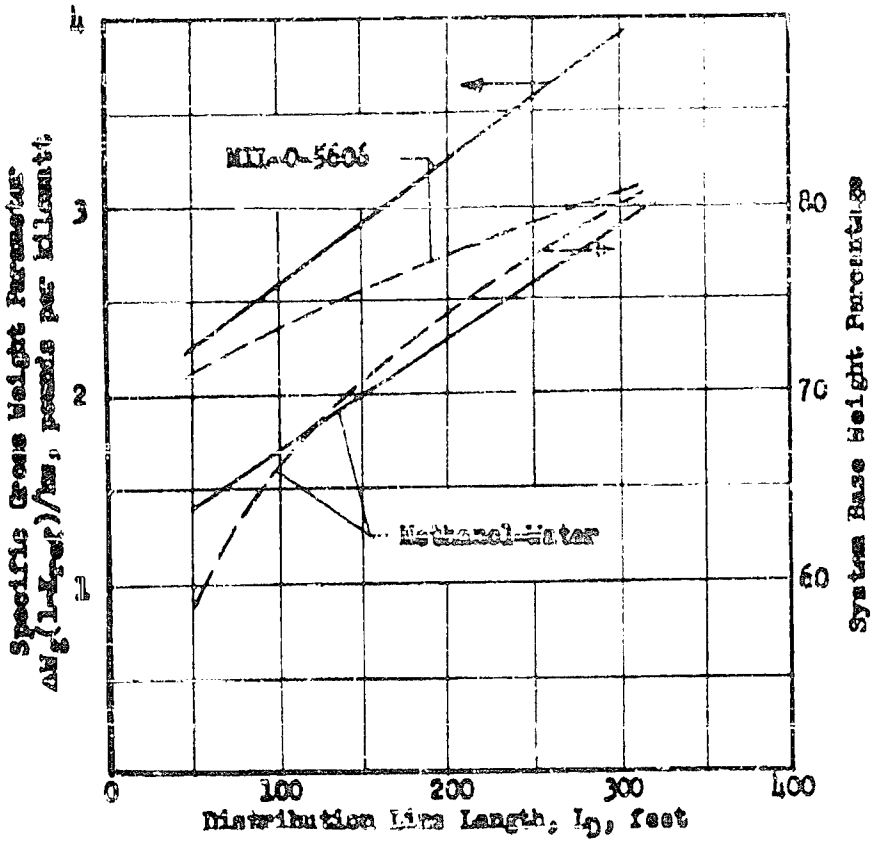


Figure 10. Typical Variation of System Gross Weight Parameter of Ram Air System with Distribution Line Length for Two Transfer Fluids. Altitude, 50,000 feet. Flight Speed, M_{∞} = 0.8. Equipment Temperature T_{Eq} = 190°F.

2. Comparison of Overall Weight Effects of Fluids

Typical effects of the use of the two fluids with different lengths of transfer lines are illustrated in Figure 10. The altitude is 55,000 feet, the flight Mach number, M_{∞} = 0.8 and the equipment temperature, T_{Eq} = 190°F. The total ram air temperature is T^0_{∞} = 17°F. This gives an overall temperature potential of 190 - 17 = 173°F.

The absolute difference in the gross weight parameter due to the two fluids is smaller when the distribution line is short. The difference is 0.85 pound per kilowatt at a line length of 50 feet, compared to 1 pound per kilowatt at a line length of 300 feet. However, the relative increase at 50 feet is 61 percent, compared to 35 percent at 300 feet. The greater percentage increase at short length is due to the fact that in order to optimize the system the hydraulic fluid requires a much larger heat exchanger than the methanol-water system. This heat exchanger represents a greater percentage of the total gross weight when the line length is short. This is also indicated by the difference in the percentage of total gross weight represented by the base weight. At 300 feet line length the percentages of

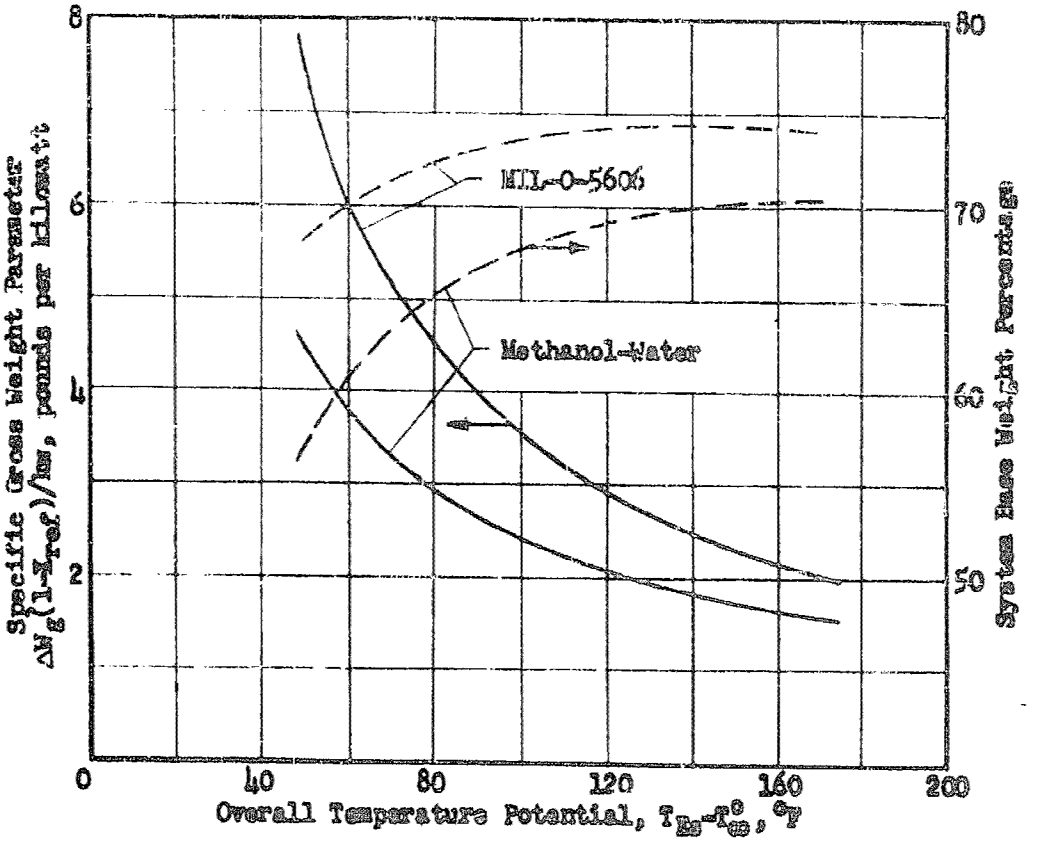


Figure 11. Typical Variation of System Gross Weight Parameter of Ram Air System with Overall Temperature Potential for Two Transfer Fluids. Altitude, 40,000 feet. Flight Speed, $M_{\infty} = 1.2$. Distribution Line Length, L_D = 100 feet

system base weight represent 80 and 81 percent of the total. They are practically the same for both transfer fluids, indicating the same increase of 35 percent in both ultimate component and base weight penalties due to the use of the hydraulic oil. At 50 feet line length, the base weight for the hydraulic fluid is 71 percent, as compared to 59 percent for the methanol-water solution, which indicates that for the shorter system an increase in ultimate component penalty to reduce the base weight is less effective.

The effect of available temperature potential on the comparative aircraft gross weight increase due to the use of the two transfer fluids is illustrated in Figure 11 for typical operating conditions. The altitude is 40,000 feet, the flight Mach number, $M_{\infty} = 1.2$ and the line length L_D = 100 feet. At small temperature potential the ultimate component penalty increases rapidly with a small decrease in mean heat exchanger surface temperature, while base weight decreases at a smaller rate. Therefore, the increase in base weight resulting from the use of a poorer transfer fluid can not be compensated for effectively by increasing the ultimate component penalty. The percentage base weight of the system using the poorer transfer fluid must be greater and the total gross weight increase is appreciable.

At a temperature potential of 50°F, the percentage base weight of the system with the hydraulic fluid is 68 percent, that of the system with the methanol-water solution is 57 percent. The total gross weight of the system using the hydraulic fluid is 69 percent greater. The base weight of the system using the hydraulic fluid is more than twice that of the methanol-water system, while the ultimate component penalty is increased by about one-fourth.

For high temperature potential the ram air system, like the expendable system, can be designed for greatly different transfer fluids without appreciable effect on the total gross weight of the system. This is shown in Figure 11 by a difference of only 25 percent between the gross weight of the hydraulic oil and methanol-water systems at 169°F temperature potential. At this temperature potential a small increase in the ultimate component penalty adequately compensates for the increase of base weight due to a poorer transfer fluid. Also the absolute gross weight at high temperature potential is small so that the added aircraft gross weight, using an inferior transfer fluid, would not represent a large aircraft weight increase.

3. Estimation of Overall Weight Effects of Fluids by Means of Expendable System Data

Comparison of the optimum design data calculated for the ram air cooling system with those for the expendable cooling system indicates to what extent it is possible to estimate the effect of designing for a different transfer fluid in one cooling system, if data on the effects of designing for both fluids in an expendable system are available. As the basis of comparison should be taken the variable which can be correlated directly with the operating condition of the ultimate component of the cooling system. This is the base weight percentage of the system corresponding to the reference fluid. Then, the operating time of an expendable system of equal temperature potential, distribution line length and similar cooling capacity, corresponding to the base weight percentage of the reference fluid obtained with the other cooling system, should be an adequate basis for predicting the relative gross weight of the other system using a different transfer fluid.

In Figure 10, at a line length of 50 feet the respective values of the gross weight parameter and base weight percentage for the methanol-water solution and the MIL-O-5606 fluid are 1.4 and 2.25 pounds per kilowatt and 59 and 71 percent. Therefore, the gross weights are in the ratio of 1:1.61. For the same base weight percentage of 59 for the methanol-water transfer fluid, the expendable system having also a line length of 50 feet has, as shown in Figure 9, a relative gross weight of 1.04 and a corresponding operating time of about 8 minutes. At this operating time, Figure 9 shows the relative gross weight of the expendable system using the MIL-O-5606 fluid to be 1.72 and the corresponding base weight percentage to be probably greater than 70 percent. Thus, the gross weights of the expendable systems are in the ratio of 1:1.65, which compares very closely with the ratio of 1:1.61 determined for the ram air system. However, since the temperature potentials of the two systems are somewhat different, being 150° and 173°F, respectively, the actual agreement would probably be not quite as close.

At 300-foot line length the effect of the difference in temperature potential between 150° and 173°F is quite apparent. In Figure 10, the respective values of the gross weight parameter and base weight percentage for the methanol-water solution and the MIL-O-5606 fluid are 2.9 and 3.9 pounds per kilowatt, and 80 and 81 percent. Therefore, the gross weights are in the ratio of 1:1.35. For the base weight percentage of 80, the expendable system having a line length of 300 feet has, as shown in Figure 8, a relative gross weight of 1.10 and a corresponding operating time of about 6 minutes. At this operating time, the relative gross weight of the expendable system using the MIL-O-5606 fluid is 1.7 and the base weight percentage is about 86 percent. Thus, the gross weights of the expendable system are in the ratio of 1:1.54 which is considerably different than the value given above for the ram air system. However, the agreement is improved when the difference in temperature potential is taken into account. An estimate of the effect can be obtained from Figure 11 which, however, is for 100 feet of line length. The relative gross weights shown for a temperature potential of 150°F are in the ratio of 1:1.35, while those for a temperature potential of 173°F are estimated by extrapolation to be in the ratio of 1:1.23. If the same relative variation could be assumed to be applicable also to a system with 300 feet of distribution line, the gross weights of the ram air system, corresponding to those indicated by Figure 8 for the expendable system, would be in the ratio of 1:1.35 (1.35/1.23) = 1:1.48. This indicates somewhat better agreement.

