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RESEARCH MEMORANDUM

CONSIDERATIONS IN THE ADAPTATION OF LOW-COST FUELS TO
GAS-TURBINE-POWERED COMMERCIAL AIRCRAFT

By Henry C. Barnett and Richard J. McCafferty

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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RESEARCH MEMORANDUMCONSIDERATIONS IN THE ADAPTATION OF LOW-COST FUELS TO
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SUMMARY

In recent months interest has increased in the possible use of distillate and residual fuel oils as fuels for commercial gas-turbine aircraft. However, the use of such fuels entails the solution of many problems pertaining to fuel physical properties and combustion characteristics. This report reviews some of these problems and discusses the status of current knowledge in relation to their solution.

INTRODUCTION

For some time fuel cost has been accepted as a major consideration in the conversion of commercial airline operations from piston-engine aircraft to gas-turbine-engine aircraft. For example, it has been estimated (ref. 1) that fuel cost represents about 20 percent of the direct operating cost of airlines operating with piston engines, and this cost may increase to 33 percent for airlines operating with turbine-propeller engines.

The most frequently proposed fuel for use in gas-turbine transports is kerosene, but in recent months there has been increased interest in the possibility of further fuel-cost reductions by use of low-cost distillate and residual fuel oils. These fuel oils are all considerably cheaper than aviation gasoline, and the residual types are substantially less costly than kerosene. Despite the attractiveness of the cost figures, the physical properties and combustion characteristics of such fuels offer many problems that must be solved before successful utilization in commercial aircraft can be achieved.

The present report discusses the properties of distillate and residual fuel oils and indicates the influence of these properties on engine performance and handling procedures. Brief discussions of relative costs and availability are included.

AVAILABILITY OF PETROLEUM PRODUCTS

The yields of products derived from a barrel of crude oil by present refinery methods are listed in the following table along with the daily production of the various fractions, based upon a current crude-oil production rate of about 6,500,000 barrels per day (ref. 2):

Product	Yield, percent of crude	Daily production, bbl	Low-cost fuel oils obtained, grade
Gasoline	45	2,925,000	
Kerosene	5	325,000	
Distillate fuels	18	1,170,000	1, 2, and Diesel
Residual fuels	19	1,235,000	4, 5, 6
Lubricants	5	325,000	
Other products and losses	8	520,000	
Total crude	100	6,500,000	

The so-called low-cost fuels referred to in the INTRODUCTION are obtained from distillate and residual fractions as indicated in the preceding table. These fuels are commonly designated by numbers corresponding to certain commercial specifications (table I). The more conventional uses of the distillate fuels are home heating, Diesel engine operation, and industrial heating, in which it is impractical to heat the fuel to improve flow characteristics. Residual fuels are residues from petroleum stills and in marketed form are blended with less viscous materials. These fuels are used in applications in which it is feasible to heat the fuel for flow improvement.

It has been estimated (ref. 3) that the daily requirement of fuel for gas-turbine-powered nonmilitary aircraft will be approximately 13,000 barrels by 1962. This figure is based upon an estimate that the commercial jet-fuel demand will be about 15 percent of the aviation-gasoline demand in 1962, which is predicted to be twice the consumption in 1951 (44,000 bbl/day in 1951).

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The requirement of 13,000 barrels per day of jet fuel could easily be met by fuels from the kerosene, distillate-oil, or residual-oil fractions of the crude. In the case of kerosene and the lighter fuel oils, however, there would be an overlap with military requirements, and production of the military fuel, JP-4, would decrease the availability of kerosene for other purposes. The significance of this overlap in future plans cannot be evaluated accurately until more reliable information is available on the jet-fuel requirements for military and airline operations.

Because of the dual demand on kerosene for commercial and military operations, the possible use of heavier fractions of petroleum for commercial aircraft may become more attractive. It is emphasized, however, that high emergency requirements of heavy distillates and residual oils for other purposes could appreciably reduce the availability of such fuels for aviation. The heavier distillate oils and residual oils are much less affected by emergency production of JP-4 fuel than is kerosene. This fact is illustrated in figure 1 (estimated from the preceding availability table and ref. 4). For zero production of JP-4, the percentages on the ordinate of this figure correspond to the percentages of crude shown in the table. As the "all-out" production of JP-4 fuel increases, the availability of each of the three stocks decreases. The percentage decrease in kerosene for all-out production of JP-4 is quite large (72 percent); whereas distillate fuels and residual fuels decrease moderately, 25 and 3 percent, respectively.

COST OF PETROLEUM PRODUCTS

Fuel prices at airports depend upon airport location relative to refineries and bulk terminals; however, prices quoted in the literature for petroleum stocks are reasonably uniform on a relative basis. Some relative costs (March, 1952) of petroleum products are presented in figure 2 (from ref. 5).

The cost of kerosene is about 55 percent the cost of grade 100/130 aviation gasoline; and any further savings must come from use of grade 2 or heavier fuel oils. Current prices for aviation gasoline may range between 20 and 25 cents per gallon. If commercial gas-turbine aircraft were able to utilize distillate fuels such as grade 2 or 4 fuel oil, savings in fuel costs might be expected; if grade 5 or 6 fuel oil were used, marked savings could be realized.

On the other hand, representatives of the petroleum industry have emphasized that the heavier fuel oils (grade 5 and 6) would be impossible to hold to a narrow specification. Consequently, grade 4 probably represents the heaviest fuel oil that might be considered for aviation uses.

The current price differential between kerosene and grade 4 fuel oil is about 3 cents, and this difference would diminish if any attempt were made to write more rigorous specifications than those shown in table I for grade 4. The current price differential between kerosene and grade 2 fuel oil is still less (1 cent); therefore, little saving could be expected through the use of grade 2 with narrow aviation specifications.

PHYSICAL PROPERTIES OF PETROLEUM PRODUCTS

In addition to cost and availability considerations, the physical properties of distillate and residual fuels offer problems relating to engine performance, handling, and safety. In order to clarify later discussion on these three factors, existing data on physical properties are reviewed to indicate the variations to be expected for distillate and residual fuel oils (see table II). Data on fuel oils 1, 2, and 4 were compiled from surveys of the U. S. Bureau of Mines (refs. 6, 7, and 8). Data on fuel oils 5 and 6 are quite scarce; therefore, it is necessary to resort to comparisons of single samples of these two fuels with averages for the three lower grades. Comparisons are made between the properties of the fuel oils and JP-4 fuel. The kerosene-type jet fuel (JP-1) is not included in these comparisons, since its properties are very similar to those of grade 1 fuel oil with the exception of volatility. The volatility of JP-1 fuel is between that of grade 1 fuel oil and JP-4 fuel.

Wherever possible, the influence of temperature on certain properties is presented. These variations with temperature were estimated by methods described in references 9 and 10.

Density

Under current fuel-oil specifications, appreciable variations of density are encountered among marketed stocks, as is illustrated in figure 3 for grades 1, 2, and 4 fuel oils. The maximum percentage deviation from the average curves increases as the grade of fuel oil becomes heavier. For grade 1 fuel oil, the maximum deviation is 2.7 percent; for grade 2, 6.7 percent; and for grade 4, 8.0 percent.

In figures 3(a) and (b) it is also seen that for the numerous samples examined, none had specific gravities as high as that permitted by the specifications. Figure 3(d) compares the average gravities of fuel oils 1, 2, and 4 with single samples of grades 5 and 6 fuel oil and with JP-4 fuel.

Volatility

One of the commonly accepted measures of fuel volatility is the A.S.T.M. distillation curve. The curves of figure 4 indicate the variations of volatility under a given specification and the relative volatility among the grades of fuel oil. The higher the temperatures on such plots, the lower the volatility.

Some of the samples included in the evaluations shown in figures 4(a) and (b) are near the upper limits of the current specifications. Only grades 1 and 2 must meet A.S.T.M. distillation requirements (see table I). As was the case with the specific-gravity data (fig. 3), the spread between minimum and maximum values of distillation temperature tends to increase as the grade of fuel oil becomes heavier.

In figure 4(d), distillation data for four grades of fuel oil are compared with data for JP-4 fuel. All these fuel oils are considerably less volatile than JP-4 fuel, as indicated by the high distillation temperatures. Similar data for grade 6 fuel oil are indeterminate, and the curve for grade 5 fuel oil is incomplete because of cracking of the sample at 1025° F.

Vapor Pressure

Vapor pressure - temperature curves for the fuel oils and JP-4 fuel are presented in figure 5. It is apparent (fig. 5(d)) that the volatility of the fuel oils is much less than that of JP-4 fuel. At 100° F the vapor pressure of grade 1 fuel oil is about one-fiftieth that of JP-4 fuel.

