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RESEARCH MEMORANDUM

FUEL CHARACTERISTICS PERTINENT TO THE DESIGN OF AIRCRAFT FUEL SYSTEMS

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

Because of the importance of fuel properties in design of aircraft fuel systems the present report has been prepared to provide information on the characteristics of current jet fuels. In addition to information on fuel properties, discussions are presented on 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 variables such as pressure and temperature on physical properties is indicated. References are cited to provide fuel system designers with sources of information containing more detail than is practicable in the present report.

INTRODUCTION

During recent years specifications for turbojet fuels have undergone considerable change as a result of the continuous growth in understanding of just 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 fact 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 gasolines as applied to aircraft powered by the conventional piston-type engine. Although the "feel" or "know how" gained from this experience is invaluable, the widely different characteristics of turbojet fuels compared with aviation gasoline somewhat limit the applicability of existing fuel system design data to current and proposed turbojet aircraft.

Considerable information has been acquired on the characteristics of turbojet fuels; however, the data are scattered throughout the technical literature and are not readily obtainable by the designer. For this reason the present report has been written in order to provide a single source of data on turbojet 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, the present 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.

The data presented are restricted to current turbojet fuels and two fuels of possible interest in the distant 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 practicable 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.

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.

The limits of the properties for the four gasolines are all the same with the exception of antiknock value (fuel grade) and each of the limits for each property is based upon years of experience and research on performance of fuels in piston-type engines. For example, controls are maintained on fuel sulfur and gum content in order to insure engine reliability as to cleanliness and long life; heat of combustion is limited in order to insure greater fuel economy and long range; freezing point is limited to insure 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 insure satisfactory starting, absence of vapor lock, and minimum weathering. All the numerical limits on these properties represent compromises between over-all performance needs and availability needs.

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 is available from petroleum crude with existing refinery equipment. As a result the next several years saw intense effort devoted to the development of a turbojet fuel specification satisfactory from performance considerations as well as availability. The process of developing such a specification is gradual and must necessarily parallel engine development and fuel performance requirements.

The stepwise development of the current MIL-F-5624A (JP-4) fuel specification provides an example of the influence of fuel and engine research on specification requirements. In table II it is seen 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 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 from the fact that many of the requirements were found to be restrictive on availability and others had been shown by systematic performance research to be unnecessarily restrictive or too liberal. For example, a limitation on bromine number, a measure of unsaturated hydrocarbon content of a fuel, was included since it was suspected that unsaturates promoted carbon deposition in engines and greatly increased gumming tendencies. At the same time the requirements on gum content were liberalized to conform to the bromine number limit. Other changes as discussed previously were based upon availability and performance considerations.

The second revision to 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 the time of this change the permissible aromatic content was lowered to 25 percent by volume and the bromine number was increased to 30. This change resulted from the fact that aromatic content had been found to be more significant than bromine number as a factor in carbon-forming tendency. The March 1949 revision added a requirement on specific gravity (0.728-0.802) because of the importance of this factor in aircraft design considerations.

The JP-3 specification remained unaltered until May 1951 at which time a requirement was added to limit the mercaptan sulfur content 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 development tests.

Throughout the growth of the JP-3 specification, considerable opposition was encountered to the high volatility of the fuel. This reaction resulted from the excessive entrainment (slugging) losses that occurred during rapid climb. In spite of these losses there was considerable reluctance to a possible lowering of volatility because of expected difficulties in engine starting, cold weather performance, and increased tank explosive hazard. The arguments against lower volatility were mollified by the results of engine performance studies that indicated satisfactory operation on a fuel similar in most characteristics to JP-3 fuel but having a Reid vapor pressure of 2.0 to 3.0 pounds per square inch. The selection of 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 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 resulted in redefinition of the specific gravity limits.

At this writing JP-4 fuel is accepted as the primary military fuel for turbojet aircraft; however, an additional specification (MIL-F-7914(AER), JP-5) has been activated to control the properties of a special blending component for use in certain Naval aircraft operations. This component resembles a high-flash kerosene and in application will be blended 3 parts by volume with 1 part by volume MIL-F-5572 (115/145 grade) aviation gasoline. The properties of a fuel blend of this type are presented in table III together with properties for a typical high-flash kerosene meeting the JP-5 specification.

A comparison of the properties of the special blend in table III with the jet fuel specifications, table I, shows that the special blend meets all the requirements of a JP-4 fuel with the exception of freezing point. The freezing point of the special blend is -60° F, which is somewhat higher than the maximum allowable freezing point of -76° F. However, the use of the special blend (table III) is necessitated by logistic considerations and the advantages to be gained by its use outweigh the disadvantages arising from the high freezing point. For this reason the freezing point requirement for the high-flash component has been established at -40° F maximum.

TYPICAL INSPECTION DATA FOR AVIATION FUELS

The specifications discussed in the foregoing section have been developed to insure satisfactory handling properties and performance and adequate availability, but the nature of petroleum fuels is such that commercial fuels may vary considerably in physical properties and still meet the specification requirements. This fact complicates the problem of 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 IV to VI. In addition to these data, table VII has been included to illustrate the nature of an aviation gasoline and two grades of fuel oil (number 2 and number 6). Fuel oils have been suggested as possible fuels for future jet aircraft, providing means can be found to improve their combustion properties in jet engines.

The data shown in tables IV to VI indicate that wide variations can and do occur in acceptable fuels under the various specifications. From the standpoint of 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 IV to VI, have been examined to establish these ranges. These data are summarized in table VIII.

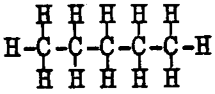
For design purposes, many of the ranges of the individual properties should be extended to the limits of the specification to provide for a fuel system that will operate adequately with any fuel procured under a given specification. Accordingly, ranges of variation in physical properties have been extended in table IX to values up to the limits of the specification. This alteration places the data in table IX on a more realistic basis than the data in table VIII; consequently, table IX represents a more logical set of target values upon which fuel system designs may be based. The average values in this table are based upon current production fuels and could be considerably different for fuels that might be produced under "all out" conditions.

COMPOSITION AND PHYSICAL PROPERTIES OF FUELS

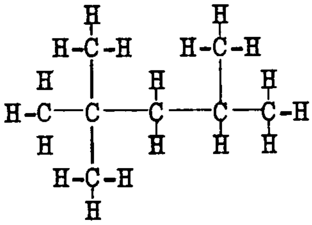
Fuel Composition

Fuels derived from petroleum are substantially 100-percent hydrocarbon mixtures. Only very small quantities, rarely exceeding 1 percent, of nonhydrocarbon compounds are likely to be present in aircraft fuels. The hydrocarbons found in such fuels may be divided into four classes: paraffins, cycloparaffins, aromatics, and olefins.

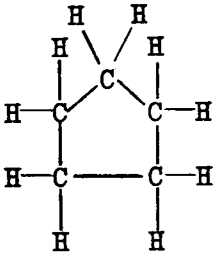
Paraffins and cycloparaffins. - Paraffins have a chain-like structure of carbon atoms, and cycloparaffins contain rings of carbon atoms with the rings usually composed of 5 or 6 carbon atoms. Examples of these compounds are illustrated:



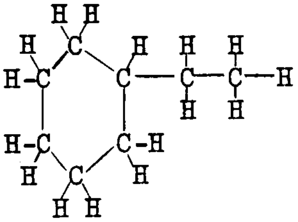
Straight-chain paraffin
(normal pentane)



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



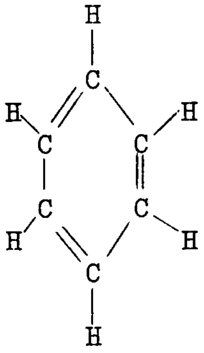
Cycloparaffin
(cyclopentane)



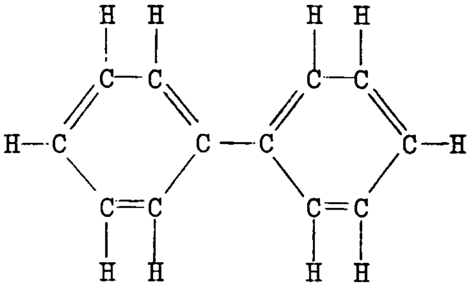
Cycloparaffin
(ethylcyclohexane)

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

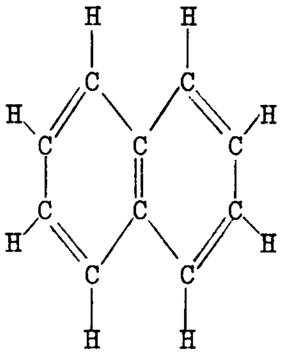
Aromatics. - Aromatics are those hydrocarbons which contain the characteristic 6-membered benzene ring. The three classes of aromatics are: single-ring aromatics, multi-ring aromatics with no two rings sharing a single carbon atom, and multi-ring aromatics where two rings share two common carbon atoms. 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:



Single-ring aromatic
(benzene)



Multi-ring aromatic
(no common carbon atom)
(biphenyl)

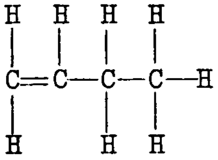


Multi-ring aromatic
(2 common carbon atoms)
(naphthalene)

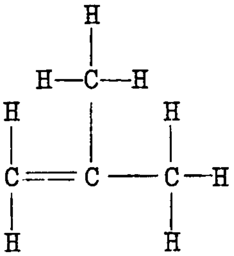
The concentration of aromatics of all classes is limited to a maximum of 25 volume percent by present jet fuel specifications (see table I), but currently available fuels usually contain about 10 to 15 percent total aromatics and 0.5 to 3.0 percent of the multi-ring type with most of these believed to be of the type where 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.

<u>Olefins</u>. - Olefins are hydrocarbons which have 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 olefins), in a ring (cycloolefins), or on a chain attached to an aromatic ring (aromatic olefins). Some

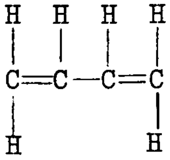
olefins may have two or more of the carbon-to-carbon double bonds, in which case they are called polyolefins (usually diolefins). Examples of olefin structures are as follows:



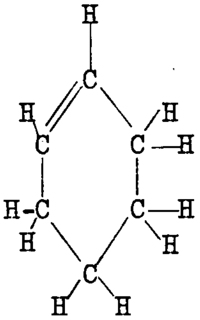
Monoolefin
(butene-1)



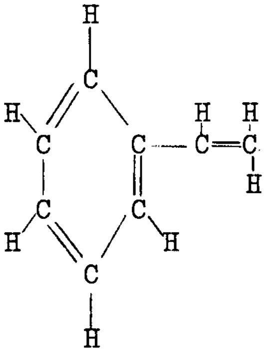
Monoolefin
(isobutene)



Diolefin
(1,3-butadiene)



Cycloolefin
(cyclohexene)



Aromatic olefin
(styrene)

Olefins are limited in jet fuels by the specification of a maximum bromine number (table I). For JP-3 and JP-4 fuels the maximum bromine number is 30, which is equivalent to approximately 20 percent olefin. Olefins are not present in virgin fuels but are formed in refinery cracking operations and are present in most current jet fuels in 0 to 10 percent concentration.

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 GRS synthetic rubber. Atmospheric oxygen or traces of some metals can act as catalysts. These highly reactive types of 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 which 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 JP-3 and JP-4 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, or thiophanes.

Thiophenols and mercaptans are slightly acidic and are usually removed by caustic washing or variations thereof in refinery processing. Thiophenol is a very unlikely component in adequately processed fuels, and mercaptan sulfur is limited in the present JP-3 and JP-4 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 10 milligrams per 100 milliliters or 0.01 percent by weight. Additional gum may form during storage because of the presence of reactive olefins. 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.

Physical Properties of Fuels

In connection with the discussion of table IX, it has been 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 several of the physical properties of particular interest in fuel system design.

Density. - Fuel density is of interest in airframe design since this factor controls the weight loading with completely full tanks and, when combined with the heat of combustion of a fuel, is used in range calculations. Density also enters into the calibration of tank gages and fuel-metering devices. Density is not specified for reciprocating engine fuels and, in practice, covers a fairly small range for a single grade of fuel. A considerable range of densities can be encountered under a single jet fuel specification, and limits on specific gravity have been established for jet fuels. These specific gravity requirements, at a temperature of 60° F, have been shown in table I and discussed in connection with tables VIII and IX. From the values established in tables VIII and IX, plots have been prepared to show the influence of temperature on fuel specific gravity. These plots are presented in figure 1.

The maximum, minimum, and average specific gravities of actual JP-1 fuels procured under specification MIL-F-5616 are indicated in figure 1(a). The values of specific gravity at 60° F correspond to the values given in tables VIII and IX. Also shown on figure 1(a) are curves showing the maximum specific gravity permitted by the specification and the minimum specific gravity that might be expected for JP-1 fuels. The minimum specific gravity is not controlled directly by specification; however, the requirement of a minimum flash point of 110° F provides an indirect control of the minimum specific gravity.

The variation of specific gravity with temperature was calculated from the following equation:

$$\rho_T = \rho_{60} [1 + k (60 - T)] \tag{1}$$

where

ρ_T specific gravity at temperature T

ρ_{60} specific gravity at 60° F

k mean coefficient of thermal expansion

T temperature, $^\circ$F

This linear relation may be applied at temperatures up to the values indicated in the following table. For extrapolations beyond these temperatures reference 3 should be consulted.

Specific gravity at 60° F	Maximum temperature for equation (1), °F
0.64	250
.68	350
.72	400
.76	500
.80	650
.84 and higher	900

Values of k for equation (1) are given in reference 3 and are repeated in the following table:

A.P.I. gravity range	Specific gravity range at 60° F	Mean coefficient of thermal expansion, k
79 and lighter	0.672 and lighter	0.0008
78.9 - 65.0	.673 - 0.720	.0007
64.9 - 51.0	.721 - .775	.0006
50.9 - 35.0	.776 - .850	.0005
34.9 - 15.0	.851 - .965	.0004
14.9 - 0	.966 - 1.076	.00036

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The A.P.I. (American Petroleum Institute) gravity shown in the foregoing table is a unit in common use in the petroleum industry. It is related to specific gravity by

$$^{\circ}\text{A.P.I.} = \frac{141.5}{\text{Specific gravity }(60/60^{\circ}\text{ F})} - 131.5 \qquad \text{(1a)}$$

Data similar to those shown in figure 1(a) are shown in figures 1(b) and 1(c) for JP-3 and JP-4 fuels, respectively. Examination of figures 1(a), 1(b), and 1(c) reveals that the maximum deviation of specific gravity from the average curve for any of these three fuels is about ±6.5 percent.

Figure 1(d) shows a comparison of the average curves for JP-1, JP-3, and JP-4 fuels with typical curves for an aviation gasoline and two fuel oils (see table VII). Considering gasoline to be the reference fuel, the ratios of specific gravities of the other fuels to gasoline at 60° F are as follows:

Fuel	Specific gravity ratio at 60° F
Aviation gasoline	1.00
JP-3	1.08
JP-4	1.10
JP-1	1.15
Number 2 fuel oil	1.22
Number 6 fuel oil	1.36

Properties of fuel and bunker oils vary widely; therefore, the inclusion of typical examples of these fuels in figure 1(d) and the foregoing table is of interest merely to indicate the possible magnitude of specific gravity variation if such fuels are ever considered for aviation purposes.

Heat of combustion. - In the preceding section, it has been indicated that fuel density and fuel heat content are significant in evaluation of aircraft flight range. For this reason relations from which estimates of heat of combustion can be made are presented herein.

The gross, or upper, heat of combustion of a fuel is the amount of heat released when the fuel is completely burned to yield CO_2 gas and water in the liquid phase. The net, or lower, heat of combustion is the amount released when CO_2 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 and 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 has been shown that the minimum heat of combustion acceptable for JP-3 and JP-4 fuels is 18,400 Btu per pound. It is doubtful if 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 A.P.I. gravity. This latter product is called the aniline-gravity constant. The following equation, taken from reference 4, can be used for aircraft fuels:

$$H_N = 17,898 + 0.1104 \, A \times G \qquad (2)$$

where

H_N net heat of combustion, Btu/lb

A aniline point, $^{\circ}$F

G gravity, $^{\circ}$A.P.I.

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

$$H_N = 22{,}130 + \frac{2560}{S - 1.53} \tag{3}$$

where

H_N net heat of combustion, Btu/lb

S specific gravity (60/60° F)

Equation (3) 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 in figure 2(a). The abscissa of this figure has been changed to be linear in specific gravity rather than degrees A.P.I. used in reference 1. Because of the interest in calculations for volume-limited aircraft, figure 2(b) has been included to illustrate the variation of heats of combustion per unit volume with specific gravity and aniline point.

A comparison of net heats of combustion for aviation gasoline, the two fuel oils, and the three jet fuels is given in the following table. The net heats of combustion were estimated from equation (3) with the aid of specific gravities shown in tables VII and IX.

Fuel	Specific gravity, 60/60° F			Net heat of combustion, Btu/lb		
	Min.	Max.	Typical	Min.	Max.	Typical
Aviation gasoline	-----	-----	0.704	------	------	19,030
JP-3	0.728	0.802	-----	18,630	18,940	------
JP-4	.747	.825	-----	18,510	18,870	------
JP-1	.775	.850	-----	18,360	18,750	------
Number 2 fuel oil	-----	-----	.861	------	------	18,290
Number 6 fuel oil	-----	-----	.957	------	------	17,630

The heats of combustion given in this table are on a weight basis and it is apparent from figure 2(b) that the relative order of heating value would be reversed for a volume basis.

Freezing point. - Atmospheric temperature measurements have shown (ref. 5) that ambient temperatures as low as -137° F may be encountered at 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 insure 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.

The restriction of freezing point to a maximum of -76° F has one great disadvantage in the jet fuel field in that it becomes restrictive on availability. In reference 6 it is shown that the availability (percent of crude) could be increased from 13 percent to 20 percent for a 100° F flash point fuel if the freezing point were increased from -76° F 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 3 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 increases 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 3 indicate that end points greater than 480° F would produce fuels with freezing points in excess of -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 3 have been 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 3 for estimates of jet fuel freezing points.

Water solubility in fuels. - The subject of water solubility is somewhat incompatible with the more conventional fuel properties discussed in the preceding sections. Its inclusion at this point, however, is considered necessary because of the importance of water solubility in relation to low-temperature handling characteristics.

Insofar as low-temperature performance is concerned, the presence of water in fuels can be a more serious hazard than the presence of high-boiling components, inasmuch as the latter are controlled by the freezing-point specification. At some stage in fuel handling and processing, most fuels are substantially saturated with water which may, in low-temperature applications, become troublesome when water begins to separate and freeze.

In a study reported in reference 7, an effort is made to correlate the water-solubility characteristics of various fuels. The results of this study indicate that for approximations of water solubility in hydrocarbon fuels, a linear relation between the logarithm of solubility and reciprocal of the absolute temperature may be used. This relation shows that solubility increases as temperature increases. Pure hydrocarbon studies also indicate that solubility of water increases as the hydrogen-carbon ratio decreases.

The following equation, based on data for pure hydrocarbons, has been proposed for the estimation of the solubility of water in hydrocarbon fuels.

$$\log S = -(4200\,H/C + 1050)(1/T - 0.0016) + 2.00 \qquad (4)$$

where

S solubility of water in hydrocarbon, mol percent

H/C hydrogen-carbon weight ratio

T temperature, $^{\circ}K$

This equation gives poor agreement with the solubility for water reported for some pure hydrocarbons and is believed to be accurate only within ± 50 percent for refinery streams.

By means of this equation figure 4 has been prepared to illustrate water solubility in fuels of different hydrogen-carbon ratios. An average curve representative of straight-run petroleum fractions (ref. 8) would fall between the curves for hydrogen-carbon ratios of 0.16 and 0.17. Typical values of jet fuel hydrogen-carbon ratios for use in equation (4) are found in table VIII.

Viscosity. - Fuel viscosity data are necessary in the calculation of line losses in aircraft fuel systems; consequently, data have been collected to indicate the variation of viscosity with fuel temperature for jet fuels supplied under current specifications. With the exception of specification MIL-F-5616 (JP-1), the viscosities of current jet fuels are not regulated by specification; therefore, existing data have been accumulated incidentally to the usual fuel inspection procedures.

For many years A.S.T.M. viscosity-temperature charts have afforded a convenient method for representing the viscosity-temperature relationships for petroleum products. The coordinates of this paper are adjusted according to an equation of the following form (ref. 9):

$$\log \log (\mu + c) = A \log T + B \tag{5}$$

where

μ kinematic viscosity, centistokes

T absolute temperature, °R

c,A,B constants

Viscosities plotted against temperatures on these charts produce linear relations for a given fuel; consequently, it is possible from two experimental viscosity-temperature points to estimate viscosities over a wide temperature range. If only one viscosity-temperature point is known, the whole curve can be approximated with reasonable accuracy by drawing a line through the point parallel to a line previously established for another fuel. The latter practice is not recommended except within the range of viscosities generally associated with fuels similar to aviation gasoline, JP-1, JP-3, and JP-4.

Viscosity-temperature characteristics for several fuels are illustrated in figure 5. Although the data upon which these curves are based are rather limited, it is believed that the average relations may be used with reasonable confidence since stocks from several sources are represented.

The spread in viscosity to be expected for jet fuels at two temperatures is estimated in the following table:

Fuel	Viscosity at -40° F, centistokes		Viscosity at 68° F, centistokes	
	Minimum	Maximum	Minimum	Maximum
JP-1	4.0	12	1.3	2.3
JP-4	2.5	6.5	.9	1.5
JP-3	1.5	6.0	.6	1.5

Curves for typical number 2 and number 6 fuel oils are also shown in figure 5. Such fuels have viscosities considerably higher than those of the more conventional fuels and, if ever considered for use as aircraft fuels, will increase the difficulties of low-temperature handling. In figure 5, the use of the word typical in reference to the two fuel oils is somewhat misleading inasmuch as the kinematic viscosity according to specifications may vary between 200 to 600 centistokes and, in certain cases, even the minimum limit may be waived (ref. 10).

Linear extrapolations of viscosity-temperature curves in the low temperature range should be handled with discretion since the slope of the curves will change sharply at temperatures below the freezing point. All the curves shown on figure 5 have been extrapolated to the lowest temperature at which the linear relation can be safely assumed to hold.

Volatility. - 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 6 illustrates the variation that may be expected in distillation curves for the three jet fuels within the specification limits. Although the particular group of JP-1 fuels used in figure 6(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 same observation is true in figure 6(b) where it is seen that the maximum envelope at the 100-percent point is about 40° F lower than the specification requirement. Samples of JP-4 represented by the data in figure 6(c) coincide with the specification limits at the 10-percent and 100-percent points. Figure 6(d) completes the comparison of distillation data for the average curves of the three jet fuels, a typical aviation gasoline, and a number 2 fuel oil.

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 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 pounds per square inch to 5 pounds per square inch. These tests were made in unstoppered bottles at atmospheric pressure with samples alternately heated and cooled between 70° F 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:

$$P_R = S\left(\frac{a}{\rho T_{20} + b} + c\right) \tag{6}$$

where

P_R	Reid vapor pressure, pounds per square inch
S	slope of A.S.T.M. distillation curve at 10-percent point, $(T_{15}-T_5)/10$
a,b,c	constants
ρ	specific gravity
T_{20}, T_{15}, T_5	20-, 15-, and 5-percent A.S.T.M. distillation points, °F

The constants in this equation 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 (6) 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 11 and 12.

Another volatility relation of interest is the effect of composition on Reid vapor pressure. Considerable data have been accumulated for fuel stocks in the gasoline range and several of the relations for such stocks are shown in figure 7. Additional data are shown in figure 8 for heavier fuels such as JP-3 and JP-4 and for a 1-pound Reid vapor pressure stock prepared by cutting the light ends from a JP-3 fuel. All data in figures 7 and 8 conform to the following linear equation:

$$P_{R,b} = P_{R,1} N_1 + P_{R,2} N_2 \tag{7}$$

where

$P_{R,b}$ 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.

N_1, N_2 volume fraction of components 1 and 2

Reid vapor pressures are not precise measures of true vapor pressures, however, for most practical uses greater precision than that provided by the Reid determination is not required. 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 zero.

True vapor pressures may be estimated from Reid vapor pressures by a method described in reference 2 (pp. 244-254). The equation (ref. 2) for true vapor pressure at 100° F is:

$$P_0 - P_R = 0.0223\ P_R + \frac{0.0119\ P_R\ S}{1-0.0368\ P_R} \tag{8}$$

where

P_0 true vapor pressure at $V/L = 0$, lb/sq in.

P_R Reid vapor pressure, lb/sq in.

S slope of A.S.T.M. distillation curve at 10-percent evaporated point, $(T_{15}-T_5)/10$

In order to calculate the variation of true vapor pressure with temperature, the following equation (ref. 2) may be used:

$$A_{0,T} = A_{0,100} + b\ (100-T) \tag{9}$$

where

T temperature, °F

A pressure function (subscripts refer to V/L and temperature)

b temperature coefficient $= 0.056 + \dfrac{262}{\dfrac{A_{0,100}}{b} + 560} - 0.04\sqrt{S}$

Values of A may be determined from figure 9; however, for greater accuracy, table XXVIII of reference 2 should be used.

The first step in determination of the true vapor pressure - temperature curve is to calculate P_0 from equation (3). The value of $A_{0,100}$ may then be obtained from figure 9. Next, b is calculated as indicated in equation (9). A sample calculation of b is described in reference 2. Equation (9) may then be used to determine values of $A_{0,T}$ at different temperatures. The values of P_0 corresponding to the computed values of $A_{0,T}$ may be read from figure 9.

Although equations (8) and (9) 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 are compared in the following table with calculated values for vapor-liquid ratio of zero:

Temperature, °F	Slope = 12.3		Slope = 7.6		Slope = 3.9	
	Obs.	Calc.	Obs.	Calc.	Obs.	Calc.
100	3.0	3.6	2.8	3.1	2.7	2.9
150	6.6	7.1	6.3	6.7	6.2	6.7
190	----	----	----	----	11.1	12.1
200	12.7	13.0	12.9	13.1	----	----

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. Figure 10 presents calculated true vapor pressure curves for fuels having slopes up to 12 and varying in Reid vapor pressure between 2 pounds per square inch and 7 pounds per square inch. 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.

Latent heat of vaporization. - Although no effort has been made to present a comprehensive discussion of latent heat of vaporization, this section has been included to indicate variations that may be found among jet fuels. This information may be of interest in design problems concerned with the proximity of heat sources to fuel system components. An additional application may be the prediction of heat requirements for prevaporization for engines that utilize vaporized fuel.

Latent heats of vaporization for JP-1, JP-3, JP-4, aviation gasoline, and fuel oil were calculated by a method described in reference 1. The results of these calculations are shown in figure 11. Maximum and minimum limits are shown for JP-1, JP-3, and JP-4 based upon the maximum and minimum A.S.T.M. distillation and specific gravity data from table VIII. Calculations for aviation gasoline and fuel oil are based upon data in table VII.

The percentage variation of latent heats (fig. 11) that might be expected for the three jet fuels is indicated in the following table:

Fuel	Temperature, °F		
	100	300	450
JP-1	2	4.7	7.6
JP-3	2.6	5.7	45.8
JP-4	3.4	9.2	21.4

The relative magnitude of latent heats (fig. 11) for all five fuels is shown in the following table:

Fuel	Latent heat, Btu/lb					
	Temperature, °F					
	100		300		450	
	Min.	Max.	Min.	Max.	Min.	Max.
JP-1	151	154	127	133	105	113
JP-3	153	157	123	130	72	105
JP-4	149	154	120	131	89	108
Aviation gasoline	---	[a]156	---	[a]119	---	[a]65
Number 2 fuel oil	---	---	---	[a]131	---	[a]116

[a]Typical values not maximums.

Dielectric constant. - With the development of the capacity-type fuel gage for use in aircraft careful attention was directed to the electrical as well as 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, the density. The quantity (K-1)/D is called the capacity index and is the fuel characteristic which 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 proportional directly 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.

During the past three years the Armour Research Foundation of the Illinois Institute of Technology has been conducting an investigation of the dielectric characteristics of current aircraft fuels. This study conducted for the U. S. Air Force involved measurements on approximately 160 fuel samples. The first portion of this work has been summarized in reference 13 and an analysis of the data has been made at the Naval Air Experimental Station and reported in reference 14.

It is not the intention of the present report to review the entire Armour 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 figure 12 which is based upon data from reference 13. For JP-1 fuels (fig. 12(a)), the deviation from average is approximately ±2 percent; for JP-3 fuels (fig. 12(b)) the deviation varies between 3.2 percent and 5.8 percent over the temperature range shown. In figure 12(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 12(b). The deviation for these JP-4 types varies between 3.4 percent and 7.0 percent. Figure 12(d) compares dielectric constants of the three types of jet fuels with 100/130 grade aviation gasoline and two fuel oils. The relative order of the six fuels is the same as that found for density (fig. 1(d)) and viscosity (fig. 5). The method by which data for the two fuel oils were estimated will be described later.

The variation of capacity index (K-1)/D with temperature is illustrated in figure 13. The units of density used in computing capacity index are pounds per gallon.

The spread of data in figures 12 and 13 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 specifications. The range of specific gravity for the JP-1 samples reported in reference 13 is not so wide as the range permitted by specifications. This fact is illustrated in the following table:

Fuel	Specific gravity at 32° F			
	Reference 12		Permitted by specification	
	Min.	Max.	Min.	Max.
JP-1	0.8019	0.8466	0.785	0.862
JP-3	.7434	.8117	.739	.812
JP-4	.7524	.8300	.760	.837

The data for the two fuel oils in figures 12(d) and 13(d) were estimated by extrapolating the linear relation between density and dielectric constant. This line was established by plotting the Armour data (ref. 13) for all fuels and at two temperatures, 32° F and 77° F. All of 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

$$K = 1.667\rho + 0.785 \tag{10}$$

where

ρ specific gravity at any temperature

K dielectric constant at the same temperature

From this relation dielectric constants for the two fuel oils were estimated with specific gravities from figure 1(d).

Solubility of gases in fuels. - The trend toward use of fuels less volatile than gasoline has emphasized the need for protection against explosive mixtures in fuel tanks. One possible protective measure is the use of inert gases over liquid fuel in tanks. The use of inert gases presents the problem of solubility of such gases in fuel. A similar problem is the solubility of air in fuel and both problems are intimately related to fuel system performance.

Investigations of solubility of gases in hydrocarbons have been reported in references 15, 16, and 17. Portions of the data from these investigations are shown in figure 14 to illustrate the solubility of carbon dioxide, oxygen, nitrogen, and air in pure hydrocarbons and kerosenes. The solubility is expressed in terms of the Bunsen absoprtion coefficient, which is defined as the volume of gas, reduced to 32° F and 1 atmosphere pressure, absorbed at the experimental temperature by unit volume of liquid under a partial gas pressure of 760 millimeters.

The influence of solvent type and temperature on solubility of carbon dioxide is shown in figure 14(a). The solubility decreases as temperature increases in all hydrocarbon solvents investigated. Solubility of carbon dioxide in kerosene is appreciably lower than in the other fuels, particularly at low temperatures. At high temperatures, the solubility becomes more nearly independent of fuel type. It is also seen in this figure that solubility in an aromatic (toluene) fuel is greater than in the paraffinic fuels.

In figure 14(b) the solubility of oxygen is very similar to that of carbon dioxide as regards relative behavior in different paraffinic solvents; however, oxygen solubility in toluene is very nearly the same as that of oxygen in kerosene. The latter result is very different from the solubility of carbon dioxide in toluene and kerosene (fig. 14(a)). The Bunsen coefficients for oxygen are considerably lower than those of carbon dioxide.

The solubility of nitrogen (fig. 14(c)) is similar to solubility of oxygen but greater spread is apparent among the pure paraffinic hydrocarbon solvents. The Bunsen absorption coefficients for nitrogen are lower than those of both carbon dioxide and oxygen.

Figure 14(d) compares solubility data for oxygen and nitrogen in kerosene (ref. 15) with data on solubility of air in kerosene (ref. 17). The kerosenes used in the two investigations differ, so no direct relation is to be expected. The calculated curve for air in this figure was determined by interpolation between the curves for oxygen and nitrogen based upon oxygen-nitrogen volume ratio of 21 to 79. The experimental curves for air in the two kerosenes reported in reference 17 are unusual in that both curves pass through a minimum. No explanation for this result is apparent.

The data used in figures 14(a), (b), and (c) were obtained by the same investigators (refs. 15 and 16) and for all systems except toluene-oxygen and toluene-nitrogen there is a decreasing solubility with increasing temperature. For these cases and others reported in reference 16 where solubility decreases with increasing temperature, the following equation quite closely predicts the temperature effect:

$$\log \alpha = a - b \log T \tag{11}$$

where

α Bunsen absorption coefficient

T temperature, °R

a,b constants depending on gas and fuel

Equation (11) may be applicable to the estimation of the solubility of gases in fuels at any temperature if data are available at two temperatures to permit the evaluation of the constants a and b. However, equation (11) obviously does not fit abovementioned toluene-oxygen and toluene-nitrogen data nor the kerosene-air data from reference 17 (fig. 14(d)) and may not be generally valid.

