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PROPERTIES OF AIRCRAFT FUELS

By Henry C. Barnett and Robert R. Hibbard

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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PROPERTIES OF AIRCRAFT FUELS[1]

By Henry C. Barnett and Robert R. Hibbard

SUMMARY

Since publication of the NACA RM's E53A21 and E53I16, interest in fuel properties at high temperature has increased. This interest is prompted by problems arising from the possible use of fuel as a heat sink in supersonic aircraft now being designed. For this reason, the two previous publications have been combined, and wherever possible the data have been extended to cover properties of fuels up to temperatures as high as 400° F. Recently available data on properties not included in the original compilations have been introduced in the present report, and some of the existing data on fuel characteristics have been revised to improve accuracy and utility.

INTRODUCTION

During recent years, specifications for jet-engine fuels have undergone considerable change as a result of the continuous growth in understanding of what may be required of a fuel with regard to availability, performance, and handling. Although necessary, the constant changing of specifications has to some extent imposed a handicap on those portions of the aeronautical industry that must rely on fixed fuel properties for design purposes. This is particularly true of the aircraft manufacturer whose job it is to combine airframe, engine, and fuel into a satisfactory flight vehicle.

The most serious problem involving fuel that confronts the aircraft manufacturer is the problem of fuel-system design; and, because of the obvious importance of the fuel system to ultimate reliability of the aircraft, it is essential that existing knowledge of fuel characteristics be made available to the designer. Past experience of the fuel-system designer has been built upon knowledge of the characteristics and performance of aviation gasoline as applied to aircraft powered by the conventional piston engine. Although the "feel" or "know how" gained from this experience is invaluable, the widely different characteristics of

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[1] This report supersedes NACA RM's E53A21 and E53I16 by the same authors.

jet-engine fuels compared with aviation gasoline somewhat limit the applicability of existing fuel-system-design data to current and proposed jet aircraft.

Considerable information has been acquired on the characteristics of jet-engine fuels; however, the data are scattered throughout the technical literature and are not readily obtainable. This report has been written in order to provide a single source of data on jet-engine fuel properties for use in fuel-system design. Much of this information is incomplete and must necessarily be extended as results of research now in progress become available.

In addition to information on fuel properties, this report includes discussions of fuel specifications, the variations among fuels supplied under a given specification, fuel composition, and the pertinence of fuel composition and physical properties to fuel-system design. In some instances, the influence of external variables such as pressure and temperature on physical properties is indicated. Two appendixes are included. Appendix A briefly reviews the various laboratory test procedures that are required by military specifications and indicates the significance of each to aircraft performance. In appendix B are some of the data that were used to estimate the accuracy of a few of the relations that are presented in the body of the report.

The data presented are restricted to current jet-engine fuels and several fuels of possible interest in the future. For fuels other than these, it is suggested that references 1 and 2 be consulted for information on properties and performance characteristics. Throughout the text, numerous references are cited in order to provide the reader with sources of information containing more detail than is practical in the present report.

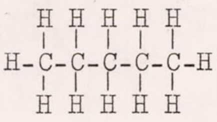
Special acknowledgement is due Major L. G. Burns and Captain J. W. Hitchcock, Wright Air Development Center, Dayton, Ohio, for assistance in the collection of reference material.

FUEL COMPOSITION

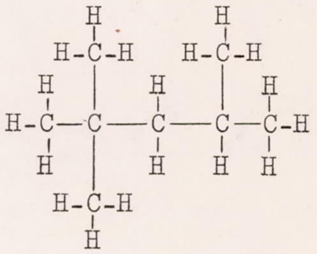
Jet-engine fuels are substantially 100-percent-hydrocarbon mixtures, and any given fuel may contain several thousand individual hydrocarbon compounds. For example, aviation gasoline within its narrow boiling range may contain as many as 300 individual hydrocarbons, whereas JP-4 fuel with its wide boiling range may contain as many as 5,000 to 10,000 hydrocarbons. The distribution of hydrocarbons found in petroleum-derived fuels varies from one crude-oil source to another; however, the refiner can, by control of refining methods, meet the physical and thermal property requirements of aircraft use. Only very small quantities, rarely exceeding 1 percent, of nonhydrocarbon compounds are likely to be present in aircraft fuels. The hydrocarbons found in jet-engine fuels may be divided into four classes: paraffins, cycloparaffins, aromatics, and olefins.

Paraffins and Cycloparaffins

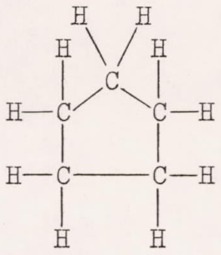
Paraffins have a chain-like structure of carbon atoms, and cycloparaffins contain rings of carbon atoms with the rings usually composed of five or six carbon atoms. Examples of these compounds are illustrated as follows:



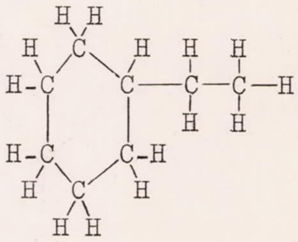
Straight-chain paraffin
(n-pentane)



Branched-chain paraffin
(2,2,4-trimethylpentane or isooctane)



Cycloparaffin
(cyclopentane)



Cycloparaffin
(ethylcyclohexane)

Paraffins and cycloparaffins are very similar in most of their properties and together make up 75 to 90 percent of most aircraft fuels. They are stable in storage, clean-burning, and do not attack any normal construction material. The paraffins are the least dense of the hydrocarbons and have the highest heats of combustion per unit weight and the lowest per unit volume. Cycloparaffins are more dense than paraffins but their densities do not approach those of aromatics discussed in the following section.

Aromatics

Aromatics are those hydrocarbons that contain the characteristic six-member benzene ring. The three classes of aromatics are: single-ring aromatics, multiring aromatics with no two rings sharing a single carbon atom, and multiring aromatics with two rings sharing two common carbon atoms. All members of the latter two classes have boiling points above 400° F, as do some members of the first class. Examples of the three classes of aromatics are as follows:

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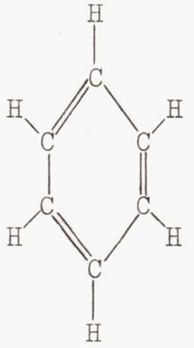
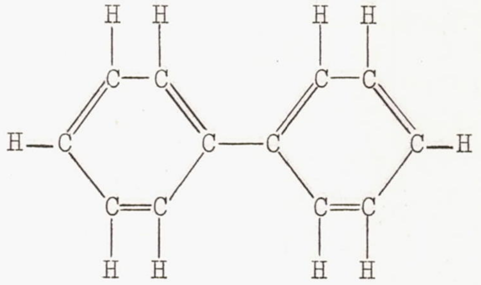
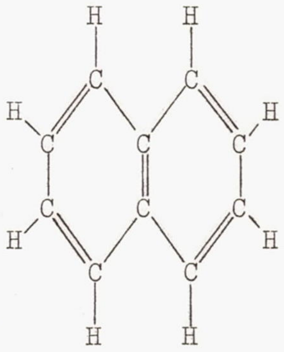


Single-ring aromatic
(benzene)



Multiring aromatic
with no common carbon atom
(biphenyl)

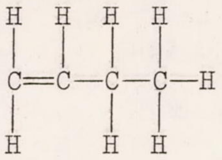


Multiring aromatic
with two common carbon atoms
(naphthalene)

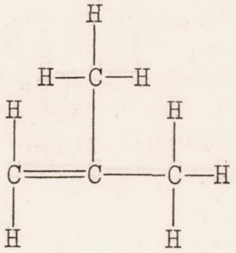
The concentration of aromatics of all classes is limited to a maximum of 25 volume percent by present jet-fuel specifications, but currently available fuels usually contain about 10 to 15 percent total aromatics and 0.5 to 3.0 percent of the multiring type; most of the latter are believed to be of the type in which two carbon atoms are shared by two rings. Aromatics are stable in storage, smoky in burning, have high solvency powers, and tend to swell many elastomers. As a class, the aromatics have the highest densities of the hydrocarbon compounds and have the lowest heats of combustion per unit weight and the highest per unit volume.

Olefins

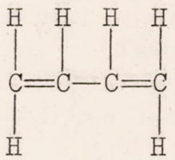
An olefin is a hydrocarbon that has a characteristic carbon-to-carbon double bond, this bond being more reactive chemically than those in aromatic hydrocarbons. The carbon atoms in the molecule may be arranged in a chain (aliphatic olefin), in a ring (cycloolefin), or on a chain attached to an aromatic ring (aromatic olefin). Some olefins may have two or more carbon-to-carbon double bonds, in which case they are called polyolefins (usually diolefins). Examples of olefin structures are as follows:



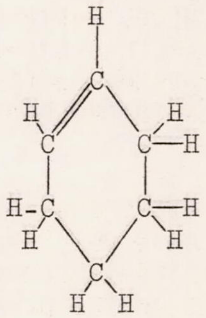
Monoolefin
(butene-1)



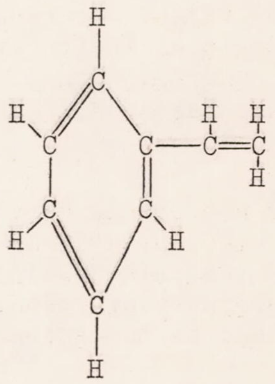
Monoolefin
(isobutene)



Diolefin
(1,3-butadiene)



Cycloolefin
(cyclohexene)



Aromatic olefin
(styrene)

Olefins are limited in jet fuels by the specification of a maximum bromine number. For jet-engine fuels, the maximum olefin content is 5.0 percent by volume.

Some types of aromatic olefins and diolefins are very reactive and, in the presence of catalysts, will polymerize to form high-molecular-weight gum. For example, the members of these classes shown (styrene and 1,3-butadiene) are polymerized industrially to form GR-S synthetic rubber. Atmospheric oxygen or traces of some metals can act as catalysts. These highly reactive hydrocarbons are present in very low concentrations (below 0.2 percent) and are indirectly limited in marketed fuels by the accelerated gum test included in aircraft fuel specifications. Olefins are nearly as clean burning as paraffins and are intermediate between paraffins and cycloparaffins in such properties as density and heating values on both weight and volume bases.

Nonhydrocarbons

Nonhydrocarbon compounds that may be present in aviation fuels contain sulfur, oxygen, or nitrogen. Sulfur compounds are found in greater concentration than oxygen or nitrogen compounds. The present specifications for jet-engine fuels limit the total sulfur content to a maximum of 0.4 percent by weight. Sulfur may be present as thiophenols, mercaptans, sulfides, disulfides, thiophenes, thiophanes, and possibly as free sulfur.

Thiophenols and mercaptans are slightly acidic and are usually removed by caustic washing or variations thereof in refinery processing. Thiophenol is an unlikely component in adequately processed fuels, and mercaptan sulfur is limited in the present specifications to a maximum of 0.005 percent by weight. Mercaptans are undesirable components of aviation fuels because of their extremely disagreeable odor and corrosive tendencies toward cadmium. Other sulfur compounds mentioned in the foregoing discussion are believed to be innocuous in the concentrations encountered.

Oxygen may be present in very small quantities as phenols or naphthenic acids. The latter compounds may have some objectionable corrosive properties. Caustic washing will completely remove these compounds in normal refinery practice. No limit on the presence of such compounds is included in the current aircraft fuel specifications.

Nitrogen compounds are present in aircraft fuels in trace quantities only; however, there is evidence that these compounds contribute to gum formation.

Fuel gum consists of high-molecular-weight, nonvolatile organic compounds containing hydrogen, carbon, and oxygen and possibly sulfur and nitrogen. Gum is found in marketed fuels up to the amount permitted by specifications, usually 7 milligrams per 100 milliliters or about 0.01 percent by weight. Additional gum may form during storage because of the presence of reactive material. Gum compounds may be soluble or insoluble and, in the latter case, may cause filter clogging and controls sticking. Within limits of current specifications, there is no indication that gum will affect the combustion process.

AIRCRAFT FUEL SPECIFICATIONS

The requirements for various aircraft fuels under current specifications are presented in table I. The first four columns of this table list the permissible limits on physical properties for gasolines now used by the military services. The remaining columns present requirements for four turbojet fuels. A discussion of aircraft fuel specifications and their significance is presented in appendix A.

Aviation Gasolines

The limits of the properties for the first three gasolines of table I are all the same with the exception of antiknock value (fuel grade). The fourth and highest performance fuel (grade 115/145) differs in heat of combustion and aniline-gravity product. The limits for each property are based upon years of experience and research on performance of fuels in piston engines. For example, controls are maintained on fuel sulfur and gum content in order to promote engine reliability as to cleanliness and long life; heat of combustion is limited in order to ensure optimum fuel economy and long range; freezing point is limited to promote reliability of fuel-system performance in cold-weather operations; volatility, as exemplified by the A.S.T.M. distillation curve and Reid vapor pressure, is limited to promote satisfactory starting, absence of vapor lock, and minimum weathering. All the numerical limits on these properties represent compromises between over-all performance and availability needs.

Jet-Engine Fuels

The introduction of the turbojet engine to the field of aircraft propulsion brought about an entirely new set of fuel requirements. The first turbojets utilized MIL-F-5616 (JP-1) fuel; however, it was quickly recognized that large fleets of jet aircraft operating under all-out emergency conditions would consume considerably more JP-1 fuel than would be available from crude petroleum with existing refinery equipment. As a result, during the next several years intense effort was devoted to the development of a turbojet fuel specification satisfactory from performance as well as availability considerations. The process of developing such a specification is gradual and must necessarily parallel engine development and changes in fuel performance requirements.

The stepwise development of the current MIL-F-5624C jet-fuel specification provides an example of the influence of fuel and engine research on specification requirements. Table II shows that the original proposal for JP-3 fuel was made in January, 1947. The requirements for this fuel were largely dictated by the desire to establish a military fuel of maximum availability; however, a few of the limits on certain properties were based upon research data and operational experience that had been obtained at that time.

In December, 1947, the first specification AN-F-58 was established for JP-3 fuel. Some of the restrictions on the physical properties of this fuel differed from those of the original proposal. These changes resulted because some of the requirements had been shown by systematic performance research to be unnecessarily restrictive and others were too liberal. For example, a limitation on bromine number, a measure of unsaturated hydrocarbon content of a fuel, was included because it was suspected that unsaturated hydrocarbons promoted carbon deposition in engines and greatly increased gumming tendencies. At the same time the requirements on gum content were liberalized. Other changes as discussed previously were based upon availability and performance considerations.

The second revision of the JP-3 specification was made in March, 1949, and the designation was changed to AN-F-58a and later to MIL-F-5624. At that time the permissible aromatic content was lowered to 25 percent by volume, and the bromine number was increased to 30. These changes were made because it had been found that aromatic content was more significant than bromine number as a factor in carbon-forming tendency. The March, 1949, revision added limits to specific gravity (0.728 to 0.802), because of the importance of this factor to aircraft design.

The JP-3 specification remained unaltered until May, 1951, at which time the mercaptan sulfur content was limited to a maximum of 0.005 percent by weight. This revision resulted from corrosion difficulties, possible rubber swell problems, and objectionable odors that were being encountered during engine tests.

Throughout the growth of the JP-3 specifications, considerable opposition to the high volatility of the fuel was voiced because of the excessive entrainment (slugging) losses that occurred during rapid climb. In spite of these losses, there was considerable reluctance to decrease volatility, because of expected difficulties in engine starting, cold-weather performance, and increased tank explosion hazard. The arguments against lower volatility were mitigated by the results of engine performance studies that indicated satisfactory operation on a fuel similar in some characteristics to JP-3 fuel but having a Reid vapor pressure of 2.0 to 3.0 pounds per square inch. This range of vapor pressure represented a compromise between the desired engine performance and fuel availability. Because of this drastic change in volatility, the new fuel became known as JP-4 under the specification issued in May, 1951, (table II). The change in Reid vapor pressure was accompanied by the elimination of the 90-percent distillation requirement and the addition of a maximum limit of 250° F on the 10-percent distillation point. The limitation of the 10-percent point, in effect, places a more precise restriction on the minimum volatility of the fuel, since the accuracy of the Reid-vapor-pressure determination is questionable at pressures as low as 2 pounds per square inch. The change in volatility also required new specific-gravity limits.

In December, 1953, the JP-4 specification was altered to eliminate the 10-percent and end-point requirements and to add limiting values on the 20-, 50-, and 90-percent points on the distillation curve. The revision was made to prevent the use of exceptionally heavy petroleum stocks that could meet the 10-percent requirement by the addition of a small quantity of a very volatile component such as butane. Although such blends could meet the over-all specification, the volatile component is easily lost by weathering in storage and in flight; and the remaining heavy portion would not be suitable for aircraft use.

At the time A.S.T.M. distillation requirements were revised, in December, 1953, the API gravity range was narrowed to 10°. This change was made to ease the burden of the airframe and engine designers in development of fuel systems and fuel controls. The 10° API spread was considered the minimum that could be tolerated without a severe loss in fuel availability. In addition to the foregoing changes, the maximum limits on existent and potential gum were lowered and a smoke-volatility index was added to ensure clean-burning fuels.

The MIL-F-5624C specification was introduced in May, 1955, and incorporates changes in volatility and specific gravity. These changes were dictated more by the desire for universal availability than by technical considerations. That is, emergency use would involve operation of aircraft on fuels available throughout the world; therefore, broadening of the specification was needed to permit engine development for the maximum variations in fuels that might occur.

The current MIL-F-5624C (JP-4) fuel is accepted as the primary military fuel for turbojet aircraft; however, an additional fuel, MIL-F-5624C (JP-5), has been established to control the properties of a special blending component for use in naval aircraft operations. This component resembles a high-flash-point kerosene and in application is blended 2 or 3 parts by volume with 1 part by volume MIL-F-5572 (115/145 grade) aviation gasoline. The properties of fuel blends of this type are presented in table III together with properties of the individual blend components. A comparison of data for the special blends with table I indicates that with the exception of freezing point and 50-percent-distillation point the properties of the two components combine to meet the JP-4 specifications.

Fuel Oils

There are, of course, no aircraft specifications for fuel oils; however, these materials have from time to time excited interest as possible commercial jet-aircraft fuels. Fuel oils are currently marketed for household and industrial uses under the specifications shown in table IV. These specifications would undoubtedly be modified if fuel oils were applied to aircraft powerplants. There is no means of predicting these alterations; consequently, for the purposes of subsequent discussion, the variation of fuel properties under a given specification will be considered in comparison with the existing specifications under which fuel oils are marketed.

The fuel oils are derived from distillate and residual fractions of petroleum and are commonly identified by numbers (table IV) corresponding to the various specification requirements. The more conventional uses of the distillate fuels (numbers 1 and 2) are for home heating, Diesel engines, and industrial heating where it is impractical to heat the fuel to improve flow characteristics. Residual fuels (numbers 4, 5, and 6) are residues from petroleum stills that are blended with less viscous materials. These fuels are used where it is feasible to heat the fuel.

TYPICAL INSPECTION DATA FOR JET-ENGINE FUELS AND FUEL OILS

Jet-Engine Fuels

The specifications discussed in the foregoing section have been developed to ensure satisfactory handling properties and performance and adequate availability, but the nature of petroleum is such that marketed fuels may vary considerably in physical properties and still meet the specification requirements. This fact complicates fuel-system design inasmuch as an acceptable system is expected to function reliably even with fuels representing the extremes in physical properties that might be procured under a given specification. In order to illustrate variations to be expected in the properties of fuels of the same grade, representative inspection data have been compiled in tables V to VII.

The data shown in tables V to VII indicate that wide variations can and do occur in fuels meeting the various specifications. With respect to fuel-system design, however, it is important to know what the maximum ranges of variation may be for the different fuel properties. For this reason, a number of fuel-inspection sheets, in addition to those shown in tables V to VII, have been examined to establish these ranges. These data are summarized in table VIII. Data for JP-5 fuel were supplied by the Bureau of Aeronautics, Department of the Navy. Data for JP-4 and JP-3 fuels are from references 3 and 4, respectively.

In addition to the properties shown in table VIII, there are other properties that are useful in evaluation of thermal characteristics discussed later in this report. These additional properties are estimated for the average jet fuels in table VIII by methods described in reference 1. The results are shown in table IX.

Fuel Oils

Data on physical properties of samples of fuel oils are compared, and the variations to be expected under existing specifications (table IV) are shown in table X. Data for fuel oils 1, 2, and 4 were compiled from surveys of the U. S. Bureau of Mines (refs. 5 to 7). Data on fuel oils 5 and 6 are quite scarce; therefore, it has been necessary to compare the properties of single samples of these two fuels with averages for the three lower grades. Additional properties for average fuel oils of the lighter grades are also shown in table IX.

PHYSICAL PROPERTIES OF FUELS

In connection with the discussion of table VIII, it is shown that, for the purposes of fuel-system design, it is important to know the variation of physical properties among fuels supplied under a given specification. It is equally important to know how a given physical property will vary with environmental changes; that is, how properties such as density or volatility may vary with temperature. In the succeeding paragraphs, the effects of these environmental changes are discussed for physical properties of particular interest in fuel-system design.

Density

Fuel density is of interest in airframe design since it controls weight loadings with completely full tanks; and, when combined with the heat of combustion, it is used in flight-range calculations. Density is also a factor in the calibration of tank gages and fuel-metering devices.

Density is commonly expressed in terms of true density (mass per unit volume), specific gravity relative to water at 60° F, or API (American Petroleum Institute) gravity. These terms are interrelated by the following equations at 60° F:

$$\text{Density (lb/cu ft)} = 62.43 \times \text{specific gravity} \tag{1}$$

$$\text{Density (lb/gal)} = 8.347 \times \text{specific gravity} \tag{2}$$

$$^{\circ}\text{API} = \frac{141.5}{\text{Specific gravity } (60^{\circ}/60^{\circ}\text{ F})} - 131.5 \tag{3}$$

These equations are presented graphically in figure 1.

Density is not specified for reciprocating-engine fuels and, in practice, covers a fairly narrow range for a single grade of fuel. A much wider range is found under a single jet-fuel specification, and limits on API gravity have been established for jet fuels. These limits in terms of specific gravity at 60° F and in API gravity are given in table I. A range of 10° to 12° API is permitted in the current JP-3, JP-4, and JP-5 specifications.

Fuel density decreases with increasing temperature. Several methods are available in the literature for estimating this change. The following equation gives the most easily used method:

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$$\rho_t = \rho_{60}\left[1 + C_{ex}(60 - t)\right] \tag{4}$$

where

C_{ex} mean coefficient of thermal expansion

t temperature, °F

ρ_t specific gravity at temperature t

ρ_{60} specific gravity at 60° F

Values of C_{ex} for use with equation (4) are given in figure 2 for varying 60° F gravities.

However, over wide ranges of temperature and pressure, more precise estimates of gravity require more complex procedures. A plot of specific gravity up to the critical temperature and up to pressures of 600 pounds per square inch is given in reference 8 for fuels of varying 60° F gravities. Expansion ratio (i.e., specific gravity at 60° F/specific gravity at t) is correlated with a modulus containing 60° F gravity and viscosity in references 9 and 10. The latter reference states that the use of this modulus permits the accurate prediction of specific gravity for a variety of fuels almost to their critical temperatures. Specific gravity at varying temperatures and pressures is correlated with the pseudocritical properties of the fuels (ref. 11). The molal average boiling points and the characterization factors of fuels have been used to estimate expansion ratios (ref. 1). Both the critical constants required in reference 11 and the boiling points and factors required in reference 1 can be easily estimated from A.S.T.M. distillation and API gravity data. Several of these methods are compared against one set of experimental data (ref. 12) in appendix B-1. Equation (4) is recommended for temperatures up to 400° F.

The effect of changing temperature on the specific gravities of fuels is shown in figure 3. Curves are presented for jet-engine fuels and fuel oils having minimum, average, and maximum specific gravities. These curves were calculated from equation (4) and figure 2 using specific gravities at 60° F from tables VIII and X. Maximum and minimum limits from specifications are shown. In the case of JP-1 fuel (fig. 3(a)), there is no minimum specific gravity (table I); however, the flash-point requirement, 110° F, indirectly controls the minimum gravity. Examination of figure 3 shows that the specific gravity of individual samples of fuels may vary widely from average values. The difference is greatest at the highest temperature and may be as much as $6\frac{1}{2}$ percent for jet fuels and $8\frac{1}{2}$ percent for fuel oils.

In figure 3(b) the maximum and minimum curves for the actual fuel samples lie outside the limits of the specification. Most of these samples were procured under the MIL-F-5624A specification (table II) and do not meet the more restrictive gravity range now required by the current MIL-F-5624C specification. Regardless of this fact, the average curves shown in these figures would be expected to be about the same for both specifications.

The specific-gravity - temperature relations for the average quality fuels are shown in figure 3(h). Typical samples of aviation gasoline and fuel oils numbers 5 and 6 are included for comparison. Considering gasoline to be the reference fuel, the ratios at 60° F of the specific gravities of the other fuels (fig. 3(h)) to gasoline are given in the following table:

Fuel	Specific-gravity ratio at 60° F
Aviation gasoline (115/145 grade)	1.00
JP-1	1.17
JP-3	1.10
JP-4	1.11
JP-5	1.20
Number 1 fuel oil	1.18
Number 2 fuel oil	1.22
Number 4 fuel oil	1.32
Number 5 fuel oil	1.35
Number 6 fuel oil	1.38

Volatility

A.S.T.M. distillation and Reid vapor pressure. - Fuel-system designers are particularly interested in variations of volatility among fuels because of the influence of this property on vapor and entrainment losses, vapor lock, and flammability hazards. Fuel volatility is regulated in current aircraft fuel specifications by limitations of the

A.S.T.M. distillation (D86-52) curve and the Reid vapor pressure. Figure 4 illustrates the variation that may be expected in distillation curves for jet fuels and fuel oils. Because the particular group of JP-1 fuels used in figure 4(a) does not produce a maximum envelope curve as high as the permissible specification limits, it is obvious that certain JP-1 fuels having higher distillation temperatures could be procured under the MIL-F-5616 specification.

The volatility of other jet fuels is illustrated in figures 4(b) to (d). As indicated previously in connection with density, the JP-3 fuel samples (fig. 4(b)) were procured under the MIL-F-5624A specification and the maximum envelope lies outside the limits of the current specification. The average curve, however, is probably about the same by both specifications. This observation is also applicable to JP-5 data in figure 4(d).

Figures 4(e) to (g) show A.S.T.M. distillation curves for the fuel oils. Comparison of these three grades of fuel oil indicates that the spread between minimum and maximum temperatures tends to increase as the fuel oil becomes heavier.

Figure 4(h) compares all the average distillation data with curves for single samples of 115/145 grade aviation gasoline and a number 5 fuel oil. The curve for the number 5 fuel oil is incomplete because cracking occurred at 1025° F.

It has generally been accepted that the temperature at the 10-percent-evaporated point is indicative of the fuel volatility; that is, the lower this temperature, the greater the volatility. This relation has generally held true for gasolines but may be erroneous in the case of fuels such as JP-3 because of the manner in which the volatility is achieved. For example, the JP-3 specification requires the Reid vapor pressure to be between 5 and 7 pounds per square inch, and this requirement can be met by adding a small percentage of a high-vapor-pressure component to a relatively low-vapor-pressure stock. In such a case, the final blend would have the desired Reid vapor pressure, but the addition of this small percentage of the high-vapor-pressure component would have small effect on the 10-percent distillation temperature. Some fuels meeting the JP-4 specification have been prepared by blending or pressurizing very low-vapor-pressure components with relatively small amounts of highly volatile materials. These fuels can be expected to show rapid losses in Reid vapor pressure during storage.

Laboratory aging tests conducted by the Sun Oil Company on JP-3 fuels indicated a loss of about 15 percent in volume for a fuel pressurized with pentanes and a loss of about 3 percent in volume for a fuel pressurized with butanes. These losses corresponded to a decrease of Reid vapor pressure from 6.5 to 5 pounds per square inch. These tests were made in unstoppered bottles at atmospheric pressure with samples alternately heated and cooled between 70° and 120° F during a 24-hour cycle.

An empirical equation relating Reid vapor pressure, specific gravity, 20-percent A.S.T.M. distillation point, and slope of the distillation curve at the 10-percent point has been developed:

$$P_R = S\left(\frac{a}{\rho_{60}t_{20} + b} + c\right) \tag{5}$$

where

a,b,c	constants
P_R	Reid vapor pressure, lb/sq in.
S	slope of A.S.T.M. distillation curve at 10-percent-evaporated point, $(t_{15}-t_5)/10$
t_{20},t_{15},t_5	20-, 15-, and 5-percent A.S.T.M. distillation temperature, °F
ρ_{60}	specific gravity at 60° F

The constants in equation (5) vary with the class of fuel as follows:

Fuel	a	b	c
Aviation gasolines	486	-50	-4.33
JP-4	114	-89	-.45
JP-3	46	-104	.42

From equation (5) and these constants, the Reid vapor pressures were calculated from distillation data and specific gravities for 21 aviation gasolines, 36 JP-3 fuels, and 20 JP-4 fuels. Average deviations of observed Reid vapor pressures from calculated values were ±0.5, ±0.5, and ±0.33 pound per square inch for the aviation gasolines, JP-3 fuels, and JP-4 fuels, respectively. Data for aviation gasolines and 23 of the JP-3 fuels used in the development of the equation were taken from references 4 and 13.

The Reid vapor pressures of two-component blends can be estimated from the following linear equation:

$$P_{R,b} = P_{R,1}N_1 + P_{R,2}N_2 \tag{6}$$

where

N_1,N_2	volume fractions of components 1 and 2
$P_{R,b}$	Reid vapor pressure of blend, lb/sq in.

$P_{R,1}, P_{R,2}$ Reid vapor pressures of components 1 and 2, lb/sq in.

This equation appears sufficiently precise for most applications as shown in appendix B-2. Presumably the Reid vapor pressures of blends containing more than two components can be estimated by simply expanding equation (6); however, substantiating data are not available.

Reid vapor pressures are not precise measures of true vapor pressures. Reid vapor pressures are measured by the A.S.T.M. D323-52 method in which a vapor-liquid volume ratio v/l of 4 is specified. This ratio represents a departure from the true vapor-pressure measurement in that true vapor pressure is by definition the pressure at a vapor-liquid volume ratio of 0.

True vapor pressure. - True vapor pressures at 100° F are slightly higher than Reid vapor pressures and may be calculated from the latter by using the following equation (ref. 2):

$$P_{0,100} - P_R = 0.0223\ P_R + \frac{0.0119\ P_R S}{1 - 0.0368\ P_R} \tag{7}$$

where

P_R Reid vapor pressure ($v/l = 4$), lb/sq in.

$P_{0,100}$ true vapor pressure at 100° F ($v/l = 0$), lb/sq in.

S slope of A.S.T.M. distillation curve at 10-percent-evaporated point, $(t_{15} - t_5)/10$

It is often necessary to estimate true vapor pressures over a range of temperatures. Classically the vapor-pressure - temperature relation is expressed by

$$\log P = A - B/T \tag{8}$$

where

A,B constants

P absolute pressure

T absolute temperature

This equation works well over only a limited temperature range, since B, which is directly proportional to the latent heat of vaporization, is not a true constant. However, the linear relation between log pressure and reciprocal temperature has been developed into a practical method for estimating vapor pressures of petroleum-derived fuels by introducing the concept of pressure function (ref. 2). Pressure function is a modified log pressure term and is related to pressure by the following equation:

$$\log P = 1.167199 + 5.2553 \log(1 - 0.00687917\ A) \tag{9}$$

where

A pressure function, kilofeet

P absolute pressure, lb/sq in.

This equation is also the standard pressure-altitude relation up to 35 kilofeet. Pressures can be converted into pressure functions by equation (9), by using table XXVIII of reference 2, or figure 5 of this report.

Through this pressure function, vapor pressures can be expressed as linear functions of temperature in °F by either of the following equations:

$$A_{0,t} = A_{0,100} + b(100 - t) \tag{10}$$

$A_{0,t}, A_{0,100}$ pressure functions at t and 100° F, respectively, for v/l ratio of 0 (the subscripts indicate v/l ratio and temperature, respectively)

b temperature coefficient, a constant characteristic of each fuel

t temperature, °F

and

$$A_{0,t} = b(t_n - t) \tag{11}$$

where

t_n normal boiling point of fuel (i.e., at 1 atm), °F

Equations (10) and (11) are used rather than equation (8) because the log-pressure - temperature relation is normalized to pressure and temperature conditions nearer those of interest (i.e., pressures encountered in flight and temperatures around the boiling points). This permits linear relations to hold more closely than would be possible using equation (8).

The determination of the vapor-pressure - temperature relation of a fuel, then, requires the determination of the constant plus a knowledge of either the true vapor pressure at 100° F (for use with eq. (10)) or the normal boiling point (for use with eq. (11)). The constant b can be evaluated in several ways, depending on what fuel inspection data are available.

If the Reid vapor pressure and the 10-percent slope are known, b can be estimated from

$$b = 0.056 + \frac{262}{\frac{A_{0,100}}{b} + 560} - 0.04\sqrt{S} \tag{12}$$

The first step in determination of the true-vapor-pressure - temperature curve is the calculation of $P_{0,100}$ from equation (7). The value of $A_{0,100}$ may then be obtained from figure 5. Next, b is calculated as indicated in equation (12). A sample calculation of b is described in reference 2. Equation (10) may then be used to determine values of $A_{0,t}$ at different temperatures. The values of $P_{0,t}$ corresponding to the computed values of $A_{0,t}$ may be read from figure 5. Although equations (10) and (12) were derived from data on gasolines, their use for JP-4 fuels appears justified by limited NACA data given in appendix B-3. Therefore, this method was used to calculate true-vapor-pressure curves for fuels having slopes up to 12 and varying in Reid vapor pressure between 2 and 7 pounds per square inch. These curves are presented in figure 6. In the absence of A.S.T.M. distillation data, average 10-percent slopes may be assumed to be 2 for gasolines and 4 for JP-3 and JP-4 fuels.

The curves shown in figure 6 do not describe the volatility of fuels having Reid vapor pressures less than 2 pounds per square inch. Furthermore, the methods of calculation described by equations (10) and (12) should be avoided for low-vapor-pressure fuels. In order to estimate the true vapor-pressure characteristics of such fuels, the method reported in reference 14 should be used.

For these higher-boiling fuels and in the absence of flash-point data, b can be estimated from

$$b = 0.142 + \frac{212}{T_n} - 0.04\sqrt{S} \tag{13}$$

where

T_n normal boiling point, °R

The normal boiling point in $^{\circ}R$ T_n is estimated by adding 5° plus 460° to the 10-percent distillation temperature; however, the latter should be corrected to true temperature by using an emergent-stem correction on the thermometer (ref. 14). For JP-1 and JP-5 fuels, T_n is approximately the A.S.T.M. 10-percent-evaporated temperature plus 470°.

If only flash-point data are available, b can be estimated by

$$b = \frac{86.5}{t_n - t_f} \tag{14a}$$

where

t_f flash point, $^{\circ}F$

t_n normal boiling point, $^{\circ}F$

When both distillation and flash-point data are available, b can be most accurately determined by using both equations (13) and (14a). The first step in this procedure is the calculation of b from equation (13). This value is then used to estimate the normal boiling point by substituting into the following rearranged form of equation (14a):

$$t_n = \frac{86.5}{b} + t_f \tag{14b}$$

The resulting value for t_n is then substituted into equation (13), with care to add 460° to convert to $^{\circ}R$. These operations are repeated until a normal boiling point and a value of b are obtained that satisfy both equations. These values can then be used with equation (11) to calculate the pressure function of the fuel at any desired temperature. This pressure function can then be converted to pressure in pounds per square inch by methods previously given.

Vapor pressure curves for JP-1 and JP-5 fuel and the fuel oils calculated from equations (11), (13), and (14) are shown in figure 7. In figure 7(f) the average curves for these fuels are compared with vapor-pressure data for more volatile fuels calculated from equations (10) and (12).

Vapor-liquid ratio. - Another useful relation in fuel-system design is the variation of vapor pressure with vapor-liquid ratio. Equations have been developed for the calculation of this relation, and their use has been confirmed for jet fuels and fuel oils as well as aviation gasoline (ref. 15). The equations are not recommended for use at temperatures very much in excess of the normal boiling point or at pressures much above atmospheric. Consideration is being given to the extension or modification of the equations for use with pressures as high as 200 pounds per square inch (ref. 15).

The following equation represents the variation of vapor pressure with v/l at constant temperature:

$$A_{v/l,t} = A_{0,t} + a\left(1 - 0.01515\ A_{0,t}\right)(v/l)^{0.75} \qquad (15)$$

In order to use this equation it is necessary to know $A_{0,t}$. This quantity has been previously calculated for various fuels from equations (10) and (11) and is expressed as pressure in figures 6 and 7. These figures may be used in solving the above equation by selecting values of pressure at a specific temperature and reconverting to $A_{0,t}$ by use of figure 5, table XXVIII of reference 2, or equation (9).

The parameter a in equation (15) can be estimated from the following equation:

$$a = 3.3\left(1 - \frac{6.6}{bS + 6.6}\right) \qquad (16)$$

The value of b in equation (16) can be determined from the following equation:

$$b = 0.5181(1 - 0.0024\ A_{0,100}) - 0.04\sqrt{S}\ (1 + 0.0032\ A_{0,100}) \qquad (17)$$

In equation (17), $A_{0,100}$ corresponds to the value of pressure at 100° F in figures 6 and 7. For convenience in solving equations (15) to (17) reference 15 includes tables to simplify the calculations of a, b, and $(v/l)^{0.75}$. The determination of values from equation (15) can be further simplified by use of figure 8, which represents the combination of equations (16) and (17) given by

$$\frac{a}{S(a - 3.3)} = 0.0000194\ A_{0,100}\ (9.69 + \sqrt{S}) - 0.00606\ (12.953 - \sqrt{S}) \qquad (18)$$

Freezing Point

Atmospheric temperature measurements have shown (ref. 16) that ambient temperatures as low as -137° F may be encountered at high altitude. Even with aerodynamic heating in high-speed aircraft, skin temperatures and, in turn, aircraft tank temperatures might still be well below fuel freezing temperatures. In order to ensure reliable fuel-system operation at altitudes where low temperatures are encountered and in geographical areas subject to low-temperature ground conditions, aircraft fuel specifications limit fuel freezing temperatures to a maximum of -76° F for all fuels except JP-5. As previously mentioned, JP-5 is often blended with aviation gasoline, and the blend has a freezing point of about -60° F (table III).

The restriction of freezing point to a maximum of -76° F has one great disadvantage in the jet fuel field in that it restricts availability. In reference 17 it is shown that the availability (percent of crude petroleum) could be increased from 13 percent to 20 percent for a 100° F flash-point fuel if the freezing point were increased from -76° to -50° F. Regardless of the advantage in increased availability, no upward revision of freezing-point specification is likely to occur until problems of fuel handling at low temperature are solved and means are found for the efficient utilization of high-boiling fuels in jet engines.

Certain components of petroleum-derived materials have high freezing points; and, in the case of jet fuels, the less volatile constituents may be very near the maximum allowable freezing point. There is no rigorous correlation between volatility and freezing point; however, figure 9 illustrates a general trend based upon Bureau of Mines data for cuts of crude petroleum. This figure shows that freezing points for water-free fuels increase as the end point of the fuel increases. The scatter among these data can be attributed to differences in hydrocarbon composition of the cuts.

Although the data in figure 9 indicate that end points greater than 480° F would produce fuels with freezing points higher than -76° F, it is known that jet fuels with higher end points have been made and that such fuels have freezing points below -76° F. The data in figure 9 are presented simply to illustrate a trend of freezing point with end point and are not considered representative of commercial jet fuels. For this reason the reader is cautioned not to use figure 9 for estimates of jet-fuel freezing points.

Viscosity

Viscosity data are necessary for the calculation of line losses in aircraft fuel systems and may be required for the estimation of injection-nozzle performance; consequently, data have been collected to indicate the viscosities that may be expected for a variety of fuels over a range of temperatures. Viscosities are not regulated for JP-3 and JP-4 fuels in current specifications, but maximum limits at low temperatures are established for JP-1 and JP-5 fuels (table I).

For many years A.S.T.M. viscosity-temperature charts have afforded a convenient method for representing the viscosity-temperature relations of petroleum products. The coordinates on these charts are adjusted to an equation of the following form (ref. 18):

$$\log \log (\nu + c) = A \log T + B \qquad (19)$$

where

A,B,c constants

T absolute temperature, $^{\circ}R$

ν kinematic viscosity, centistokes

Viscosities plotted against temperature on these charts produce linear relations for a given fuel. It is possible, therefore, to estimate viscosities over a wide range of temperatures from experimental data taken at two temperatures. If only one viscosity-temperature point is known, viscosities at other temperatures can be estimated by drawing a line through the point parallel to lines previously established for similar fuels. This practice is not recommended except within the range of viscosities generally associated with aircraft fuels.

Viscosity-temperature characteristics for average or typical fuels are plotted on the A.S.T.M. chart in figure 10. Although the data upon which these curves are based are rather limited, it is believed that the average slopes shown may be used with reasonable confidence since stocks from several sources are represented. Solid straight lines are shown for each fuel over the range where equation (19) is applicable. This equation cannot be applied to temperatures below the freezing or pour points of the fuels, and the lines have been terminated at these points. There are also unpublished experimental data and data from reference 19 that indicate deviations from the linear relation at high temperatures; therefore, dotted lines have been drawn in figure 10 for the high-temperature portions of the curves. Although only approximations, the dotted portions will give more accurate estimates of viscosity than will extrapolations of the straight lines.

Viscosity decreases markedly with temperature (fig. 10), the effect being greater with the more viscous fuels. At a given temperature there are also wide differences in viscosity among the fuels. The heavier fuels are so viscous at low temperatures that heating would be required to produce suitable pumping and atomizing characteristics.

Water Solubility

Most aircraft fuels are substantially saturated with water during some stage of their processing and handling. The solubility of water in hydrocarbons is quite low and is not easily determined. It has been established, however, that this solubility decreases rapidly with decreasing temperature and that the log of the solubility is inversely proportional to the absolute temperature (ref. 20). It has also been shown that aromatics dissolve more water than do the other common classes of hydrocarbons (ref. 20).

Only a limited amount of data is available on the solubility of water in jet-engine fuels. Examples from references 21 to 23 are shown in figure 11 where weight-percent water is shown as a function of temperature for a gasoline, a JP-3 fuel, a JP-4 fuel, and two kerosenes. Between 120° and 20° F the solubility decreases by a factor of 5 to 20, and lowering the temperature of a water-saturated fuel causes much of the water to separate. For example, lowering the temperature of the JP-4 fuel shown in figure 11 from 120° to 20° F reduces the solubility from 0.024 to 0.0047 weight-percent water in fuel. This change would cause about 1.3 pounds of water to separate from 1000 gallons of fuel. At the lower temperature the water would freeze and could clog aircraft filters as reported in reference 21.

Reference 21 shows that a dry fuel can become substantially saturated with only a brief exposure to liquid water. Reference 22 also shows that fuels quickly come to an equilibrium water content with the water in the atmosphere. At a given temperature for both fuel and air, a fuel will be fully saturated if exposed to air with 100-percent relative humidity, and will, for example, be 25-percent saturated if contacted by air having 25-percent relative humidity. This suggests (ref. 22) that, in aircraft tanks with good venting, fuels can lose much of their dissolved water during climb after take-off since the cold ambient air would have a low absolute humidity and would pick up water from the relatively warm fuel.

Solubility of Gases

There is considerable interest in the solubility of gases in fuels resulting from the possible use of combustion products for tank inerting and of compressed gases to transfer fuel through aircraft fuel systems. These solubilities follow Henry's Law quite closely (i.e., the mass dissolved is directly proportional to pressure), and, therefore, gases will separate out of a saturated fuel if the pressure is reduced. This separated gas phase can present problems in the pumping and flow of fuels.

The literature contains a fairly large amount of data on the solubility of the common gases in pure hydrocarbons, but there is often a substantial disagreement between sources as to the solubilities within a given system. There is much less data for aircraft fuels, particularly JP-4 and JP-5, the fuels of greatest current interest. However, a method is proposed in reference 24 that appears to give accurate estimates of the solubility of many gases in any fuel at any temperature. The method is mathematically complex and requires the critical temperatures, pressures, and fugacities of both solute and solvent for its solution. These properties can be evaluated for a given system; and, through the use of this method, solubilities of air in kerosene were calculated at three temperatures. The calculated results were within 10 percent of experimental results in this case (ref. 24).

Since the method of reference 24 is difficult to apply, a more simple correlation was sought to permit rough estimates of gas solubilities in aircraft fuels. Reference 25 presents a tabulation of the literature values for the Ostwald coefficients for several gases in a variety of solvents. The Ostwald coefficient is defined as the volume of gas dissolved in 1 volume of solvent, the gas volume measured at the conditions of solution. This coefficient is independent of pressure. The Bunsen coefficient is often used and is the volume of gas, reduced to 32° F and 1.0 atmosphere pressure, dissolved in 1 volume of fuel at a gas partial pressure of 1.0 atmosphere. The Bunsen coefficient can be calculated from the Ostwald coefficient by

$$\alpha = \beta \frac{492}{T} \tag{20}$$

where

T temperature of solution, °R

α Bunsen coefficient

β Ostwald coefficient

A study of the data given in reference 25 suggested that for oxygen, nitrogen, and air dissolved in petroleum fractions there were fair correlations between the Ostwald coefficients and the specific gravities of the fractions at the temperature of solution. These correlations are described in appendix B-4, and figure 12 was developed from them. This figure permits estimates of Ostwald coefficients over a range of temperatures for fuels of varying specific gravities. The data scatter for fuels in the correlations (appendix B-4) indicates that coefficients estimated from figure 12 may be accurate to about ±25 percent. The method of reference 24 is recommended if higher precision is required.

Reference 25 also lists data for carbon dioxide, carbon monoxide, helium, neon, and argon. For carbon dioxide and monoxide there was no correlation with solvent density, and for the other gases there was insufficient data to attempt a correlation. For all these gases Ostwald coefficients are plotted in figure 13 over a range of temperatures for several hydrocarbon solvents. These data may be useful to indicate the order of solubilities that may be found in hydrocarbon fuels. For carbon dioxide, unlike the other gases, there is a decrease in Ostwald coefficient with increasing temperature, and the solubility of this gas is very high. This high solubility may prove troublesome if combustion products are used for tank inerting.

Surface Tension

There is occasional interest in the surface tension of fuels. Values for this property can be found for various petroleum fractions in reference 26 and in the International Critical Tables. Most of these data were obtained near room temperature.

Surface tensions can also be estimated by using the classical equation of Ramsay and Shields (1893) as given, for example, in reference 27. In this equation

$$\sigma\left(\frac{M}{D}\right)^{2/3} = 2.12\ (T_{cr} - 6 - T) \tag{21}$$

where

D density at temperature of measurement, g/cc

M molecular weight

T temperature of measurement, $^{\circ}K$

T_{cr} critical temperature, $^{\circ}K$

σ surface tension, dyne/cm

For a given fuel, the density at any temperature and the molecular weight and critical temperature can be estimated from correlations given in reference 1, thus permitting the calculation of surface tension at any temperature. Less precise estimates can also be made based only on the 60° F specific gravity of the fuel, since both molecular weight and critical temperature can be approximated from this property. Figure 14 is the result of such estimates and is based on molecular weight - gravity relations for group III fuels taken from reference 1 and critical-temperature - gravity relations from reference 8. (Group III fuels are those having characterization factors between 11.7 and 12.0, a range including most jet-engine fuels.) Surface tensions can be estimated for fuels of varying 60° F specific gravities up to their critical temperatures.

Surface tensions estimated by interpolation from figure 14 at the lower temperatures ran slightly below but within 2 dynes per centimeter of data given in the International Critical Tables and reference 26. The temperature coefficient at the lower temperatures is approximately the same, -0.05 dyne per $^{\circ}F$, as given in reference 26. No surface-tension data at high temperatures are known; therefore, no comparison can be made. However, surface tension must decrease to zero at the critical temperature, and the temperatures shown on figure 14 for zero surface tension are close to the critical temperature of these fuels. In general, it is believed that surface tensions can be estimated from this figure within 4 dynes per centimeter with the possible exception that unusual fuels may have surface-active impurities that can reduce the surface tension to below estimated values. The presence of such impurities can be determined only by direct measurement of surface tension.

Dielectric Constant

With the development of the capacitance-type fuel gage for use in aircraft, attention was directed to the electrical as well as the physical properties of fuels. The gage consists essentially of a capacitor immersed in the fuel tank. The pointer of the gage deflects proportionally to the height of the fuel in the capacitor and to a quantity $(K-1)/D$, where K is the dielectric constant and D is the density in pounds per gallon. The quantity $(K-1)/D$ is called the capacity index and is the fuel characteristic that determines the accuracy of the gage.

Where fuel tanks are nonuniform, the tank and capacitor must be designed and contoured to complement each other so that the increase of capacitance as the fuel rises is directly proportional to the volume of fuel in the tank. The gages are calibrated to read directly in pounds, and the desired accuracy is ±2 percent full scale.

The dielectric characteristics of current aircraft fuels were investigated in a study involving measurements on approximately 160 fuel samples. The first portion of this work is summarized in reference 28, and an analysis of the data is reported in reference 29.

It is not the intention of the present report to review the entire study; however, a few figures are included herein to illustrate the variations in dielectric characteristics that might be encountered with fuels procured under existing specifications.

The dielectric constants of fuels vary linearly with temperature as shown in figures 15(a) to (c), which are based upon data from reference 28. For JP-1 fuels (fig. 15(a)), the deviation from average is approximately ±2 percent; for JP-3 fuels (fig. 15(b)) the deviation varies between 3.2 percent and 5.8 percent over the temperature range shown. In figure 15(c) data are shown for 30 fuels that approximate the characteristics of JP-4 fuels. These fuels were prepared by evaporating 10 percent of the light ends of the JP-3 fuels shown in figure 15(b). The deviation for these JP-4 fuels varies between 3.4 and 7.0 percent.

The spread of data in figures 15(b) and (c) is probably representative for JP-3 and JP-4 fuels inasmuch as the specific gravities of the samples investigated approximately covered the range permitted by the

The range of specific gravities for the JP-1 fuel samples reported in reference 28 is not so wide as the range permitted by specifications. This is illustrated in the following table:

Fuel	Specific gravity at 32° F			
	Ref. 28		Permitted by specification	
	Min.	Max.	Min.	Max.
JP-1	0.8019	0.8466	0.785	0.862
JP-3	.7434	.8117	.752	.792
JP-4	.7524	.8300	.763	.813

In order to estimate dielectric constants for fuels other than those in figures 15(a) to (c), the data in reference 28 were plotted for all fuels at two temperatures, 32° and 77° F. All these data fell in a single linear pattern, and deviations from a faired line through the points were no greater than ±2 percent. The equation of the line is

$$K = 1.667\rho + 0.785 \tag{22}$$

where

ρ specific gravity at any temperature

K dielectric constant at the same temperature

An additional check of equation (22) was made with data from references 30 and 31. These data indicate that the equation applies for paraffinic and cycloparaffinic hydrocarbons over a range of temperatures from -184° to 410° F. The dielectric constants for pure aromatics are somewhat higher than those of paraffins, particularly in the high-density range. For this reason it is recommended that equation (22) be used with caution for fuels containing high percentages of aromatics. There is no accurate method to set the limiting value of aromatic concentration for use in this equation; however, on the basis of data available at this time it is suggested that equation (22) be used for estimation of dielectric constants only with fuels containing less than 25 percent (by volume) aromatics. Changes in dissolved-water content within the limits imposed by solubility had a negligible effect on dielectric constant (ref. 28).

Equation (22) is used to estimate the dielectric constants for the fuel oils and JP-5 fuel. The specific-gravity curves of figure 3 were used in making these estimates. The results are presented in figures 15(d) to (g). The dielectric constants for various fuels are compared in figure 15(h).

THERMAL PROPERTIES OF FUELS

In addition to the physical properties discussed in the preceding section, there are certain thermal properties that play an important part in the design of aircraft fuel systems. In the past many of these properties have been significant from a safety standpoint and are now even more vital under high-temperature conditions that may exist in supersonic aircraft. The succeeding portions of this section review these properties and describe the variations to be expected for jet fuels and fuel oils.

Heat of Combustion

The gross, or upper, heat of combustion of a fuel is the amount of heat released when a unit weight of fuel is completely burned to yield carbon dioxide gas and water in the liquid phase. The net, or lower, heat of combustion is the amount released when carbon dioxide and gas-phase water are the products. The difference between the gross and net heats is equal to the latent heat of evaporation of the water formed in burning a unit weight of fuel; this difference is proportional to the hydrogen content of the fuel. Only the net heat of combustion is of practical significance since the exhaust temperatures of all engine cycles are so high that only gas-phase water is discharged.