It is apparent that when the above method of estimating the overall gross weight effect due to designing for another transfer fluid, based on equal reference base weight percentages and an equivalent operating time for definition of the operating condition, is used, actual optimum design values are not checked accurately. For systems such as the ram air system, having low ultimate component penalty and considerable design flexibility, the predicted relative changes in gross weight when using a different transfer fluid would always be greater than the actual change. This is illustrated by the fact that the base weight percentage for the MIL-O-5606 fluid at the same operating time of the expendable system is always greater than the base weight percentage calculated for the corresponding operating condition of the ram air system. The possibility of compensating for increased base weight by means of increasing the ultimate component penalty of the ram air system makes the use of poorer transfer fluids somewhat less penalising.

For systems of greater ultimate component penalty, use of the method illustrated in the preceding and application of the expendable system data, such as those of Figures 7, 8 and 9, should furnish close estimates of the effects of different transfer fluids. In general, good qualitative estimates of transfer fluids effects should be obtained for any type of cooling system using the expendable system data as shown.

SECTION VI

CONCLUSIONS

For the optimum design of aircraft equipment cooling systems, the most desirable physical property of a heat transfer fluid is high specific heat. Second in importance is low viscosity, being followed by high density and low Prandtl number.

The probable maximum variation in cooling system gross weight, using any of the fluids that may deserve consideration, is in the relative range from 1 to 3. The physical characteristics of the distribution systems do not differ appreciably, except for required flow rates, pumping power and heat exchanger size.

The choice of the heat transfer fluid is most critical with long distribution line lengths and when there is but a small temperature difference, 75°F or less, between the equipment and the ultimate heat sink. At temperature differences of 150°F, or greater, the defects of the heat transfer fluid can be compensated for by allowing the penalty of the ultimate component of the system to increase.

The choice of the heat transfer fluid is of reduced significance with short distribution line length. The greater the gross weight of the ultimate heat rejection system, the less important is the choice of the heat transfer fluid. For ram air systems imposing a small penalty on the aircraft for supply of the atmospheric air to the cooling system, the effect of the heat transfer fluid is such that the probable maximum relative range of the gross weight of the system for the available fluids would be 1 to 2. For expendable systems operating for 3 hours or more, or for bleed air systems, both imposing a considerable penalty on the aircraft for providing the ultimate cooling medium, the maximum relative range of the gross weight of the system for the available fluids would be 1 to 1.5. However, since such systems have, in general, a great gross weight, the relatively small percentage increase due to the use of a less desirable heat transfer fluid would make the increase in aircraft gross weight not negligible.

The effects of the choice of the heat transfer fluid on different cooling systems vary. However, they can be compared on the basis of equal percentages of gross weight attributable to the distribution system and the intermediate heat exchanger when the same fluid is used. This permits prediction of the relative change in gross weight resulting from designing for a different fluid in one system when the resulting relative change is known for another system.

As a reference fluid, water has the most desirable properties of the fluids investigated for use as a forced convection heat transfer medium. It has the most suitable combination of the physical properties of specific heat, viscosity, density and thermal conductivity, which control heat transfer, as well as the most desirable properties in terms of corrosiveness, combustibility, toxicity, and stability. However, it is unsuitable for use

in aircraft cooling systems because of its high freezing point of 32°F. It should be considered as a reference fluid to be used as the basis for judging the suitability of other fluids as heat transfer media.

Since water cannot be used, the most desirable fluids for heat transfer systems are the aqueous solutions. In this class of fluids, organic liquids are added to lower the freezing point of water. However, this addition is detrimental to the heat transfer properties. A methanol-water solution freezing at -65°F is the best fluid in this class of liquids but does have a low flash point. The greatest increase in cooling system gross weight that may result from the use of this fluid, rather than water, would be 15 percent.

If safety and non-flammability are important, then an ethylene glycol-water solution should be considered for use. However, the latter's viscosity is high at low temperatures which may cause difficulty at start-up. Relative to water, the maximum probable increase of cooling system gross weight due to the use of this fluid would be about 25 percent.

All fluids considered may be grouped into seven general classes and may be listed in the following order of preference as far as heat transfer properties are concerned:

1) Water (reference fluid)
2) Aqueous solutions
3) Hydrocarbons
4) Organic-inorganic compounds
5) Oxygenated hydrocarbons
6) Fluoro- and chloro-hydrocarbons
7) Silicones

In the hydrocarbons group which contains fuels, lubricants, and hydraulic fluids, the fuels are much better heat transfer fluids than the lubricants and hydraulic fluids which have high viscosity and relatively low thermal conductivity and rank about with the oxygenated hydrocarbons.

The organic-inorganic compounds rank next below the hydrocarbons, followed by the oxygenated hydrocarbons. The fluoro- and chloro-hydrocarbons are inferior because of very low specific heat and thermal conductivity. The silicones are least desirable because of high viscosities and low specific heat. Lower-viscosity Silicones would rank with the fluoro- and chloro-hydrocarbons except for their low flash points.

In the wide temperature range up to 600°F, water again has the most desirable heat transfer properties. The only other fluids, discussed in this report, which can be used up to this temperature are the Fluorochemicals O-75 and N-43, Silicone fluid DC-550, and Ucon 50-HB-280-X.

It has been possible to calculate or to obtain data from various sources on most of the following properties: boiling point, vapor pressure, flash point, fire point, freezing point, pour point, latent heat, density, specific heat, viscosity, thermal conductivity, combustibility, and effect on elastomers.

Data on the stability, toxicity and corrosiveness of fluids have been difficult to obtain or estimate. Available data are difficult to interpret. Very unstable fluids and toxic fluids have not been considered. In general, fluids having relatively safe or high flash and fire points have been investigated. However, a few fluids having low flash points such as alcohols and aviation fuels have been included, some because of their availability in aircraft, others because of superior heat transfer properties.

The available methods which have been collected and are here proposed for the estimation of physical property values give results of sufficient accuracy for the engineering evaluation of existing and new heat transfer fluids.

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APPENDIX I

PROPERTIES OF HEAT TRANSFER FLUIDS BELOW 300°F

The following tables contain data on the properties of heat transfer fluids investigated and considered applicable up to 300°F. The data for several other fluids in the same temperature range are given in Tables 4 to 13 in Section III. The sequence of tables in this appendix is in accordance with the order of group numbers assigned to the various classes of fluids in Section III. page 46.

In all tables, a number in parentheses following a property designation refers to a specific reference for the fluid listed in one of the items of the table.

Table 18. Properties of Water-Methyl Alcohol Solution Freezing at -85°F

At 100°F the density of this solution is 13 percent less than that of pure water, the specific heat is 11 percent less, the viscosity is 29 percent greater, and the thermal conductivity is 34 percent less.

1. Chemical composition, solution of 68 weight-percent methyl alcohol and 32 percent water
2. Average molecular weight, 25.4
3. Initial boiling point, 162°F at 760 mm Hg
4. Flash point (2), about 60°F
5. Freezing point, -85°F

Temp. °F	6. Init. vapor pressure (1) mm Hg	7. Approx. latent heat (3) Btu/lb	8. Density (4) Gms/cc	9. Specific heat (5) Btu/lb-°F	10. Viscosity (6) centipoises	11. Thermal conductivity (7) Btu/hr - ft²(°F/ft)
-50					4.90	0.164
0			0.906	0.660	2.52	0.164
50	38	379	0.884	0.748	1.54	0.164
100	171	358	0.862	0.788	0.88	0.165
150	590	341	0.838	0.806*	0.54	0.165*
200	1650	328	0.813	0.821*	0.33	0.165*
250	3930	317	0.781	0.830*	0.21**	0.165*
300	8050	308	0.749	0.838*	0.14**	0.165*

*Extrapolated linearly
**Extrapolated on ASTM Chart D341-43

Table 18, continued

12. Color, colorless

13. Combustibility (2), combustible

14. Toxicity (2), toxic

15. Stability, stable to 300°F, no data above 300°F

16. Solubility, soluble in water

17. Effect on elastomers (8), some elastomers swell

18. Specific references for this fluid:

(1) Chia Chu, J., Distillation Equilibrium Data, Reinhold Publishing Corp., New York, 1950, pp. 143-146.
(2) Sax, I. N., Handbook of Dangerous Materials, Reinhold Publishing Corp., New York, 1951, p. 242.
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Table 19. Properties of Water-Ethyl Alcohol Solution Freezing at -65°F

At 100°F the density of this solution is 14 percent less than pure water, specific heat 19 percent less, viscosity 112 percent greater, and thermal conductivity 61 percent less.

1. Chemical composition, solution of 70 weight-percent ethyl alcohol and 30 percent water

2. Average molecular weight, 51.4

3. Initial boiling point, 176°F at 760 mm Hg

4. Flash point (2), 80°F

5. Freezing point, -65°F

Temp. °F	6. Init. vapor pressure (1) mm Hg	7. Approx. latent heat (3) Btu/lb	8. Density (4) Gm/cc	9. Specific heat (5) Btu/lb-°F	10. Viscosity (6) centipoises	11. Thermal conductivity (7) Btu/hr-ft²(°F/ft)
-60						0.142
0			0.899	0.64	11.8 **	0.142
80	20	600	0.876	0.77	3.27	0.141
100	106	584	0.853	0.81	1.43	0.141
150	418	566	0.820	0.85	0.71	0.141
200	1230	552	0.804	0.84*	0.455	0.140
250		534	0.779	0.84*	0.30**	0.140*
300	6930	513	0.738	0.83*	0.21**	0.140*

12. Color, colorless

13. Combustibility (2), combustible

14. Toxicity (2), relatively non-toxic

15. Stability, stable to 300°F, no data above 300°F

16. Corrosiveness, corrosive but can be inhibited

17. Solubility, soluble in water

18. Effect on elastomers, some elastomers may swell

*Extrapolated linearly
**Extrapolated on ASTM Chart D341-43

Table 19, continued

19. Specific references for this fluid:

(1) Chin Chu, J., Distillation Equilibrium Data, Reinhold Publishing Corp., New York, 1950, pp. 87-90.
(2) Sax, I. N., Handbook of Dangerous Materials, Reinhold Publishing Corp., New York, 1951, p. 139.
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Table 20. Properties of Water-Ethyl Alcohol Solution Freezing at -85°F

At 100°F the density of this solution is 17 percent less than pure water, specific heat 17 percent less, viscosity 80 percent greater, and thermal conductivity 67 percent less.

1. Chemical composition, solution of 82.5 weight-percent ethyl alcohol and 17.5 percent water

2. Average molecular weight, 36.1

3. Initial boiling point, 174°F at 760 mm Hg

4. Flash point (2), 70°F

5. Freezing point, -85°F

Temp. °F	6. Init. vapor pressure (1) mm Hg	7. Approx. latent heat (3) Btu/lb	8. Density (4) Gms/cc	9. Specific heat (5) Btu/lb-°F	10. Viscosity (6) centi-poises	11. Thermal conductivity (7) Btu/hr - ft²(°F/ft)
-80						0.126
0			0.868	0.65*	8.2**	0.123
50	20	521	0.846	0.69	2.50	0.121
100	111	503	0.823	0.73	1.23	0.119
150	443	494	0.799	0.76	0.68	0.117
200	1346	478	0.773	0.77	0.428	0.115
250		463	0.744	0.76	0.27*	0.113*
300	7850	446	0.704	0.79	0.20*	0.111*

12. Color, colorless

13. Combustibility (2), combustible

14. Toxicity (2), relatively non-toxic

15. Stability, stable to 300°F, no data above 300°F

16. Corrosiveness, corrosive but can be inhibited

17. Solubility, soluble in water

18. Effect on elastomers, some elastomers may swell

*Extrapolated linearly
**Extrapolated on ASTM Chart D341-43

Table 20, continued

19. Specific references for this fluid:

(1) Chin Chu, J., Distillation Equilibrium Data, Reinhold Publishing Corp., New York, 1950, pp. 87-90.
(2) Sax, I. N., Handbook of Dangerous Materials, Reinhold Publishing Corp., New York, 1951, p. 139.
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Riedel, L., Chem. Ing. Tech., Vol. 23, 1951, p. 465;
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Table 21. Properties of R. M. Hollingshead Corp. Water-Base Fluid H-2

Below are given the physical properties of a water-base fluid, H-2, manufactured by the R. M. Hollingshead Corporation. At present, this hydraulic fluid is in use in some Naval aircraft.