Heat of Combustion

The net heats of combustion for the fuel oils estimated from specific gravities (ref. 10) are listed in the following table together with data for JP-4 fuel (ref. 9):

Fuel oil, grade	Net heat of combustion (estimated)					
	Btu/lb			Btu/cu ft		
	Min.	Max.	Av.	Min.	Max.	Av.
JP-4 fuel	18,590	18,840	18,740	88.3x10 ⁴	93.8x10 ⁴	90.8x10 ⁴
1	18,520	18,670	18,570	92.2	94.9	94.2
2	18,140	18,620	18,400	93.2	100.2	96.8
4	17,420	18,230	17,930	99.1	106.9	102.4
5	-----	-----	^a 17,800	----	-----	^a 103.7
6	-----	-----	^a 17,620	----	-----	^a 105.2

^aSingle sample.

On a weight basis, the average heats of combustion decrease as the density of the fuel becomes greater; on a volume basis, the heats of combustion increase with density. As indicated in the table, there is an overlap on the ranges of gravity for each type of fuel. For example, some of the less dense samples of grade 2 fuel oil may have heats of combustion within the range for grade 1 fuel oils.

Latent Heat of Vaporization

The latent heats of vaporization for three fuel oils are presented in figure 6. These data were estimated by a method described in reference 10. Average curves are not shown in figures 6(a) and (c) because of the narrow spread between minimum and maximum limits. The three distillate fuel oils are compared with JP-4 fuel in the following table:

Fuel oil, grade	Latent heat, Btu/lb, at -									
	200° F		300° F		400° F		500° F		600° F	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
^a JP-4	136	143	120	131	102	117	---	---	---	---
1	135	139	125	128	113	116	97	103	71	87
2	135	142	124	133	113	123	98	113	79	100
4	145	147	134	139	123	129	111	120	96	110

^aData from reference 9.

The latent heats of vaporization for all four fuels are of the same order of magnitude at the low temperatures, but at the high temperatures the latent heats increase as the fuel density increases.

Viscosity and Pour Points

The variations of viscosity with temperature for fuel oils are shown in figure 7. The samples of fuel oils 1 and 2 all fall within the limits of the specifications (table I); however, some samples of fuel oil 4 fall outside both the minimum and maximum specification limits. Regardless of this condition, the samples were averaged, because the original reference sources (refs. 6, 7, and 8) stated that these samples had been marketed as grade 4 fuel oils.

The comparison of fuel-oil viscosities with data for JP-4 fuel (fig. 7(d)) indicates that much higher viscosities may be encountered in the heavier grades of fuel oil. At 100° F the viscosity of grade 6

fuel oil is approximately 450 times that of JP-4 fuel. The pour point (indicated on the curves in fig. 7) is a measure of the tendency of the fuel to flow and is determined by a standard A.S.T.M. procedure (D97). In general, the heavier the fuel, the higher the temperature necessary to maintain the fuel in fluid condition. This relation is illustrated in figure 8, where the trend is in the direction of increasing pour point with increasing end point, the end point being an indication of the heaviness of the fuel. This relation is not rigorous, however, because of the influence of fuel composition. The scatter is attributable to differences in composition of the samples.

Sulfur and Ash Content

The sulfur content of several fuel oils is compared with that of JP-4 fuel in figure 9, which shows clearly that appreciable quantities of sulfur are found in the heavier fuels. However, it should be recognized that the current specification for JP-4 fuel allows a maximum sulfur content of 0.4 percent by weight, and average grade 1 and 2 fuel oils are within this limit. On the other hand, the specifications for these two fuel oils permit higher percentages of sulfur than 0.4 (see tables I and II).

The ash contents of fuel oils are shown in the following table:

Fuel oil, grade	Number of samples	Ash content, percent by weight		
		Min.	Max.	Av.
1	53	0	0.010	0.0004
2	107	0	.020	.0008
4	6	0	.18	.03

These data indicate that the heavier fuel oils may be expected to have greater ash contents. The data for grade 4 fuel oil are not considered conclusive, inasmuch as one sample showed an ash content of 0.18 percent by weight, and the remaining five samples contained no ash.

PROBLEMS RELATED TO AIRCRAFT RANGE

Heats of Combustion and Specific Gravities

In the preceding discussion, it has been shown that for hydrocarbon fuels the net heating value per unit weight decreases and the heating value per unit volume increases as the specific gravity increases. Unfortunately, this inverse relation is not consistent with the two main

requirements for increased flight range. It is desirable to have high heating value per unit weight, because low total weight is important in establishing maximum range; it is also desirable to maintain high heating value per unit volume because of aircraft volume limitations.

The following table shows the gains to be expected on the basis of heating value and specific gravity:

Fuel oil, grade	Net heat of combustion				Specific gravity, 60/60° F	Change, percent
	Btu/lb	Change, percent	Btu/cu ft	Change, percent		
JP-4 fuel	18,740	--	90.8X10 ⁴	--	0.777	--
1	18,570	-1	94.2	4	.813	5
2	18,400	-2	96.8	7	.842	8
4	17,930	-4	102.4	13	.915	18
5	^a 17,800	-5	^a 103.7	14	.934	20
6	^a 17,620	-6	^a 105.2	16	.957	23

^aSingle sample.

For all the fuel oils, an increase in specific gravity (and in turn, volume heat content) over JP-4 is apparent, although the heat content on a weight basis is lower. On the other hand, the gain in volume heat content may be cancelled by the induced drag arising from the increase in fuel weight. For this reason the anticipated gains in flight range may not be realized.

This fact is illustrated in figure 10 for an assumed volume-limited aircraft. A grade 6 fuel oil shows a 10-percent gain in range over JP-4, whereas the volume heat content previously discussed showed an expected increase of 16 percent. The other fuel oils in figure 10 show similar trends in comparison with JP-4.

The data in figure 10 are illustrative of possible flight-range increases from the use of high-density fuels in a volume-limited aircraft. Similar data were estimated for an assumed supersonic bomber, a supersonic interceptor, and a subsonic bomber, all of which were altered in design to permit maximum range with each fuel. The supersonic bomber and interceptor show much smaller potential range increases than does the volume-limited aircraft. In the case of the subsonic bomber, an increase in fuel density indicated a decrease in aircraft range. It is emphasized that these calculated data are preliminary in nature and are significantly dependent upon the assumed aircraft configuration and conditions.

Combustion Efficiency

Effects of volatility and fuel injection. - One of the major performance problems to be faced with low-cost (low-volatility) fuels is the attainment of high combustion efficiency. There is a decided tendency in some combustion chambers for efficiency to decrease as the volatility of the fuel decreases. This tendency is illustrated in figure 11 for various petroleum fractions. Included also are JP-1 fuel and a Diesel oil. The data in this figure are reported in reference 11, and the effect of volatility shown is confirmed by other data reported in references 12 and 13.

The tendency for high-volatility (low 50-percent point) fuels to give higher efficiencies is presumably accounted for by the fact that vaporization is rapid; and, under the test conditions chosen, combustible fuel-air mixtures are obtained in the low velocity zone of the combustor. Conversely, the high-boiling fuels vaporize more slowly and have insufficient time for complete burning.

That the relation shown in figure 11 varies from one engine to another indicates that the degree of depreciation of efficiency with fuel type is dependent upon the adequacy of the engine design for vaporizing and burning the fuel. For this reason, difficulty may be expected in the use of the fuel oils in current engines. Furthermore, it is probable that the use of the heavier fuels would necessitate development of a special combustion chamber.

One method by which the vaporization characteristics may be improved in a given combustor is improvement of injection-nozzle design. The effect of nozzle design on efficiency (ref. 14) is shown in figure 12, in which a flared-tip nozzle is compared with an unflared-tip nozzle. In both cases the nozzles had a fixed orifice size. The modified (flared-tip) nozzle simply increases the spray angle, particularly at low fuel flows. The original nozzle produced a spray angle of about 80° , whereas the new nozzle produced an angle of 180° at the low fuel flows. No effect of the flared tip on droplet size was apparent.

The increase in efficiency (fig. 12) achieved with the modified nozzle may be attributed to the fact that with the wider spray angle a more satisfactory mixture of fuel and air was produced in the primary zone of the combustor. It is emphasized that such changes cannot be made indiscriminately, since other performance factors, such as carbon deposition and altitude operational limits, could be affected. These factors will be discussed in the following section of this report.

The effect of injection variables on combustion efficiency is further demonstrated in figure 13 (ref. 15) for gasoline and Diesel oil. Fuel-injection nozzles having capacities of 3 and 10 gallons per hour were used

in these tests. In both cases, the low-capacity nozzle produced better atomization, particularly at low flows; but the temperature rise of gasoline with the 3-gallon nozzle is low, and that of Diesel oil is high. This result is attributed to the fact that gasoline is by nature a volatile fuel, and improved atomization tends to improve its vaporization. Consequently, the mixtures of fuel and air achieved in the combustion chamber are overrich and combustion is more difficult. Diesel oil is not a volatile fuel; therefore, the improved atomization with the smaller nozzle enhances its vaporization characteristics to the point that satisfactory mixtures of fuel and air are produced in the combustion chambers. In this particular test of Diesel oil, the temperature rise of the small nozzle drops below that of the large nozzle at high fuel flows because of the low inlet-air pressure and high inlet-air temperature. These conditions combine to produce overrich mixtures even with Diesel oil.