In table I it is shown that the minimum heat of combustion acceptable for JP-3 and JP-4 fuels is 18,400 Btu per pound. It is doubtful that the average heat of combustion for these fuels will ever be more than 2 to 3 percent greater than this minimum figure. Heats of combustion for JP-1 fuels are not limited by specifications, and on the basis of data in table VIII appear to be 1 or 2 percent lower than those of JP-3 and JP-4 fuels. The spread of heating value among JP-1 fuels will probably be no greater than ±1.5 percent of the average value.

A fairly precise relation exists between the net heat of combustion of hydrocarbon fuels and the product of the aniline point and the API gravity, or aniline-gravity product. The following equation, taken from reference 32, can be used for aircraft fuels:

$$q_n = 17608 + 0.2054\,\mathscr{A}G - 7.245\times10^{-6}(\mathscr{A}G)^2 - 140\ (\%\ \text{Sulfur}) \qquad (23)$$

where

$\mathscr{A}$ aniline point, °F

G gravity, °API

q_n net heat of combustion, Btu/lb

The sulfur correction in equation (23) is in a different form from that given in reference 32 but gives substantially identical results.

If aniline points are not available, the net heat of combustion can be estimated with somewhat less precision from specific gravity alone using the following equation:

$$q_n = 22,130 + \frac{2560}{\rho_{60} - 1.53} \tag{24}$$

where

ρ_{60} specific gravity at 60° F

Equation (24) was calculated from a curve for net heat of combustion presented in reference 1. This curve, together with a curve for gross heat of combustion, is reproduced in part as the dotted line in figure 16(a). The abscissa of this figure has been changed to be linear in specific gravity rather than °API used in reference 1. Because of the interest in calculations for volume-limited aircraft, figure 16(b) is included to illustrate the variation of heats of combustion per unit volume with specific gravity and aniline point.

Heats of combustion are determined for a process in which the products of combustion are brought back to the initial reactant temperature. A reference temperature of 77° F is usually chosen. The effect of varying temperature on heats of combustion is negligible over a wide range and less than the normal precision of measurement of heating values, as shown in appendix B-5.

Latent Heat of Vaporization

A method described in reference 1 permits the estimation of latent heats of vaporization from A.S.T.M. distillation and API gravity data. The averaged data for jet fuels and fuel oils in tables VIII and X have been used to calculate the variation of latent heat of vaporization with temperature (fig. 17). A curve for the 115/145 grade aviation gasoline (table III) is included for comparison. The curves for the fuels converge at low temperatures with a total spread of about 9 Btu per pound at 200° F. In the high-temperature portion of the figure the curves are extended to the critical temperatures.

Not shown are data to indicate the latent heats of vaporization for maximum- and minimum-quality fuels under each specification. However, check calculations based on the physical-property variations shown in tables VIII and X indicate that the spread between maximum and minimum heats of vaporization for jet fuels would not exceed 10 Btu per pound up to 400° F. At temperatures up to 600° F the spread may be as great as 20 Btu per pound.

Specific Heat

Specific heats for petroleum fuels in the liquid state are shown in figure 18 as functions of API gravity and temperature. This plot is based upon the following equation from reference 33:

$$c_p = \frac{1}{\sqrt{\rho_{60}}}(0.388 + 0.00045\ t) \qquad (25)$$

where

c_p specific heat at constant pressure, Btu/lb/°F

t temperature, °F

ρ_{60} specific gravity at 60° F

For fuels having characterization factors of about 11.6, the agreement between figure 18 and the following correlation developed in reference 34 is quite good:

$$c_p = 0.6811 - 0.308\rho_{60} + t(0.000815 - 0.000306\rho_{60})(0.055k + 0.35) \qquad (26)$$

where

k characterization factor

Since the jet fuels of interest (table IX) have characterization factors of 11.6 to 11.8, the use of figure 18 should be satisfactory for estimation purposes. If greater accuracy is desired, equation (26) should be used for the characterization factor of interest.

Still another correlation is presented in reference 1 where specific heats are given as functions of temperature, API gravity, and volumetric average boiling point. This relation is perhaps a little easier to use than that of reference 34, since characterization factors are not required. The values obtained from the relation in reference 1 are about 5 percent higher than those determined from figure 18.

Enthalpy

Enthalpy diagrams are useful for determining the capacity of fuels to absorb heat or the amount of heat required to accomplish a given change in the temperature or the state of a fuel. Such diagrams can be constructed for any fuel using the correlations of, for example, reference 1 between the heat capacities and latent heats and the distillation and gravity of the fuel. Enthalpy diagrams for average quality JP-3, JP-4, and JP-5 fuels are given in figure 19. The saturated-liquid curves on this figure are used to estimate the amount of heat that can be absorbed in the liquid phase alone. The saturated-vapor curve is used when the fuels are completely vaporized. The region between these two curves represents conditions of partial vaporization, and the lines above the saturated-vapor curve show the enthalpy of superheated vapor. Also shown are lines of constant pressure to indicate the pressures required to vaporize the fuel.

As an example of the use of these diagrams, consider the average quality JP-4 fuel in the liquid phase and at an initial temperature of 100° F (fig. 19(b)). The initial enthalpy is 48 Btu per pound as shown by the saturated-liquid curve at 100° F. Assume that 250 Btu per pound are to be added to this fuel giving a final enthalpy of 298. This heat addition can be made in several ways:

(1) The fuel can be kept completely in the liquid phase. The final temperature will then be 520° F as shown by the temperature of saturated liquid at an enthalpy of 298 Btu per pound (fig. 19(b)). A pressure greater than 8 atmospheres would be required to keep the fuel liquid.

(2) The latent heat of vaporization can be fully exploited as a heat sink and the fuel completely vaporized. The final temperature of the vapor will then be 335° F as indicated by the saturated-vapor curve at an enthalpy of 298. A pressure of around 0.7 atmosphere or lower will be required for complete vaporization.

(3) The fuel can be partially vaporized at temperatures between 520° and 335° F depending on the pressure. For example, at a pressure of 2.0 atmospheres, a partial vaporization will yield a final temperature of 380° F with a fuel being in a mixed phase.

These enthalpy diagrams show that the latent heat of vaporization is only available as a heat sink at moderately high temperatures or low pressures. This is especially true with low-volatility fuels such as JP-5. For example, JP-5 fuel could be fully vaporized at 350° F, but the pressure in the evaporator would have to be below about 0.2 atmosphere (fig. 19(c)). These vapors would have to be recompressed before they could be fed to an engine. This recompression would present a major pumping problem.

Although only three enthalpy diagrams are presented for fuels of interest in this study, reference 1 contains diagrams for petroleum fractions with mean average boiling points varying between 200° and 800° F and characterization factors of 11 and 12. Cross interpolation between these diagrams can be used to construct enthalpy diagrams for a wide variety of fuels.

Flammability Properties of Fuels

A large amount of information is available on the combustion of hydrocarbons; however, a complete review of this material is beyond the scope of this report. Some aspects of combustion research are directly related to aircraft fuel systems, and these are discussed briefly. In the succeeding sections, flammability limits, ignition temperatures, flame propagation rates, and quenching distances are discussed.

Flammability limits. - Homogeneous, gas-phase, hydrocarbon-air systems are flammable only over a definite range of concentrations. At any given temperature and pressure there is a lean (lower) limit for a fuel which represents the minimum concentration of fuel in air required for combustion and below which concentration flames cannot propagate. Similarly, there is a rich (upper) limit which defines the maximum amount of fuel in air that will support combustion. Flammability limits vary depending on whether the flame is propagated upward, downward, or horizontally. The widest limits are found with upward propagation where convective forces help the flame travel through the fuel-air mixture. Much of the data in the literature is for upward propagation, since these studies were aimed at determining the flammability hazards involved in the storage of fuels and the widest limits were desired to give margins of safety.

There are some variations in the reported flammability limits due to apparatus variables. This is especially true for limits determined at low pressures where the quenching effects of chamber walls become an important factor; however, there is fair agreement in the literature for flammability limits determined at 1 atmosphere. It has long been recognized that lean-limit mixtures of all hydrocarbons contain about the same heat of combustion per unit volume of fuel-air mixture, and on this basis the fuel concentrations for lean-limit mixtures at 1 atmosphere can be calculated from the following equations taken from the correlations of reference 35 and converted to English units:

$$L = \frac{1.87\times10^{6}}{q_{n}M} \qquad (27)$$

where

L lean-limit concentration, percent by volume

M molecular weight

q_n net heat of combustion, Btu/lb

Lean limits calculated from equation (27) can also be expressed in terms of fuel-air ratio by

$$L_{f/a} = \frac{L \times M}{(100 - L) \times 28.97} \tag{28}$$

where

$L_{f/a}$ lean-limit concentration, fuel-air ratio

Rich-limit concentrations can be estimated from the correlations of reference 35 by the following equations:

$$R = L + \frac{143}{M^{0.7}} \tag{29}$$

$$R_{f/a} = \frac{R \times M}{(100 - R) \times 28.97} \tag{30}$$

where

R rich-limit concentration, volume percent

$R_{f/a}$ rich-limit concentration, fuel-air ratio

Equations (27) to (30) were derived from pure-hydrocarbon data but are applicable to practical fuels. The equations require heats of combustion and molecular weights as input variables. Heats of combustion can either be estimated by the methods previously described, or a value of 18,500 Btu per pound can be used for aircraft fuels with an inaccuracy no greater than 3 percent. The molecular weights required in these equations are for the vaporized portion of the fuel. If the fuel is completely vaporized, the molecular weight of the whole fuel as estimated from charts in reference 1 can be used. Concentration limits have been calculated on this basis for various fuels of minimum, maximum, and average volatility. These are listed in the following table in terms of both volume percent and fuel-air ratio:

Fuel	Flammability limits			
	Volume percent		Fuel-air ratio	
	Lean	Rich	Lean	Rich
JP-1				
Minimum volatility	0.62	4.66	0.035	0.28
Maximum volatility	.71	5.15	.035	.27
Average volatility	.67	4.96	.035	.27
JP-3				
Minimum volatility	.76	5.40	.035	.26
Maximum volatility	1.70	7.16	.035	.25
Average volatility	.90	6.15	.035	.25
JP-4				
Minimum volatility	.74	5.34	.035	.26
Maximum volatility	.90	6.15	.035	.25
Average volatility	.80	5.63	.035	.26
JP-5				
Minimum volatility	.57	4.38	.035	.28
Maximum volatility	.62	4.68	.035	.28
Average volatility	.60	4.53	.035	.28
No. 1 fuel oil				
Minimum volatility	.53	4.18	.035	.28
Maximum volatility	.61	4.61	.035	.29
Average volatility	.58	4.45	.035	.28
No. 2 fuel oil				
Average volatility	.52	4.09	.035	.29
No. 4 fuel oil				
Average volatility	.45	3.71	.035	.29

These calculated concentrations are slightly in error because equations (27) to (30) were developed from flammability-limit data obtained at room temperature, while much higher temperatures are actually required for complete vaporization of these fuels. Temperatures of about 300° F are required for complete vaporization of jet fuels to produce rich-limit mixtures. However, the inaccuracies due to the temperature effect are not large as shown by the following comparison between estimated limits and those experimentally measured at 300° F (ref. 36):

Fuel	Flammability limits, fuel-air ratio			
	Calculated		Measured at 300° F	
	Lean	Rich	Lean	Rich
JP-1	0.035	0.27	0.037	0.31
JP-3	.035	.25	.037	.30

The preceding paragraph deals with the calculation of limit concentrations under conditions where the fuel is completely vaporized and where the molecular weight of the vapor can be estimated with fair precision. Under conditions of partial vaporization, the molecular weight of the vapor will vary both with the properties of the fuel and to a lesser extent with the fraction vaporized; this fraction will be small in fuel tanks unless the tanks are nearly empty. Reference 37 contains a table that includes estimates of vapor molecular weights under fuel-tank conditions as a function of the fuel's 10-percent-distillation temperature. These data are plotted as the line in figure 20 along with points for seven fuels taken from reference 12 for 2-percent evaporation. The agreement between the two references is good. Lean and rich flammability limits can be estimated for fuel-tank conditions by using molecular weights from this figure in equations (27) to (30).

Relatively little work has been done on the flammability limits of mists and sprays because of the difficulty in preparing stable mists of known concentration. However, it is fairly well established that the flammability limits of evenly dispersed small droplets are much the same as for vapors. For example, the limits for a mist of 10-micron JP-1 fuel droplets at 32° F are compared in the following table with the limits for vaporized JP-1 fuel at 300° F (both experiments are from reference 36):

Flammability limits of JP-1, fuel-air ratio			
Mist at 32° F		Vapor at 300° F	
Lean	Rich	Lean	Rich
0.043	0.23	0.037	0.31

The mist has a slightly narrower flammability range, but much of the difference may be due to the difference in temperature between the two experiments.

Flammability limits change with pressure. The effect of varying pressure on the limits of n-hexane is shown in figure 21 for pressures below 1 atmosphere (ref. 38) and in figure 22 for pressures to 10 atmospheres (ref. 39). The subatmospheric limits (fig. 21) were measured with upward propagation in a 2-inch-diameter tube, and both the narrowing of the flammability region below 10 inches of mercury absolute and the low pressure limit of about $1\frac{1}{4}$ inches of mercury absolute reflect the quenching effect of the tube walls at low pressures. Wider flammability ranges at low pressures and lower pressure limits would be found in larger systems such as aircraft fuel tanks. The superatmospheric limits (fig. 22) were measured with horizontal propagation, and for this reason the flammability range is somewhat narrower than would be obtained with upward propagation. This figure shows a marked widening of the flammability limits at higher pressures.

Up to this point the limits discussed have been composition limits for homogeneous systems with the fuels either vaporized or evenly dispersed as mists. In cases where there is a relatively large amount of fuel as, for example, in fuel tanks, there are both upper and lower temperature limits, which are functions of both the composition limits and the volatility of the fuel. For example, 115/145 octane gasoline has a vapor pressure of about 3 pounds per square inch absolute at 60° F. Under equilibrium conditions, this pressure is sufficient to give a fuel-air ratio of about 0.6 in the tank free space above the fuel. This fuel-air ratio is about twice the rich limit; therefore, the free space above 115/145 octane gasoline is nonflammable at 60° F under equilibrium conditions. It should be emphasized that this free space can be flammable under nonequilibrium conditions such as when a tank has just breathed in air. Under equilibrium conditions this fuel would have to be cooled to about 30° F before the vapor pressure is sufficiently reduced to pass below the rich-limit concentration.

On the other hand, a typical JP-5 fuel has a vapor pressure of about 0.01 pound per square inch absolute at 60° F, equivalent to a fuel-air ratio of about 0.003. This is well below the lean limit, and the tank free space will be nonflammable provided that liquid fuel is not dispersed in this space. As previously shown, fuel mists in air are nearly as flammable as fuel vapors in air, and a fuel tank containing JP-5 fuel at 60° F can be flammable if shaken sufficiently to disperse liquid fuel droplets through the tank free space. The temperature of JP-5 fuel must be raised to about 135° F before the vapor pressure becomes sufficient to exceed the lean-limit concentration.

Altitude-temperature flammability envelopes are often discussed in regard to flight safety. These envelopes can be derived from flammability-limit and fuel-vapor-pressure data. Typical envelopes, reproduced from reference 2, are shown as figure 23. However, the narrowing of those envelopes at high altitude with the flammability ceiling at 62,000 feet (fig. 23) is the result of using flammability-limit data that were obtained in small tubes with low ignition energies. Wider limits at low pressures and lower pressure limits for flammability have been obtained using higher-energy ignition systems as shown in figure 24 (ref. 36). The use of a surge generator, which gave about a 100-millijoule spark energy, extended the flammability limits of an aviation gasoline down to about 0.5 inch of mercury absolute. This is equivalent to an altitude of 75,000 feet. Further, the flammability range is nearly as wide at very low pressures as at 1 atmosphere.

Since it is believed that lean- and rich-concentration limits are substantially constant up to pressure-altitudes of at least 75,000 feet, altitude-temperature diagrams were calculated using equations (27) and (29), molecular weights from figure 20, and vapor-pressure data extrapolated from figures 6 and 7. These diagrams are given in figure 25 for the various average-volatility fuels.

Figure 25 is believed to be a somewhat better criterion for flight safety than figure 23, since it indicates no flammability ceiling.

Fire hazards may exist in fuel tanks at conditions well outside the envelopes shown in figures 23 and 25 since these figures were based on equilibrium conditions. Flammable mixtures can result at temperatures and altitudes well above the indicated upper limits if the tanks breathe in air. Flammable mixtures can also be found at temperatures and altitudes far below the lower limits shown if mechanical forces disperse liquid fuel into the tank free space. It appears that complete freedom from possible tank explosions can only be attained through inerting.

Ignition temperatures. - Flammable mixtures can be ignited by sparks, hot solids, hot gases, shock waves, or by the injection of spontaneously flammable agents; however, only ignition by hot solids will be considered herein.

The most widely used type of thermal ignition test is one in which a liquid fuel is dropped into a heated crucible or flask. The lowest temperature that will cause an ignition is called the spontaneous-ignition temperature or autogenous-ignition temperature. This temperature for typical fuels and lubricants is listed in the following table (refs. 40 and 41):

Fuel or lubricant	Spontaneous ignition temperature, °F
100/130 Grade aviation gasoline	844
Low-volatility aviation gasoline	900
Unleaded motor gasoline	568
Kerosene	480
JP-3 fuel	
Sample A	484
Sample B	502
JP-4 fuel	484
JP-5 fuel	
Sample A	473
Sample B	477
No. 1 fuel oil	490
No. 2 fuel oil	498
No. 4 fuel oil	505
No. 6 fuel oil	765
SAE 10 lubricating oil	720
SAE 60 lubricating oil	770

Jet fuels have ignition temperatures that are among the lowest found for hydrocarbons and that are considerably lower than those for aviation gasoline.

Increasing pressure decreases ignition temperature as shown below (unpublished NACA data):

Pressure, atm	Ignition temperature, °F	
	JP-4 fuel	JP-5 fuel
1	484	477
5	383	415
9	374	408

Flame propagation. - A flammable mixture, once ignited, will continue to react until the reaction is either complete or is quenched. The reaction takes place in a discrete reaction zone and may occur either as a normally propagating flame or as a detonation. Flame propagation in a static system or in laminar flow is a relatively slow process; velocities are of the order of 1 to 2 feet per second for most hydrocarbon-air systems at ambient temperatures and 1 atmosphere pressure. This velocity increases with increasing temperature, the effect being approximately proportional to the 1.5 power of the ratio of absolute temperatures. Changing pressure has little effect on laminar flame-propagation rates. Flame velocities vary with fuel-air ratio and are highest for mixtures just slightly richer than stoichiometric; stoichiometric fuel-air ratios are about 0.068 for aircraft fuels. In turbulent flow, flame-propagation rates are increased but never by a factor of more than about 10. There is about an eightfold increase in pressure as the result of normal propagation in a closed, adiabatic system.

Detonation is a much more rapid process and may reach velocities of the order of 5000 feet per second in hydrocarbon-air systems. The ranges of fuel-air ratios that will detonate are much narrower than the flammability ranges previously discussed; that is, a more nearly ideal combustible mixture is a requisite more for detonation than for normal propagation. While the final pressure after detonation in an adiabatic system is only about 8 times the initial pressure, a transient pressure of 15 to 20 times the initial pressure travels with the detonation wave. For this reason detonations can be more destructive than normal combustion.

Quenching. - Flames will be extinguished rather than propagate through too narrow a constriction. This is called quenching and is the basis for the Davy lamp and for flame arresters. The quenching distance is the smallest separation between parallel plates that will just allow a flame to pass, and the quenching diameter is the minimum diameter of a tube through which a flame will propagate. The quenching diameter is 1.25 to 1.50 times the quenching distance.

Quenching distances are influenced by mixture composition, pressure, and temperature. For nearly ideal mixtures (slightly richer than stoichiometric), the quenching distance of the common hydrocarbons in air is approximately given by the following equation:

$$QD = 0.1\left(\frac{520}{T}\right)^{0.5}\left(\frac{1}{P}\right)^{0.9} \tag{31}$$

where

P absolute pressure, atm

QD quenching distance, in.

T temperature, $^{\circ}R$

3543

PRACTICAL PROBLEMS OF FUEL COMPOSITION AND PHYSICAL PROPERTIES IN AIRCRAFT FUEL-SYSTEM DESIGN

The foregoing section presents data on the composition and physical properties of aircraft fuels. In the design of aircraft fuel systems, these properties are associated with certain problems which, if not properly resolved, can become very practical obstacles to reliable aircraft performance. Some of these problems are storage stability, fuel cleanliness, corrosion, inerting, low-temperature effects, and vapor and entrainment loss. In the succeeding sections these problems are discussed and, where possible, the influences of fuel composition and physical properties are defined.

Storage Stability and Fuel Cleanliness

Fuel quality may be changed in three ways between the refinery and the aircraft fuel tank because of handling and storage factors. The fuel may (1) lose varying amounts of its more volatile components through evaporation, (2) increase in gum content, and (3) pick up extraneous materials such as dust and rust.

The loss of volatile components has been previously mentioned in the section on volatility and, in extreme cases, might present an engine operational problem in regard to starting. The loss of these components as functions of initial fuel quality and subsequent handling and the exact effect of these losses on engine performance are complex problems that are not discussed.

The gum content of fresh jet fuel, as required by the present military specifications, should not exceed 7 milligrams per 100 milliliters. These specifications also require that the gum content should not exceed 14 milligrams per 100 milliliters after laboratory-accelerated aging, and presumably the latter concentration indicates the order of concentrations that might be encountered in field-aged fuels. The fuel specifications do not differentiate between soluble and insoluble gum; either or both may be found in jet fuels within the required concentration limits.

Gum content is limited in reciprocating-engine fuels primarily to reduce induction-system deposits. Jet engines are considerably more tolerant of gum, and there is no indication that soluble-gum contents up to several times that permitted by the present specifications will adversely affect performance. However, insoluble gum may clog filters and cause sticking of controls and valves, although at present no case is known of engine operational problems that were caused by fuel-derived gum.

The use of inhibitors to ensure storage stability is a precaution necessary for control of jet fuels,which may be produced from a variety of petroleum stocks. It should not be assumed from this practice that all jet fuels are unstable. The degree of instability of any particular jet fuel depends upon the compositions of the stocks from which it is derived. In general, it may be said that the thermally cracked stocks are more unstable than virgin or straight-run stock. Many of the latter would have good stability without the use of additives.

Suitable inhibitors for improvement of storage stability of aviation gasoline have been known for sometime, but the same inhibitors are not satisfactory for jet fuels. Investigations are being conducted, however, to evaluate the stability of jet fuels and to determine effective types of inhibitors (refs. 42 and 43). Although these investigations are not complete, it is probable that improved stability of jet fuels will result.

While fuel gum does not appear to be a current problem, there have been operational difficulties caused by extraneous materials that were picked up by the fuels during shipping and storage. The presence of suspended material in jet fuels is more serious than in the case of gasoline, because the higher densities and viscosities of jet fuels will resist settling of the material before fuel is introduced to the aircraft tanks. The condition is also aggravated by the higher fuel flows used for jet fuels in comparison with those for piston-engine fuels.

Inasmuch as jet-engine fuel systems contain devices such as injection nozzles, pumps, and metering devices designed to close tolerance, the presence of any suspended material in the fuel represents a threat to the reliability of the system. Rust and dirt in fuels must be considered housekeeping problems that are primarily the responsibility of the fuel supplier and aircraft servicing personnel. Still, the fuel-system designer must recognize the difficulty of obtaining a completely clean fuel and provide for the removal of reasonable quantities of dirt and rust that may be present in the fuel even with proper handling procedures.

Corrosion

Two of the minor components that may be present in aircraft fuels are definitely corrosive towards some airframe and engine materials. These components are mercaptans and naphthenic acids.

Mercaptans are sulfur compounds often found in petroleum streams but seldom in concentrations higher than 0.1 percent mercaptan sulfur by weight. These compounds are relatively easy to remove by refinery treating processes, and current JP-3 and JP-4 specifications limit the mercaptan sulfur concentration to a maximum of 0.005 percent. At high concentrations mercaptans attack cadmium plate and form a yellow gelatinous material in a few hours; at low concentrations the attack is slower. There is no evidence that mercaptans attack any other metals likely to be present in aircraft.

In an investigation conducted by the Pratt and Whitney Aircraft Division of the United Aircraft Corporation, fuels containing mercaptans were pumped through cadmium-plated screens for 10 to 50 hours at 140° F. The results are as follows:

Mercaptan sulfur, percent by weight	Added water, percent by weight	Time at 140° F, hr	Weight loss, mg
None	None	5	None
0.005	None	50	5.0
.005	0.5	50	8.0
.020	None	15	101.2
3.0	None	10	126

Similar data have been reported by the Esso Laboratories of the Standard Oil Development Company for bright cadmium strips $\left(\frac{1}{2} \text{ by } 1\frac{1}{2} \text{ in.}\right)$ immersed in mercaptan-containing fuels both with and without a separate water phase. The results are as follows:

Mercaptan sulfur, percent by weight	Time at 125° F, days	Weight loss, mg	
		Fuel alone	Fuel plus water
None	48	0	1 (gain)
0.005	40	1	7
.05	48	1	12
.2	48	0	22
.4	48	1 (gain)	13

It can be concluded from the foregoing data and additional data from the Texas Company and reference 44 that the mercaptan sulfur will cause corrosion of cadmium. Furthermore, the corrosion becomes greater if water is present in the fuel. Even with the quantity of mercaptan sulfur permitted by specifications, a certain amount of corrosion will occur. However, data are not available to indicate whether the specification limit on mercaptan sulfur is consistent with the corrosion that may be tolerated for cadmium-plated aircraft parts.

Naphthenic acids are organic acids and are likely to be present in greater quantities in the higher-boiling jet fuels than in the lower-boiling aviation gasolines. Their concentration is not limited in the present fuel specifications but can be estimated from the neutralization number of the fuel. A neutralization number of 1 is equal to about 0.3 to 0.5 percent acid depending on the molecular weight of the acid.

Zinc is rapidly attacked by naphthenic acids to yield zinc naphthenates, which are soluble in the fuel. Data supplied by the Texas Company indicate the corrosion of galvanized strips (1 by 6 in.) during a 5-day period at 190° F as shown in the following table:

Neutralization number	Weight loss, mg		
	Dry fuel	Water-saturated fuel	Fuel plus free water
0.025	10	33	5
.025	8	22	25
.06	12	15	5
.06	10	13	29
.21	95	100	101
.30	115	129	71

The fuels used in these tests were not full jet fuels but were possible jet-fuel components that were selected to provide contrast in neutralization numbers.

Additional data from the Texas Company and reference 45 indicate little or no effect of napthenic acids on aluminum alloys. The effect on magnesium appears to be marginal. If a free-water phase is present, especially in the presence of metal couples, a severe attack on magnesium and aluminum can be expected (ref. 45).

In the investigations of references 46 and 47 it is concluded that lead, cadmium-plated steel, copper, brass, and zinc are the more susceptible metals to fuel corrosion in comparison with tin, steel, black iron, magnesium, and aluminum.

The results reported in reference 46 also indicate a relation between corrosion and fuel neutralization number, as shown in figure 26. In other studies the relation has not been found to be so well defined. The air-well metal-strip corrosion test (Federal Test Method VV-L-791d) was used to determine the corrosion results in reference 47.

Deterioration of Rubber Materials

Fuels may contain components that tend to promote the deterioration of rubber materials in fuel systems and tanks. Variations in the concentrations of some components even for fuels procured under the same specification may cause difficulties. This fact was clearly demonstrated shortly after World War II when low-aromatic aviation gasolines began to appear in service, resulting in an epidemic of gasket leakage trouble. This was due to the swelling and shrinking of the gasket materials then in use with changing aromatic concentration. The Rubber Swell Index was added to the gasoline specifications to control this fuel property. There is no longer a gasket problem, and the index has been eliminated from the fuel specifications.

Later investigations (refs. 44 and 48) were conducted to evaluate the influence of jet-fuel components on rubber materials used in aircraft construction. Reference 44 reports the effect of mercaptans on three Buna N and three Thiokol synthetic rubbers. Buna N materials Rev. L, Rev. N, and P-3 were stable in JP-3 fuels containing 0.005 percent mercaptan sulfur. Thiokol PR-1 and PST showed very slight deterioration in the same fuel, whereas Thiokol FA-1 deteriorated in all fuels. When the mercaptan concentration was increased to 0.05 percent, Thiokols PR-1 and PST showed increased deterioration, while the Buna N rubbers remained stable. These results were confirmed with the additional conclusion that the concentration of particularly harmful mercaptan compounds would not be sufficiently high to cause damage with JP-3 fuels if the total mercaptan sulfur content were limited to a maximum of 0.005 percent (ref. 48).

Low-Temperature Filtration

In earlier sections of this report the water-solubility characteristics of fuels are described, and mention is made of gum content and suspended foreign material that may be present from fuel handling procedures. The existence of any of these materials, water, gum, rust, or dirt, establishes the need for filter protection in fuel systems.

The presence of water in fuels is the greatest problem confronting the fuel-system designer at low-temperature conditions. Filters can be clogged by ice crystals formed when the fuel is cooled in flight (ref. 21). The water may initially be present either in solution alone or in solution plus a suspended water phase. Since fuels are often in contact with water during processing and handling, it can be assumed that most fuels are near saturation. Fuels may also hold a suspended water phase for several days (ref. 21); and it is probable that jet fuels, because of higher densities and viscosities, may hold suspended water longer than do aviation gasolines. Data reported in reference 49 show that filter icing is no problem if the fuel contains no entrained or extraneous water.

When fuel temperatures are reduced below 32° F, the water may freeze and clog filter elements. This water may (1) crystallize before contact with the filter and be caught on the upstream face of the filter, (2) be present as supercooled liquid droplets and turn to ice upon contact with the filter element, or (3) pass through the element and freeze on other downstream parts of the fuel system.

There is at present no complete understanding of all the factors contributing to filter icing; however, pertinent discussions are contained in references 21 and 50 to 53. Some of the major factors contributing to the rate at which ice will clog filters are the water content of the fuel, the temperature and capacity of the filter element, the rate of cooling, and the degree of supercooling.

There are several possible methods for reducing filter clogging. Among these methods are filter scraping, fuel preheating, filter washing with alcohol, and dual filter systems. These methods all lead to greater complexity of the fuel system. From the standpoint of fuel-system designer, perhaps the most attractive method is the use of fuel additives. Several laboratories have investigated the use of additives, and certain additives have shown promise as freezing-point depressants and as auxiliary liquids for removal of water from filters.

Some of the more promising additives have disadvantages. For example, the addition of 0.1 to 1.0 percent of low-molecular-weight alcohols to the fuel will keep ice from forming (ref. 21); however, the alcohols are readily extracted by water and also greatly increase the capacity of the fuel to pick up water. The use of alcohols, therefore, may be effective only if added at the time of fueling, and this procedure is not considered practical in actual service operations. Another additive (not available commercially) has been reported by the California Research Corporation to be resistant to extraction by water. Other organizations have also been active in this field, and it is conceivable that additives will eventually be utilized to eliminate the problem of filter icing.

The problem of filter clogging has been approached in a unique way by the Shell Development Company. It was decided that, since water is often present in supercooled droplet form and solidifies upon striking the filter, the clogging of filters would be reduced by making the filter surface hydrophobic. Improvements in filterability were made by coating the filter with surface-active agents, or minute quantities of a surface-active agent could be added to the fuel to reduce ice formation on other parts of the fuel system as well as on the filter. The possible success of this method is dependent on finding an additive that will remain soluble in the fuel at -76° F.

Tank Inerting

In the field of safety engineering it is often said that the most hazardous fuel tank is an empty one. This expression is, of course, based upon the fact that many accidents arise from the carelessness of personnel in handling tanks that contain no liquid fuel. Even though liquid fuel is not present, there is no assurance that fuel vapor is not present. For this reason, it should be recognized that the only safe tank is one that contains no fuel in either vapor or liquid state.

The fuel-system designer must be concerned with tanks that are never completely free of the flammability hazard. At all times fuel is present in either the vapor or liquid state or both. Even the most volatile aircraft fuels can form flammable mixtures under nonequilibrium vaporization conditions, and the least volatile fuels can yield flammable mists from the impact of an external force.

Since flammable mixtures are probably present throughout a major part of the operating regime to which a fuel tank is subjected, the best possible approach to reduction of the hazard is to eliminate or reduce the flammability limits of the fuel-air mixture. No hydrocarbon-oxygen inert mixture is flammable at oxygen concentrations below about 10 percent (ref. 54); therefore, control of the oxygen concentration to a level below this value by inerting will yield nonflammable fuel systems. In reference 55, a proposed inerting system is described in which a 6-percent concentration of oxygen is arbitrarily chosen as the limit to allow for tank breathing and for release of dissolved air from the fuel.

The practical aspects of the inerting problem are beyond the scope of this paper; however, numerous investigations have been conducted to evaluate the merits of various proposed inerting systems. Many of the pertinent references on these investigations are cited in reference 56. In addition, a discussion of solubility of gases in fuels is presented in an earlier portion of the present paper. This information, too, must be considered in the application of inerting systems to aircraft.

Thermal Stability

The stability of aircraft fuels in storage has long been an important factor. For this reason gum tests are used in the procurement specifications to ensure stability for long periods of time at near-ambient temperatures. Of more recent concern is the stability of fuels at much higher temperatures and for relatively short times. These temperatures result from aerodynamic heating during supersonic flight and use of the fuel as a heat sink. At the higher temperatures small amounts of solids are formed in the fuels, and these solids may impair engine performance. Operational troubles from this source are now sporadic but will certainly become more severe as flight speeds increase.

Aerodynamic heating of aircraft structures and of fuel in tanks, especially integral tanks, becomes significant when flight speeds approach Mach 2. The stagnation temperature, that is, the temperature of the air film in contact with the aircraft, can be calculated from the following equation:

$$T_{stag} = T_a \left[1 + \eta_r \left(\frac{\gamma - 1}{2}\right) (\text{Mach})^2\right] \tag{32}$$

3543

where

T_a	ambient temperature, °R
T_{stag}	stagnation temperature, °R
γ	ratio of specific heats, c_p/c_v
η_r	recovery factor (near 1)

With assumptions of a recovery factor of 0.9 and an ambient temperature of -67° F (393° R), stagnation temperatures are shown for several Mach numbers in the following table:

Mach number	Stagnation temperature, °F
0	-67
1	-50
2	215
3	570
4	1065

Various aspects of the thermal problems associated with high-speed flight can be found in a series of papers in the July, 1955, Transactions of the ASME (refs. 57 to 65).

No experimental data are available on the rate at which fuels are heated in fuel tanks during high-speed flight. This would obviously vary with airframe and fuel-tank geometry; however, analytical studies have been made in this field. One such analysis (ref. 66), based on a cylindrical integral fuselage tank, indicates that the fuel would reach a temperature of 380° F in 3 hours of flight at Mach 3 and an altitude of 90,000 feet provided the fuel was not allowed to evaporate. Reference 58 does not show final fuel temperatures but does show that aerodynamic heating can cause a 20-percent boiloff fuel loss in a 3-hour flight at Mach 2 and 50,000 feet. References 58, 66, and 67 all show that the aerodynamic heating of fuels can be greatly reduced by using a small amount of insulation.

While aerodynamic heating will become increasingly important, a more immediate thermal problem arises from the use of the fuel as a heat sink. In many current turbojet engines the lubricant is cooled by heat exchange with the fuel as the latter flows to the combustor. As a result, the fuel may be heated to temperatures high enough to form small amounts of insoluble products. These products may foul the lubricant-to-fuel exchangers, or they may clog atomizer screens and orifices. Pratt & Whitney Aircraft have made a thorough study of the effect of fuel and operating variables on the clogging of filters and nozzles. This work has shown that fuel composition, temperature, and residence times are the variables that are important in the thermal degradation of fuels. Even though fully meeting the current military specifications, fuels may vary widely in their tendency to form filter-clogging solids. This is shown in filter-clogging tests where one JP-4 fuel gave excessive pressure drop across the filter in 3 hours of running time, while another JP-4 fuel gave only negligible clogging in 10 hours at the same test conditions. Moderate increases in temperature greatly increased filter clogging, and fuels that were stable at 250° F were quite unstable at 300° F. Increases in residence time gave moderate increases in filter clogging. Changes in pressure were of little consequence, since most of the work in this field is done at pressures sufficiently high to keep the fuel in the liquid phase.

The extent of most chemical reactions is dependent on both temperature and residence time; therefore, both must be stated to establish the degree of reaction. This interdependence of temperature and time is shown in figure 27 for two reactions, the cracking of naphtha and gas oil and the formation of gum in jet fuels. The solid lines show the temperature against time required for 1-percent cracking as calculated from reference 68. The dotted line is a relation that is believed to indicate, semiquantitatively at least, the conditions that will give troublesome amounts of gum with current, good-quality jet fuels. The energy of activation calculated for the dotted line is about 20 kilocalories per mole, which is the same as that reported in reference 69 in studies on the storage stability of motor gasolines. The time scale in figure 27 runs from 5 seconds to over 1 year. Problems with gum formation may arise with good jet fuels at any temperature-time condition above the dotted line. Fuels with poor stability may give trouble at conditions well below this line.

Figure 27 shows that problems of thermal instability through gum formation occur at temperatures 400° to 500° F below those required for 1-percent cracking. This instability of fuels at such comparatively moderate temperatures is due to the presence of very small amounts of minor nonhydrocarbon components in the fuels. References 70 and 71 show that the removal of less than 1 percent of the fuel by chromatography (i.e., percolation through silica gel) would greatly increase the stability of the fuels. The materials removed from the fuels in both cases contained practically all the sulfur, oxygen, and nitrogen compounds that were originally present. Dissolved oxygen may play an important role in fuel stability (ref. 72). For some fuels the removal of dissolved oxygen greatly reduced their filter-clogging tendencies; however, for other fuels the effect was slight.

Since the thermal instability of jet fuels may be largely attributed to low concentrations of minor components, these fuels could be improved by refining processes that remove these components or convert them to more stable compounds. Hydrogenation (ref. 73) and acid treating (ref. 74) have proven effective in this regard. Since some crude sources yield stable fuels even without special processing, fuels meeting present requirements can be made by using only selected stocks (ref. 74). The use of inhibitors represents an inexpensive means of improving stability, and fair success has been achieved in this direction in many instances (refs. 71, 73, and 74). These inhibitors have been effective not in reducing the amount of insolubles formed but in changing the physical nature of the solids so that they are less prone to clog filters (refs. 74 and 75). However, at the present state of the art, additives have not reduced exchanger fouling (ref. 75) and have not been uniformly successful in improving the stability of all fuels.

One of the biggest problems facing both the producers and users of jet fuels is the evaluation of the thermal stability of these fuels. Many different laboratory test rigs have been used (refs. 70, 71, 72, and 75), but there is little assurance that any of them will give completely satisfactory correlation with the performance of fuels in flight. The test rig that is now being most widely used is a prototype fuel system in which the fuel is pumped through an electrically heated tube and filtered through a sintered stainless-steel disk. Filter-clogging tendencies are rated from the rate of increase in pressure drop across the disk; exchanger fouling tendencies may be estimated from the appearance of the heater tube after each experiment. The rig is being cooperatively evaluated by the Coordinating Research Council. As now operated, this rig gives fairly good correlation with the results of one engine fuel-system mockup (ref. 74); however, there is an occasional complete lack of correlation with this mockup, and there is no assurance that there will be any correlation with the fuel systems of other engines. The rig is also moderately expensive and somewhat more cumbersome to operate than would be desired for a routine laboratory inspection test.

In general, the thermal stability of jet fuels appears to be the biggest single fuel problem now being encountered. While the fuel is now being used as a heat sink only to cool the engine lubricant, wider uses are being discussed. For example, the fuel may serve as the heat sink to cool the flight crew, the electronic gear, and the hydraulic systems (refs. 57, 60, and 61). These additional heat loads plus the factor of aerodynamic heating of the fuel in tanks will certainly increase the severity of the thermal-stability problem.

Fuel Vapor and Entrainment Losses

Vapor losses. - The problem of fuel vapor loss in aircraft tanks at altitude has been recognized for years, and reliable relations have been established for aviation gasolines to permit estimation of losses from easily measured fuel properties. Unfortunately, these relations do not provide an accurate prediction of the vapor losses encountered with heavier fuels of the JP-3 and JP-4 types. Reference 76 reports that experimental vapor losses with JP-3 fuels are slightly lower than those with aviation gasolines of equivalent Reid vapor pressures. It is concluded in this study (ref. 76) that of the existing equations for prediction of vapor loss, the following best represents JP-3 fuel data:

$$l = \left[\frac{T_i^2}{4ST_i + 16T_{10} - 0.02\,T_{10}\,(T_i - 560)}\right] \log \frac{P_{0,T_i}}{P_a} + 1 \qquad (33)$$

where

l	weight percent loss
P_a	absolute ambient pressure in tank
P_{0,T_i}	true vapor pressure of fuel at initial fuel temperature (eq. (7))
S	slope of A.S.T.M. distillation curve at 10-percent-evaporated point
T_i	initial fuel temperature, $^{\circ}R$
T_{10}	10-percent A.S.T.M. distillation temperature, $^{\circ}R$

In order to simplify the use of equation (33), the bracketed term has been calculated for various values of T_{10} and S at an initial fuel temperature of 110° F. The results are shown in figure 28 which, together with figure 29, indicates the losses that might be expected at 110° F for different JP-3 fuels. The value of the true vapor pressure $P_{0,t}$ on the abscissa of figure 29 can be approximated from figures 6 and 7.

Although equation (33) might be used to approximate vapor losses for JP-4 fuels, more accurate estimates may be made from results of vapor-loss studies reported in reference 12. These investigations were conducted by Thompson Products Incorporated for the Coordinating Research Council. The loss data obtained are compiled in figure 30 and are correlated with a volatility factor, which is determined from the A.S.T.M. distillation curve for any given fuel. The volatility factor is the sum of the volume average boiling point and the temperature at points on the A.S.T.M. distillation curve up to 10-percent evaporated; consequently, the chart represents the combination of fuel temperature and tank pressure (vented tanks) that will maintain losses to a maximum of 10 percent.

In order to demonstrate the use of figure 30, assume that it is desired to estimate the tank pressurization required to maintain losses at a maximum of 10 percent at various fuel temperatures. For this example, the average-quality JP-4 fuel shown in figure 4(c) was used. The volume average boiling point for this fuel is 320° F (table IX), and the 10-percent-evaporated point is 215° F (fig. 4(c)). The volatility factor is the sum of these two values, 535. A horizontal line drawn on figure 30 indicates the pressure-temperature conditions that will hold the vapor loss at 10 percent. If it were desired to determine the pressure-temperature combinations that would maintain losses at 5 or 1 percent, the volatility factors would be estimated by adding the volume average boiling point to the 5- or 1-percent-evaporated points from figure 4(c).

Entrainment losses. - At low rate of climb, fuel losses occur by the process of evaporation, and such losses may be predicted as described in the preceding section. At high rates of climb evaporation losses still occur, but an additional loss results from entrainment of liquid fuel. Entrainment results from the rapid release of fuel vapor and air from the fuel, and the vigorous foaming thus produced carries liquid fuel out of the tank vent. The problem of fuel entrainment losses has been under study for several years, but no satisfactory methods for prediction of such losses have been devised.

Entrainment losses may be quite high depending upon several factors such as vent size, fuel depth in the tank, and fuel composition. Studies have indicated losses as high as 60 percent for JP-3 fuels.

Investigations (refs. 77 and 78) have been conducted to determine methods by which entrainment losses might be eliminated; no completely satisfactory solution has been found. The use of additives has been studied as well as ground-cooling of fuel and redesign of tank vents. The NACA has conducted a limited investigation to show the effect of vent size and various baffle arrangements within the vent on total fuel lost in simulated flight. The results are shown in figure 31 where the total fuel loss during simulated flight is plotted against the maximum pressure differential across the vent that is encountered at any time during the flight. This figure shows that the effect of the various baffle arrangements and vent sizes is simply to increase the maximum pressure differential. The higher the pressure differential the lower the fuel loss will be.

Previous investigations have indicated that perhaps the most promising method for elimination or reduction of entrainment losses is tank pressurization. Studies have shown (ref. 79) that tank pressurization to 0.2 pound per square inch would virtually eliminate entrainment losses for a fuel with a Reid vapor pressure of 2 pounds per square inch.

For additional information on the subject of fuel vaporization and entrainment losses, the reader is referred to references 2, 76, 79, and 80.

CONCLUDING REMARKS

The primary objective of this report is to collect available fuel data useful to the fuel-system designer; therefore, the original contributions of the report are rather limited. Perhaps the most important contribution is the survey of jet fuels, which shows clearly the range of variation in fuel properties the designer must consider in fuel-system problems. The effects of external influences such as pressure and temperature on many of these properties are illustrated. In addition, an effort is made to indicate adequate methods by which some easily measured fuel properties may be used to predict other properties more difficult to determine by laboratory measurement.

Tables, charts, and equations are included to assist the designer, but it should be recognized that much of this information is empirical and as such should be used with discretion. In addition, many fuel properties are discussed only briefly and generally, since specific data are not available. These cases obviously represent areas where further investigation would be helpful to the designer.

Each subject treated in this study has been condensed to yield what is believed to be the most useful of the existing data related to fuel-system design. It is recognized, however, that in many problems a broader treatment of a given subject may be required. For this reason the inclusion of references is deliberately liberal in order to provide the reader additional sources of information.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 27, 1956

APPENDIX A

AIRCRAFT FUEL SPECIFICATIONS, THEIR SIGNIFICANCE, AND DEVELOPMENT

Control of chemical composition and physical properties of aircraft fuels is required to promote aircraft performance and reliability. This control is exercised through the military procurement specifications listed in table I. These specifications include restrictions on chemical composition, physical properties, and combustion properties. Conformance with these restrictions is controlled by fuel inspections made by prescribed test methods. The military fuel specifications require that tests be run in accordance with the procedures given in the Federal Test Method VV-L-791. These methods are for the most part identical to A.S.T.M. procedures.

Chemical Composition

Major hydrocarbon classes. - Aircraft fuels are almost entirely made up of paraffin, cycloparaffin, aromatic, and olefin hydrocarbons. The paraffins and cycloparaffins are similar in most properties and are often classed together as "saturates." The aromatics and olefins each have distinctive properties, and the determination of each is required in military fuel specifications. The determination of the saturates is not required but can be estimated by the difference between 100 percent and the sum of the aromatics and olefins.

The aromatics are more strongly adsorbed on silica gel than are the other hydrocarbon classes, and this property is the basis for their determination. The test VV-L-791e-3703 or the A.S.T.M. Proposed Method of Test for Hydrocarbon Types in Jet Propulsion Fuels by the Fluorescent-Indicator Adsorption (FIA) Method is made by forcing a small sample down through a column of fine silica gel contained in a long, small-diameter, glass tube. The aromatics are concentrated in the upper zone of the column, and the length of this aromatic-wet silica gel divided by the total length of fuel-wet gel gives the fraction of aromatics in the sample. The length of the aromatic-wet segment is determined by use of ultraviolet light and a fluorescent indicator, which stays with the aromatic components of the fuel.

Aromatic concentration is of interest since these compounds have a greater tendency to form smoke and combustor coke than have the other common classes of hydrocarbons. The earlier jet-fuel specifications attempted to control these combustion characteristics only through limiting the aromatic concentration, but more recent specifications have included other combustion-control tests. These will be discussed later. Aromatics are currently limited to a maximum of 20 volume percent for JP-1 fuel and 25 volume percent for JP-3, JP-4, and JP-5 fuels.

Olefins are less strongly adsorbed on silica gel than are aromatics but more strongly adsorbed than saturates. Therefore, in the FIA method (VVL-791-3703) they appear as a middle zone and can be determined in the same way as aromatics. Olefins can also be estimated from their bromine number (VVL-791-3701 and A.S.T.M. D-1158) since they are the only class of hydrocarbons that react easily with bromine. The relation between bromine number and percent olefin is given by

$$\text{Percent olefin} = \frac{\text{Bromine number} \times \text{molecular weight}}{160}$$

No significant amounts of olefins are found in virgin (i.e., uncracked) fuels, but large amounts are formed in cracking processes. Cracked fuels may contain over 50 percent olefins. The bromine-number procedure is not completely specific towards olefins (see the appendix to A.S.T.M. D-1158); therefore, jet fuels may have bromine numbers of 1 to 3 even in the absence of olefins.

A bromine-number maximum was included in the earlier jet-fuel specifications, not because olefins were undesirable components, but because olefins were often accompanied by very small amounts of reactive diolefins. These latter compounds tend to form gum in storage. For a while there was a tendency to minimize the importance of the bromine number; however, the most recent specification (MIL-F-5624C) places a maximum of 5 percent on the olefin content. This limit requires that jet fuels either be made from nearly virgin stocks or that they be treated to remove excess olefins.

Minor components. - The concentrations of several minor components are limited, either directly or indirectly, since these are known or believed to adversely affect aircraft performance and reliability. These components include: (1) sulfur compounds, (2) gum and gum-forming compounds, (3) water-soluble components, and (4) sodium-containing compounds.

It is previously indicated that a variety of sulfur compounds may be present in aircraft fuels in small concentrations. Many of these are innocuous; but two types, mercaptan sulfur and free sulfur, are closely restricted by the specifications. Total sulfur is also restricted but at a higher concentration level.

Total sulfur is determined by burning the fuel and measuring the amount of sulfur oxides that are formed. The fuel is burned in a lamp (VV-L-791 5201.5 or A.S.T.M. D90), and the oxides determined either volumetrically or gravimetrically. It is believed that, in jet fuels, total sulfur is objectionable only in that the oxides formed during combustion may have some tendency to corrode hot engine parts. Total sulfur up to 0.4 percent is permitted in the current specifications; this value is sufficiently high to permit practically all refinery-produced fuels to pass the specification without special treatment for sulfur removal.

Mercaptans are a particular type of organic sulfur compound with slightly acidic properties. They can be qualitatively detected by shaking a sample of fuel with sodium plumbite reagent followed by adding a pinch of sulfur (VVL-791-5203.2 or A.S.T.M. D484) or quantitatively determined by titration with standard silver nitrate solution (VVL-791-5204 or A.S.T.M. D-1219). The former is called the "doctor test," and a fuel that is "doctor sweet" has a mercaptan concentration sufficiently low to very easily pass the specifications. Mercaptans have notoriously foul odors and also attack cadmium plate and some types of synthetic rubber. For these reasons, they are limited to a maximum concentration of 0.005 percent mercaptan sulfur in the current fuel specifications.

Free sulfur present in fuels corrodes copper. This property is the basis of the test (VVL-791-5313 or A.S.T.M. D-130) in which a polished copper strip is suspended in the fuel for 3 hours at 212° F. Only a slight tarnish is permitted. The test is sensitive to very small but unknown concentrations of free sulfur and is included in the fuel specifications to protect fuel systems.

Gums are resinous, nonvolatile components and are permitted only in trace amounts. Concentrations are expressed in terms of milligrams per 100 milliliters or roughly thousandths of a percent. The aircraft fuel specifications require the determination of both existent gum, that is, gum already present, and of potential gum, that is, gum in the fuel after an accelerated aging test. The gum is determined in either case by evaporating samples to dryness under a jet of superheated (450° F) steam and measuring the weight of residue (VVL-791-3302.3 or A.S.T.M. D-381). Existent gum is determined in the sample as received and potential gum after the fuel has been artificially aged by holding for 16 hours at 212° F under an oxygen pressure of 100 pounds per square inch (VVL-791-3354.3 or A.S.T.M. D-873-49). The current JP specifications limit the existent gum to 7 milligrams per 100 milliliters and the potential gum to 14 milligrams per 100 milliliters. These limits have been set to ensure that fuel, either fresh or aged, does not contain appreciable quantities of materials that will foul fuel-system components or deposit in the vaporizer tubes of vaporizing combustors. The accelerated aging test is believed to be equivalent to storing a fuel in drums for 1 to 2 years in the desert. Gum by either test may be soluble or insoluble; presumably the insoluble gum is more objectionable as to its effect on fuel-system components. However, the current specifications do not differentiate between these two, and only total gum is measured.

The water-tolerance test has been a part of aviation-fuel specifications for some time and is used to exclude water-soluble components (such as alcohols) from such fuels. The test is made by shaking 80 milliliters of fuel and 20 milliliters of water in a graduated cylinder and observing the volumes of each phase after settling (VVL-791-3251.4 or A.S.T.M. D1094). No more than 0.5 milliliter change in the fuel volume is permitted. This test has been amended to require that no scum or suspended matter be formed at the fuel-water interface. This change was made because it was found that fuels which gave filter fouling in service usually showed a scum or lace at the interface. This scum is believed to be due to the presence of trace amounts of sodium soaps that may be responsible for filter clogging. Objections have been raised to the amended test, since some potentially attractive additives will form scum even though they do not cause filter clogging. However, the scum test remains as an interim control until a more direct measurement of the filter-clogging tendency of fuels is developed.