At 100°F the specific heat is 21 percent less than pure water, the density is 7 percent greater, the viscosity is 2150 percent greater, and the thermal conductivity is 36 percent less. Removal of the viscosity additive which is present in the fluid would improve its suitability as a heat transfer fluid.

1. Chemical composition (1), water, ethylene glycol, and additives

2. Boiling point, 228°F at 760 mm Hg

3. Freezing point (1), -65°F

Temp. °F	4. Vapor pressure (1) mm Hg	5. Latent heat Btu/lb	6. Density (1) Gms/cc	7. Specific heat (1) Btu/lb-°F	8. Viscosity (1) centipoises	9. Thermal conductivity (2) Btu/hr-ft²(°F/ft)
-50	0.07*	no data available	1.116*	0.690*	730	0.255*
0	0.9		1.099	0.695	34.6	0.238*
50			1.079	0.702	21.2	0.234
100	31		1.066	0.708	14.68	0.232
150			1.046	0.786		0.230
200	385		1.030*	0.870	3.55	0.228
250			0.998*	0.95*		0.226*
300	2300		0.960*	1.02*		0.225*
-40					422	
80					15.73	
130					10.96	
170					6.22	
190					4.54	

10. Coefficient of expansion (1), 0.00029 per °F at 68°F

11. Combustibility (1), non-combustible

12. Toxicity (1), non-toxic

*Extrapolated linearly
**See comments

Table 21, continued

15. Stability (1), excellent but inhibitors may be depleted, no data for higher temperatures above 300°F

16. Corrosiveness (1), contains water but inhibitors prevent normal corrosion; will attack painted parts

15. Solubility, soluble in water

16. Effect on elastomers (1), little or no effect on plastics; rubber swells but does not deteriorate

17. Specific references for this fluid:

(1) Letter and bulletin received from R. M. Hollingshead Company, 3/6/52.
(2) Bates, K. O. and Hazzard, G., Ind. Eng. Chem., Vol. 37, 1945, p. 193.

18. Specific comments on physical properties:

a. The liquid has a very peculiar viscosity-temperature variation. Do not extrapolate without more investigation.
b. Special procedures would be required to prevent corrosion.
c. Peculiar specific heat-temperature curve. Needs further investigation. Data estimated partly from enthalpy-temperature curve. Extrapolation above 200°F is uncertain.
d. Since the exact compositions are unknown, no estimate of molecular weight is given in this table.
e. The method of Othmer was used to estimate latent heat given in this table.
f. The thermal conductivity given in this table is assumed the same as that of ethylene glycol-water mixtures. The values were also checked by empirical equations.
g. The additive to the basic glycol-water mixture has as its principal effect an appreciable increase of the viscosity of the mixture.

Table 22. Properties of Water-Ethylene Glycol Solution Freezing at -65°F

This fluid is to be compared to the Hollingshead Corp. fluid H-2 used as a hydraulic fluid in some Naval aircraft. The properties of both fluids are very similar, except that the viscosity of the pure water-glycol solution is very much lower because of the viscosity additive in the H-2 fluid.

At 100°F the density of this liquid is 8 percent greater than that of pure water, the specific heat is 24 percent less, the viscosity is 360 percent greater, and the thermal conductivity is 40 percent less.

1. Chemical composition, solution of 62.5 weight percent ethylene glycol and 37.5 percent water

2. Average molecular weight, 48

3. Initial boiling point, 232°F at 760 mm Hg

4. Flash point, see comments

5. Freezing point, approximately -65°F

Temp. °F	6. Init. vapor pressure (1) mm Hg	7. Approx. latent heat (2) Btu/lb	8. Density (1) Gm/cc	9. Specific heat (1) Btu/lb-°F	10. Viscosity (1) centi-poises	11. Thermal conductivity (1) Btu/hr-ft²(°F/ft)
-50			1.118	0.663	550*	0.234**
0			1.101	0.695	34	0.228**
50	6	396	1.086	0.730	7.6	0.223
100	32	386	1.069	0.763	3.14	0.218
150	125	375	1.051	0.795	1.70	0.213
200	360	364	1.029	0.830	0.97	0.209
250	1100	352	1.008	0.863	0.64	0.203
300	2450	338	0.981	0.898	0.45	0.198

12. Coefficient of expansion (1), 3.1×10^{-4} per °F at 0-100°F

13. Surface tension (1), 60 dynes per centimeter at 77°F

14. Color, colorless

*Unmitful extrapolation on ASTM Chart D341-43
**Extrapolated linearly

15. Combustibility, this mixture is probably non-combustible since the Hollingshead H-2 fluid composed mainly of water-ethylene glycol is non-combustible

16. Toxicity, non-toxic

17. Stability, good up to 300°F, no data above 300°F

18. Corrosiveness, must add inhibitors to reduce corrosiveness

19. Solubility (1), soluble in water

20. Effect on elastomers, rubber swells but does not deteriorate

21. Specific references for this fluid:

    (1) Technical bulletin on Glycols of Carbide and Carbon Chemicals Corp.
    (2) Othmer, D. F., Ind. Eng. Chem., Vol. 32, 1940, p. 841.

22. Specific comments on physical properties:

    a. The flash point of pure ethylene glycol is 240°F. It is quite likely that this solution will not burn.

Table 23. Properties of Water-Propylene Glycol Solution Freezing at -65°F

At 100°F the density of this solution is 3 percent greater than that of water, the specific heat is 18 percent less, the viscosity is 360 percent greater and the thermal conductivity is 47 percent less.

1. Chemical composition, 1, 2 propanediol 61 weight percent and 39 weight percent water

2. Molecular weight (average), 65.7

3. Boiling point (1), 228°F at 760 mm Hg

4. Flash point (see comments), greater than 225°F

5. Freezing point (1), -65°F

6. Pour point (see comments), less than -50.5°F

Temp. °F	7. Vapor pressure (1) mm Hg	8. Latent heat (2) Btu/lb	9. Density (1) Gms/cc	10. Specific heat (1) Btu/lb-°F	11. Viscosity (1) centipoises	12. Thermal conductivity (1) Btu/hr - ft²(°F/ft)
-50			1.088*	0.738**	140	0.203
0	1.2		1.071*	0.780**	44	0.199
50	8.5	290	1.052*	0.800	11	0.195
100	45	282	1.030*	0.821	4.3	0.191
150	180	274	1.004*	0.844	2.1	0.186
200	540	267	0.976*	0.866	1.05	0.182
250	1360	258	0.944*	0.887**	0.70	0.177
300	3300	249	0.910*	0.908**	0.45	0.171

13. Color (3), clear, water-white

14. Odor (3), odorless

15. Combustibility (4), combustible (see comments)

16. Toxicity (3), low toxicity

17. Stability (3), good up to 300°F, no data above 300°F

*Calculated and extrapolated using data for pure water and pure propylene glycol at all temperatures and data for mixture at only one temperature
**Extrapolated linearly
***Estimated using data of mixtures at other percent compositions

Table 23, continued

16. Corrosiveness, non-corrosive when used with inhibitor

19. Solubility (3), completely miscible with water and alcohol

20. Effect on elastomers (3), rubber suitable

21. Specific references for this fluid:

(1) Booklet on Glycols, published by Carbide and Carbon Chemicals Corporation, 1947.
(2) Othmer, D., Ind. Eng. Chem., Vol. 32, 1940, p. 891.
(3) Booklet on Celanese Organic Chemicals, Celanese Corporation of America, New York.
(4) Sax, I. N., Handbook of Dangerous Materials, Reinhold Publishing Company, New York, 1951, p. 327.

22. Specific comments on physical properties:

a. No data available on flash point of mixture but it will be greater than the flash point of the pure propylene glycol.
b. No data available on pour point of mixture but it will be greater than pour point of the pure propylene glycol.
c. No information available on combustibility of the 61 percent solution. It is assumed, however, to be combustible.

Table 24. Properties of Water-Cellusolve Solution Freezing at -65°F

This solution has high thermal conductivities and specific heats which are typical of water-soluble hydrocarbon solutions. However, the flash point and boiling point are quite low.

At 100°F the density of this liquid is 3 percent less than that of water, the specific heat is 21 percent less, the viscosity is 54 percent greater, and the thermal conductivity is 38 percent less.

1. Chemical composition (1), 58.4 weight percent Cellusolve ($C_2H_5OCH_2CH_2OH$) and 41.6 percent water

2. Molecular weight (average), 39.8

3. Boiling point (1), 214°F at 760 mm Hg

4. Flash point (1), greater than 114°F

5. Freezing point (1), -65°F

Temp. °F	6. Vapor pressure (1) mm Hg	7. Latent heat (4) Btu/lb	8. Density (1) Gm/cc	9. Specific heat (1) see comments Btu/lb-°F	10. Viscosity (1) centi-poises	11. Thermal conductivity (2, 3) see comments Btu/hr-ft²(°F/ft)
-30			1.023**	0.68	10.6***	0.196
0	0.8*		1.008**	0.72	5.1***	0.205
50	6.6*	575	0.994	0.78	2.0***	0.215
100	37*	559	0.979	0.75	1.05***	0.225
150	160*	544	0.963**	0.82	0.61***	0.234
200	575*	528	0.948**	0.86	0.41***	0.244
250	1500*	510	0.936**	0.90	0.30***	0.253
300	4000*	491	0.910**	0.93	0.21***	0.263

12. Color (1), colorless

13. Odor (1), mild and agreeable

14. Combustibility (3), no data except on pure Cellusolve but believed to be combustible or a moderate fire hazard

15. Toxicity (5), toxic effects negligible unless inhaled in appreciable amounts

*Extrapolated using Cox chart and boiling point at 1 atmosphere
**Extrapolated linearly
***Extrapolated using data of solutions containing different percent of Cellusolve

16. Stability (1, 5), fairly stable at moderate temperatures. May form peroxides at higher temperatures especially above 300°F.

17. Corrosiveness, believed to have little corrosive action. See comments.

18. Solubility (1), soluble in water

19. Effect on elastomers (1), will not affect unvulcanized rubber

20. Specific references for this fluid:

(1) Bulletin of Carbide and Carbon Co. "Cellusolve and Carbitol Solvents", 1/1/47.
(2) Palmer, G., Ind. Eng. Chem., Vol. 40, 1948, p. 89.
(3) Riedel, L., Chem. Ing. Tech., Vol. 23, 1951, p. 465.
(4) Othmer, D. F., Ind. Eng. Chem., Vol. 32, 1940, p. 194.
(5) Sax, I. N., Handbook of Dangerous Materials, Reinhold Publishing Corp., New York, 1951, p. 89.

21. Specific comments on physical properties:

a. Corrosiveness assumed to be same as other glycol ethers.
b. Specific heats assumed to be same as glycol ethers and variation with temperature assumed same as glycols.
c. Thermal conductivity calculated by method of Palmer and variation with temperature assumed same as ethylene glycols.

Table 25. Properties of Water-Glycerine Solution Freezing at -52°F

This fluid is mildly combustible and has a high density, moderately high thermal conductivity and specific heat. In this respect it is similar to propylene glycol and ethylene glycol-water mixtures.

At 100°F the density of this liquid is 18 percent greater than water, the specific heat is 12 percent less, the viscosity is 1100 percent greater, and the thermal conductivity is 42 percent less.