Complete solubility curves for air in JP-3 and JP-4 types of fuel are unavailable; however, values for three samples of each at 60° F are cited in reference 18. The averages for these samples are compared in the following table with an average for three samples of kerosene (JP-1) and with the average cited for gasolines in reference 2 (p. 225).

Fuel	Bunsen absorption coefficient
Gasoline	0.228
JP-3	.224
JP-4	.183
JP-1	.132

In concluding the discussion of gas solubility, a word of caution is in order regarding the use of the Bridgeman and Aldrich equation for air solubility in gasoline.

$$\alpha = a\rho(1 - b\rho) \qquad (12)$$

where

ρ specific gravity of gasoline at 60/60° F

This equation has been found satisfactory for gasolines; however, reference 17 indicates that the equation does not apply for air solubility in kerosene-type fuels.

Flammability characteristics of fuels. - A considerable quantity of research information is available on the subject of fuel flammability characteristics. Since a review of this information is beyond the scope of this report only a few studies of interest in the design of fuel systems will be discussed. The specific problems included in this discussion are: (1) the concentrations of fuel in air required to yield combustible mixtures; and (2) the rate of flame propagation once the mixture is ignited.

Homogeneous, gas-phase, hydrocarbon-air systems are flammable over only 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 the fuel in air required for combustion and below which concentration flame will not propagate. Similarly, there is a rich (upper) limit which defines the maximum amount of fuel in air which will support combustion and beyond which flames will not propagate. These limits have been determined in many laboratories with many different apparatuses with varying results. The variations encountered are the result of variations in combustion-chamber geometry and ignition source.

Flammability limits vary with pressure and a typical pressure-fuel concentration limit diagram determined in a 2-inch diameter tube is shown for n-hexane in figure 15 (ref. 19). The lean and rich limits are only slightly affected by pressure down to pressures of about 10 inches of mercury absolute, but the range of fuel concentrations yielding a flammable mixture decreases below this pressure until a lower pressure for flammability is reached in a 2-inch tube at about one inch of mercury absolute, below which no mixture can be ignited. Substantially the same pressure-composition limit diagrams are obtained for all hydrocarbons that are likely to be used as aircraft fuels.

Caution should be exercised in applying these data to aircraft fuel tanks because of the relatively small size of the flammability limit test apparatus. The concentration limits are little affected by the size of the apparatus at pressures above about 10 inches of mercury absolute, but below this pressure, concentration limits will widen with increasing volume. It is also probable that a much lower low pressure limit for flammability would be found in aircraft tanks than the value of 1 inch of mercury absolute observed in the 2-inch tube. Increasing temperature will slightly widen the concentration limits and slightly lower the minimum pressure for flammability.

Neglecting mist effects, the possibility of having a flammable fuel-air mixture in a fuel tank at any given temperature and pressure is governed by the composition-pressure requirements illustrated in figure 15 and the vapor pressure-temperature characteristics of the fuel. If the fuel has sufficiently low vapor pressure at the temperature of interest so that fuel-air mixtures richer than the lean limit cannot be attained, then a flammable mixture cannot be generated in a fuel tank. Similarly, if the fuel has a sufficiently high vapor pressure so that the rich limit is exceeded a flammable mixture will not exist in the tank, <u>provided that equilibrium conditions are attained and the concentration of fuel in the vapor phase is that theoretically possible for the fuel</u>. This proviso is underlined since flammable mixtures can be formed under nonequilibrium conditions even with very volatile fuels when the over-rich equilibrium fuel concentrations are diluted with air.

Assuming equilibrium vaporization conditions and again neglecting mist effects, flammability limit envelopes as functions of temperature and altitude are plotted for fuels of varying Reid vapor pressure in figure 16 (refs. 2 and 5). Superimposed on these envelopes are average temperature altitude lines for tropical, standard, and arctic conditions. Figure 16 should not be accepted as representative of requirements for complete safety since:

(1) Equilibrium vaporization is assumed.

(2) Calculations are based on flammability limit data obtained in relatively small combustion tubes and it is likely that some fuel-air mixtures in aircraft tanks will be flammable at altitudes greater than the 62,000 feet shown in figure 16.

(3) The effects of mists (suspended fuel droplets) have been neglected.

The presence of suspended liquid fuels in the form of mists can extend the lower temperature (lean) limits of flammability far below those shown in figure 16. The lower flammability limit for hydrocarbon mist-air systems is at about 0.04 fuel-air ratio as reported by the Bureau of Mines under contract with the Army Air Forces. This lean limit concentration of 0.04 fuel-air ratio for liquid-air systems is about the same as the lean limit concentration for the vapor-air system shown in figure 15 and shows that well dispersed liquid in air is about as flammable as equivalent concentrations of vapor in air. The extension of flammability limits for kerosene due to mist effects are shown in figure 17 (ref. 20).

The lean temperature limits for gasolines and jet fuels under assumed equilibrium conditions may be estimated from the following equation reported in reference 21:

$$T_L = T_f - 8 - 0.024\ T_{10} \qquad (13)$$

where

T_L lean flammability limit temperature, °F

T_f flash point, °F

T_{10} 10-percent A.S.T.M. distillation point, °F

The flash point is linearly related to T_{10} as shown in reference 22.

$$T_f = 0.69\ T_{10} - 126 \qquad (14)$$

Combining equations (13) and (14)

$$T_L = 0.67\ T_{10} - 134 \qquad (15)$$

Reference 21 presents the following relation between rich and lean flammability limits.

$$T_R - T_L = 34 + 0.109\ T_{10} \qquad (16)$$

Combining equations (15) and (16)

$$T_R = 0.78\ T_{10} - 100 \qquad (17)$$

Equations (15) and (17) together with values of T_{10} from table VIII have been used to estimate the possible variation in sea-level lean and rich temperature limits for jet fuels procured under a single specification. These estimates are presented in the following table:

Fuel	Sea-level lean temperature limit, °F				Sea-level rich temperature limit, °F			
	Min.	Max.	Av.	Spread between min. and max.	Min.	Max.	Av.	Spread between min. and max.
JP-1	85	113	98	28	155	188	171	33
JP-4	-6	34	15	40	49	95	74	46
JP-3	-56	6	-24	62	-10	62	28	72

These data show clearly that the lean and rich flammability temperature limits decrease as the volatility increases. More significant than this result, however, is the fact that under a single specification the variations in limits for different batches of the same fuel may be quite large. For example, the spread in T_{10} for 43 samples of JP-4 fuel is shown to be 59° F (table VIII). This variation of T_{10} indicates a variation of 40° F and 46° F for lean and rich temperature limits, respectively, as calculated from equations (15) and (17).

For convenience in estimating sea-level flammability limits in terms of fuel temperatures, equations (15) and (17) have been plotted in figure 18. An additional plot has been prepared (fig. 19) to illustrate the flammability envelopes for minimum, maximum, and average samples of JP-1, JP-3, and JP-4 fuels. The curves in this figure were prepared by taking the sea-level rich and lean temperatures from the above table and constructing the altitude portion of the curves by interpolations from figure 16. Since the sea-level limits for figure 19 are calculated from T_{10} alone and without regard for Reid vapor pressure, no comparison should be drawn between figures 16 and 19 on the effect of vapor pressure on the flammable envelopes.

It has long been recognized that the lean limit fuel-air mixtures for all hydrocarbons contain about the same amount of combustibles in terms of heat of combustion per unit volume. In reference 23, this heat content was calculated for a variety of hydrocarbons and found to average 10.4 kilocalories per mole of fuel-air mixture. The fuel concentration required for the lean-limit mixture can be calculated from this average value by use of the following equation in which conversion has been made to English units:

$$L = \frac{1.87 \times 10^6}{\Delta H \times M} \tag{18}$$

where

L lean limit concentration, percent by volume

ΔH net heat of combustion, Btu/lb

M molecular weight

The rich concentration limit can also be estimated by the following relation:

$$R = L + \frac{143}{M^{0.7}} \tag{19}$$

where

R rich limit, percent by volume

Equations (18) and (19) are applicable to pure hydrocarbons and also to those cases where petroleum-derived fuels are fully vaporized and where the net heat of combustion and molecular weight can be estimated from distillation and gravity data by use of the charts on pages 15, 21, and 138 of reference 1 and figure 2(a) of this report. For cases where the fuel is only partly vaporized, the average molecular weight of vaporized fraction must be estimated. For the fully vaporized case and from the distillation and gravity data from table VIII, the lean and rich limits for JP-1, JP-3, and JP-4 fuels of minimum, maximum, and average volatilities are compared in the following table:

Fuel	Lean limit, volume percent	Rich limit, volume percent
JP-1		
Min. volatility	0.62	4.62
Max. volatility	.70	5.13
Av. volatility	.67	4.94
JP-4		
Min. volatility	0.73	5.27
Max. volatility	.91	6.28
Av. volatility	.81	5.72
JP-3		
Min. volatility	0.75	5.39
Max. volatility	1.06	7.05
Av. volatility	.88	6.11

Temperature limits for flammability will increase if evaporation losses occur. The best equations available for estimating the magnitude of this increase are based upon pure hydrocarbon and gasoline data (ref. 21).

$$\Delta T_L \text{ or } \Delta T_r = L\sqrt{S}\,(1.7 - 0.03\,L) \tag{20}$$

where

ΔT_L and ΔT_r change in lean and rich temperature limits, respectively, $^{\circ}F$

L fuel evaporated, percent by weight

S slope of A.S.T.M. distillation curve at 10-percent point

The calculation of L is described in a later section of this paper.

The foregoing discussion is concerned with the concentrations of fuel in air required for flammability. In addition, it is of interest to know what rates of flame propagation are possible with hydrocarbon fuels if ignition occurs. There are no reliable relations for the estimation of flame speeds of commercial fuel blends; however, fundamental studies of pure hydrocarbon flame speeds do provide a few data indicative of the behavior of hydrocarbon mixtures.

For homogeneous gas phase mixtures, the laminar hydrocarbon-air propagation rates are quite low, of the order of 1 to 2 feet per second. Under turbulent conditions the order of propagation may increase to approximately 300 feet per second and under conditions conducive to detonation may reach 5000 feet per second. These rates are not greatly influenced by hydrocarbon type or volatility provided that the fuel is sufficiently volatile to produce near-ideal mixtures.

When fuels are burned in shallow troughs the rate of flame propagation down the trough is influenced by volatility (data obtained by Shell Dev. Co.). This result is illustrated in figure 20 where the relation between fuel vapor pressure and flame velocity is presented.

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

The foregoing section has presented 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 which will not be discussed.

The gum content of fresh fuel should not exceed the 10 milligrams per 100 milliters as required by the present military specifications. These specifications also require that the gum content should not exceed 20 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; and either or both may be found in jet fuels within the required concentration limits.

Under certain conditions several factors could contribute to gum. For example, new drums and containers may contain rolling, drawing, and beading compounds, degreasing solvents, paint, and lacquer all of which might increase the gum content.

Gum content is limited in reciprocating engine fuels primarily to cut down on induction system deposits. There is no indication that soluble gum contents up to several times that permitted by the present specifications will adversely affect jet engine performance. However, insoluble gum may clog filters and cause sticking controls and valves, although at present no case is known of engine operational problems which were caused by fuel-derived gum.

Some storage stability data for jet fuels can be found in reference 24. In general, it appears that aviation gasoline is slightly more stable than JP-1 and that JP-3 is considerably less stable than JP-1; JP-4 may be slightly more stable than JP-3 because of its reduced end point.

While fuel gum does not appear to be a current problem, there have been operational difficulties caused by extraneous materials which 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 aggravated by the higher fuel flows used for jet fuels in comparison with those for piston-engine fuels. The possible difficulties arising from the presence of such materials is indicated by tests which showed that 10 grams of 10-micron and finer Arizona road dust per 1000 gallons of fuel will damage and cause sticking of engine fuel controls. One turbojet engine manufacturer has reported that 80 grams of dust per 1000 gallons of fuel will stop an engine in a very short time.

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 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 which may be present in aircraft fuels are definitely corrosive towards some airframe 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, hours	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 $\left(\frac{1}{2}'' \times 1\frac{1}{2}''\right)$ 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 25 that mercaptan sulfur will cause corrosion of cadmium. Furthermore the corrosion becomes greater if water is present in the fuel. It is also apparent that 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 apt 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.

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 (1X6 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 components of jet fuels which were selected to provide contrast in neutralization numbers.

Additional data from The Texas Company and reference 26 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 and especially in the presence of metal couples, a severe attack on magnesium and aluminum can be expected. Some information on this subject is presented in reference 26.

Further information on corrosion is reported in references 27 and 28. In these investigations it is concluded that lead, cadmium-plated steel, copper, brass, and zinc are the more susceptible metals to fuel corrosion in comparisons with tin, steel, black iron, magnesium, and aluminum. It was also found that JP-3 fuel is more corrosive than JP-1 fuel.

The results reported in reference 27 also indicate a relationship between corrosion and fuel neutralization number, as shown in figure 21. In other studies the relation has not been found to be so well defined. The air-well metal strip corrosion test (Federal Specification VV-L-791d) was used to determine the corrosion results in reference 27.

Deterioration of Rubber Materials

Certain fuels contain components which tend to promote the deterioration of rubber materials in fuel systems and tanks. Variations in the concentrations of such 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.

Before this time, wartime gasolines had contained reasonably high concentrations of aromatics in order to maintain required antiknock quality without limiting availability. With the end of the war the question of availability was no longer critical; consequently, the required antiknock quality could be maintained with paraffinic fuels. This reduction in aromatic concentration resulted in an epidemic of gasket leakage troubles in military aircraft. These troubles were attributed to the fact that nonaromatic fuels cause shrinkage whereas aromatics tend to swell rubber materials. As an interim solution to this problem, the military gasoline specification was revised to require a minimum of 10 percent aromatics.

The obvious permanent solution to this problem is to find materials resistent to the expected composition changes in fuels, and investigations were initiated to achieve this objective. Simultaneously a panel of the NACA Subcommittee on Aircraft Fuels was requested to study the problem of rubber swelling to determine an adequate control of fuel properties for inclusion in aviation fuel specifications. As a result of this study, the panel recommended that the aniline point of the fuel not exceed 130° F or that the Rubber Swell Index not be less than 43. The Rubber Swell Index is defined as follows:

$$\text{Rubber Swell Index} = 100 \times \frac{\text{Specific dispersion}}{\text{Aniline point } (^{\circ}\text{F}) + 100}$$

This index was subsequently included in the aviation gasoline specification.

Although the study conducted by the panel was intended to remedy gasoline difficulties, five JP-3 fuels and one JP-1 fuel were included in the experimental programs. The results indicated that the Rubber Swell Index was satisfactory for Jet fuels. It was decided, however, that further studies would be required before the necessity for a Rubber Swell Index in jet fuel specifications could be established.

Later investigations (refs. 25 and 29) were conducted to evaluate the influence of jet fuel components on rubber materials used in aircraft construction. Reference 25 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 by reference 29 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.

Low-Temperature Filtration

In earlier sections of this report the water solubility characteristics of fuels have been described, and mention has been made of gum content and foreign suspended material that may be present from fuel handling procedures. The existence of any one 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 from water in the fuel when the fuel is cooled in flight (ref. 30). The water may initially be present in either solution alone or in solution plus a suspended water phase. In the presence of free water fuels will become saturated in a few hours. Since fuels are often in contact with water during processing and handling it can be assumed that most fuels are near saturation. Fuels may hold up a suspended water phase for several days (ref. 30) and it is probable that jet fuels, because of higher densities and viscosities, may hold up suspended water longer than do aviation gasolines. Data reported in reference 18 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 solidify on the downstream face of the element or on other downstream parts of the fuel system. The amount of water that may drop out of a fuel when the temperature is lowered can be estimated from figure 4.

There is at present no complete understanding of all the factors contributing to filter icing; however, pertinent discussions are contained in references 30 to 34. 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 problems. 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 the fuel system designer, perhaps the most appealing 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. 30); 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 and this particular additive is said to be resistant to extraction by water. Other organizations have also devoted some effort to the study of additives and it is conceivable that effective practical 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 present in supercooled droplet form and solidifies upon striking the filter, the clogging of filters could be reduced by making the filter surface hydrophobic. Improvements in filterability were made by coating the filter with surface active agents. It was suggested that a more acceptable solution would be the addition of minute quantities of a surface active agent to the fuel as a means of reducing ice formation on other parts of the fuel system as well as on the filter. The possible success of this method is dependent upon the discovery of 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 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. 35); therefore, control of the oxygen concentration to a level below this value by inerting will yield nonflammable fuel systems.

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 36. In addition, a discussion of solubility of gases in fuels has been presented in an earlier portion of the present paper. This information, too, must be considered in the application of inerting systems to aircraft.

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 relationships do not provide an accurate prediction of the vapor losses encountered with heavier fuels of the JP-3 and JP-4 types. Reference 37 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. 37) that of the existing equations for prediction of vapor loss, the following best represents JP-3 fuel data:

$$L = \left[\frac{T^2}{4\ ST + 16\ T_{10} - 0.02\ T_{10}\ (T-560)}\right] \log \frac{P_0}{P} + 1 \qquad (21)$$

where

L weight percent loss

T initial fuel temperature, $^{\circ}R$

S slope of A.S.T.M. distillation curve at 10-percent evaporated point

T_{10} 10-percent A.S.T.M. distillation, $^{\circ}R$

P_0 true vapor pressure of fuel at initial fuel temperature (equation (8))

P absolute ambient pressure in tank

In order to simplify the use of equation (21), 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 22. This figure, together with figure 23, indicates the losses that might be expected at 110° F for different fuels. The value of the true vapor pressure P_0 on the abscissa of figure 23 can be calculated from equations (8) and (9) or approximated from figure 10.

Data for average JP-3 and JP-4 fuels from table VIII and figure 6 were used to compare the expected weight losses of fuel by vaporization up to an altitude of 60,000 feet and for an initial fuel temperature of 110° F. The results indicate that the loss for an average JP-3 fuel would be about 15 percent and for an average JP-4 fuel about 9 percent.

Entrainment losses. - At low rates 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 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. 38 and 39) have been conducted to determine methods by which entrainment losses might be eliminated, yet 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 on total fuel lost in simulated flight. The results are shown in figure 24 where the total fuel loss during simulated flight is plotted against the maximum pressure differential encountered at any time during the flight. It is apparent from this figure 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. 17) that pressurization to 0.2 pounds 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, 17, 37, and 40.

CONCLUDING REMARKS

The primary objective of this report has been 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 have been illustrated. In addition, an effort has been 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 have been 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 have been 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.

Another fact to consider in the use of the data is the limited information on JP-4 fuel. Although this fuel is of greatest current interest, commercial samples have been available for only a short period; consequently, the accumulated experimental data are rather limited. Fortunately, however, many of the equations and charts presented are sufficiently sound to permit application to fuels of the JP-4 type.

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 has been deliberately liberal in order to provide the reader additional sources of information.

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REFERENCES

1. Maxwell, J. B.: Data Book on Hydrocarbons. Second ed., D. Van Nostrand Co., Inc., 1951.

2. Anon.: CRC Handbook. Coordinating Res. Council, Inc., 1946.

3. Nelson, W. L.: Petroleum Refinery Engineering. McGraw-Hill Book Co., Inc., 1936, p. 118.

4. Jessup, R. S., and Rothberg, Simon: Final Report on the Relation between Net Heat of Combustion, Aniline Point, and Gravity of AN-F-58 Fuels. Nat. Bur. Standards, July 18, 1949.

5. Warfield, Calvin N.: Tentative Tables for the Properties of the Upper Atmosphere. NACA TN 1200, 1947.

6. Sweeney, W. J., Blackwood, A. J., and Guyer, W. R. F.: Report on Aviation Gas Turbine Fuels. Paper presented at Nat. Aircraft Propulsion Meeting, I. A. S. (Cleveland), March 28, 1947.

7. Hibbard, R. R., and Schalla, R. L.: Solubility of Water in Hydrocarbons. NACA RM E52D24, 1952.

8. Griswold, John, and Kasch, J. E.: Hydrocarbon-Water Solubilities at Elevated Temperatures and Pressures. Ind. and Eng. Chem., vol. 34, no. 7, July 1942, pp. 804-806.

9. Sanderson, R. T.: Viscosity-Temperature Characteristics of Hydrocarbons. Ind. and Eng. Chem., vol. 41, no. 2, Feb. 1949, pp. 368-374.

10. Gruse, William A., and Stevens, Donald R.: The Chemical Technology of Petroleum. Second ed., McGraw-Hill Book Co., Inc., 1942, p. 606.

11. Holliman, W. C., Barker, M. G., and Potts, Nancy: Survey of Commercial Aviation-Gasoline Characteristics, March 1947 Production. R. I. 4273, Bur. Mines, May 1948.

12. Blade, O. C.: National Annual Survey of Aviation Gasoline and Aviation Jet Fuel, Oct. 1951 Production. Rep. of Investigations 4889, Bur. Mines, May 1952.

13. Petersen, C. C.: Studies to Determine the Electrical and Physical Properties of Fuels. A. F. Tech. Rep. No. 6224, Armour Res. Foundation of Illinois Inst. Tech., Oct. 1950. (Purchase Order No. 33-(038)-3793. E. O. No. 601-301.)

14. Bartberger, C. L.: Preliminary Report on Effects of Fuel Characteristics on Capacitor Type Fuel Quantity Gages: Analysis of Armour Research Foundation Data on Fuel Characteristics. Rep. No. NAES-INSTR-4-51, Aero. Instr. Lab., U. S. Naval Base Station (Philadelphia), Feb. 5, 1951.

15. Glendinning, W. G., and Bedwell, M. E.: Solubility of Gases in Liquids Used in Aircraft. Part I - Measurement of Gas Solubility. Rep. No. Chem. 464, British R. A. E., Oct. 1949.

16. Glendinning, W. G., and Bedwell, M. E.: Solubility of Gases in Liquids Used in Aircraft. Part II - Solubility of Atmospheric Gases, Hydrogen and Carbon Monoxide. Rep. No. Chem. 477, British R. A. E., Feb. 1951.

17. Derry, L. D., Evans, E. B., Faulkner, B. A., and Jelfs, E. C. G.: Vapour and Air Release from Aviation Fuels. Jour. Inst. Petroleum (London), vol. 38, no. 343, July 1952, pp. 475-514; discussion, pp. 515-525.

18. Anon.: Low Temperature Pumping Characteristics and Physical Properties of Aviation Gas Turbine Fuels. Prepared by the Analysis Panel on Low Temperature Turbine Fuel Data of Civil Aircraft Fuels Performance Group, Aviation Fuels Div., Coordinating Research Council, Inc., June 1, 1949.

19. DiPiazza, James T., Gerstein, Melvin, and Weast, Robert: Flammability Limits of Hydrocarbon-Air Mixtures. Reduced Pressures. Ind. and Eng. Chem., vol. 43, no. 12, Dec. 1951, pp. 2721-2725.

20. MacLennan, A. M.: A Study of Kerosine Mist Explosions. Rep. No. Chem. 448, British R.A.E., Sept. 1949.

21. Anon: CFR Handbook. Coordinating Res. Council, Inc., 1944, p. 64.

22. Cleveland Laboratory Aircraft Fire Research Panel: Preliminary Survey of the Aircraft Fire Problem. NACA RM E8B18, 1948.

23. Spakowski, Adolph E.: Pressure Limits of Flame Propagation of Pure Hydrocarbon-Air Mixtures at Reduced Pressure. NACA RM E52H15, 1952.

24. Altman, Robert W.: The Storage Characteristics of Fuels Under Severe and Moderate Climatic Storage Conditions. A.A.F. Tech. Rep. No. 5636, Air Materiel Command, Wright Field (Dayton, Ohio), Sept. 25, 1947.

25. O'Hara, J. W., and Elliott, E. R.: Investigation of the Effect of Mercaptan Compounds in Jet Engine Fuels on Metal and Rubber Materials. AEL-1138, Naval Air Material Center, Aero. Eng. Lab. (Philadelphia), Sept. 26, 1950.

26. Paige, H., and Ketcham, S. J.: The Effects of Naphthenic Acids on the Corrosion Behavior of Aluminum Alloys in Fuel Tanks. Rep. No. AML NAM AE411049, Pt. I, Naval Air Material Center, Aero. Materials Lab., April 13, 1951.

27. Sneed, Richard W.: Study of the Correlation of Fuel Acidity with Corrosion of Metals Used in Aircraft Fuel Systems. Memo. Rep., Materials Lab. Headquarters Air Material Command, April 17, 1951.

28. Sneed, R. W., and Altman, R. W.: Studies of the Corrosion Characteristics of Jet Propulsion Fuels. Memo. Rep., Air Materiel Command, Wright-Patterson Air Force Base, Dayton (Ohio), June 25, 1951.

29. Lundblad, C. E.: Investigation of the Effect of Certain Jet Fuel Impurities on Rubber Components in Aircraft Fuel Systems. Memo. Rep., Power Plant Lab. Headquarters Air Materiel Command, Eng. Div., April 21, 1950.

30. Krynitsky, John A., Crellin, John W., and Carhart, Homer W.: The Behavior of Water in Jet Fuels and the Clogging of Micronic Filters at Low Temperatures. NRL Rep. 3604, Jan. 11, 1950. (NRL Problem No. C01-10D, BuAer Problem No. TEDNRL-pp-502.)

31. Rothenberg, A. J.: One Twentieth (1/20) Scale Filter Tests and Low Temperature Investigation on Fuels Selected by Coordinating Research Council. Rep. No. Ing. ER-149, Inglewood Lab., Thompson Products, Inc. (Cleveland), April 9, 1951.

32. Williams, C. G.: Fuels and Lubricants for Aero Gas Turbines. Jour. Inst. Petroleum, vol. 33, no. 281, May 1947, pp. 267-306.

33. Anon.: Engineering and Development Test (Climatic Hanger Cold) of Fuel System of P-80B Airplane. Letter Final Report on APG Project No. 4-48-5-CHC. Eglin Air Force Base, May 25, 1948.

34. Bloomquist, C. R., Demuth, F. F., Lee, J. C., and Teichman, O. E.: The Effect of Fuel-Carried Dirt and Ice on Turbo Jet Power Control Systems. A. F. Tech. Rep. No. 6441, Armour Res. Foundation of Illinois Inst. Tech., U. S. Air Force, Air Materiel Command, Sept. 1950. (Contract No. AF33(038)-6494, E. O. No. R540-74.)

35. Coward, H. F., and Jones, G. W.: Limits of Inflammability of Gases and Vapors. Bull. 279, Bur. Mines, 1939.

36. Weiss, Solomon, and Pesman, Gerard J.: Bibliography of Unclassified Aircraft-Fire Literature. NACA RM E9H03, 1949.

37. Anon.: Altitude Performance of Gas Turbine Fuels of Varying Volatility. Final Rep., Aviation Fuels Div., Coordinating Research Council, Inc., April 1951. (Contract No. NOa(s) 10555 and Amendments 1 and 2, U.S. Navy Bur. Aeronautics.)

38. Rothenberg, Arthur J.: Surface and Interfacial Tension and Foam Stability of Jet Fuels. Rep. No. Ing. ER-125, Inglewood Lab., Thompson Products, Inc. (Cleveland), March 1, 1950.

39. Ross, Sidney: The Inhibition of Foaming. Rensselaer Poly. Inst. Bulletin, Engineering and Sciences Series, No. 63, May 1950.

40. Finn, R. F., and Kolfenbach, J. J.: Memorandum on Volatility Aspects of Jet Fuel. Res. Div., Esso Labs., Standard Oil Development Co., Sept. 12, 1952.

TABLE I - SPECIFICATIONS OF AIRCRAFT FUELS

Specification	MIL-F-5572				MIL-F-5616	MIL-F-5624A		MIL-F-7914(AER)
Fuel Grade	80[a]	91/98[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)	--------	250(max)	410(max)
40	167(min)	167(min)	167(min)	167(min)	--------	--------	--------	--------
50	221(max)	221(max)	221(max)	221(max)	--------	--------	--------	--------
90	275(max)	275(max)	275(max)	275(max)	490(max)	400(min)	--------	--------
End point	338(max)	338(max)	338(max)	338(max)	572(max)	600(max)	550(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.	5.5-7.0	5.5-7.0	5.5-7.0	5.5-7.0	--------	5.0-7.0	2.0-3.0	-------
Aromatics, percent by volume	--------	--------	--------	--------	20(max)	25(max)	25(max)	25(max)
Bromine number	--------	--------	--------	--------	3.0(max)	30.0(max)	30.0(max)	30.0(max)
Total sulfur, percent by weight	0.05(max)	0.05(max)	0.05(max)	0.05(max)	0.20(max)	0.4(max)	0.4(max)	0.5(max)
Mercaptan sulfur, percent by weight	--------	--------	--------	--------	--------	0.005(max)	0.005(max)	0.005(max)
Air-jet residue, mg/100 ml	3.0(max)	3.0(max)	3.0(max)	3.0(max)	5.0(max)	10.0(max)	10.0(max)	10.0(max)
Accelerated gum, mg/100 ml	6.0(max)	6.0(max)	6.0(max)	6.0(max)	8.0(max)	20.0(max)	20.0(max)	20.0(max)
Heat of combustion, Btu/lb	18,700(min)	18,700(min)	18,700(min)	18,700(min)	--------	18,400(min)	18,400(min)	18,300(min)
Specific gravity, 60/60° F	-----------	-----------	-----------	-----------	0.850(max)	0.728-0.80	0.747-0.825	0.780-0.850
Gravity, °A.P.I.	-----------	-----------	-----------	-----------	----------	63-45	58-40	50-35
Viscosity at -40° F, centistokes	-----------	-----------	-----------	-----------	10.0(max)	-----------	-----------	20.0(max)
Flash point, °F	-----------	-----------	-----------	-----------	110(min)	-----------	-----------	140(min)

[a] Octane number.

TABLE II - CHRONOLOGICAL DEVELOPMENT OF THE JP-4 SPECIFICATION

Date	Jan. 1947	Dec. 12, 1947	Mar. 30, 1949	Jan. 26, 1950	May 23, 1951	
New designation				MIL-F-5624	MIL-F-5624A	
Old designation	Proposed	AN-F-58	AN-F-58a	AN-F-58a	MIL-F-5624	-----------
Fuel grade	JP-3	JP-3	JP-3	JP-3	JP-3	JP-4
A.S.T.M. distillation D86-52, $^{\circ}F$						
Percentage evaporated						
10	-------	--------	--------	--------	--------	250(max)
90	-------	425(min)	400(min)	400(min)	400(min)	--------
End point	550-600	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)
Loss, percent	-------	1.5(max)	1.5(max)	1.5(max)	1.5(max)	1.5(max)
Freezing point, $^{\circ}F$	-76(max)	-76(max)	-76(max)	-76(max)	-76(max)	-76(max)
Reid vapor pressure, lb/sq in.	5.0-8.0	5.0-7.0	5.0-7.0	5.0-7.0	5.0-7.0	2.0-3.0
Aromatics, percent by volume	30(max)	30(max)	25(max)	25(max)	25(max)	25(max)
Bromine number	--------	14(max)	30(max)	30(max)	30(max)	30(max)
Total sulfur, percent by weight	0.5(max)	0.5(max)	0.5(max)	0.5(max)	0.4(max)	0.4(max)
Mercaptan sulfur, percent by weight	--------	--------	--------	--------	0.005(max)	0.005(max)
Air-jet residue, mg/100 ml	5.0(max)	10(max)	10(max)	10(max)	10(max)	10(max)
Accelerated gum, mg/100 ml	8.0(max)	20(max)	20(max)	20(max)	20(max)	20(max)
Heat of combustion, Btu/lb	18,400(min)	18,200(min)	18,400(min)	18,400(min)	18,400(min)	18,400(min)
Specific gravity, 60/60° F	-----------	-----------	0.728-0.802	0.728-0.802	0.728-0.802	0.747-0.825
Gravity, °A.P.I.	-----------	-----------	63-45	63-45	63-45	58-40
Viscosity, centistokes						
-40° F	6.0(max)	10(max)	-----------	-----------	-----------	-----------
100° F	0.8(min)	-------	-----------	-----------	-----------	-----------

TABLE III - PROPERTIES OF A TYPICAL JP-5 STOCK AND A SPECIAL BLEND OF JP-5 AND MIL-F-5572 (115/145 Grade) AVIATION GASOLINE[a]

	JP-5	Blend
A.S.T.M. distillation D86-52, °F		
Percentage evaporated		
Initial point	357	142
5	371	192
10	375	230
20	385	289
30	393	338
40	402	371
50	411	394
60	421	407
70	433	420
80	448	436
90	464	457
End point	502	499
Residue, percent	0.7	1.1
Loss, percent	0.2	1.0
Freezing point, °F	---	-60
Reid vapor pressure, lb/sq in.	0.2	2.0
Aromatics, percent by volume	---	13.4
Bromine number	---	0.5
Air-jet residue, mg/100 ml	---	2
Accelerated gum, mg/100 ml	---	4
Hydrogen-carbon ratio	---	0.164
Heat of combustion, Btu/lb	---	18,670
Specific gravity, 60/60° F	0.808	0.785
Gravity, °A.P.I.	43.5	48.7
Aniline point, °F	----	142.2
Flash point, °F	142	-----

[a] Three parts by volume JP-5 and one part aviation gasoline.