Physical Properties

Volatility. - The volatility of aircraft fuels is measured and controlled through distillation and either Reid vapor pressure or flash point. Distillation gives data indicative of the over-all volatility of the fuel, while the other two tests measure the initial tendency of the fuel to vaporize. The volatility specifications for aircraft fuels have been established with consideration of both engine and airframe requirements and of availability. It is believed that highest engine performance could be obtained with engines designed for and run on high-volatility fuels. Such fuels would, however, require tank pressurization with airframe penalties which would more than overbalance the gains in engine performance. The design of the airframe fuel system would be eased by the use of fuels of low volatility; however, this would complicate engine design. Fuels of very low volatility might also have objectionably high viscosities and freezing points. Therefore, the specified fuel volatilities are a compromise between engine and airframe requirements with full consideration for availability, since the petroleum industry cannot supply large quantities of narrow-boiling-range fuels.

Distillations are run with 100 milliliters of fuel in a closely prescribed apparatus and at a carefully controlled rate. Vapor temperatures are recorded for various percentages distilled (VVL-791-1001.7 or A.S.T.M. D-86). Since the distillation is run in a relatively simple apparatus and with a small degree of fractionation, the resulting data do not directly give much of the information that would be useful. For example, this distillation does not give the fuel temperature for initial boiling, does not isolate any of the fuel components or indicate their boiling point, and does not give the true final boiling point of the fuel. However, the distillation has been run in substantially the same manner since 1921 and, because of its reproducibility and many years of wide usage has developed into a most significant test. Many empirical correlations have been developed relating distillation to a variety of fuel properties and to engine performance.

The current jet-fuel specifications control the distillation 20-percent, 90-percent, and final boiling points (table I). Maximums are set at the 20-percent point to eliminate "dumbbell" fuels, that is, fuels blended from stocks of widely differing volatility. The 90-percent and final-boiling-point limits are to control the concentrations of high-boiling materials, which might present problems in regard to engine performance.

The front end of the distillation curve gives some measure of the initial tendency for a fuel to vaporize; however, this tendency can be more precisely evaluated from either the Reid vapor pressure or the flash point of the fuel. The Reid vapor pressure is determined in a bomb in which 1 volume of fuel and 4 volumes of air are sealed off and raised to 100° F (VVL-791-1201.4 and A.S.T.M. D-323). This pressure, in pounds per square inch absolute, is the vapor pressure of a partially air-saturated fuel at a vapor-liquid ratio of 4. The Reid vapor pressure of a fuel is slightly less than the true vapor pressure at 100° F but usually within 10 percent. The specifications require JP-3 fuel to have a Reid vapor pressure of 5 to 7 pounds per square inch and JP-4 fuel a Reid vapor pressure of 2 to 3 pounds per square inch (table I). The higher values of these limits were set to control the pressure developed in fuel tanks and the losses that may result in flight. The lower limits ensure that fuels have sufficient volatility for engine starting. As previously mentioned, the airframe and engine have conflicting requirements as to volatility, and narrow ranges of Reid vapor pressure are specified to facilitate the design of both.

Reid vapor pressure is not specified for JP-1 and JP-5 fuels, but in its place there is a flash-point requirement. The Reid vapor pressure would be well below 1 pound per square inch for both types of fuel, and the flash point provides a more sensitive indication of the initial tendency of these fuels to vaporize. The flash point is the temperature to which a fuel must be heated to generate sufficient vapor to form a flammable mixture. Several methods have been used for this determination, but the one required for aircraft fuels is the Tag closed-cup procedure. In this procedure, the sample is slowly heated in a closed container and a small flame periodically directed through a port therein until the lowest temperature is found at which the vapors will ignite (VVL-791-1101.4 or A.S.T.M. D-56). For aircraft fuels, this temperature is also the temperature at which the fuels will have a vapor pressure of approximately 10 millimeters of mercury. Minimum flash points of 110° and 140° F are specified for JP-1 and JP-5 fuels, respectively (table I), these limits having been set to minimize the explosive hazards in bulk storage. As shown in an earlier section of this report, these fuels still present flammability hazards at altitude and in combat.

Liquid properties. - The physical properties, other than volatility, that are limited by the aircraft fuel specifications are gravity, viscosity, and freezing point. These are not independently variable properties since, for hydrocarbons and especially for conventional fuels from petroleum, fuels can have only narrow ranges of gravity, viscosity, and freezing point for a given volatility.

Gravity is determined with a hydrometer (VVL-791-401.3 or A.S.T.M. D-287) either at 60° F or corrected to this temperature by use of tables. Gravity is expressed in °API, and specific gravity can be determined from API gravity (fig. 1). For a single grade of aircraft fuel (JP-4, e.g.) the greatest possible range of gravity from extremes of crude sources and refinery processing would be about 12° API. This is equivalent to variations in specific gravity of about ±3 percent of the midvalue.

Kinematic viscosity is determined by timing the rate of fuel flow through a capillary under a gravity head and at controlled temperatures (VVL-791-305.2 or A.S.T.M. D-445). The results are usually expressed in centistokes (centistoke = 0.01 stoke). If the driving force through the capillary is a pressure rather than a gravity head, then absolute viscosity is determined; this has the unit of poise or centipoise (0.01 poise). Stokes can be converted to poises by multiplying by the density of the fuel at the temperature of the test.

Viscosities vary more widely than do gravities for a given grade of fuel. Maxima of 10 (-40° F) and 16.5 (-30° F) centistokes have been set for JP-1 and JP-5 fuels, respectively (table I). These limits were established because the pressure drop through fuel systems increases with increasing viscosity, and an attempt was made to eliminate fuels of very high viscosities.

The freezing point is the temperature at which crystals are first formed upon slowly cooling a fuel (VVL-791-1411.3 or A.S.T.M. D-910). The specifications require a freezing point of -76° F or below for all aviation fuels except JP-5, for which -40° F is permitted (table I). The reasons for specifying a maximum freezing point are obvious, but the required limits are sometimes questioned. The British require only a -40° F freezing point in jet fuels. The current freezing-point requirement is one of the more difficult specifications for some refineries to meet, especially for less volatile fuels of the JP-1 and JP-5 types.

Combustion Properties

Two combustion properties are controlled in the current specifications; these are the heats of combustion and the carbon-forming tendencies of fuels. Heats of combustion are measured either directly or indirectly through correlations with other properties. Carbon-forming tendencies are controlled through a combination of volatility and a lamp test. These specifications are discussed below.

Heat of combustion. - Minimum values for the net, or lower, heats of combustion are required in the aviation fuel specifications. The net heat is the amount of heat released when liquid fuel is burned to yield gas-phase water and carbon dioxide. Experimental measurement is made by burning about 1 gram of sample in a bomb under 25 to 40 atmospheres of oxygen and measuring the temperature rise in a calorimeter (VVL-791-2502.3 or A.S.T.M. D-240). This procedure requires carefully controlled experiments and calibration and, when properly run by skilled personnel, is reproducible to about 60 Btu per pound. However, reproducibilities of this order are not easily obtained; therefore, the specifications permit this determination to be waived, and in its place require that fuels meet a minimum aniline-gravity product. The aniline-gravity product is the product of the aniline point in $^{\circ}$F and the gravity in $^{\circ}$API; and, as previously shown, a quite precise correlation exists between it and heats of combustion. The aniline point is the lowest temperature at which a 1:1 blend of fuel and aniline is miscible. This point is easily determined (VVL-791-3601.3 or A.S.T.M. D-611).

While the maximum possible range of heating values that can be obtained for hydrocarbon fuels is quite small, the extreme importance of getting the most available heat into a fuel tank has resulted in minimum heating-value specifications. These require that JP-4 fuel have a minimum net heat of 18,400 Btu per pound or a minimum aniline-gravity product of 5250 and that JP-5 fuel have minimums of 18,300 Btu per pound or 4500 aniline-gravity product (table I).

Carbon-forming tendencies. - Jet fuels, otherwise meeting fuel specifications, can vary widely in their tendency to form smoke and combustor coke. For this reason, a burning quality test has been added to the specifications in the form of the smoke point. The smoke point is the maximum height, in millimeters, at which a fuel can be burned in a standard wick lamp without smoking (VVL-791-2107). Clean-burning fuels have high smoke points, and fuels with high carbon-forming tendencies have low smoke points. A minimum smoke point of 20 millimeters is specified for JP-5 fuel (table I). For JP-4 fuels, the correlation between combustor coke and a combined function of smoke point and volatility is better than the correlation with smoke point alone. This function is called the smoke-volatility index (SVI) and is defined as

$$\text{SVI} = \text{smoke point, mm} + 0.42\ (\text{percent boiling point below } 400^{\circ}\text{ F in A.S.T.M. distillation})$$

A minimum SVI of 54 is required for JP-3 and JP-4 fuels (table I).

APPENDIX B

ACCURACY OF SEVERAL CORRELATING METHODS

B-1 Specific Gravity as Function of Temperature

Specific gravities to 450° F and inspection data for eight fuels have been determined (ref. 12). These experimental data were compared for four fuels with the specific gravities calculated by the methods of references 1, 8, and 11 and the simple linear equation (4) of this report. The procedures of references 9 and 10 could not be checked because both require viscosity data that were not available. The experimental and calculated results are shown in figure 32. The deviations of the several methods are shown in figure 33. It appears that, over the temperature range covered, there is little difference in accuracy among the several methods. All appear accurate within about 2 percent. Equation (4) is more easily applied and can be recommended for this reason alone up to 400° F. At higher temperatures this equation yields systematically high results; consequently, one of the other methods should be used. Which of these is preferable is not known.

B-2 Reid Vapor Pressures of Blends

A simple linear relation appears to hold between the Reid vapor pressures of blends and the fraction of each component in the blend (eq. (6) of this report). This is shown in figure 34(a) by NACA data for several blends of aviation gasoline components. It is further shown in figure 34(b) (NACA data) for heavier stocks such as JP-1, JP-3, and JP-4 fuels and for a 1-pound stock made by cutting the light ends from a JP-3 fuel. The deviations from a straight line are usually within the limits of experimental measurement.

B-3 Accuracy of Equations (10) and (12) in Estimating True

Vapor Pressures of JP-4 Fuels

Although equations (10) and (12) were derived from data for gasolines, their use for JP-4 fuels appears justified on the basis of a few experiments in NACA laboratories. In these rather cursory tests, the vapor pressures of three JP-4 fuels were measured at three temperatures in a Reid vapor-pressure bomb ($v/l = 4$). The results were corrected to a v/l ratio of zero using equation (15) and are compared in the following table with calculated values:

Temperature, $^{\circ}F$	Vapor pressure, lb/sq in.					
	Slope = 12.3		Slope = 7.6		Slope = 3.9	
	Observed	Calculated	Observed	Calculated	Observed	Calculated
100	3.2	3.6	3.0	3.1	2.8	2.9
150	7.4	7.1	6.9	6.7	6.5	6.7
190	----	----	----	----	11.1	12.1
200	14.6	13.0	14.3	13.1		

Two of the JP-4 fuels used in these tests were selected because of their unusually high 10-percent-point slopes compared to most gasoline-type fuels. An examination of numerous fuel-inspection sheets indicates that the slopes for gasolines vary up to a maximum of 4, whereas JP-3 fuels vary up to 6 and JP-4 fuels have slopes as high as 12.

B-4 Correlation of Gas-Solubility Data

Reference 25 lists Ostwald coefficients for several gases in a variety of solvents and often over a range of temperatures. Inspection of these data showed that, at constant temperature, the coefficient increases with a decrease in the specific gravity of the fuel and also that, for a given fuel, the coefficient increases with increase in temperature. Since for a given fuel specific gravity decreases with increasing temperature, it appeared that the Ostwald coefficient might be related to the specific gravity of the solvent at the temperature at which the solubility is being determined. By so doing, the influence on solubility both of varying the fuel specific gravity at constant temperature and of varying temperature for a single fuel might be covered. Accordingly, Ostwald coefficients were plotted against the specific gravity of the fuels and lubricants at the temperature of solution using equation (4) to estimate these gravities at the different temperatures. These plots are shown for oxygen, nitrogen, and air in figure 35. The points shown are all for petroleum fractions; the pure-hydrocarbon data gave a greater scatter. The straight lines from figure 35 along with equation (4) were then used to calculate the effect of 60° F specific gravity and temperature on gas solubility as shown in figure 12. The accuracy of the correlations given in figure 12 may be estimated by the scatter of data from the lines drawn in figure 35.

B-5 Effect of Varying Initial Temperature on Heat of Combustion

The effect of varying temperature on heats of combustion can be calculated from the difference between the heat content of the reactants and the heat content of the products as the temperature is raised from the reference value to higher values. This difference is small compared to the heats of combustion of fuels. Data sufficiently precise for this calculation are available only for pure hydrocarbons.

In order to illustrate the magnitude of the effect of temperature, heats of combustion were calculated over a temperature range from 77° to 1000° F for isooctane (2,2,4-trimethylpentane) and benzene using data from reference 19. Over this temperature range the maximum difference in heating value is about 45 Btu per pound for isooctane and 15 Btu per pound for benzene as shown in figure 36. These differences are within the accuracies usually obtained in the experimental determination of this property.

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TABLE I. - SPECIFICATIONS OF AIRCRAFT FUELS

Specification	MIL-F-5572A				MIL-F-5616	MIL-F-5624C		
Fuel grade	80[a]	91/96[a]	100/130	115/145	JP-1	JP-3	JP-4	JP-5
A.S.T.M. distillation D86-52, °F								
Percentage evaporated								
10	167(max)	167(max)	167(max)	167(max)	410(max)	--------	--------	400(max)
20	--------	--------	--------	--------	--------	240(max)	290(max)	--------
40	167(min)	167(min)	167(min)	167(min)	--------	--------	--------	--------
50	221(max)	221(max)	221(max)	221(max)	--------	350(max)	370(max)	--------
90	275(max)	275(max)	275(max)	275(max)	490(max)	470(max)	470(max)	--------
End point	338(max)	338(max)	338(max)	338(max)	572(max)	--------	--------	550(max)
Sum of 10- and 50-percent points	307(min)	307(min)	307(min)	307(min)	--------	--------	--------	--------
Residue, percent	1.5(max)	1.5(max)	1.5(max)	1.5(max)	1.5(max)	1.5(max)	1.5(max)	1.5(max)
Loss, percent	1.5(max)	1.5(max)	1.5(max)	1.5(max)	1.5(max)	1.5(max)	1.5(max)	1.5(max)
Freezing point, °F	-76(max)	-76(max)	-76(max)	-76(max)	-76(max)	-76(max)	-76(max)	-40(max)
Reid vapor pressure, lb/sq in.	5.5 to 7.0	5.5 to 7.0	5.5 to 7.0	5.5 to 7.0	--------	5.0 to 7.0	2.0-3.0	--------
Aromatics, percent by volume	--------	--------	--------	--------	20.0(max)	25.0(max)	25.0(max)	25.0(max)
Bromine number	--------	--------	--------	--------	3.0(max)	5.0(max)	5.0(max)	5.0(max)
Total sulfur, percent by weight	0.05(max)	0.05(max)	0.05(max)	0.05(max)	0.20(max)	0.40(max)	0.40(max)	0.40(max)
Mercaptan sulfur, percent by weight	---------	---------	---------	---------	---------	0.005(max)	0.005(max)	0.005(max)
Existent gum, mg/100 ml	3.0(max)	3.0(max)	3.0(max)	3.0(max)	5.0(max)	7.0(max)	7.0(max)	7.0(max)
Potential gum, mg/100 ml	6.0(max)	6.0(max)	6.0(max)	6.0(max)	8.0(max)	14.0(max)	14.0(max)	14.0(max)
Heat of combustion, Btu/lb	18,700(min)	18,700(min)	18,700(min)	18,900(min)	--------	18,400(min)	18,400(min)	18,300(min)
Aniline-gravity product	7500(min)	7500(min)	7500(min)	10,000(min)	--------	5250(min)	5250(min)	4500(min)
Gravity, 60°/60° F								
Specific	----------	----------	----------	----------	0.850(max)	0.780 to 0.739	0.802 to 0.751	0.845 to 0.788
°API	----------	----------	----------	----------	----------	50 to 60	45 to 57	36 to 48
Viscosity, centistokes								
-30° F	----------	----------	----------	----------	----------	---------	---------	16.5(max)
-40° F	----------	----------	----------	----------	10.0(max)	---------	---------	---------
Smoke-volatility index	----------	----------	----------	----------	----------	54.0(min)	54.0(min)	---------
Smoke point, mm	----------	----------	----------	----------	----------	---------	---------	20(min)
Flash point, °F	----------	----------	----------	----------	110(min)	---------	---------	140(min)
Explosiveness, percent	----------	----------	----------	----------	----------	---------	---------	50(max)

[a] Octane number.

TABLE II. - CHRONOLOGICAL DEVELOPMENT OF JP-4 SPECIFICATION

Date	Jan., 1947	Dec. 12, 1947	Mar. 30, 1949	Jan. 26, 1950	May 23, 1951		Dec. 7, 1953	May 18, 1955
New designation				MIL-F-5624	MIL-F-5624A		MIL-F-5624B	MIL-F-5624C
Old designation		AN-F-58	AN-F-58a	AN-F-58a				
Fuel grade	Proposed JP-3	JP-3	JP-3	JP-3	JP-3	JP-4	JP-4	JP-4
A.S.T.M. distillation D86-52, °F								
Percentage evaporated								
10	--------	--------	--------	--------	--------	250(max)	--------	--------
20	--------	--------	--------	--------	--------	--------	270(max)	290(max)
50	--------	--------	--------	--------	--------	--------	370(max)	370(max)
90	--------	425(min)	400(min)	400(min)	400(min)	--------	470(max)	470(max)
End point	550 to 600	600(max)	600(max)	600(max)	600(max)	550(max)	--------	--------
Residue, percent	--------	1.5(max)	1.5(max)	1.5(max)	1.5(max)	1.5(max)	1.5(max)	1.5(max)
Loss, percent	--------	1.5(max)	1.5(max)	1.5(max)	1.5(max)	1.5(max)	1.5(max)	1.5(max)
Freezing point, °F	-76(max)	-76(max)	-76(max)	-76(max)	-76(max)	-76(max)	-76(max)	-76(max)
Reid vapor pressure, lb/sq in.	5.0 to 8.0	5.0 to 7.0	5.0 to 7.0	5.0 to 7.0	5.0 to 7.0	2.0 to 3.0	2.0 to 3.0	2.0 to 3.0
Aromatics, percent by volume	30(max)	30(max)	25(max)	25(max)	25(max)	25(max)	25(max)	25(max)
Bromine number	--------	14(max)	30(max)	30(max)	30(max)	30(max)	--------	5.0(max)
Total sulfur, percent by weight	0.5(max)	0.5(max)	0.5(max)	0.5(max)	0.4(max)	0.4(max)	0.4(max)	0.4(max)
Mercaptan sulfur, percent by weight	--------	--------	--------	--------	0.005(max)	0.005(max)	0.005(max)	0.005(max)
Existent gum, mg/100 ml	5.0(max)	10.0(max)	10.0(max)	10.0(max)	10.0(max)	10.0(max)	7.0(max)	7.0(max)
Potential gum, mg/100 ml	8.0(max)	20.0(max)	20.0(max)	20.0(max)	20.0(max)	20.0(max)	14.0(max)	14.0(max)
Heat of combustion, Btu/lb	18,400(min)	18,200(min)	18,400(min)	18,400(min)	18,400(min)	18,400(min)	18,400(min)	18,400(min)
Aniline-gravity product	-----------	-----------	-----------	-----------	-----------	-----------	5,250(min)	5,250(min)
Gravity, 60°/60° F								
Specific	-----------	-----------	0.728 to 0.802	0.728 to 0.802	0.728 to 0.802	0.747 to 0.825	0.759 to 0.802	0.751 to 0.802
°API	-----------	-----------	63 to 45	63 to 45	63 to 45	58 to 40	55 to 45	57 to 45
Viscosity, centistokes								
-40° F	6.0(max)	10.0(max)	--------	--------	--------	--------	--------	--------
100° F	0.8(min)	-----------	--------	--------	--------	--------	--------	--------
Smoke-volatility index	-----------	-----------	--------	--------	--------	--------	54.0(min)	54.0(min)

TABLE III. - PROPERTIES OF TYPICAL JP-5 STOCKS AND A 115/145 AVIATION GASOLINE AND SPECIAL BLENDS OF THESE COMPONENTS

	115/145	JP-5 sample [a]A	1/3 By volume 115/145 and 2/3 by volume JP-5 A	JP-5 sample [a]B	1/4 By volume 115/145 and 3/4 by volume JP-5 B
A.S.T.M. distillation, D86-52, °F					
Percentage evaporated					
Initial point	116	360	136	357	142
5	132	373	166	371	192
10	141	382	191	375	230
20	154	399	237	385	289
30	167	409	291	393	338
40	181	419	351	402	371
50	198	429	396	411	394
60	209	439	418	421	407
70	219	449	431	433	420
80	231	459	445	448	436
90	248	473	463	464	457
End point	327	502	496	502	499
Freezing point, °F	<-76	-48	-66	---	-60
Reid vapor pressure, lb/sq in.	6.2	---	2.7	---	2.0
Aromatics, percent by volume	0.5	14.3	10.0	14.0	13.4
Hydrogen-carbon ratio	0.190	0.160	0.169	0.156	0.164
Heat of combustion, Btu/lb	19,070	18,600	18,750	-----	18,670
Aniline-gravity product	------	6,271	7,661	-----	6,925
Gravity, 60°/60° F					
Specific	0.693	0.815	0.777	0.808	0.785
°API	73	42.2	50.7	43.5	48.7
Flash point, °F	-----	140	<-30		

[a] Samples of JP-5 fuel used in the above blends differed slightly.

TABLE IV. - DETAILED REQUIREMENTS FOR FUEL OILS[a,b]

Fuel oil, number[c]		Flash point, °F, minimum	Pour point, °F, maximum	Water and sediment, percent by volume, maximum	Carbon residue on 10-percent bottoms, percent, maximum	Ash, percent by weight, maximum	Distillation temperatures, °F			Kinematic viscosity, centistokes, at -				Gravity, °API, minimum	Corrosion at 122° F (50° C)
							10-Percent point, maximum	90-Percent point, maximum	End point, maximum	100° F		122° F			
										Maximum	Minimum	Maximum	Minimum		
1	A distillate oil intended for vaporizing pot-type burners and other burners requiring this grade of fuel	100 or legal	0	Trace	0.15	----	420	---	625	2.2	1.4	---	--	35	Pass
2	A distillate oil for general-purpose domestic heating for use in burners not requiring number 1 fuel oil	100 or legal	[d]20	0.10	0.35	----	---	675	---	4.3	----	---	--	26	----
4	An oil for burner installations not equipped with preheating facilities	130 or legal	20	0.50	----	0.10	---	---	---	26.4	5.8	---	--	--	----
5	A residual-type oil for burner installations equipped with preheating facilities	130 or legal	---	1.00	----	0.10	---	---	---	----	32.1	81	--	--	----
6	An oil for use in burners equipped with preheaters permitting a high-viscosity fuel	150	---	2.00	----	----	---	---	---	----	----	638	92	--	----

[a] A.S.T.M. D396-48T.

[b] Because of the necessity for low-sulfur fuel oils used in connection with heat treatment, nonferrous metal, glass, and ceramic furnaces, and other special uses, a sulfur requirement may be specified in accordance with the following table:

Fuel oil, number	Sulfur, max. percent
1	0.5
2	1.0
4	No limit
5	No limit
6	No limit

Other sulfur limits may be specified only by mutual agreement between the purchaser and the seller.

[c] It is the intent of these classifications that failure to meet any requirement of a given grade does not automatically place an oil in the next lower grade unless in fact it meets all requirements of the lower grade.

[d] Lower or higher pour points may be specified whenever required by conditions of storage or use; however, these specifications shall not require a pour point lower than 0° F under any conditions.

TABLE V. - TYPICAL INSPECTION DATA FOR MIL-F-5616 (JP-1) FUELS

Sample	A	B	C	D	E	F	G	H	I	J
A.S.T.M. distillation D86-52, $^{\circ}$F										
Percentage evaporated										
Initial point	353	346	320	323	338	336	326	310	320	320
10	366	360	334	333	362	355	334	320	334	346
20	---	---	---	338	366	360	340	322	340	---
30	---	---	---	342	369	365	344	326	344	---
40	---	---	---	347	373	370	348	328	350	---
50	386	384	352	351	377	375	352	332	355	383
60	---	---	---	357	381	381	362	336	361	---
70	---	---	---	364	387	387	372	340	370	---
80	---	---	---	374	393	394	385	346	384	---
90	421	420	393	394	404	405	410	358	406	448
End point	445	448	438	429	424	446	460	403	458	496
Residue, percent	---	---	---	---	1.5	1.0	1.2	1.0	1.0	1.2
Loss, percent	---	---	---	---	0	1.0	0.3	0	0	0.5
Freezing point, $^{\circ}$F	<-76	<-76	<-76	<-76	<-80	<-76	-----	<-76	----	<-76
Aromatics, percent by volume										
A.S.T.M. D875-46T	15	15	7	8	----	15	-----	16.5	----	19.6
Silica gel	----	----	----	----	----	15	-----	16	14.0	----
Total sulfur, percent by weight	0.01	0.01	0.01	0.016	0.04	0.023	-----	<0.05	0.04	0.03
Existent gum, mg/100 ml	5	3.0	----	-----	0.8	1.0	-----	-----	2.5	----
Potential gum, mg/100 ml	----	----	----	-----	2.0	0	-----	1.0	4.4	----
Gravity, $60^{\circ}/60^{\circ}$ F										
Specific	0.834	0.835	0.800	0.802	0.832	0.831	0.796	0.786	0.796	0.811
$^{\circ}$API	38.2	38	45.3	44.8	38.5	38.7	46.2	48.5	46.2	43.0
Viscosity at -40° F, centistokes	----	5.65	5.65	5.81	9.65	9.2	----	----	5.9	8.97
Flash point, $^{\circ}$F	----	----	112	112	----	---	----	----	---	----

TABLE VI. - TYPICAL INSPECTION DATA FOR MIL-F-5624C (JP-3) FUELS

Sample	A	B	C	D	E
A.S.T.M. distillation D86-52, °F					
Percentage evaporated					
Initial point	117	118	116	113	111
10	178	144	149	169	172
20	205	153	164	198	215
30	226	166	181	218	245
40	246	184	200	236	271
50	267	205	224	254	297
60	292	229	262	270	323
70	322	306	346	293	349
80	363	426	403	324	385
90	415	468	438	388	425
End point	487	500	485	473	488
Residue, percent	1.0	1.3	1.0	1.0	1.0
Loss, percent	1.0	0.7	1.5	1.2	1.0
Freezing point, °F	<-76	<-76	---	<-76	---
Reid vapor pressure, lb/sq in.	5.8	5.6	6.3	6.2	5.7
Aromatics, percent by volume					
A.S.T.M. D875-46T	10	---	---	---	---
Silica gel	9	---	---	7.0	7.0
Bromine number	0.5	1.0	---	3.0	0.5
Total sulfur, percent by weight	0.1	0.025	---	0.06	0.07
Existent gum, mg/100 ml	1.0	1.9	---	0.5	0.5
Potential gum, mg/100 ml	5.0	1.0	---	15.8	3.4
Heat of combustion, Btu/lb	18,680	------	---	18,765	18,675
Gravity, 60°/60° F					
Specific	0.748	0.737	0.739	0.742	0.756
°API	57.7	60.5	60.0	59.2	55.7

TABLE VII. - TYPICAL INSPECTION DATA FOR MIL-F-5624C (JP-4) FUELS

Sample	A	B	C	D	E	F
A.S.T.M. distillation D86-52, °F						
Percentage evaporated						
Initial point	148	130	137	---	140	137
10	218	235	250	240	250	195
20	255	---	---	---	---	219
30	288	---	---	---	---	238
40	319	---	---	---	---	256
50	349	340	344	---	376	276
60	378	---	---	---	---	296
70	409	---	---	---	---	319
80	441	---	---	---	---	349
90	475	408	413	---	456	402
End point	561	482	---	460	480	487
Residue, percent	1.1	1.0	1.5	---	1.2	1.3
Loss, percent	1.0	1.0	0.5	---	1.3	0.7
Freezing point, °F	<-76	<-76	<-76	<-76	<-76	<-76
Reid vapor pressure, lb/sq in.	2.1	2.3	2.3	2.6	3.2	2.6
Aromatics, percent by volume						
A.S.T.M. D875-46T	---	17.5	14.7	15	13.3	---
Silica gel	25	----	----	---	----	9.7
Bromine number	8.0	1.7	1.46	1.0	0.8	1.5
Total sulfur, percent by weight	0.1	0.013	0.014	0.08	0.041	0.03
Mercaptan sulfur, percent by weight	---	-----	-----	----	0.0007	0.003
Existent gum, mg/100 ml	11	1.0	1.0	1.0	3.4	8.0
Potential gum, mg/100 ml	15	2.3	1.0	2.3	4.6	12.0
Heat of combustion, Btu/lb	18,500	---	-----	----	------	18,725
Gravity, 60°/60° F						
Specific	0.793	0.777	0.779	0.790	0.790	0.756
°API	46.8	50.5	50.0	47.5	47.5	55.7

TABLE VIII. - VARIATIONS OF PHYSICAL PROPERTIES AMONG JET FUELS

	JP-1				JP-3[a]				JP-4[b]				JP-5			
	Number of fuels averaged	Minimum	Maximum	Arithmetic average	Number of fuels averaged	Minimum	Maximum	Arithmetic average	Number of fuels averaged	Minimum	Maximum	Arithmetic average	Number of fuels averaged	Minimum	Maximum	Arithmetic average
A.S.T.M. distillation D86-52, $^{\circ}$F																
Percentage evaporated																
Initial point	73	270	350	326	38	87	118	108	23	122	165	144	22	312	376	359
10	72	327	369	347	38	116	208	164	23	183	245	216	64	356	411	390
20	--	332	389	353	--	140	262	201	23	205	286	250	19	391	416	404
40	54	340	420	362	13	184	350	255	--	---	---	---	--	---	---	---
50	73	344	434	370	38	205	427	303	23	262	361	319	31	414	444	428
90	71	364	466	407	38	388	493	437	23	362	468	425	46	456	527	475
End point	71	400	520	448	38	453	560	497	23	441	522	487	61	479	560	511
Freezing point, $^{\circ}$F	--	---	<-76	<-76	--	---	<-76	<-76	--	---	-77	<-76	35	-80	-40	-49
Reid vapor pressure, lb/sq in.	--	---	----	----	36	5.1	7.0	5.9	23	2.3	3.0	2.6	--	---	---	---
Aromatics, percent by volume	22	7	19.6	14.2	26	4.3	19.2	11.2	23	6.6	17.9	11.3	63	7.4	22.0	15.8
Bromine number	16	0.4	2.8	1.1	30	0.1	17.0	2.54	22	0	3.33	1.59	63	0.5	5.0	2.2
Total sulfur, percent by weight	23	0.01	<0.05	0.036	30	0.017	0.45	0.09	23	0.015	0.27	0.08	61	0.023	0.49	0.15
Mercaptan sulfur, percent by weight	--	----	-----	-----	--	0	0.003	0.0008	23	0.0001	0.004	0.0016	35	0.0002	0.003	0.0014
Existent gum, mg/100 ml	16	0	5.0	1.87	7	0.5	9.8	3.2	12	0.2	3.6	1.3	47	0.1	6.4	2.2
Potential gum, mg/100 ml	12	1.0	6.0	3.03	6	1.0	16.0	7.4	8	0.8	5.0	2.1	57	0.3	17.1	4.4
Hydrogen-carbon ratio	14	0.143	0.168	0.153	29	0.151	0.178	0.166	17	0.147	0.184	0.164	--	------	-----	------
Heat of combustion, Btu/lb	13	18,385	18,635	18,479	32	18,442	19,002	18,710	23	18,504	18,945	18,678	59	18,436	18,634	18,522
Aniline-gravity product	--	------	------	------	--	------	------	------	23	5650	7877	6891	59	4710	6607	5534
Gravity, 60°/60° F																
Specific	65	0.784	0.836	0.810	38	0.729	0.799	0.760	--	0.760	0.801	0.773	62	0.808	0.842	0.827
$^{\circ}$API	--	49.0	37.7	43.1	--	62.7	45.5	54.7	23	54.8	45.2	51.5	--	43.6	36.6	39.6
Aniline point, $^{\circ}$F[b]	--	-----	-----	-----	22	118.6	152	134.5	23	124.0	144	133.8	44	128	153	139
Viscosity, centistokes																
-30° F	--	-----	-----	-----	--	-----	-----	-----	16	2.4	5.3	3.26	--	-----	-----	-----
-40° F	20	5.65	9.65	7.62	23	1.77	5.6	2.91	--	-----	-----	-----	52	10.1	19.7	16.1
Flash point, $^{\circ}$F	14	110	125	117	--	-----	-----	-----	--	-----	-----	-----	52	125	159	147

[a] Data from ref. 4.

[b] Data from ref. 3.

TABLE IX. - ESTIMATED PROPERTIES OF AVERAGE JET FUELS AND FUEL OILS[a]

	Jet fuels				Fuel oils		
	JP-1	JP-3	JP-4	JP-5	No. 1	No. 2	No. 4
Boiling points, °F							
Weight average	376	290	313	433	439	511	560
Mean average	377	252	296	432	437	506	554
Molal average	376	240	290	431	434	502	547
Volumetric average	374	302	320	430	438	508	554
Slope of A.S.T.M. distillation curve							
10-percent slope,	1.3	4.5	4.7	2.5	2.6	4.0	3.8
$\frac{t_{70}-t_{10}}{60}$	0.6	3.6	2.4	0.9	1.2	1.6	1.9
Characterization factor	11.6	11.7	11.8	11.6	11.8	11.7	11.0
Molecular weight	151	112	125	169	174	198	206
Critical properties							
Temperature, °F	715	615	642	773	770	847	923
Pressure, lb/sq in.	360	754	530	330	328	303	338

[a] Estimated from ref. 1.

TABLE X. - VARIATIONS OF PHYSICAL PROPERTIES OF FIVE GRADES OF FUEL OIL

	Fuel oil, number													
	1				2				4				5	6
	Number of samples averaged	Minimum	Maximum	Arithmetic average	Number of samples averaged	Minimum	Maximum	Arithmetic average	Number of samples averaged	Minimum	Maximum	Arithmetic average	(Single sample)	(Single sample)
A.S.T.M. distillation D86 or D158, °F, *Percentage evaporated:*														
Initial point	67	326	386	350	134	312	470	372	10	378	470	421	560	-----
10	67	365	418	385	135	373	511	437	10	422	548	470	700	-----
50	67	406	475	434	135	448	557	505	9	468	670	554	940	-----
90	67	446	560	498	135	509	650	586	10	539	738	637	-----	-----
End point	67	476	625	540	135	570	712	641	10	614	760	692	-----	-----
Pour point, °F	43	-85	-5	-41	91	-35	20	-7	15	-30	5	-8	40	-----
Cloud point, °F	44	-78	-10	-36	101	-20	32	5	--	-----	-----	-----	-----	-----
Sulfur, percent by weight	63	0.01	0.51	0.13	132	0.014	0.94	0.298	15	0.22	2.33	0.966	0.68	0.81
Gravity, 60°/60° F														
Specific	--	0.792	0.821	0.813	---	0.803	0.884	0.842	--	0.870	0.983	0.915	0.934	0.957
°API	67	47.2	40.7	42.5	135	44.7	28.5	36.4	15	31.2	12.4	23	19.9	16.2
Viscosity at 100° F, centistokes	57	1.49	2.16	1.72	134	2.08	4.28	2.84	15	2.11	47.5	16.7	185	[a]154
Flash point, °F	53	125	168	140	126	132	224	167	15	160	240	205	290	214
Aniline point, °F	55	113	171	148	118	122	175	151	--	-----	-----	-----	-----	-----

[a] Measured at 122° F.

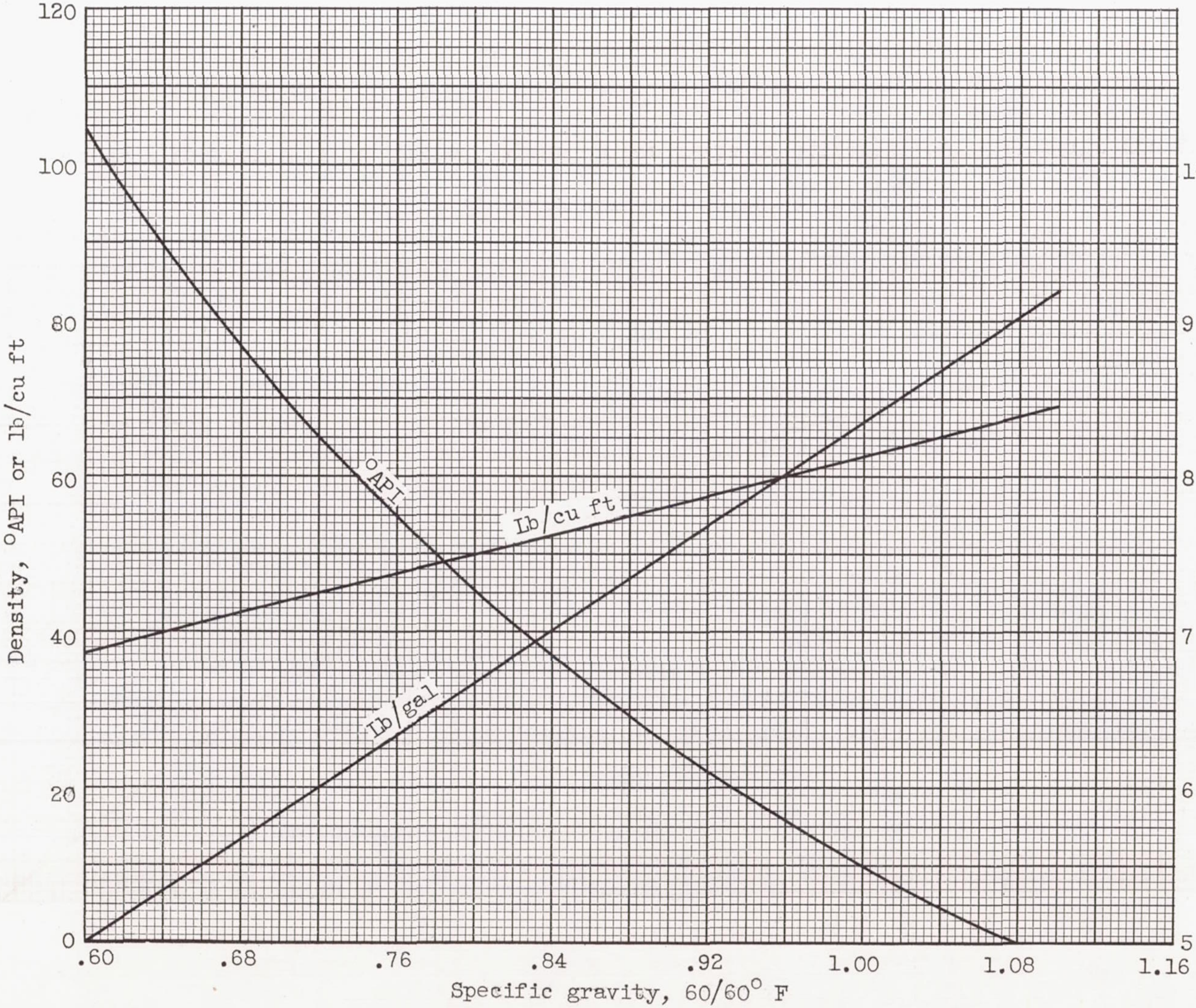


Figure 1. - Density-gravity relations.

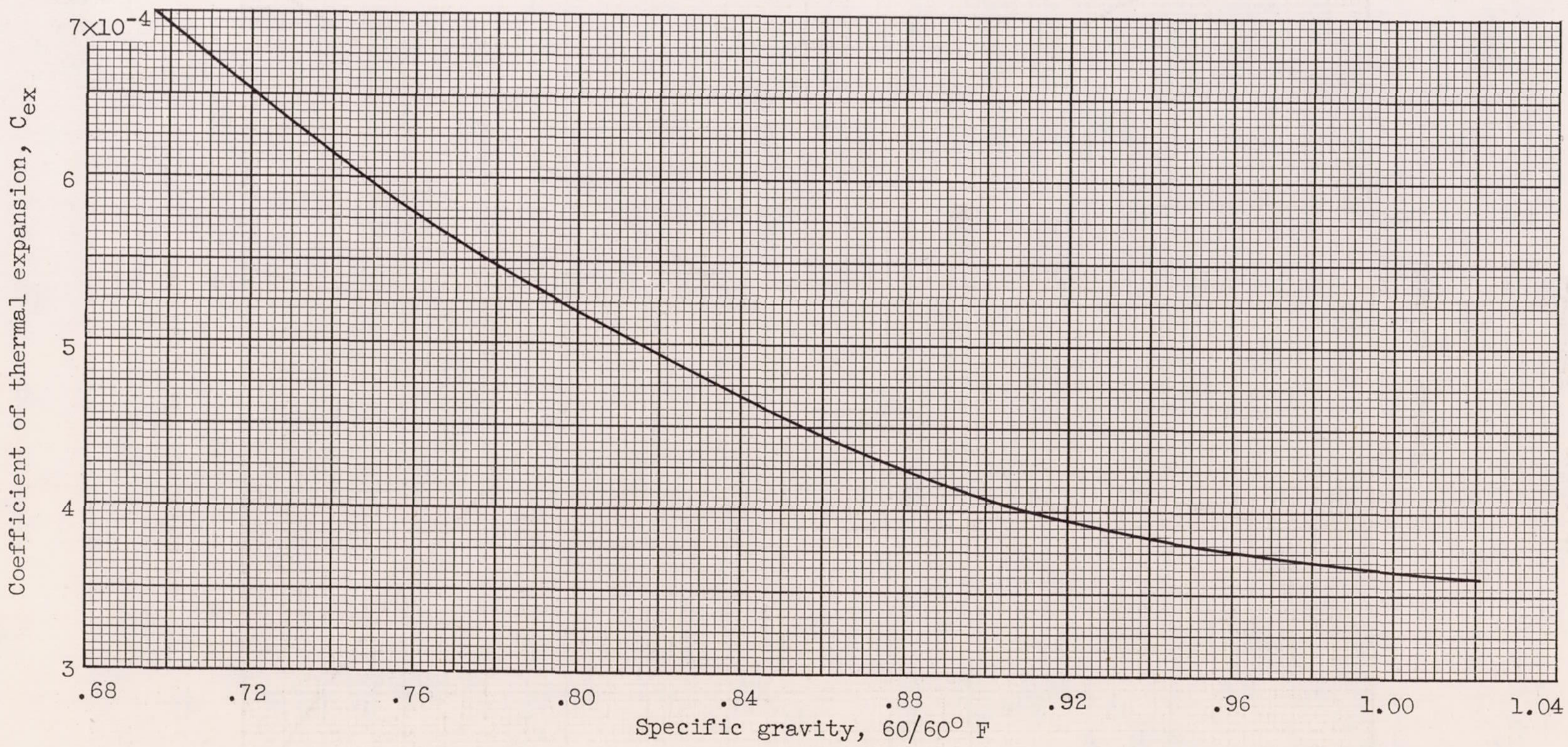
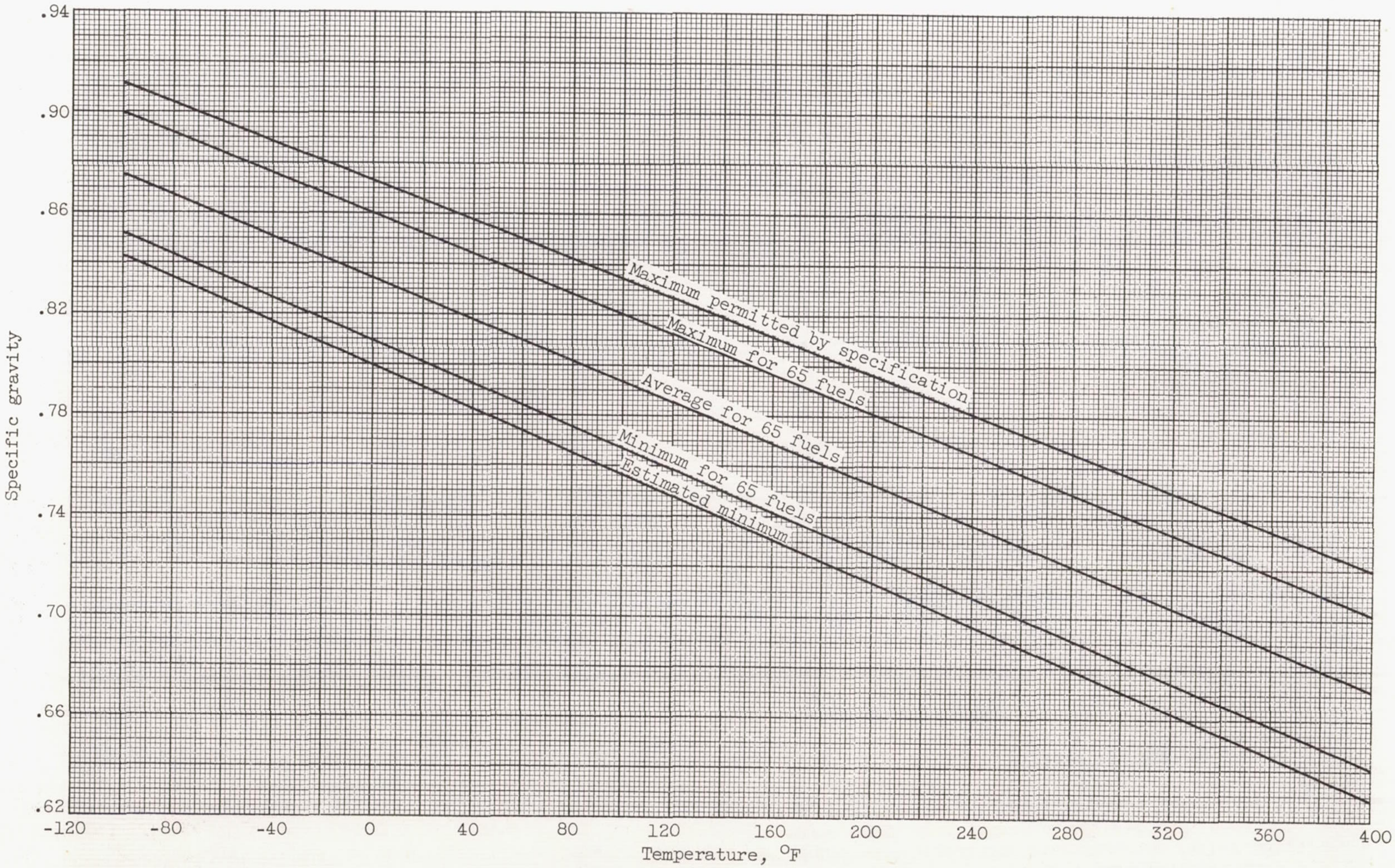
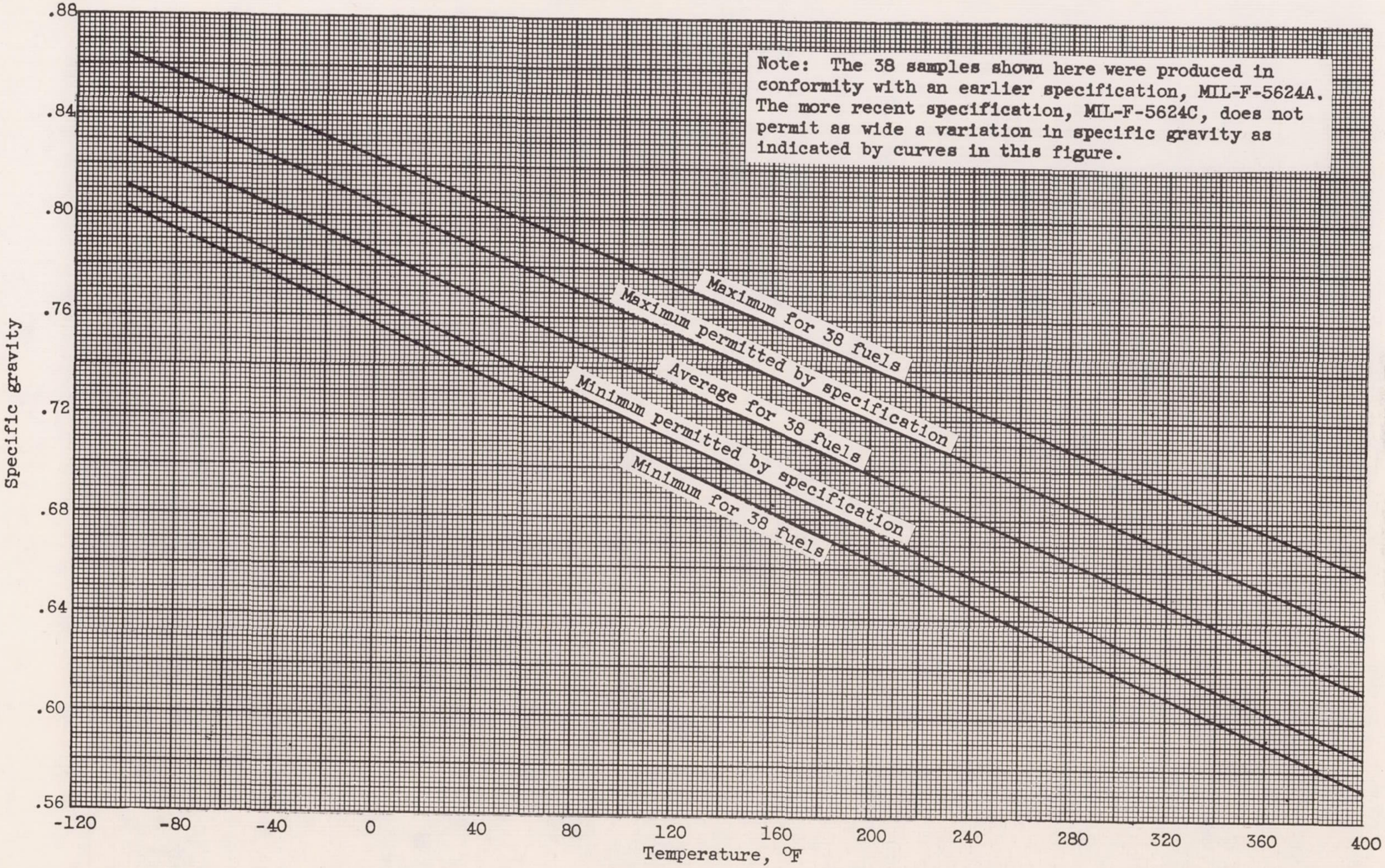


Figure 2. - Coefficients of thermal expansion for fuels of different 60° F specific gravities.



(a) MIL-F-5616 (JP-1) fuel.

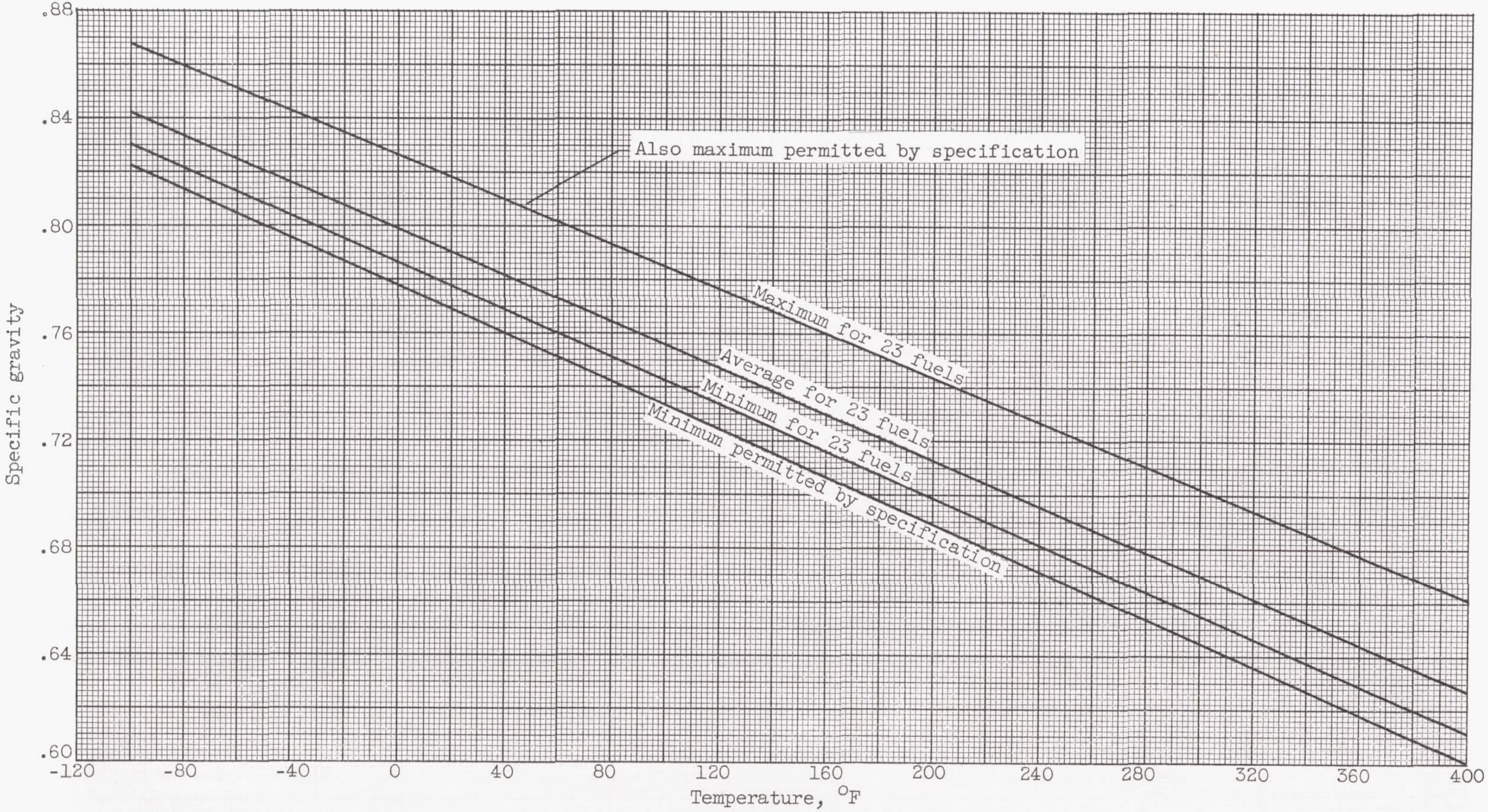
Figure 3. - Variation of specific gravity with temperature.