Another obvious approach to better fuel-air mixture preparation is the use of preheated or prevaporized fuel. The fact that high efficiencies may be attained by use of vaporized fuel has been verified in NACA investigations (refs. 16 and 17). These studies show that, although combustion efficiency and other performance factors are improved, the distribution of the vapor fuel in the primary zone of the combustion chamber is critical. The use of preheated or vaporized fuel also presents the problem of supplying the necessary heat to the fuel, as discussed in a later section.

PROBLEMS RELATED TO AIRCRAFT RELIABILITY

Engine Starting

The process of ignition in an engine is dependent upon the presence of a flammable mixture at the source of ignition, which is in turn dependent upon fuel volatility and the method by which fuel is delivered to the combustion chambers. Because of these requirements, the problem of ignition of the heavier fuels may be expected to be difficult.

The fuel-flow requirements for ignition of three fuels in a tubular combustion chamber at sea-level conditions are shown in figure 14 (ref. 18). For a given inlet-air temperature, the fuel flow required for ignition increases as fuel volatility decreases. At high inlet-air temperatures the differences in required fuel flows are much smaller than at low temperatures.

The data from figure 14 are cross-plotted in figure 15 to indicate the influence of volatility on required fuel flows for ignition. Since the fuel oils have A.S.T.M. 10-percent distillation points in excess of 365° F, it is apparent that greater fuel flows will be required for ignition in this particular combustor. The data at 355° F 10-percent point (fig. 15) are for a kerosene-type fuel.

Similar effects of volatility on engine starting are found at altitude conditions (fig. 16). The lower the fuel volatility, the greater the required fuel flow for ignition. At high altitudes the differences among the fuels are greater.

Another important factor to consider in the problem of igniting low-volatility fuels is the quantity of energy available for ignition. Investigations (refs. 19 and 20) of this factor indicate that the lower the fuel volatility, the greater the quantity of energy required for ignition. By use of surface discharge spark plugs, ignition may be effected at very high altitudes. Such results may be due to creation of combustible mixture near the plug by the high-energy discharge itself. Thus, fuel volatility is less critical if sufficient energy is available for ignition.

In addition to volatility, the fuel viscosity will play an important part in the ignition of the heavier fuels. Viscosity influences drop sizes obtained from liquid-fuel injection nozzles; consequently, the more viscous fuels (fig. 7) must be injected at higher pressures to achieve satisfactory spray for ignition.

Altitude Operational Limits

In early investigations (ref. 21) of turbojet-engine performance it was shown that an increase in fuel flow will increase combustor temperature rise until a limiting point is reached. Fuel-flow increases beyond this point will result in an exhaust-gas temperature decrease, and continued enrichment will ultimately result in blow-out. This blow-out point is called "rich blow-out" and is attributed to the presence of so much fuel vapor in the primary zone that the resultant mixture will not burn. This belief leads to the obvious conclusion that fuel volatility plays an important part in determining altitude operational limits, since a volatile fuel is more likely to form rich mixtures in the primary zone than a nonvolatile fuel. Fortunately, this trend is in the right direction insofar as the utilization of low-cost low-volatility fuels is concerned. However, equal difficulties could be anticipated with an opposite trend, that is, "lean blow-out". In this case the low-volatility fuels at low flow conditions would not produce sufficient vapor in the primary zone to support combustion. These possible difficulties impose upon the designer responsibility for planning a combustion chamber in which fuel volatility at the instant of delivery to the chamber is sufficient to produce the desired fuel-air mixture.

A plot of altitude operational limits for two fuels is shown in figure 17. At 95 percent of rated engine speed, the kerosene-type fuel gave limits considerably above those obtained with gasoline. This result is

consistent with the previously mentioned belief that the more volatile fuel (gasoline) vaporizes more readily than the kerosene and at high fuel-flow rates produces an overrich mixture in the primary zone. Although data are lacking on fuel oils (boiling range 421° to 692° F), one test (ref. 22) indicated that a Diesel oil in the boiling range of 364° to 664° F was satisfactory with respect to altitude operational limits at 100 percent of rated engine speed; but at lower speeds the altitude limit was lower than that obtained with more volatile fuels.

Carbon Deposition

Another difficulty in the utilization of fuel oils for aircraft propulsion is the problem of carbon deposition. Numerous investigations have been conducted to determine the carbon-forming tendencies of various fuels, and several correlations between fuel properties and engine deposits have been developed. One of the most promising correlations (ref. 23) is shown in figure 18. As indicated on this plot, the higher the volumetric average boiling point and the lower the hydrogen-carbon ratio, the greater the amount of carbon deposited. Although only one correlation line is shown in figure 18, other operating conditions would produce different lines.

The dotted lines on figure 18 indicate the relative quantities of carbon that might form if the various fuel oils were used in a particular combustor. On the basis of its physical properties, grade 4 fuel oil would be expected to form much more carbon than fuels of the JP-4 or kerosene type.

Pressure also has an important effect on carbon deposition, as shown in figure 19. The largest quantities of carbon occur at low altitude (high pressure). This fact, considered together with the properties of the fuel oils, suggests that the application of such fuels to future high-compression engines may be exceedingly difficult. Tangible evidence of this belief is presented in figure 20, which shows a large deposit of carbon obtained in a 2-hour run with a Diesel fuel at sea-level conditions.

Exhaust Deposits and Corrosion

In regard to exhaust deposits and corrosion, experience with heavy fuels in aircraft gas-turbine engines is nonexistent; however, experience with such fuels in industrial gas turbines adequately demonstrates some of the problems that may be encountered.

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Deposits. - Combustion of residual fuels in gas turbines produces deposits of ash on surfaces exposed to the exhaust-gas stream. Analyses reported in reference 24 indicate that these deposits consist largely of sodium sulfate and vanadium pentoxide. Sodium vanadates may also be present. Melting points for these substances are as follows:

Deposit	Melting point, °F
Sodium metavanadate	1166
Sodium pyrovanadate	1209
Vanadium pentoxide	1274
Sodium orthovanadate	1591
Sodium sulfate	1623

Melting points for these substances are very near the maximum temperatures at turbine entries; consequently, the possibility exists for such materials to be present in both solid and molten state.

An effort was made (ref. 24) to remove sodium from fuel oils, and a satisfactory method was found. However, it was concluded that the method would be difficult to apply on an inexpensive commercial scale. No satisfactory method was found for removal of vanadium. Various concentrations of vanadium and sodium were added to kerosene in order to evaluate the effect of these materials on turbine-blade deposits. Results indicated that sodium produced more than twice the deposit obtained with an equal weight concentration of vanadium. It was also found that a trace of carbon in the exhaust-gas stream almost completely prohibited ash deposits.

Corrosion. - The problem of corrosion may arise from the presence of sulfur, vanadium, and sodium in residual fuels. Sulfur has no appreciable effect on most present-day alloys (ref. 24); however, there is some evidence that intercrystalline penetration may occur and result in fatigue failure of certain materials. Sulfur may corrode certain nickel alloys at high temperatures in a reducing atmosphere. Sodium sulfate appears to have little corrosive effect below 1470° F; however, corrosion increases rapidly above this temperature and becomes severe as the melting point of the salt is approached at 1623° F. Vanadium is the most corrosive agent in the fuel, and its effect on some alloys may be serious. There is some evidence that a light coating of vanadium oxide is just as damaging as a heavy coating.

PREHEAT REQUIREMENTS IN UTILIZATION OF HEAVY FUELS

There are three situations to be evaluated in the determination of preheat required for heavy fuels, the amount of heat required (1) to maintain the fuel in fluid condition (above pour point and at suitable viscosity for pumping), (2) to maintain a suitable viscosity for atomization to ensure satisfactory combustion, and (3) to provide a vapor pressure satisfactory for starting purposes.

It is known that kerosene can be pumped and atomized satisfactorily and that its ignition characteristics are satisfactory with proper injection and ignition systems. The Reid vapor pressure of kerosene is about 0.1 pound per square inch; therefore, for ignition purposes it may be assumed arbitrarily that any heavy fuel utilized in aircraft must be preheated to a temperature sufficiently high to achieve a comparable vapor pressure. For a grade 4 fuel oil, this temperature would be about 200° F (fig. 5(d)).