TABLE IV - 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, °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, °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
Air-jet residue, mg/100 ml	5	3.0	------	-----	0.8	1.0	-----	-----	2.5	-----
Accelerated gum, mg/100 ml	-----	-----	------	-----	2.0	0	-----	1.0	4.4	-----
Specific gravity, 60/60° F	0.834	0.835	0.800	0.802	0.832	0.831	0.796	0.786	0.796	0.811
Gravity, °A.P.I.	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, °F	----	----	112	112	----	---	----	----	---	

TABLE V - TYPICAL INSPECTION DATA FOR MIL-F-5624A (JP-3) FUELS

Sample	A	B	C	D	E	F	G	H
A.S.T.M. distillation D86-52, °F								
Percentage evaporated								
Initial point	117	100	104	118	100	116	113	111
10	178	146	208	144	130	149	169	172
20	205	---	---	153	157	164	198	215
30	226	---	---	166	294	181	218	245
40	246	---	---	184	350	200	236	271
50	267	302	368	205	377	224	254	297
60	292	---	---	229	398	262	270	323
70	322	---	---	306	424	346	293	349
80	363	---	---	426	454	403	324	385
90	415	486	421	468	493	438	388	425
End point	487	530	453	500	560	485	473	488
Residue, percent	1.0	---	1.2	1.3	1.0	1.0	1.0	1.0
Loss, percent	1.0	---	0.8	0.7	1.0	1.5	1.2	1.0
Freezing point, °F	<-76	<-76	-80	<-76	-76		<-76	---
Reid vapor pressure, lb/sq in.	5.8	6.4	6.3	5.6	5.5	6.3	6.2	5.7
Aromatics, percent by volume								
A.S.T.M. D875-46T	10	14	9.5	----	----	-----	---	---
Silica gel	9	---	---	----	----	-----	7.0	7.0
Bromine number	0.5	2.0	6.0	1.0	3.5	-----	3.0	0.5
Total sulfur, percent by weight	0.1	0.07	0.20	0.025	0.31	-----	0.06	0.07
Air-jet residue, mg/100 ml	1.0	9.8	2.0	1.9	6.7	-----	0.5	0.5
Accelerated gum, mg/100 ml	5.0	------	3.0	1.0	16.0	-----	15.8	3.4
Heat of combustion, Btu/lb	18,680	18,715	18,670	-----	-----	-----	18,765	18,675
Specific gravity, 60/60° F	0.748	0.780	0.790	0.737	0.730	0.739	0.742	0.756
Gravity, °A.P.I.	57.7	49.8	47.5	60.5	62.3	60.0	59.2	55.7

TABLE VI - TYPICAL INSPECTION DATA FOR MIL-F-5624A (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
Air-jet residue, mg/100 ml	11	1.0	1.0	1.0	3.4	8.0
Accelerated gum, mg/100 ml	15	2.3	1.0	2.3	4.6	12.0
Heat of combustion, Btu/lb	18,500	---	-----	-----	-----	18,725
Specific gravity, 60/60° F	0.793	0.777	0.779	0.790	0.790	0.756
Gravity, °A.P.I.	46.8	50.5	50.0	47.5	47.5	55.7

TABLE VII - PHYSICAL PROPERTIES OF A TYPICAL AVIATION GASOLINE AND TWO FUEL OILS

	[a]AN-F-48	Number 2 fuel oil	Number 6 fuel oil
A.S.T.M. distillation D86-52, °F[b]			
Percentage evaporated			
Initial point	105	358	---
10	144	436	---
20	162	---	---
30	178	---	---
40	191	---	---
50	202	---	---
60	210	---	---
70	219	---	---
80	225	---	---
90	236	572	---
End point	299	614	---
Residue, percent	0.5	---	---
Loss, percent	1.5	---	---
Freezing point, °F	<-76	---	---
Reid vapor pressure, lb/sq in.	6.6	---	---
Aromatics, percent by volume			
A.S.T.M. D875-46T	7.5	---	---
Silica gel	6.0	---	---
Bromine number	5.6	---	---
Total sulfur, percent by weight	<0.005	0.22	0.81
Accelerated gum, mg/100 ml	4.4	----	----
Hydrogen-carbon ratio	0.184	----	----
Heat of combustion, Btu/lb	18,980	18,340	17,700
Specific gravity, 60/60° F	0.704	0.861	0.957
Gravity, °A.P.I.	69.5	32.8	16.3
Carbon residue	----	0.13	----
Aniline point, °F	----	135.3	----
Viscosity, centistokes			
100° F	----	2.4	----
122° F	----	---	154
Flash point, °F	----	170	214

[a] 100/130 grade (NACA fuel number 48-359).

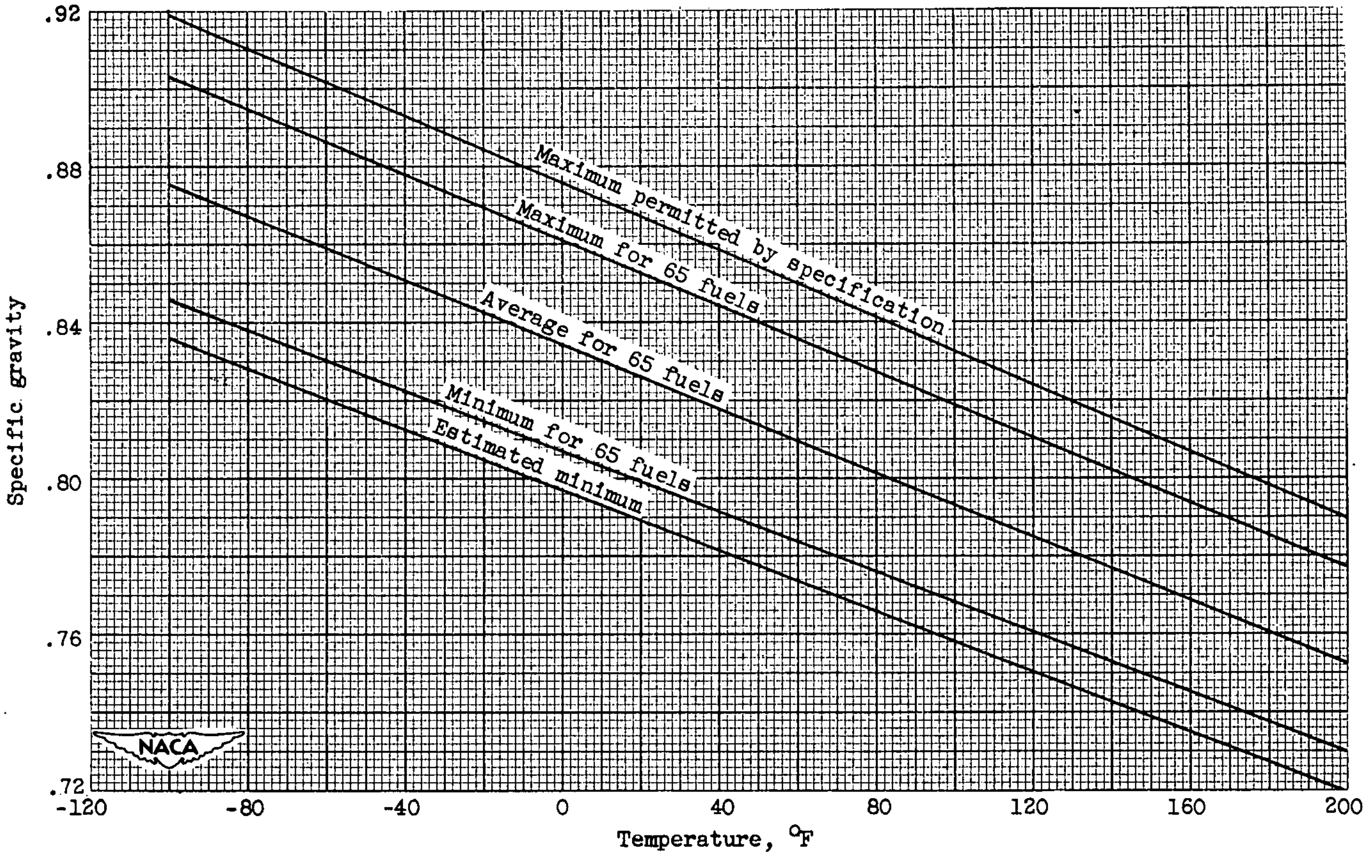
[b] A.S.T.M. D158 distillation method used for fuel oils.

TABLE VIII - VARIATIONS OF PHYSICAL PROPERTIES AMONG JET FUELS

	JP-1				JP-3				JP-4			
	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, °F												
Percentage evaporated												
Initial point	73	270	350	326	38	87	118	108	40	110	150	135
10	72	327	369	347	38	116	208	164	43	191	250	223
40	54	340	384	362	13	184	350	255	23	250	360	282
50	73	344	434	370	38	205	427	303	40	264	376	313
90	71	364	466	407	38	388	493	437	40	357	475	417
End point	71	400	520	448	38	453	560	497	41	410	561	484
Freezing point, °F	--	---	<-76	<-76	--	---	<-76	<-76	--	---	<-76	<-76
Reid vapor pressure, lb/sq in.	--	---	---	---	36	5.1	7.0	5.9	41	2.0	3.0	2.6
Aromatics, percent by volume A.S.T.M., D875-46T	22	7	19.6	14.2	26	4.3	19.2	11.2	19	0.6	17.5	12.5
Bromine number	16	0.4	2.8	1.1	30	0.1	17.0	2.54	21	0.6	8.0	2.1
Total sulfur, percent by weight	23	0.01	<0.05	0.036	30	0.017	0.45	0.09	16	0.009	0.277	0.060
Mercaptan sulfur, percent by weight	--	----	-----	-----	--	0	0.003	0.0008	--	-----	-----	-----
Air-jet residue, mg/100 ml	16	0	5.0	1.87	7	0.5	9.8	3.2	12	0.4	1.6	0.98
Accelerated gum, mg/100 ml	12	1.0	6.0	3.03	6	1.0	16.0	7.4	13	0.4	4.6	1.86
Hydrogen-carbon ratio	14	0.143	0.168	0.153	29	0.151	0.178	0.166	--	------	------	------
Heat of combustion, Btu/lb	13	18,385	18,635	18,479	32	18,442	19,002	18,710	2	18,500	18,725	18,613
Specific gravity, 60/60° F	65	0.784	0.836	0.810	38	0.729	0.799	0.760	22	0.752	0.809	0.777
Gravity, °A.P.I.	--	49.0	37.7	43.1	--	62.7	45.5	54.7	--	56.7	43.3	50.5
Viscosity at -40° F, centistokes	20	5.65	9.65	7.62	23	1.77	5.6	2.91	--	----	----	----
Flash point, °F	14	110	125	117	--	----	---	----	--	----	----	----

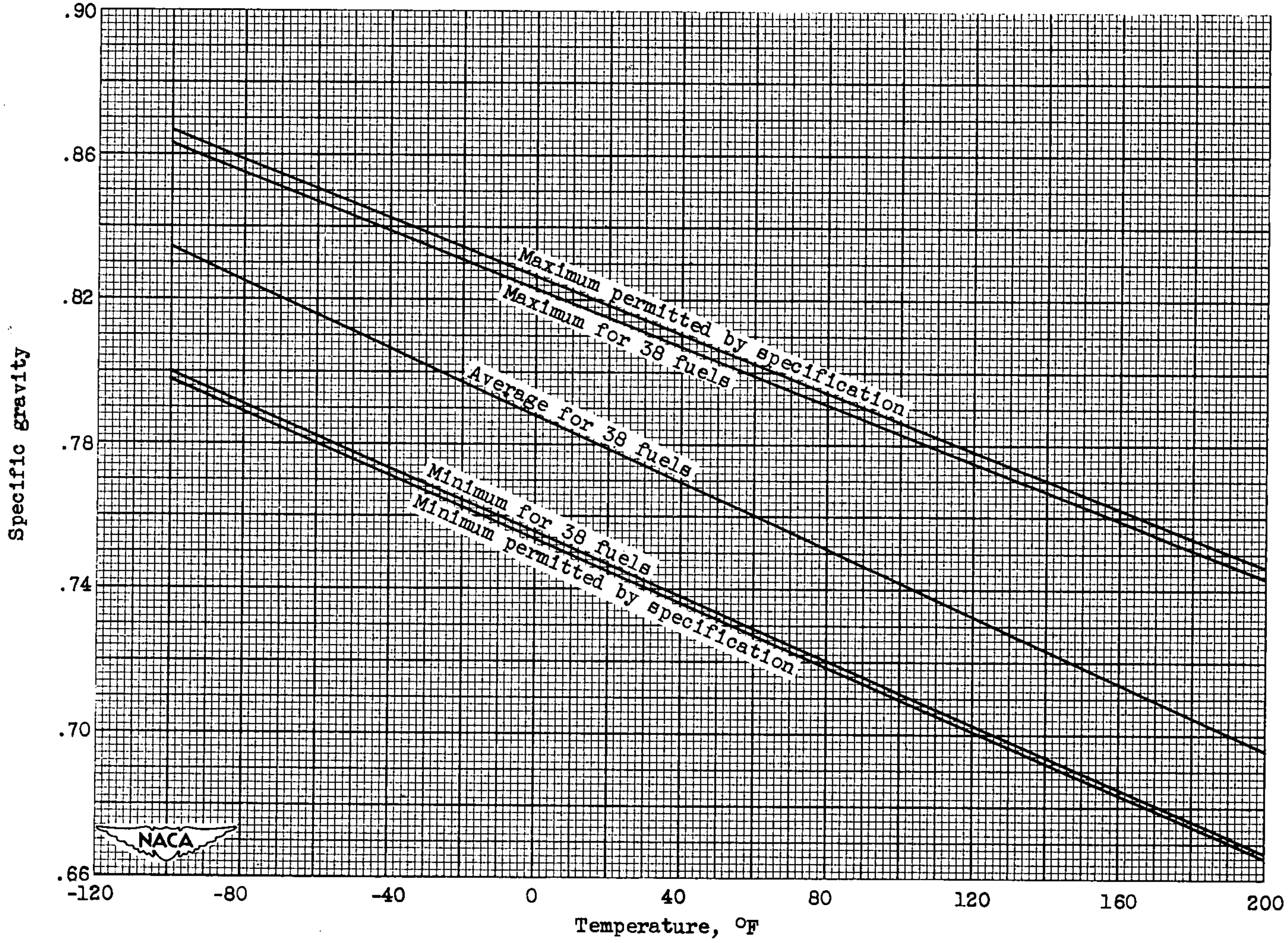
TABLE IX - ESTIMATED VARIATIONS OF PHYSICAL PROPERTIES OF JET FUELS

	JP-1			JP-3			JP-4		
	Minimum	Maximum	Estimated average	Minimum	Maximum	Estimated average	Minimum	Maximum	Estimated average
A.S.T.M. distillation D86-52, °F									
Percentage evaporated									
10	320	410	350	---	---	---	190	250	230
40	---	---	---	---	---	---	---	---	---
50	---	---	---	---	---	---	---	---	---
90	350	490	410	400	500	450	---	---	---
End point	400	572	450	450	600	500	400	550	480
Residue, percent	---	1.5	1.0	---	1.5	1.0	---	1.5	1.0
Loss, percent	---	1.5	1.0	---	1.5	1.0	---	1.5	1.0
Freezing point, °F	---	-76	<-76	---	-76	<-76	---	-76	<-76
Reid vapor pressure, lb/sq in.	---	----	----	5.0	7.0	6.0	2.0	3.0	2.5
Aromatics, percent by volume	0	20	12	0	25.0	12.5	0	25	13
Bromine number	0.3	3.0	1.0	0	30.0	3.0	0	30.0	2
Total sulfur, percent by weight	0	0.20	0.05	0	0.4	0.15	0	0.40	0.10
Mercaptan sulfur, percent by weight	---	----	----	0	0.005	0.001	0	0.005	0.002
Air-jet residue, mg/100 ml	0	5.0	2.0	0	10.0	5.0	0	10.0	1.0
Accelerated gum, mg/100 ml	0	8.0	3.0	0	20.0	10.0	0	20.0	2.0
Heat of combustion, Btu/lb	---	---	-----	18,400	19,000	18,700	18,400	18,900	18,650
Specific gravity, 60/60° F	0.775	0.850	0.800	0.728	0.802	0.770	0.747	0.825	0.785
Gravity, °A.P.I.	51.0	35.0	45.3	62.8	44.8	52.2	58.0	40.0	48.8
Viscosity at -40° F, centistokes	4.0	10.0	7.0	----	----	----	----	----	----



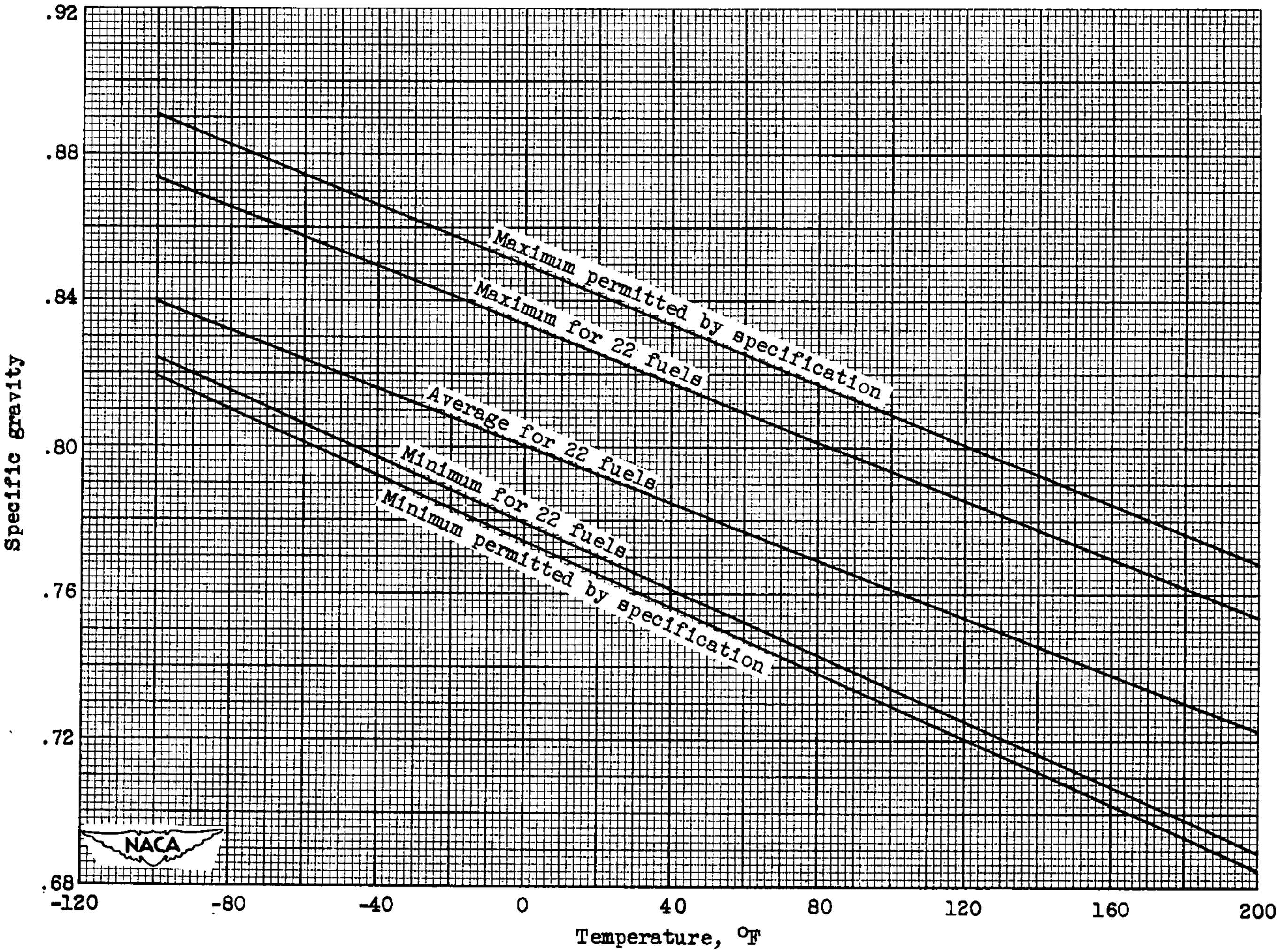
(a) MIL-F-5616 (JP-1) fuel.

Figure 1. - Variation of specific gravity with temperature.



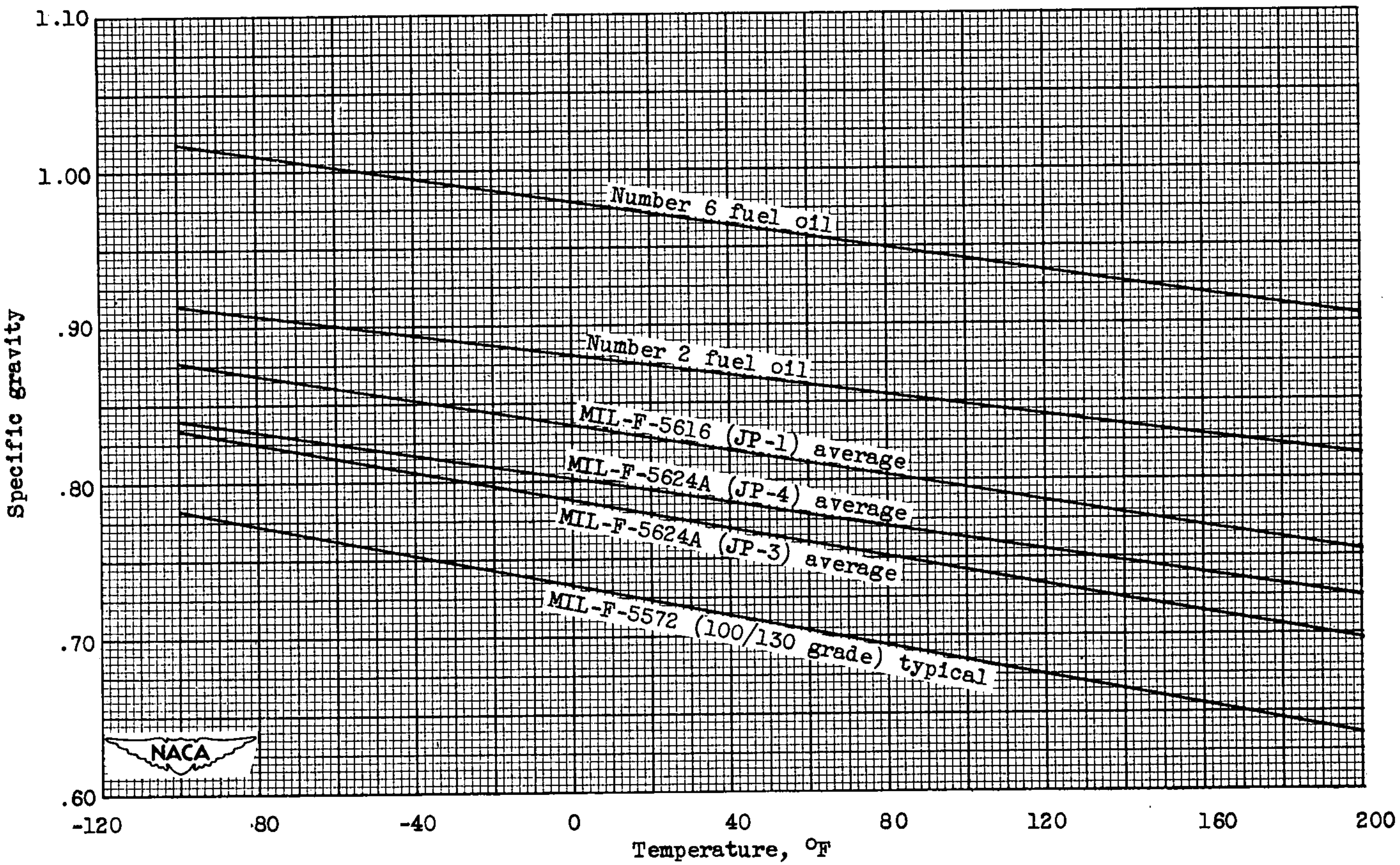
(b) MIL-F-5624A (JP-3) fuel.

Figure 1. - Continued. Variation of specific gravity with temperature.



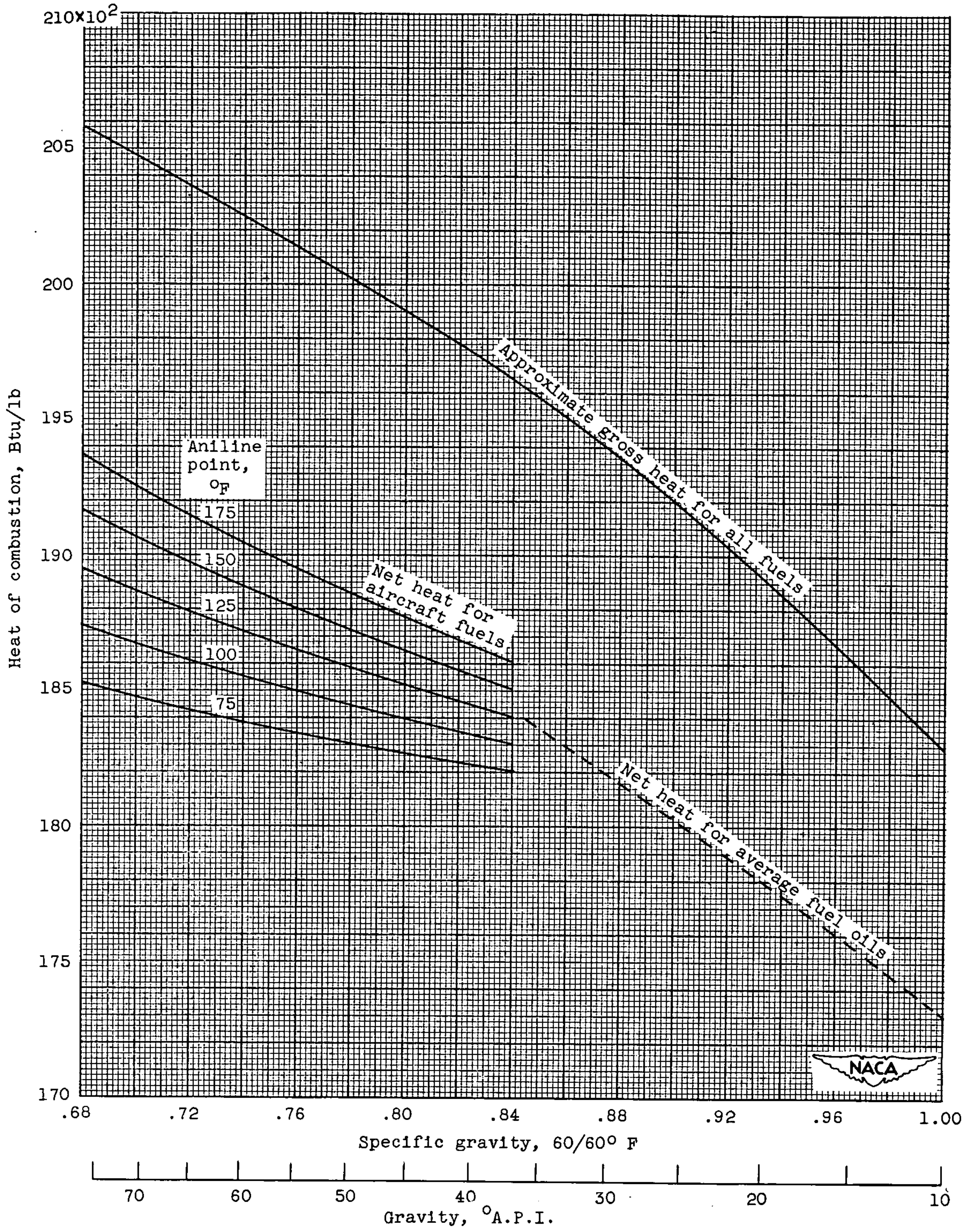
(c) MIL-F-5624A (JP-4) fuel.

Figure 1. - Continued. Variation of specific gravity with temperature.



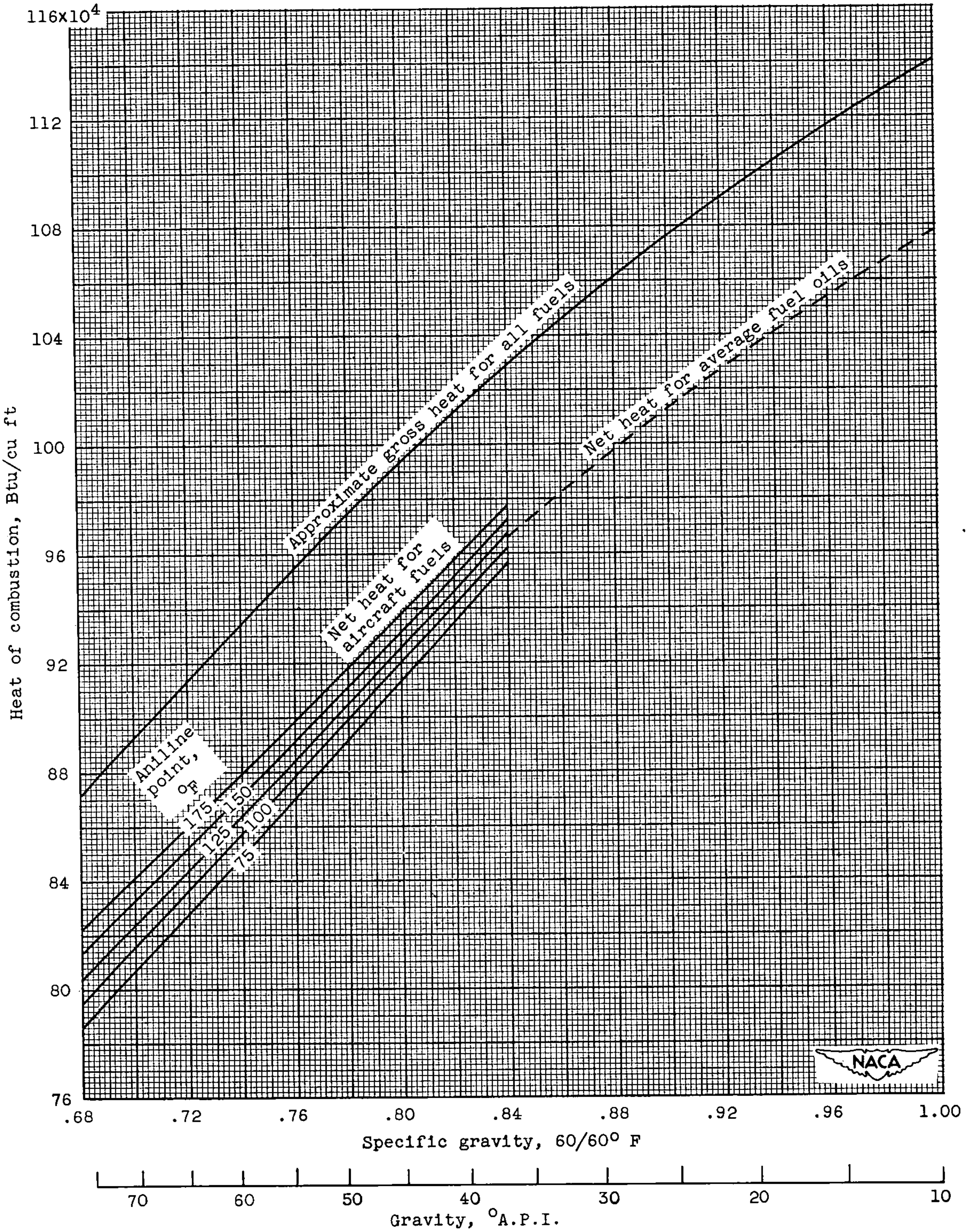
(d) Comparison of several fuels.

Figure 1. - Concluded. Variation of specific gravity with temperature.



(a) Heat of combustion per unit weight.

Figure 2. - Relation between heat of combustion, specific gravity, and specific gravity - aniline point for hydrocarbon fuels. (Based on refs. 1 and 4.)



(b) Heat of combustion per unit volume.

Figure 2. - Concluded. Relation between heat of combustion, specific gravity, and specific gravity - aniline point for hydrocarbon fuels. (Based on refs. 1 and 4.)