1. Chemical composition, 67 weight percent glycerol ($C_3H_8O_3$) and 33 weight percent water

2. Molecular weight (average), 39.3

3. Boiling point (1), 236°F at 760 mm Hg

4. Flash point (see comments), greater than 320°F

5. Freezing point (1), -52°F

Temp. °F	6. Vapor pressure (1) mm Hg	7. Latent heat (4)*** Btu/lb	8. Density (1) Gm/cc	9. Specific heat (5) Btu/lb-°F	10. Viscosity (1) centi-poises	11. Thermal conductivity (6) Btu/hr-ft²(°F/ft)
-50			1.21	0.52**	2080	0.19**
0	1.9*		1.19	0.62	220	0.21**
50	10.0*	450	1.15**	0.72	29.9	0.203
100	44.5*	438	1.17**	0.82**	8.1	0.210
150	142	426	1.15**	0.92**	3.48	0.215
200	402	412	1.14**	1.02**	1.85	0.220**
250	970*	389	1.12**	1.12**	1.15****	0.225**
300	2000*	384	1.11**	1.22**	0.81****	0.23**

12. Color (1), varies from water-white to yellow color depending on purity of glycerol

13. Odor, odorless

14. Combustibility (7), combustible (see comments)

15. Toxicity (2), non-toxic

*Extrapolated using Cox chart
**Extrapolated linearly
***Estimated using method of Othmer
****Extrapolated using ASTM Chart D341-43

Table 25, continued

16. Stability (1), fairly stable up to 300°F, no data above 300°F

17. Corrosiveness (3), slight corrosive action, may be reduced by inhibitors (see comments)

18. Solubility (1), soluble in water and the lower alcohols

19. Effect on elastomers (8), natural rubber, neoprene, butyl and buna-N show good resistance to glycerol

20. Specific references for this fluid:

(1) Booklet Glycerine Producers Association, 295 Madison Avenue, New York 17, New York.
(2) Launoy, L., J. Pharm. Chem., Vol. 2, 1942, p. 99.
(3) Evans, T. A., J. Inst. Production Engineers, Vol. 30, 1951, p. 62.
(4) Othmer, D. F., Ind. Eng. Chem., Vol. 32, 1940, p. 841.
(5) Gucker, F. T., Jr. and Marsh, G. A., Ind. Eng. Chem., Vol. 40, 1948, p. 908.
(6) Davis, D. S., Chem. and Met. Eng., Vol. 46, 1939, p. 356.
(7) Sax, I. N., Handbook of Dangerous Materials, Reinhold Publishing Corp., New York, 1951, p. 189.
(8) Dunkle, H. H. and Fetter, E. C., Chem. Eng., Vol. 53, 1946, p. 107.

21. Specific comments on physical properties:

a. Pure glycerol is mildly combustible. No data on aqueous solutions, but is is assumed that the present mixture is combustible.
b. To reduce the slight corrosive action of glycerol-water solutions 1.5 percent sodium benzoate in combination with 0.1 percent sodium nitrite has been used.

Table 26. Properties of Jet Fuel JP-4

At 100°F the density of this liquid is 25 percent less than that of water, the specific heat is 30 percent less, the viscosity is 10 percent less and the thermal conductivity is 76 percent less.

1. Chemical composition, mixture of hydrocarbons ranging from 5 to 12 carbon atoms

2. Molecular weight (4), 126

3. Initial boiling point (5), 214°F at 760 mm Hg

4. Flash point (7), 65°F

5. Freezing point, -76°F

Temp. °F	6. Init. vap. pressure (5) mm Hg	7. Latent heat (2) Btu/lb	8. Density (3) Gms/cc	9. Specific heat (8), (1) Btu/lb-°F	10. Viscosity (1)* centipoises	11. Thermal conductivity (6) Btu/hr - ft²(°F/ft)
-50			0.826	0.408	3.6	0.0901
0	15.5		0.804	0.439	1.69	0.0887
50	53	159	0.782	0.470	1.01	0.0847
100	140	154	0.758	0.502	0.682	0.0861
150	320	148	0.734	0.535	0.502	0.0848
200	643	143	0.707	0.567	0.389	0.0835
250	1180	136	0.677	0.600	0.312	0.0822
300	2000	129	0.642	0.632	0.260	0.0808

12. Color, clear, water-white

13. Odor, pleasant

14. Combustibility, highly combustible

15. Toxicity, non-toxic when breathed in small amounts

16. Stability, stable to 300°F. In the presence of oxygen gum is formed unless stabilized by an antioxidant at most temperatures.

17. Corrosiveness, non-corrosive

18. Solubility, insoluble in water

*Estimated, see comments

19. Effect on elastomers, natural rubber unsuitable. Neoprene and some synthetics are suitable.

20. Specific references for this fluid:

(1) Letter to W. Robinson, 5/26/53, from WADC, WCLEM-2.
(2) Maxwell, J. P., Data Book on Hydrocarbons, D. Van Nostrand Co., New York, 1950, p. 116.
(3) Ibid., p. 143.
(4) Ibid., p. 21.
(5) Ibid., p. 44.
(6) Cragoe, C. S., Miscellaneous Publications of Bureau of Standards, No. 97, 1929.
(7) Drickamer, R. R., P-V-T Relationships of Organic Compounds, Handbook Publishers, Inc., Sandusky, Ohio, 1952, p. 292.
(8) Forsch, A. R. and Whitman, W. G., Ind. Eng. Chem., Vol. 18, 1926, p. 793.

21. Specific comments on properties:

Viscosity estimated from average value for JP-4 fuel at -40°F assuming same viscosity-temperature coefficient as JP-3.

Table 27. Properties of Jet Fuel JP-3

At 100°F the density of this liquid is 23 percent smaller than that of water, the specific heat is 30 percent smaller, the viscosity is 18 percent less and the thermal conductivity is 75 percent less.

1. Chemical composition, mixture of hydrocarbons composed mainly of 5 to 12 carbon atoms

2. Molecular weight (6), 122

3. Initial boiling point (7), 146°F at 760 mm Hg

4. Flash point (8), 65°F

5. Freezing point (2), less than -76°F

Temp. °F	6. Init. vap. pressure (3) mm Hg	7. Latent heat (3) Btu/lb	8. Density (2) (4) Gms/cc	9. Specific heat (1) Btu/lb-°F	10. Viscosity (2) centi-poises	11. Thermal conductivity (9) Btu/hr - ft²(°F/ft)
-50			0.814	0.413	2.37	0.0906
0	53		0.792	0.443	1.27	0.0893
50	150	161	0.769	0.473	0.796	0.0880
100	370	153	0.746	0.506	0.560	0.0867
150	800	148	0.720	0.539	0.418	0.0854
200	1500	142	0.693	0.572	0.331	0.0840
250	2580	135	0.662	0.606	0.273	0.0827
300	4100	128	0.627	0.638	0.228	0.0813

12. Color, clear, water-white

13. Odor, pleasant

14. Combustibility, highly combustible

15. Toxicity, non-toxic when breathed in small amounts

16. Stability, stable to about 300°F. In the presence of oxygen gum is formed unless stabilized by an antioxidant at most temperatures.

17. Corrosiveness, non-corrosive

18. Solubility, insoluble in water

19. Effect on elastomers, natural rubber unsuitable. Neoprene and some synthetics are suitable.

Table 27, continued

20. Specific references for this liquid:

(1) Forsch, A. R. and Whitman, W. G., Ind. Eng. Chem., Vol. 18, 1926, p. 793.
(2) Letter to W. Robinson, 5/26/53, from WADC, WCLEM-2.
(3) Maxwell, J. B., Data Book on Hydrocarbons, D. Van Nostrand Co., New York, 1950, p. 119.
(4) Ibid., p. 143.
(5) Ibid., p. 44.
(6) Ibid., p. 21.
(7) Aviation Fuels and Their Effects on Engine Performance. Prepared by Ethyl Corp. for U. S. Air Force, p. 115.
(8) Dreisbach, R. R., P-V-T Relationships of Organic Compounds, Handbook Publishers, Inc., Sandusky, Ohio, 1932, p. 292.
(9) Cragoe, C. S., Thermal Properties of Petroleum Products, Miscellaneous Publications of Bur. of Stds., No. 97, 1929.

Table 28. Properties of Shell Tellus Oil 15 Hydraulic Fluid

This is a relatively non-volatile, low density, low specific heat and low thermal conductivity liquid that is used for aircraft hydraulic systems.

At 100°F the density of this liquid is 14 percent less than that of water, the specific heat is 54 percent less, the viscosity is 900 percent greater and the thermal conductivity is 79 percent less.

1. Chemical composition, mixture of hydrocarbons

2. Molecular weight (4), 280

3. Approximate initial boiling point (estimated, see comments), 630°F at 760 mm Hg

4. Flash point (9) (estimated), 300°F

5. Pour point (8), -45°F

Temp. °F	6. Approx. init. vap. pressure (9) mm Hg	7. Latent heat (2) Btu/lb	8. Density (1) Gms/cc	9. Specific heat (3) Btu/lb-°F	10. Viscosity (5) (8)[a] centi-poises	11. Thermal conductivity (7) Btu/hr - ft²(°F/ft)
-30			0.912	0.373	9120	0.0792
0			0.895	0.403	264	0.0780
50		136	0.875	0.433	35	0.0769
100		134	0.857	0.463	10.1	0.0758
150		131	0.840	0.493	4.36	0.0746
200		127	0.822	0.523	2.42	0.0734
250		124	0.805	0.554	1.57	0.0723
300	10	121	0.788	0.585	1.12	0.0711

12. Color, red

13. Odor, odorless

14. Combustibility, combustible

15. Toxicity, not toxic

16. Stability, no data but probably stable to 300°F

[a] See comments

Table 28, continued

17. Corrosiveness, non-corrosive

18. Solubility, insoluble in water

19. Effect on elastomers (6), natural rubber unsuitable. Neoprene and some synthetics suitable.

20. Specific references for this fluid:

(1) Wilson, R. E. and Bahlke, W. H., Ind. Eng. Chem., Vol. 16, 1924, p. 115.
(2) Maxwell, J. P., Data Book for Hydrocarbons, D. Van Nostrand Co., New York, 1950, p. 124.
(3) Ibid., p. 93.
(4) Ibid., p. 21.
(5) Ibid., pp. 12, 16, 158, 168.
(6) Perry, J. H., Chemical Engineers' Handbook, McGraw-Hill Book Co., New York, 1951, p. 1493.
(7) Cragoe, C. S., Miscellaneous Publications of Bureau of Standards, No. 97, 1929.
(8) Letter to W. Robinson, 10/14/52, from Shell Oil Co.
(9) Dreisbach, R. R., P-V-T Relationships of Organic Compounds, Handbook Publishers, Inc., Sandusky, Ohio, 1952, p. 292.

21. Specific comments on physical properties:

a. Insufficient data for accurate estimation of flash point.
b. Approximate values only of viscosity.
c. Estimated thermal conductivity.
d. Boiling point estimated on assumption that oil has 20 carbon atoms per molecule.
e. Thermal conductivity estimated by method of Cragoe.

Table 29. Properties of Texas Co. Aircraft Hydraulic Oil AA

This is a non-volatile, low density, low specific heat and low thermal conductivity liquid that is used for aircraft hydraulic systems.

At 100°F the density of this liquid is 15 percent less than that of water, the specific heat is 53 percent less, the viscosity is 1800 percent greater and the thermal conductivity is 79 percent less.