Note: The 38 samples shown here were produced in conformity with an earlier specification, MIL-F-5624A. The more recent specification, MIL-F-5624C, does not permit as wide a variation in specific gravity as indicated by curves in this figure.

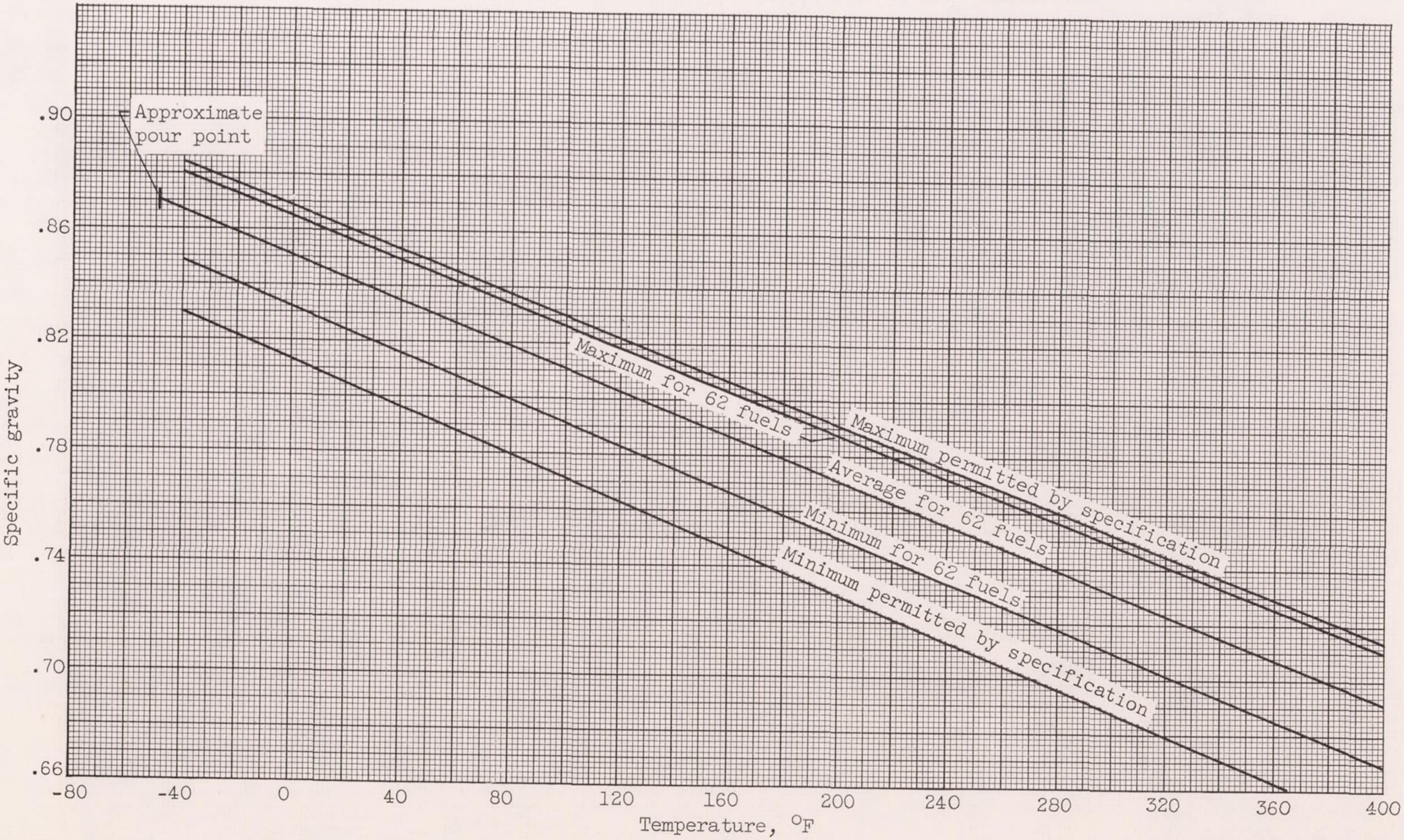
(b) MIL-F-5624C (JP-3) fuel.

Figure 3. - Continued. Variation of specific gravity with temperature.



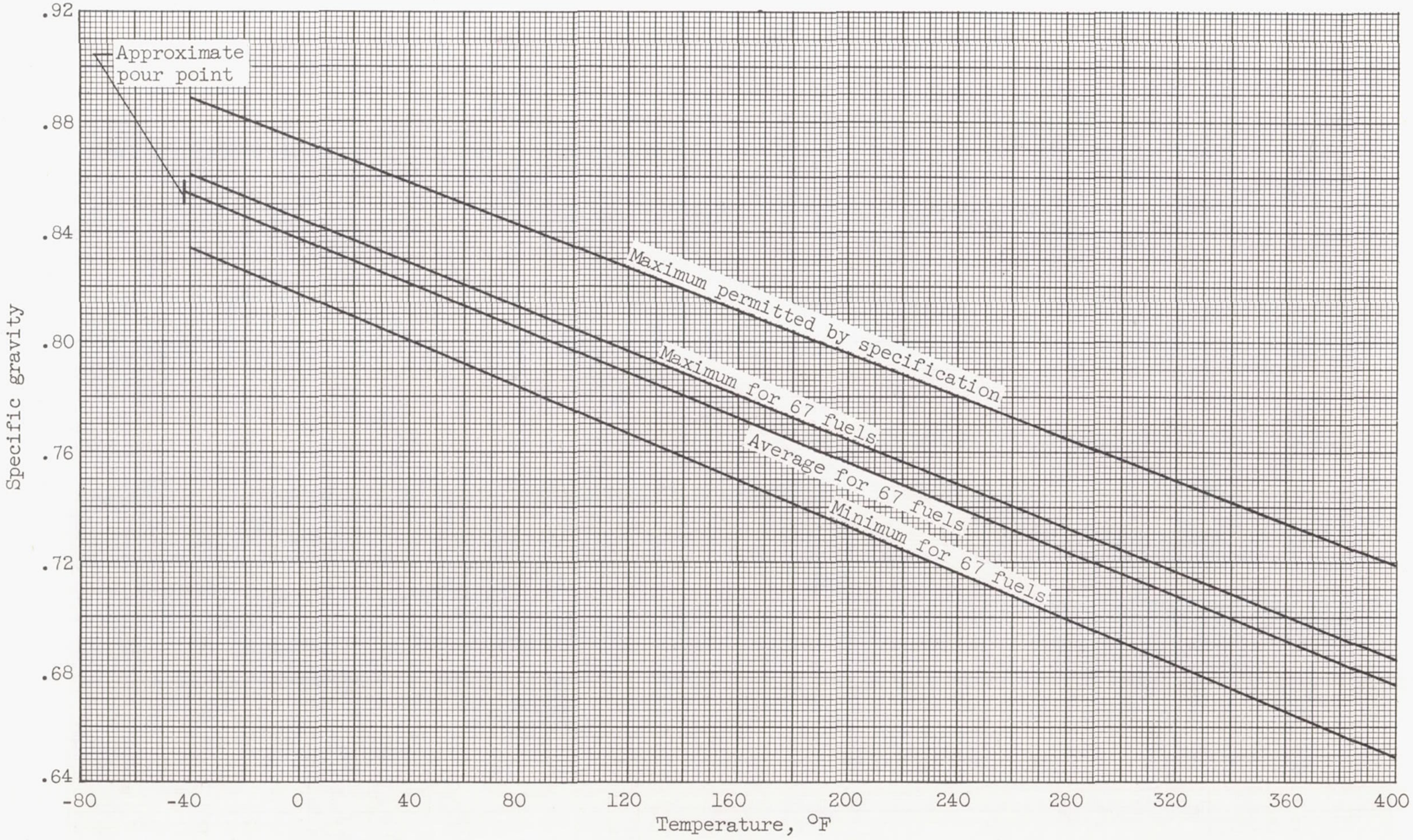
(c) MIL-F-5624C (JP-4) fuel.

Figure 3. - Continued. Variation of specific gravity with temperature.



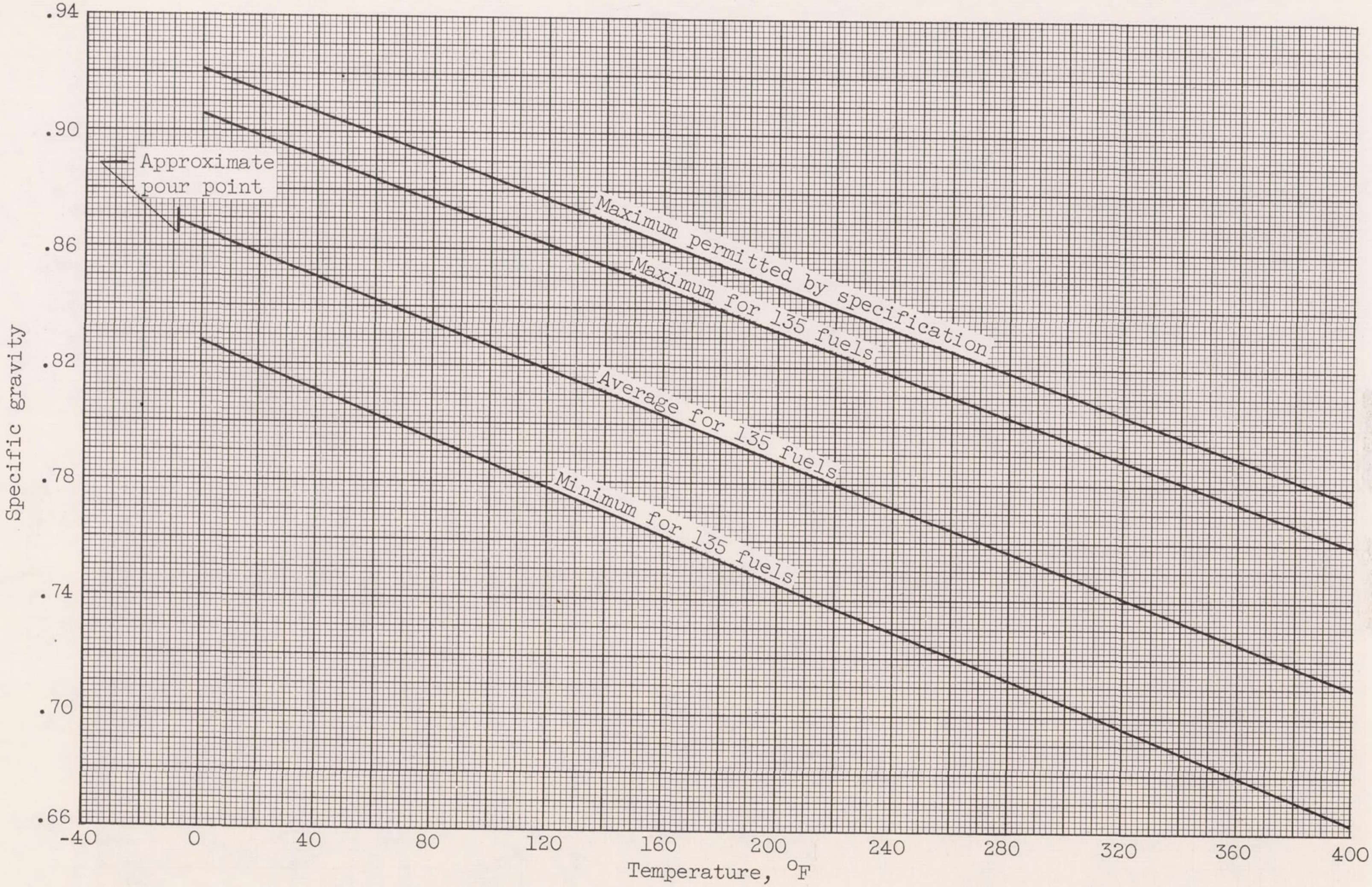
(d) MIL-F-5624C (JP-5) fuel.

Figure 3. - Continued. Variation of specific gravity with temperature.



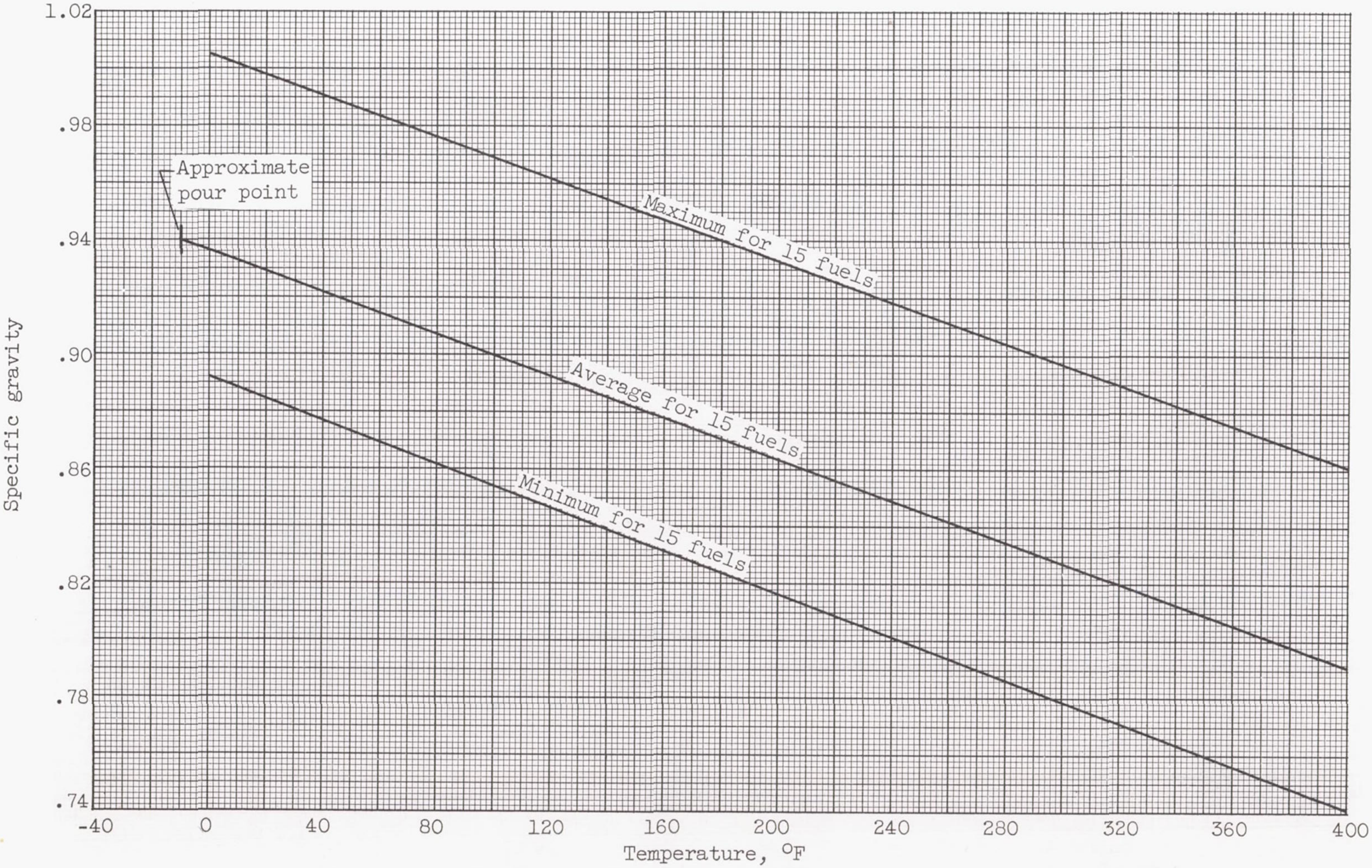
(e) Number 1 fuel oil.

Figure 3. - Continued. Variation of specific gravity with temperature.



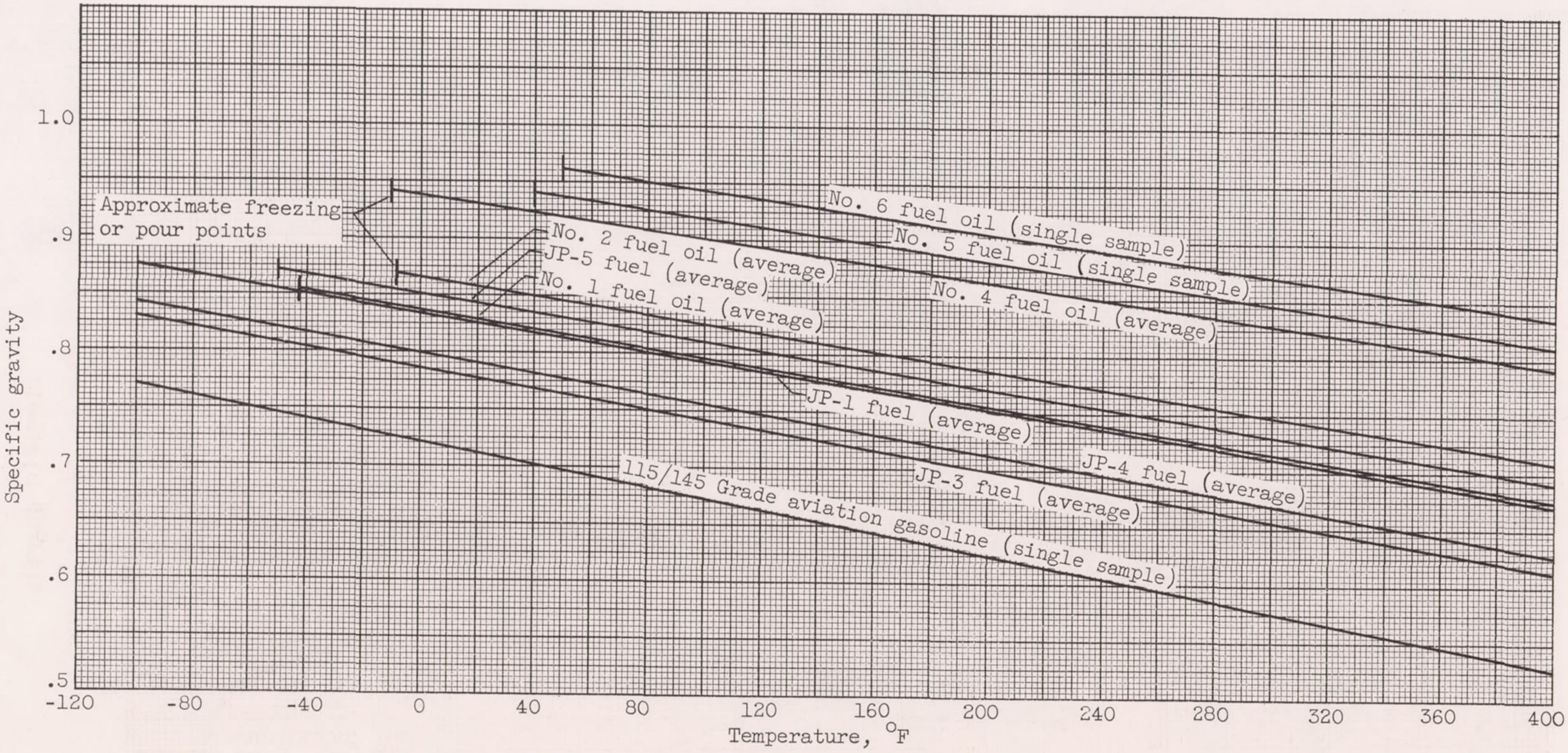
(f) Number 2 fuel oil.

Figure 3. - Continued. Variation of specific gravity with temperature.



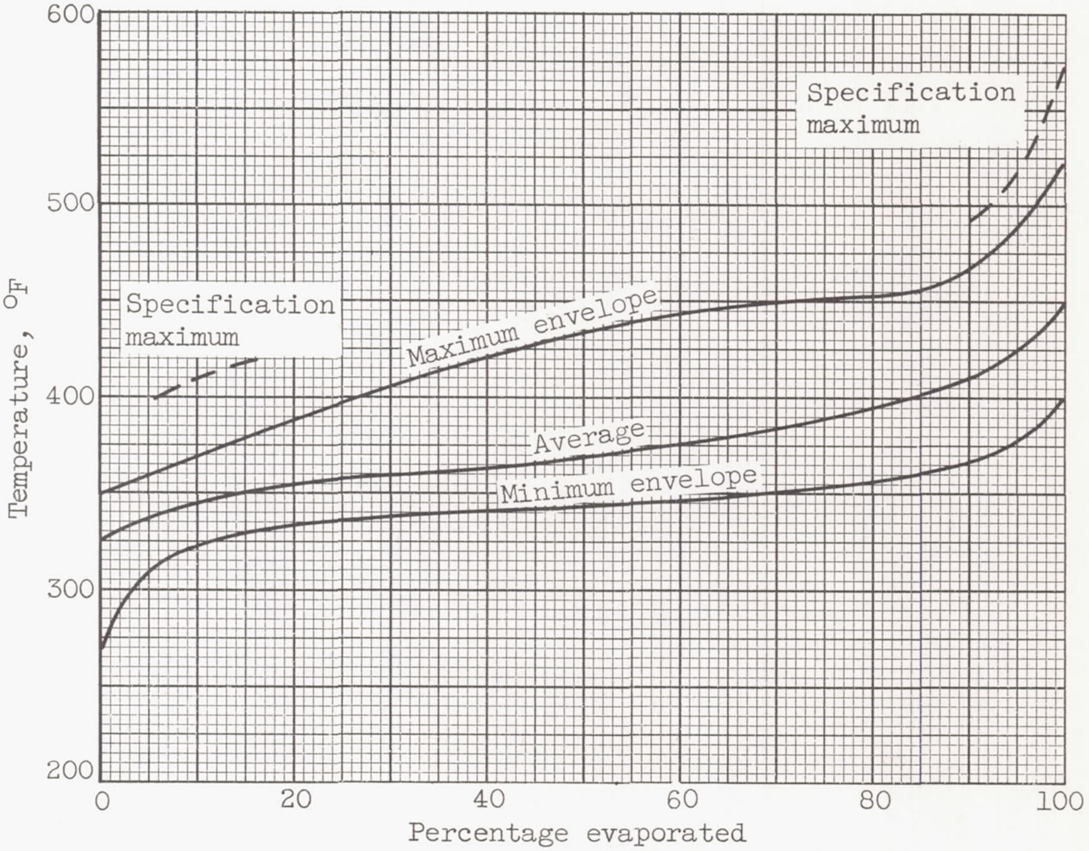
(g) Number 4 fuel oil.

Figure 3. - Continued. Variation of specific gravity with temperature.



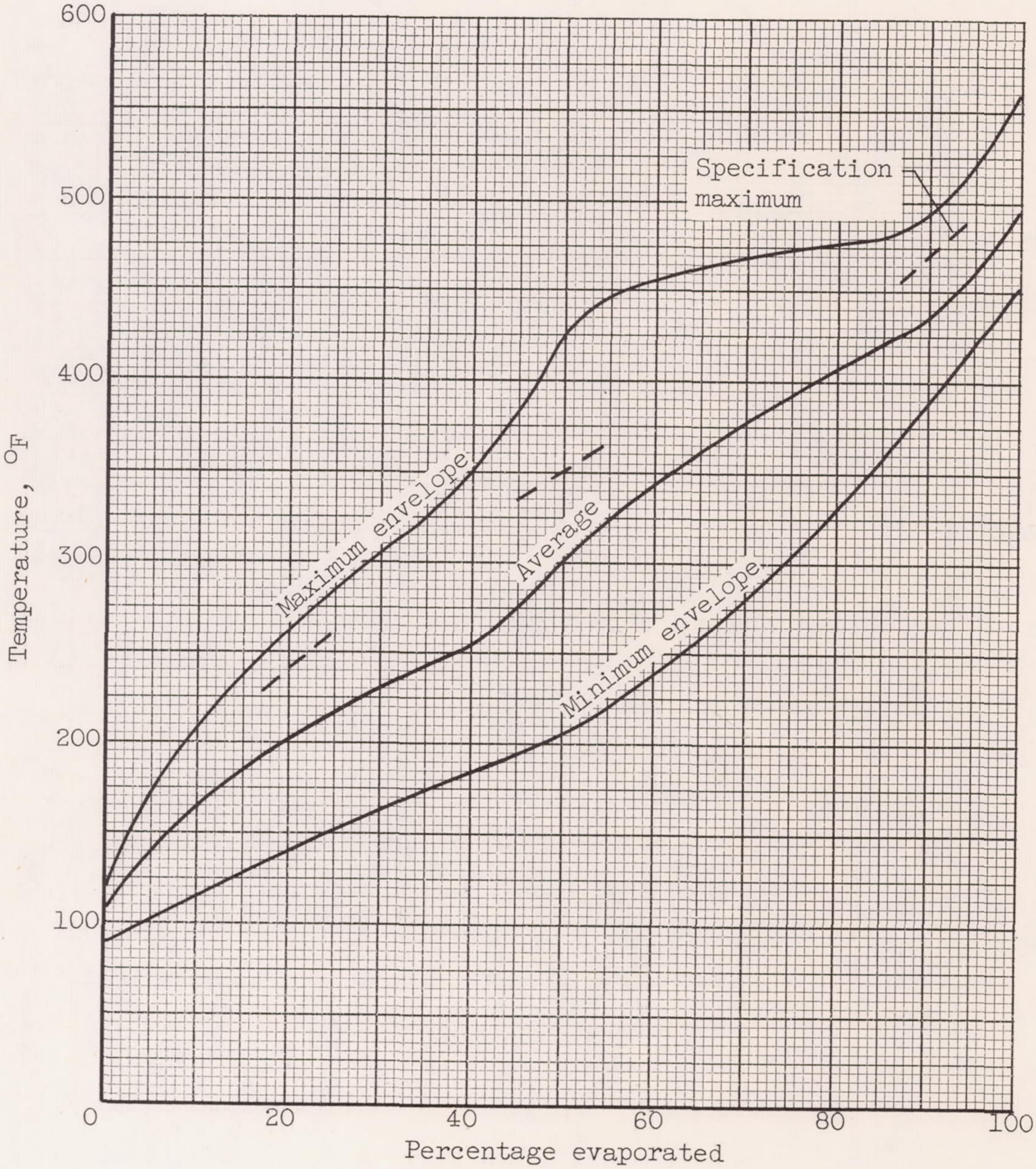
(h) Comparison of fuels.

Figure 3. - Concluded. Variation of specific gravity with temperature.



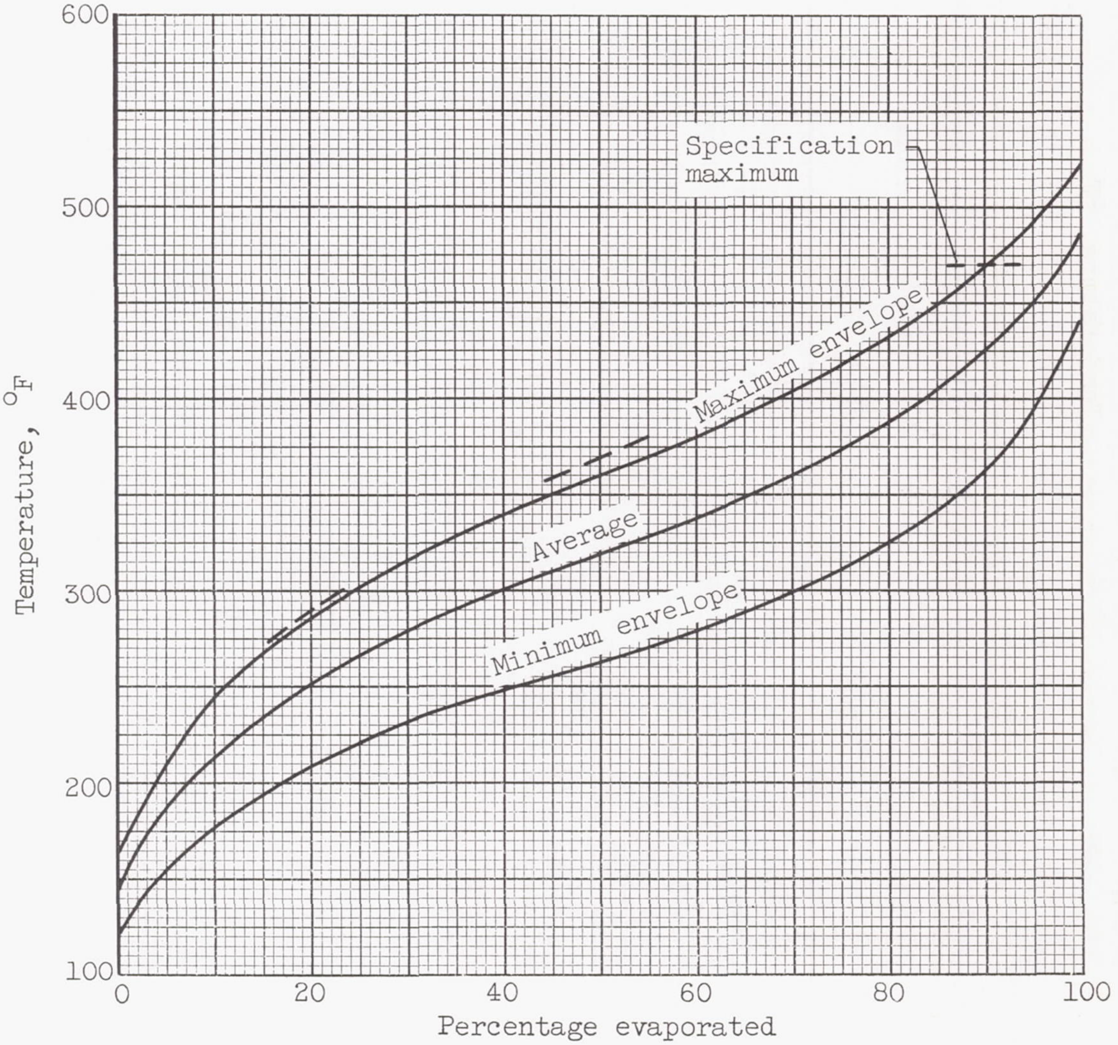
(a) MIL-F-5616 (JP-1) fuel.

Figure 4. - Variation of A.S.T.M. distillation temperatures for several fuels.



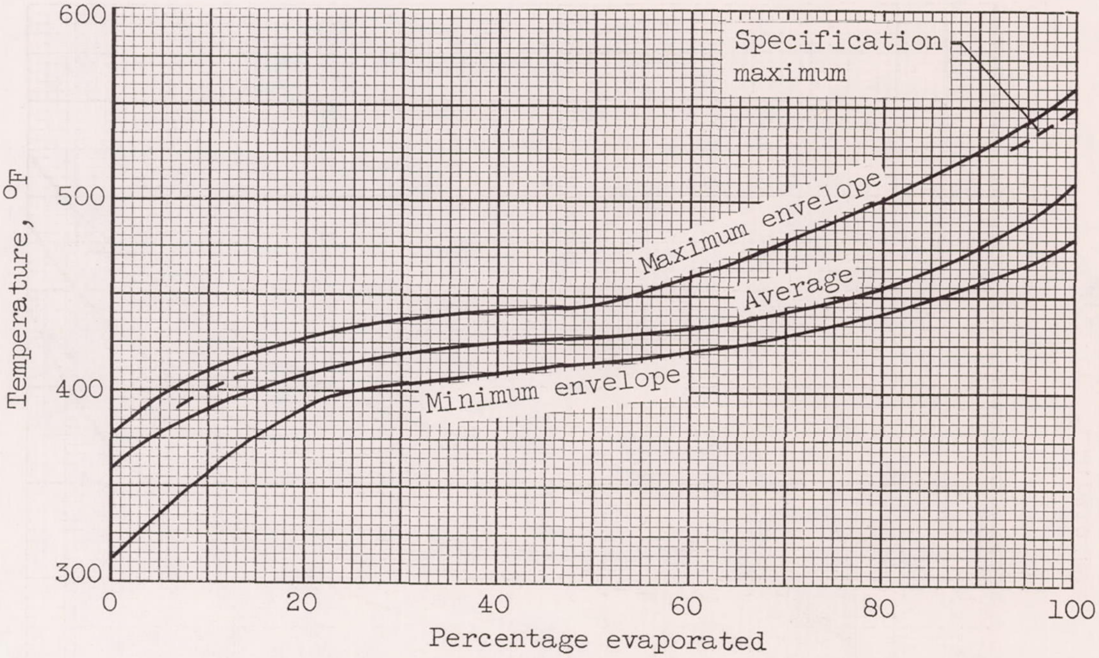
(b) MIL-F-5624C (JP-3) fuel. (The fuels represented here were produced in conformity with an earlier specification, MIL-F-5724A. The more recent specification, MIL-F-5624C, does not permit as wide variation as indicated by broken lines.)

Figure 4. - Continued. Variation of A.S.T.M. distillation temperatures for several fuels.



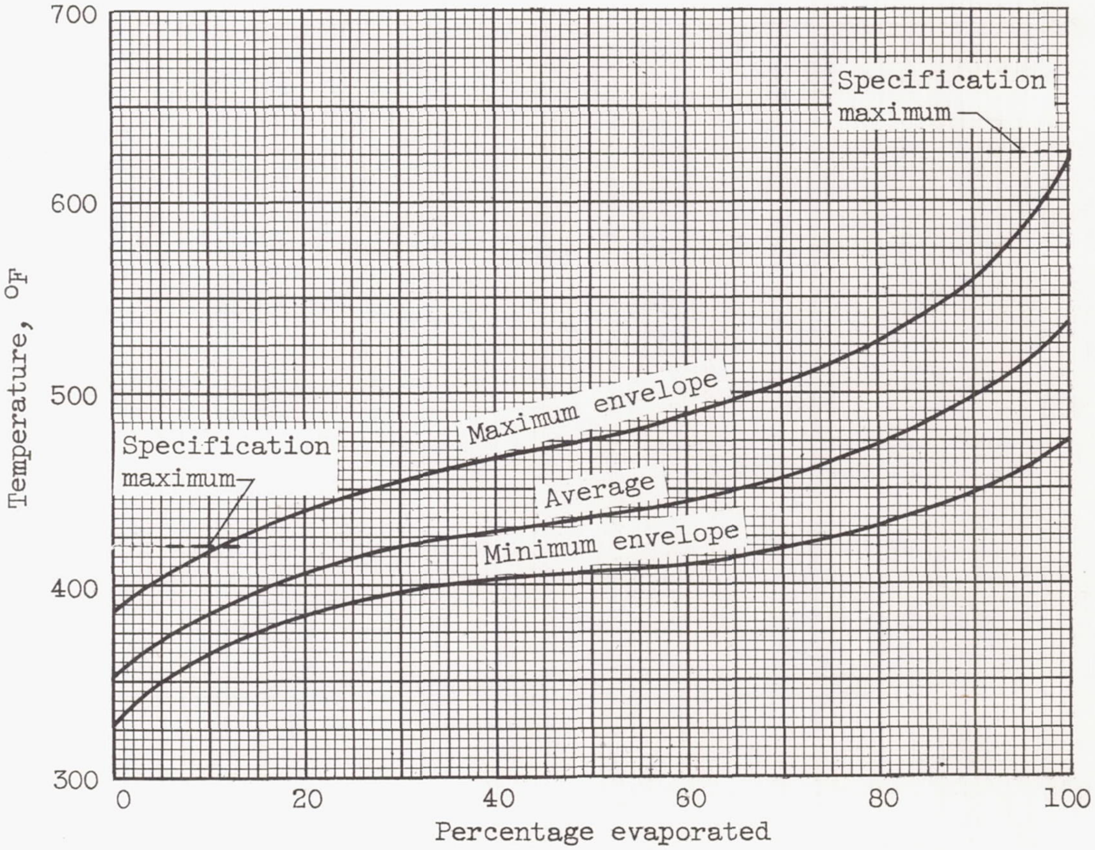
(c) MIL-F-5624C (JP-4) fuel.

Figure 4. - Continued. Variation of A.S.T.M. distillation temperatures for several fuels.



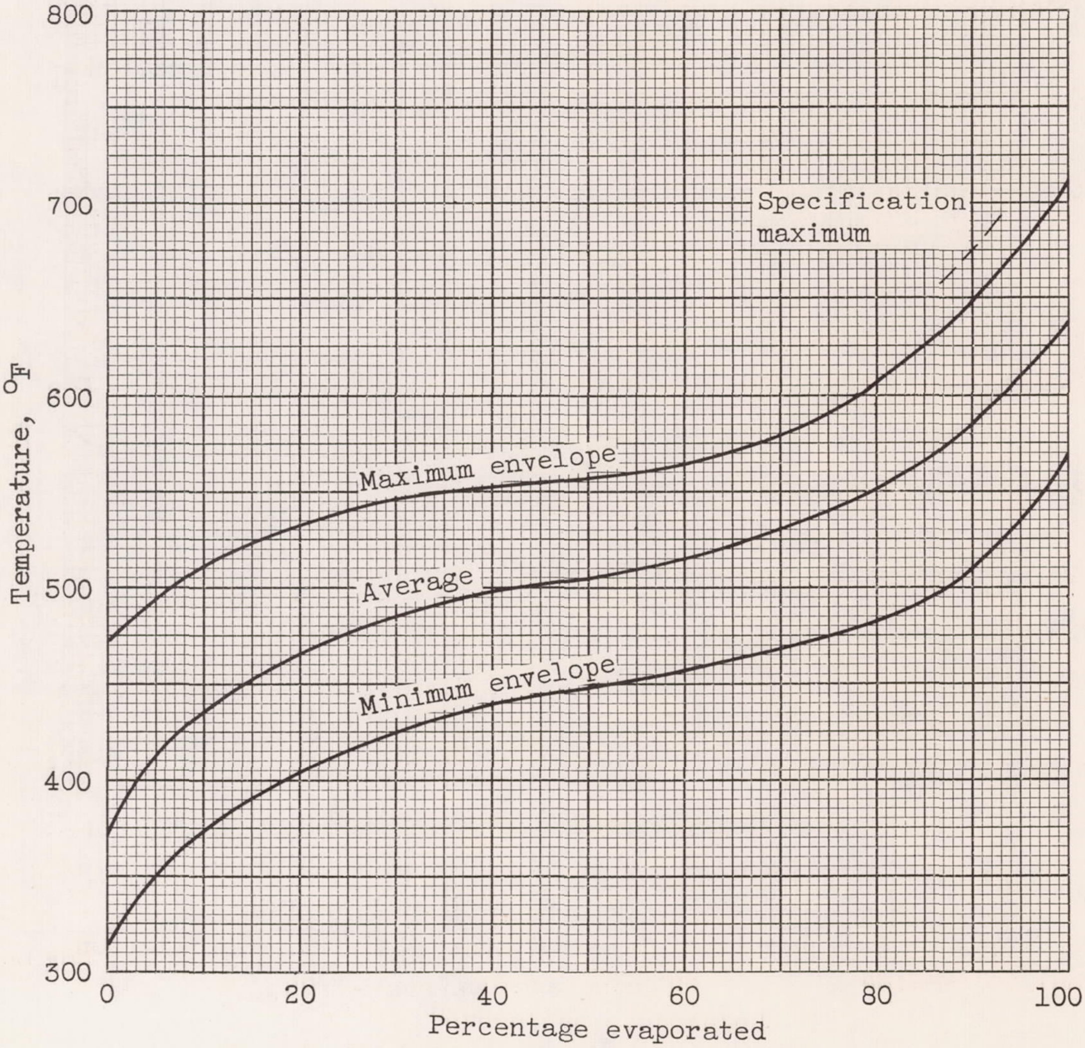
(d) MIL-F-5624C (JP-5) fuel. (The fuels represented here were produced in conformity with an earlier specification, MIL-F-5624A. The more recent specification, MIL-F-5624C, does not permit as wide variation as indicated by broken lines.

Figure 4. - Continued. Variation of A.S.T.M. distillation temperatures for several fuels.



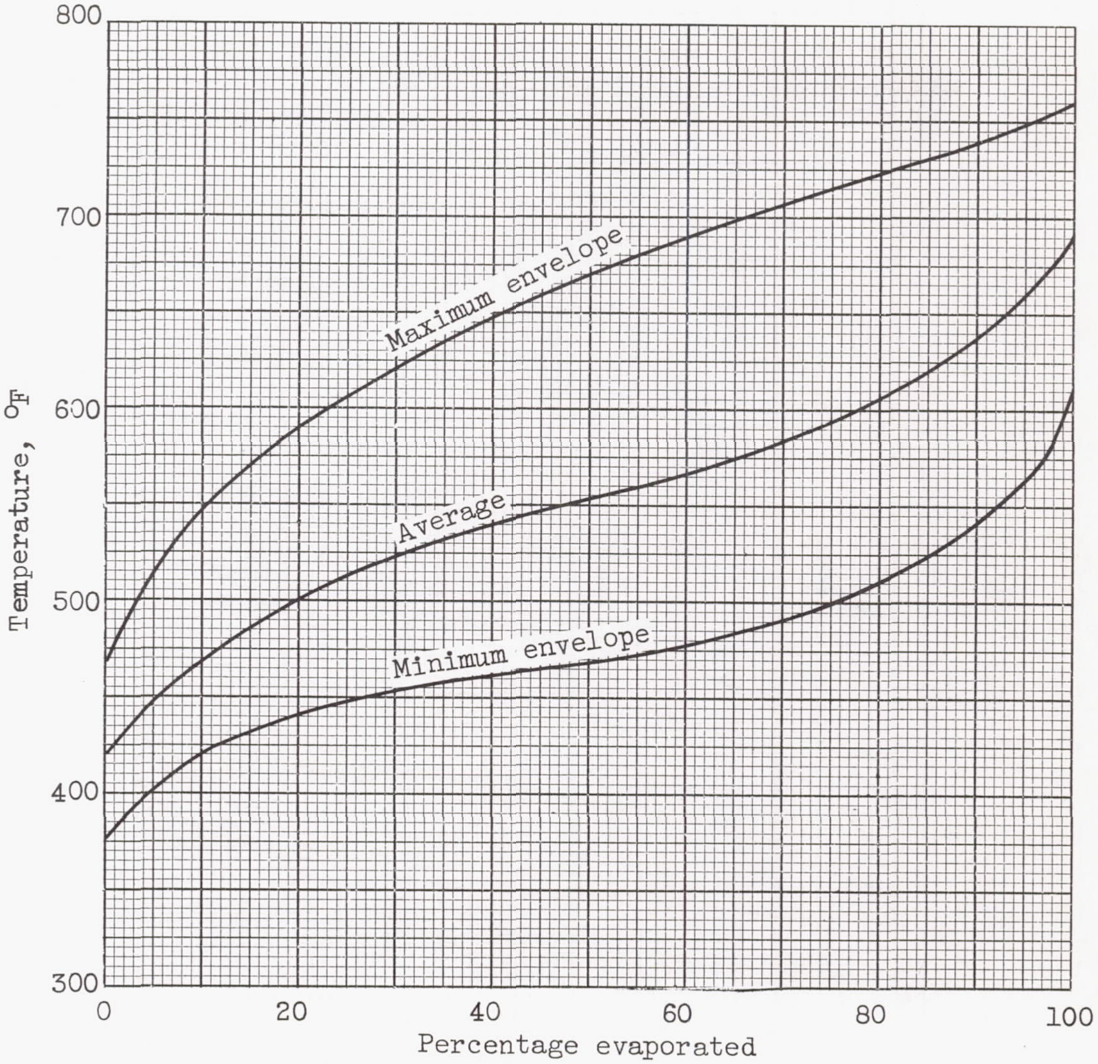
(e) Number 1 fuel oil.

Figure 4. - Continued. Variation of A.S.T.M. distillation temperatures for several fuels.



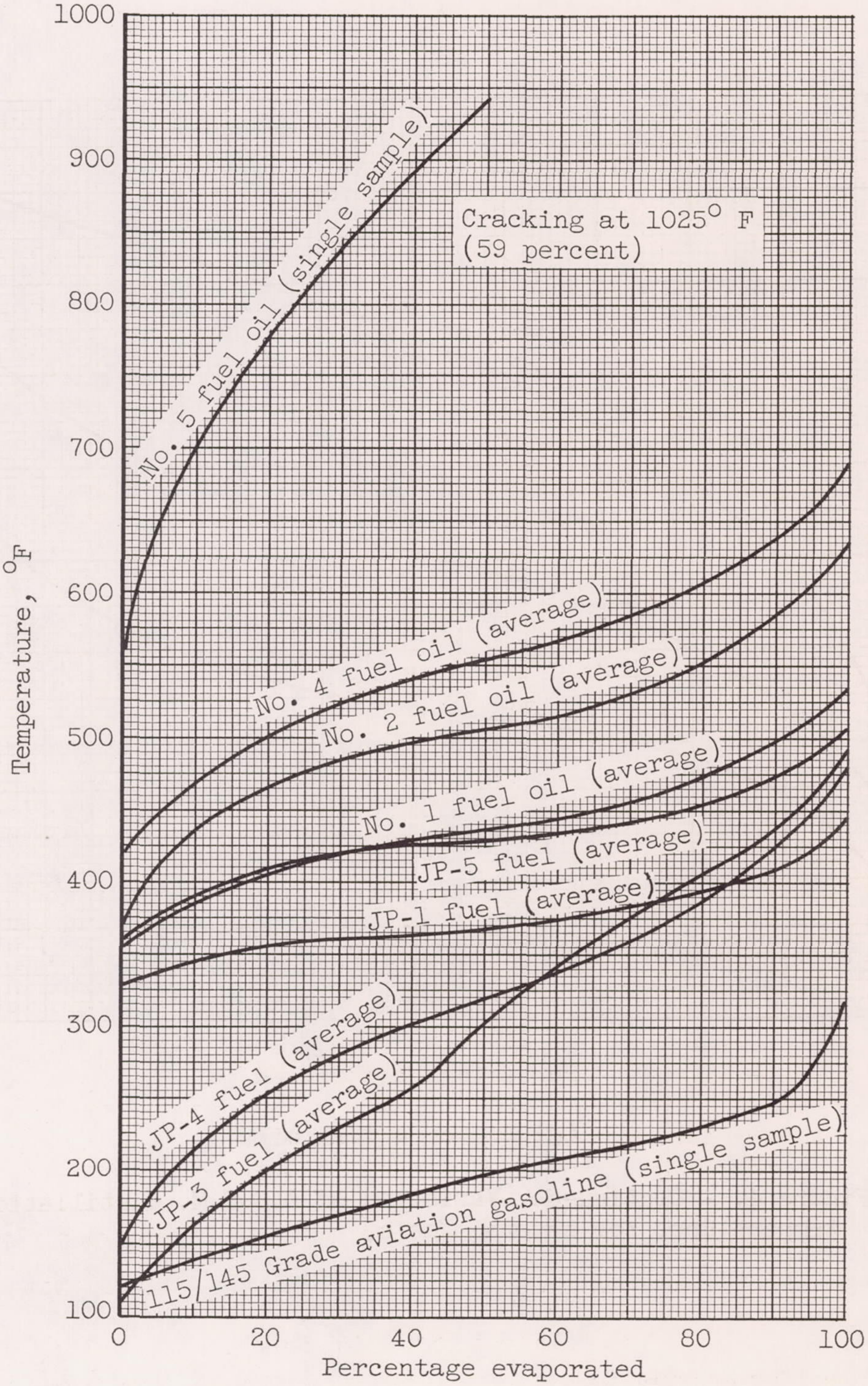
(f) Number 2 fuel oil.

Figure 4. - Continued. Variation of A.S.T.M. distillation temperatures for several fuels.



(g) Number 4 fuel oil.

Figure 4. - Continued. Variation of A.S.T.M. distillation temperatures for several fuels.



(h) Comparison of fuels.

Figure 4. - Concluded. Variation of A.S.T.M. distillation temperatures for several fuels.