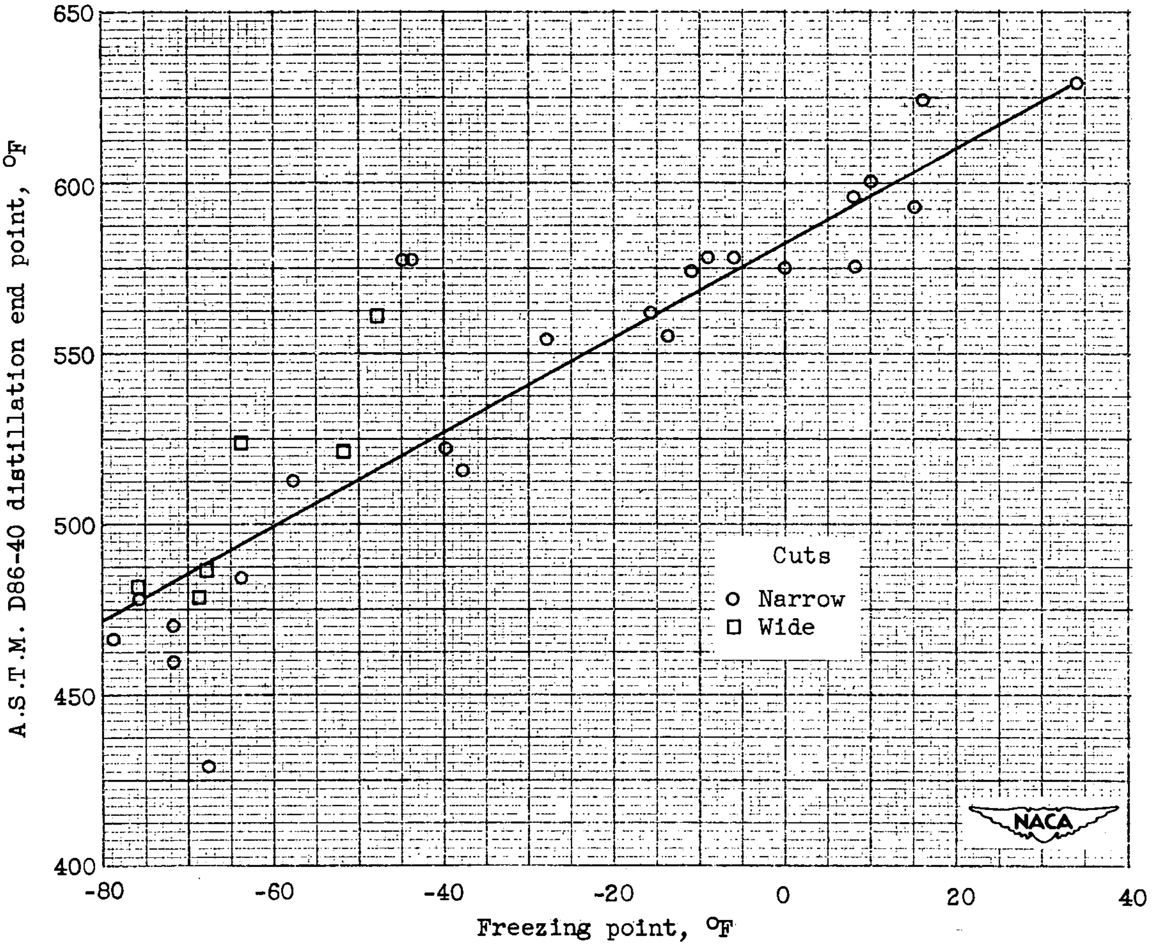


Figure 3. - Variation of freezing point with end point for crude cuts and blends. (Based on data from Bureau of Mines.)

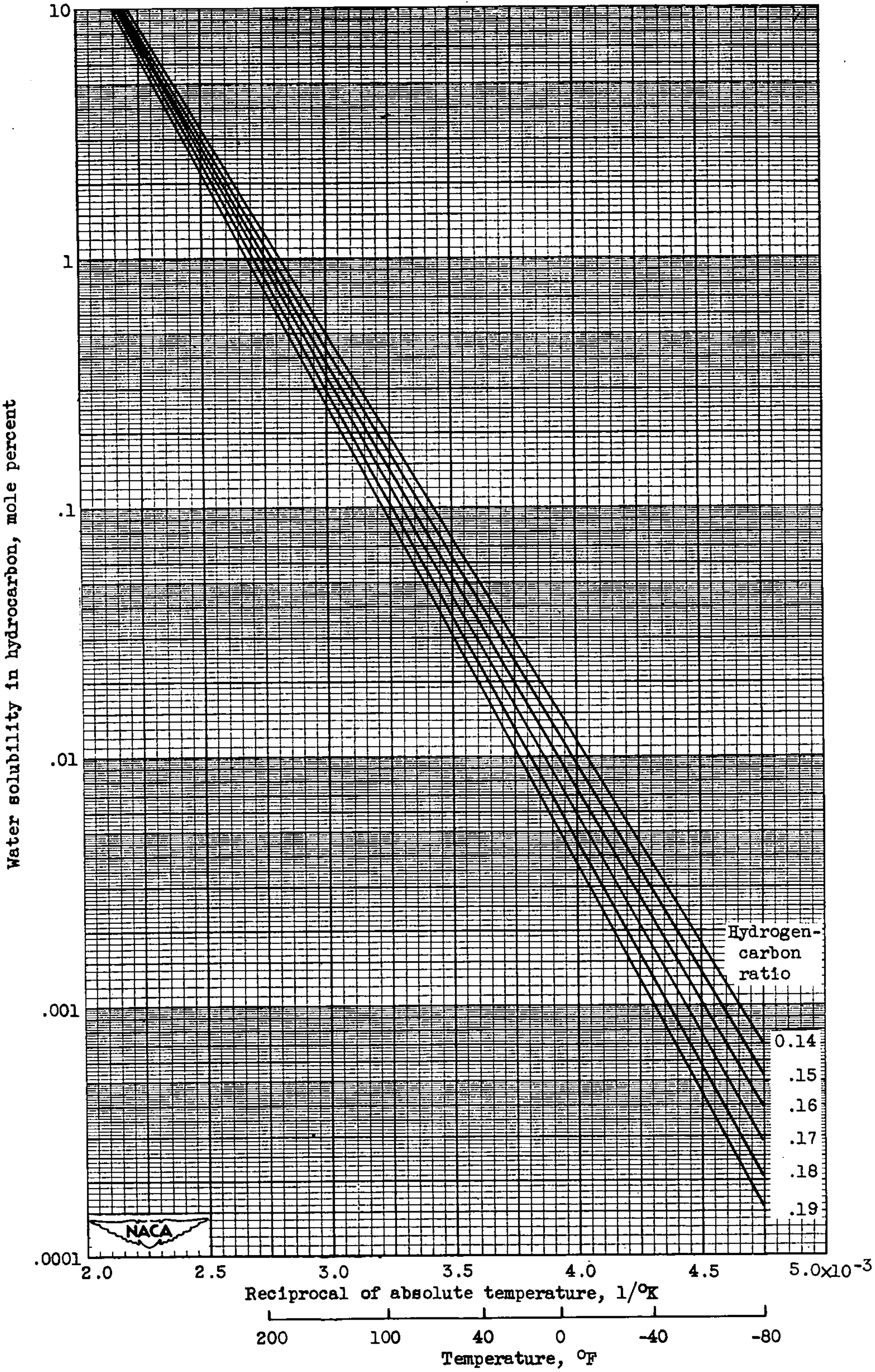


Figure 4. - Water solubility in hydrocarbon fuels.

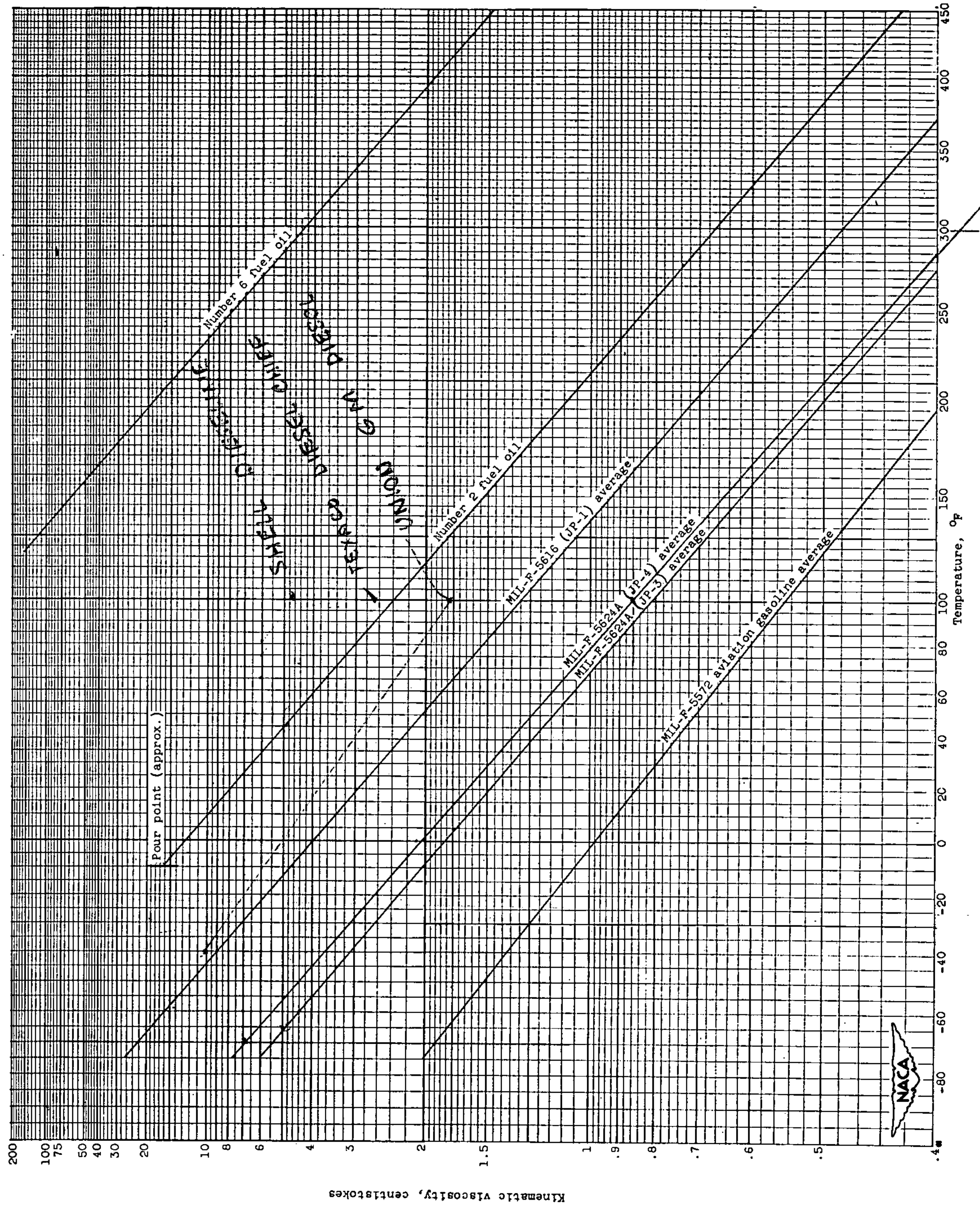
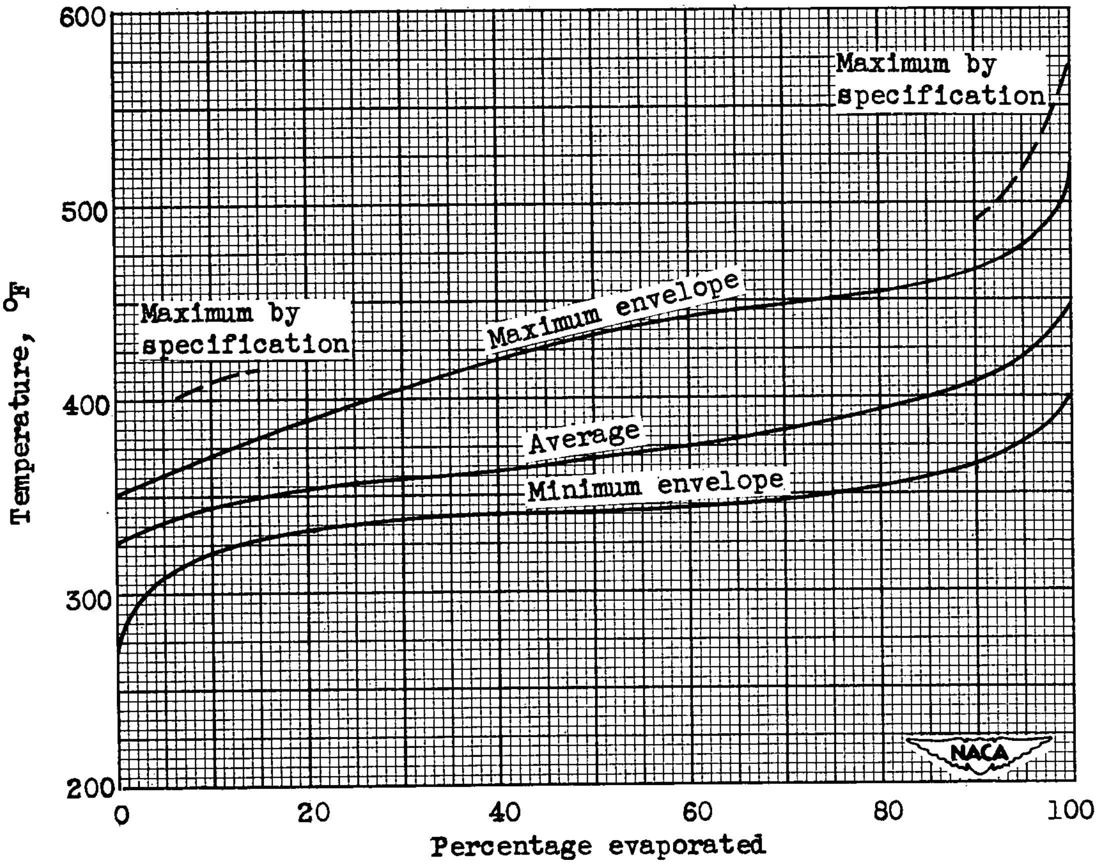
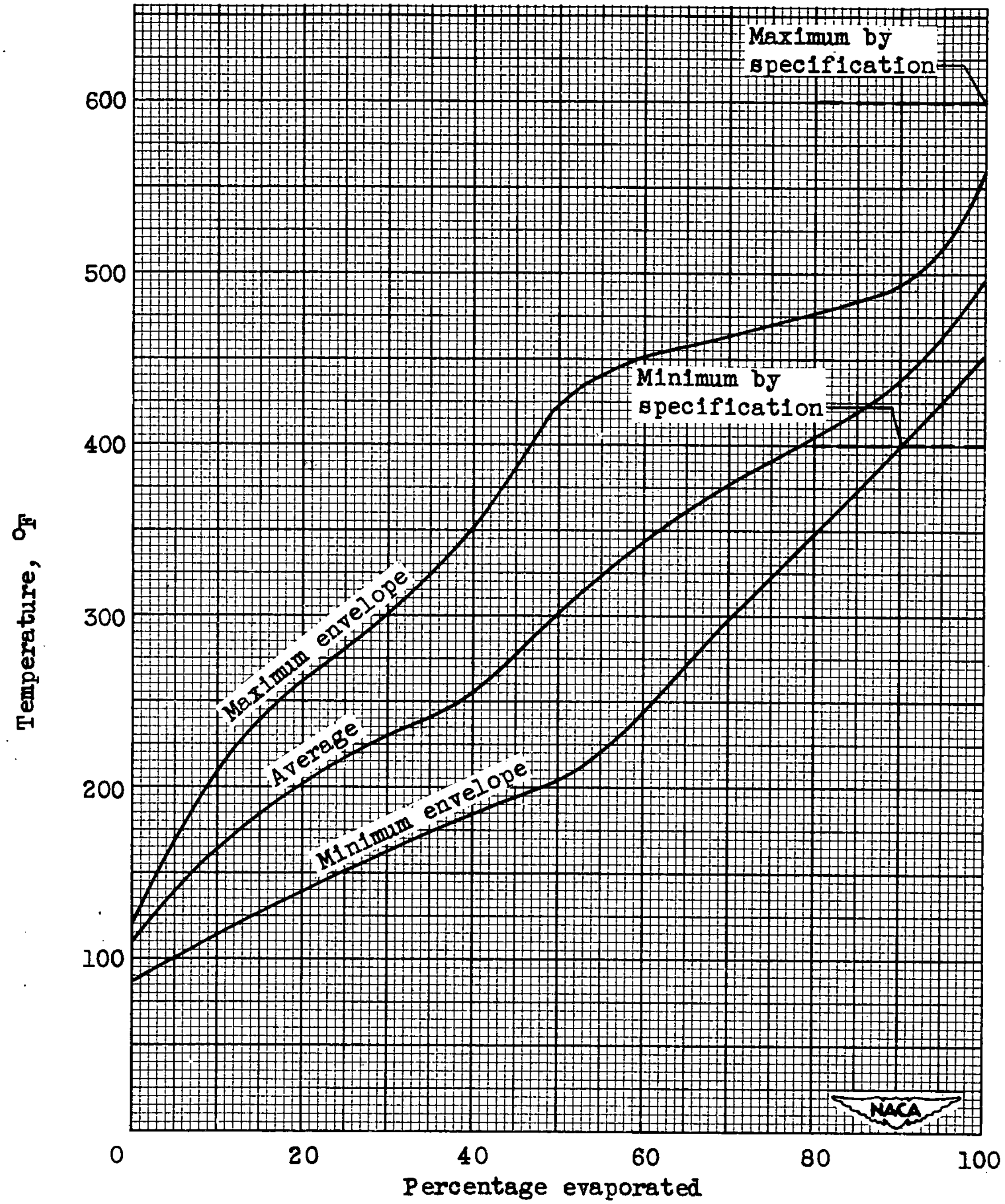


Figure 5. - A.S.T.M. viscosity-temperature relations for several fuels.



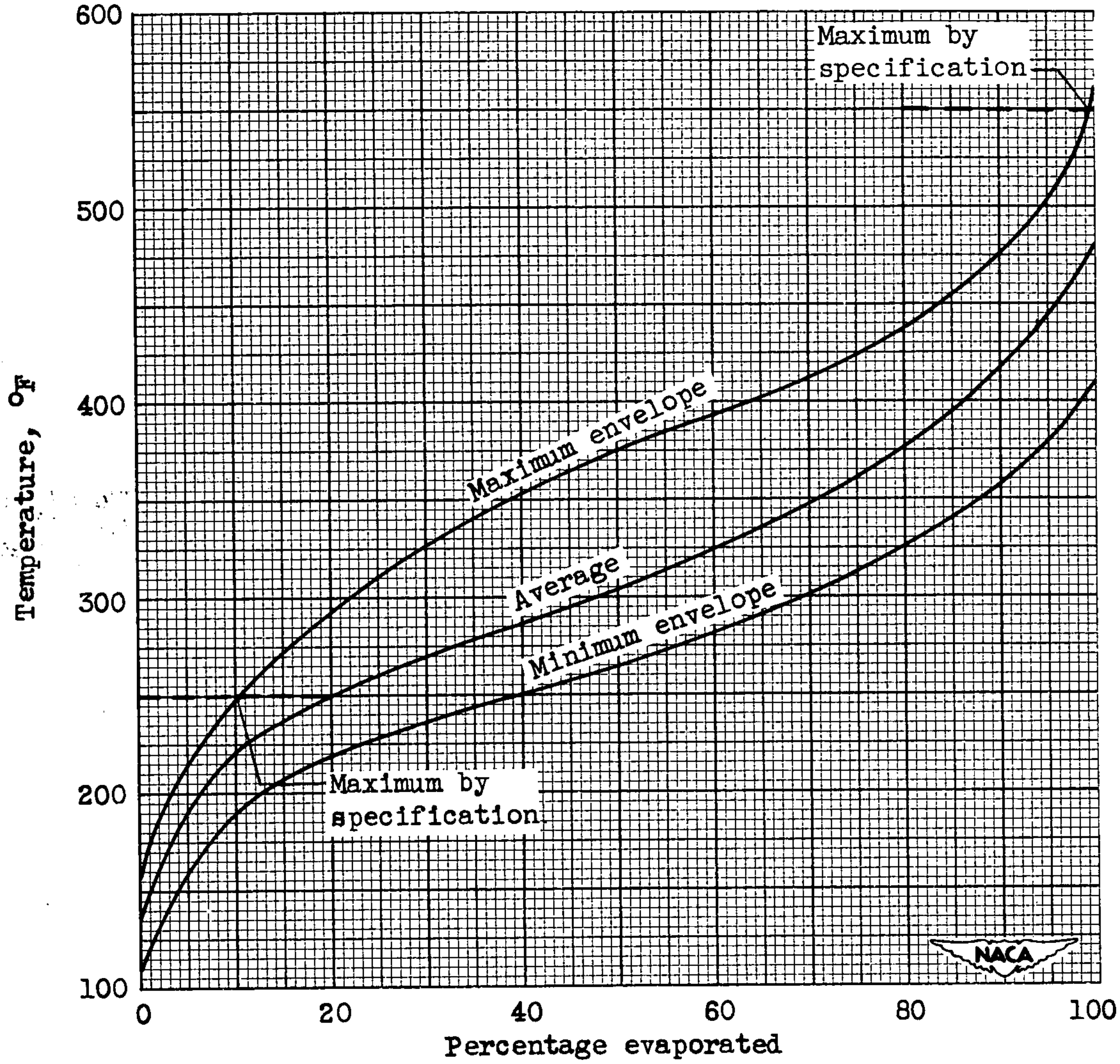
(a) MIL-F-5616 (JP-1) fuel.

Figure 6. - Variation of A.S.T.M. distillation temperatures for several fuels.



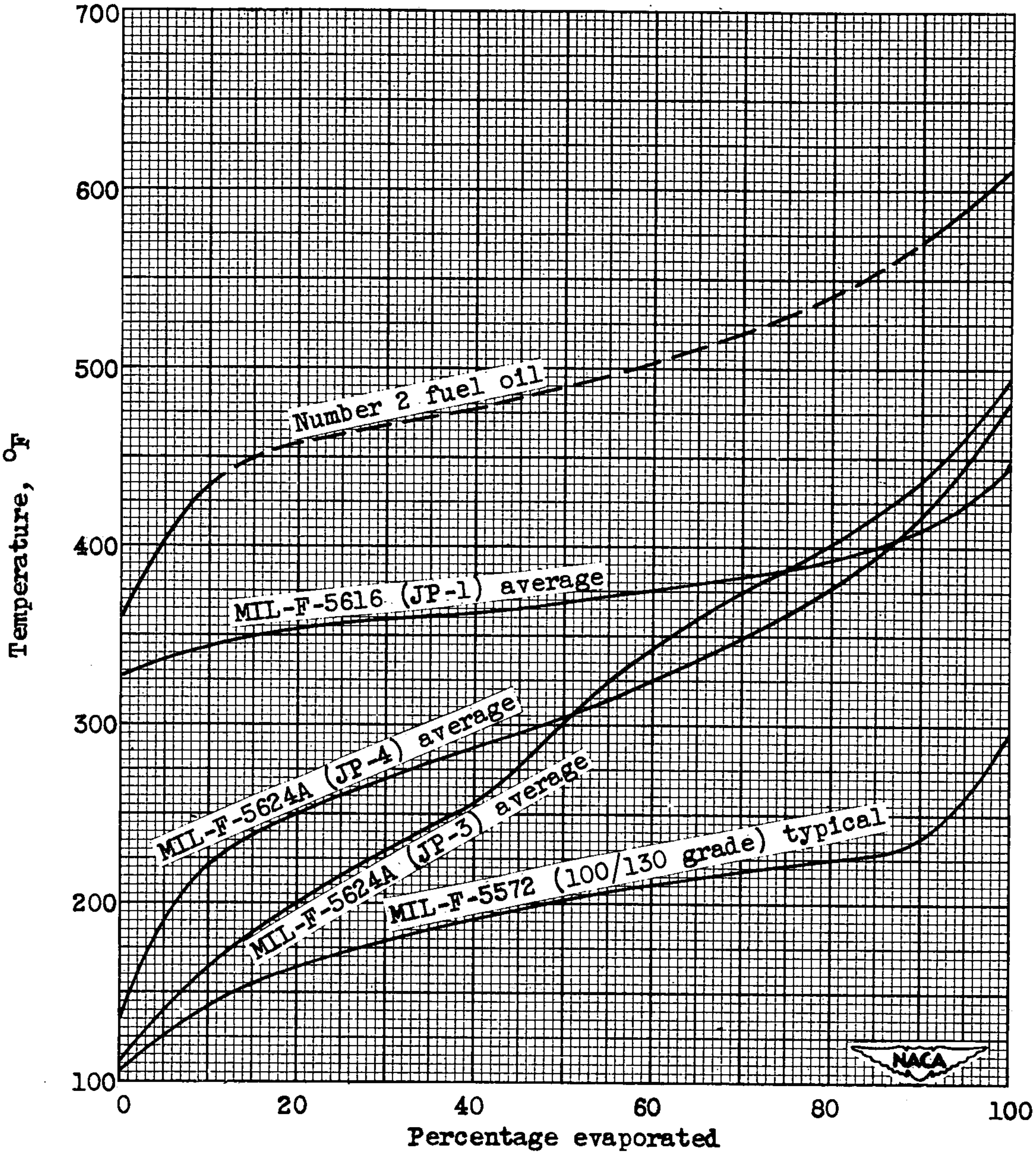
(b) MIL-F-5624A (JP-3) fuel.

Figure 6. - Continued. Variation of A.S.T.M. distillation temperatures for several fuels.



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

Figure 6. - Continued. Variation of A.S.T.M. distillation temperatures for several fuels.



(d) Comparison of several fuels.

Figure 6. - Concluded. Variation of A.S.T.M. distillation temperatures for several fuels.

JP-4, $S = \frac{238-190}{10} = 4.8$

5572, $S = \frac{155-125}{10} = 3.0$

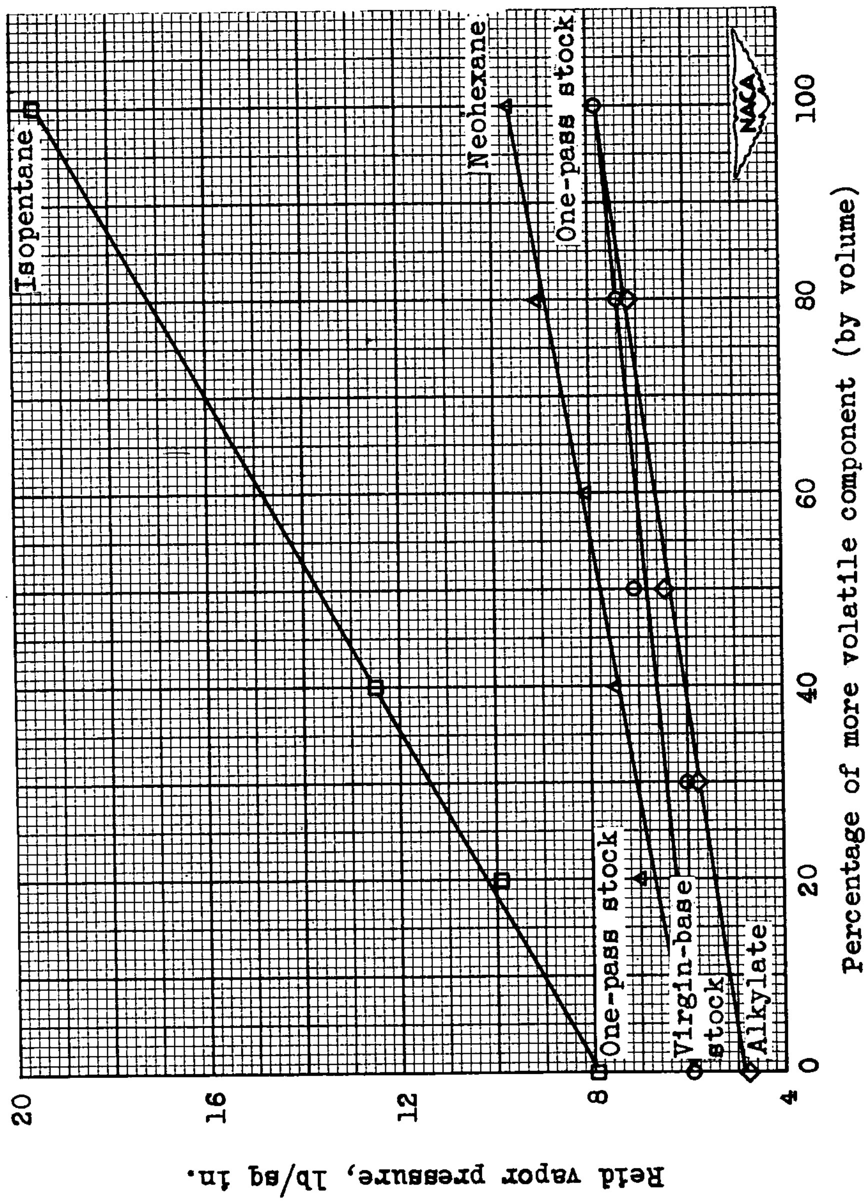


Figure 7. - Effect of composition on Reid vapor pressure.

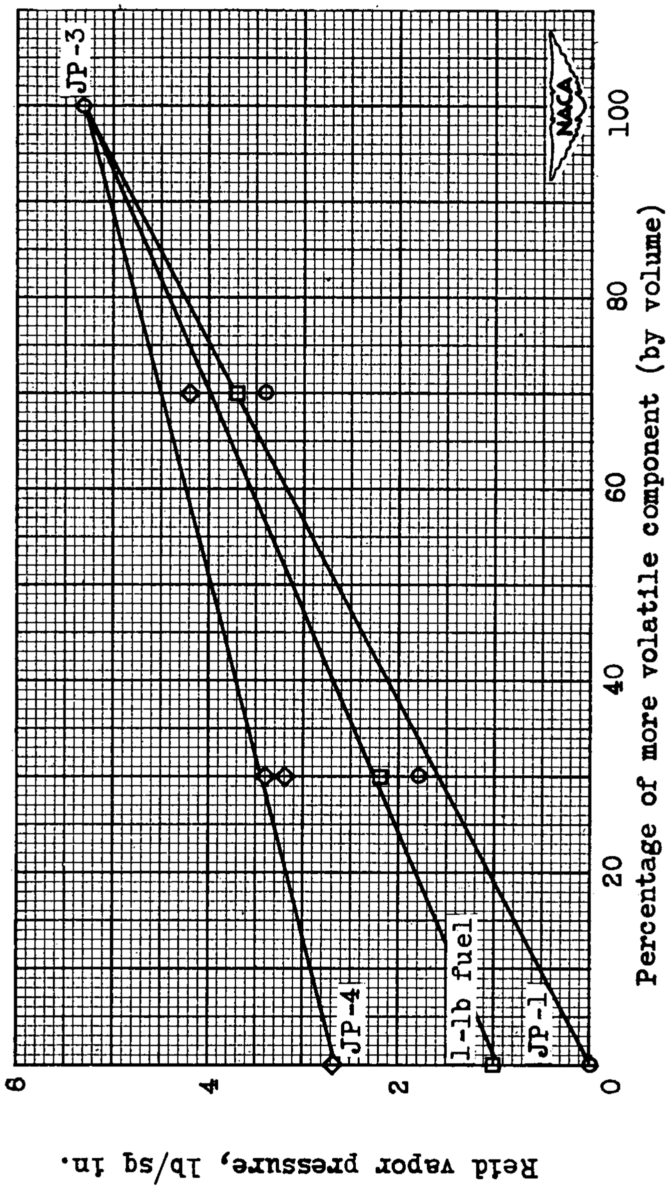


Figure 8. - Effect of composition on Reid vapor pressure.