1. Chemical composition, hydrocarbon fraction

2. Molecular weight (1), 290

3. Approximate initial boiling point (2) (estimated, see comments), 650°F at 760 mm Hg

4. Flash point (6), 205°F

5. Pour point (6), less than -75°F

Temp. °F	6. Init. vap. pressure (estim.)(2) mm Hg	7. Latent heat (3) Btu/lb	8. Density (2) Gms/cc	9. Specific heat (4) Btu/lb-°F	10. Viscosity (6) centi-poises	11. Thermal conductivity (5) Btu/hr - ft²(°F/ft)
-50			0.894	0.380	620	0.0809
0			0.878	0.410	98	0.0797
50		136	0.863	0.440	29.4	0.0785
100		132	0.846	0.471	12.7	0.0773
150		129	0.828	0.500	6.7	0.0761
200		125	0.812	0.531	4.14	0.0749
250		121	0.795	0.562	2.82	0.0737
300	43	119	0.774	0.593	2.05	0.0725

12. Color, red

13. Odor, odorless

14. Combustibility, combustible at high temperatures

15. Toxicity, non-toxic

16. Stability, oxidises at high temperature in presence of air but believed stable to 300°F

17. Corrosivness, non-corrosive

Table 29, continued

18. Solubility, insoluble in water

19. Effect on elastomers, natural rubber unsuitable. Neoprene and some synthetics suitable.

20. Specific references for this fluid:

(1) From viscosity-molecular weight relations for mid-continent oils. Private data, W. B. Kay, Ohio State University.
(2) Wilson, R. E. and Bahlke, W. H., Ind. Eng. Chem., Vol. 16, 1924, p. 115.
(3) Maxwell, J. B., Data Book on Hydrocarbons, D. Van Nostrand Co., New York, 1950, p. 124.
(4) Forsch, A. E. and Whitman, W. G., Ind. Eng. Chem., Vol. 18, 1926, p. 793.
(5) Dragoo, C. S., Misc. Publications of Bureau of Standards, No. 97, 1929.
(6) Letter to W. Robinson, 6/18/52, from Texas Co.

21. Specific comments on physical properties:

Estimated as equal to boiling point of a normal hydrocarbon having formula $C_{21}H_{44}$.

Table 30. Properties of MIL-O-6081 Grade 1010 Jet Engine Lubricating Oil

At 100°F the density of this fluid is 13 percent less than that of pure water, the specific heat is 54 percent less, the viscosity is 1240 percent greater, and the thermal conductivity is 31 percent less.

1. Molecular weight, no data

2. Boiling point (see comments), approximately 570°F at 760 mm Hg

3. Flash point (1), 265°F

4. Pour point (1), -70°F

Temp. °F	5. Vapor pressure (1) mm Hg	6. Latent heat Btu/lb	7. Density (1) Gms/cc	8. Specific heat (1) Btu/lb-°F	9. Viscosity (1) centi-poises	10. Thermal conductivity (1) Btu/hr - ft²(°F/ft)
-50		no	0.902	0.338	6750	0.0749*
0	insignificant	data	0.883	0.380	212	0.0735*
50	insignificant		0.865	0.420	30.8	0.0717
100	insignificant		0.847	0.460	8.5	0.0701
150	less than 0.5		0.829	0.498	3.8	0.0685
200	2.1		0.810	0.532	2.15	0.0669
250	8.0		0.792	0.562	1.43*	0.0653
300	25.0		0.774	0.580	0.70*	0.0637*

11. Color (1), clear and transparent

12. Odor (1), no data

13. Combustibility, slight combustibility

14. Toxicity, non-toxic

15. Stability (1), good stability to at least 300°F, no data above 300°F

16. Corrosiveness (1), does not corrode metals

17. Solubility, insoluble in water

18. Effect on elastomers, no data, but believed to affect natural rubber

*Extrapolated linearly

Table 30, continued

19. Specific references for this fluid:

(1) Letter to Ohio State University Research Foundation, 9/8/52, from Wright Air Development Center.

20. Specific comments on physical properties:

a. Boiling point approximated from vapor pressure data.
b. Combustibility, toxicity, and solubility properties taken to be the same as other hydrocarbons of similar nature.

Table 31. Properties of Standard Oil of Ohio Univis J-43 Hydraulic Fluid

At 100°F the density of this liquid is 14 percent less than that of pure water, the specific heat is 52 percent less, the viscosity is 1770 percent greater, and the thermal conductivity is 78 percent less.

1. Chemical composition, hydrocarbon mixture

2. Average molecular weight (5), 166

3. Mean average boiling point (6), 465°F at 760 mm Hg

4. Flash point (2), 200°F

5. Freezing point (2), -80°F

6. Pour point (2), -75°F

Temp. °F	7. Vapor pressure (7)* mm Hg	8. Latent heat (8) Btu/lb	9. Density (2) (9) Gms/cc	10. Specific heat (2) Btu/lb-°F	11. Viscosity (2) (5) centipoises	12. Thermal conductivity (2) Btu/hr - ft²(°F/ft)
-80			0.909	0.403	665	0.0827
0			0.887	0.430	104	0.0814
50		160	0.869	0.457	29.3	0.0800
100		157	0.850	0.475	12.1	0.0788
150	insignificant	152	0.833	0.503	7.0	0.0775
200	3	147	0.816	0.530	4.53	0.0762
250	12	143	0.800	0.560	3.24	0.0749
300	36	138	0.784	0.590	2.47	0.0736

13. Dielectric constant (3), 2 to 4 at 1×10^4 cycles per second at 20°C

14. Color, red

15. Combustibility, combustible

16. Toxicity (1), relatively non-toxic

17. Stability, no data but believed stable to 300°F

18. Corrosiveness, relatively non-corrosive

19. Acidity, non-acidic

20. Solubility, insoluble in water

*See comments

Table 31, continued

21. Effect on elastomers (4), natural rubber generally not resistant. A very few synthetic rubbers acceptable.

22. Specific references for this fluid:

(1) Sax, I. N., Handbook of Dangerous Materials, Reinhold Publishing Corp., New York, 1951, p. 214.
(2) Letter to Walter Robinson, 7/17/52, from Standard Oil Company of Ohio.
(3) Lange, N. A., Handbook of Chemistry, Handbook Publishers, Inc., Sandusky, Ohio, 1952, p. 1233.
(4) Perry, J. H., Chemical Engineers Handbook, McGraw-Hill Book Co., New York, 1950, p. 1492.
(5) Maxwell, J. F., Data Book on Hydrocarbons, D. Van Nostrand Co., New York, 1950, p. 26.
(6) Ibid., p. 18.
(7) Ibid., p. 42.
(8) Ibid., p. 122.
(9) Circular Number 154, Bureau of Standards Miscellaneous Publications.

23. Specific comments on physical properties:

a. Dielectric constant estimated from data on other hydrocarbons.
b. Vapor pressure assumed equivalent to that of a pure hydrocarbon of the same molecular weight.
c. The ASTM distillation is about 450°F initial point to over 585°F end point.

Table 32. Properties of Socony-Vacuum Mobil Aero Hydraulic Oil HFA

At 100°F the density of this fluid is 15 percent less than that of pure water, the specific heat is 53 percent less, the viscosity is 1680 percent greater, and the thermal conductivity is 78 percent less.

1. Chemical composition, hydrocarbon mixture

2. Molecular weight (1), 190

3. Approximate initial boiling point (2), 430°F at 760 mm Hg

4. Flash point (2), 200°F

5. Pour point (2), -85°F

Temp. °F	6. Avg. vapor pressure (2) mm Hg	7. Latent heat (1) Btu/lb	8. Density (2) Gms/cc	9. Specific heat (2) Btu/lb-°F	10. Viscosity (2) centi-poises	11. Thermal conductivity (2) Btu/hr - ft²(°F/ft)
-50			0.903	0.400	695	0.0827
0	3.88		0.885	0.423	88.5	0.0814
50	6.13	149	0.867	0.447	26.9	0.0801
100	9.82	145	0.849	0.471	12.1	0.0788
150	16.0	140	0.831	0.494	6.87	0.0775
200	28.0	135	0.813*	0.517	4.46	0.0763
250	44.0	130	0.795*	0.541	3.14	0.0749
300	72.5	125	0.777*	0.565	2.34	0.0737

12. Coefficient of expansion (2), 4.9×10^{-4} per °F at 68°F

13. Combustibility, combustible

14. Toxicity, relatively non-toxic

15. Stability, no data, but believed stable to 300°F

16. Corrosiveness, no data, but probably not corrosive to ferrous metals

17. Solubility, insoluble in water and soluble in hydrocarbons

18. Effect on elastomers, effects most elastomers but a few synthetics are suitable

*Extrapolated linearly

Table 32, continued

19. Specific references for this fluid:

(1) Maxwell, J. B., Data Book on Hydrocarbons, D. Van Nostrand Co., New York, 1950, pp. 21, 93.
(2) Letter from Socony-Vacuum Oil Co., New York, to W. Robinson, 7/7/52.
(3) Sax, I. N., Handbook of Dangerous Materials, Reinhold Publishing Corp., New York, 1951, p. 214.
(4) Perry, J. H., Chemical Engineers Handbook, McGraw-Hill Book Co., New York, 1950, pp. 1493-4.

20. Specific comments on physical properties:

a. This oil conforms to Spec. MIL-O-5606 for aviation petroleum hydraulic oils (2).
b. This fluid is an ordinary petroleum fraction.

Table 33. Properties of Minnesota Mining and Manufacturing Co. Fluorochemical E-13

This fluid is similar to fluorochemical C-75 in that it is thermally stable to 900°F and non-combustible. This fluid has a very high density compared to water and its properties are similar to fluid C-75.

At 100°F the density of this fluid is 86 percent greater than that of pure water, the specific heat is 72 percent less, the viscosity is 423 percent greater, and the thermal conductivity is 32 percent less.

1. Chemical composition, completely fluorinated amine with the empirical formula $(C_4F_9)_3N$

2. Average molecular weight (1), 671

3. Boiling point (1), 351°F at 760 mm Hg

4. Flash point (1), non-flammable

5. Fire point (1), non-flammable

6. Freezing point (1), -87°F

7. Pour point (1), -58°F

Temp. °F	8. Vapor pressure (1) mm Hg	9. Latent heat (3) Btu/lb	10. Density (1) Gms/cc	11. Specific heat (1) (4) Btu/lb-°F	12. Viscosity (1) centi-poises	13. Thermal conductivity (2) (see comments) Btu/hr-ft²(°F/ft)
-50			2.028	0.25*	111.3	0.0840**
0	insignif.		1.958	0.26	25.6	0.0775**
50	insignif.	36.4	1.902	0.27	7.54	0.0710**
100	insignif.	35.3	1.845	0.28	3.58	0.0645**
150	6.0	34.3	1.783	0.28	1.82	0.0576**
200	33	33.4	1.716	0.29	1.03	0.0511**
250	117	32.3	1.649	0.30	0.653	0.0445**
300	315	31.0	1.573	0.30	0.411	0.0380**

14. Coefficient of expansion (1), 0.67×10^{-3} per °F at 77° to 104°F, 1.17×10^{-3} per °F at 284° to 320°F

15. Surface tension (1), 16.1 dynes per centimeter at 77°F

*Extrapolated linearly
**Estimated by method of Palmer

16. Dielectric constant at 100 cycles per second (1), 1.86 at 77°F

17. Color (1), colorless

18. Combustibility (1), non-combustible

19. Toxicity (1), non-toxic

20. Stability (1), thermally stable to 900°F

21. Corrosiveness (1), will not corrode metals up to several hundred degrees Centigrade

22. Solubility (1), insoluble in water

23. Effect on elastomers (1), relatively no effect

24. Specific references for this fluid:

(1) Bulletin from Minnesota Mining and Manufacturing Company, St. Paul, Minnesota.
(2) Palmer, G., Ind. Eng. Chem., Vol. 40, 1948, p. 89.
(3) Othmer, D. F., Ind. Eng. Chem., Vol. 32, 1940, p. 841.
(4) Based partly on experimental data of J. Fisher, Ohio State University, Chemical Engineering Laboratory.

25. Specific comments on physical properties:

Thermal conductivity estimated at 86°F by Palmer method and temperature coefficient estimated from coefficients of other fluorocarbons.

Table 34. Properties of Freon-115

This fluid is a refrigerant. It is non-combustible and has a high density, low thermal conductivity, and low specific heat. Its other properties are similar to those of a hydrocarbon but it has a high freezing point of -31°F.

At 100°F the density of this liquid is 55 percent greater than that of water, the specific heat is 78 percent less, the viscosity is 18 percent less, and the thermal conductivity is 86 percent less.