In regard to pumpability, two values of viscosity are mentioned in the literature as the maximums that may be tolerated before pumpability problems arise. These limits are 2000 centistokes (ref. 25) and 500 centistokes (ref. 26). Despite the discrepancy in these values, both are sufficiently high to indicate that fuel oils up to grade 4 may be pumped (fig. 7(d)) so long as the fuel is in the liquid state. In fact, for fuels of the grade 4 fuel oil type or lighter, the primary reason for preheat would be to maintain the liquid state rather than to achieve a selected viscosity. This point is illustrated by the following data from figure 7(d):

Fuel oil, grade	Pour point, °F	Viscosity at pour point, centistokes
1	-37	16
2	-7	21
4	-8	1300
5	40	5000
6	50	7500

Since it is known that all these fuels could, in flight, be subjected to temperatures below these pour points, preheat would be required. Although the viscosity of the average grade 4 fuel oil is about 1300 centistokes at its pour point, this value could be decreased to 500 centistokes by preheating to 7° F.

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If it is assumed that the fuel oils may be held at or above the pour point, the remaining factor to consider is the quantity of heat required for satisfactory atomization at the combustion chamber. Information in the literature (refs. 25 and 26) indicates that a maximum viscosity of 15 centistokes is the limit for pressure atomization; therefore, it would be necessary to preheat the fuel in order to obtain this viscosity. The temperatures required for a viscosity of 15 centistokes (fig. 7(d)) are -33° , 5° , and 105° F for grades 1, 2, and 4 fuel oil, respectively.

Based on the foregoing discussion, the utilization of a fuel as heavy as grade 4 fuel oil requires a temperature of 7° F to maintain the fuel in pumpable state; a temperature of 200° F would be necessary to provide a suitable vapor pressure for ignition; a temperature of 105° F would be necessary to ensure proper atomization. The requirement of a 200° F fuel temperature for proper ignition could be reduced somewhat by use of high-energy ignition systems and by improved fuel-injection techniques. In the subsequent discussion, however, consideration is given to both conditions; that is, where the quantity of preheat is determined by the viscosity at the nozzle or by the required vapor pressure. The heat requirements for these two cases would be met at some location between the fuel tank and the fuel-injection nozzle.

Calculations of preheating requirements were made for the various grades of fuel oil. In these calculations the following conditions were assumed: flight speed, 500 miles per hour; altitude, 30,000 feet; fuel consumption per engine, 400 gallons per hour; and fuel carried, 2000 gallons per engine. These conditions approximate those of the Comet airplane. The assumed fuel tank had a diameter of 4 feet and a length of $21\frac{1}{4}$ feet. An actual fuel temperature-time curve for the Comet (ref. 27) was used to estimate the amount of fuel consumed before the remaining fuel reached the pour-point temperature. Then from heat-transfer coefficients corresponding to the assumed flight conditions, the amount of heat required to maintain the remaining fuel above the pour point and below a viscosity of 500 centistokes was calculated. Calculations were made for two effective air temperatures, -22° and -40° F. These are stagnation temperatures corresponding to ambient temperatures of -67° and -85° F, respectively. The results of the calculations are presented in figures 21 and 22.

Figure 21 shows that no heating is required for grade 1 fuel oil; however, this result is accounted for by the fact that the fuel never cools to its pour point according to the assumed fuel temperature-time curve (ref. 27). For heavier grades of fuel oil, the heat requirements increase to appreciable proportions up to about 275 kilowatts for grade 6. Under current fuel-oil specifications, it would be possible to have much

greater heat requirements than those indicated in figure 21. For example, the average properties (table II) of grade 4 fuel oil were used in preparing figure 21, yet calculations based on the maximum values in table II indicate the heat requirements to be about 2.5 and 2.0 times greater at -22° and -40° F effective air temperatures. It is emphasized that the heat requirements in figure 21 correspond to the time of flight when the maximum quantity of fuel has cooled to the required temperature for pumpability. These required quantities of heat will decrease as fuel is consumed.

Calculations were also made to indicate the influence of the maximum allowable viscosity for pumping on the preheat requirements. Since the viscosity limitation will depend upon the type of pump and its operating requirements, there is no certain method by which to estimate the highest permissible viscosity. For this reason the data in figure 21 were based upon the value of 500 centistokes given in reference 26. As mentioned previously, reference 25 cites a value of 2000 centistokes as the limiting viscosity. With this value the heat requirements were computed, and comparison with figure 21 shows the following changes:

Fuel oil, grade	Required heat input, Btu/hr, at -			
	Effective air temperature, -22° F		Effective air temperature, -40° F	
	500 cs	2000 cs	500 cs	2000 cs
1	0	0	0	0
2	64,769	64,769	142,492	142,492
4	132,870	60,438	215,249	138,144
5	687,258	428,978	810,964	532,500
6	805,372	631,722	934,232	757,000

The heat requirements do not change for fuel oils 1 and 2, since the addition of heat is necessary only to keep the fuels above the pour point. An appreciable decrease in required preheat occurs for the heavier fuel oils if a viscosity as high as 2000 centistokes can be tolerated for pumping.

The calculations in figure 21 and the preceding table were all based on a heat-transfer coefficient of $26 \text{ Btu}/(\text{hr})(\text{sq ft})(^{\circ}\text{F})$ with uninsulated tanks. Further calculation indicates that the use of insulation would effect considerable reduction in heat requirements. Similar calculations reported in reference 28 indicate that the use of 1/4-inch cork or foamed plastic insulation will reduce the heat requirement by a factor of 10.

In addition to the heat required to maintain the fuel above its pour point and below a pumping viscosity, heat must be added between the fuel tank and the fuel-injection nozzle in order to provide a certain vapor pressure or low viscosity for atomization. In figure 22 two curves are

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shown, the upper curve for heat required if vapor pressure is limiting, the lower curve for heat required if viscosity is limiting. Somewhere between these curves the true curve will fall, its position depending upon combustion-chamber design, available ignition energy, and type of injection nozzle. The quantities of heat indicated in figure 22 represent the heat to be added to raise 400 gallons per hour of fuel from the required preheat temperatures of figure 21 to the required preheat temperatures for the selected vapor pressure and viscosity of figure 22.

SAFETY AND HANDLING PROPERTIES

With respect to safety, the use of low-cost fuels is advantageous. Such fuels are more difficult to ignite, less prone to propagate a flame rapidly, and less susceptible to atomization by impact than the lighter fuels. Moreover, flammability characteristics are such that a hazardous condition would seldom exist within fuel tanks. From toxicity considerations, the low-cost fuels would offer hazards no greater than those of any other hydrocarbon fuels.

Although no comprehensive study of handling characteristics has been made, it is well to mention a few possible problems for the sake of completeness. Among these are odor, storage stability, and contamination by water, dust, and rust. All three of these will probably be more imposing problems with the fuel oils than with current fuels.

CONCLUDING REMARKS

In this discussion, four potential advantages of the heavier petroleum products were indicated:

- (1) Lower cost
- (2) Reasonable availability
- (3) Greater flight range
- (4) Greater safety

In order to realize the full value of these advantages, certain performance and handling problems must be solved. The distillate and residual fuels cannot be utilized in current turbojet engines without significant power-plant redesign, but studies to date indicate that the use of such fuels in suitably designed engines is certainly feasible. The rapidity with which the solutions to the major problems may be achieved is, of course, dependent upon the emphasis placed upon the overall problem of utilizing the heavier low-cost fuels in gas-turbine engines for commercial aircraft.

The major performance and handling problems, together with a brief statement of current knowledge, are as follows:

Engine starting. - The problem of ignition does not appear serious in light of possible use of high-energy ignition systems together with improved injection techniques. The problem can be further simplified by consideration of starting requirements in the over-all combustion-chamber design in order to provide optimum fuel-air mixtures at the spark-plug location.

Combustion performance. - Sufficient knowledge exists to indicate that requirements of combustion efficiency and altitude operation limits can be met by proper combustion-chamber design.

Combustion-chamber deposits. - The background in carbon deposition problems is excellent, yet it is apparent that the elimination of carbon deposition with distillate and residual fuels may be difficult to effect by design changes alone.

Exhaust deposits and corrosion. - Perhaps the most imposing problem in the utilization of the low-cost fuels is the problem of exhaust deposits and corrosion. This problem arises from the presence in the fuel of certain constituents that promote deposits and corrosion under high-temperature conditions. At the present time there is no economical refining procedure for complete removal of these constituents; consequently, the solution to the problem will be a compromise between the best fuel that the refiner can supply and the most resistant materials that the engine manufacturer can build into the engine. It is emphasized, however, that the seriousness of this problem would be greater for residual fuels than for distillate fuels.

Fuel-system design. - An important problem in the use of distillate or residual fuels will be the requirement of preheating or prevaporization equipment to maintain fuel fluidity and desirable fuel-injection characteristics. Although the difficulty of this problem should not be minimized, its solution is primarily dependent upon existing sound engineering principles.