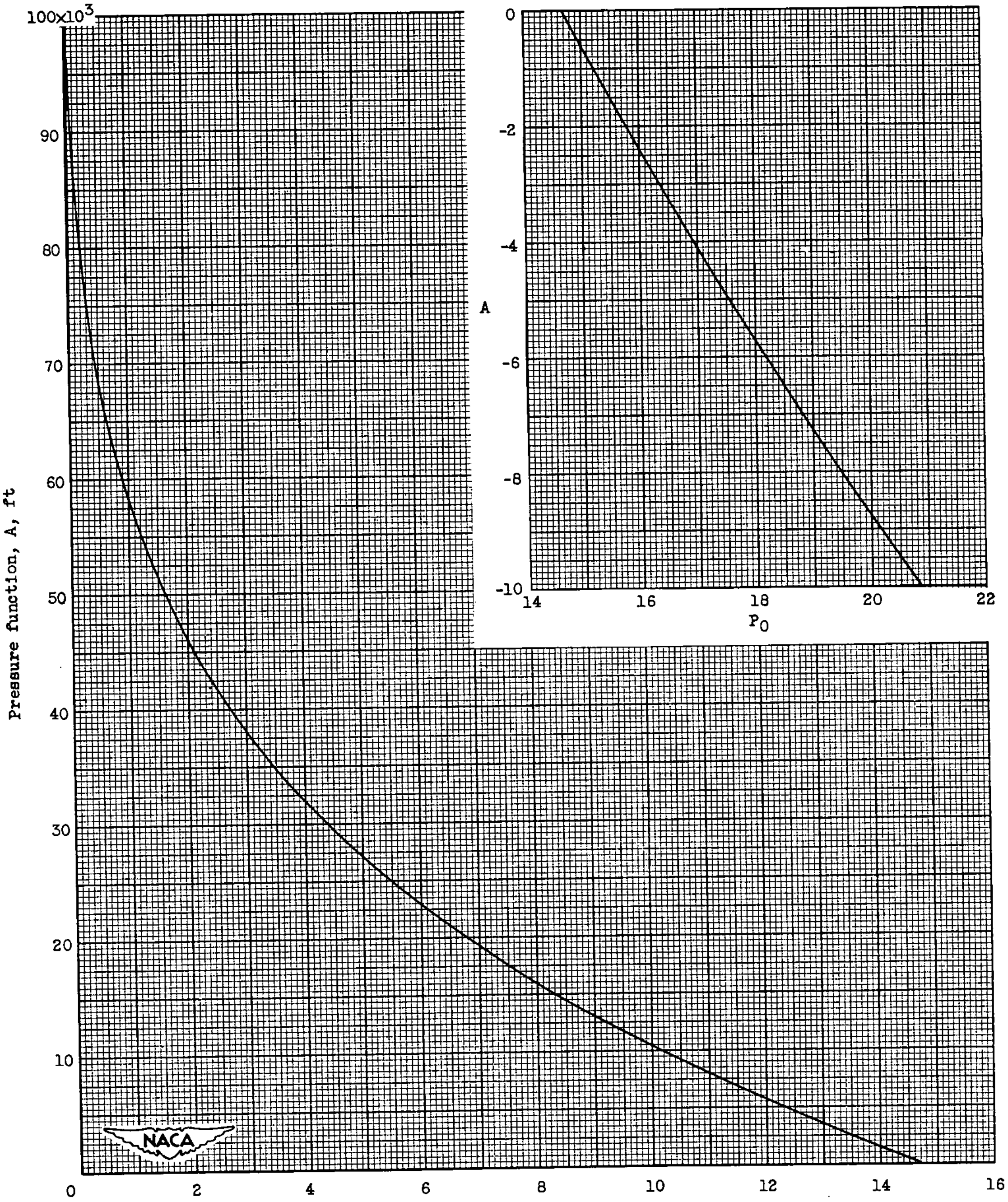
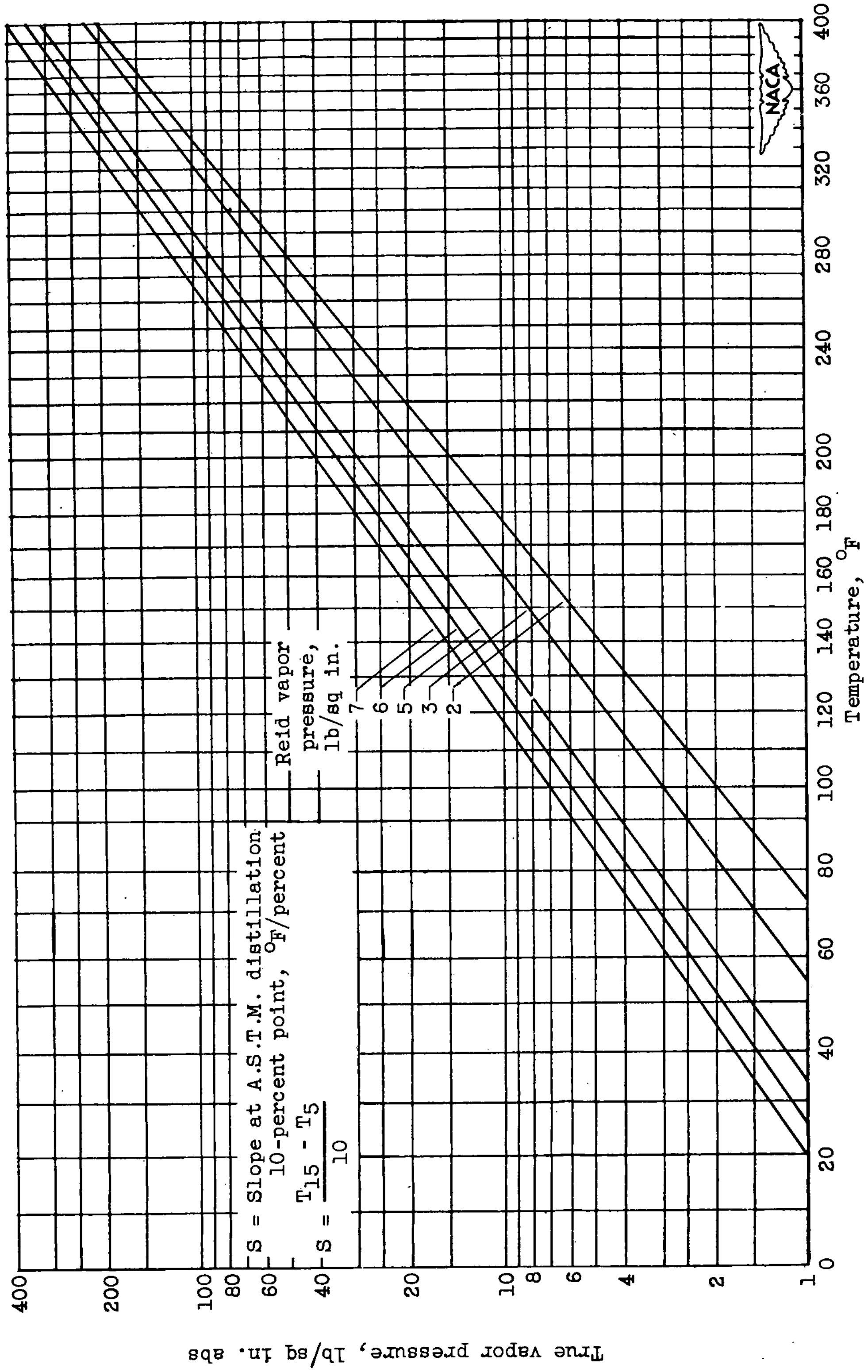
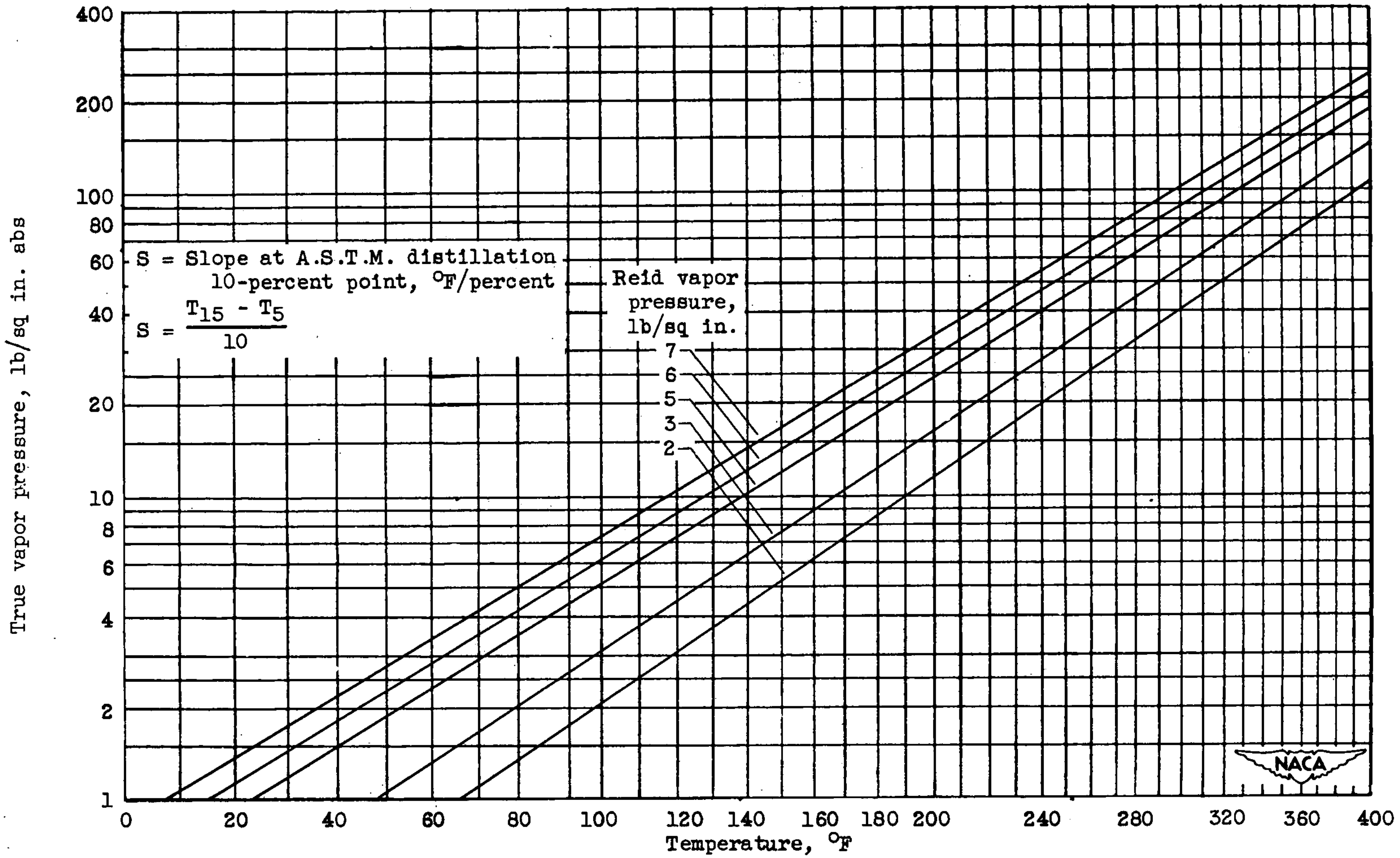


Figure 9. - Relation between true vapor pressure and A. (Based on data from ref. 2.)



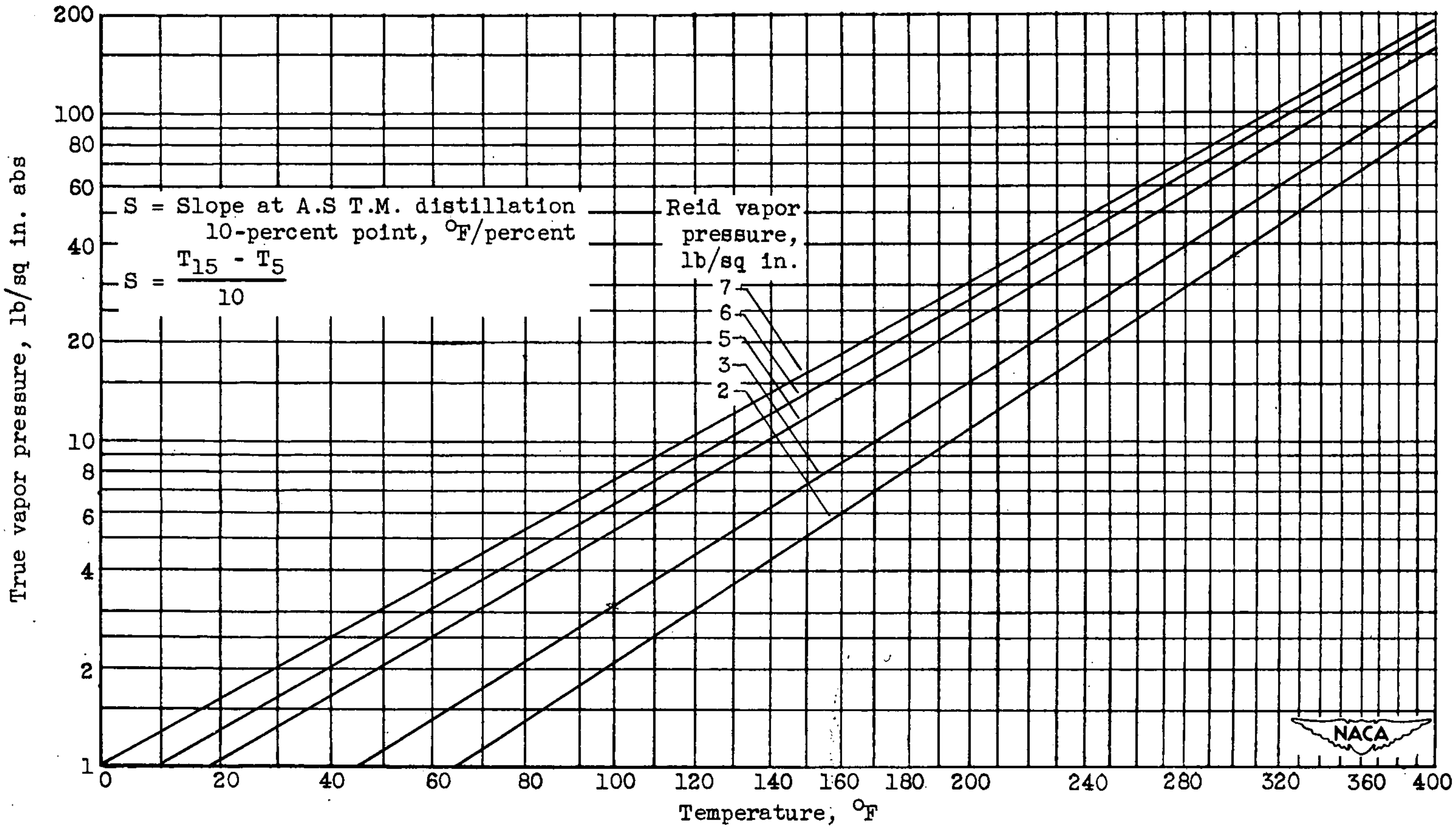
(a) Slope, 0.

Figure 10. - Variation of vapor pressure with temperature.



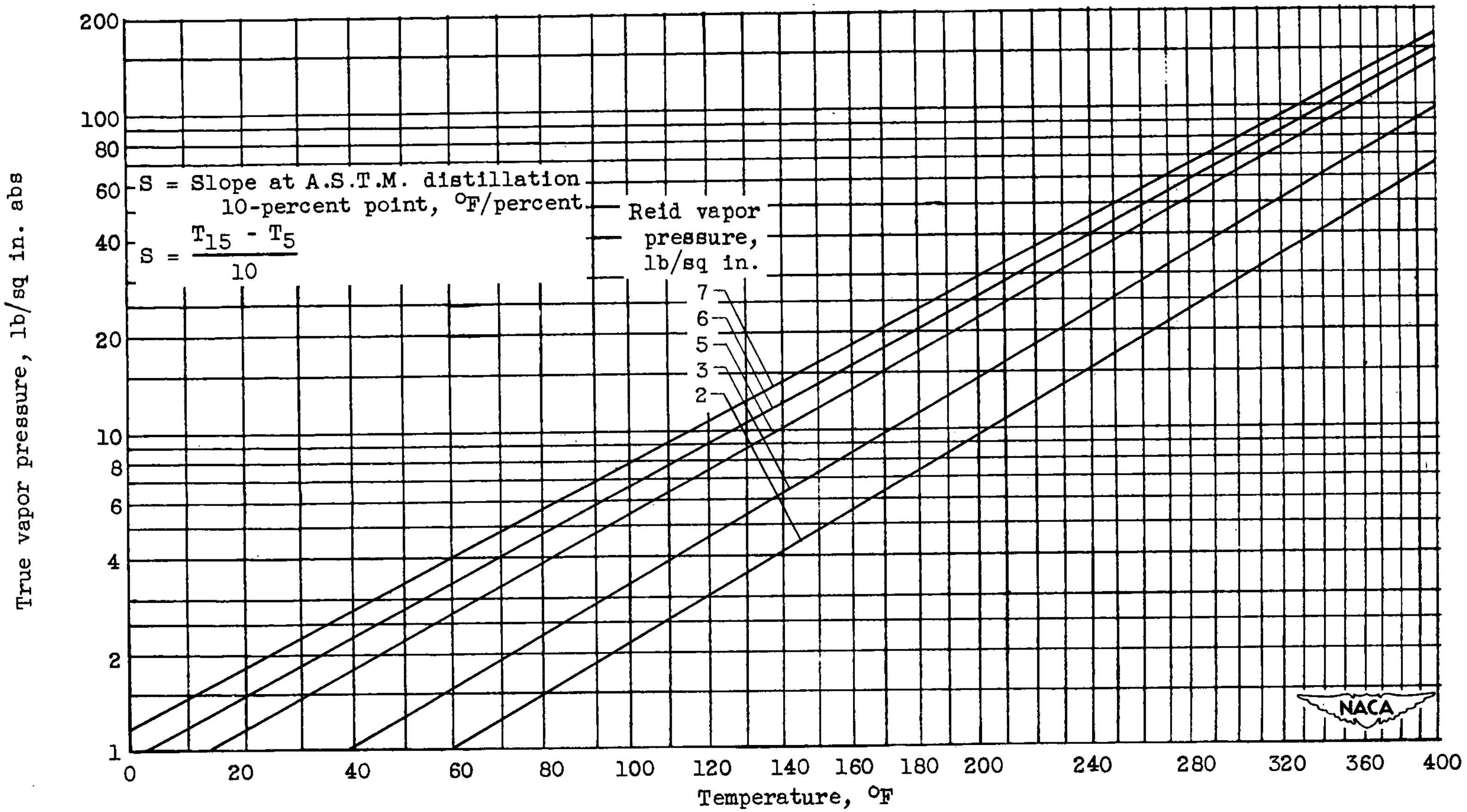
(b) Slope, 2.

Figure 10. - Continued. Variation of vapor pressure with temperature.



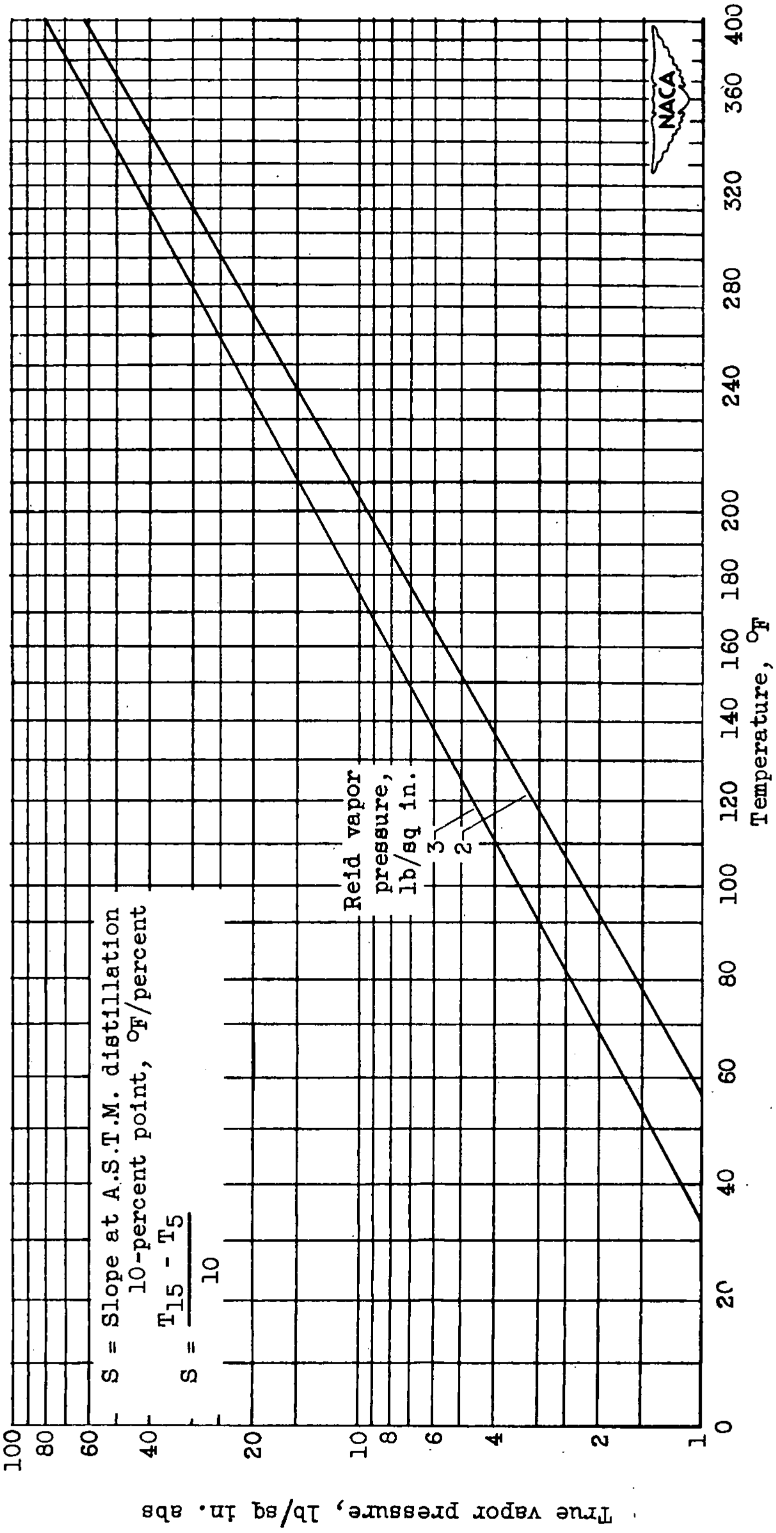
(c) Slope, 4.

Figure 10. - Continued. Variation of vapor pressure with temperature.



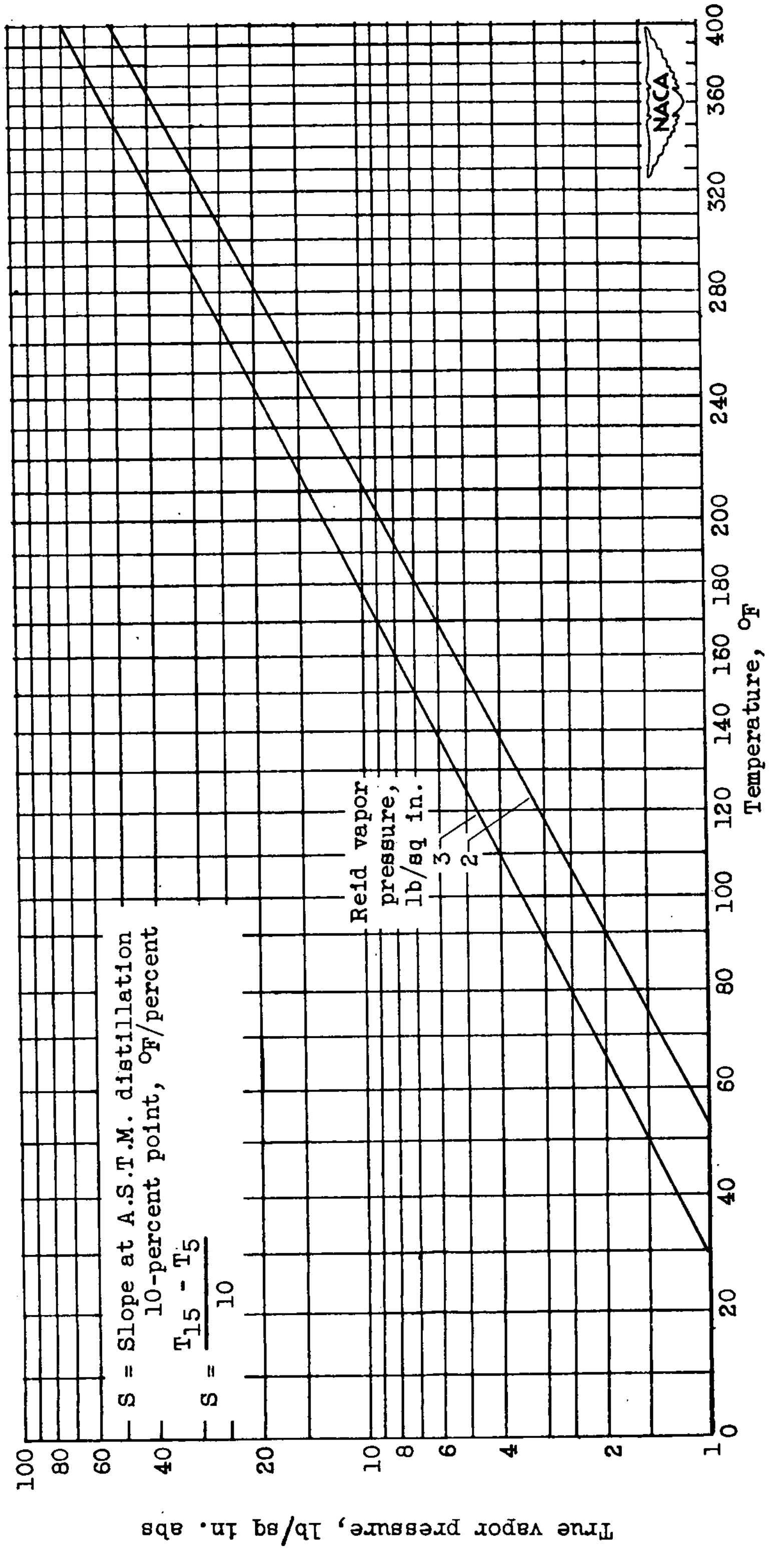
(d) Slope, 6.

Figure 10. - Continued. Variation of vapor pressure with temperature.



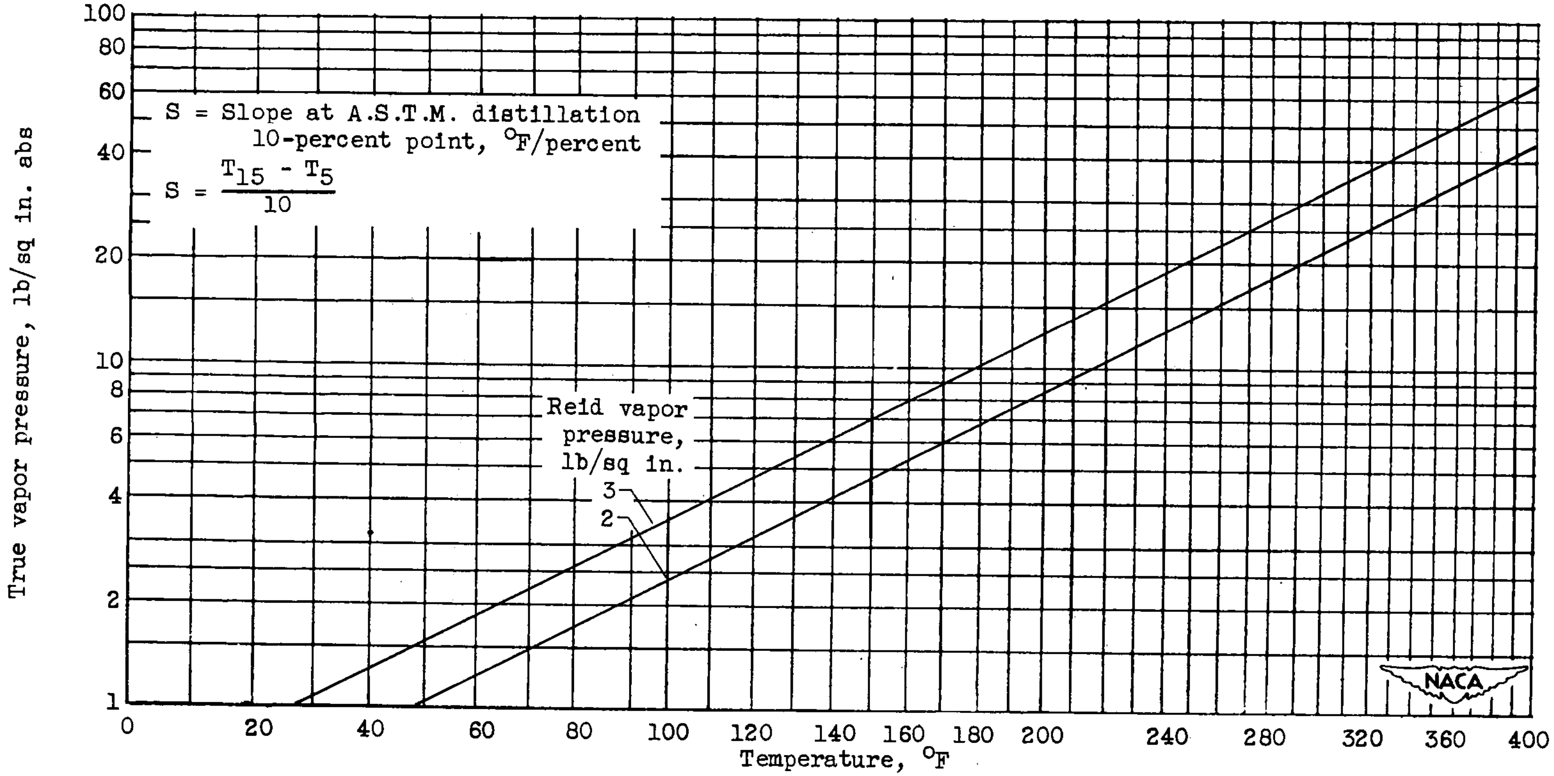
(e) Slope, 8.

Figure 10. - Continued. Variation of vapor pressure with temperature.



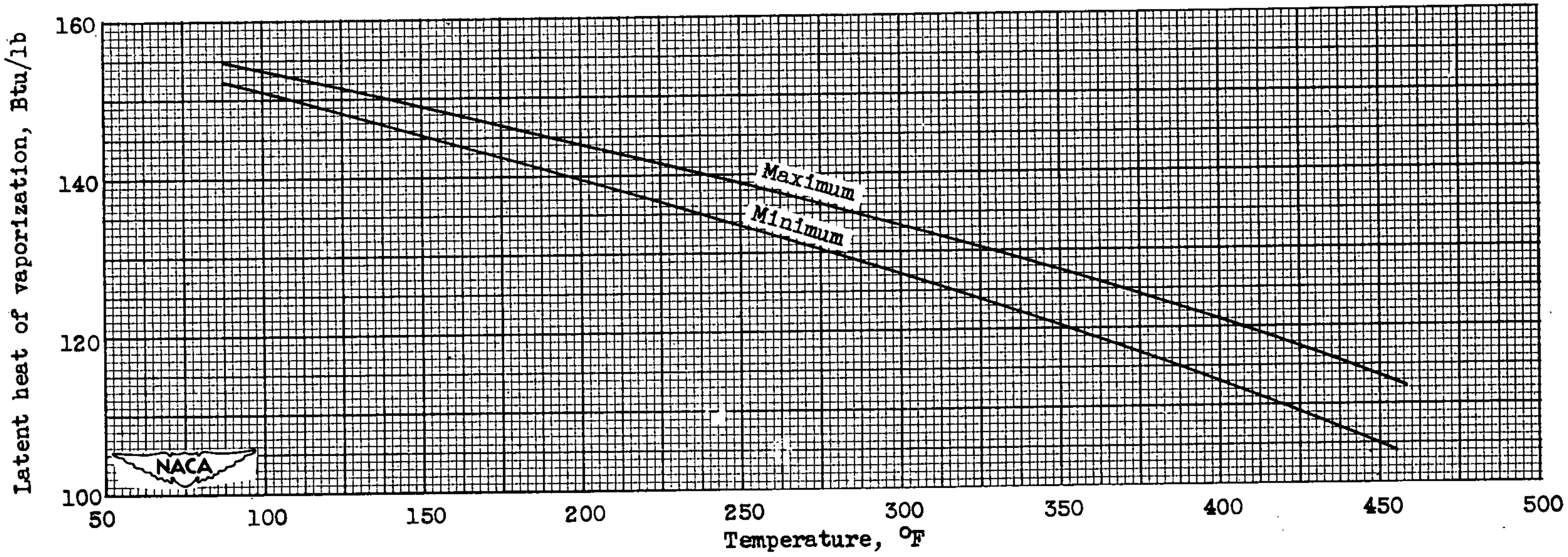
(f) Slope, 10.

Figure 10. - Continued. Variation of vapor pressure with temperature.