1. Chemical composition, $CCl_2F\text{-}CClF_2$

2. Molecular weight (1), 187.4

3. Boiling point (1), 117.6°F at 760 mm Hg

4. Flash point (1), non-flammable

5. Freezing point (1), -31°F

Temp. °F	6. Vapor pressure (1) mm Hg	7. Latent heat (1)(7)* Btu/lb	8. Density (1) Gms/cc	9. Specific heat (6) Btu/lb-°F	10. Viscosity (1) centi-poises	11. Thermal conductivity (5) Btu/hr-ft²(°F/ft)
-30			1.715***	0.2084	2.18(***)	0.0658***
0	68.3		1.660	0.2111	1.263	0.0606
50	177	67.87	1.600	0.2169	0.809	0.0558
100	542	64.46	1.536	0.2226	0.564	0.0508
150	1370	60.44	1.466	0.2284	0.418	0.0457
200	2830	55.62	1.390	0.2343	0.322	0.0407
250	5280	50.6**	1.311(***)	0.2398	0.257****	0.0353***
300	6980	44.4**	1.225***	0.2456	0.210****	0.0302***

12. Coefficient of expansion, 1.24×10^{-3} per °F at 60°F

13. Color (1), clear, water-white

14. Odor (1), similar to CCl_4

15. Combustibility, non-combustible

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*See comments
**Calculated by method of Othmer
***Extrapolated linearly
****Extrapolated using ASTM Chart D341-43

16. Toxicity (1) (2), much less toxic than group 4 classification of Underwriters Laboratory - not very toxic

17. Stability, very stable up to 150°F, no data above 150°F but believed stable to 300°F

18. Corrosiveness (4), lead, copper, and aluminum are fairly resistant. Others vary in resistance depending on conditions.

19. Solubility (3), insoluble in water

20. Effect on elastomers (4), natural rubber usually unsuitable. Neoprene and some synthetics suitable.

21. Specific references for this fluid:

(1) Catalog of E. I. du Pont de Nemours and Co., Wilmington, Del., 1938.
(2) Sax, I. N., Handbook of Dangerous Materials, Reinhold Publishing Corp., New York, 1951, p. 391.
(3) Lange, N. A., Handbook of Chemistry, Handbook Publishers, Inc., Sandusky, Ohio, 1952, p. 689.
(4) Dunkle, H. H., Felter, E. C., Chem. Eng., Vol. 53, 1946, p. 107.
(5) Markwood, W. H. and Benning, A. F., Refr. Eng., Vol. 45, 1943, p. 93.
(6) Benning, A. F. and Markwood, W. H., Ind. Eng. Chem., Vol. 32, 1940, p. 976.
(7) Dodge, B. F., Chemical Engineering Thermodynamics, McGraw-Hill Publishing Co., New York, 1944, p. 378.

22. Specific comments on physical properties:

a. The freezing point of -31°F is relatively high.
b. The boiling point is quite low.
c. Latent heat at 280° and 300°F calculated by Watson's method (7).

Table 38. Properties of Freon-11

This fluid is a refrigerant. It is non-combustible and has a high density, low thermal conductivity, and low specific heat. Its other properties are similar to those of a hydrocarbon.

At 100°F the density of this liquid is 46 percent greater than that of water, the specific heat is 78 percent less, the viscosity is 44 percent less, and the thermal conductivity is 84 percent less.

1. Chemical composition, CCl_3F

2. Molecular weight (1), 137.4

3. Boiling point (1), 74.7°F at 760 mm Hg

4. Flash point (1), non-combustible

5. Freezing point (1), -168°F

6. Temp. °F	6. Vapor pressure (1)* mm Hg	7. Latent heat (7) Btu/lb	8. Density (8) Gms/cc	9. Specific heat (6) Btu/lb-°F	10. Viscosity (8) centi-poises	11. Thermal conductivity (5) Btu/hr - ft²(°F/ft)
-50			1.633**	0.204	1.10	0.0785
0	132		1.573	0.208	0.588	0.0720
50	453	79.4	1.512	0.212	0.490	0.0656
100	1232	77.2	1.446	0.216	0.382	0.0591
150	2770	75.0	1.376	0.220	0.315	0.0525
200	5310	72.8	1.306**	0.225	0.274	0.0460
250	9360	70.5	1.233**	0.229	0.229	0.0395
300	15960	67.8	1.163**	0.233	0.203	0.0330

12. Color (1), clear, water-white

13. Odor (1), odor similar to carbon tetrachloride

14. Combustibility (1) (2), non-combustible

15. Toxicity (1) (2), only very slightly toxic

16. Stability, quite stable up to 300°F, no data above 300°F

*See comments
**Extrapolated linearly

Table 35, continued

17. Corrosiveness (4), lead, copper and aluminum are fairly resistant. Others vary in resistance depending on conditions.

18. Solubility (3), insoluble in water

19. Effect on elastomers (4), natural rubber is unsuitable; neoprene and some other synthetics are suitable

20. Specific references for this fluid:

(1) Bulletin on Thermodynamic Properties of Freon-11, published by Kinetic Chemicals, Inc., Wilmington, Del., 1942.
(2) Sax, N. I., Handbook of Dangerous Materials, Reinhold Publishing Corp., New York, 1951, p. 259.
(3) Lange, N. A., Handbook of Chemistry, Handbook Publishers Inc., Sandusky, O., 1949, p. 539.
(4) Dunkle, H. H. and Fetter, E. C., Chem. Eng., Vol. 53, 1946, p. 107.
(5) Markwood, W. H. and Benning, A. F., Refr. Eng., Vol. 45, 1943, p. 93.
(6) Markwood, W. H. and Benning, A. F., Ind. Eng. Chem., Vol. 32, 1940, p. 976.
(7) Othmer, D. F., Ind. Eng. Chem., Vol. 32, 1940, p. 841.
(8) Benning, A. F. and Markwood, W. H., J. Amer. Soc. Ref. Eng., April, 1939.

21. Specific comments on physical properties:

Vapor pressure values calculated by means of the vapor pressure equation of Markwood and Benning given in reference (1).

Table 36. Properties of Hexachlorobutadiene

This fluid is a hydraulic fluid. It is non-combustible and has a high density, low thermal conductivity and low specific heat. Its other properties are similar to those of a hydrocarbon except that the freezing point is moderately high.

At 100°F the density of this liquid is 66 percent greater than that of water, the specific heat is 80 percent less, the viscosity is 238 percent greater and the thermal conductivity is 81 percent less.

1. Chemical composition (2), $CCl_2CClCClCCl_2$

2. Molecular weight (2), 260.7

3. Boiling point (2), 419°F at 760 mm Hg

4. Flash point (2), non-flammable

5. Freezing point (2), -2.2°F

6. Temp. °F	6. Vapor pressure (2) mm Hg	7. Latent heat (3)*** Btu/lb	8. Density (2) Gms/cc	9. Specific heat (2) Btu/lb-°F	10. Viscosity (2)**** centipoises	11. Thermal conductivity (1)**** Btu/hr - ft²(°F/ft)
-50			1.746 ***	0.167 ***	31.4	0.0830
0	0.115*		1.715 ***	0.179 ***	9.25	0.0795
50	0.17 *	84.2	1.683 ***	0.192	4.16	0.0760
100	1.35 *	82.0	1.649	0.204	2.44	0.0688
150	4.8	79.6	1.612 ***	0.217 ***	1.66	0.0634
200	17.5	77.3	1.572 ***	0.229 ***	1.20	0.0580
250	52.0	74.8	1.526 ***	0.242 ***	0.923	0.0856
300	128	72.0	1.472 ***	0.254 ***	0.740	0.0473

12. Color (2), clear, water-white

13. Odor (2), mild characteristic odor

14. Combustibility (2), non-combustible

15. Toxicity (2), highly toxic

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*Extrapolated using Cox chart
**Estimated
***Extrapolated using temperature coefficients of similar compounds
****See comments

Table 36, continued

16. Stability (2), data indicates stable to 300°F, no data above 300°F. Not easily hydrolized by water or mild alkalies.

17. Corrosiveness, slightly corrosive

18. Solubility (2), insoluble in water, infinitely soluble in alcohol, ether and most chlorinated solvents

19. Effect on elastomers (2), has high solvent action on many elastomers

20. Specific references for this fluid:

(1) Palmer, C., Ind. Eng. Chem., Vol. 40, 1948, p. 89.
(2) Letter to W. Robinson, 7/18/52, from Hooker Electrochemical Company, Niagara Falls, New York.
(3) Othmer, D. F., Ind. Eng. Chem., Vol. 32, 1940, p. 841.

21. Specific comments on physical properties:

a. Viscosity obtained by plotting data on ASTM D341-32T viscosity-temperature plotting paper.
b. Thermal conductivity estimated from Palmer method (1) using temperature correction factor.
c. On hydrolysis, may form HCl and be very corrosive.

Table 37. Properties of Esso and Hess Co. Synthetic Diester Fluid MIL-H-5606 (Flexol 201)

This hydraulic fluid is an ester, but its physical properties are primarily those of a hydrocarbon. At 100°F the density of this liquid is 8 percent less than that of pure water, the specific heat is 38 percent less, the viscosity is 2700 percent greater, and the thermal conductivity is 73 percent less.

1. Chemical composition, aliphatic diester of sebacic acid with approximate formula of $C_{26}H_{50}O_4$

2. Approximate molecular weight, 427

3. Boiling point, 509°F at 10 mm Hg

4. Flash point, no data available but should be over 500°F

5. Freezing point (1), below -75°F

6. Pour point (1), -75°F

Temp., °F	7. Vapor pressure (1) mm Hg	8. Density (1) (2) (3) Gms/cc	9. Specific heat (1) Btu/lb-°F	10. Viscosity (1) (3) centipoises	11. Thermal conductivity (1) Btu/hr - ft²(°F/ft)
-50		0.979	0.390	3000	0.0968
0		0.930	0.401	294	0.0972
50		0.923	0.410	59.1	0.0977
100	insignificant	0.901	0.419	18.7	0.0981
150		0.881	0.428	9.43	0.0986
200	0.002	0.863	0.438	5.00	0.0990
250	0.01	0.845	0.447	3.26	0.0995
300	0.038	0.825	0.456	2.30	0.1000

12. Coefficient of expansion (1), 4.2×10^{-4} per °F at 77°F

13. Combustibility, combustible

14. Toxicity, no data but believed to be relatively non-toxic

15. Stability, no data but believed to be stable to 300°F

16. Corrosiveness, no information but it probably is not very corrosive

17. Solubility, no information but it probably is insoluble in water since sebacic acid and other esters of sebacic acid are insoluble

Table 37, continued

18. Effect on elastomers, no data but it probably swells some elastomers in a manner similar to hydrocarbons

19. Specific references for this fluid:

(1) Letter from Rohm and Haas Company, 7/18/52, to Walter Robinson.
(2) Nelson, W. L., Petroleum Refinery Engineering, McGraw-Hill Book Co., New York, 1950, pp. 88, 146, 162.
(3) Maxwell, J. B., Data Book on Hydrocarbons, D. Van Nostrand Co., New York, 1950, p. 143.

20. Specific comments on physical properties:

a. Very low vapor pressure.
b. High viscosity.
c. Temperature correction of thermal conductivity estimated.
d. PEL-3161 is a synthetic lubricant made commercially as a hydraulic fluid and contains 90.6 percent of di-2-ethylhexyl sebacate.
e. Vapor pressure data somewhat erratic at high temperatures.
f. The flash point should occur when the vapor pressure is about 10 to 15 mm.

Table 38. Properties of Penn State MIL-L-6387 Synthetic Ester Base Fluid

At 100°F the density of this fluid is 8 percent less than that of pure water, the specific heat is 61 percent less, the viscosity is 2070 percent greater, and the thermal conductivity is 77 percent less.