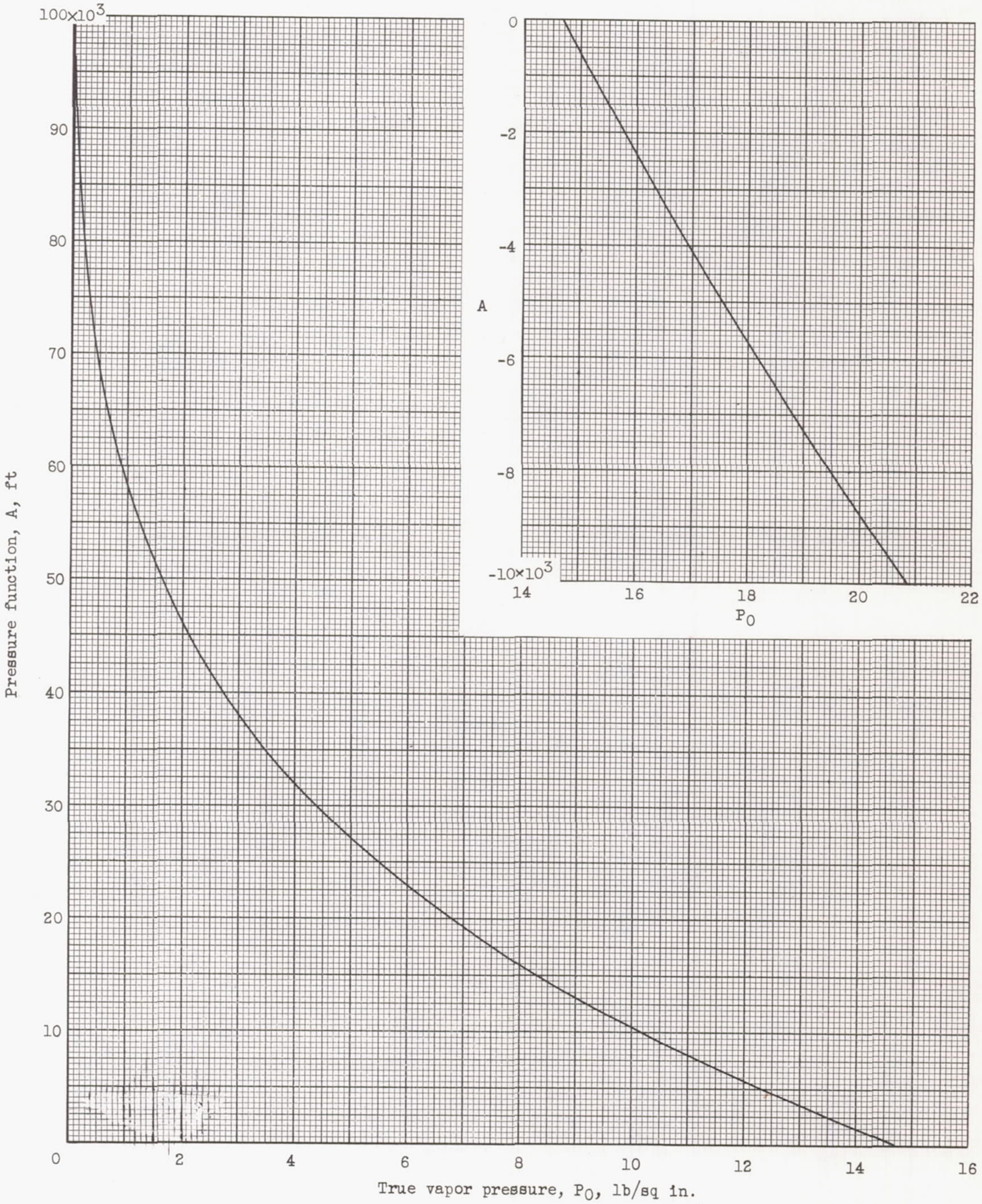
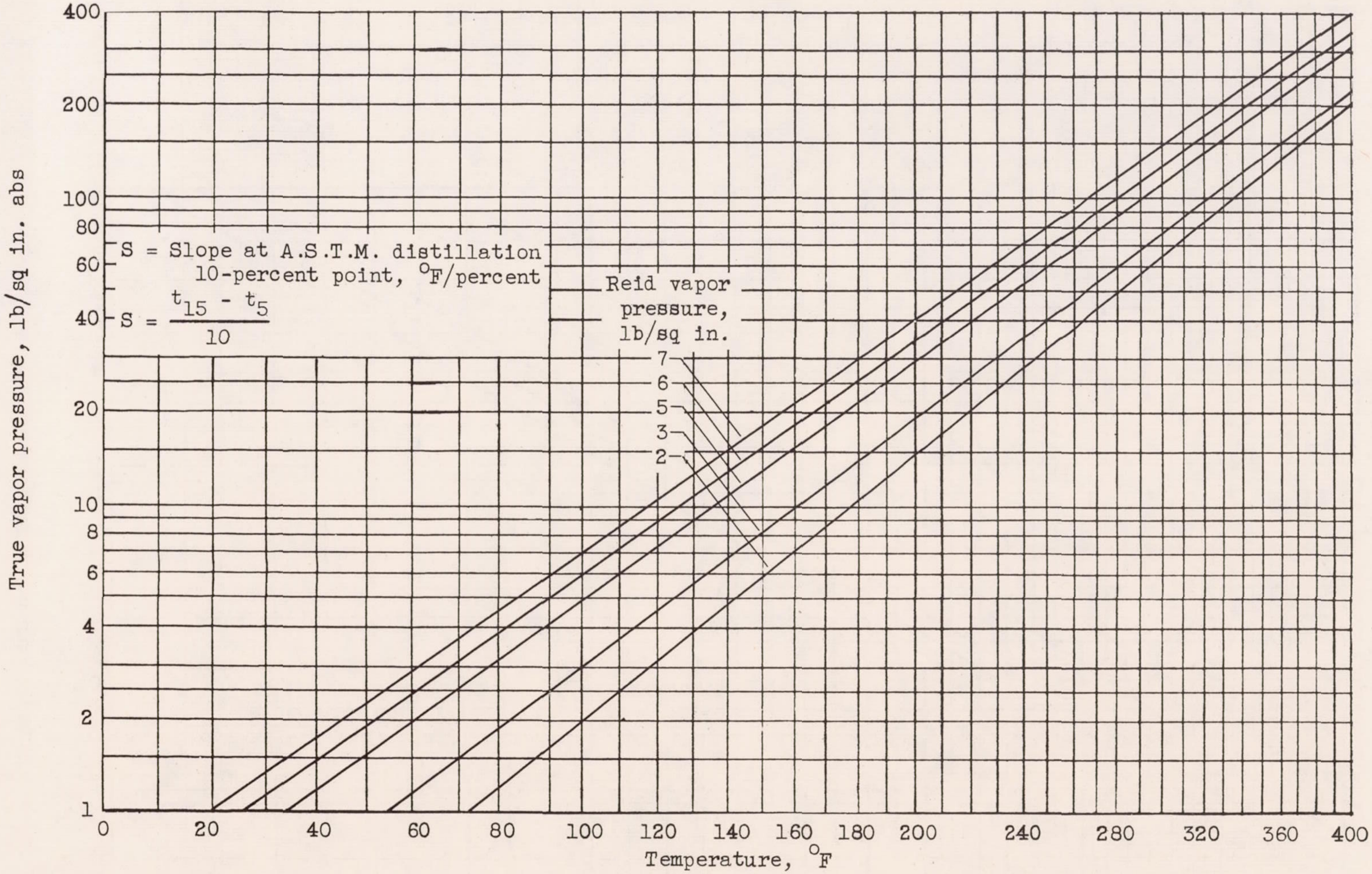
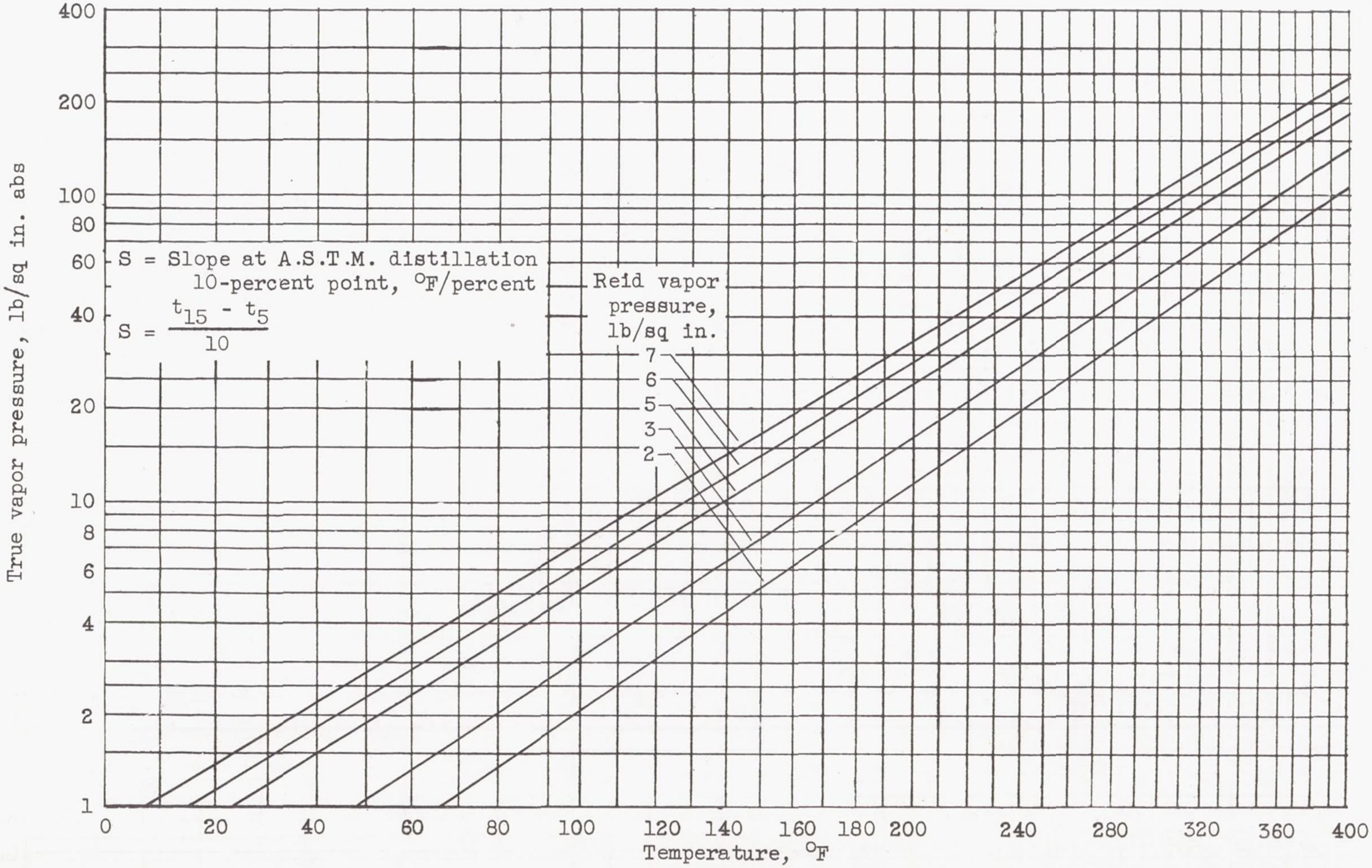


Figure 5. - Relation between true vapor pressure and pressure function. (Based on data from ref. 2.)



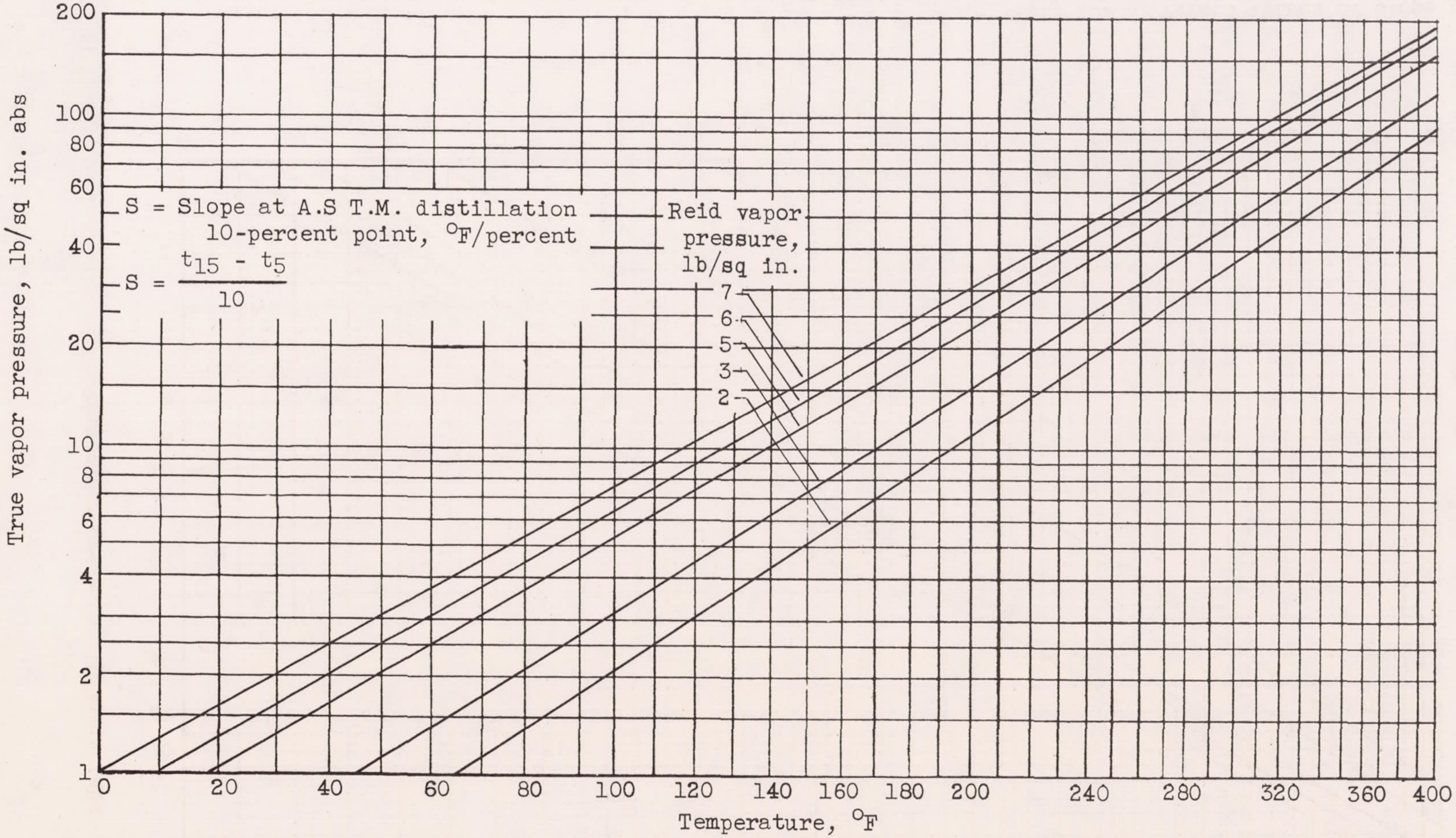
(a) Slope, 0.

Figure 6. - Variation of vapor pressure with temperature for different values of slope at A.S.T.M. distillation 10-percent-evaporated point.



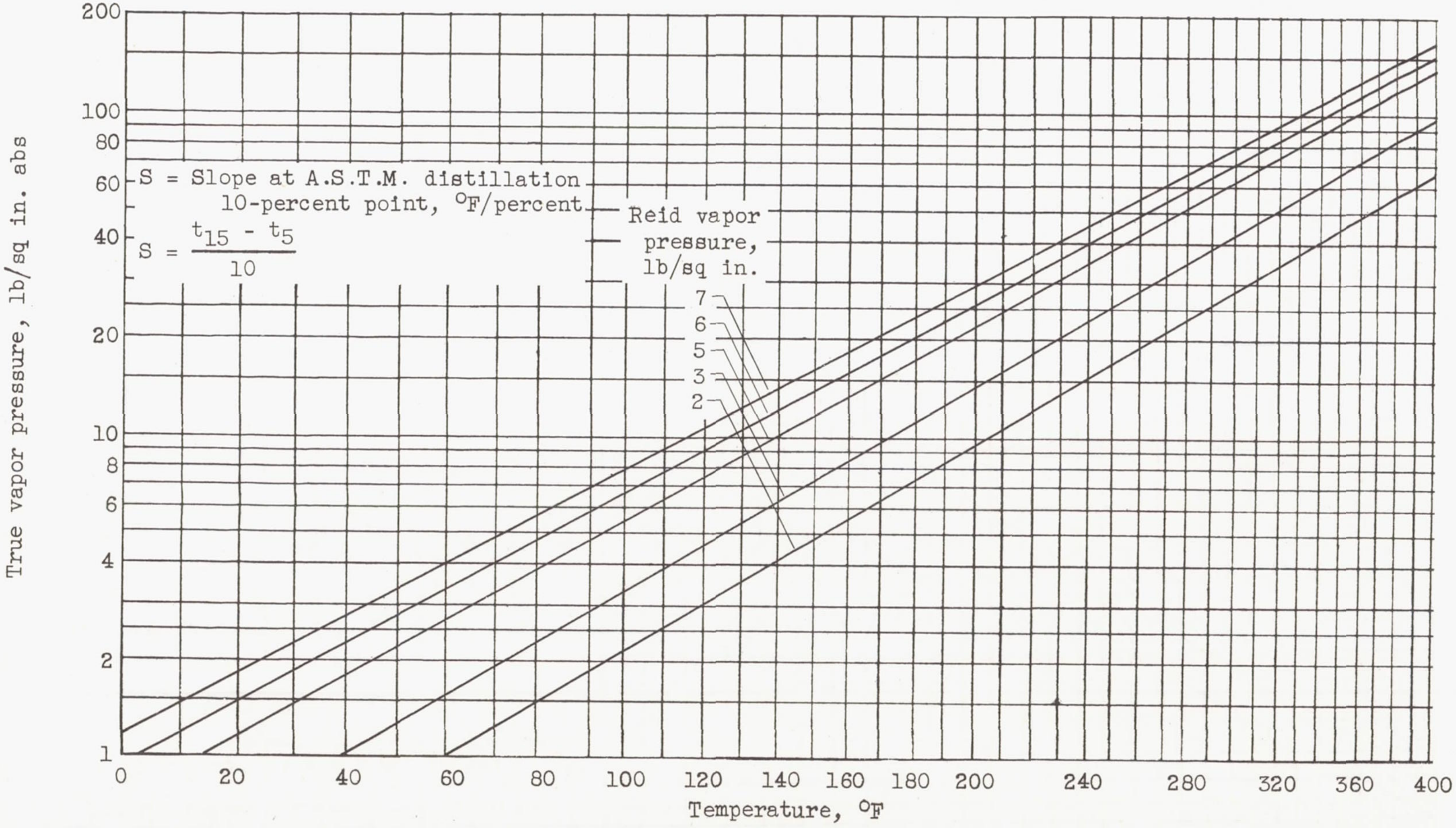
(b) Slope, 2.

Figure 6. - Continued. Variation of vapor pressure with temperature for different values of slope at A.S.T.M. distillation 10-percent-evaporated point.



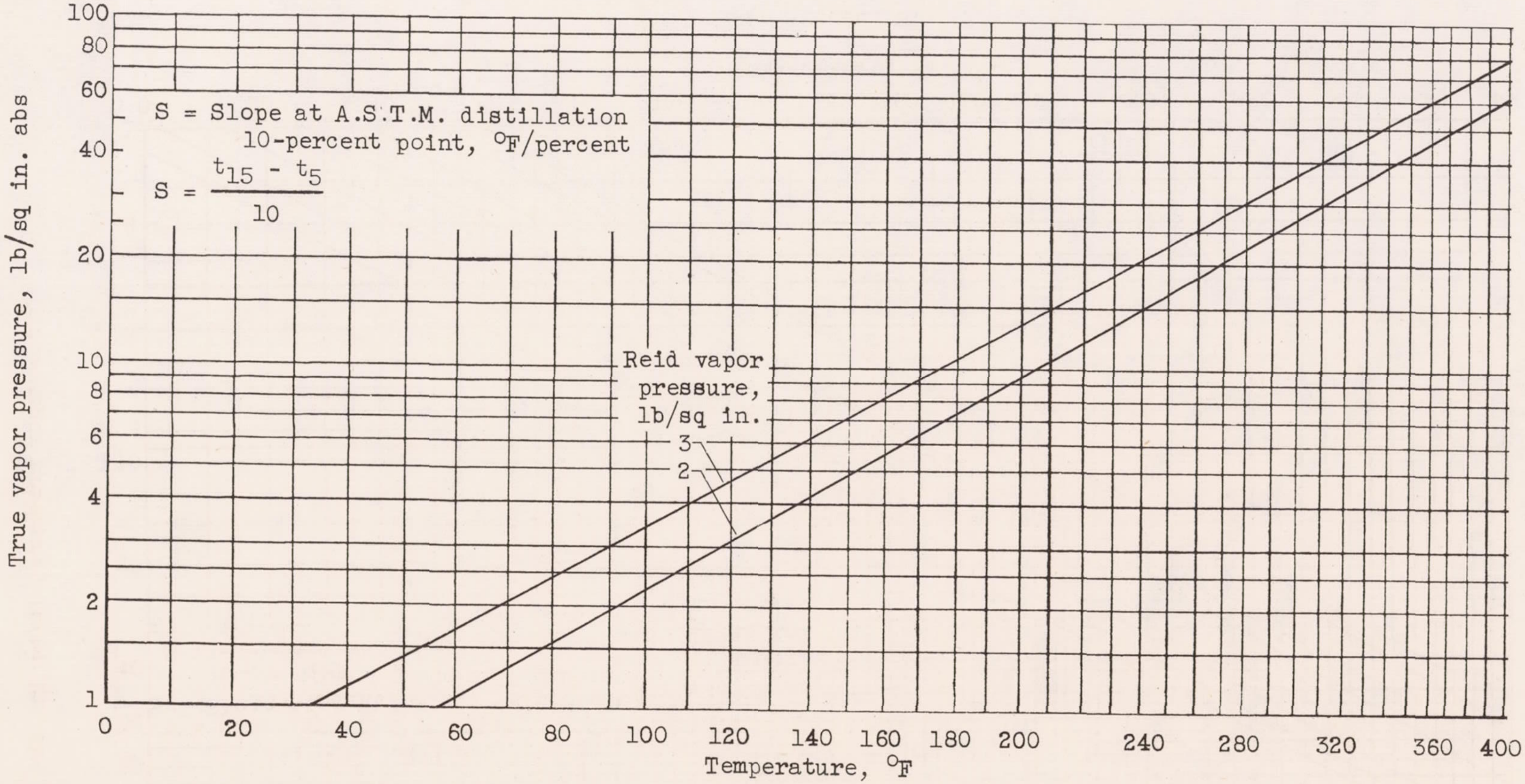
(c) Slope, 4.

Figure 6. - Continued. Variation of vapor pressure with temperature for different values of slope at A.S.T.M. distillation 10-percent-evaporated point.



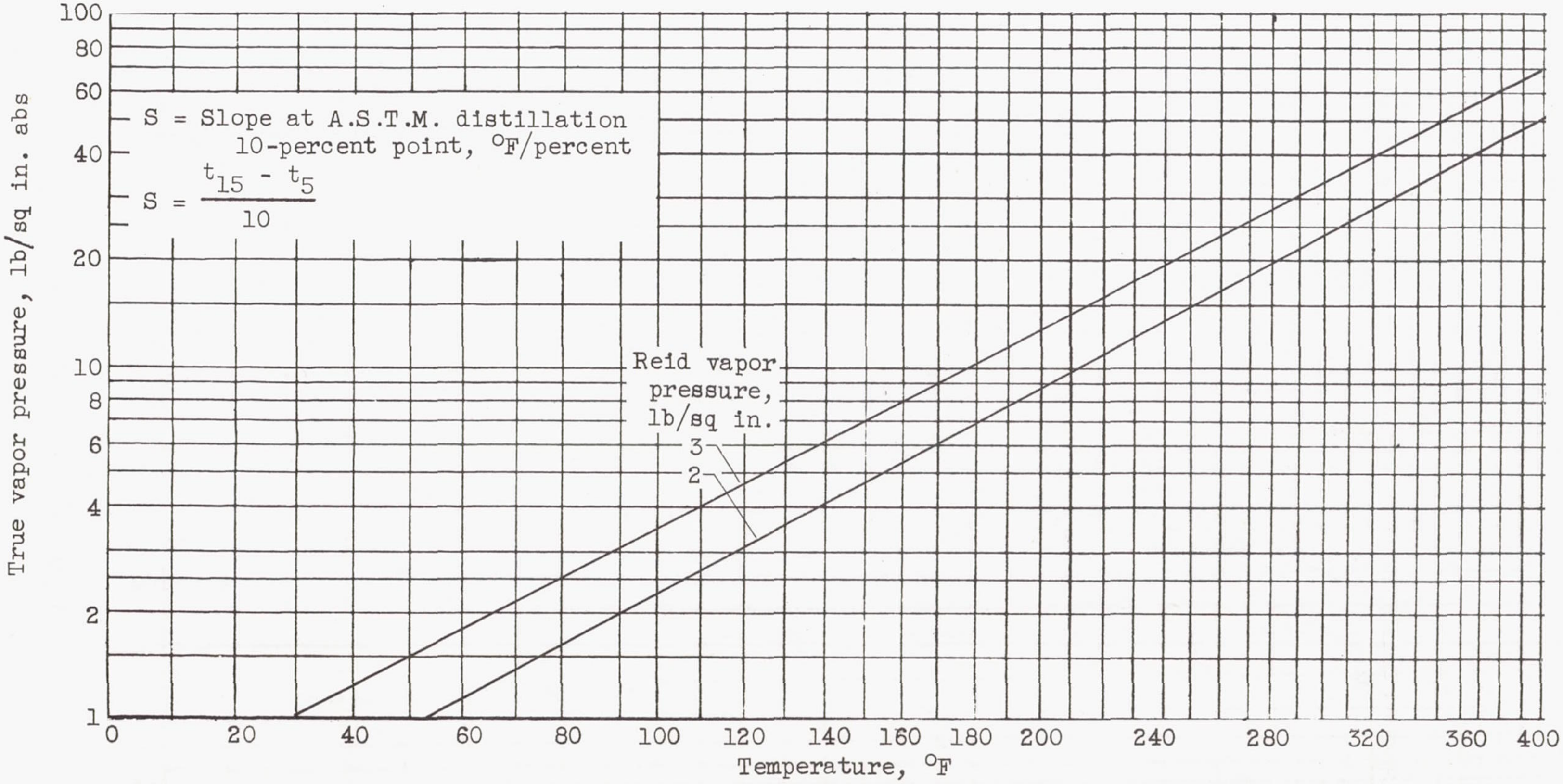
(d) Slope, 6.

Figure 6. - Continued. Variation of vapor pressure with temperature for different values of slope at A.S.T.M. distillation 10-percent-evaporated point.



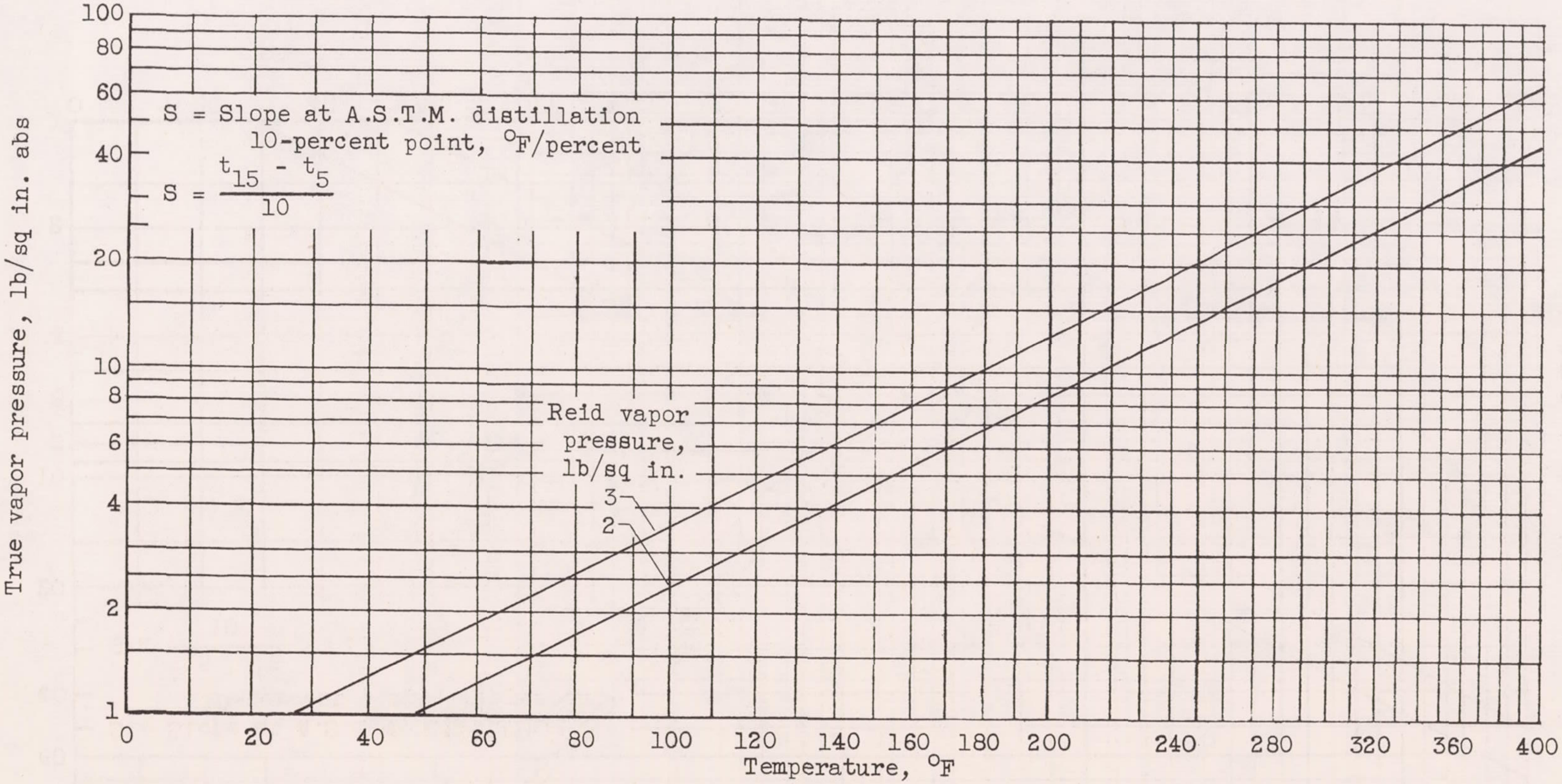
(e) Slope, 8.

Figure 6. - Continued. Variation of vapor pressure with temperature for different values of slope at A.S.T.M. distillation 10-percent-evaporated point.



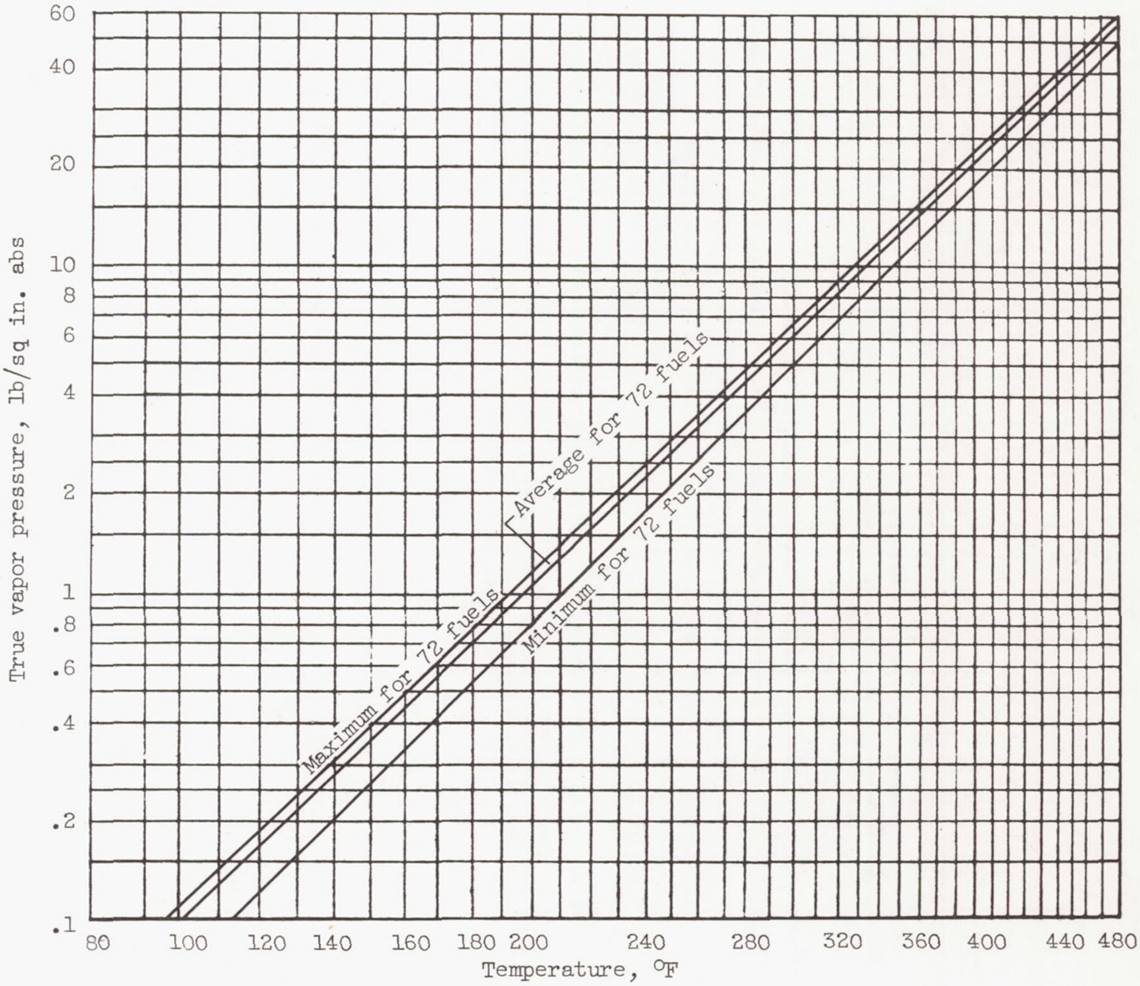
(f) Slope, 10.

Figure 6. - Continued. Variation of vapor pressure with temperature for different values of slope at A.S.T.M. distillation 10-percent-evaporated point.



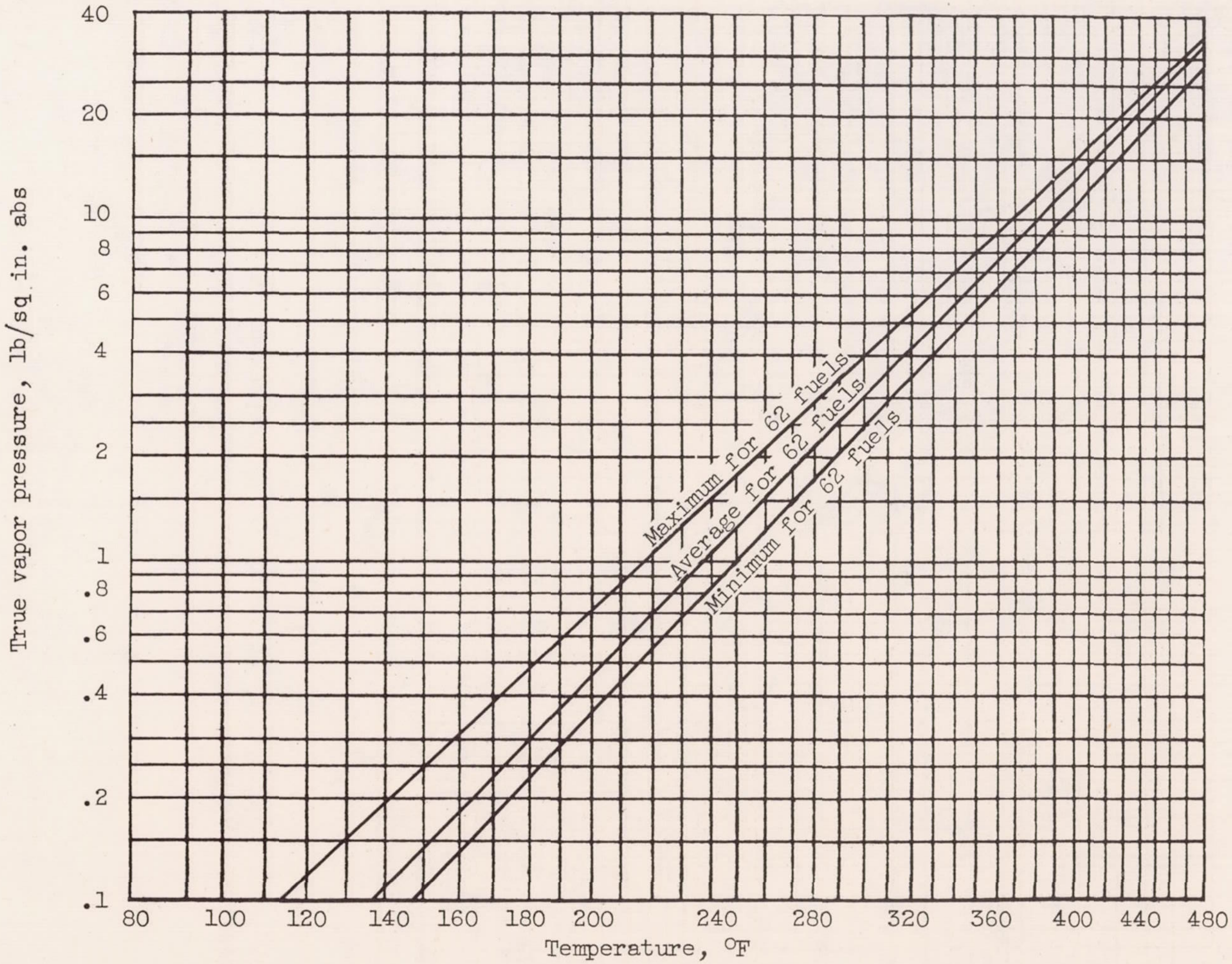
(g) Slope, 12.

Figure 6. - Concluded. Variation of vapor pressure with temperature for different values of slope at A.S.T.M. distillation 10-percent-evaporated point.



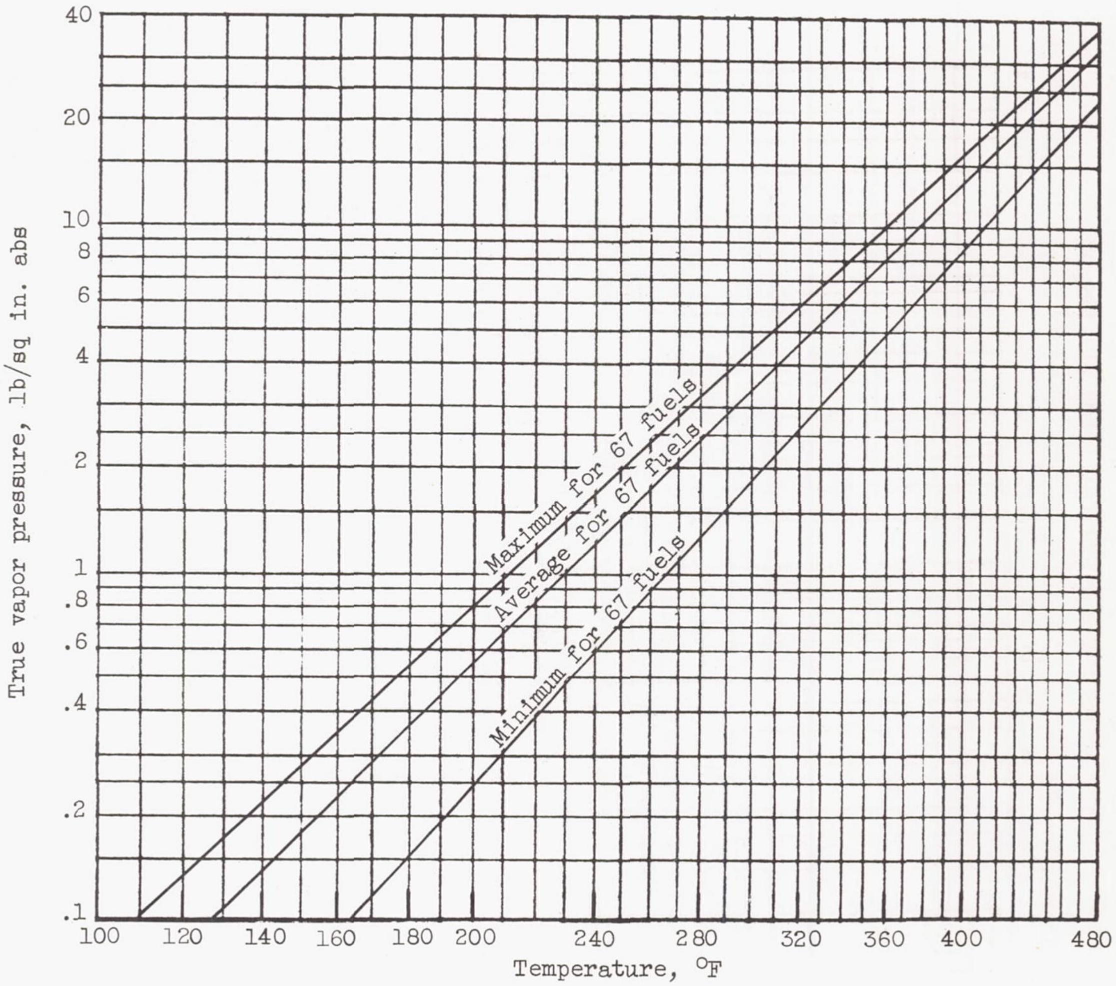
(a) MIL-F-5616 (JP-1) fuel.

Figure 7. - Variation of vapor pressure with temperature for different fuels.



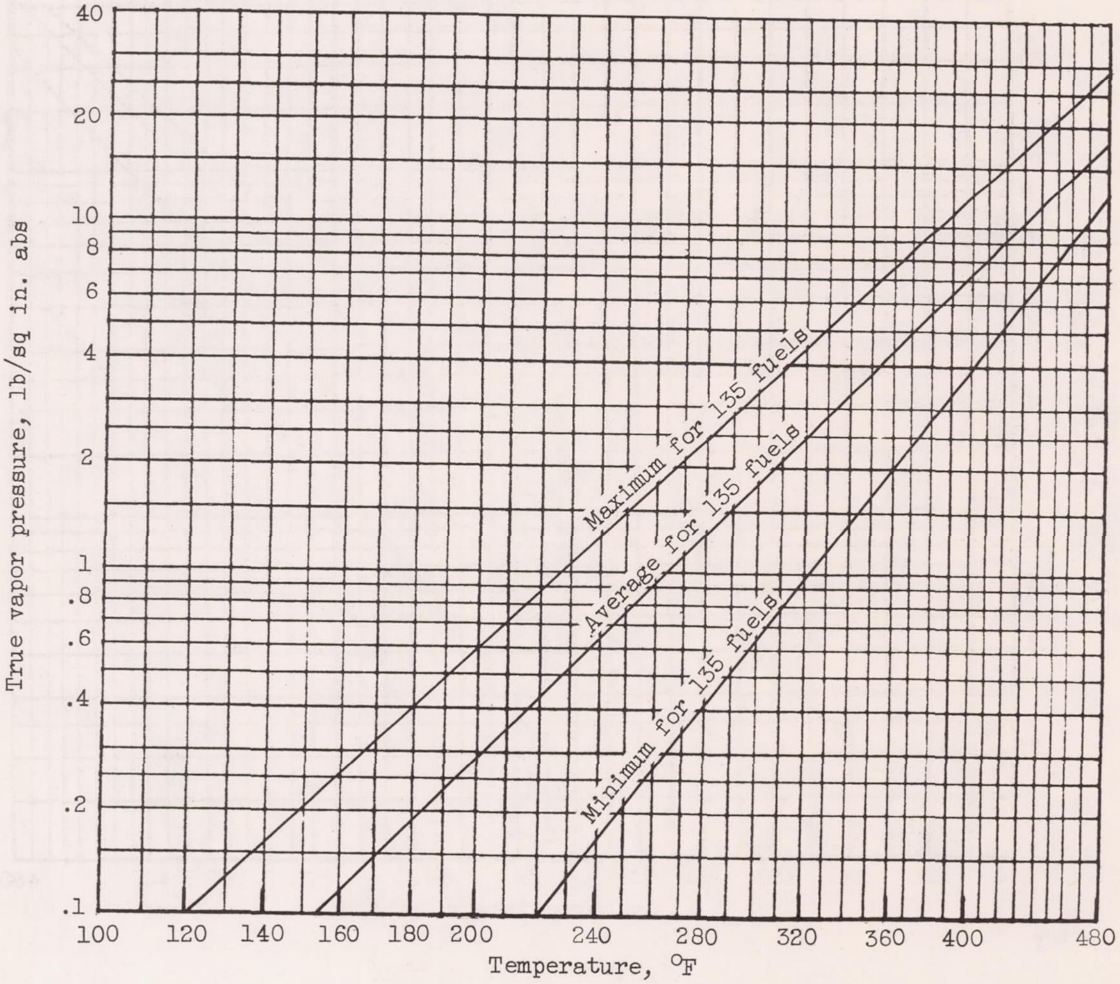
(b) MIL-F-5624C (JP-5) fuel.

Figure 7. - Continued. Variation of vapor pressure with temperature for different fuels.



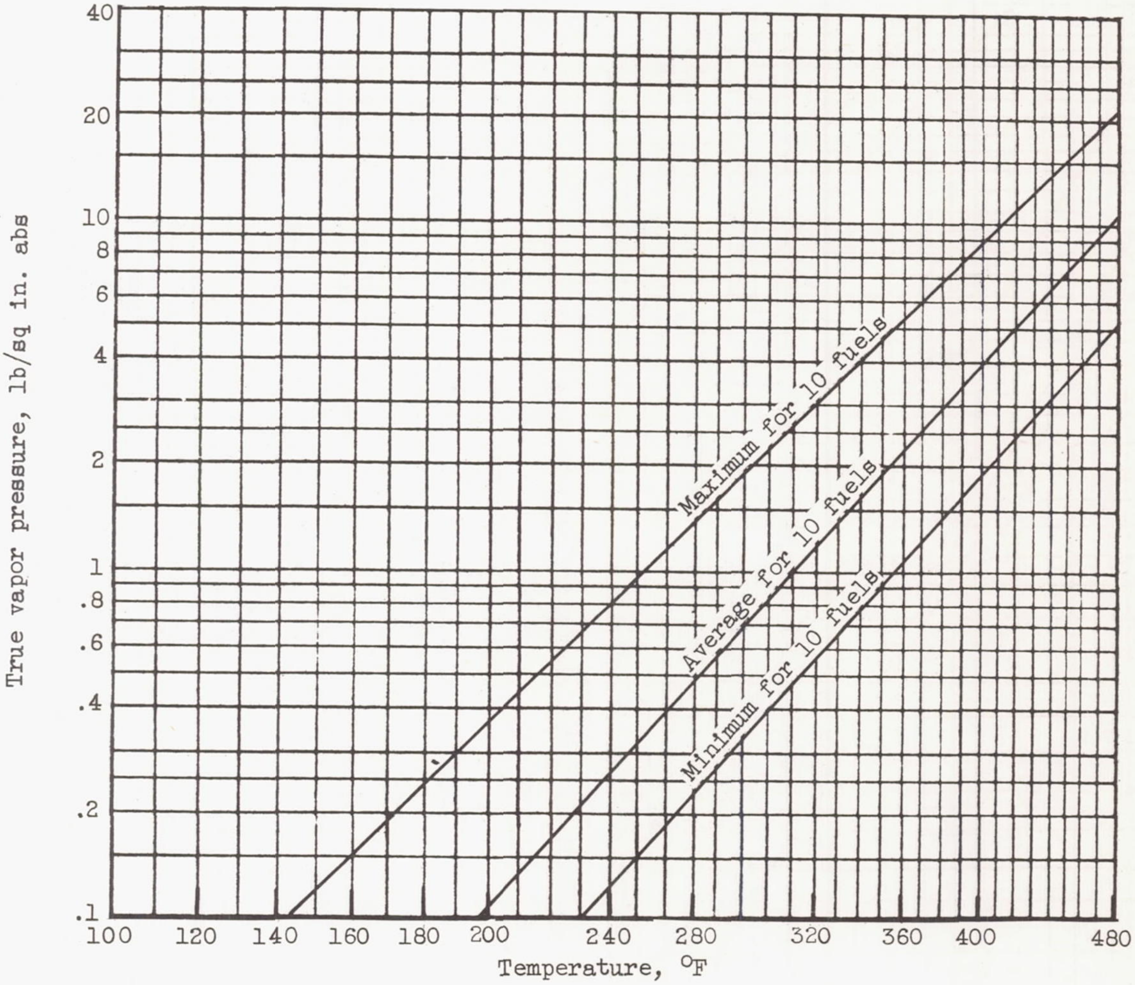
(c) Number 1 fuel oil.

Figure 7. - Continued. Variation of vapor pressure with temperature for different fuels.



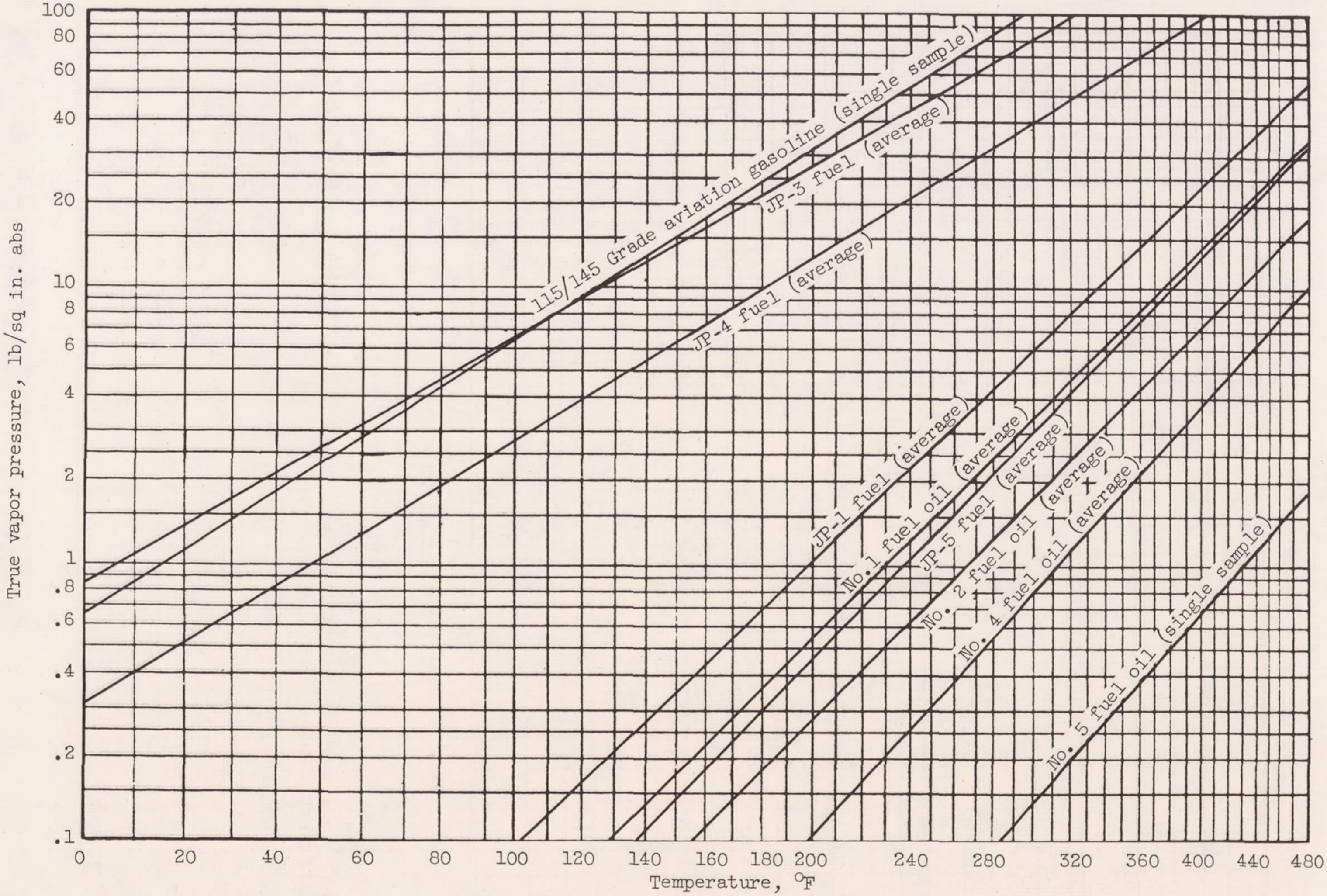
(d) Number 2 fuel oil.

Figure 7. - Continued. Variation of vapor pressure with temperature for different fuels.



(e) Number 4 fuel oil.

Figure 7. - Continued. Variation of vapor pressure with temperature for different fuels.



(f) Comparison of fuels.

Figure 7. - Concluded. Variation of vapor pressure with temperature for different fuels.

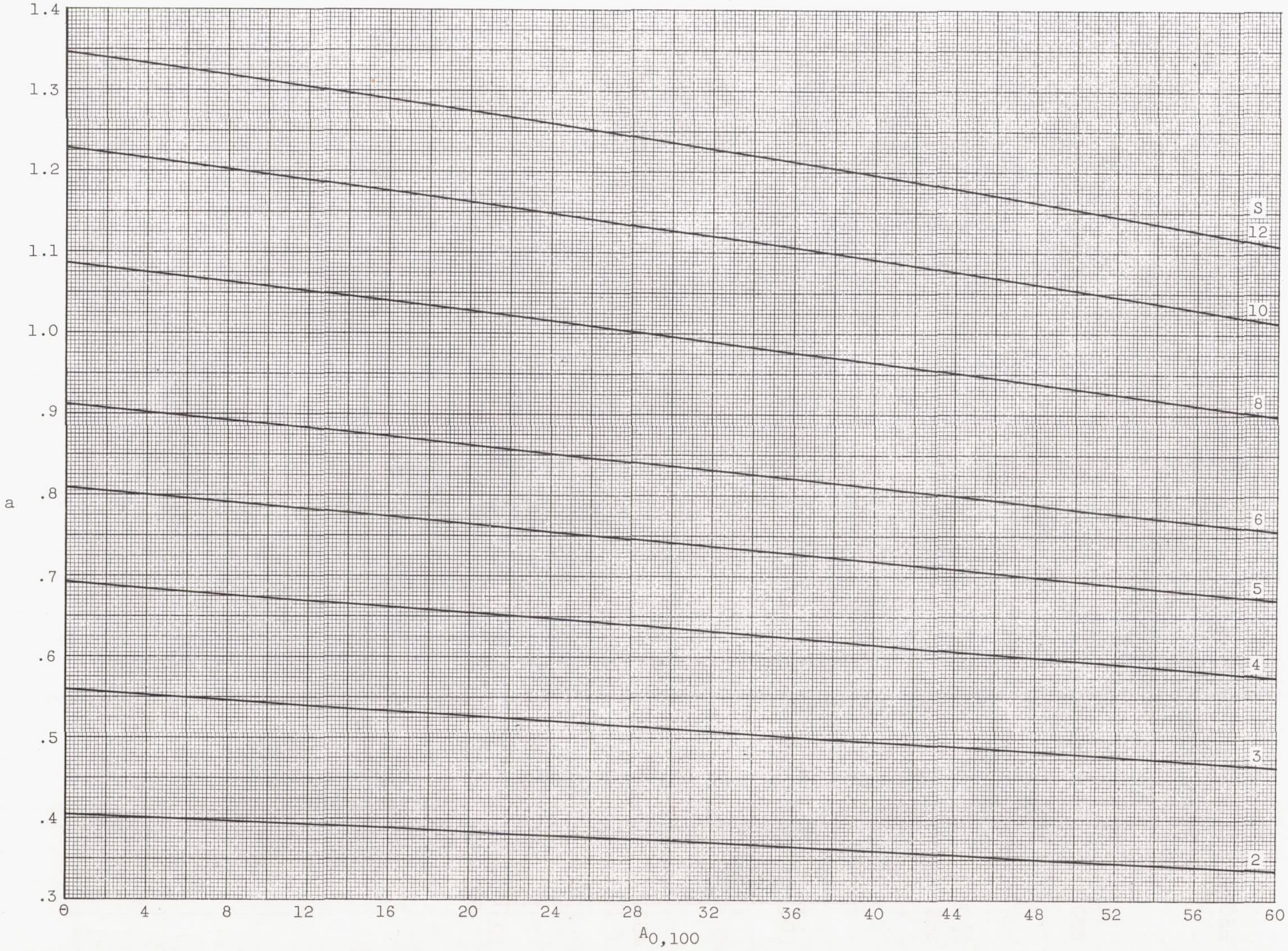


Figure 8. - Solution of equation (18) for various values of S and $A_{0,100}$.