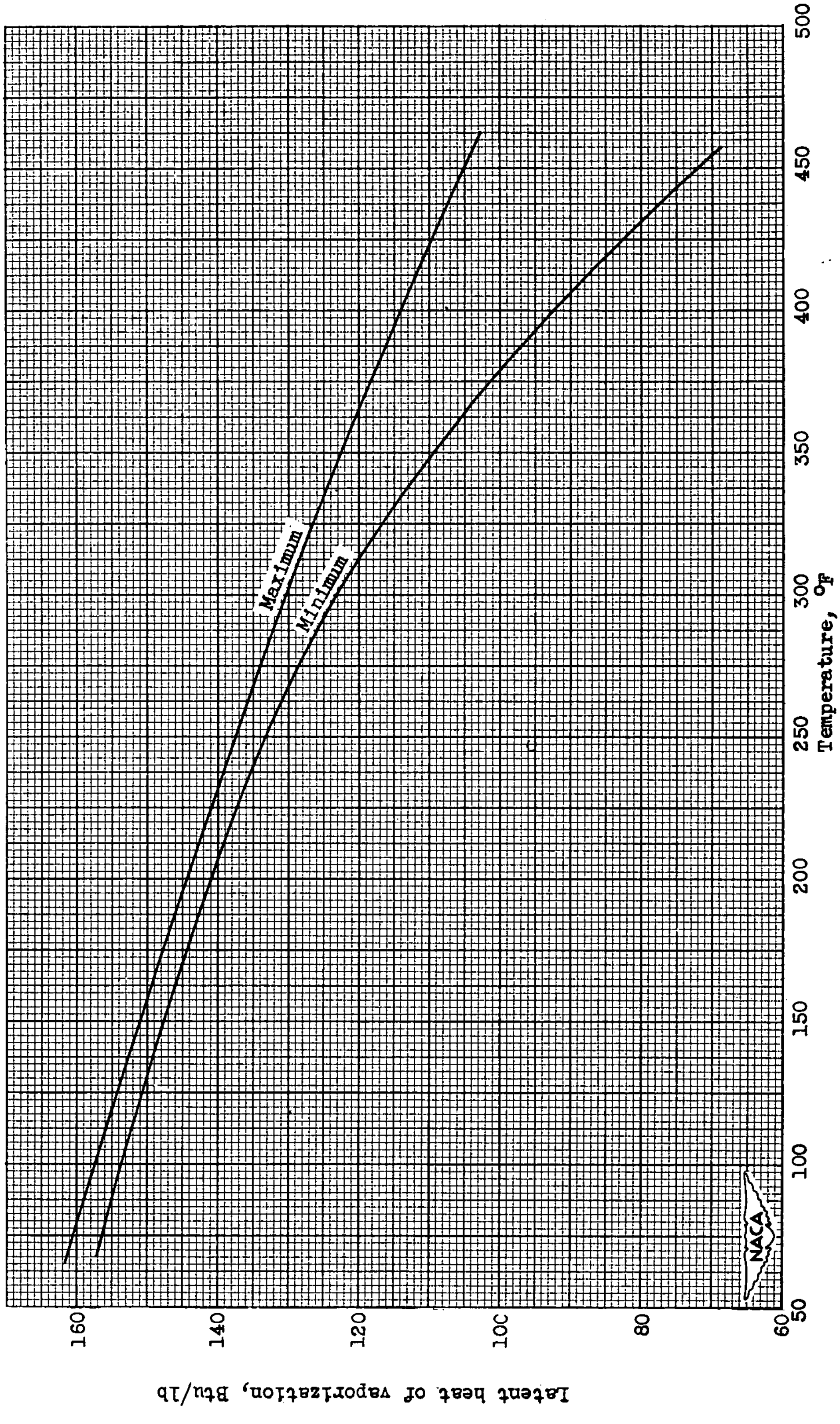
(g) Slope, 12.

Figure 10. - Concluded. Variation of vapor pressure with temperature.



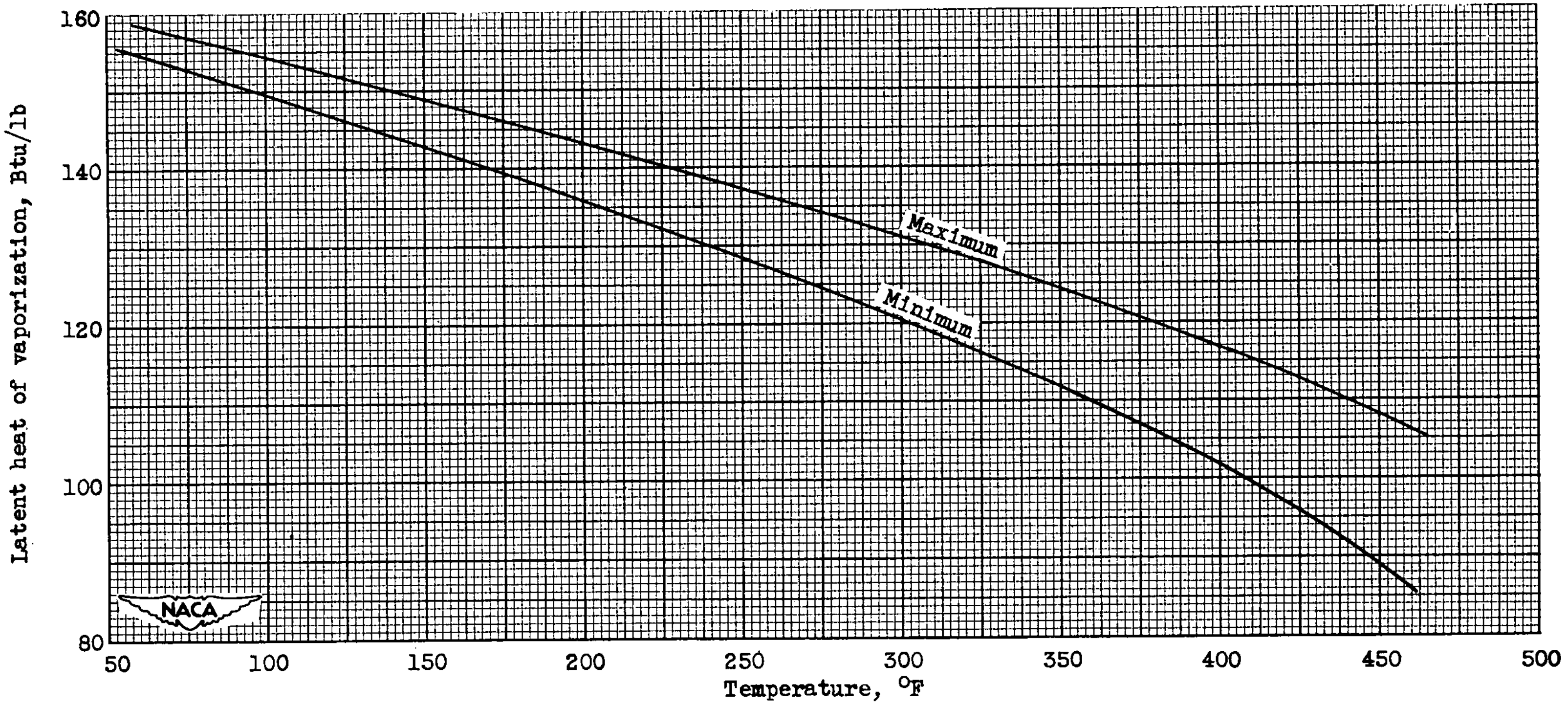
(a) MIL-F-5616 (JP-1) fuel.

Figure 11. - Variation of latent heat of vaporization with temperature.



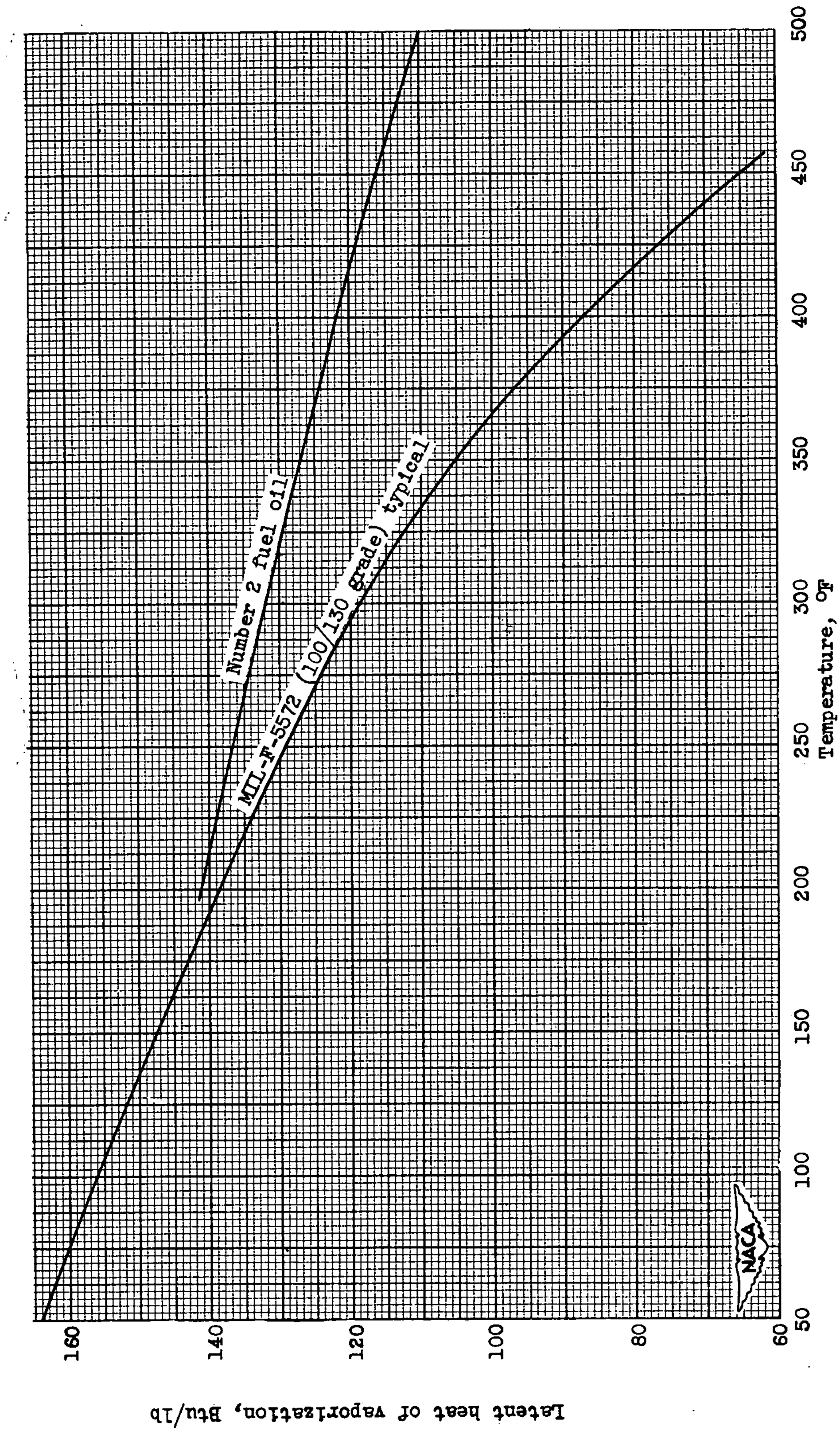
(b) MIL-F-5624 (JP-3) fuel.

Figure 11. - Continued. Variation of latent heat of vaporization with temperature.



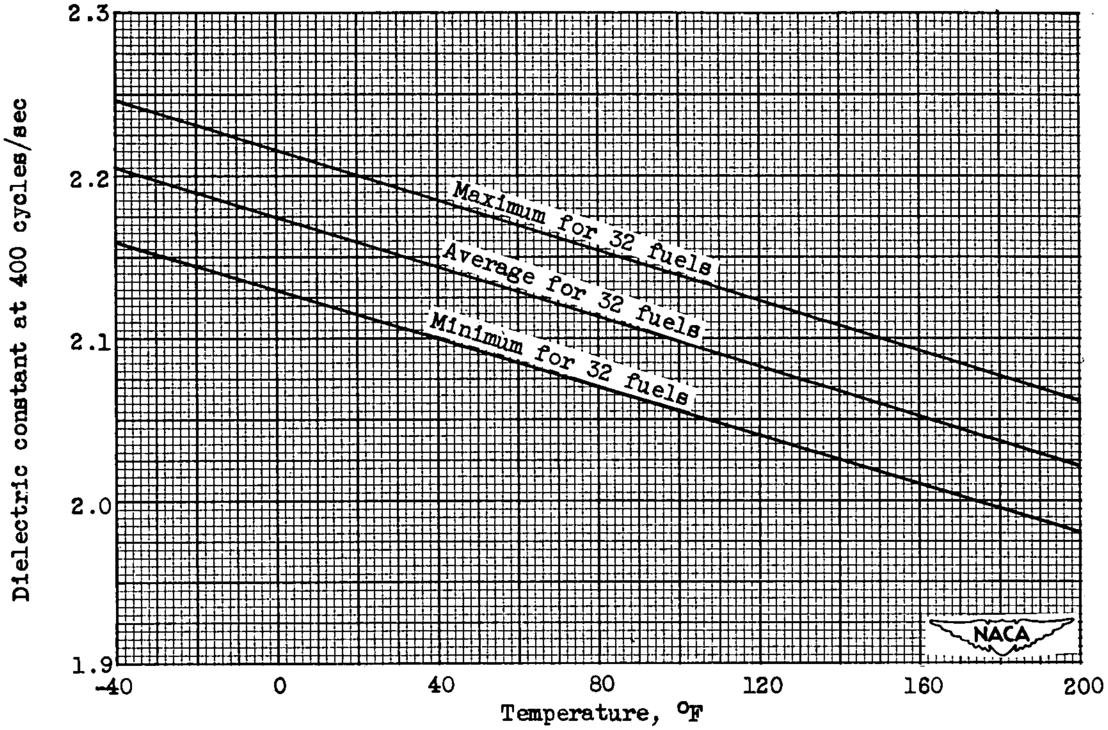
(c) MIL-F-5624A (JP-4) fuel.

Figure 11. - Continued. Variation of latent heat of vaporization with temperature.



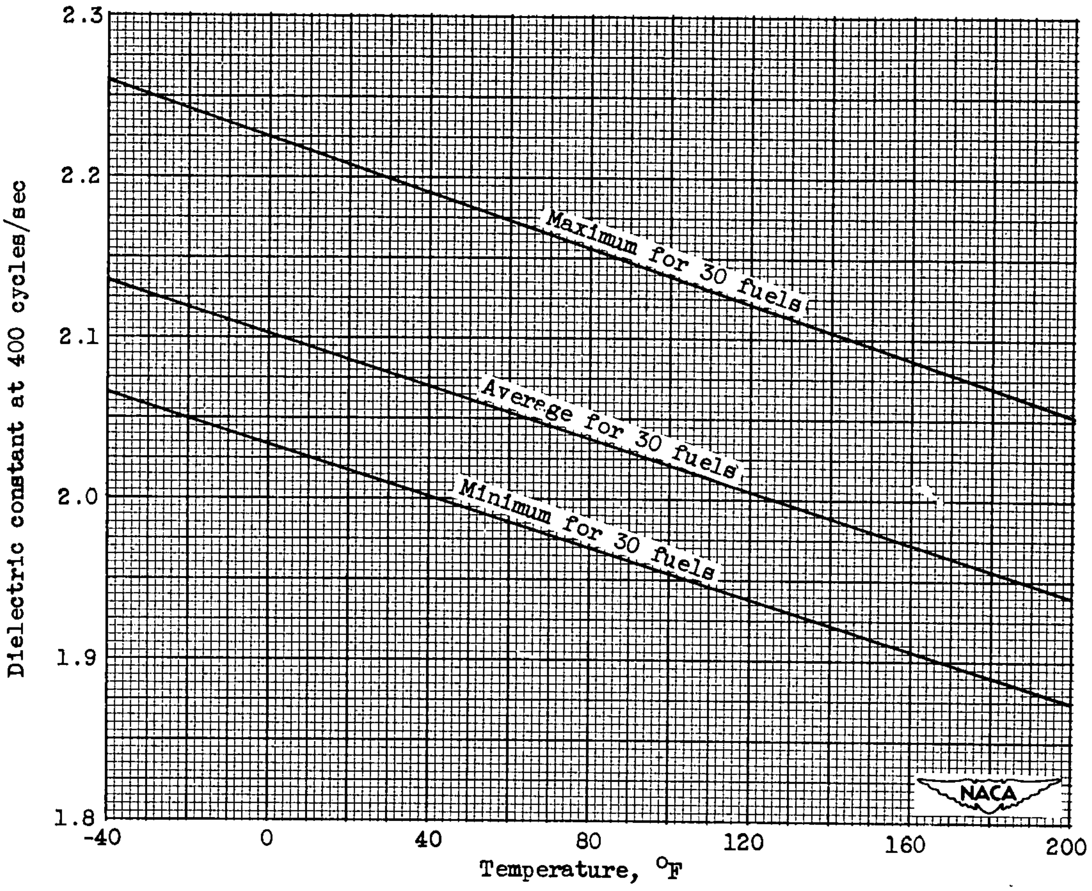
(d) Comparison between typical aviation gasoline and number 2 fuel oil.

Figure 11. - Concluded. Variation of latent heat of vaporization and temperature.



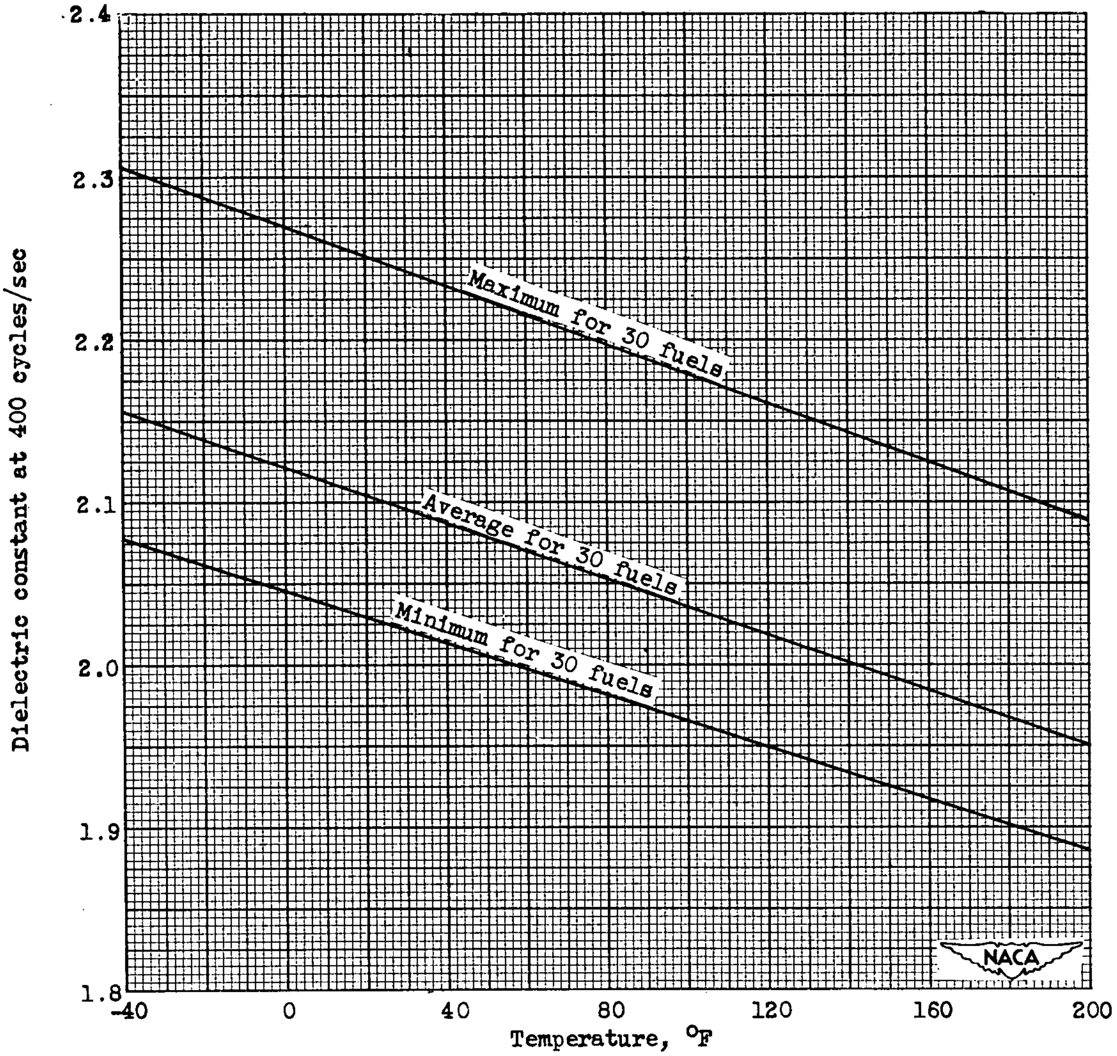
(a) MIL-F-5616 (JP-1) fuel.

Figure 12. - Variation of dielectric constant with temperature. (Based on data from ref. 13.)



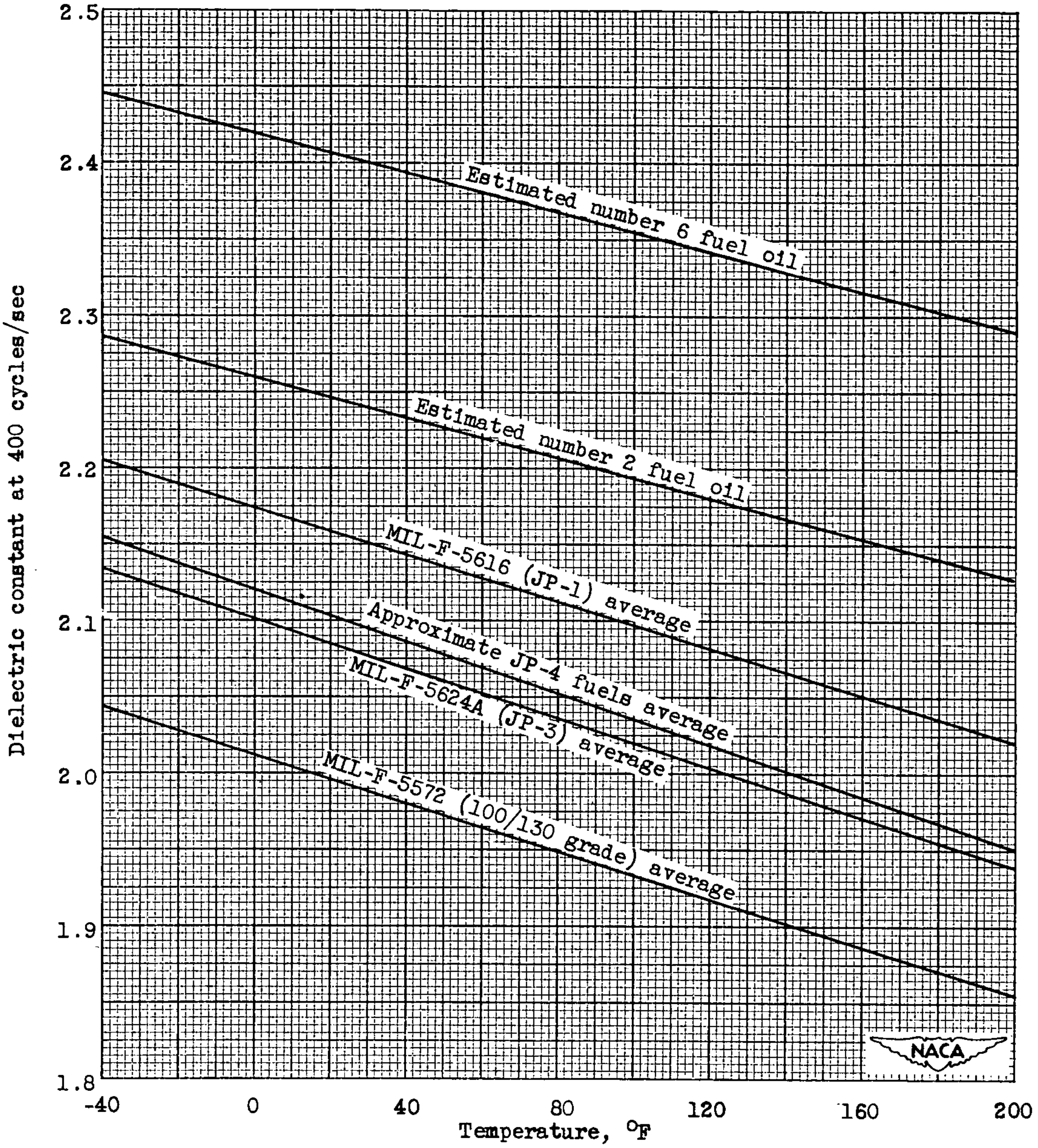
(b) MIL-F-5624A (JP-3) fuel.

Figure 12. - Continued. Variation of dielectric constant with temperature. (Based on data from ref. 13.)



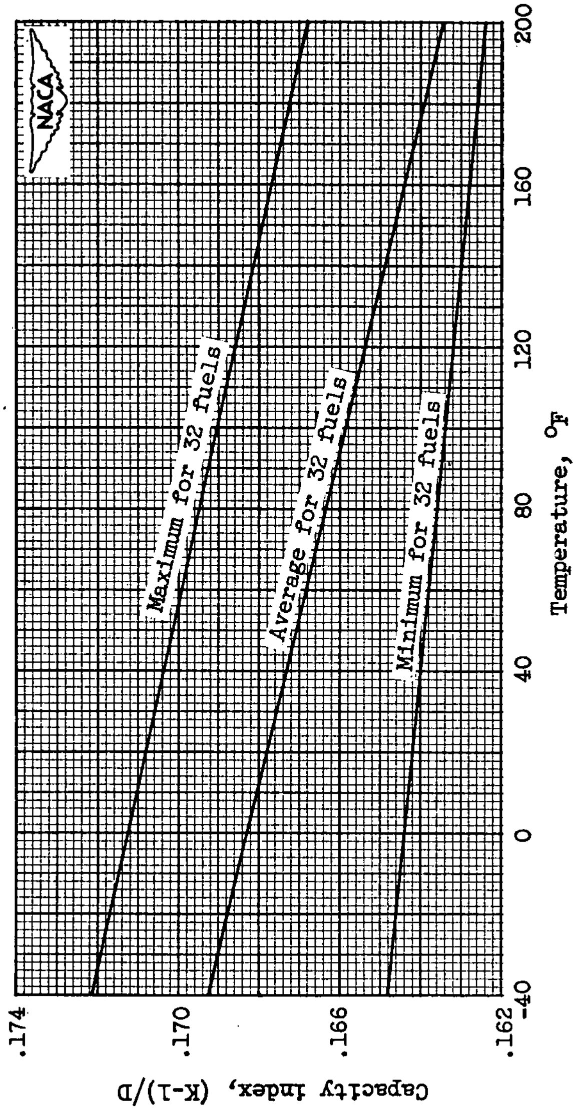
(c) Approximate JP-4 fuels.

Figure 12. - Continued. Variation of dielectric constant with temperature. (Based on data from ref. 13.)



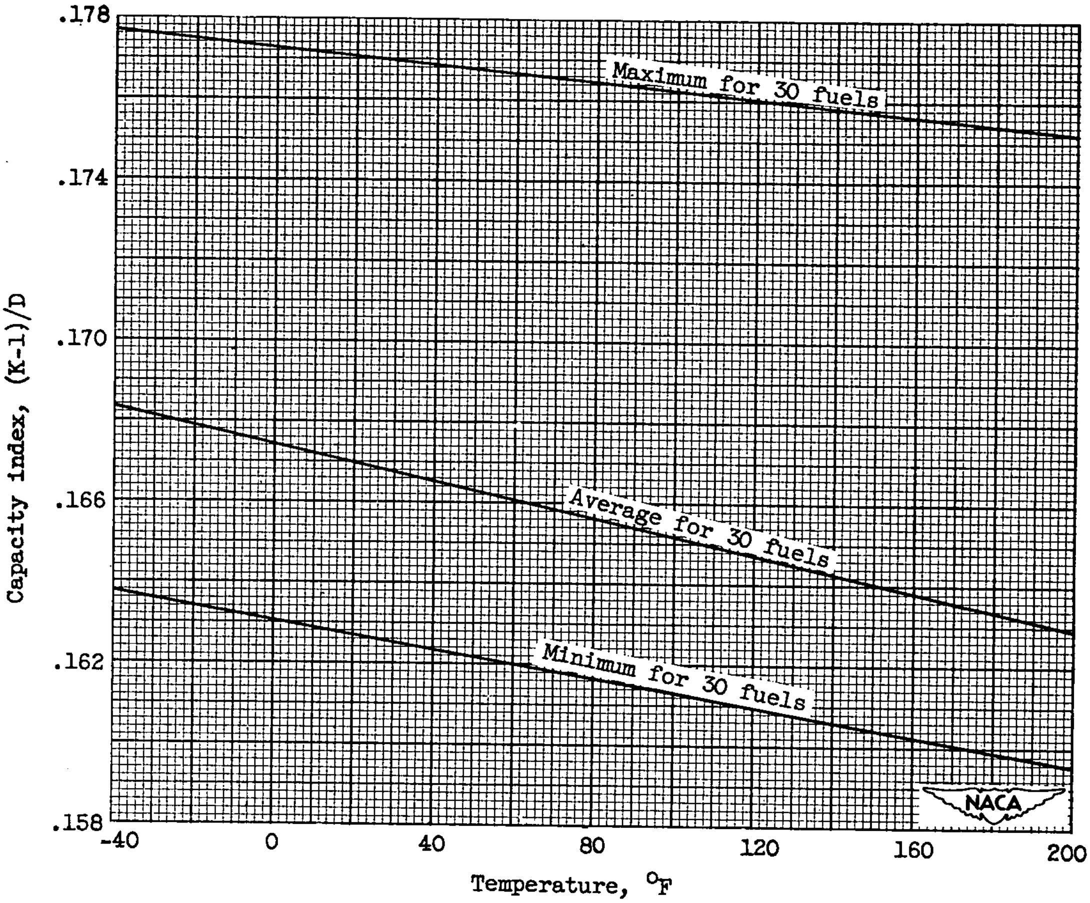
(d) Comparison of several fuels.

Figure 12. - Concluded. Variation of dielectric constant with temperature. (Based on data from ref. 13.)



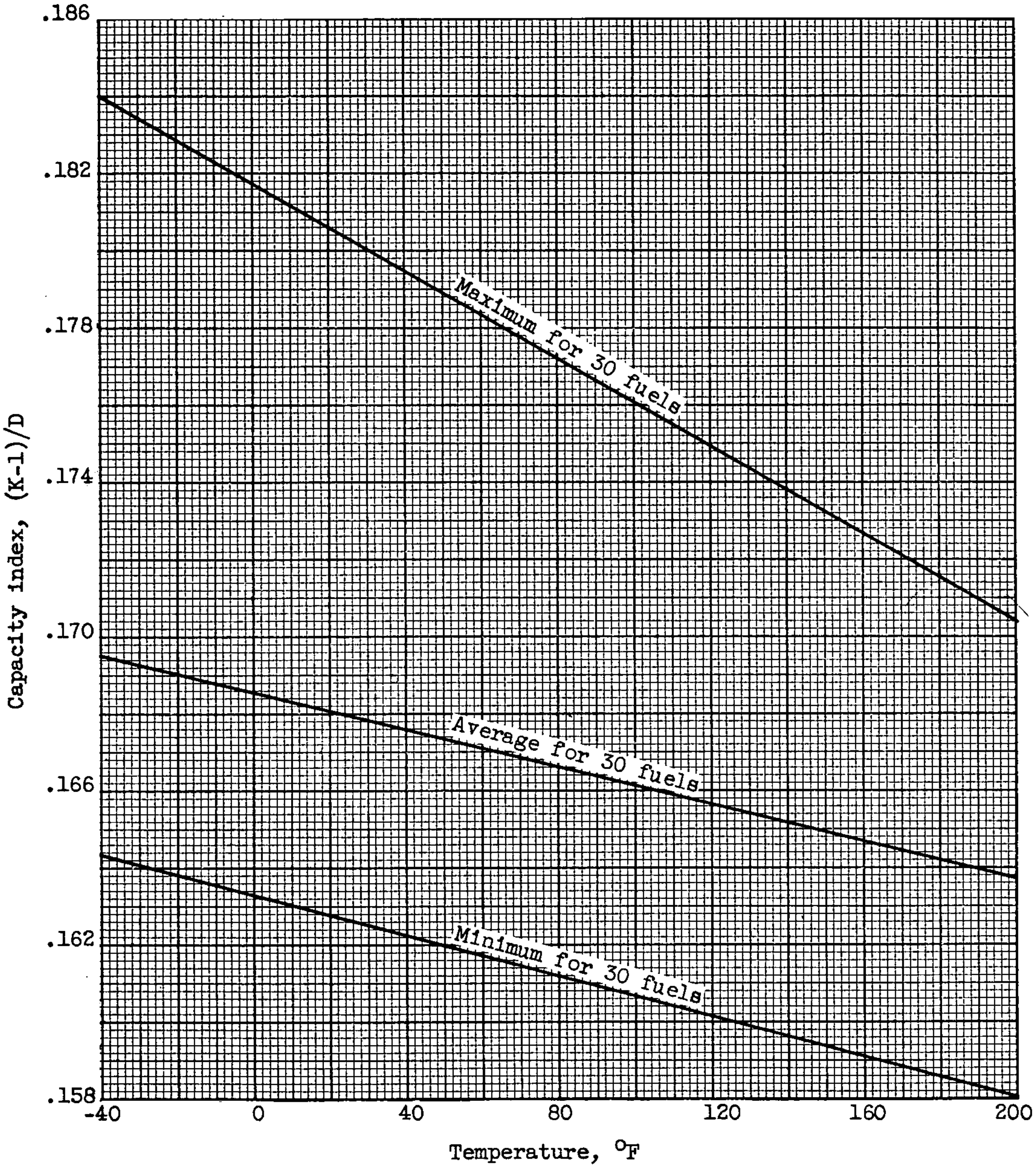
(a) MIL-F-5616 (JP-1) fuel.

Figure 13. - Variation of capacity index with temperature. (Based on data from ref. 13.)