Fuel stability, contamination, and odor. - The problem of supplying a stable and odorless fuel, free of contamination, rests primarily with the petroleum industry. It should be understood, however, that in meeting these requirements there are certain limits beyond which fuel cost may increase. For this reason these requirements must be controlled by specifications satisfactory to both supplier and consumer.

Over-all evaluation of the foregoing comments indicates that, in regard to performance and handling, the use of low-cost fuels in commercial gas-turbine-powered aircraft is feasible. On the other hand, the

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most expeditious solution of problems relating to performance and handling will not be achieved until positive steps are taken to indicate serious consideration of such fuels in commercial gas-turbine aircraft.

On the basis of the current study, as well as studies reported in related literature, it appears that the next step should be to conduct a detailed survey of the actual monetary savings that might be attained by the use of the distillate and residual fuels. Such a study conducted under ground rules satisfactory to both the airline operators and the petroleum industry should aid in determining the intensity of research and development effort that might be applied to the solution of fuel performance and handling problems.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, August 11, 1953

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TABLE I. - DETAILED REQUIREMENTS FOR FUEL OILS^{a, b}

Fuel oil, grade ^c	Flash point, °F, min.	Pour point, °F, max.	Water and sediment, percent by volume, max.	Carbon residue due on 10-percent bottoms, percent, max.	Ash, percent by weight, max.	Distillation temperatures, °F		Kinematic viscosity, centistokes, at -		Gravity, %A.P.I., min.	Corrosion at 122° F (50° C)		
						10-percent point, max.	50-percent point, max.	End point, max.	100° F			122° F	
							Max.	Min.	Max.	Min.			
1 { A distillate oil intended for vaporizing hot-type burners and other burners requiring this grade of fuel	100 or legal	0	Trace	0.15	----	430	---	---	2.2	1.4	---	35	Pass
2 { A distillate oil for general purpose domestic heating for use in burners not requiring Grade 1 fuel oil	100 or legal	20	0.10	.35	----	---	875	---	4.3	---	---	26	---
4 { An oil for burner installations not equipped with preheating facilities	130 or legal	20	.50	----	0.10	---	---	---	25.4	5.8	---	---	---
5 { A residual-type oil for burner installations equipped with preheating facilities	130 or legal	---	1.00	----	.10	---	---	---	---	32.1	81	---	---
6 { An oil for use in burners equipped with preheaters permitting a high-viscosity fuel	150	---	2.00	----	----	---	---	---	---	---	633	---	---

^aA.S.T.M. D336-48T.^bBecause of the necessity for low-sulfur fuel oils used in connection with heat-treatment, nonferrous metal, glass and ceramic furnaces, and other special uses, a sulfur requirement may be specified in accordance with the following table:

Fuel oil, grade	Sulfur, max. percent
1	0.5
2	0.1
4	No limit
5	No limit
6	No limit

Other sulfur limits may be specified only by mutual agreement between the purchaser and the seller.
^cIt is the intent of these classifications that failure to meet any requirement of a given grade does not automatically place an oil in the next lower grade unless in fact it meets all requirements of the lower grade.
^dLower or higher pour points may be specified whenever required by conditions of storage or use; however, these specifications shall not require a pour point lower than 0° F under any conditions.

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

Property	Fuel oil, grade																	
	1					2					4							
	Number of samples averaged	Min.	Max.	Arith-metic av.	Number of samples averaged	Min.	Max.	Arith-metic av.	Number of samples averaged	Min.	Max.	Arith-metic av.	Number of samples averaged	Min.	Max.	Arith-metic av.	5	6
A. S. T. M. distillation 286 cr. DISS, °F, at percentage recovered:																		
Initial point	67	326	326	350	134	312	470	372	10	378	470	421	10	378	470	421	560	---
10	67	365	418	395	135	373	511	437	10	422	548	470	10	422	548	470	700	---
30	67	406	475	434	135	448	557	505	9	469	670	554	9	469	670	554	940	---
End point	67	446	560	493	135	533	650	526	10	533	734	637	10	533	734	637	---	---
	67	476	625	540	135	570	712	641	10	614	760	692	10	614	760	692	---	---
Pour point, °F	43	-95	-5	-41	31	-35	20	-7	15	-33	5	-8	15	-33	5	-8	40	---
Cloud point, °F	44	-74	-10	-36	101	-20	32	5	---	---	---	---	---	---	---	---	---	---
Sulfur, percent by weight*	63	0.01	0.51	0.13	132	0.014	0.34	0.238	15	0.22	2.33	0.366	15	0.22	2.33	0.366	0.68	0.81
Gravity	---				---				---				---				---	
Specific, 60/60° F	67	0.732	0.821	0.813	---	0.803	0.884	0.842	---	0.870	0.883	0.815	---	0.870	0.883	0.815	0.934	0.957
SA.F.I.	67	47.2	40.7	42.5	135	44.7	28.5	36.4	15	31.2	12.4	25	15	31.2	12.4	25	19.9	16.2
Viscosity at 100° F, centistokes	57	1.44	2.16	1.72	134	2.04	4.28	2.94	15	2.11	47.5	16.7	15	2.11	47.5	16.7	185	8154
Flash point, °F	53	125	163	140	126	132	224	167	15	160	240	205	15	160	240	205	230	214
Aniline point, °F	55	113	171	143	113	122	175	151	---	---	---	---	---	---	---	---	---	---

*Measured at 122° F.



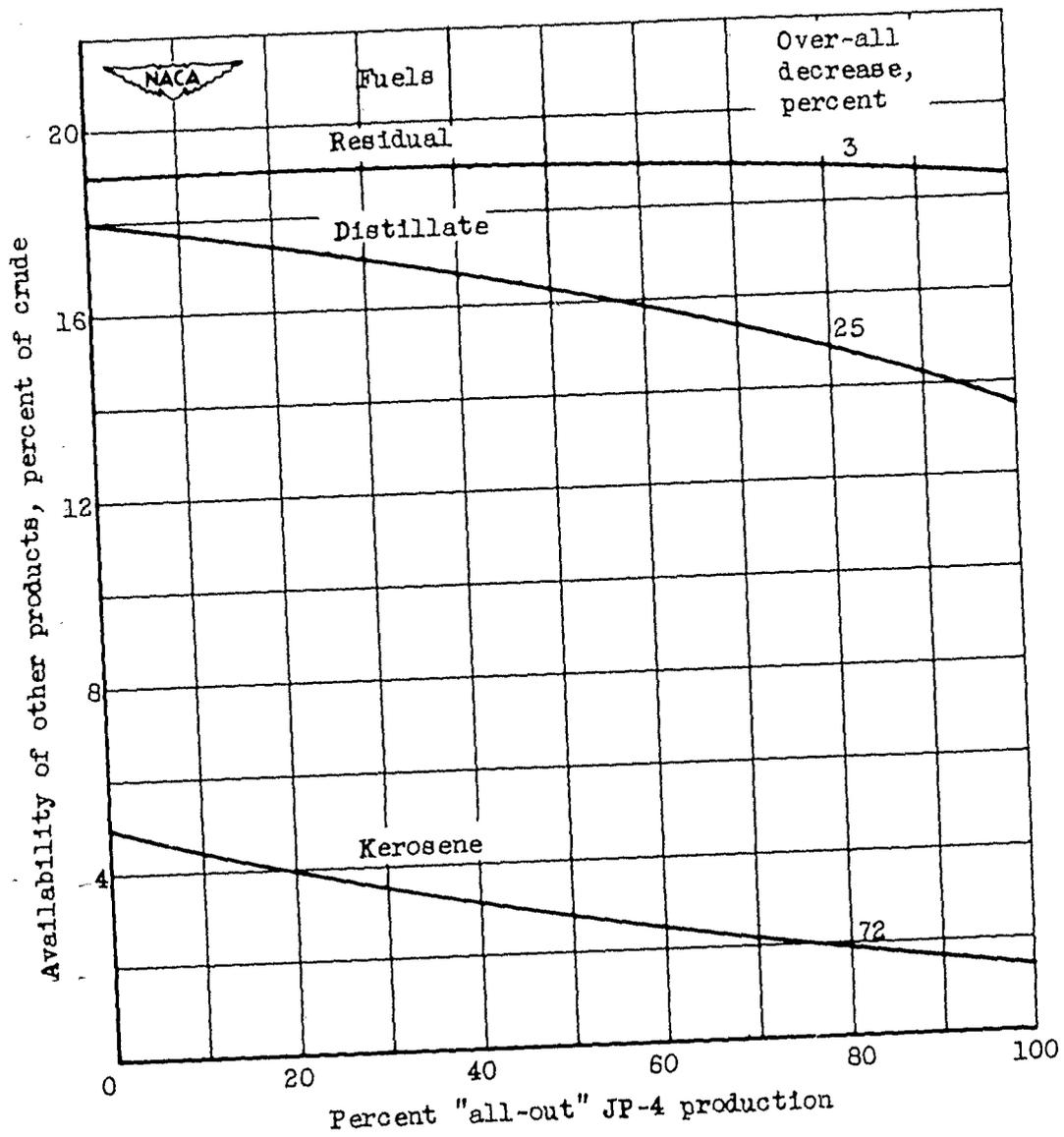


Figure 1. - Effect of JP-4 production on availability of other petroleum products.