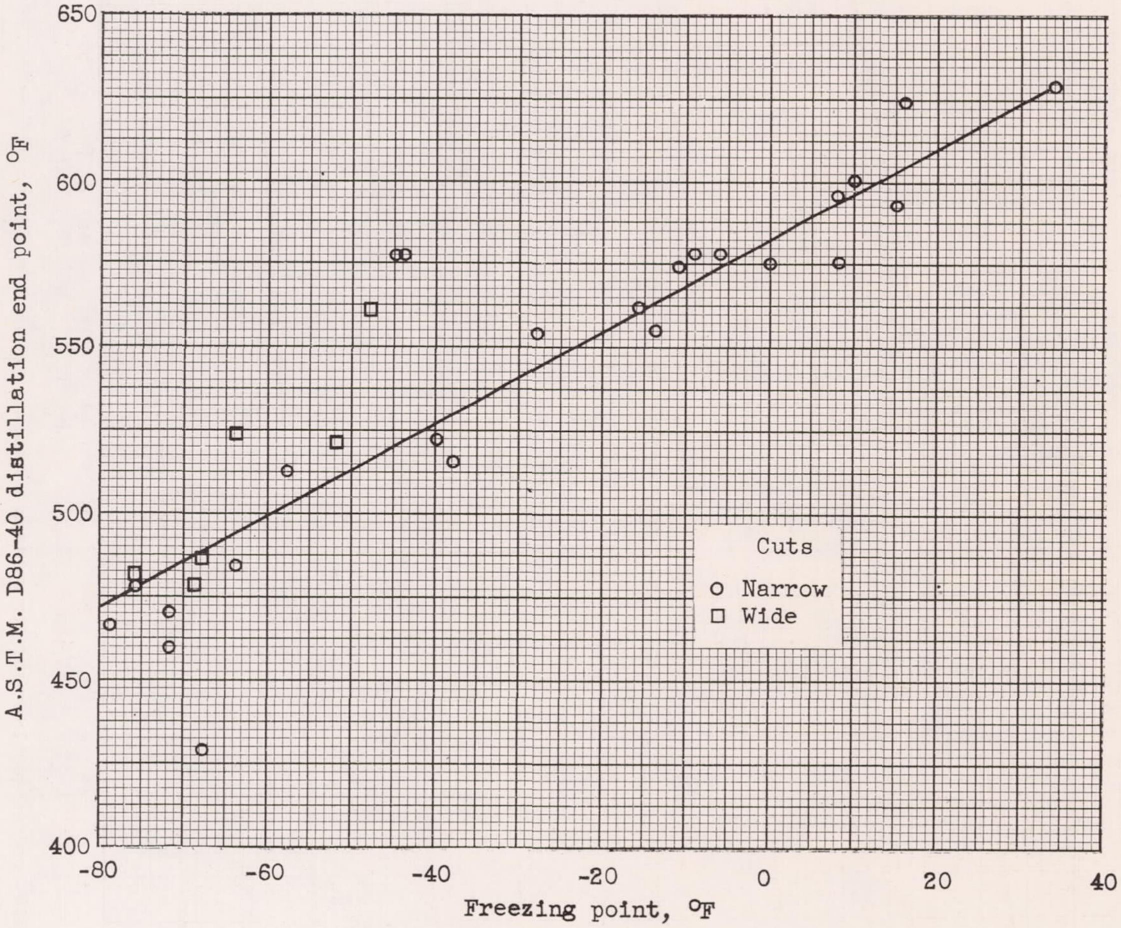


Figure 9. - Variation of freezing point with end point for crude cuts and blends. (Based on data from Bureau of Mines.)

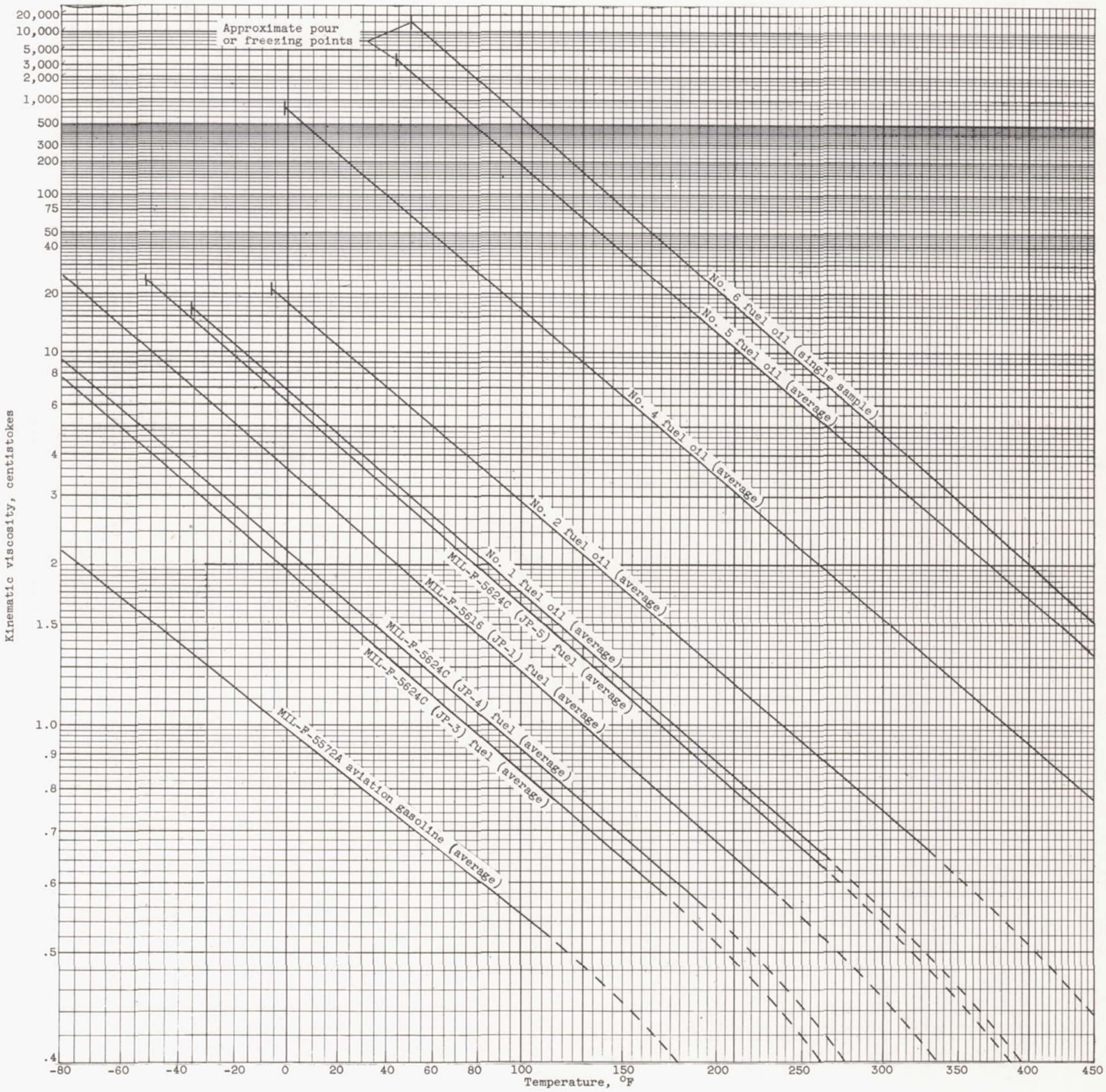


Figure 10. - Viscosity-temperature relation for several fuels.

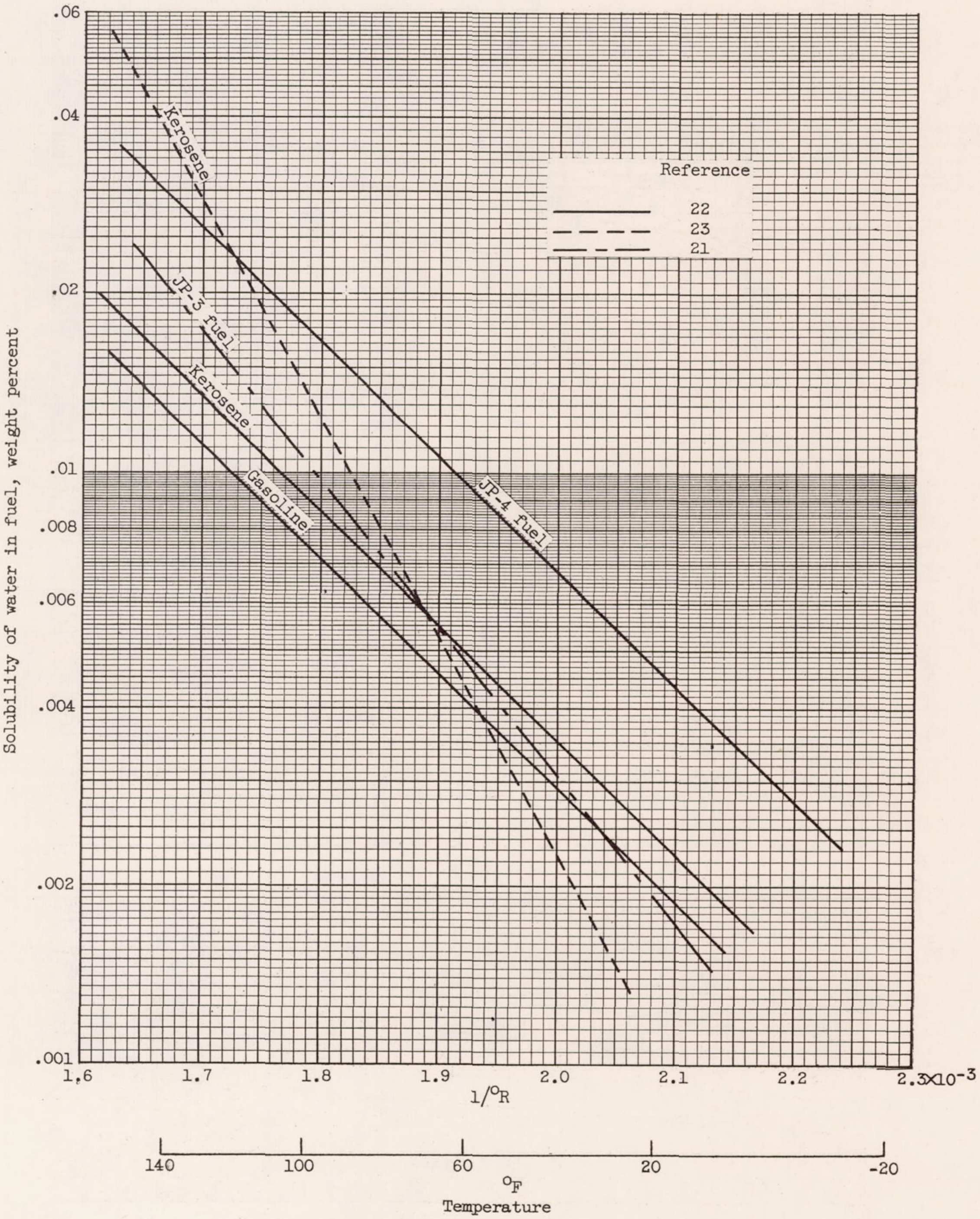


Figure 11. - Water solubility of various fuels.

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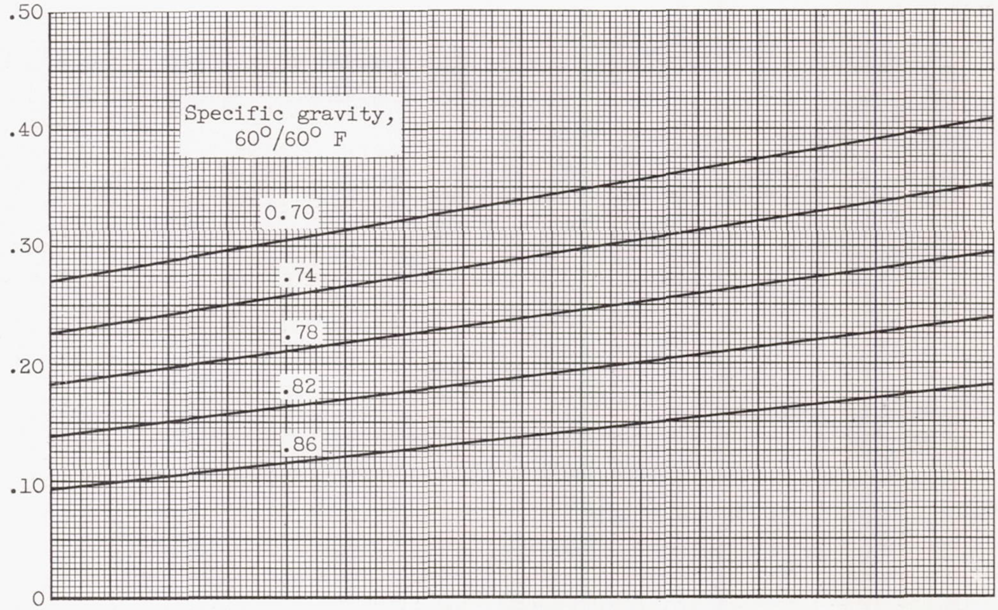
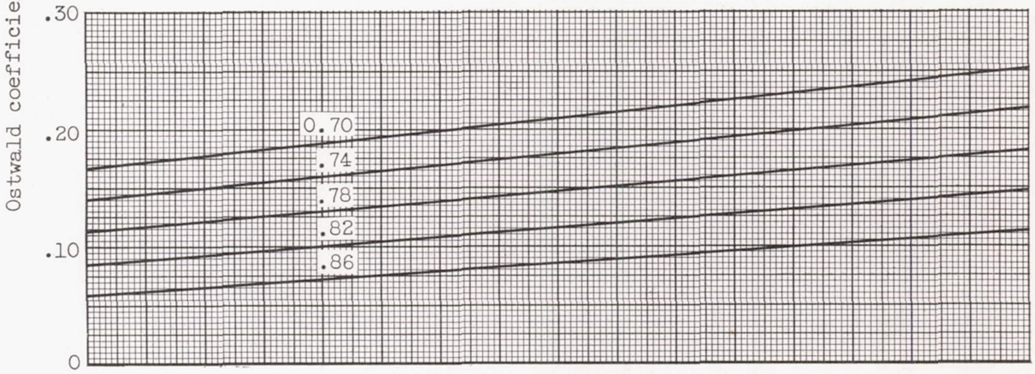
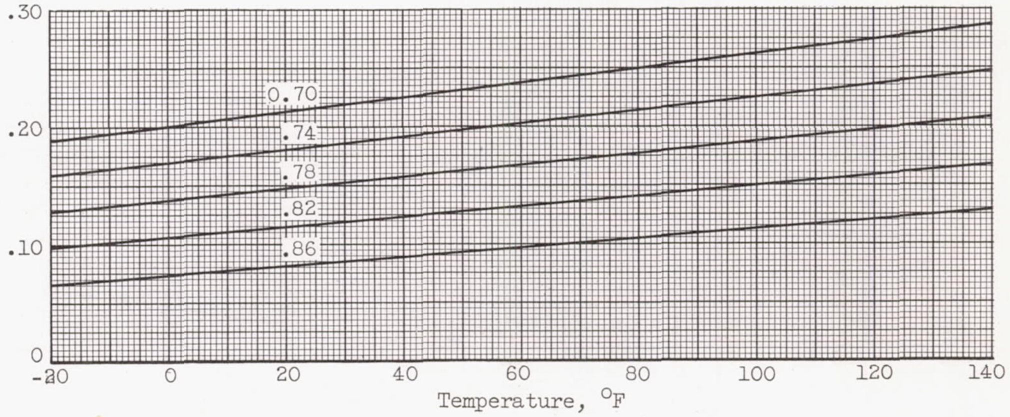


(a) Oxygen

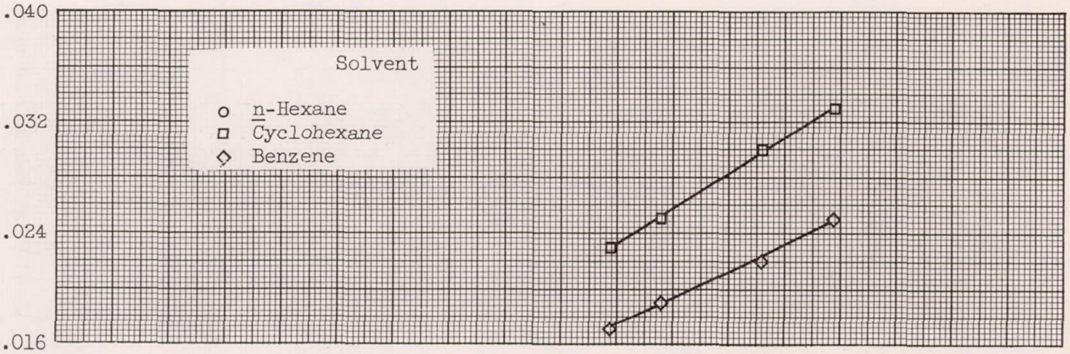


(b) Nitrogen.

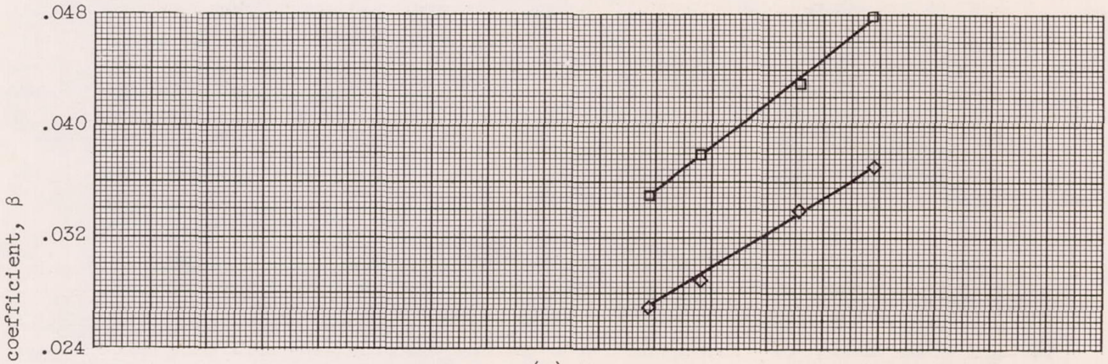


(c) Air.

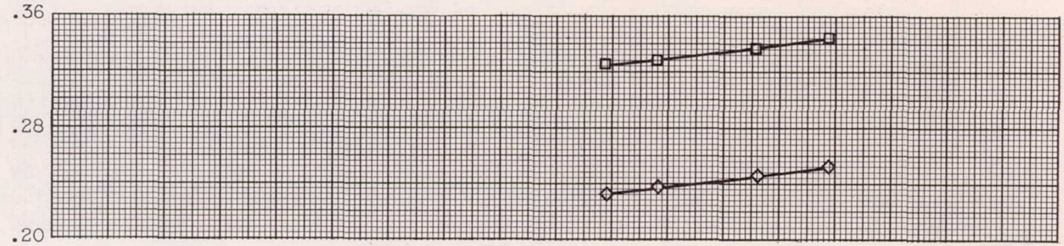
Figure 12. - Ostwald coefficients for estimating solubilities of gases in petroleum fractions.



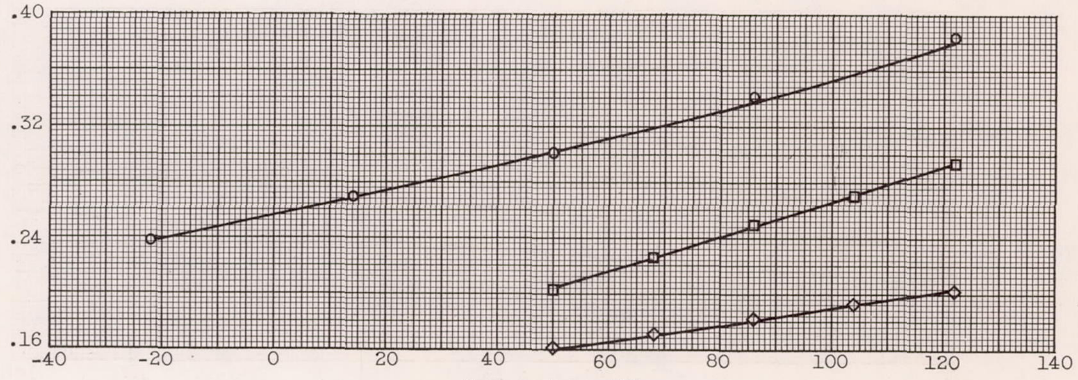
(a) Helium.



(b) Neon.

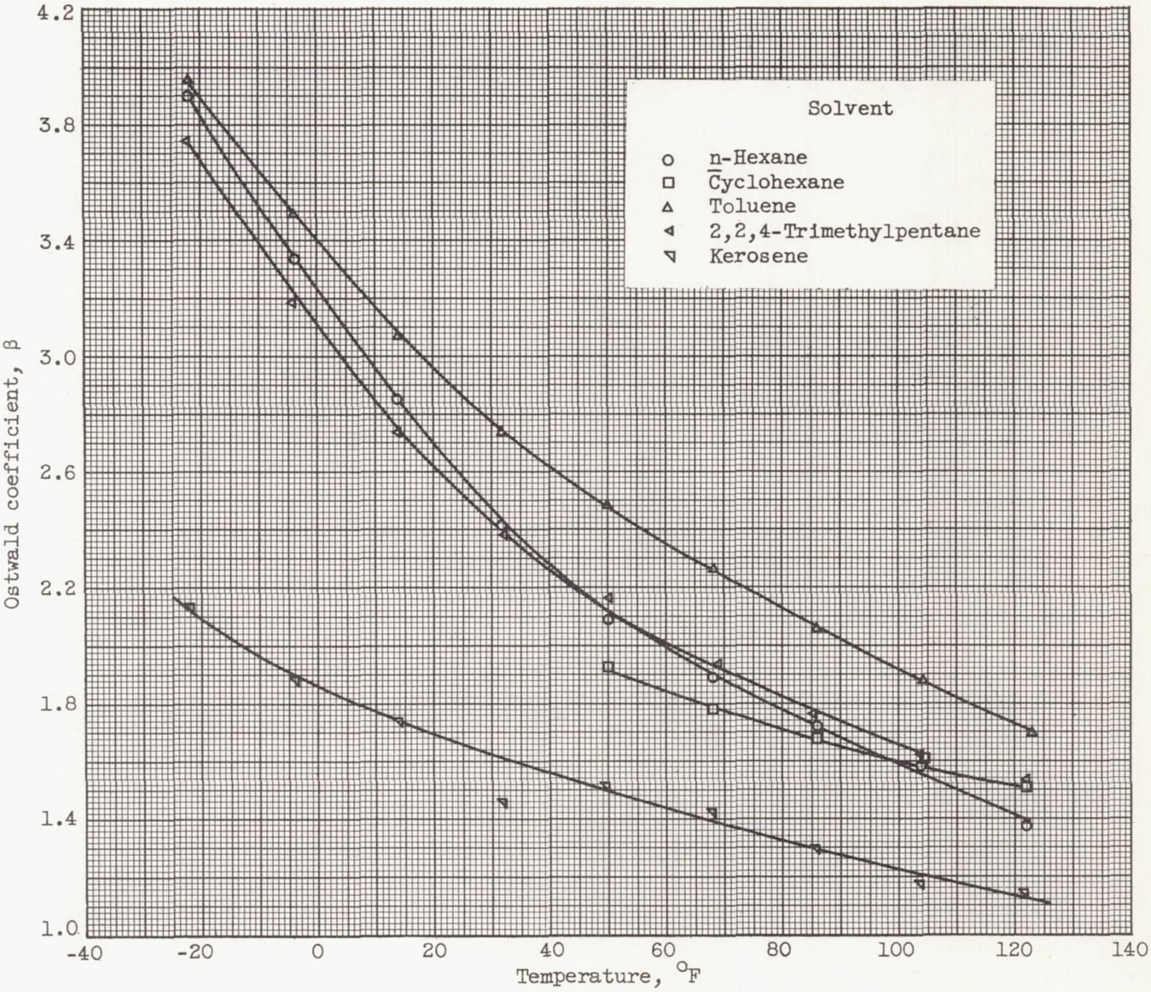


(c) Argon.



(d) Carbon monoxide.

Figure 13. - Ostwald coefficients for gases in hydrocarbon solvents (ref. 25).



(e) Carbon dioxide.

Figure 13. - Concluded. Ostwald coefficients for gases in hydrocarbon solvents (ref. 25).

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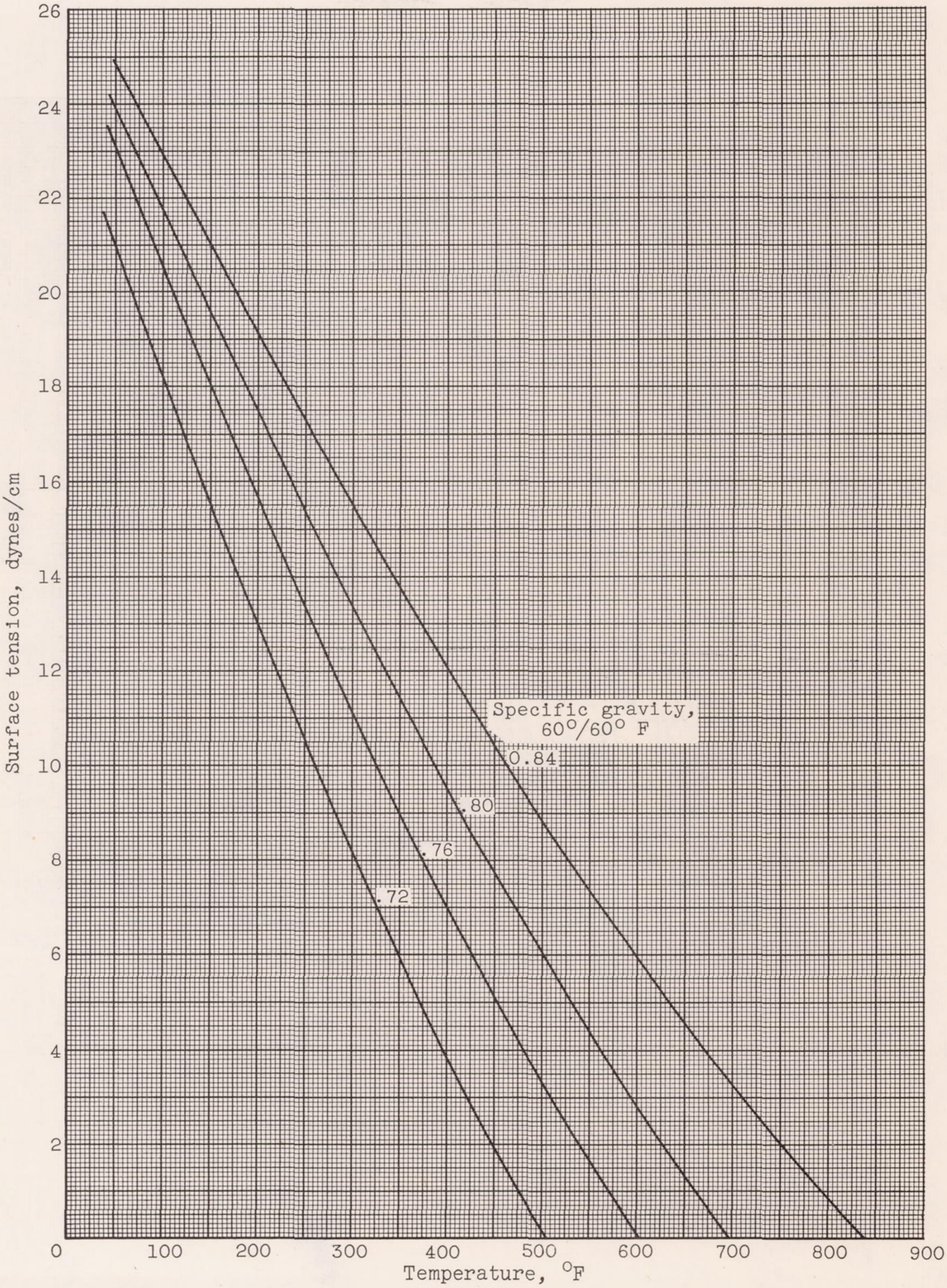
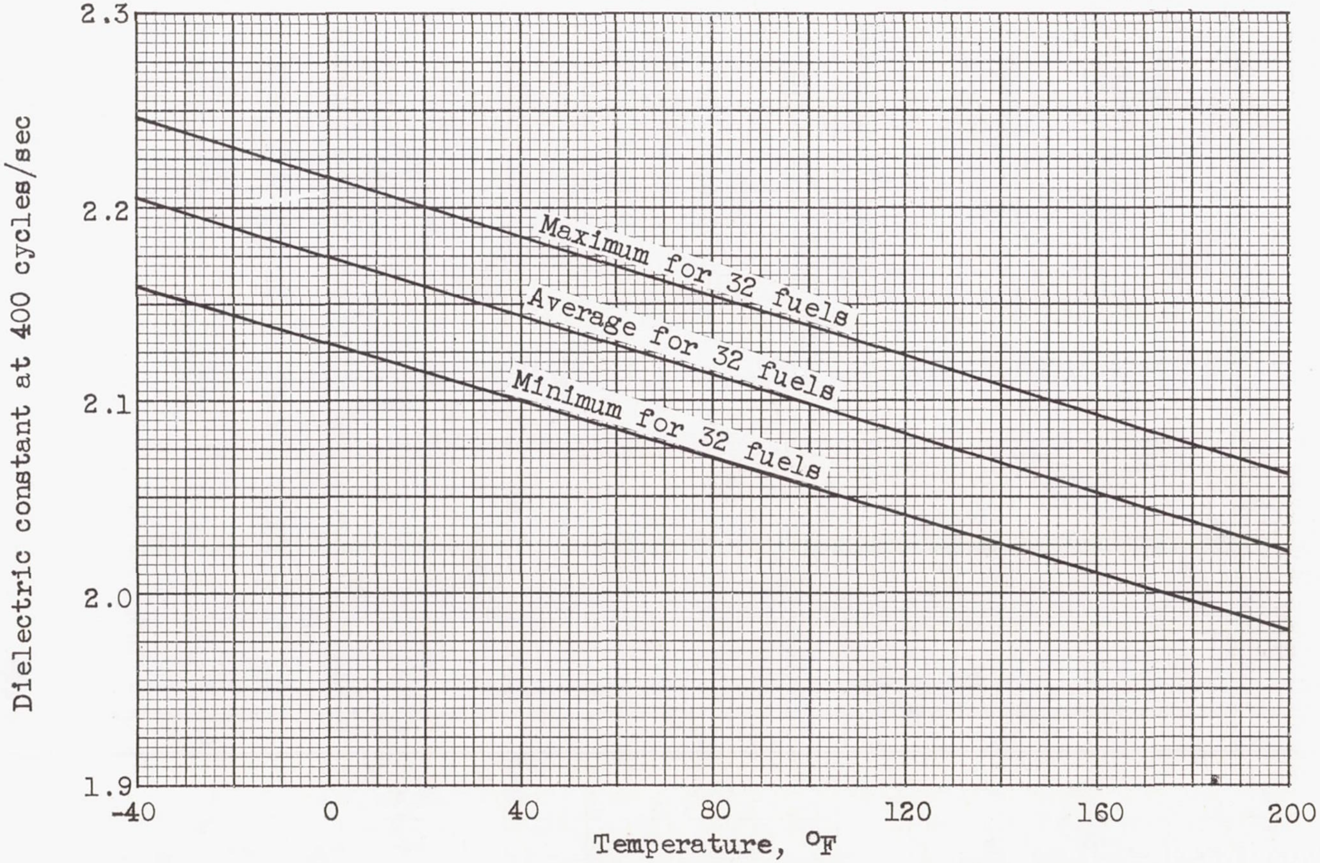
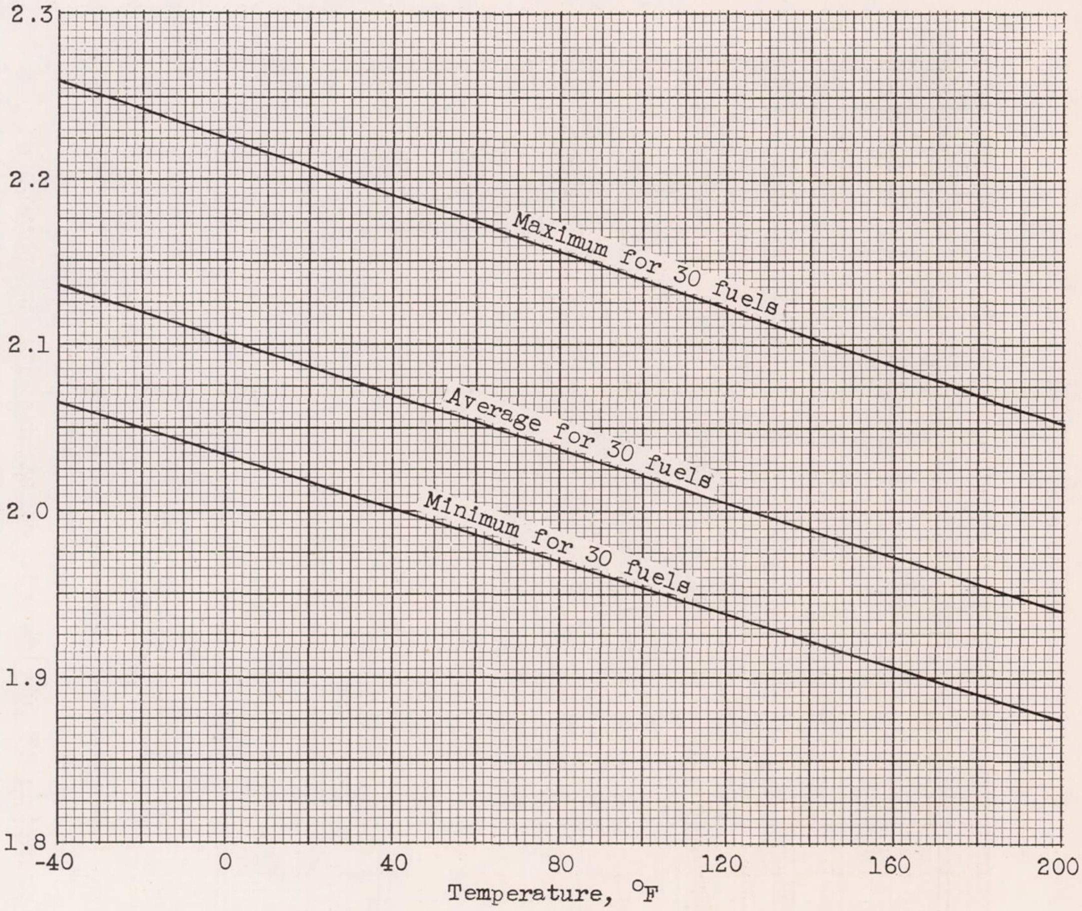


Figure 14. - Surface-tension - temperature relations for hydrocarbon fuels of varying specific gravities.



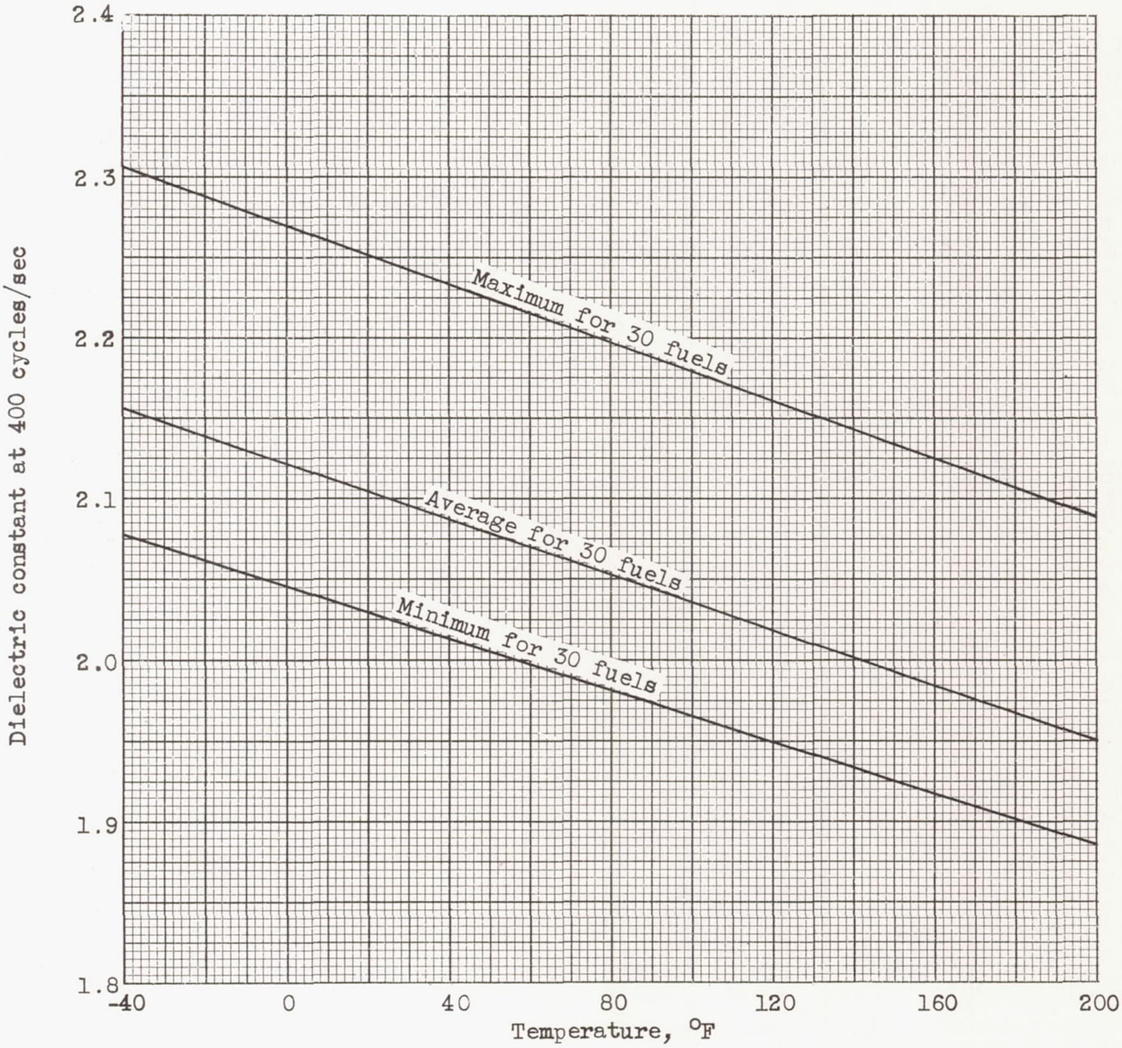
(a) MIL-F-5616 (JP-1) fuel. (Based on data from ref. 28.)

Figure 15. - Variation of dielectric constant with temperature.



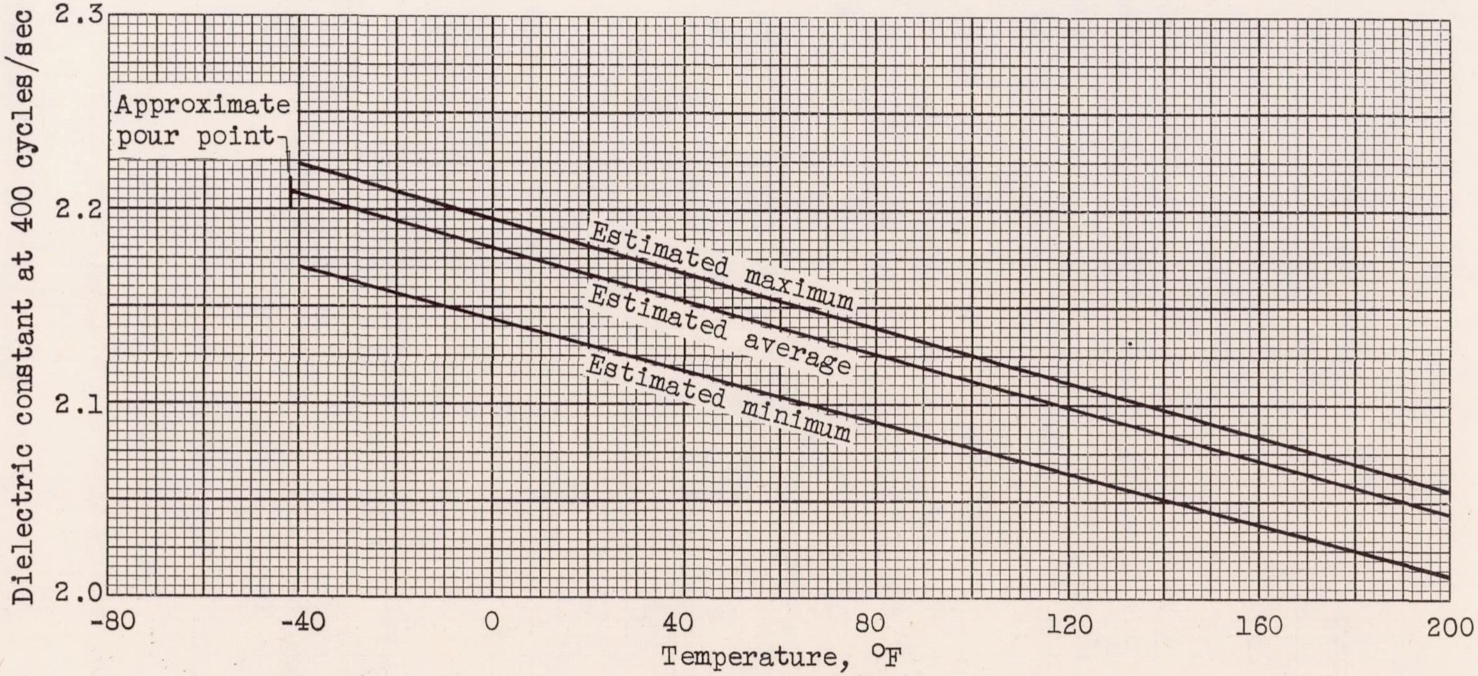
(b) MIL-F-5624C (JP-3) fuel. (Based on data from ref. 28.)

Figure 15. - Continued. Variation of dielectric constant with temperature.



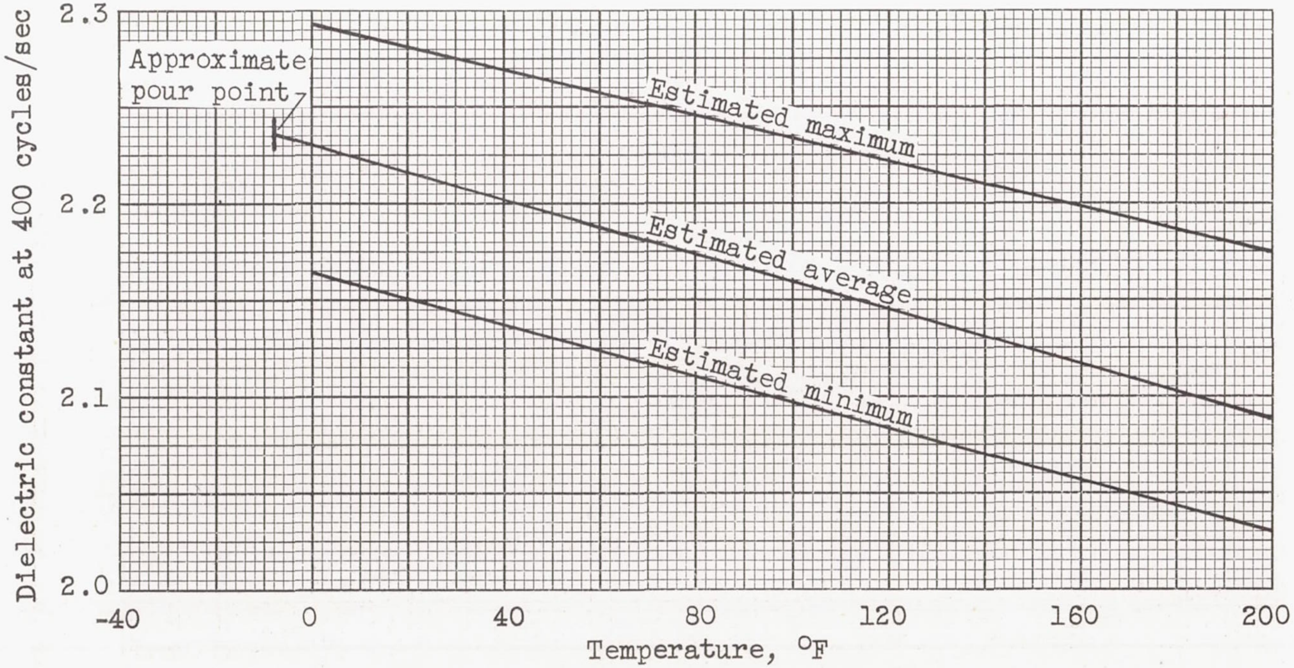
(c) Approximate JP-4 fuels. (Based on data from ref. 28.)

Figure 15. - Continued. Variation of dielectric constant with temperature.



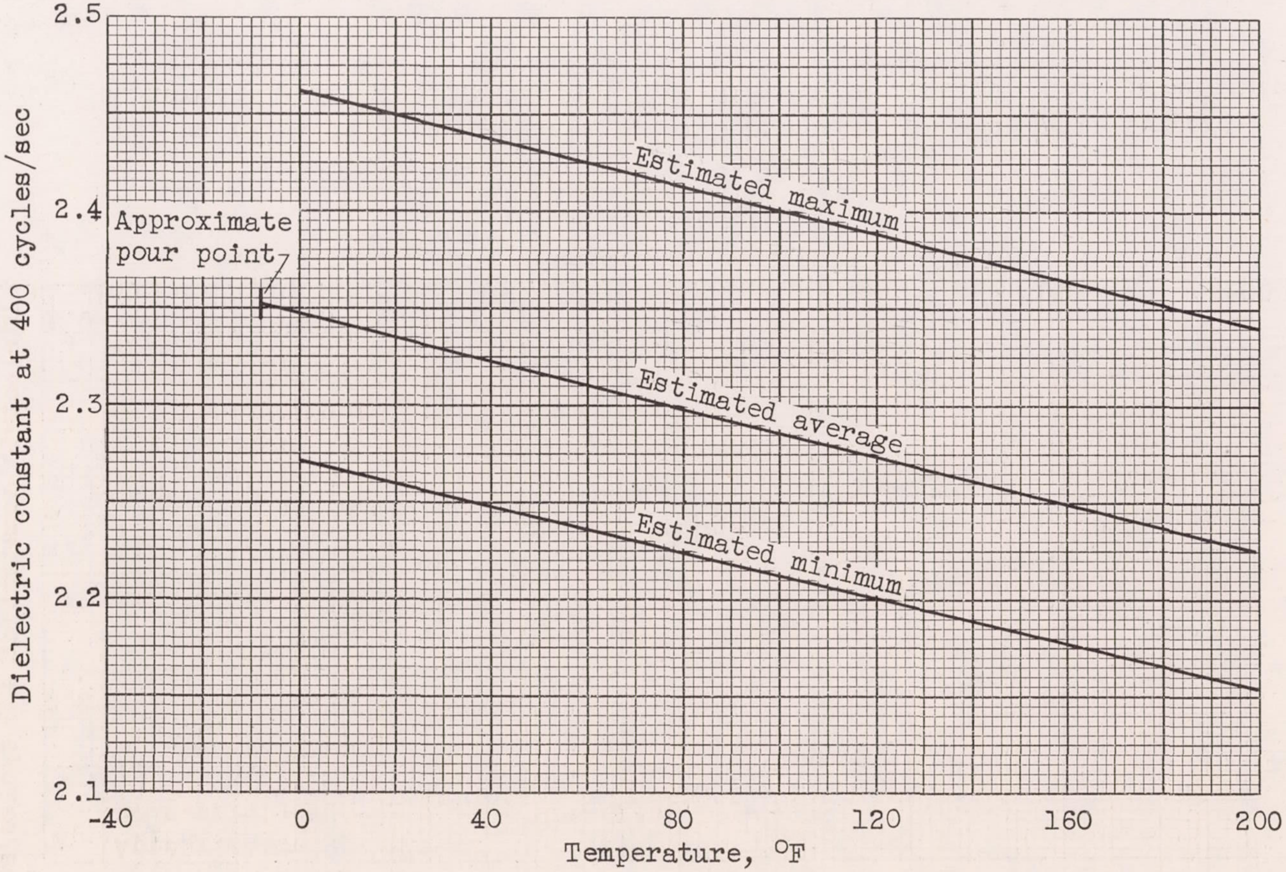
(d) Number 1 fuel oil.

Figure 15. - Continued. Variation of dielectric constant with temperature.



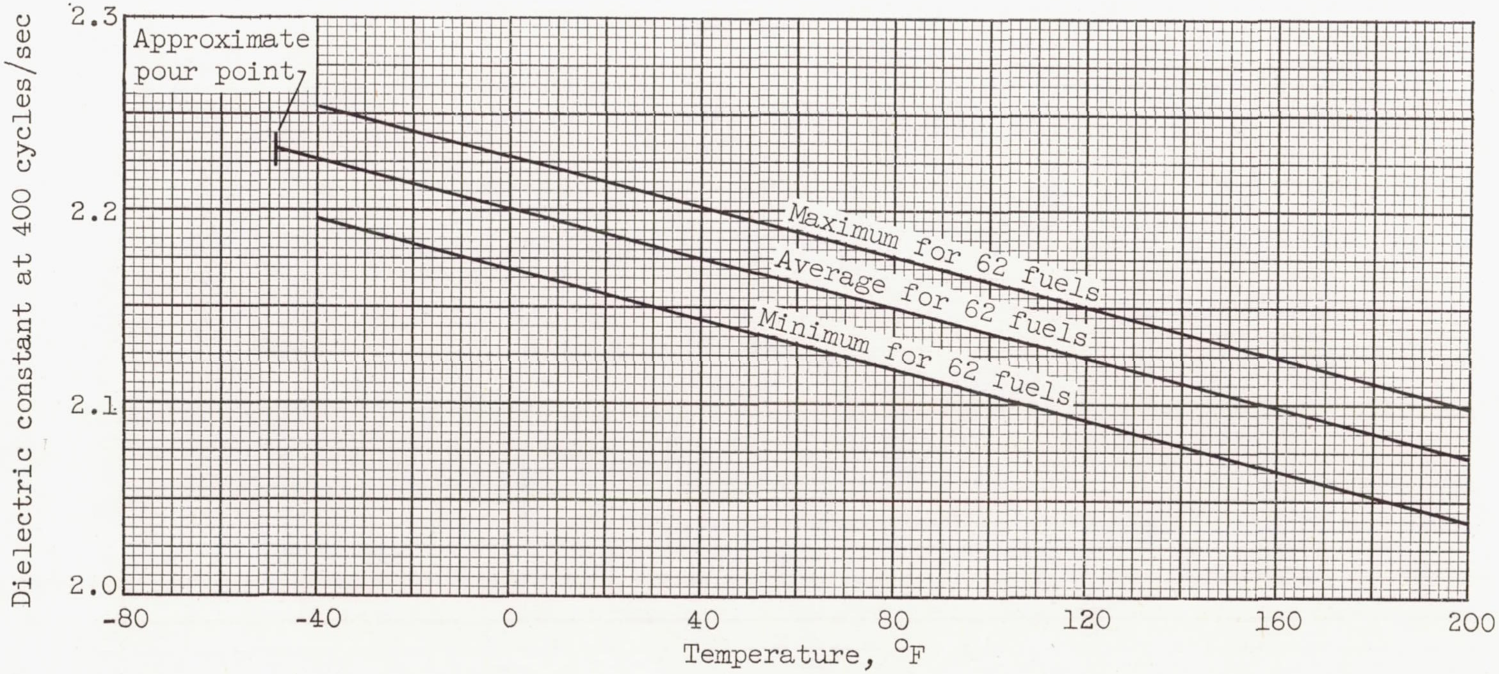
(e) Number 2 fuel oil.

Figure 15. - Continued. Variation of dielectric constant with temperature.