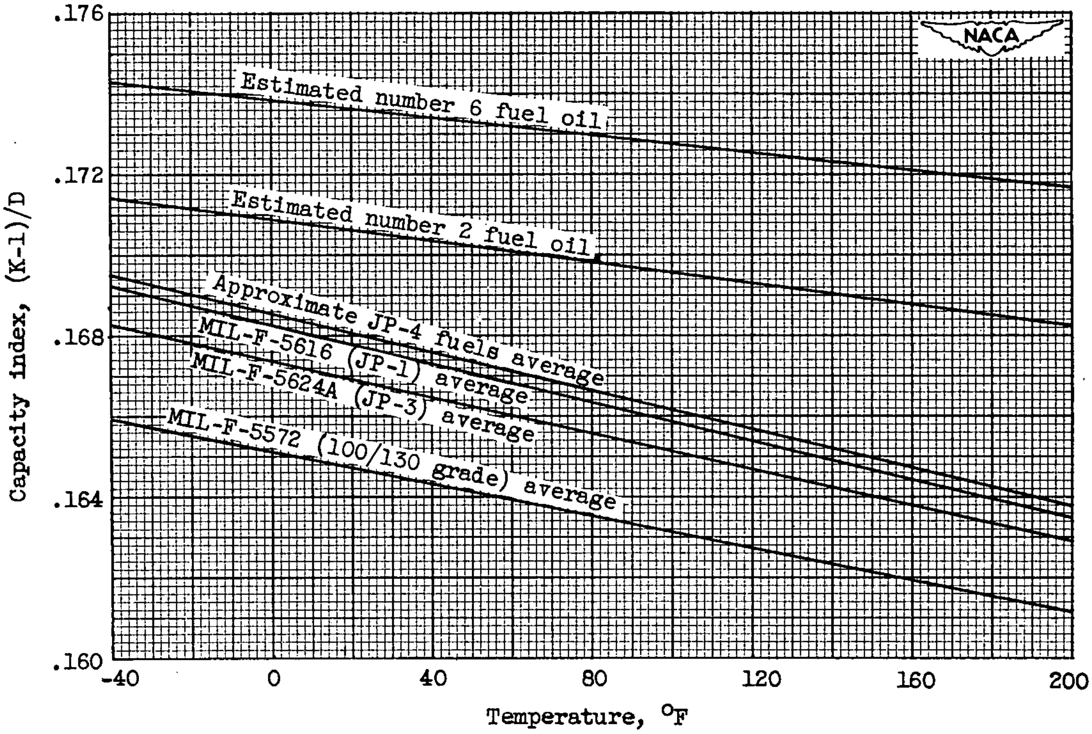
(b) MIL-F-5624A (JP-3) fuel.

Figure 13. - Continued. Variation of capacity index with temperature. (Based on data from ref. 13.)



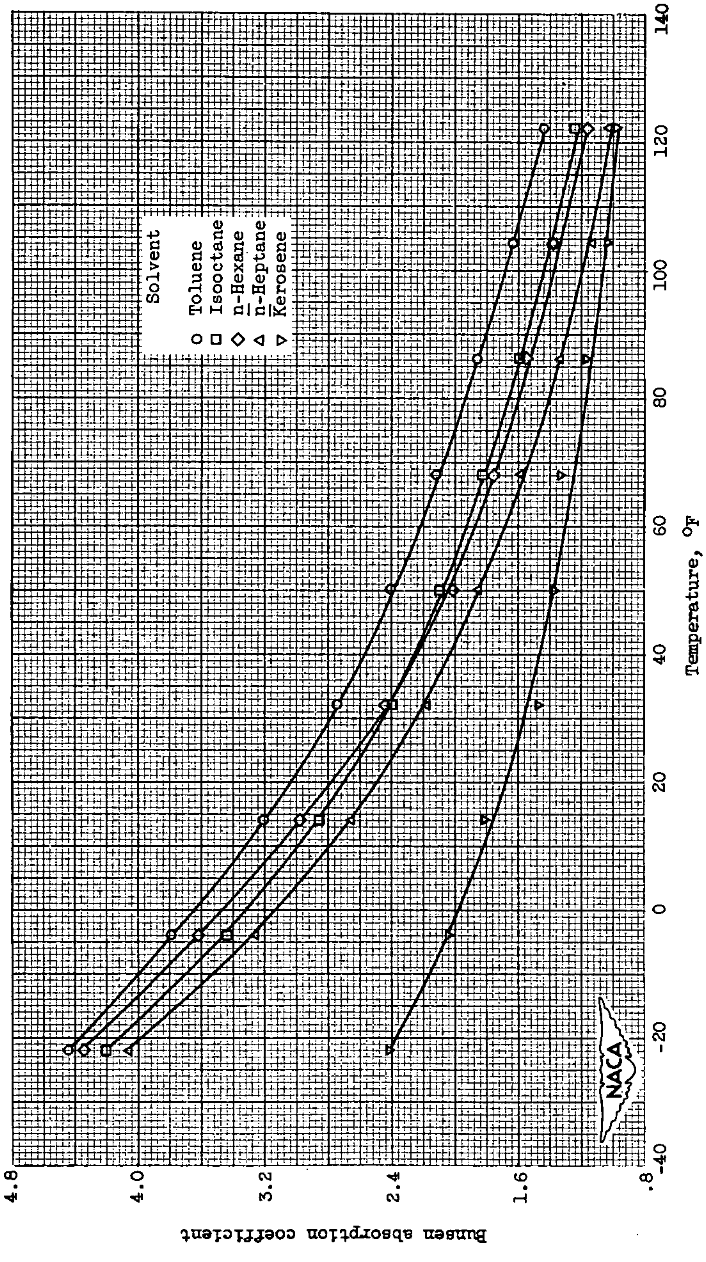
(c) Approximate JP-4 fuels.

Figure 13. - Continued. Variation of capacity index with temperature. (Based on data from ref. 13.)



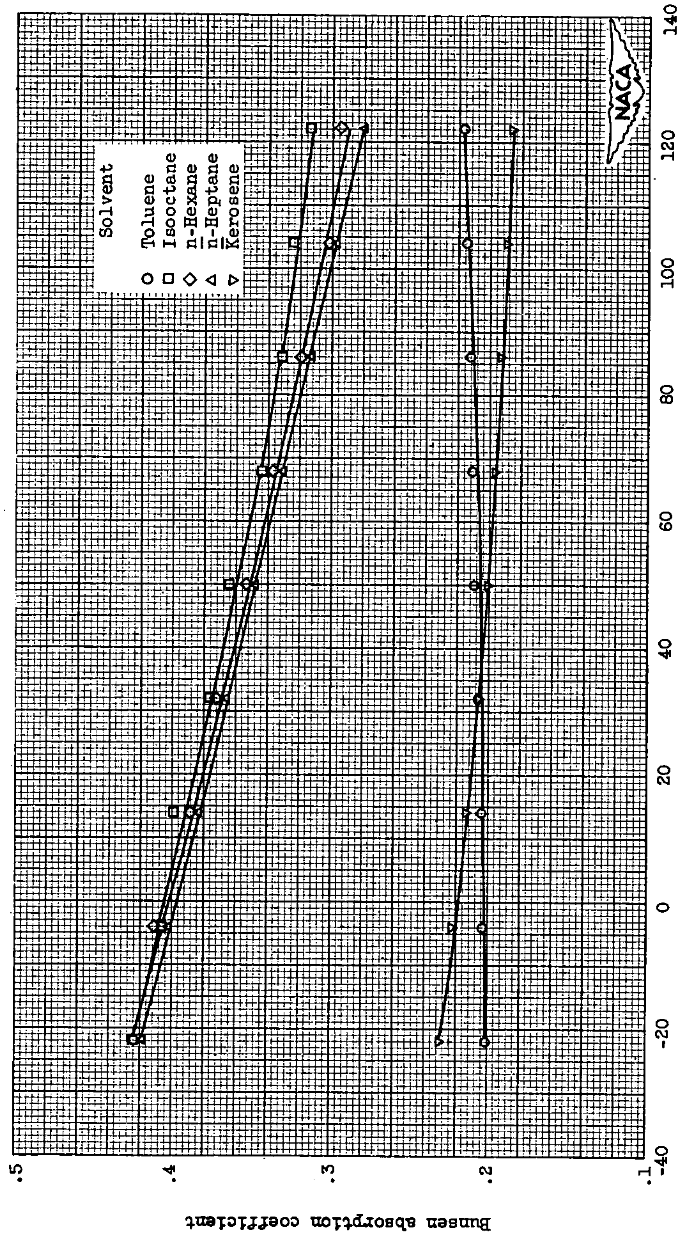
(d) Comparison of several fuels.

Figure 13. - Concluded. Variation of capacity index with temperature. (Based on data from ref. 13.)



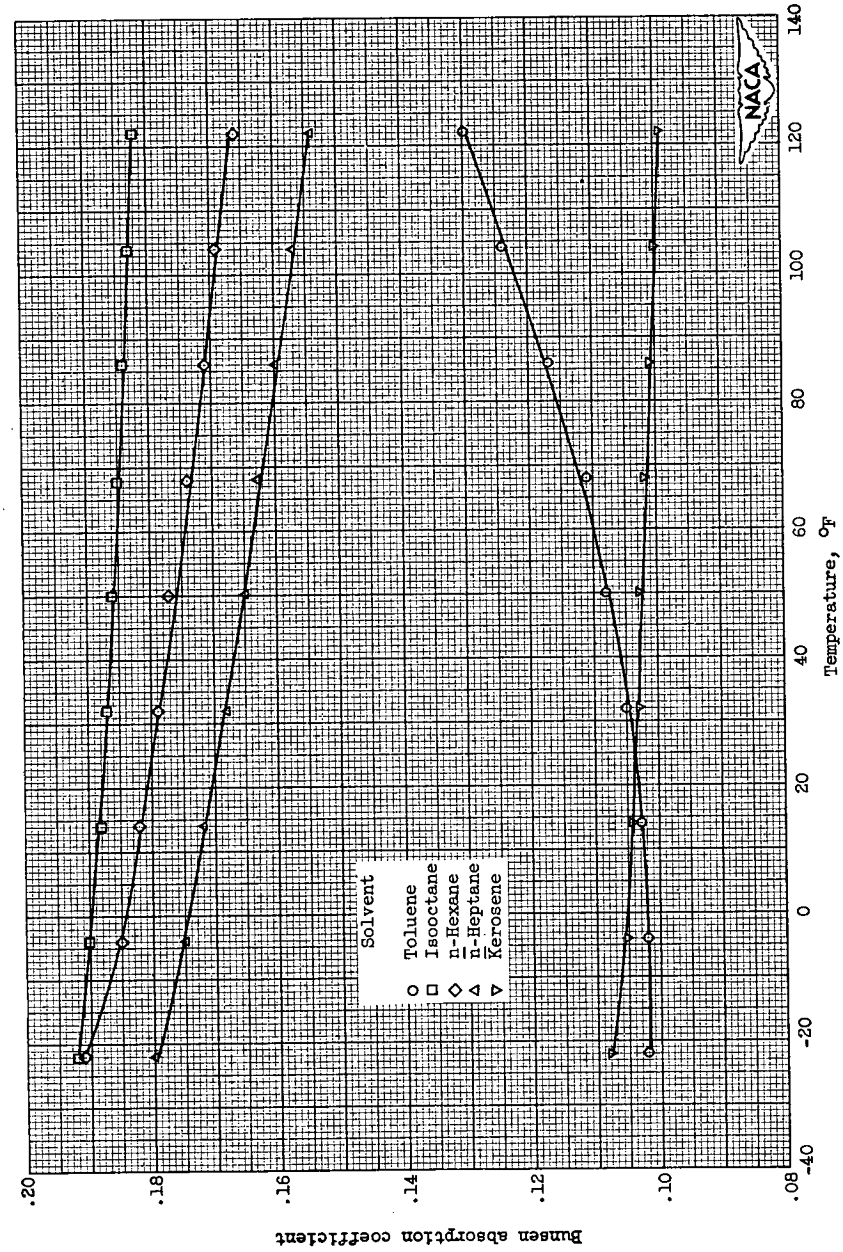
(a) Carbon dioxide.

Figure 14. - Solubility of gases in hydrocarbons.



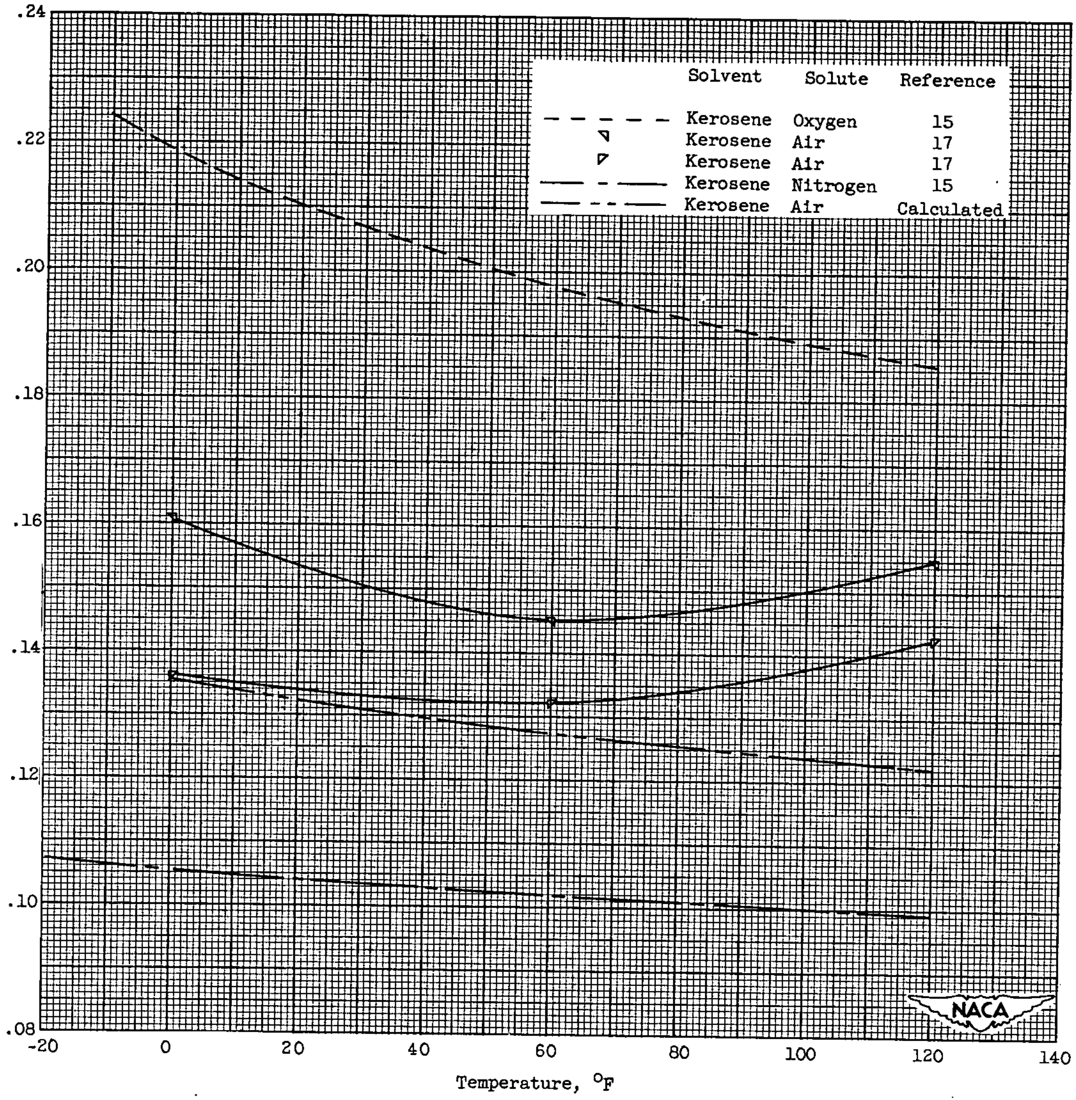
(b) Oxygen.

Figure 14. - Continued. Solubility of gases in hydrocarbons.



(c) Nitrogen.

Figure 14. - Continued. Solubility of gases in hydrocarbons.



(d) Air, oxygen, nitrogen. Curves for reference 17 represent solubility data for air in two different kerosenes. The calculated curve is based upon the two curves from reference 15.

Figure 14. - Concluded. Solubility of gases in hydrocarbons.

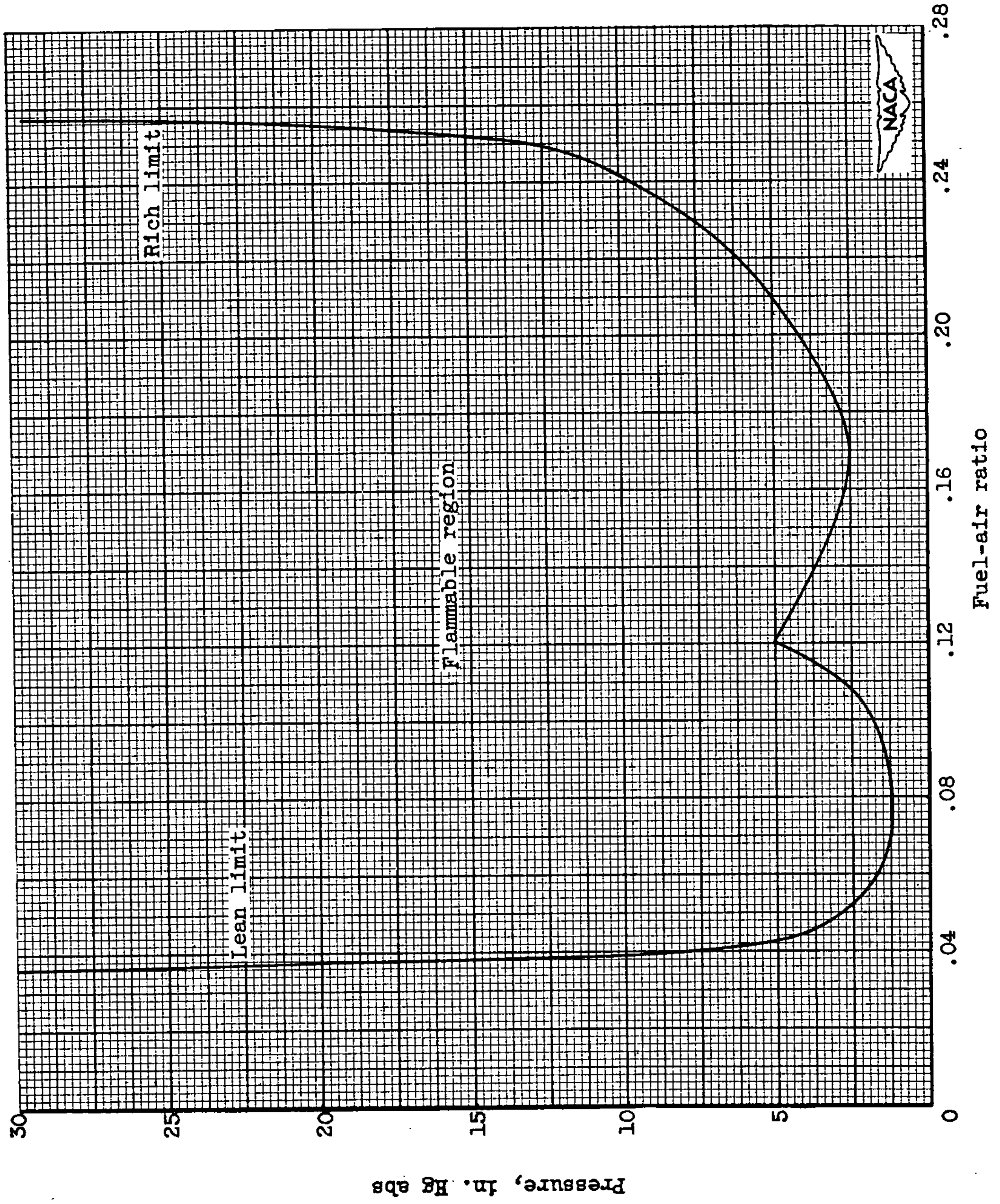


Figure 15. - Flammability limits of n-hexane in air as determined in a 2-inch tube.

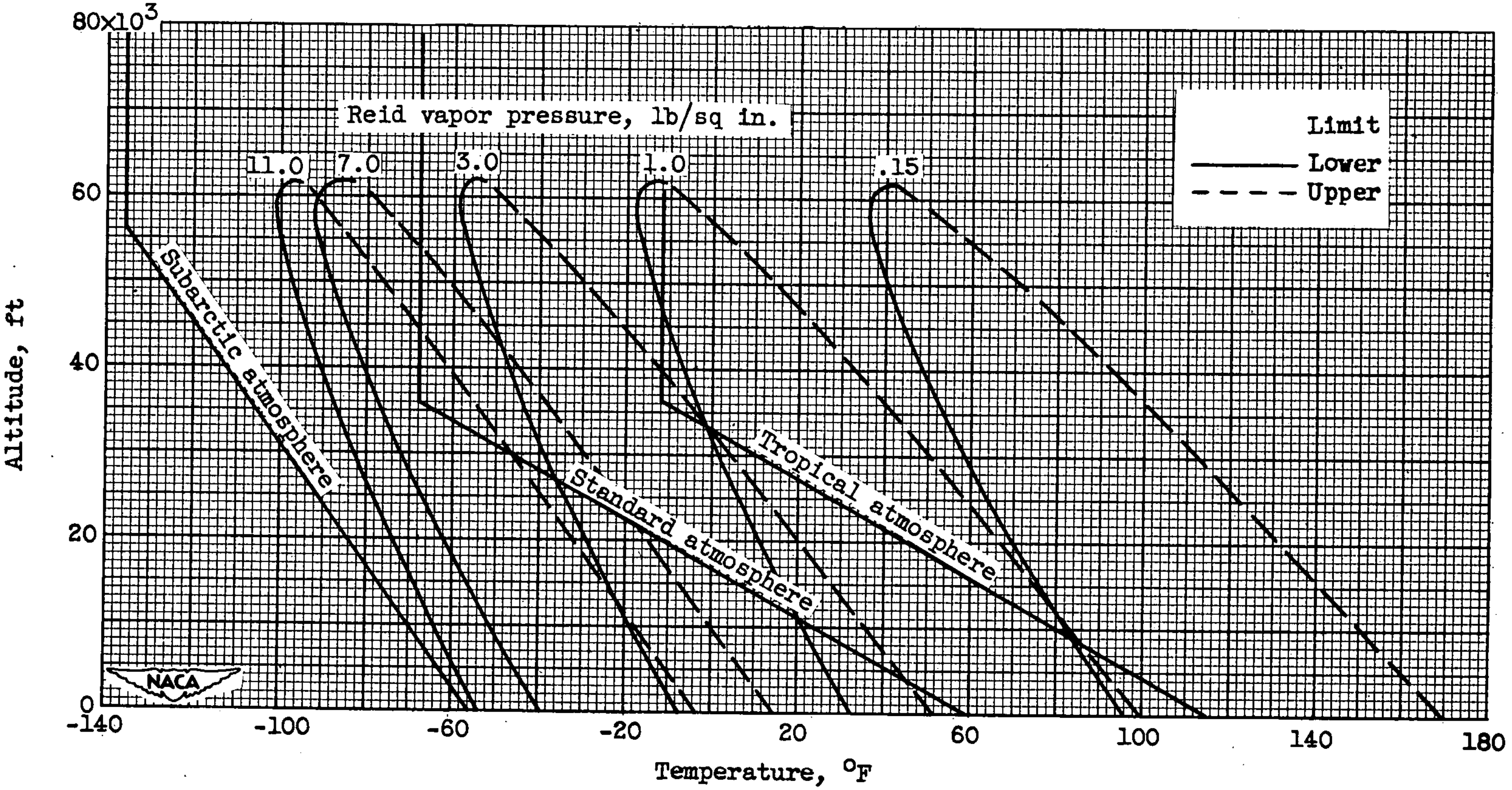


Figure 16. - Flammability limits of fuels of different volatility. (Data from refs. 2 and 5.)

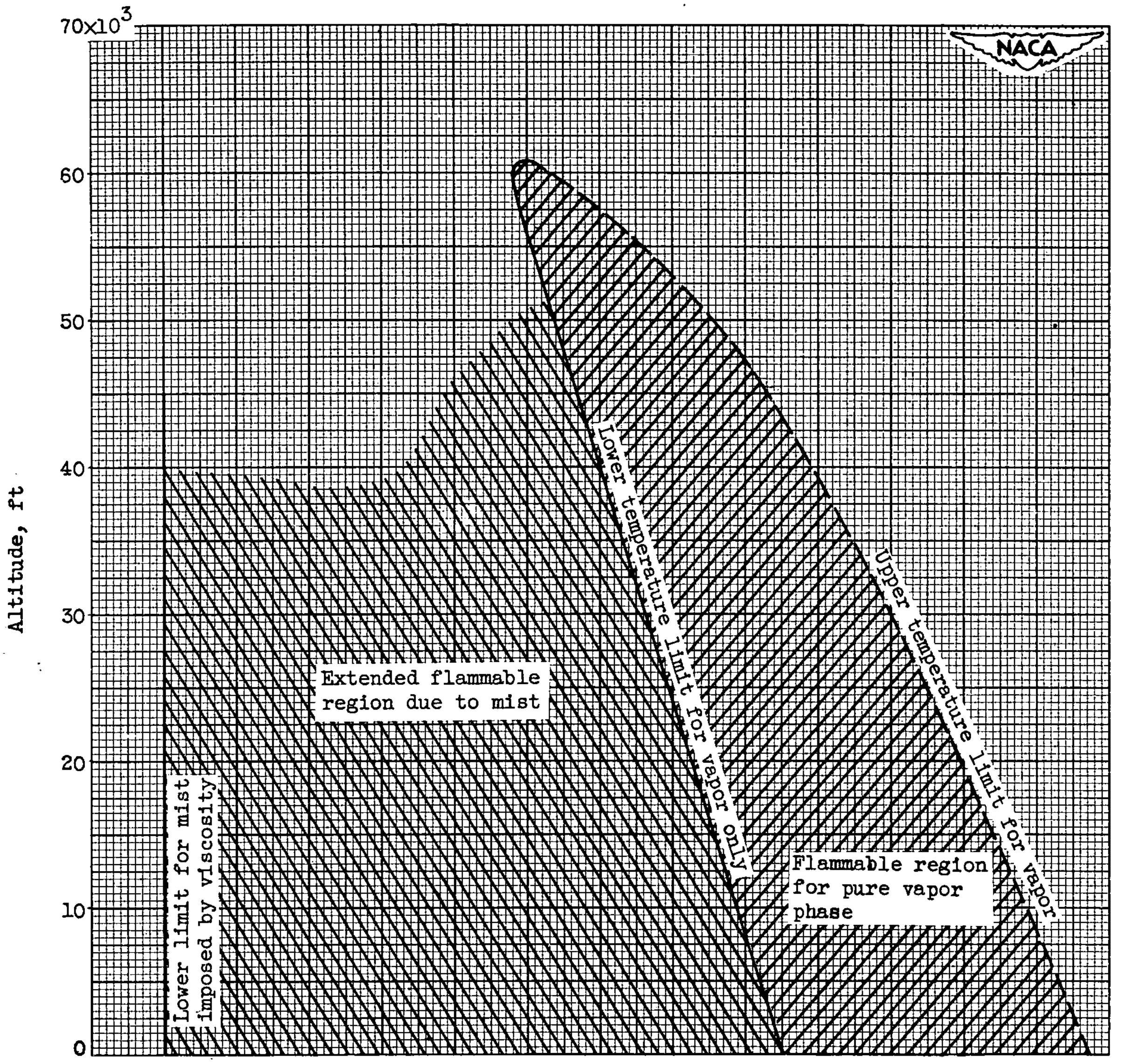


Figure 17. - Flammability limits of kerosene vapor and mist. (Data from ref. 20.)

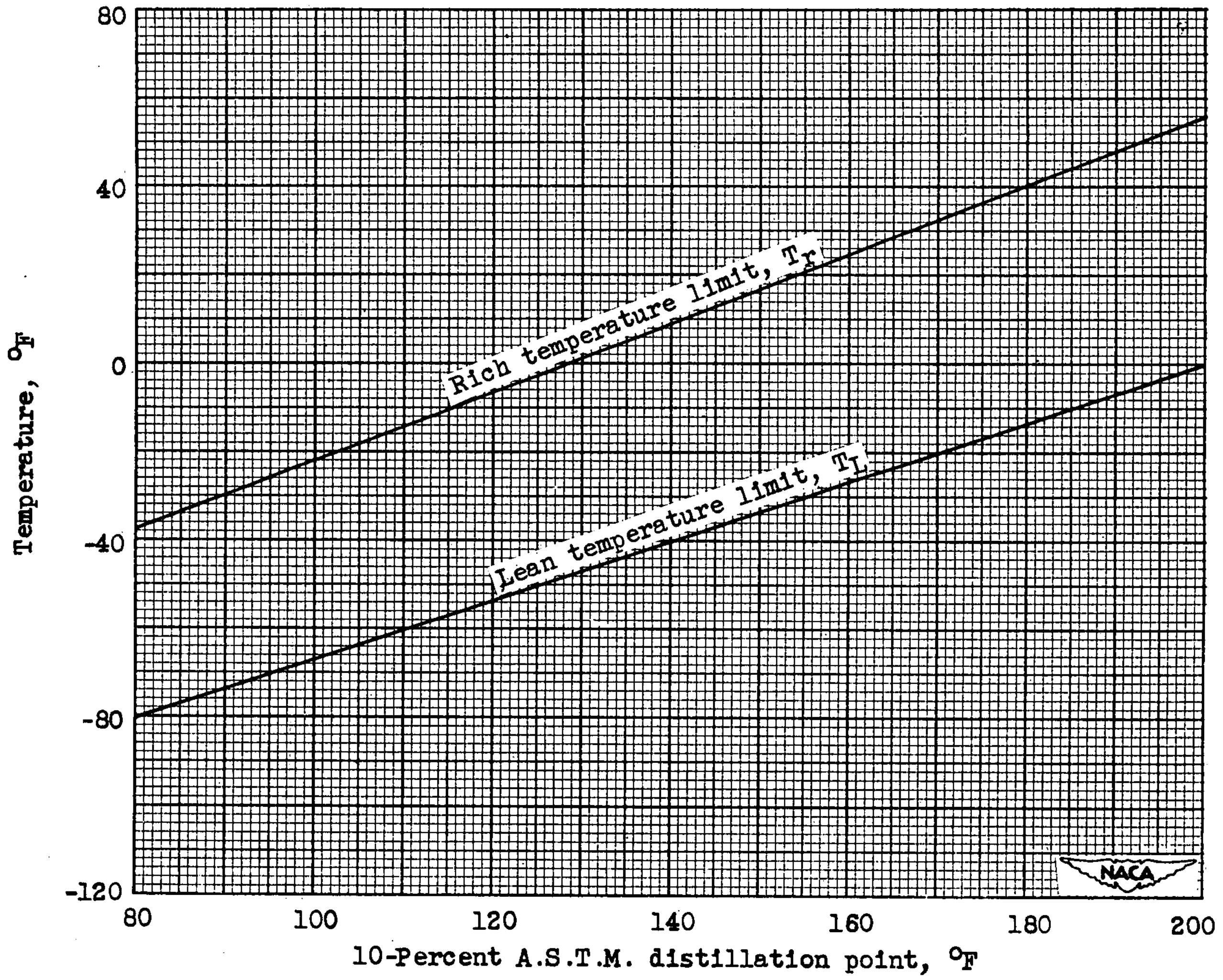
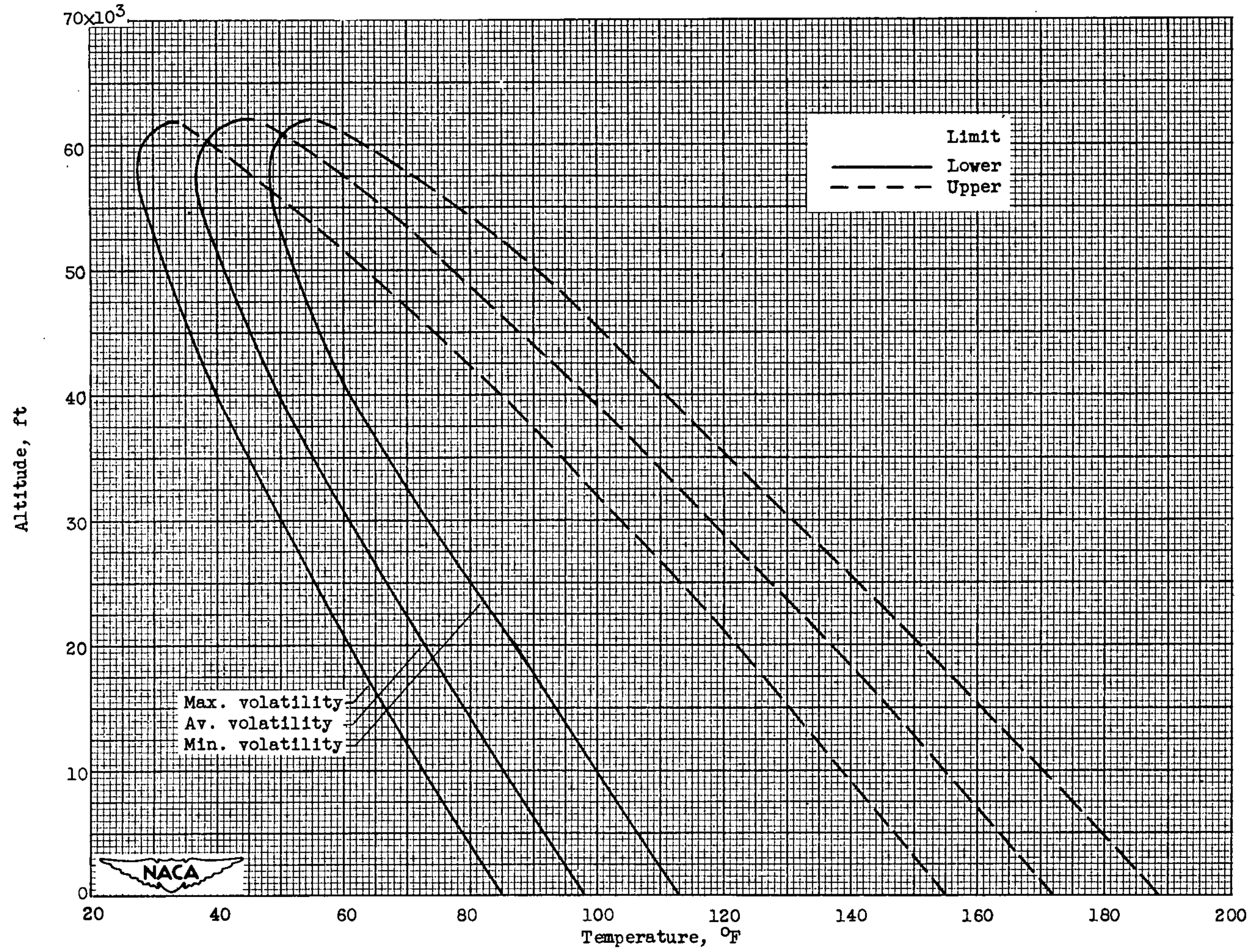
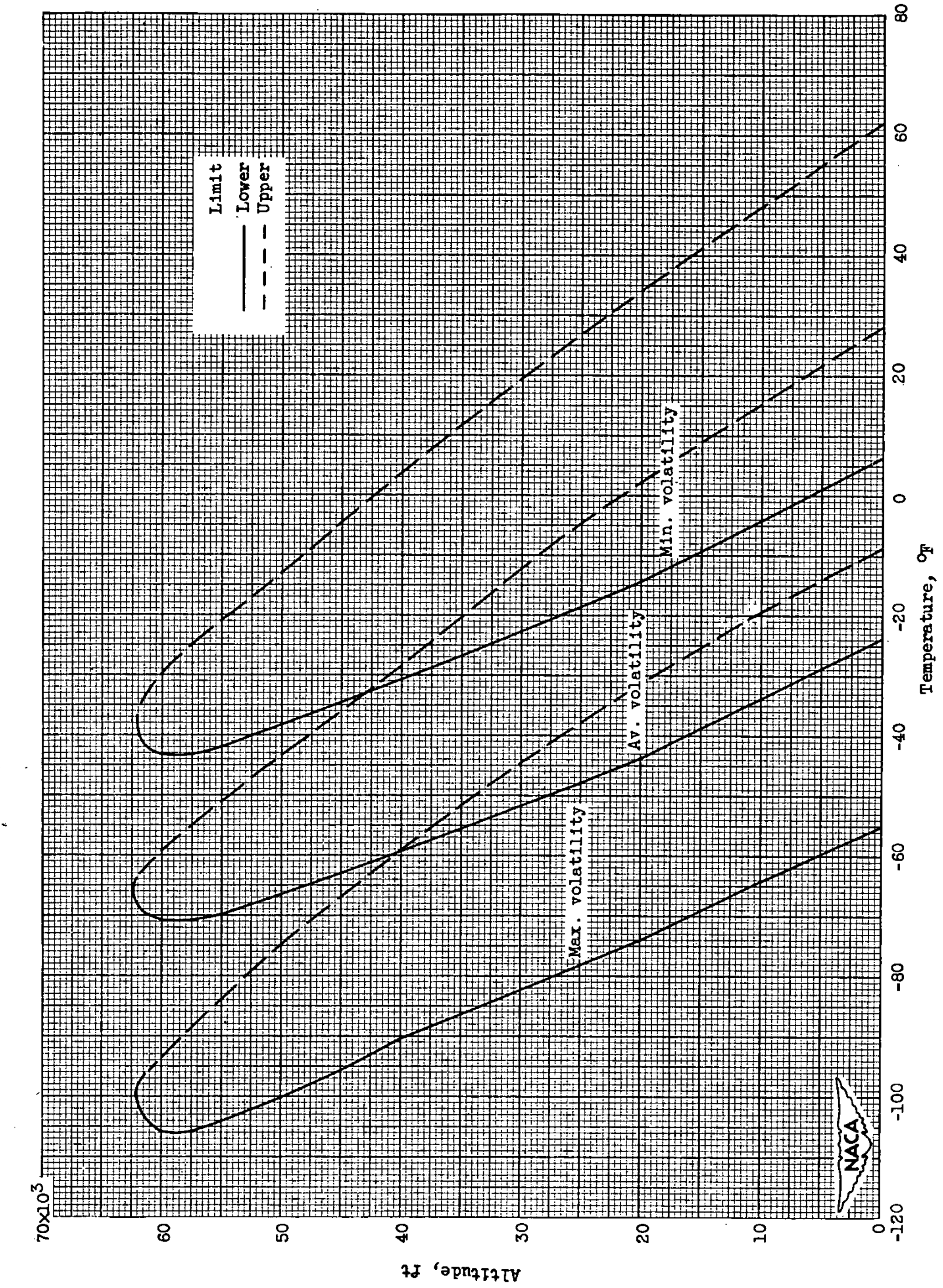