1. Chemical composition (1), a synthetic ester base

2. Molecular weight, no data

3. Boiling point (2) (see comments), 690°F at 760 mm Hg

4. Flash point (1), 415°F

5. Fire point (1), 445°F

6. Freezing point (1), below -75°F

7. Pour point (1), below -75°F

8. Vapor pressure (1) (see comments), from 0 - 300°F vapor pressure is insignificant

9. Latent heat, no data, no means of estimating without molecular weight data

Temp. °F	10. Density (1) Gms/cc	11. Specific heat (1) Btu/lb-°F	12. Viscosity (1) centi-poises	13. Thermal conductivity (1) Btu/hr - ft²(°F/ft)
-50	0.98	0.39*	1960	0.085
0	0.96	0.42	211	0.084
50	0.94	0.445	41.3	0.083
100	0.92	0.47	14.1	0.082
150	0.90	0.49	7.42	0.081
200	0.89	0.51	4.27	0.079
250	0.87	0.533	2.74	0.078
300	0.85	0.56	1.87	0.077

14. Color, no data

15. Odor, no data

16. Combustibility (1), slight combustibility

*Extrapolated linearly

17. Toxicity, no data, probably not toxic

18. Stability, no data but believed to be stable to 300°F

19. Corrosiveness, believed to be non-corrosive or very slightly corrosive due to very slight acidity

20. Solubility, probably insoluble in water since most large hydrocarbon esters are insoluble

21. Effect on elastomers, no data but probably swells some elastomers in a manner similar to hydrocarbons

22. Specific references for this fluid:

(1) Letter to W. Robinson, 7/17/52, from M. R. Fenske, Penn. State College.
(2) Maxwell, J. B., Data Book on Hydrocarbons, D. Van Nostrand Co., New York, 1950, p. 43.

23. Specific comments on physical properties:

a. Boiling point calculated by use of conversion chart on hydrocarbons from 10 mm to 760 mm pressure.
b. Vapor pressure estimated from boiling point data and assuming that vapor pressure curve is similar to Penn State MIL-O-5606.
c. Toxicity, corrosiveness, and solubility properties assumed to be same as for a typical synthetic ester base fluid. The di-2-ethyl-hexyl sebacate fluid of Rohm and Haas Co., Philadelphia, Penna., seems to be very similar to this fluid.

Table 39. Properties of Carbide and Carbon Chem. Union 50-HB-280-T Polyalkylene Glycol Derivative

At 100°F the density of this liquid is 3 percent greater than that of water, the specific heat is 55 percent less, the viscosity is 9000 percent greater, and the thermal conductivity is 74 percent less.

1. Chemical composition (1), polyalkylene glycol derivative

2. Molecular weight, no data

3. Boiling point, see comments

4. Flash point (1), 500°F

5. Fire point (1), 600°F

6. Pour point (1), -55°F

7. Vapor pressure, see comments

8. Latent heat, no data

Temp. °F	9. Density (1) Gm/cc	10. Specific heat (1) Btu/lb-°F	11. Viscosity (1) centipoises	12. Thermal conductivity (1) Btu/hr - ft²(°F/ft)
-50	1.089	0.39		0.0937
0	1.067	0.41	2650	0.0936
50	1.046	0.45	220	0.0928
100	1.024	0.48	62.2	0.0924
150	1.002	0.48	23.0	0.0923
200	0.980	0.50	12.7	0.0922
250	0.959	0.52	7.67	0.0921
300	0.937	0.54	5.17	0.0920[4]

13. Coefficient of expansion (1), 4.2×10^{-4} per °F at 68°F

14. Combustibility (2), high oxygen concentrations required for ignition. Practically non-flammable.

15. Toxicity, no data available but believed to be non-toxic

16. Stability (1), limited to maximum temperature of 500°F

[4] Extrapolated linearly

Table 39, continued

17. Corrosiveness (1), does not corrode aluminum, copper, and stainless steel. The volatile oxidation products are corrosive, however.

18. Solubility (1), quite soluble in cold water

19. Effect on elastomers (1), low swelling effect on most natural and synthetic rubbers

20. Specific references for this fluid:

(1) Letter to W. Robinson, 6/16/52, from Carbide and Carbon Chemicals Co.
(2) Bulletin by Carbide and Carbon Chemicals Co., 6/1/50.

21. Specific comments on physical properties:

a. The pour point of -35°F is relatively high.
b. Vapor pressure data not available. Probably less than 0.01 mm at 65°F.
c. Boiling point is above 500°F and is somewhat higher than comparable petroleum oils of comparable viscosities.

Table 40. Properties of Carbide and Carbon Corp. Ucon LB-30-X Polyalkylene Glycol Derivative

The properties of the Carbide and Carbon Ucon fluid LB-30-X are somewhat similar to those of the 50-HB-280-X fluid except that the fluid is insoluble in water.

At 100°F the density of this liquid is 1 percent less than that of water, the specific heat is 58 percent less, the viscosity is 930 percent greater, and the thermal conductivity is 76 percent less.

1. Chemical composition (1), polyalkylene glycol derivative

2. Molecular weight, no data

3. Boiling point, see comments

4. Flash point (1), 490°F

5. Fire point (1), 565°F

6. Pour point (1), -40°F

7. Vapor pressure, see comments

8. Latent heat, no data

Temp. °F	9. Density (1) Gm/cc	10. Specific heat (1) Btu/lb-°F	11. Viscosity (1) centipoises	12. Thermal conductivity (1) Btu/hr - ft²(°F/ft)
-50	1.086	0.39		0.0839
0	1.029	0.41	4120	0.0838
50	1.000	0.43	300	0.0852
100	0.979	0.45	63.5	0.0849
150	0.957	0.48	23.9	0.0843
200	0.935	0.50	12.2	0.0842
250	0.916	0.52	6.4	0.0838
300	0.897	0.54	4.45	0.0835

13. Coefficient of expansion (1), 4.2×10^{-4} per °F at 68°F

14. Surface tension (1), 31.0 dynes per centimeter at 77°F

15. Refractive index, 1.4526 at 68°F

Table 40, continued

16. Combustibility (2), very slightly combustible under proper conditions

17. Toxicity, no data available but believed to be non-toxic

18. Stability (2), stable for months at 500°F in some closed systems

19. Corrosiveness (2), non-corrosive to most metals. Volatile oxidation products are corrosive.

20. Solubility (2), insoluble in water but soluble in many organic materials

21. Effect on elastomers (2), low swelling effect on most natural and synthetic rubbers

22. Specific references for this fluid:

    (1) Letter to W. Robinson, 6/16/52, from Carbide and Carbon Chemicals Co.
    (2) Bulletin by Carbide and Carbon Chemicals Co., 6/1/50.

23. Specific comments on physical properties:

    a. Boiling point is probably above 400°F and is somewhat higher than comparable petroleum oils of comparable viscosities.
    b. Vapor pressure is less than 0.01 mm at 65°F and less than 1 psia at 100°F.

Table 41. Properties of John B. Pierce Foundation Amyl Silicate JT-140

The physical properties of this fluid are similar to hydrocarbons which have low specific heats, low thermal conductivities, and are combustible.

At 100°F the density of this fluid is 10 percent less than that of pure water, the specific heat is 55 percent less, the viscosity is 356 percent greater, and the thermal conductivity is 82 percent less.

1. Chemical composition, amyl silicate

2. Approximate molecular weight (1), 460

3. Boiling point (1), 460° to 500°F at 760 mm Hg

4. Flash point, approximately 200°F

5. Pour point (1), approximately -100°F

Temp. °F	6. Vapor pressure (1) mm Hg	7. Latent heat Btu/lb	8. Density (1) Gms/cc	9. Specific heat (1) Btu/lb-°F	10. Viscosity (1) centi-poises	11. Thermal conductivity (1) Btu/hr - ft²(°F/ft)
-50		[illegible]	0.962	0.404	58.6	0.0581
0		comments	0.937	0.420	15.3	0.0612
50	less than 0.1*		0.911	0.434	6.2	0.0630
100	0.51*		0.886	0.450	3.1	0.0648
150	1.67*		0.861	0.473	1.93	0.0657
200	6.2 *		0.836	0.500	1.35	0.0660
250	19.5 *		0.810	0.523	0.99	0.0675
300	53 *		0.785	0.560	0.78	0.0684

12. Coefficient of expansion (1), 5.75×10^{-4} per °F at 0 - 100°F

13. Color (1), transparent, straw

14. Odor (1), mild and pleasant

15. Combustibility, combustible since isobutyl-isopropyl silicate is also combustible

16. Toxicity (1), non-toxic on exposure to fumes

17. Stability, no data but believed stable to 300°F

*Extrapolated using Cox chart and boiling point at 1 atmosphere

18. Corrosiveness, no effect on ferrous metals

19. Effect on elastomers, no data

20. Specific references for this fluid:

(1) Letter to W. Robinson, 8/8/52, from John B. Pierce Foundation, Raritan, N. J.
(2) Othmer, D. F., Ind. Eng. Chem., Vol. 32, 1940, p. 841.

21. Specific comments on physical properties:

a. Latent heat as estimated from Othmer (2) method appeared very high. Should be investigated.
b. Vapor pressures extrapolated by Othmer (2) method.

Table 42. Properties of Organic Chemicals Co.
Aliphatic Orthosilicate Ester Oronite BF-1

This fluid is quite similar to the Isobutyl-isopropyl silicate but has a greater viscosity and higher boiling point.

At 100°F the density of this liquid is 11 percent less than that of pure water, the specific heat is 61 percent less, the viscosity is 760 percent greater, and the thermal conductivity is 82 percent less.

1. Chemical composition (1), aliphatic orthosilicate ester

2. Molecular weight, no data available

3. Boiling point (1), 710°F at 760 mm Hg

4. Flash point (1), 393°F

5. Fire point (1), 450°F

6. Pour point (1), less than -100°F

7. Vapor pressure (1), less than 1 mm below about 375°F

8. Latent heat (2), see comments

Temp. °F	9. Density (1) Gms/cc	10. Specific heat (1) Btu/lb-°F	11. Viscosity (1) centi-poises	12. Thermal conductivity (3)*** Btu/hr-ft²(°F/ft)
-50	0.887*		380	0.058
0	0.884*		45**	0.061
50	0.882	0.321*	13.5	0.063
100	0.880	0.390	6.0	0.068
150	0.877	0.454	3.33	0.066
200	0.875	0.500	2.26	0.066
250	0.872	0.550	1.65	0.067
300	0.870	0.592	1.25**	0.068

13. Surface tension (1), 28.7 dynes per centimeter at 68°F, 19.9 dynes per centimeter at 212°F

14. Refractive index (1), 1.4391 at 68°F

*Extrapolated linearly
**Extrapolated using ASTM Chart D341-43
***See comments

15. Dielectric constant (1),[4] 2.61

16. Color (1), colorless

17. Odor (1), odorless

18. Combustibility (1), combustible

19. Toxicity (1), not dangerously toxic

20. Stability (1), appears to be stable up to 500°F

21. Corrosiveness (1), very little corrosion with ferrous metals

22. Solubility (1), soluble in hydrocarbons. No data on solubility in water.

23. Effect on elastomers (1), synthetic elastomers swell, only Neoprene suitable.

24. Specific references for this fluid:

(1) Catalog of Oronite Chemical Co., San Francisco, Calif.
(2) Othmer, D. F., Ind. Eng. Chem., Vol. 32, 1940, p. 841.
(3) Smith, J. F. D., Trans. Am. Soc. Mech. Eng., Vol. 58, 1936, p. 719.

25. Specific comments on physical properties:

a. Very low pour point.
b. Latent heat data as estimated by method of Othmer (2) appear too high. Data should be obtained on this.
c. Thermal conductivity at 86°F estimated by method of Smith (3). This value is close to value of silicates of John B. Pierce Foundation. Temperature effect assumed same as amyl silicate.

[4] Special electrical grade

Table 43. Properties of Celanese Corp. Landel HF Inversyl Phosphate Hydraulic Fluid

At 100°F the density of this liquid is 16 percent greater than that of water, the specific heat is 60 percent less, the viscosity is 4600 percent greater, and the thermal conductivity is 30 percent less.