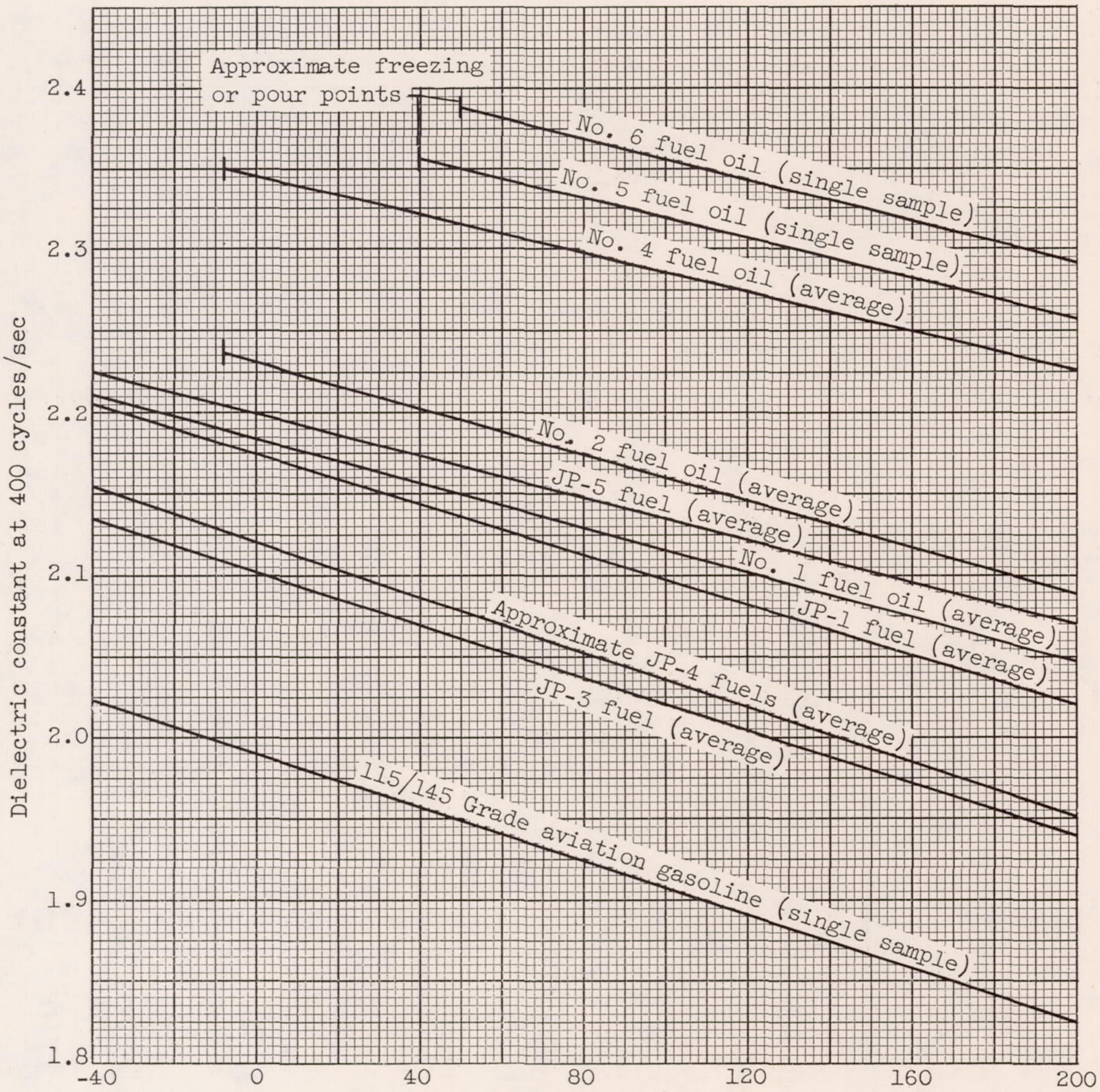
(f) Number 4 fuel oil.

Figure 15. - Continued. Variation of dielectric constant with temperature.



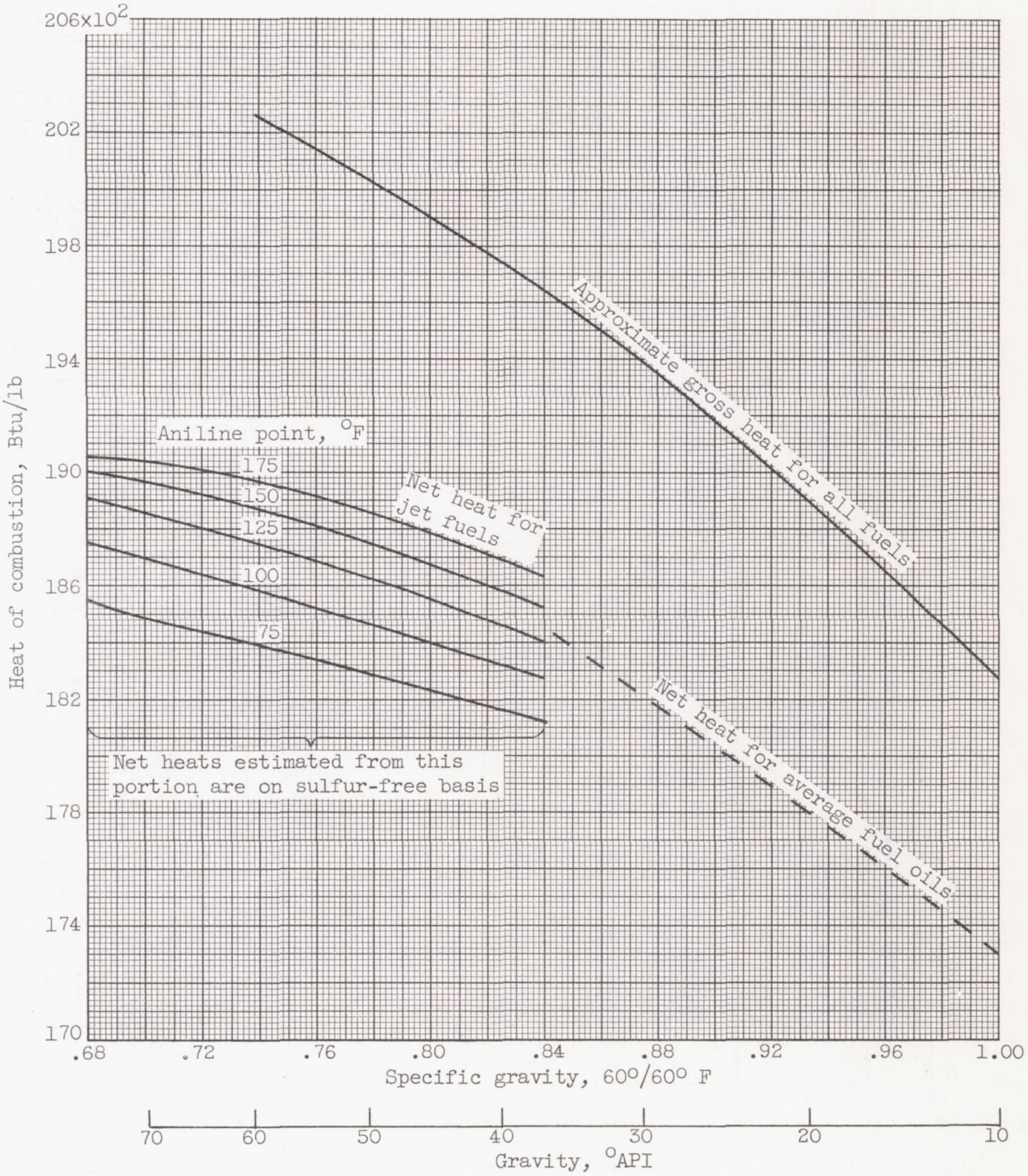
(g) MIL-F-5624C (JP-5) fuel.

Figure 15. - Continued. Variation of dielectric constant with temperature.



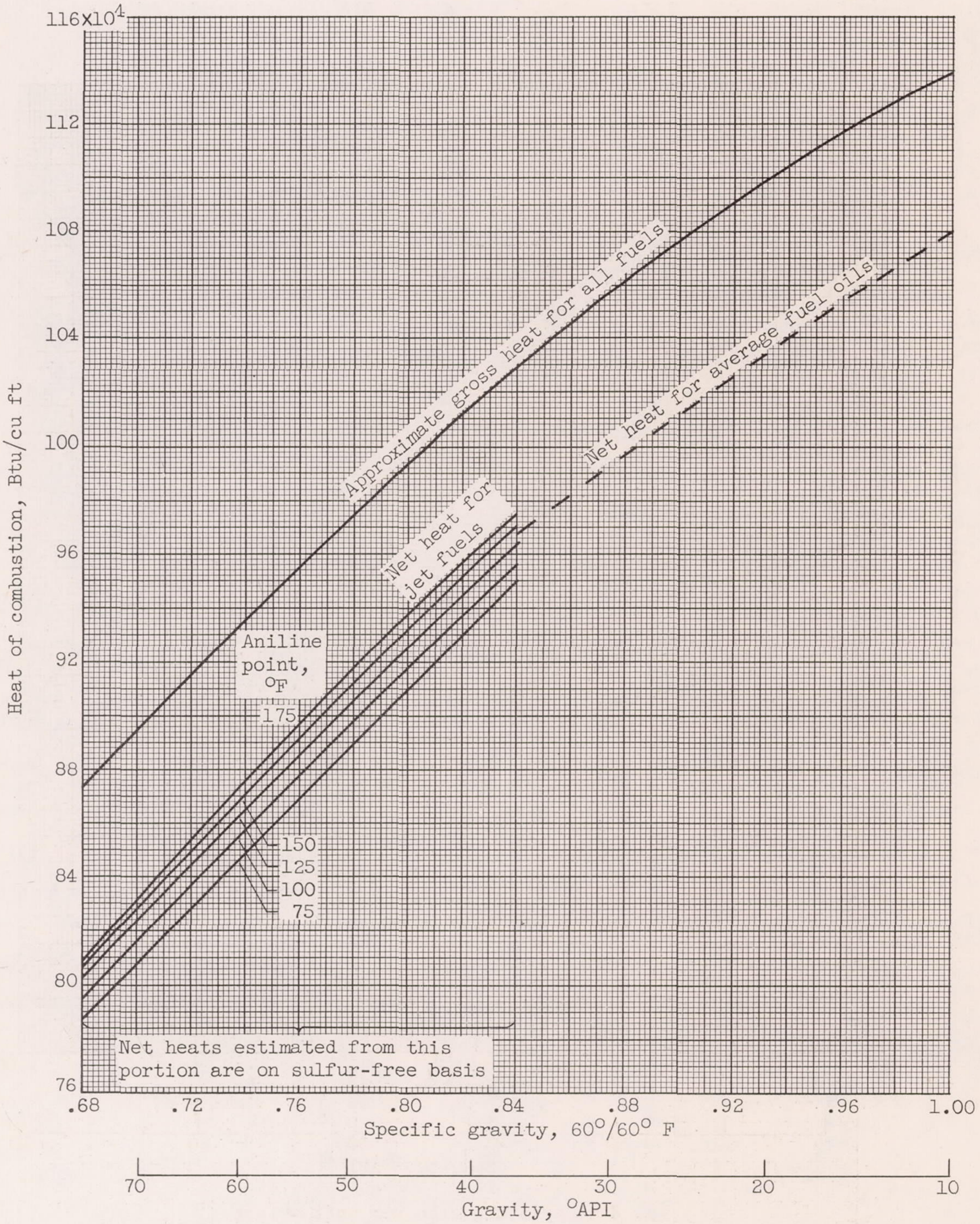
(h) Comparison of fuels.

Figure 15. - Concluded. Variation of dielectric constant with temperature.



(a) Heat of combustion per unit weight.

Figure 16. - Relation among heat of combustion, specific gravity, and aniline point for hydrocarbon fuels. (Based on refs. 1 and 32.)



(b) Heat of combustion per unit volume.

Figure 16. - Concluded. Relation among heat of combustion, specific gravity, and aniline point for hydrocarbon fuels. (Based on refs. 1 and 32.)

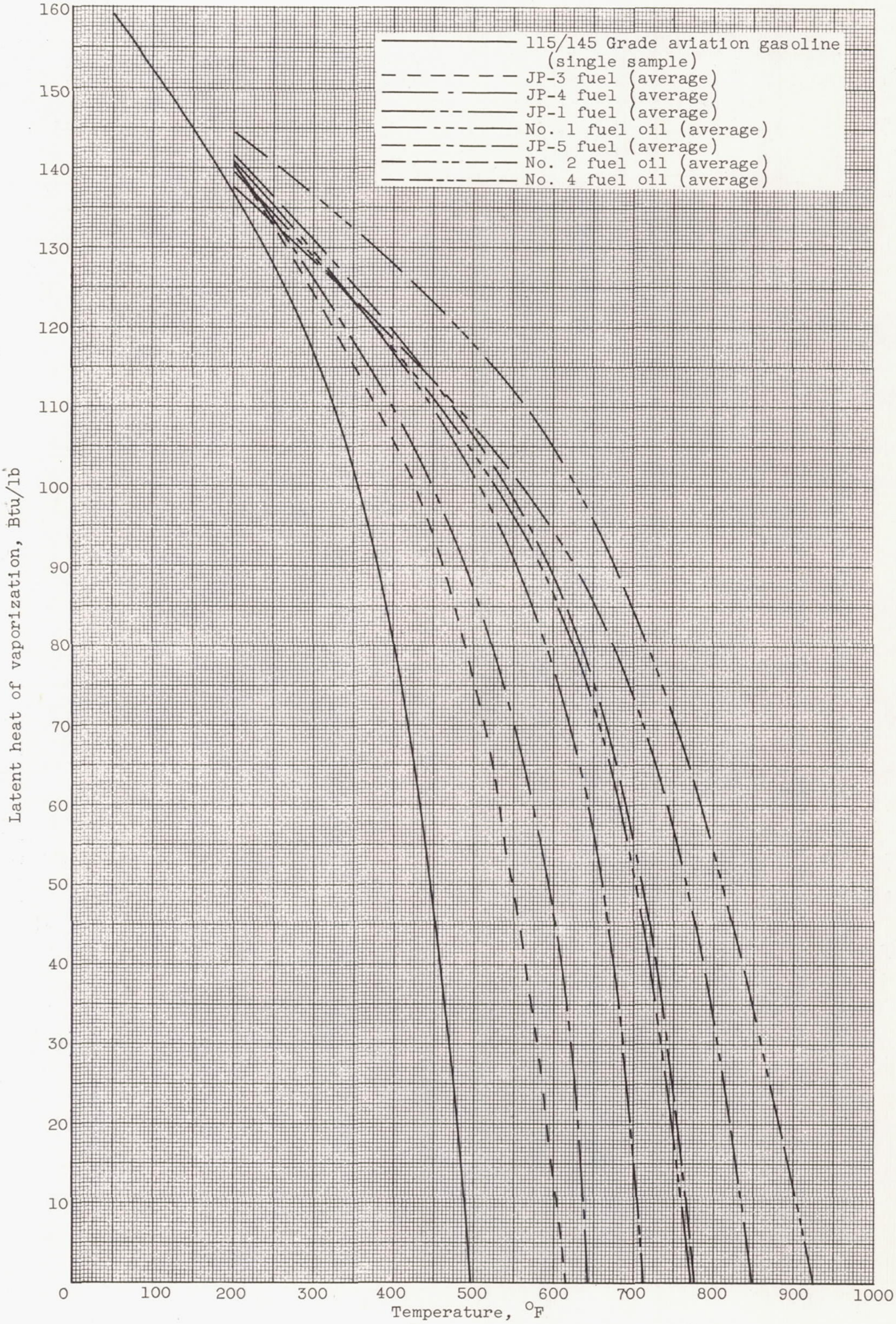


Figure 17. - Variation of latent heat of vaporization with temperature.

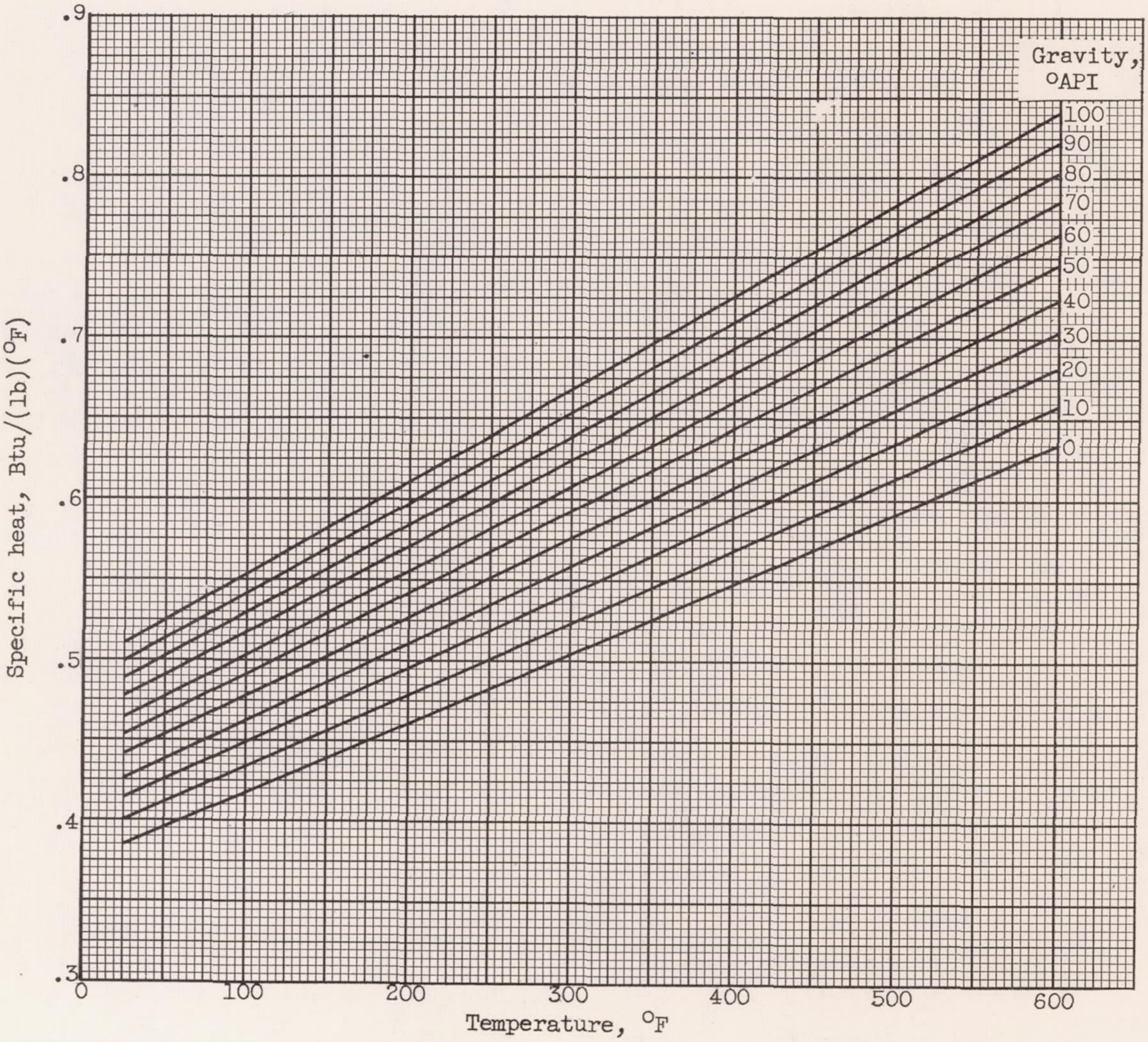
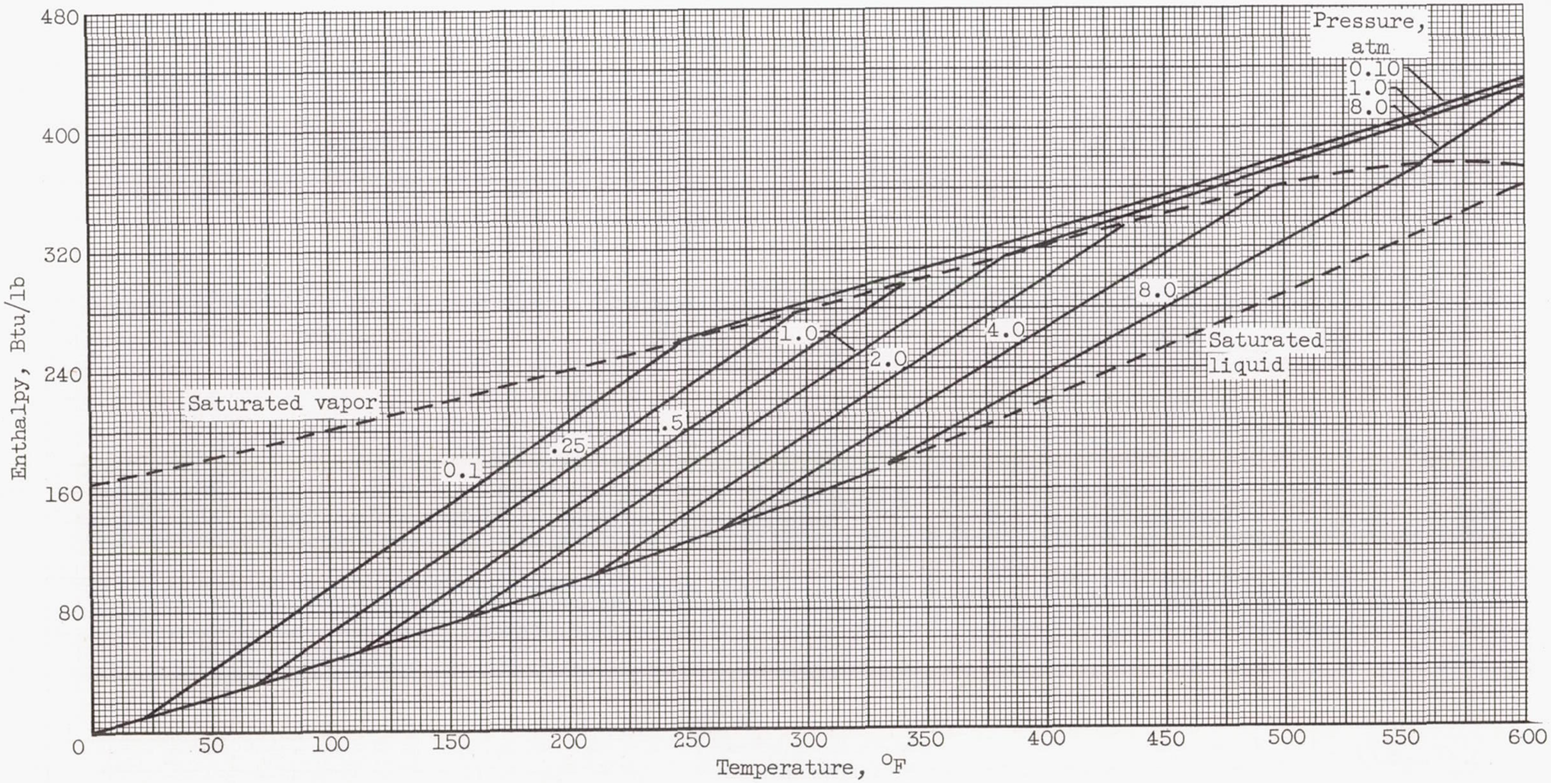
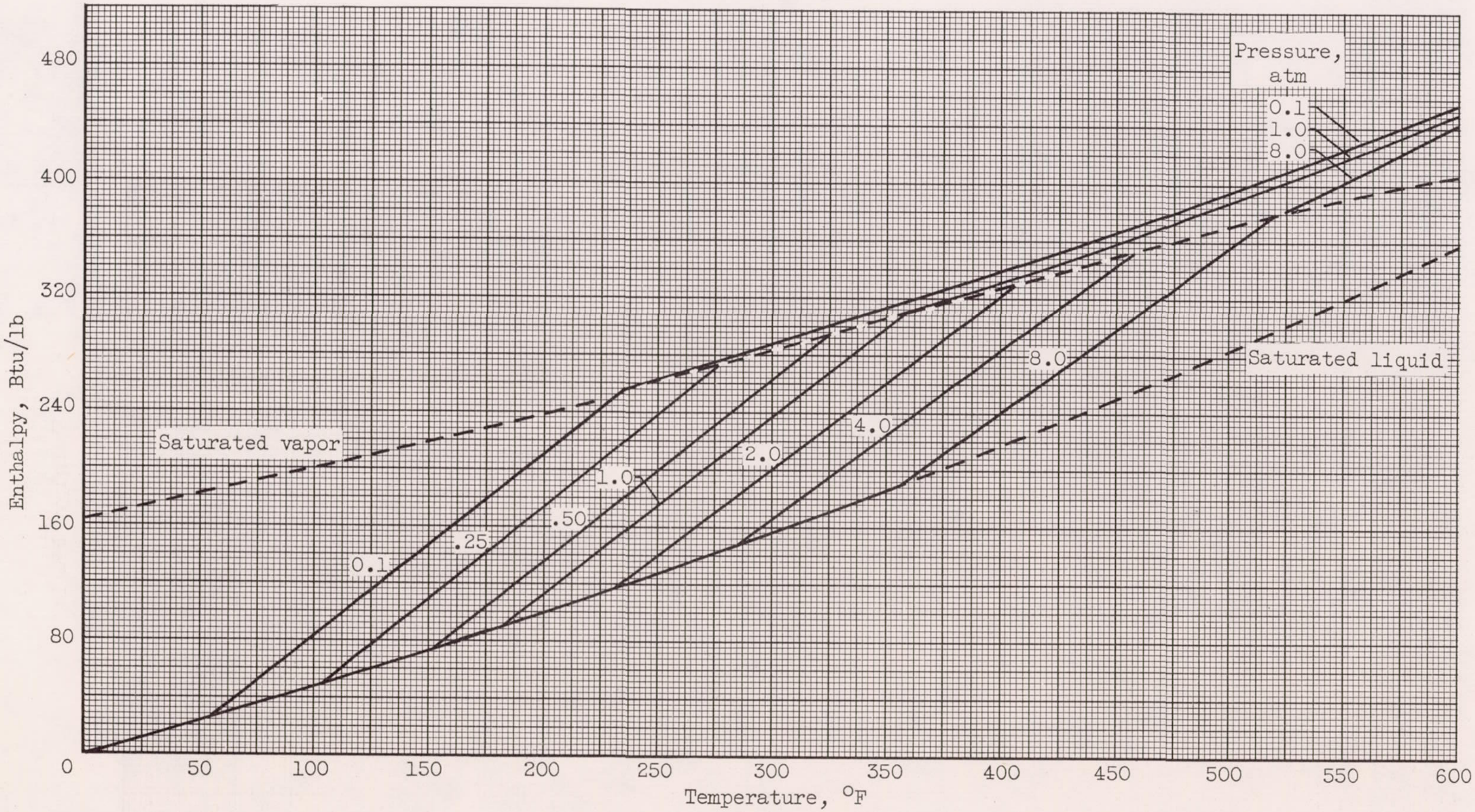


Figure 18. - Specific heats of petroleum fuels having characterization factors between 11.3 and 11.7 (based on ref. 33).



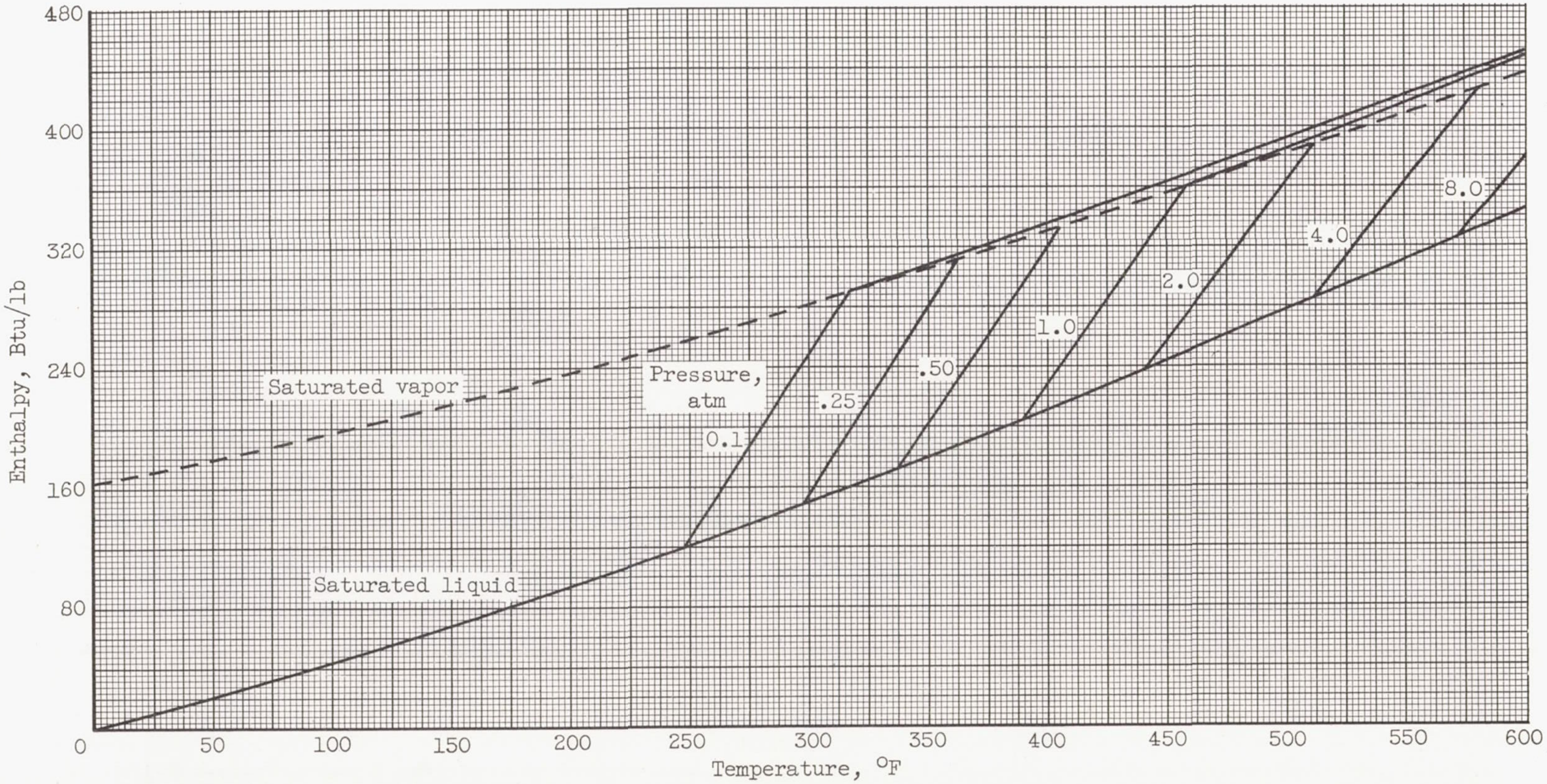
(a) JP-3 fuel.

Figure 19. - Enthalpy diagrams for average-quality jet fuels.



(b) JP-4 fuel.

Figure 19. - Continued. Enthalpy diagrams for average-quality jet fuels.



(c) JP-5 fuel.

Figure 19. - Concluded. Enthalpy diagrams for average-quality jet fuels.

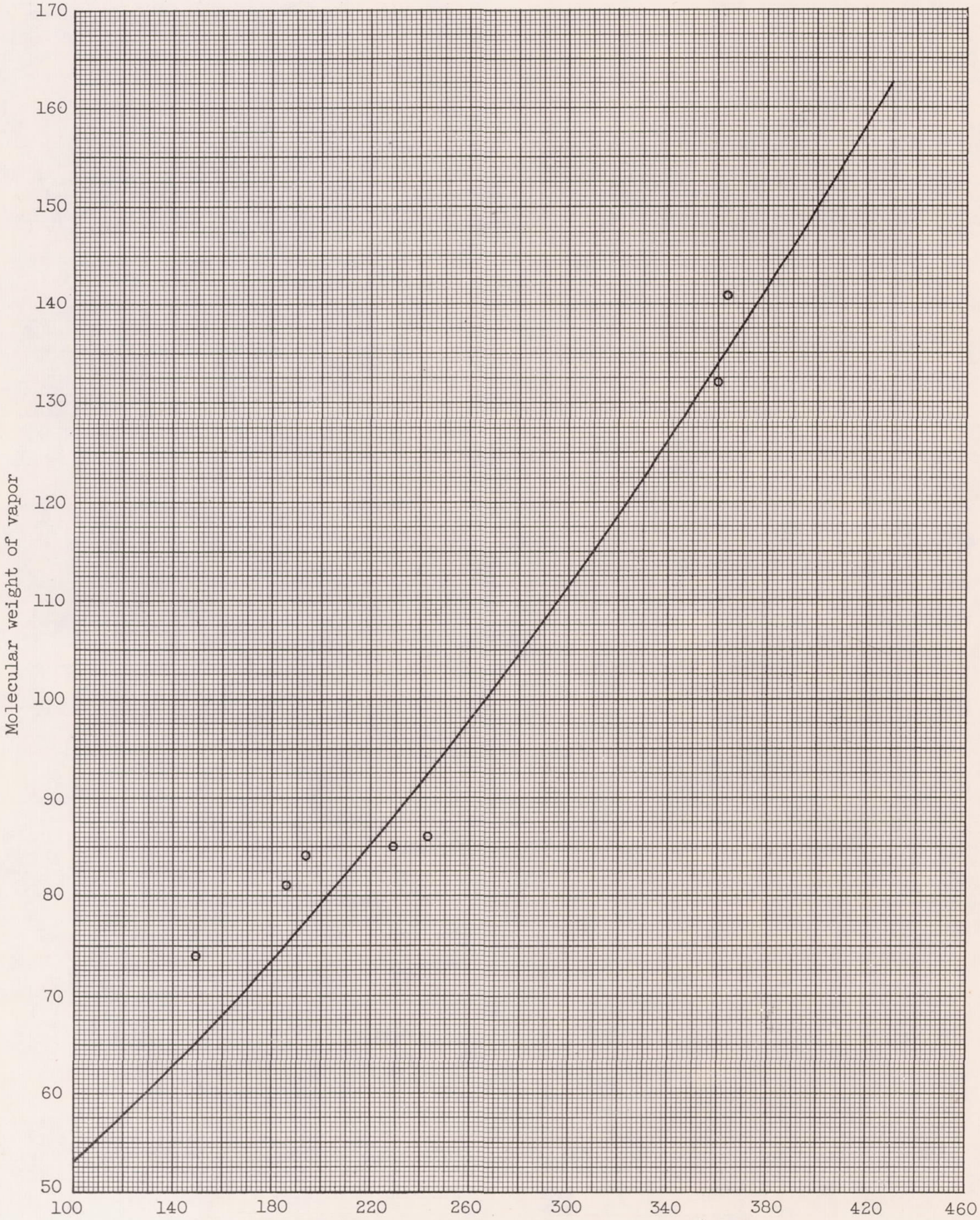


Figure 20. - Molecular weight of vapor from slightly vaporized fuel as a function of 10-percent distillation temperature. (Line taken from ref. 37; points from ref. 12 at 2-percent evaporation.)

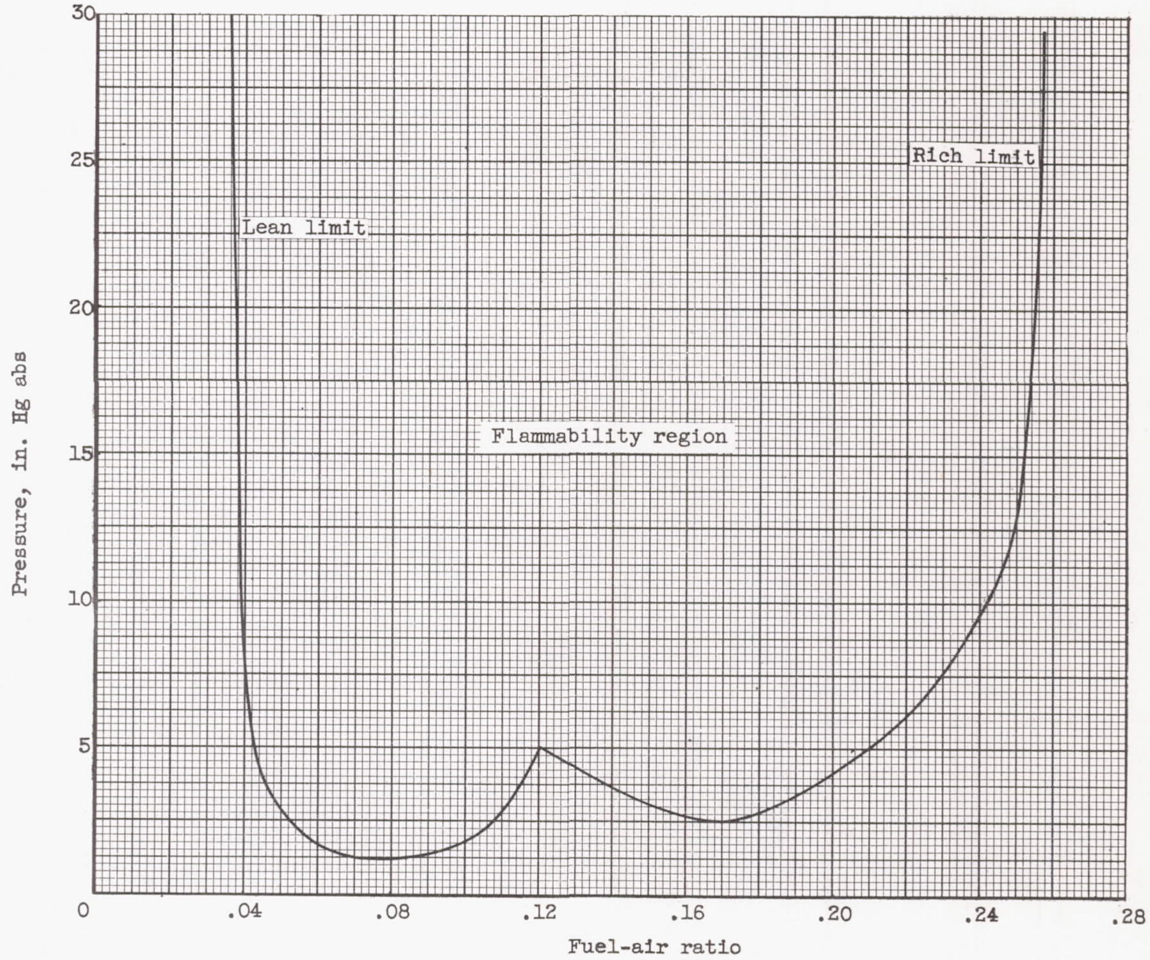


Figure 21. - Flammability limits of n-hexane in air as determined in a 2-inch tube with vertical propagation.

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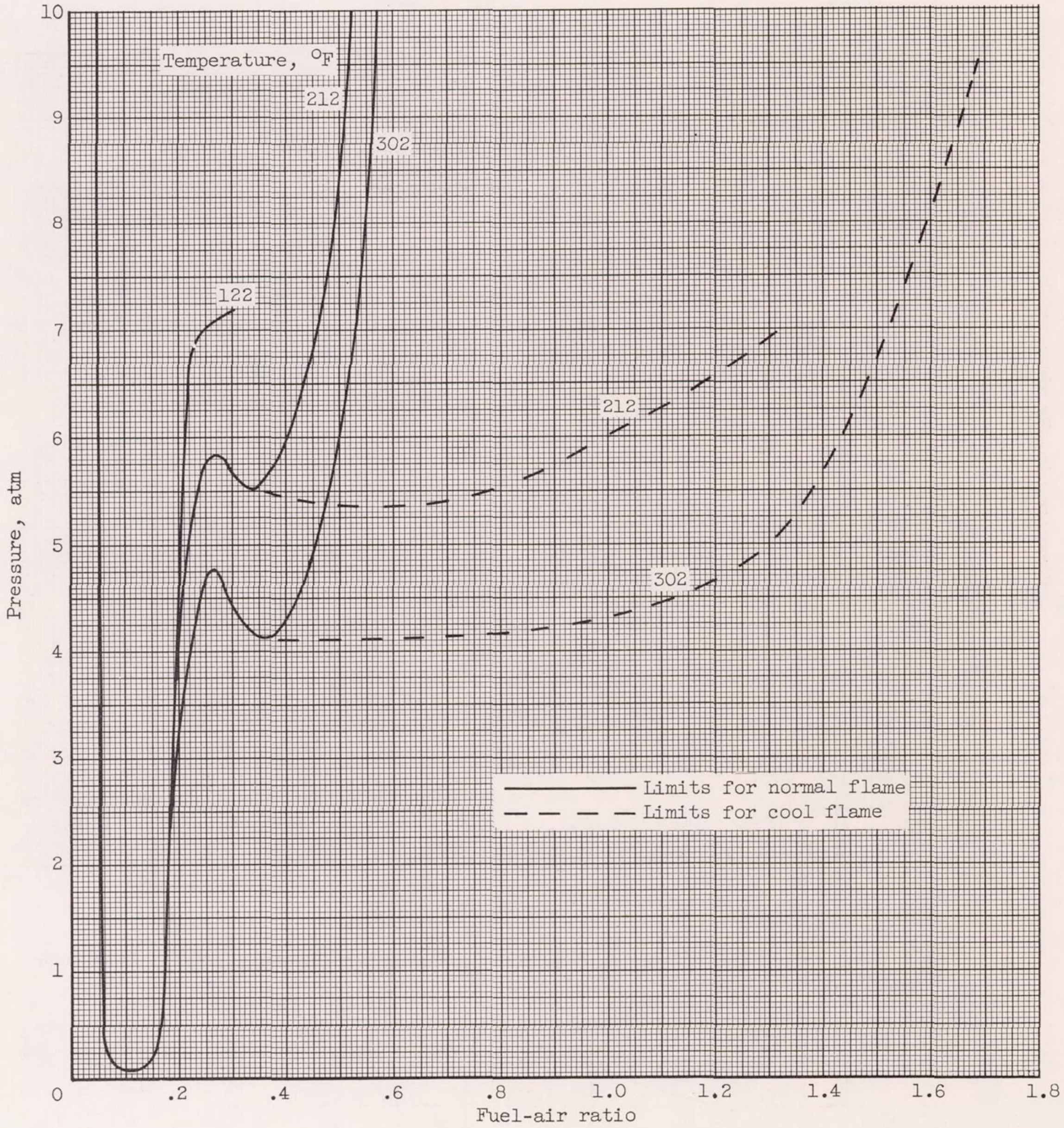


Figure 22. - Flammability limits for n-hexane at pressures between 0 and 10 atmospheres with horizontal propagation (ref. 39).

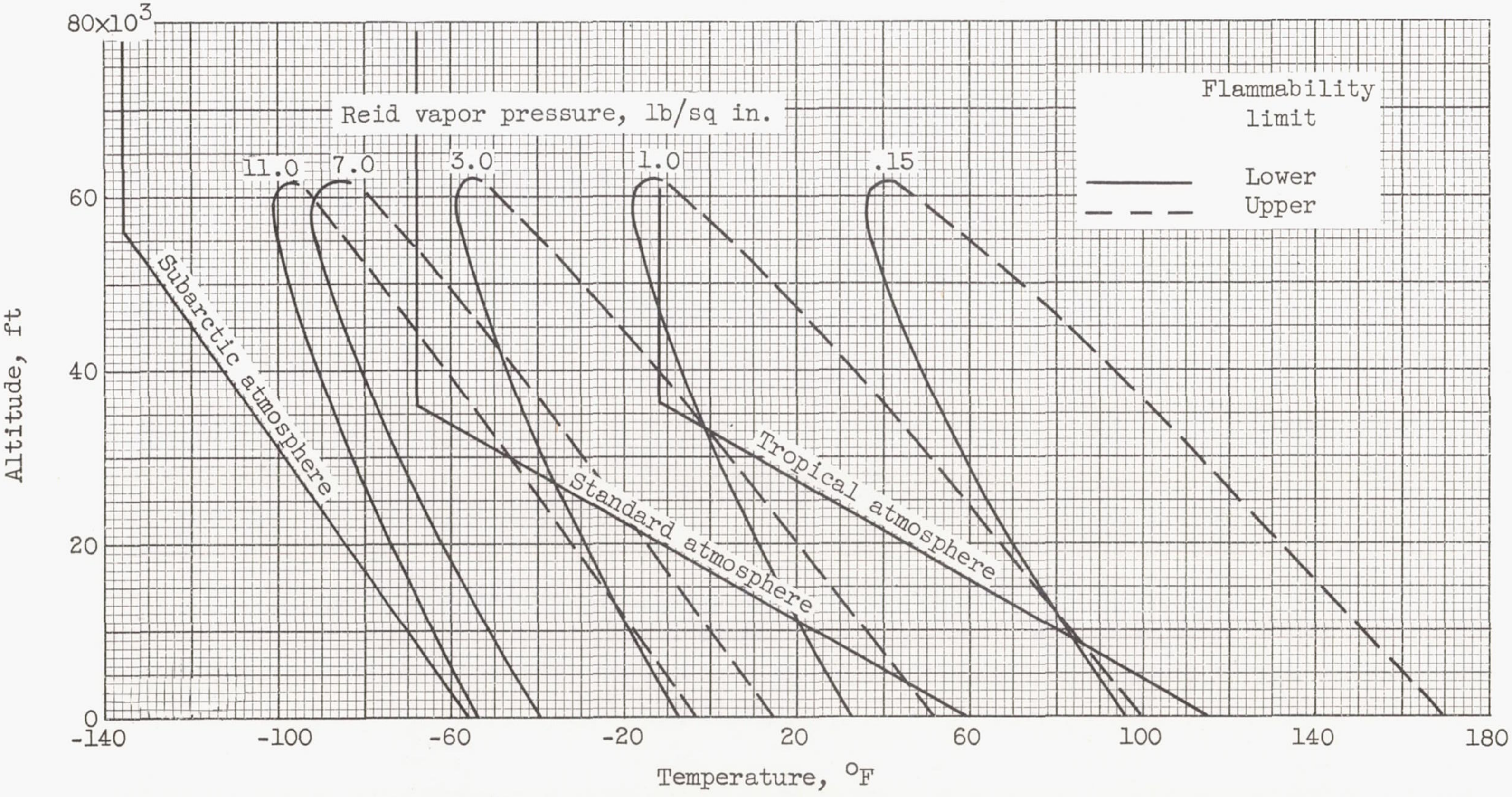


Figure 23. - Altitude-temperature flammability limits for fuels of varying vapor pressure (data from refs. 2 and 16).

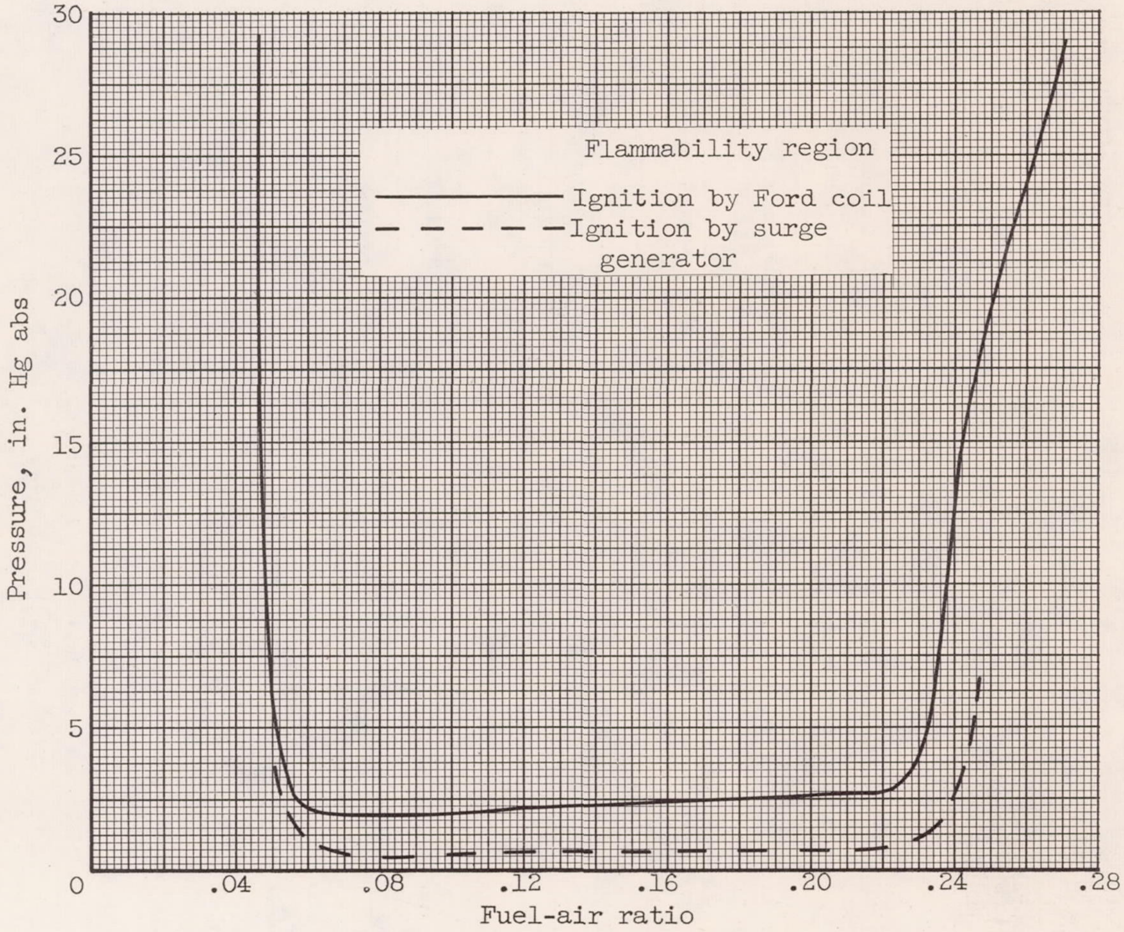
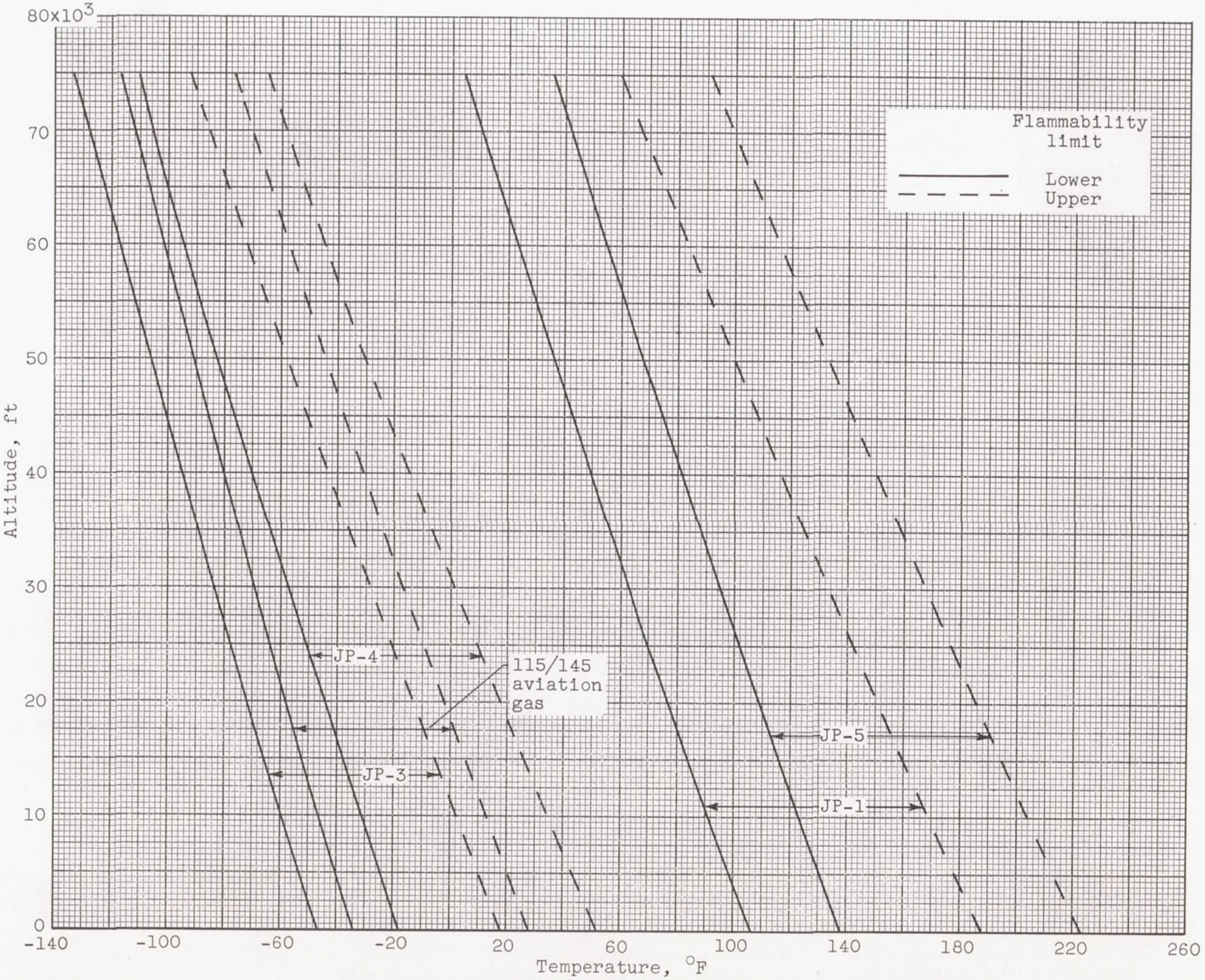
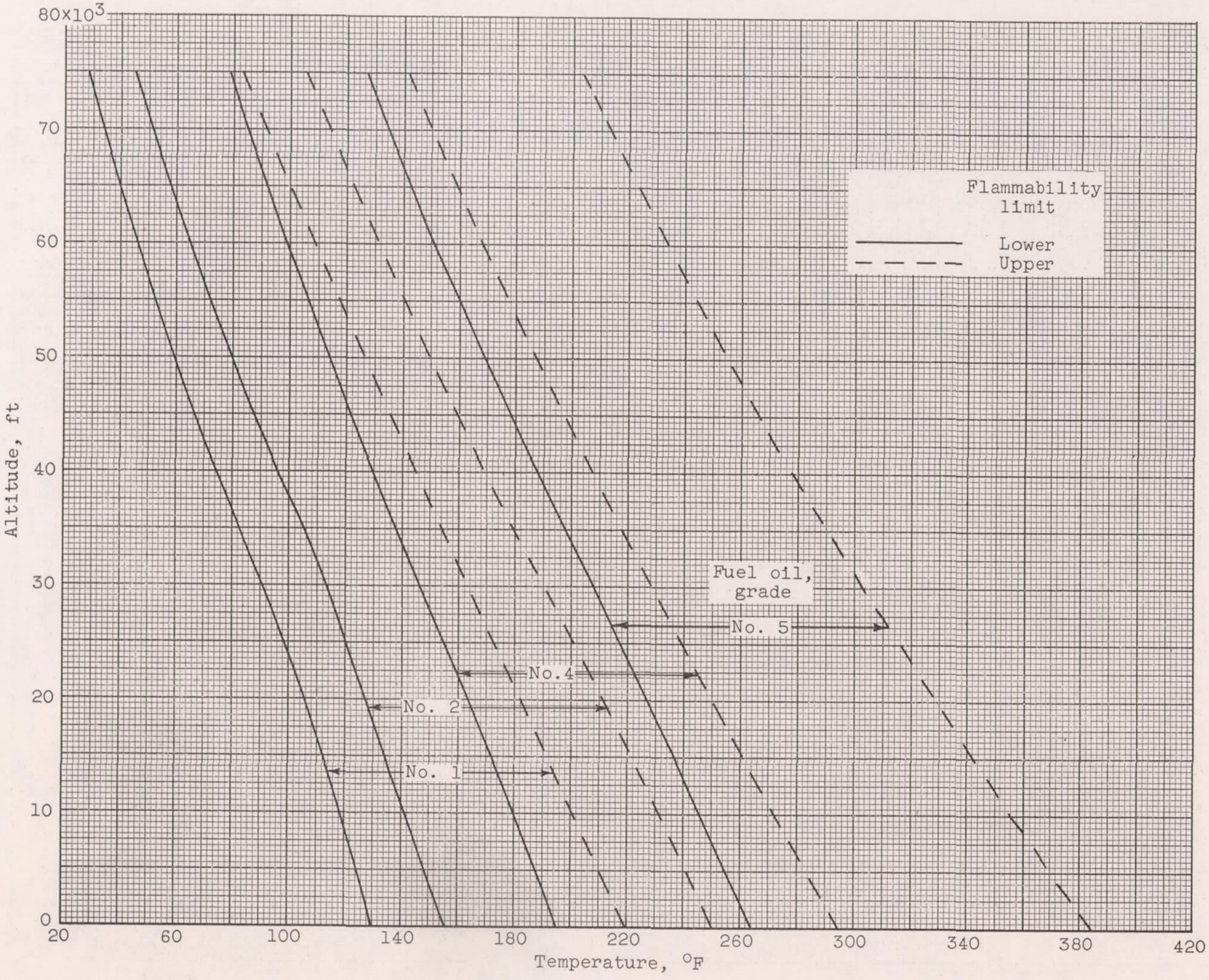


Figure 24. - Flammability limits of 100/130 octane aviation gasoline (ref. 36).