Figure 18. - Relation between sea-level rich and lean flammability limits and 10-percent A.S.T.M. distillation points.



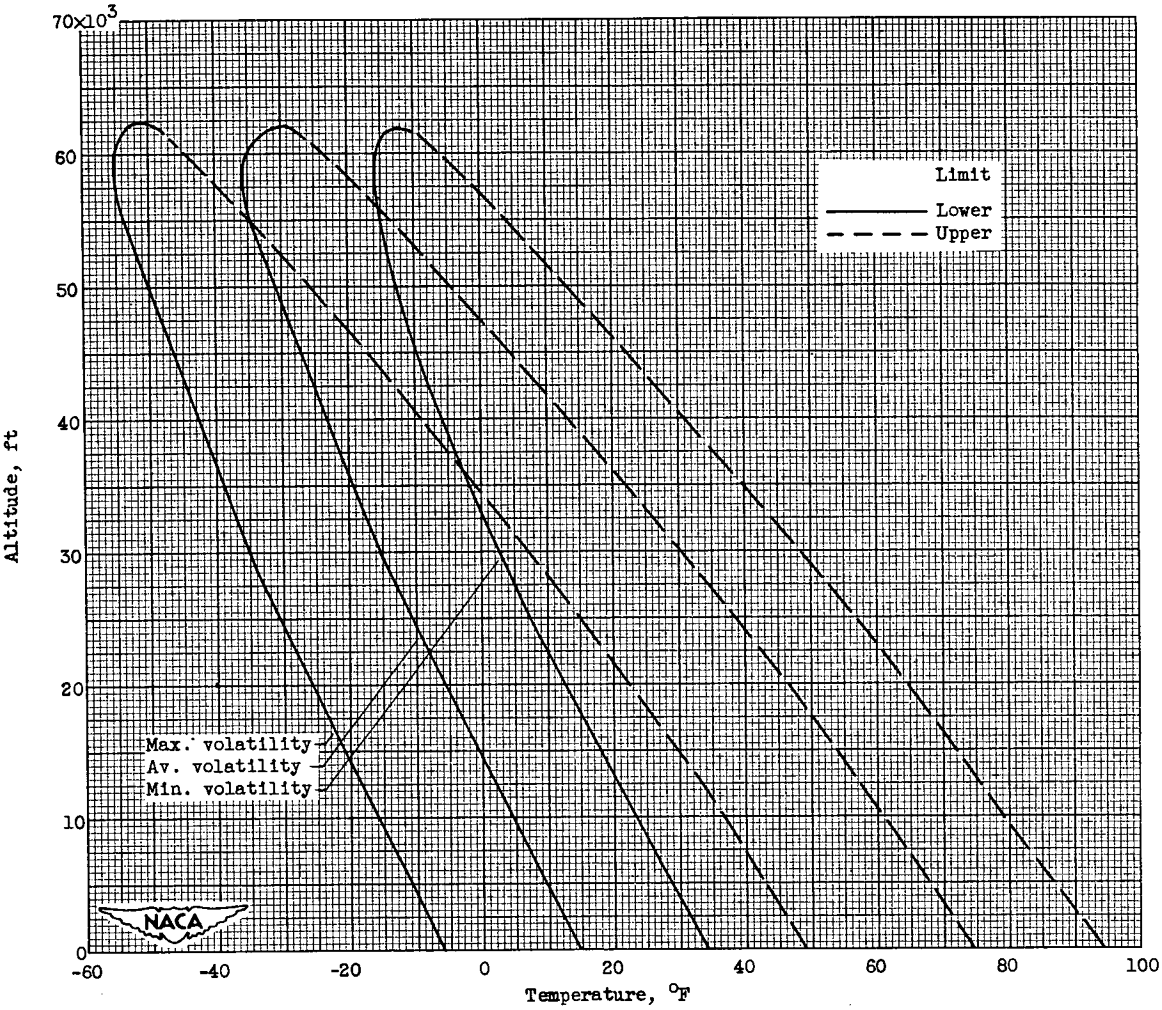
(a) MIL-F-5616 (JP-1) fuel.

Figure 19. - Calculated flammability limits of jet fuels.



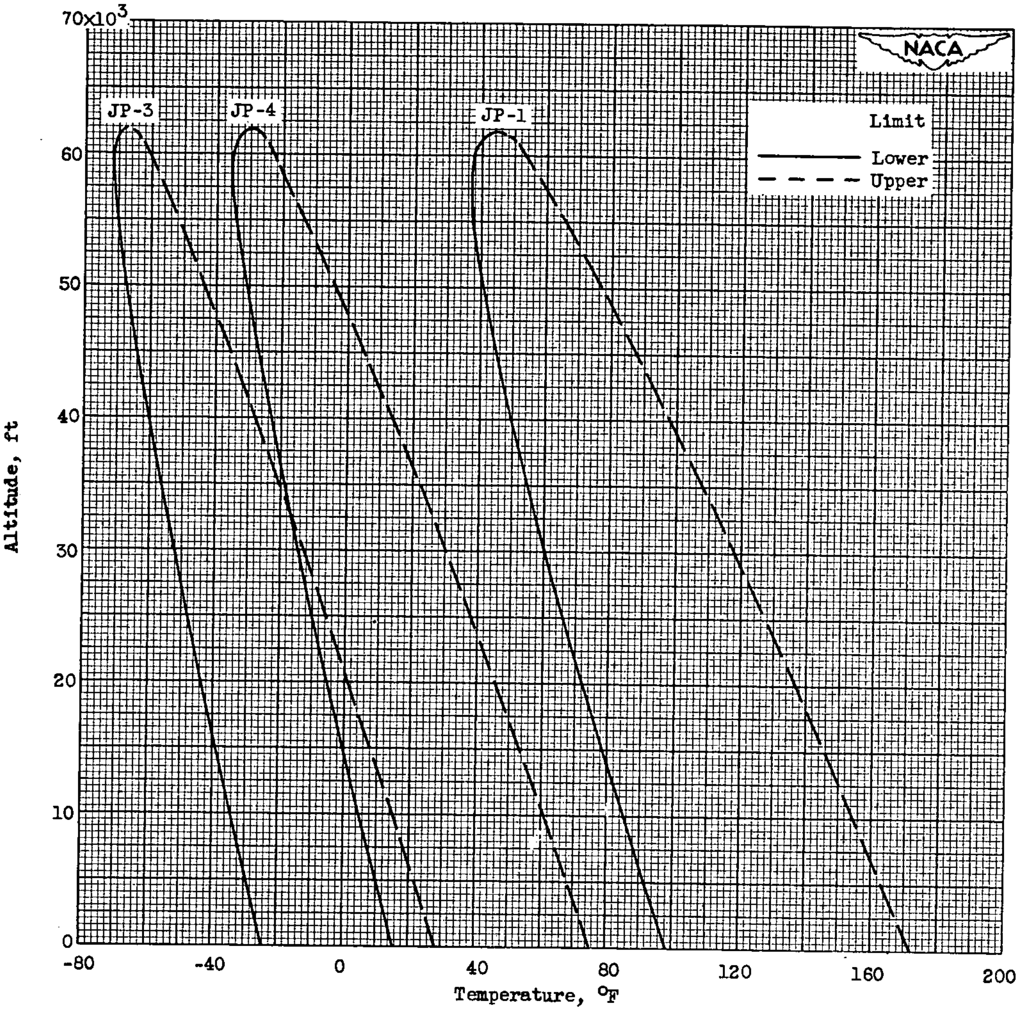
(b) MIL-F-5624A (JP-3) fuel.

Figure 19. - Continued. Calculated flammability limits of jet fuels.



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

Figure 19. - Continued. Calculated flammability limits of jet fuels.



(d) Comparison of average volatility JP-1, JP-3, and JP-4 fuels.

Figure 19. - Concluded. Calculated flammability limits of jet fuels.

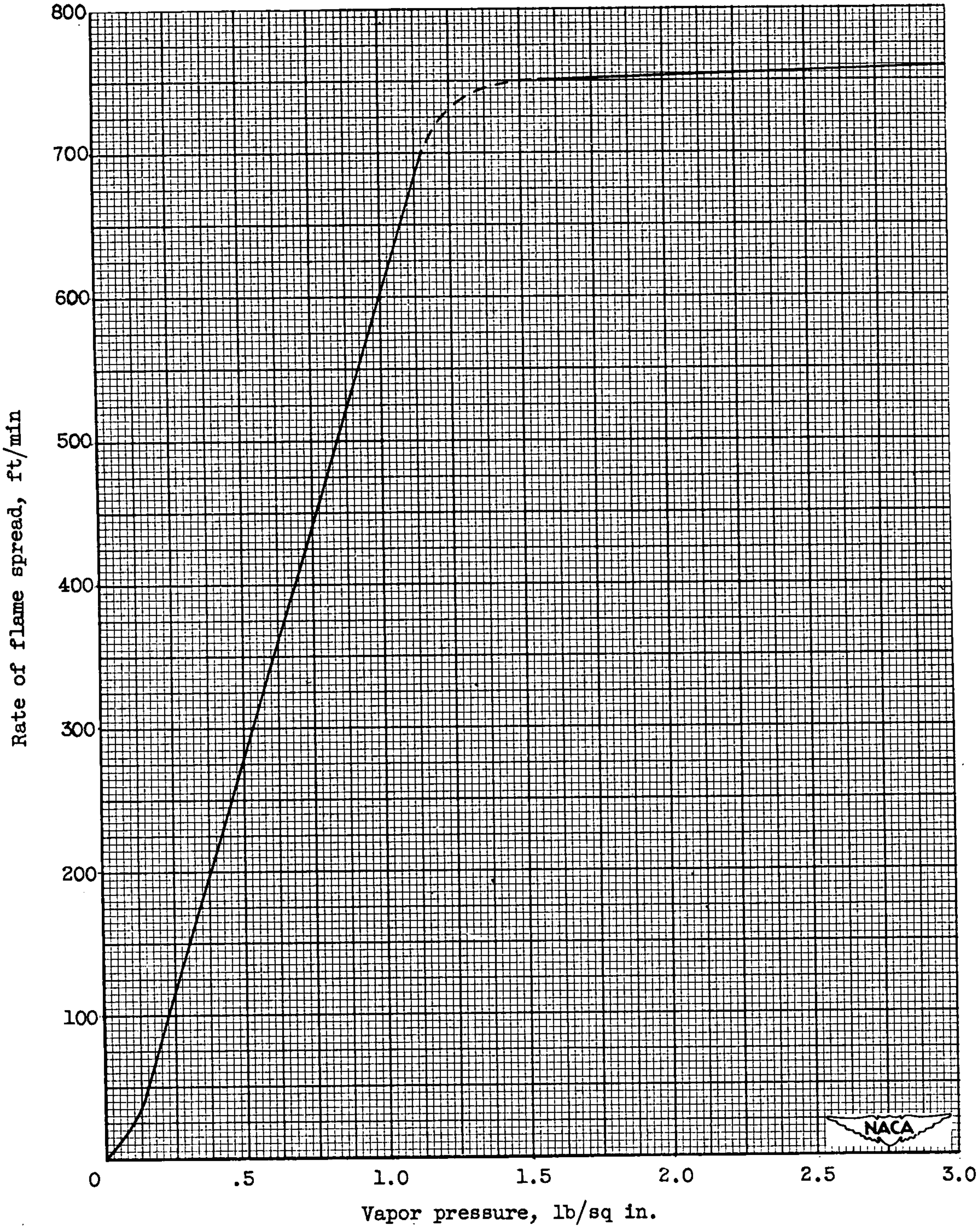


Figure 20. - Effect of volatility on flame spread in open tray. (Data from Shell Dev. Co.)

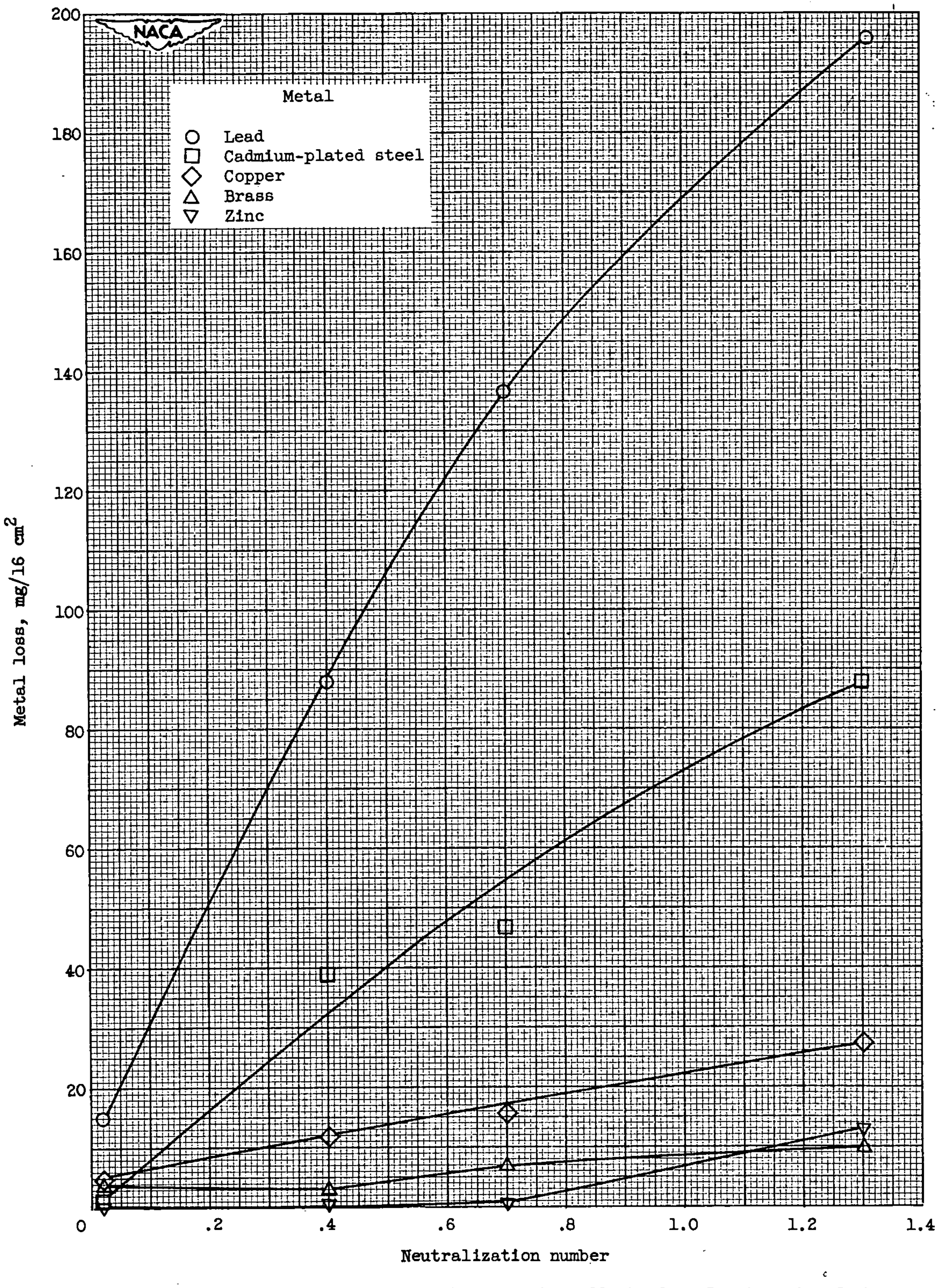


Figure 21. - Relation of acidity to corrosive effect of JP-3 jet engine fuel. (Data from ref. 27.) Corrosion determined by 48-hour air-well test, Federal Specification VV-L-791d.

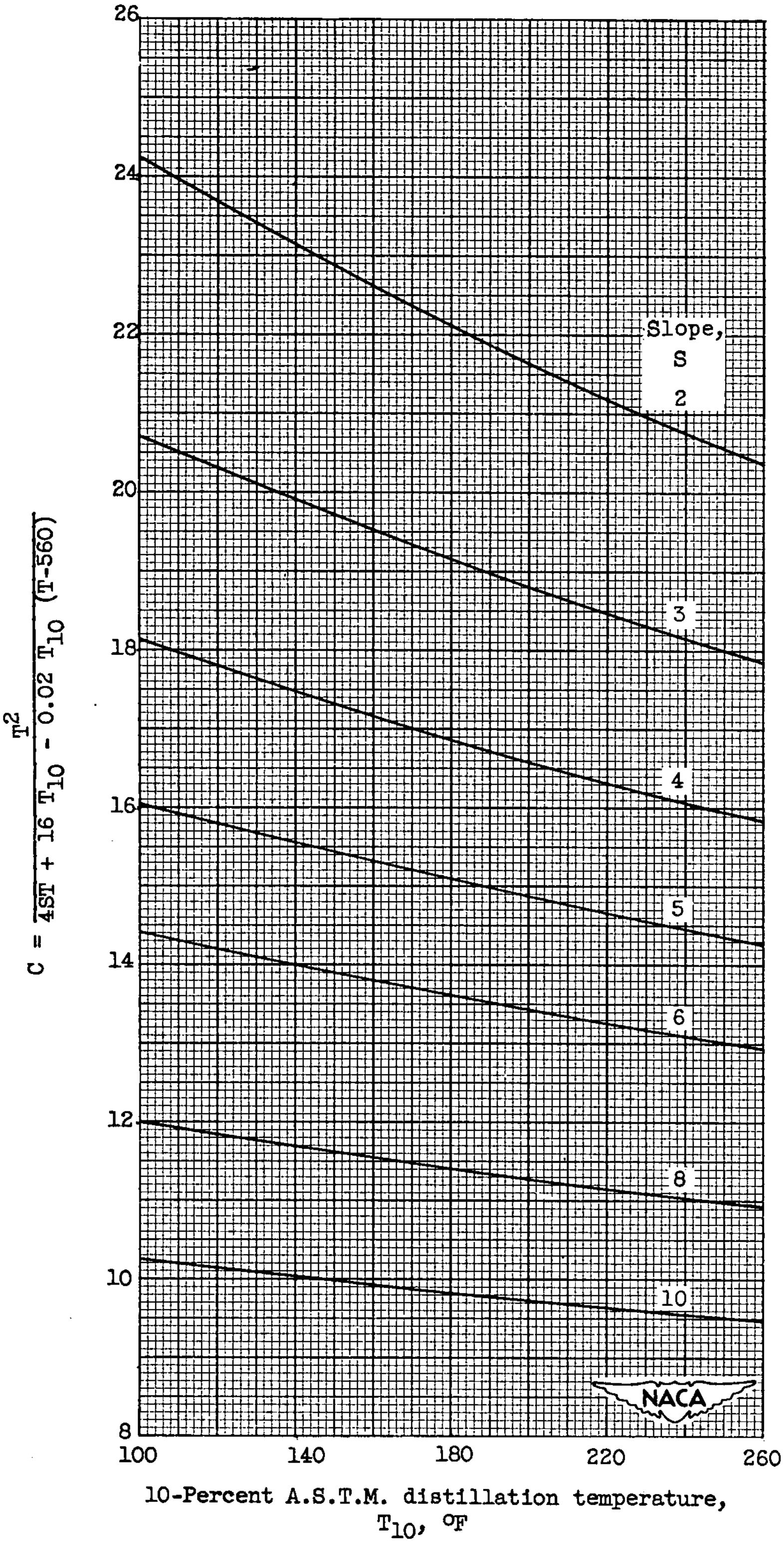


Figure 22. - Variation of C with T_{10}. This chart applies for data for initial fuel temperature of 110° F. Slope S is determined at 10-percent point of A.S.T.M. distillation curve.

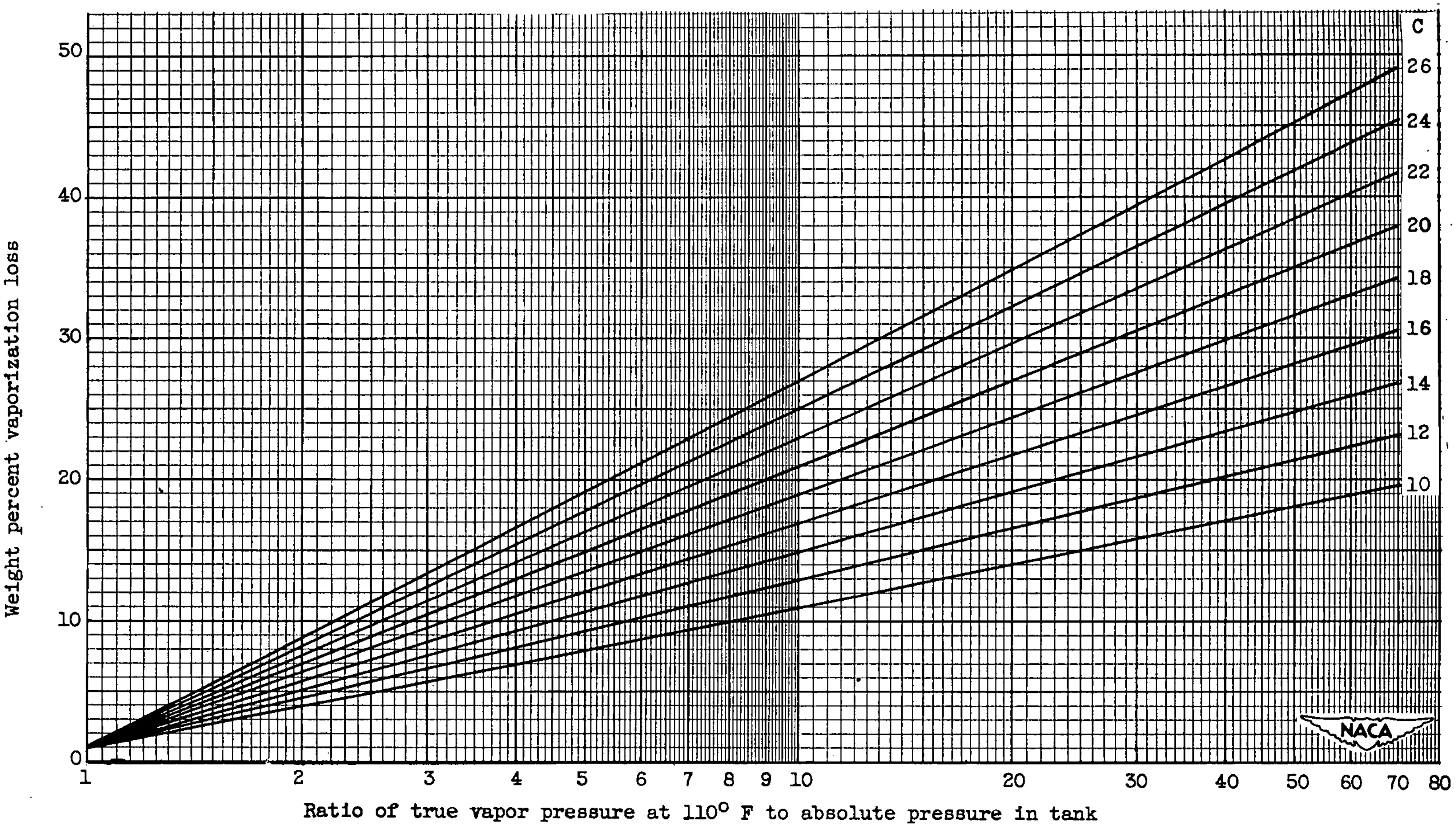
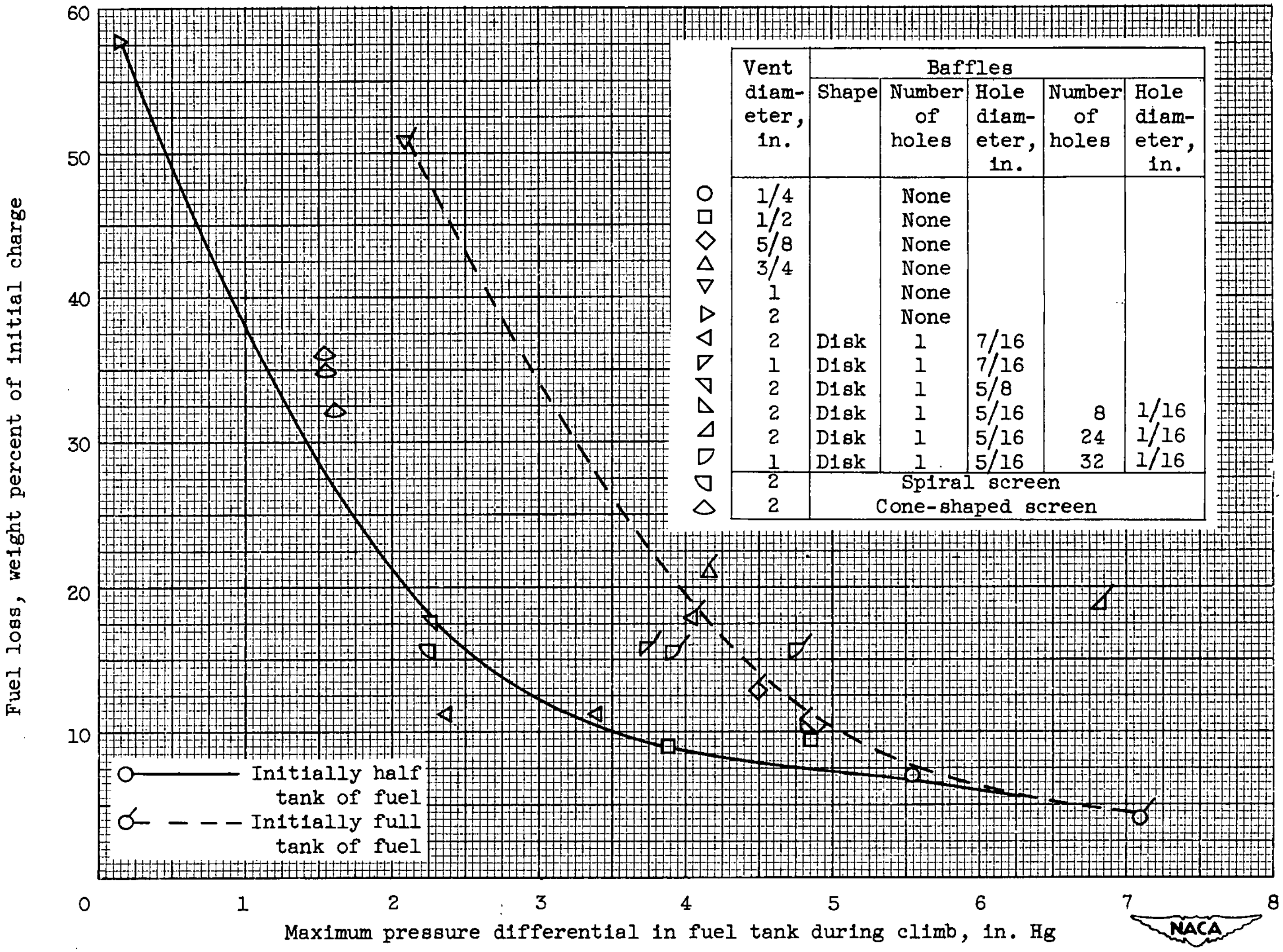


Figure 23. - Variation of vaporization losses with pressure for initial fuel temperature of 110° F. Values of C may be estimated from figure 22 for $T = 110^\circ$ F. $C = \frac{T^2}{4ST + 16\ T_{10} - 0.02\ T_{10}\ (T-560)}$.



	Vent diameter, in.	Baffles				
		Shape	Number of holes	Hole diameter, in.	Number of holes	Hole diameter, in.
○	1/4		None			
□	1/2		None			
◇	5/8		None			
△	3/4		None			
▽	1		None			
▷	2		None			
◁	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
◖	2	Spiral screen				
◇	2	Cone-shaped screen				

Figure 24. - 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.

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