1. Chemical composition, $(C_8H_9)_3PO_4$
2. Molecular weight, 368
3. Boiling point (average) (1), 528°F at 10 mm Hg
4. Flash point (average) (1), 453°F
5. Fire point (1), 688°F
6. Pour point (1), -13° to -22°F
7. Vapor pressure (1), from 0 to 300°F vapor pressure is insignificant
8. Latent heat, no data

Temp.	9. Density (1)	10. Specific heat (1)***	11. Viscosity (1) centi-	12. Thermal conductivity (see comments)
°F	Gms/cc	Btu/lb-°F	poises	Btu/hr -ft²(°F/ft)
-80	1.221	0.326*		0.076
0	1.198	0.349*	7200	0.075
30	1.178	0.372	225	0.074
100	1.152	0.405	32.3	0.073
150	1.129	0.425*	9.45	0.071
200	1.106	0.451*	4.33	0.070
250	1.083	0.474*	2.45**	0.069
300	1.060	0.497*	1.59**	0.068

13. Color (1), light amber
14. Odor (1), none
15. Combustibility (1), combustible
16. Toxicity, no data

*Extrapolated, see comments
**Extrapolated using ASTM Chart D341-43
***See comments

17. Stability (1), chemically stable but no temperature limits known. Believed to be stable to 500°F.

18. Corrosiveness (1), non-corrosive to ordinary metals

19. Solubility (1), insoluble in water

20. Effect on elastomers (1), certain rubber compounds are suitable

21. Specific references for this fluid:

(1) Letter to C. J. Geankoplis, 4/13/53, from Celanese Corp. of America.
(2) Watson, K. M., Chem. Eng. Prog., Vol. 49, 1933, p. 173.
(3) Palmer, G., Ind. Eng. Chem., Vol. 40, 1948, p. 89.

22. Specific comments on physical properties:

a. Temperature effect on specific heat (2) and thermal conductivity assumed same as for cresol.
b. Thermal conductivity estimated by Palmer (3) method.

Table 44. Properties of Dow Corning Co. DC-510 Silicone Fluid (50 Centistokes Viscosity at 25°C)

At 100°F the density of this fluid is 1 percent less than that of pure water, the specific heat is 65 percent less, the viscosity is 6400 percent greater, and the thermal conductivity is 76 percent less.

1. Chemical composition, silicone polymer

2. Molecular weight (2)*: 3230

3. Boiling point*, non-volatile

4. Flash point (2), 550°F

5. Freezing point (2), approximately -65°F

Temp. °F	6. Vapor pressure (2) mm Hg	7. Latent heat* Btu/lb	8. Density (2) Gms/cc	9. Specific heat (2) Btu/lb-°F	10. Viscosity (2) centi-poises	11. Thermal conductivity (2) Btu/hr - ft²(°F/ft)
-50		no data	1.070	0.393	696	0.0903
0			1.040	0.377	192.5	0.0891
50	insignificant		1.015	0.362	82.3	0.0879
100	insignificant		0.990	0.346	43.6	0.0867
150	insignificant		0.965	0.334	27.0	0.0855
200	insignificant		0.940	0.327	16.9	0.0843
250	insignificant		0.915	0.329	13.3	0.0831
300	insignificant		0.890	0.340	8.72	0.0819

12. Color (3), colorless to light straw

13. Odor, no data

14. Combustibility (2), slight combustibility

15. Toxicity (2), non-toxic

16. Stability (3), good stability, better than that of Dow Corning DC-200 fluids of comparable viscosities. Stable to at least 400°F.

17. Corrosiveness (2), non-corrosive to metals

18. Solubility (3), insoluble in water, soluble in most hydrocarbons and chlorinated solvents

*See comments

Table 45. Properties of Dow Corning Co. DC-550 Silicone Fluid

At 100°F the density of this fluid is 7 percent greater than that of pure water, the specific heat is 62 percent less, the viscosity is 11,600 percent greater, and the thermal conductivity is 75 percent less.

1. Chemical composition, silicone polymer

2. Molecular weight, no data

3. Boiling point (1), 482°F at less than 10 mm

4. Flash point (1), 575°F

5. Freezing point (2), -58°F

6. Vapor pressures (1), insignificant

7. Latent heat, no data

Temp. °F	8. Density (2) Gm/cc	9. Specific heat (3) Btu/lb-°F	10. Viscosity (1) centi-poises	11. Thermal conductivity (4)*** Btu/hr - ft²(°F/ft)
-50	1.147*	0.288	23000**	0.0740
0	1.120	0.319	2180	0.0728
50	1.093	0.350	262	0.0710
100	1.066	0.382	60	0.0696
150	1.039	0.413	25.4	0.0682
200	1.012	0.445	19.7	0.0667
250	0.985*	0.480	12.2	0.0652
300	0.958*	0.513	8.8	0.0638

12. Color (2), clear, yellowish color

13. Combustibility, believed only slightly combustible

14. Toxicity, believed to be non-toxic since other silicone fluids are non-toxic

15. Stability, does not gel or form gums after heating in air at 500°F for 1000 hours

*Extrapolated linearly
**Extrapolated using ASTM Chart D341-43
***Estimated using data from other silicone compounds

19. Effect on elastomers (2), it will shrink many rubber stocks in nearly the same manner as the 50-200 fluids

20. Specific references for this fluid:

(1) Letter to W. Robinson, 7/1/52, from Dow Corning.
(2) Letter to C. Geankoplis, 3/24/55, from Dow Corning.
(3) Dow Corning Silicone Notes - Dow Corning 550 fluids, properties and applications reference 5101, July 1952.

21. Specific comments on physical properties:

a. The molecular weight has been approximated from equation where log (viscosity) = 1 + .0123 mol wt.
b. Boiling point so high considered non-volatile.
c. There are no data on latent heat. The boiling point is so high that the fluid will decompose before the boiling point is reached.

Table 45, continued

16. Corrosiveness (2), non-corrosive

17. Solubility, assumed to be non-soluble in water since it is moisture resistant

18. Effect on elastomers, no data but believed to shrink many rubber stocks like DC-200 fluids

19. Specific references for this fluid:

(1) Bulletin from Dow-Corning, New Engineering Materials, 1946.
(2) Dow-Corning Silicone Notes, 8501C, July, 1932.
(3) Letter to R. H. Lynch, 11/26/47, from Dow-Corning.
(4) Bates, O. K., Ind. Eng. Chem., Vol. 41, 1949, p. 1966.

APPENDIX II

PROPERTIES OF HEAT TRANSFER FLUIDS FROM 300° TO 900°F

The following tables contain principally extrapolated data on the properties of four fluids applicable above 300°F. The data for water are given in Table 15, Section IV. - As in all other tables, specific references are indicated by numbers in parentheses.

Table 46. Minnesota Mining and Manufacturing Co. Fluorochemical O-75 at High Temperatures

1. Chemical composition (1), $C_8F_{16}O$

2. Boiling point (1), 214°F at 760 mm Hg

3. Flash point (1), non-flammable

4. Temp. °F	4. Vapor pressure psia	5. Density gm/cc	6. Specific heat Btu/lb-°F	7. Viscosity centipoises	8. Thermal conductivity Btu/hr - ft²(°F/ft)
300	61***	1.48*	0.28	0.30****	0.020*
400	200***	1.39*	0.30	0.20****	0.02 to 0.010*
500	520***	1.31*	0.31	0.15****	0.02 to 0.010*
600	1150***	1.24*	0.32	0.12****	0.02 to 0.010*

9. Stability (1), thermally stable to 1100°F

10. Corrosiveness (1), does not corrode metals up to 575° - 925°F

11. Specific references for this fluid:

    (1) Bulletin from Minnesota Mining and Manufacturing Company, St. Paul, Minnesota.

12. Specific comments on physical properties:

    a. Specific heat data are from linear extrapolation of experimental data by John Fisher, Ohio State University, 1953.
    b. Thermal conductivity data very doubtful.
    c. An estimated critical temperature of about 300°F appears very low. Vapor pressure data are meaningless above the critical temperature.
    d. Maximum probable error of viscosity is 0.04 centipoises.

*Extrapolated linearly using data below 300°F
**Extrapolated using ASTM Chart D341-43 and data below 300°F
***Extrapolated using Cox chart
****See comments

Table 47. Minnesota Mining and Manufacturing Co. Fluorochemical N-43 at High Temperatures

1. Chemical composition, $(C_4F_9)_3N$

2. Boiling point, 351°F at 760 mm Hg

3. Flash point (1), non-flammable

4. Temp. °F	5. Vapor pressure mm Hg	6. Density Gms/cc	7. Specific heat**** Btu/lb-°F	8. Viscosity***** centipoises	9. Thermal conductivity Btu/hr - ft²-(°F/ft)
300	6.1	1.57**	0.30**	0.41***	0.03****
400	30.5*	1.43**	0.31**	0.21***	0.03****
500	103*	1.29**	0.32**	0.12***	0.03 to 0.01**
600	263*	1.15**	0.32**	0.08***	0.03 to 0.01**

9. Combustibility, non-combustible

10. Stability (1), high stability to 900°F

11. Corrosiveness, will not corrode metals up to several hundred °C

12. Specific references for this fluid:

    (1) Catalog of Minnesota Mining and Manufacturing Company, No. FL-PL.

13. Specific comments on physical properties:

    a. Probable inaccuracy of density data is 0.17 at 600°F.
    b. Specific heat data are extrapolation of experimental data of John Fisher, Ohio State University, 1953.
    c. Maximum probable error of viscosity is 0.04 centipoises.

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*Extrapolated using Cox chart
**Extrapolated linearly using data below 300°F
***Extrapolated using ASTM Chart D341-43
****See comments

Table 48. Dow-Corning Co. Silicone Fluid DC-550 at High Temperatures

1. Chemical composition, silicone polymer

2. Boiling point (1), 482°F at less than 10 mm Hg

3. Vapor pressure, less than 20 to 50 mm at 600°F

Temp. °F	4. Density Gms/cc	5. Specific heat Btu/lb-°F	6. Viscosity centipoises	7. Thermal conductivity Btu/hr - ft²(°F/ft)
300	0.99*	0.51*	8.6**	0.084*
400	0.93*	0.57*	4.8**	0.080*
500	0.88*	0.63*	3.0**	0.076*
600	0.84*	0.72*	2.1**	0.072*

8. Combustibility, believed to be only slightly combustible

9. Stability (1), very stable. Does not gel or form gums even after prolonged heating in air at 500°F for 1000 hours.

10. Specific references for this fluid:

(1) Dow-Corning Booklet on Silicones.

*Extrapolated linearly using data below 500°F
**Extrapolated using ASTM Chart D-341-43

Table 49. Carbide and Carbon Corp. Ucon Fluid 50-HB-280-X at High Temperatures

1. Chemical composition, no data

2. Boiling point, no data (see comments)

3. Flash point (1), 500°F

4. Vapor pressure, (see comments)

Temp. °F	5. Density Gms/cc	6. Specific heat (1) Btu/lb-°F	7. Viscosity (1) centi-poises	8. Thermal conductivity Btu/hr - ft²(°F/ft)
300	0.94*	0.54	5.17	0.092*
400	0.89*	0.58*	2.86	0.092*
500	0.85*	0.63*	1.8**	0.092*
600	0.81*	0.67*	1.2**	0.091*

9. Combustibility (1), slightly combustible

10. Stability (1), limited to maximum of 500°F

11. Corrosiveness, no data at high temperatures

12. Specific references for this fluid:

    (1) Letter to W. Robinson, 6/16/52, from Carbide and Carbon Chemicals Company.

13. Specific comments on physical properties:

    a. No vapor pressure data available. However, since vapor pressure at flash point of 500°F is about 16 mm Hg, the vapor pressure at 600°F is below 760 mm Hg.

*Extrapolated linearly using data below 300°F
**Extrapolated using ASTM Chart D-341-43

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