(a) Aviation gasoline and average-quality JP fuels.

Figure 25. - Altitude-temperature flammability limits for various fuels.



(b) Average-quality fuel oils of varying grades.

Figure 25. - Concluded. Altitude-temperature flammability limits for various fuels.

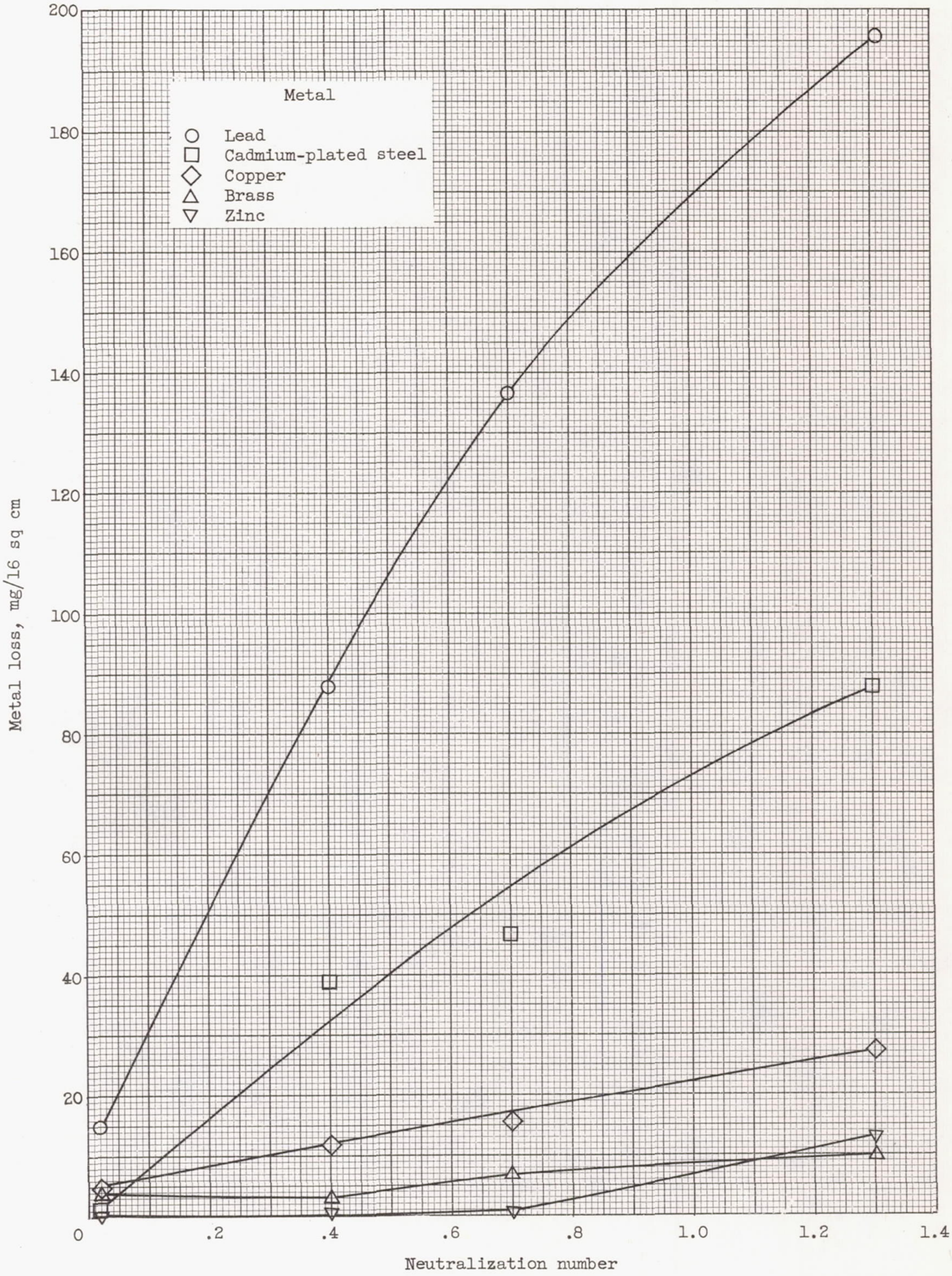


Figure 26. - Relation of acidity to corrosive effect of JP-3 jet-engine fuel. (Data from ref. 46.) Corrosion determined by 48-hour air-well test, Federal Test Method VV-L-791d.

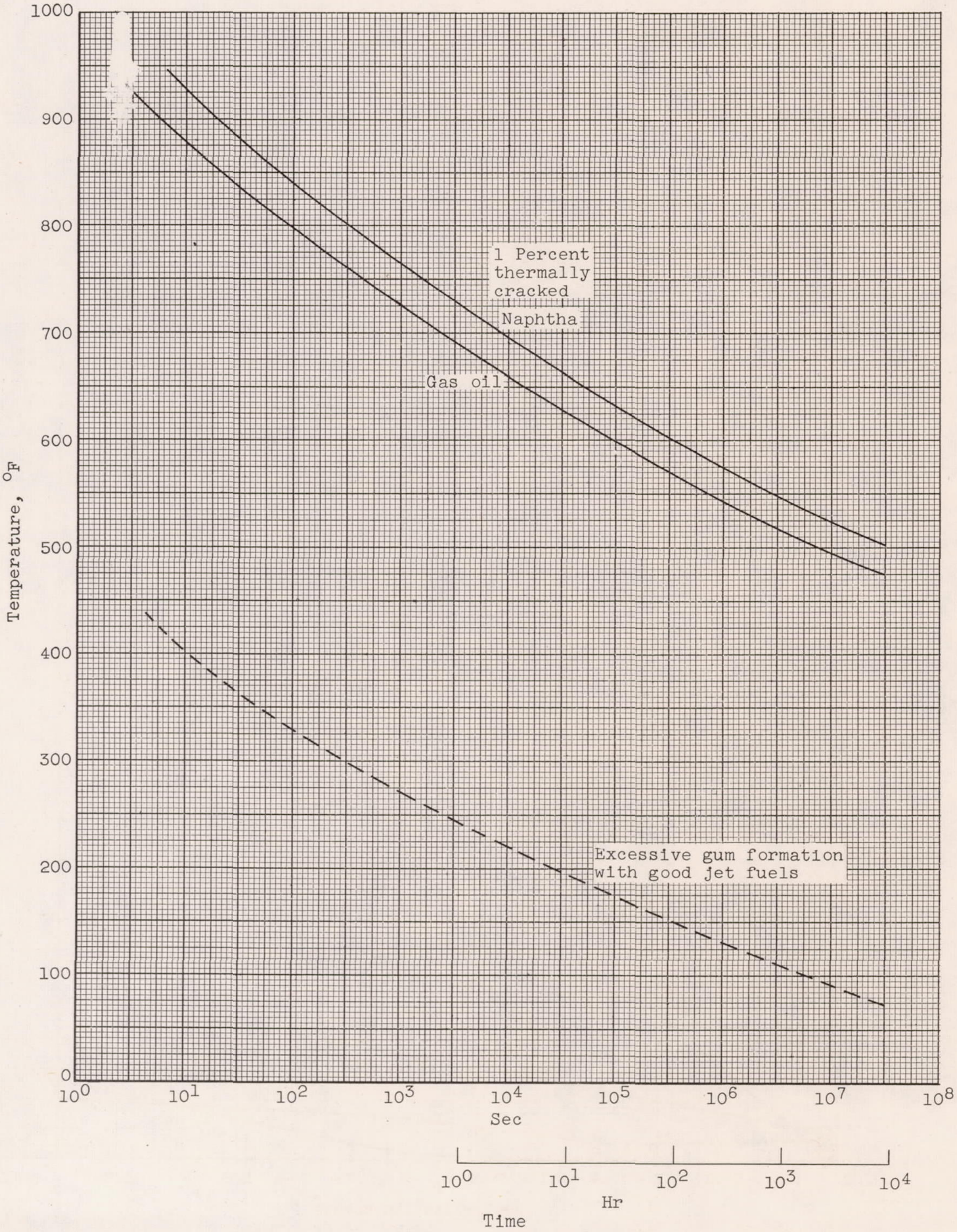


Figure 27. - Examples of interdependence of temperature and time in hydrocarbon reactions.

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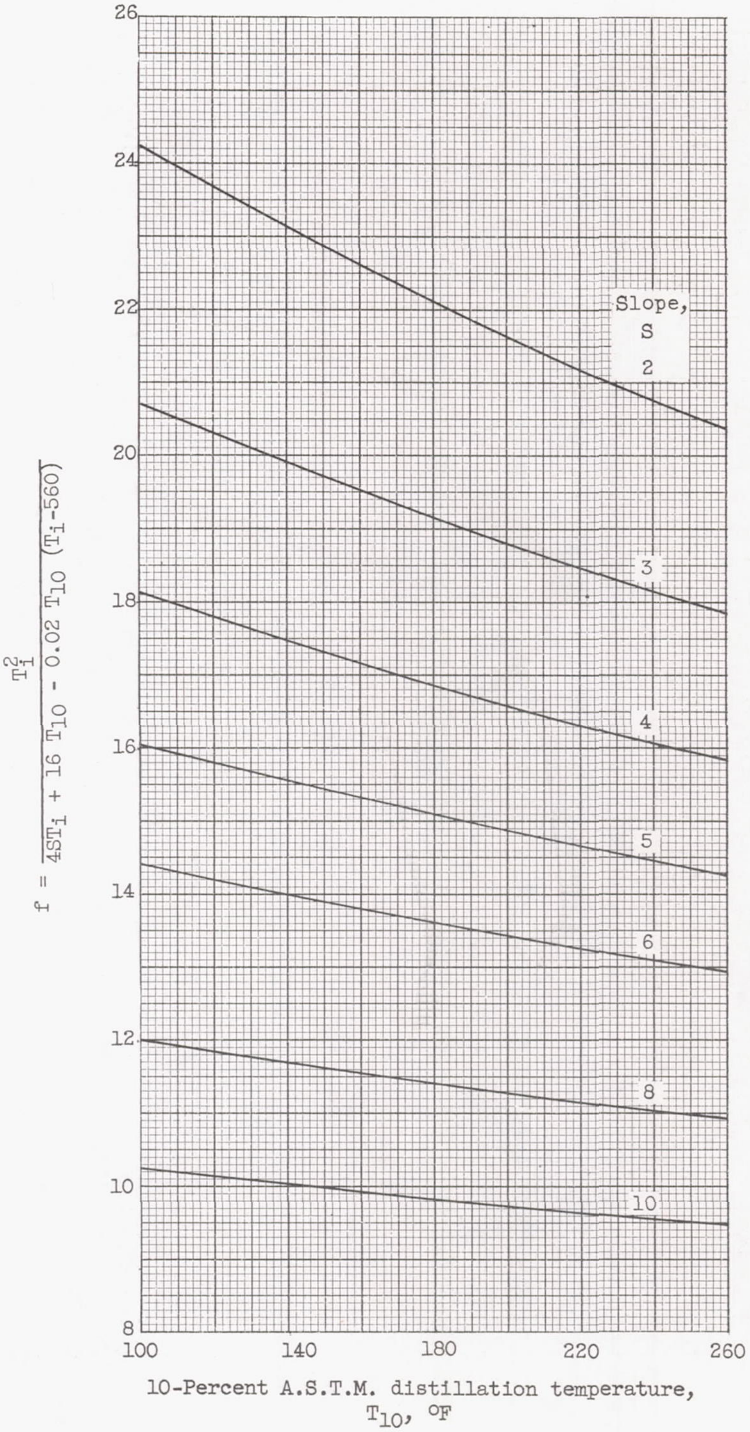


Figure 28. - Variation of f with T_{10}. This chart applies for data for initial fuel temperature of 110° F. Slope S is determined at 10-percent point of A.S.T.M. distillation curve.

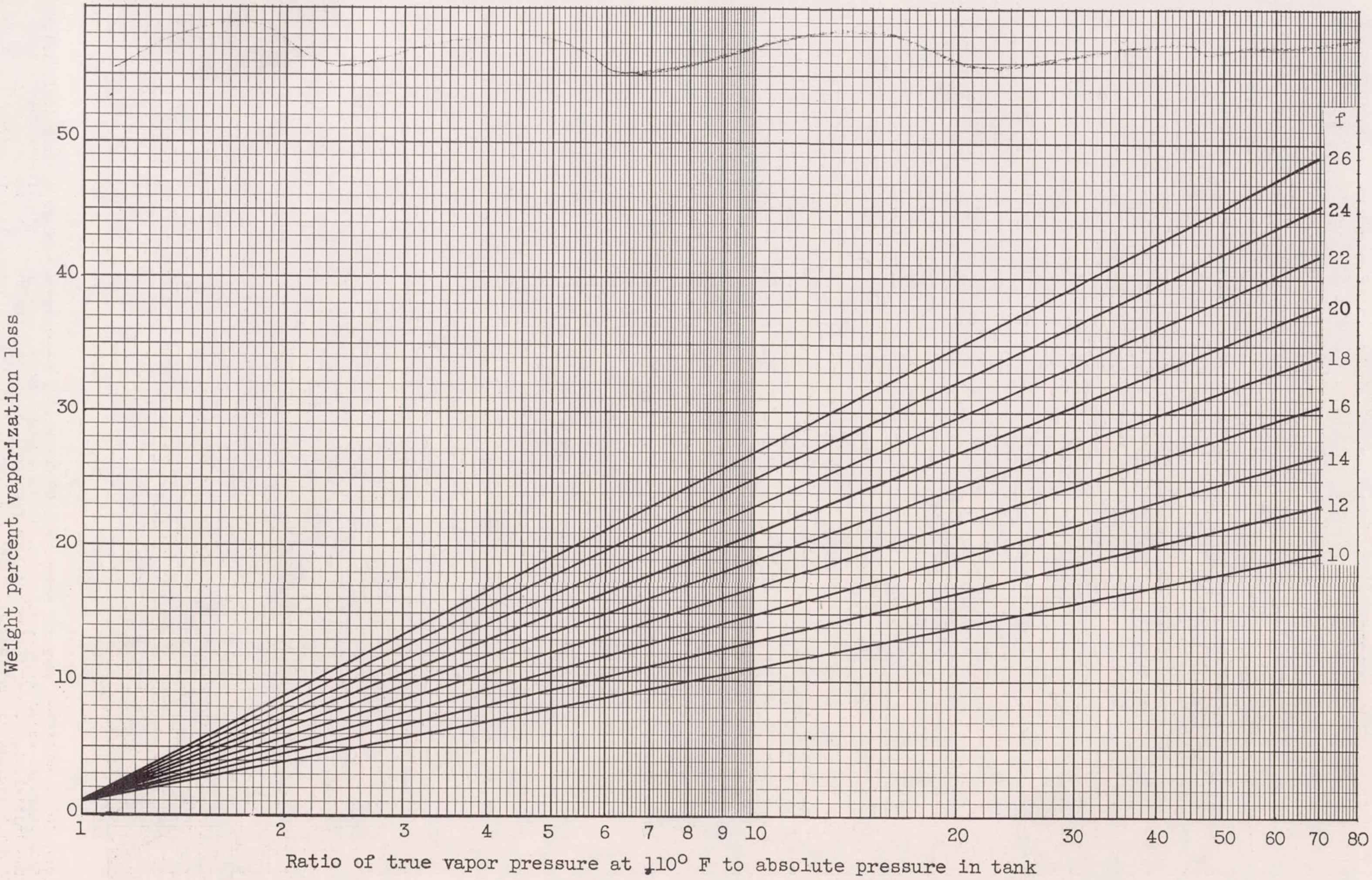


Figure 29. - Variation of vaporization losses with pressure for initial fuel temperature of 110° F. Values of f may be estimated from figure 28 for t = 110° F. $f = \frac{T_i^2}{4ST_i + 16\ T_{10} - 0.02\ T_{10}\ (T_i - 560)}$.

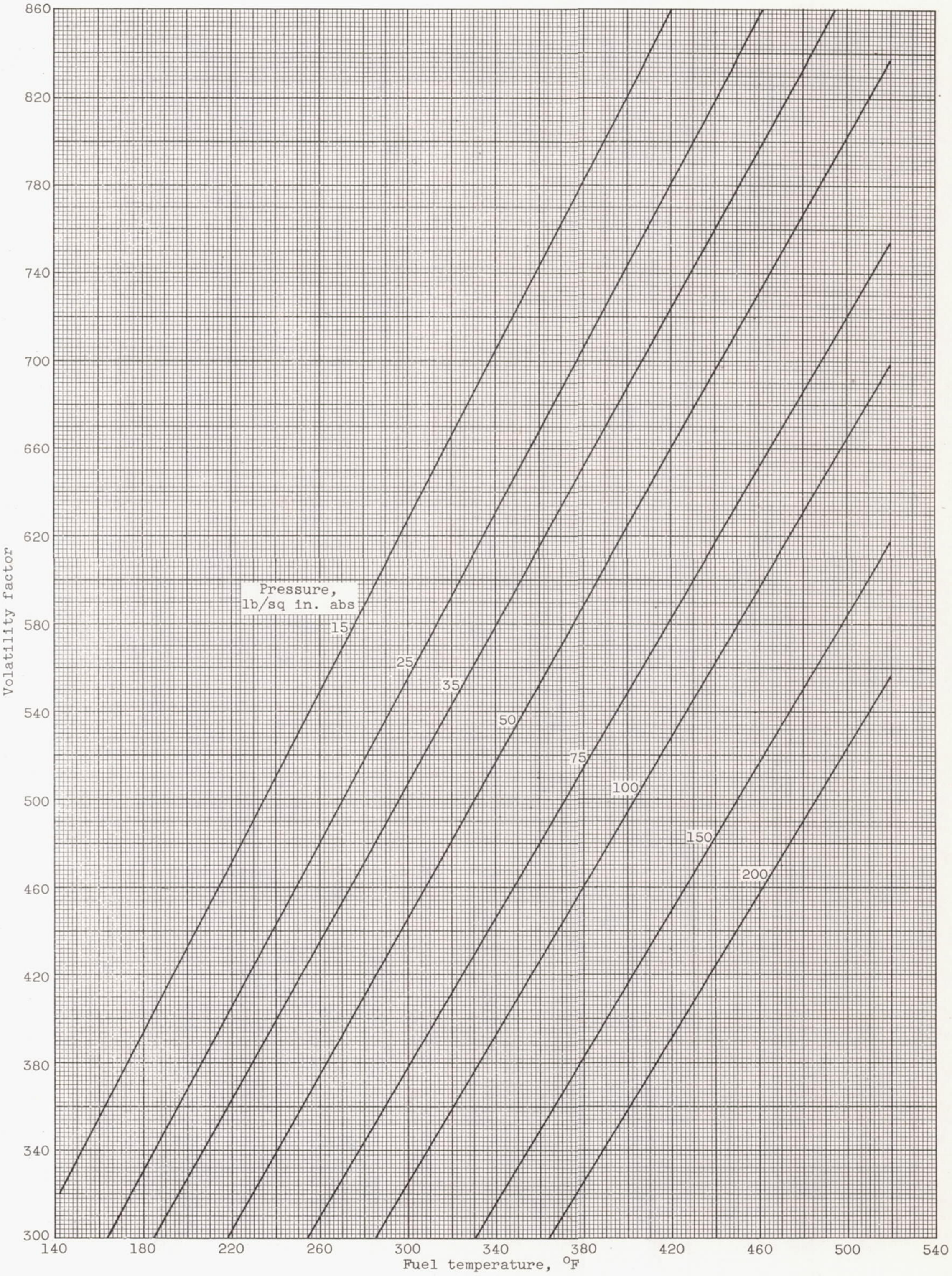
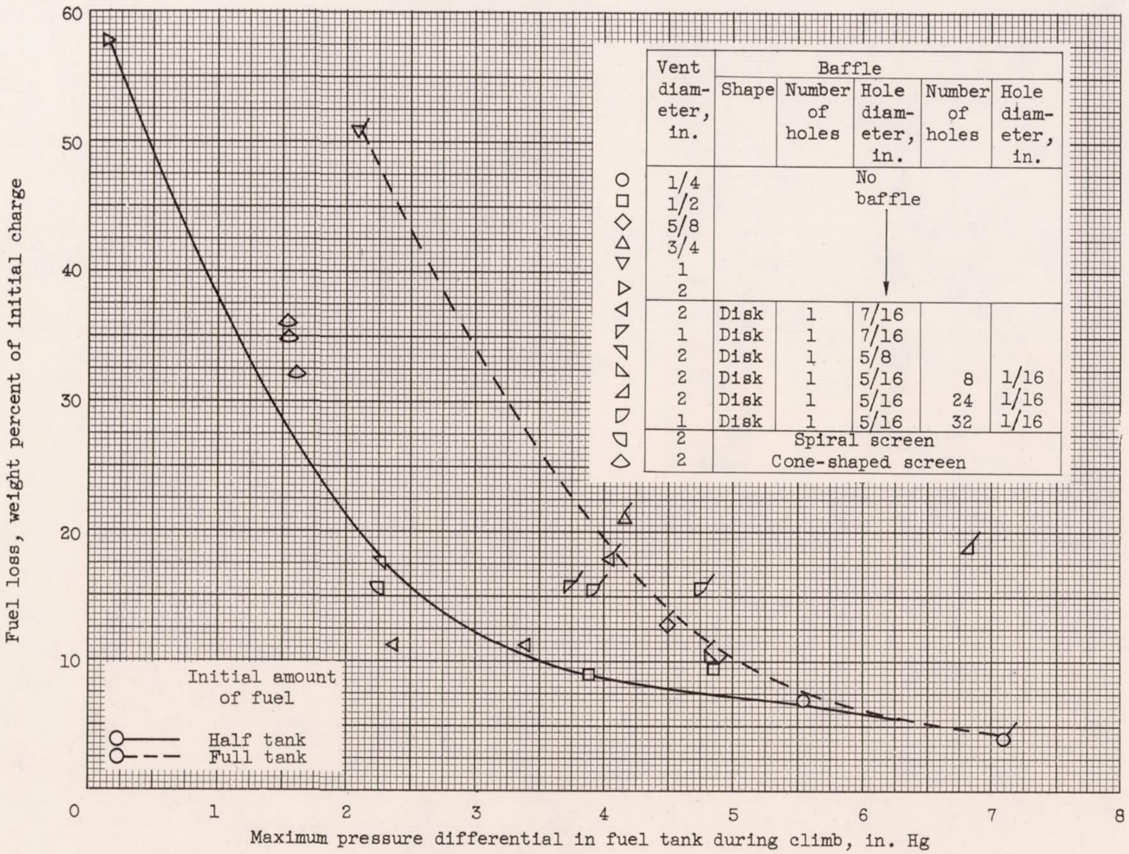
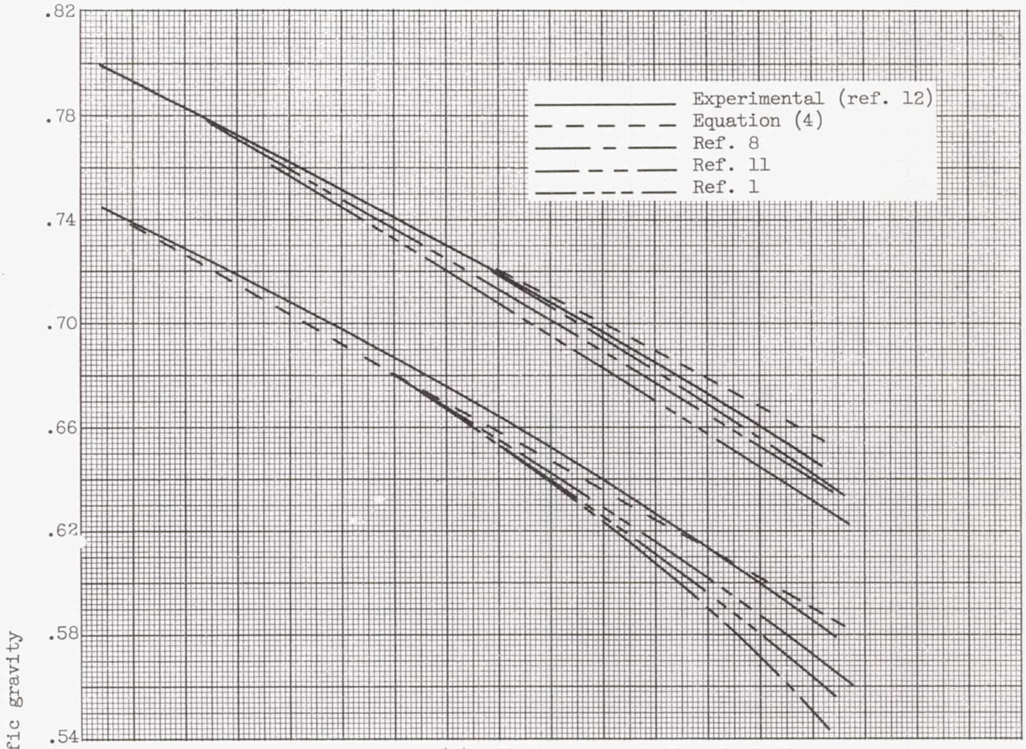


Figure 30. - Variation of vapor pressure with fuel type, temperature, and vapor loss (ref. 12). This chart is based upon experimental data for eight fuels; each pressure line is common to the initial, 1, 5, and 10 percent loss fraction; the volatility factor is the sum of the A.S.T.M. volume average boiling point and the A.S.T.M. temperature of loss fraction.

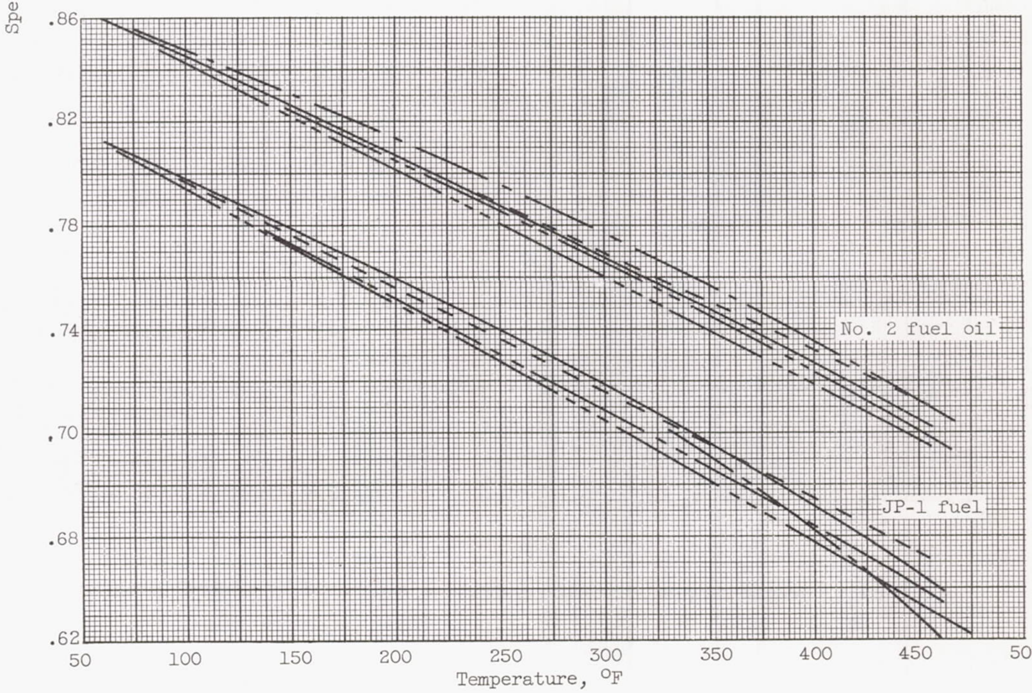


	Vent diameter, in.	Baffle				
		Shape	Number of holes	Hole diameter, in.	Number of holes	Hole diameter, in.
○	1/4	No baffle				
□	1/2					
◇	5/8					
△	3/4					
▽	1					
▷	2					
◁	2	Disk	1	7/16		
◸	1	Disk	1	7/16		
◹	2	Disk	1	5/8		
◺	2	Disk	1	5/16	8	1/16
◿	2	Disk	1	5/16	24	1/16
◡	1	Disk	1	5/16	32	1/16
ᗡ	2	Spiral screen				
⌓	2	Cone-shaped screen				

Figure 31. - Effect of vent size and baffles on fuel loss during simulated flight to 60,000 feet. Fuel type, JP-3; initial fuel temperature, 75° F; fuel tank capacity, 20 gallons; rate of climb, 10,000 feet per minute.



(a) Two JP-4 fuels.



(b) JP-1 fuel and no. 2 fuel oil.

Figure 32. - Comparison of experimental specific gravities and those estimated by several methods as functions of temperature.

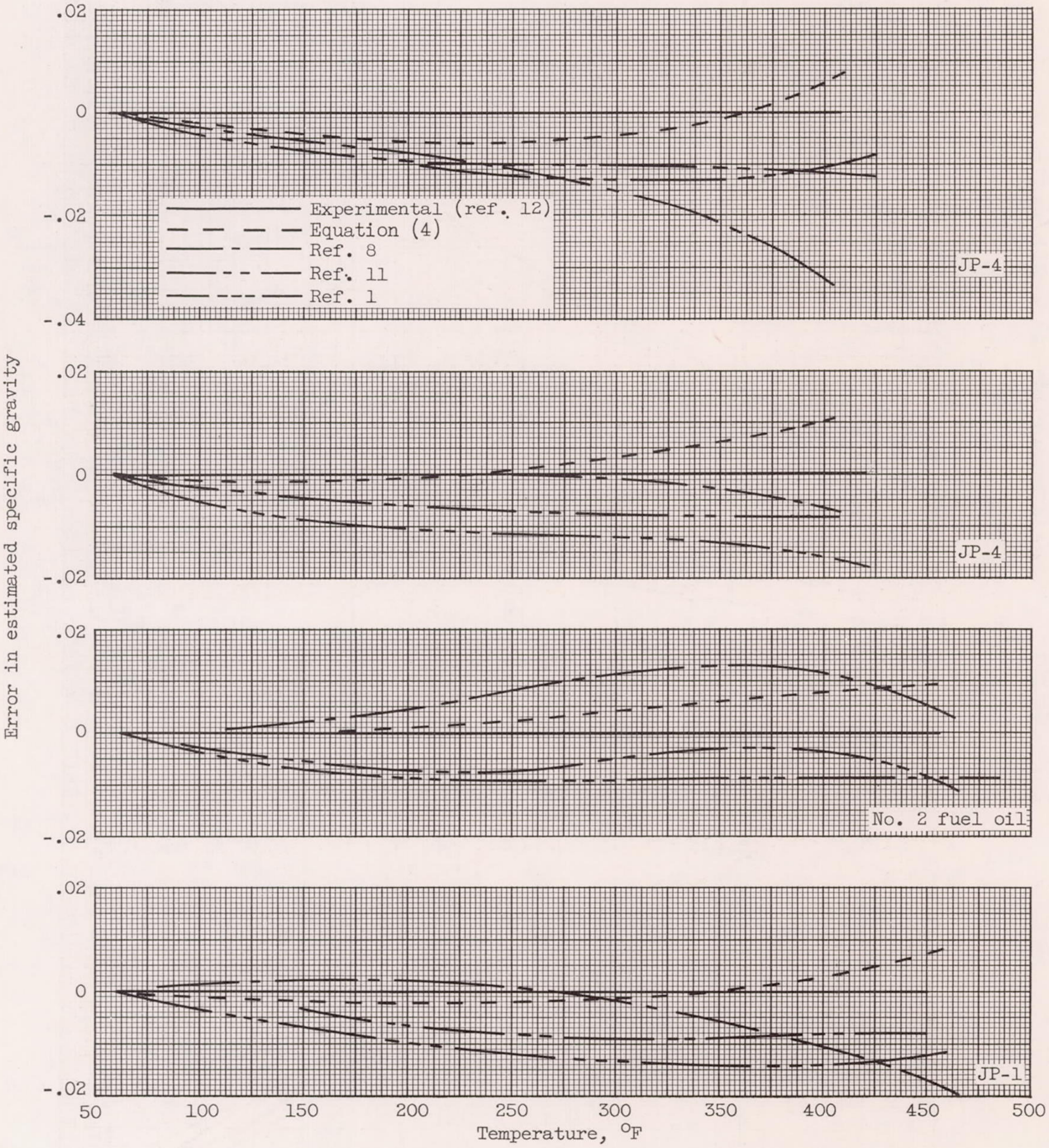
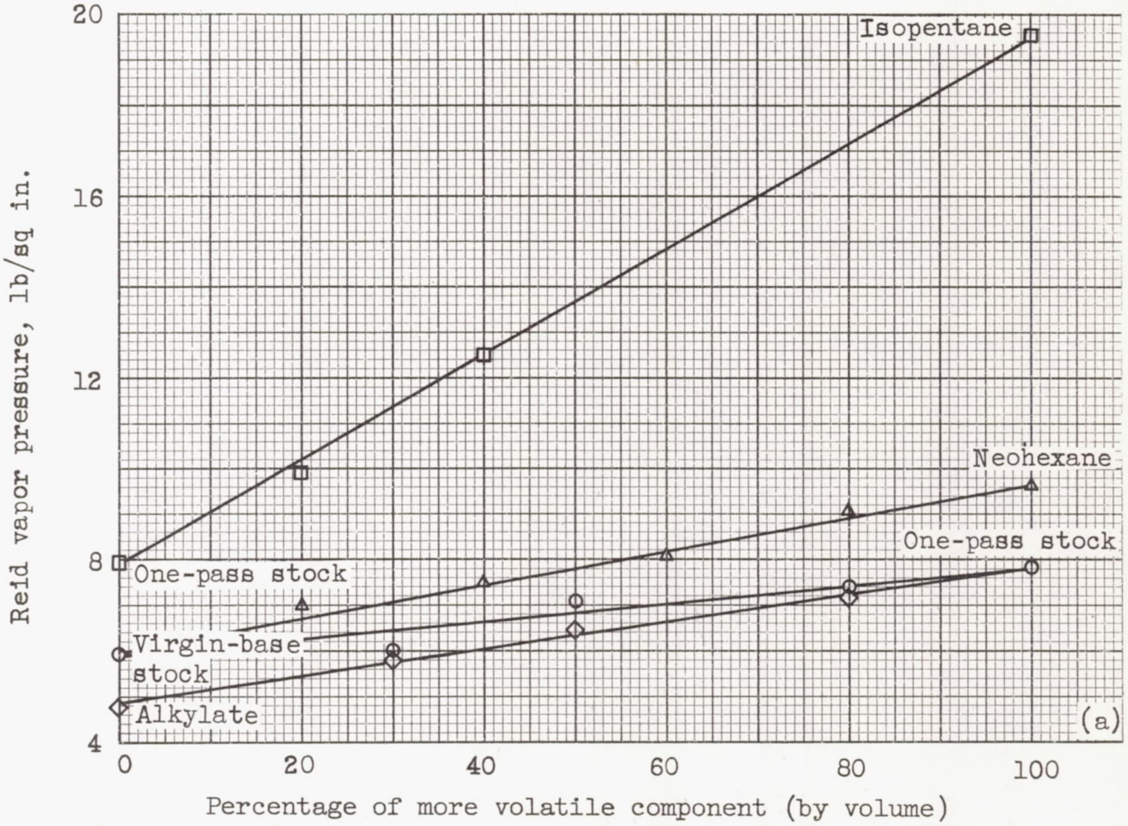
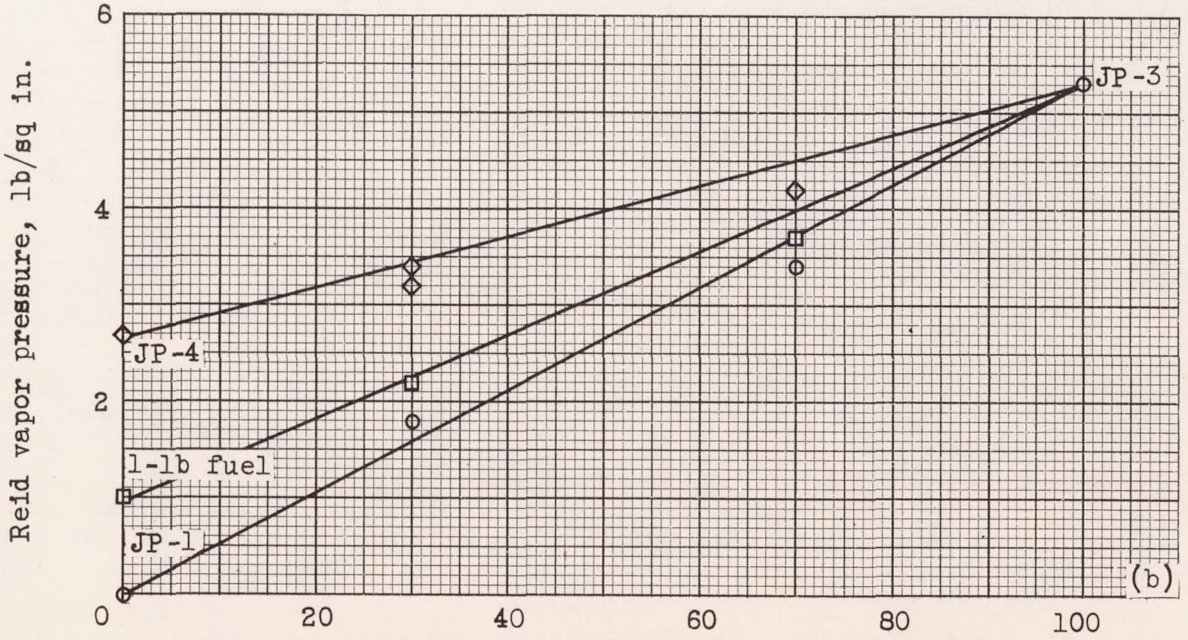


Figure 33. - Errors in specific gravities estimated by several methods.



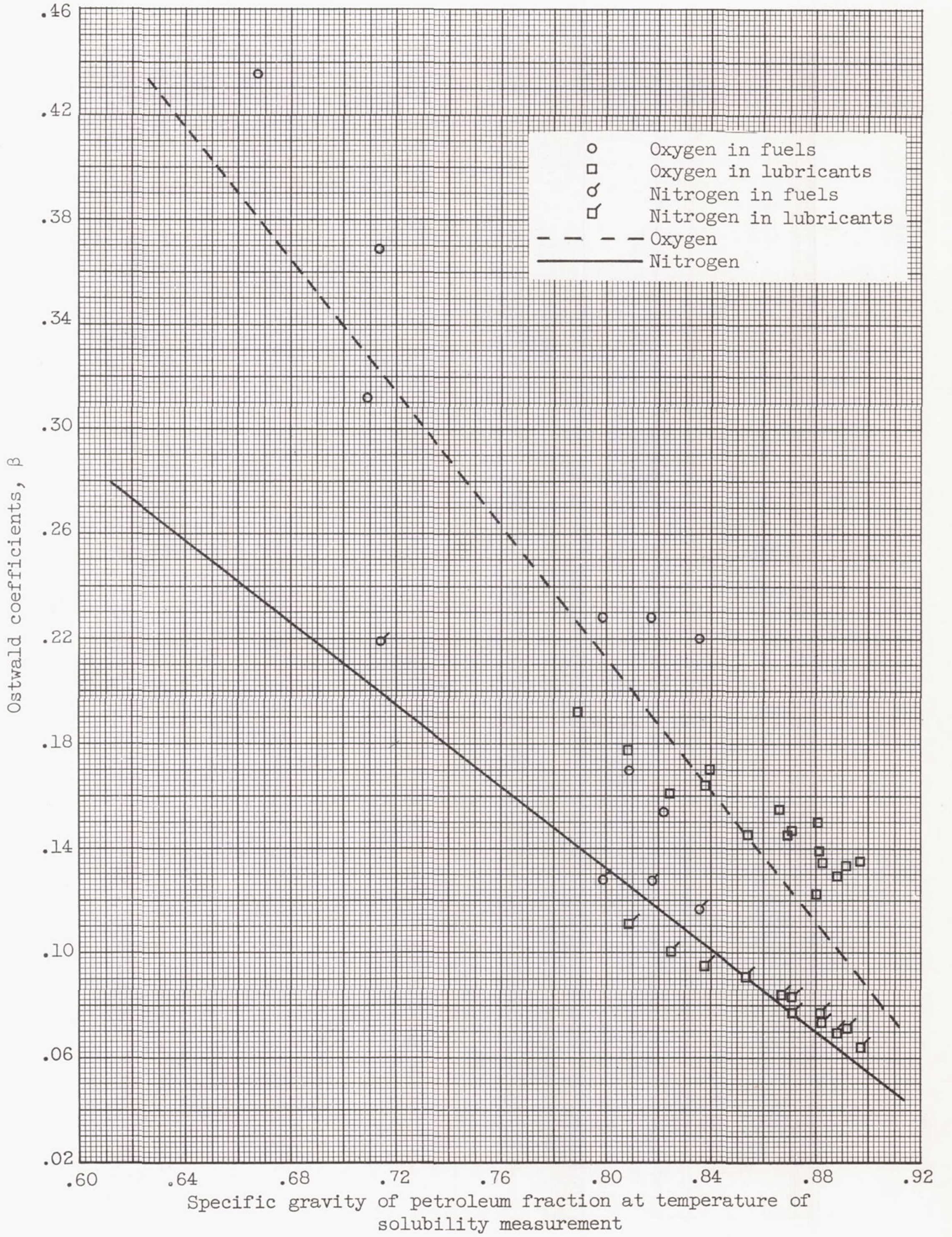
(a) Blends of aviation gasoline.

Figure 34. - Effect of composition on Reid vapor pressure.



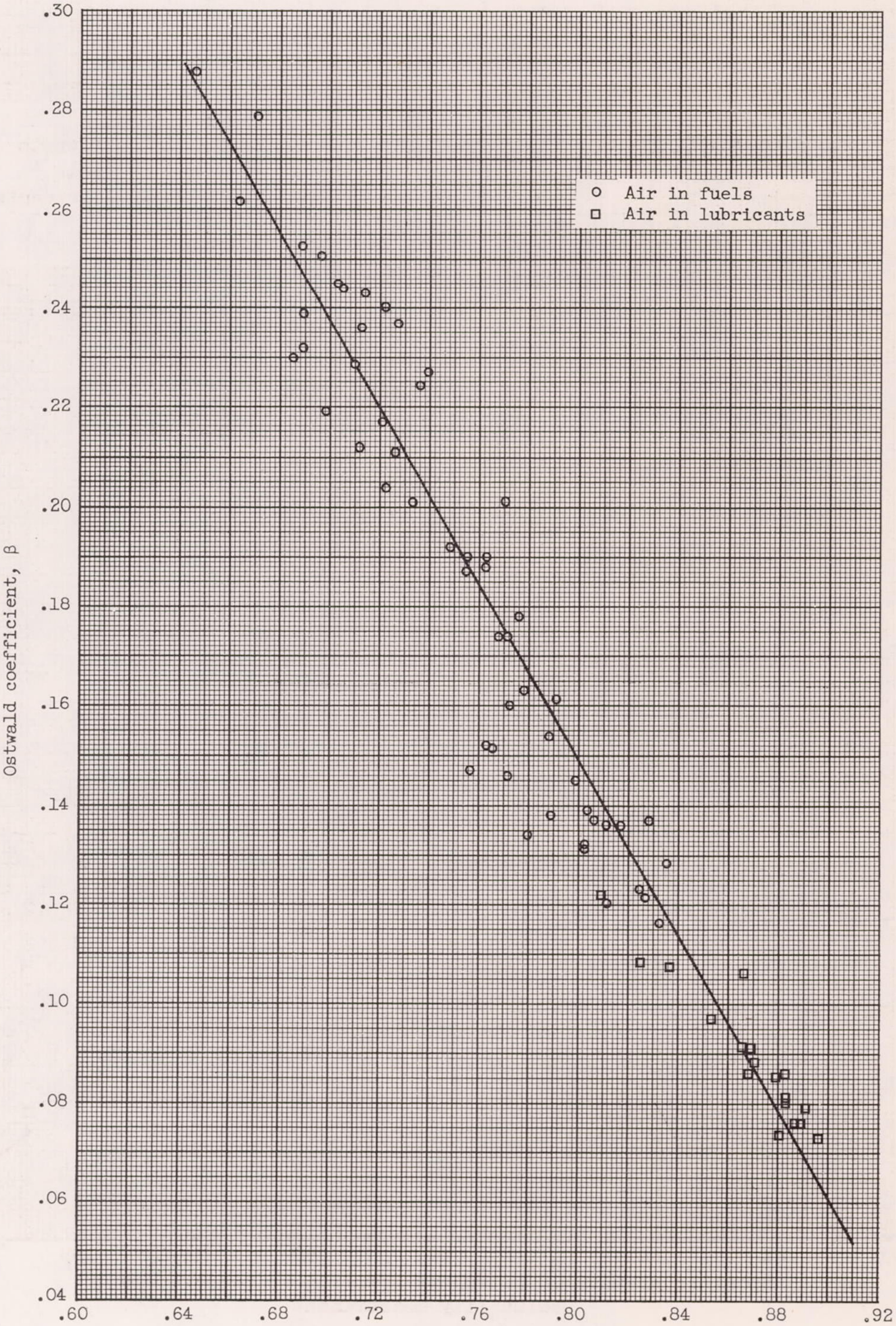
(b) JP-1, JP-3, JP-4 fuels, and a cut from JP-3 fuel.

Figure 34. - Concluded. Effect of composition on Reid vapor pressure.



(a) Oxygen and nitrogen.

Figure 35. - Correlation of Ostwald coefficients with specific gravity.



(b) Air.

Figure 35. - Concluded. Correlation of Ostwald coefficients with specific gravity.

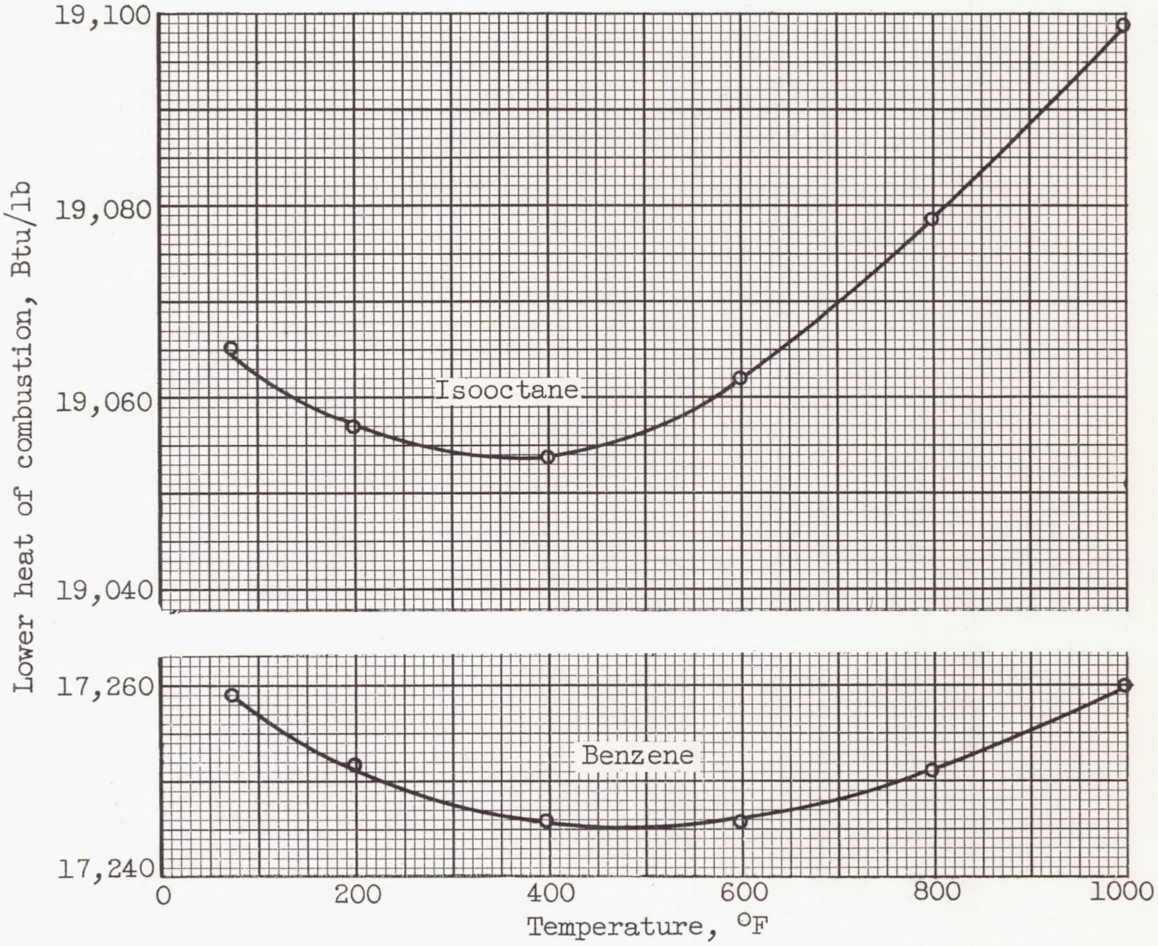


Figure 36. - Effect of varying temperature on lower heat of combustion of isooctane and benzene (data from ref. 19).

NACA - Langley Field, Va.