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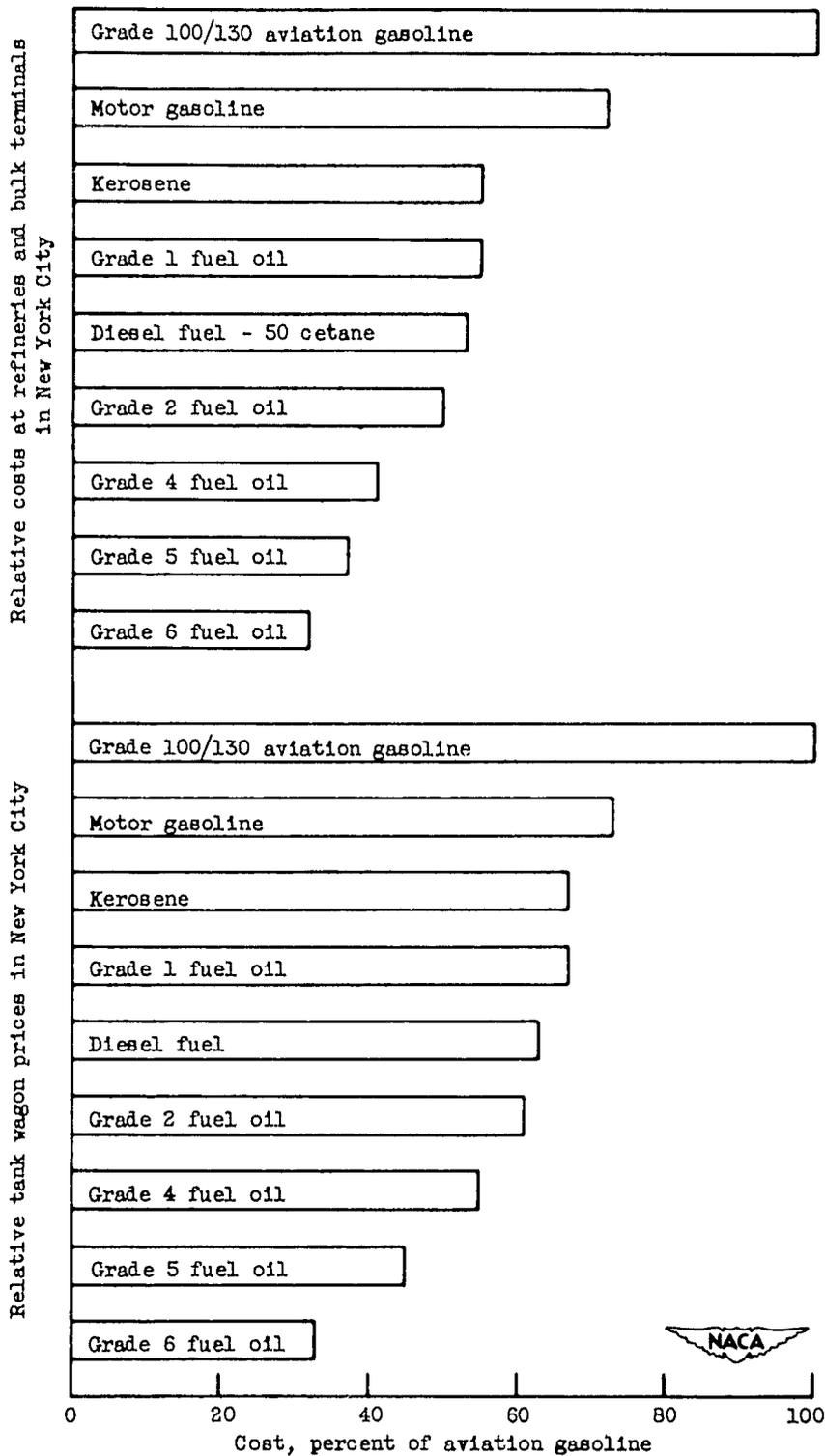
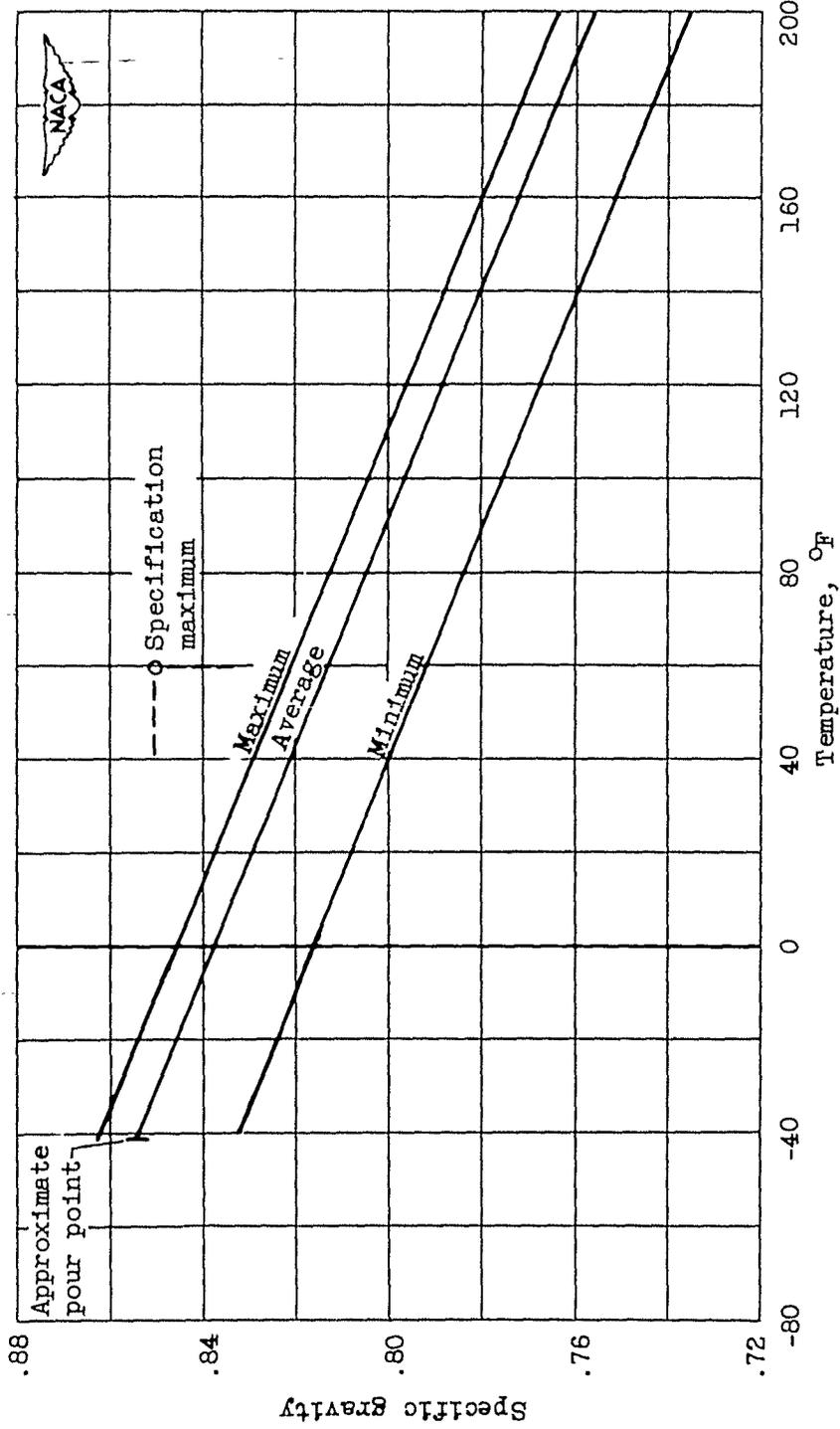


Figure 2. - Relative costs of petroleum products.



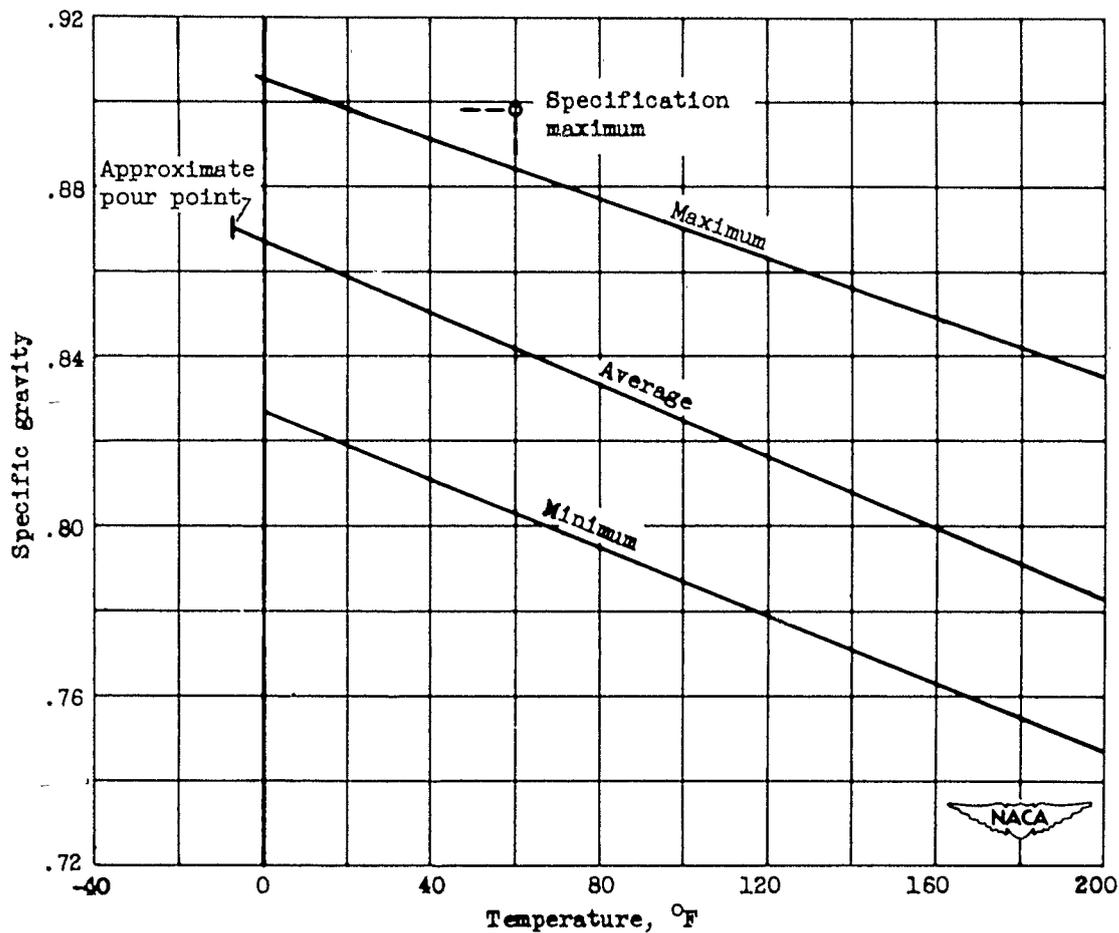
(a) Grade 1 fuel oil; 67 samples.

Figure 3. - Variation of specific gravity with temperature.

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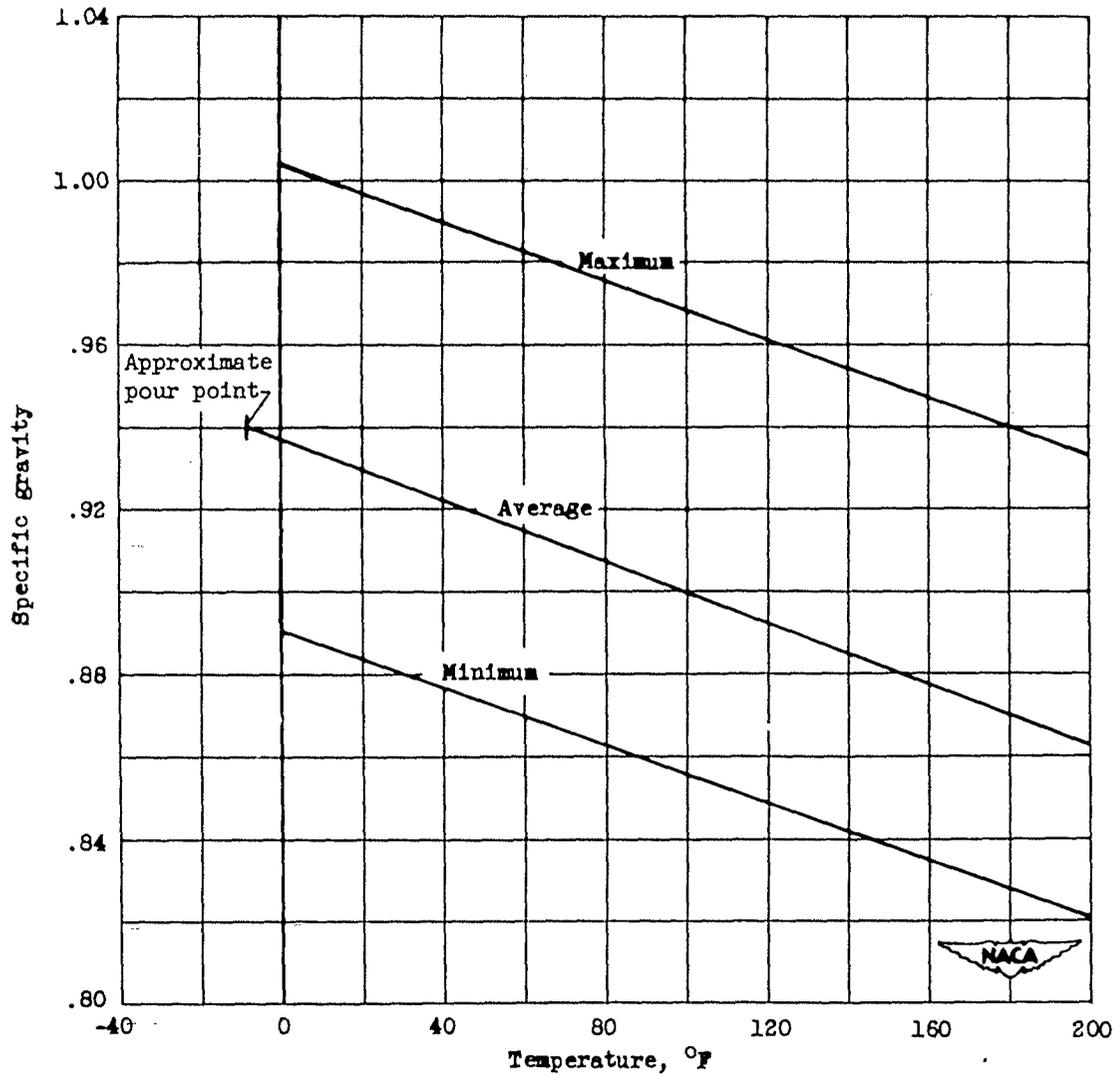
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CE-4 back



(b) Grade 2 fuel oil; 135 samples.

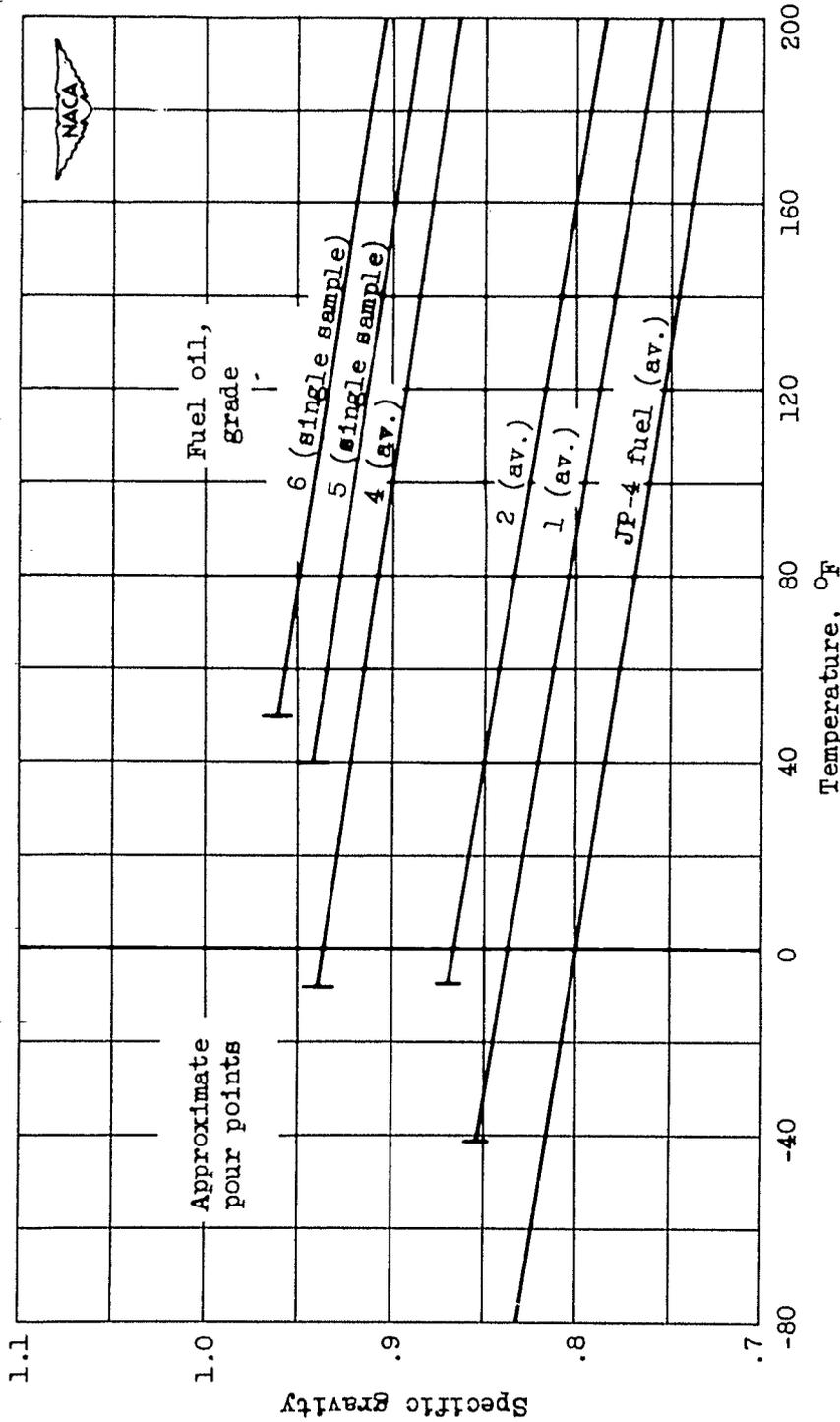
Figure 3. - Continued. Variation of specific gravity with temperature.



(c) Grade 4 fuel oil; 15 samples.

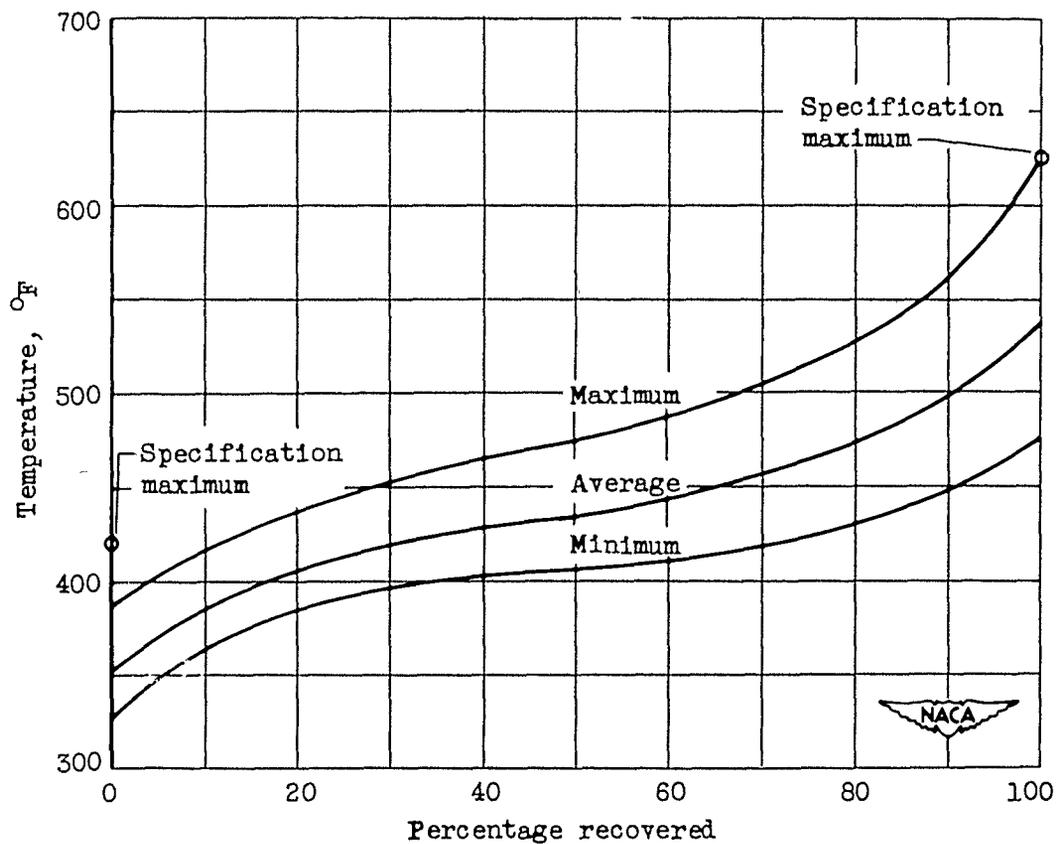
Figure 3. - Continued. Variation of specific gravity with temperature.

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(d) Comparison of several fuels.

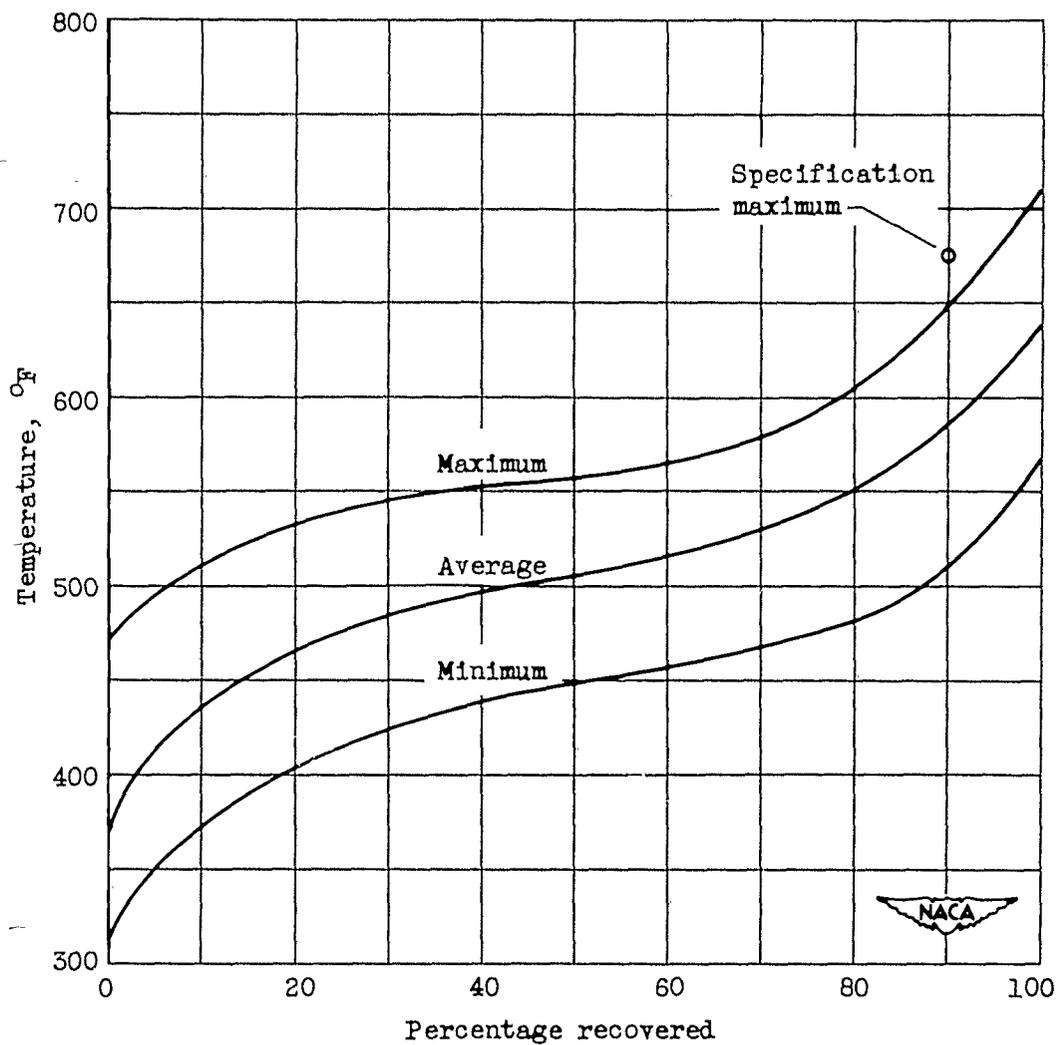
Figure 3. - Concluded. Variation of specific gravity with temperature.



(a) Grade 1 fuel oil; 67 samples.

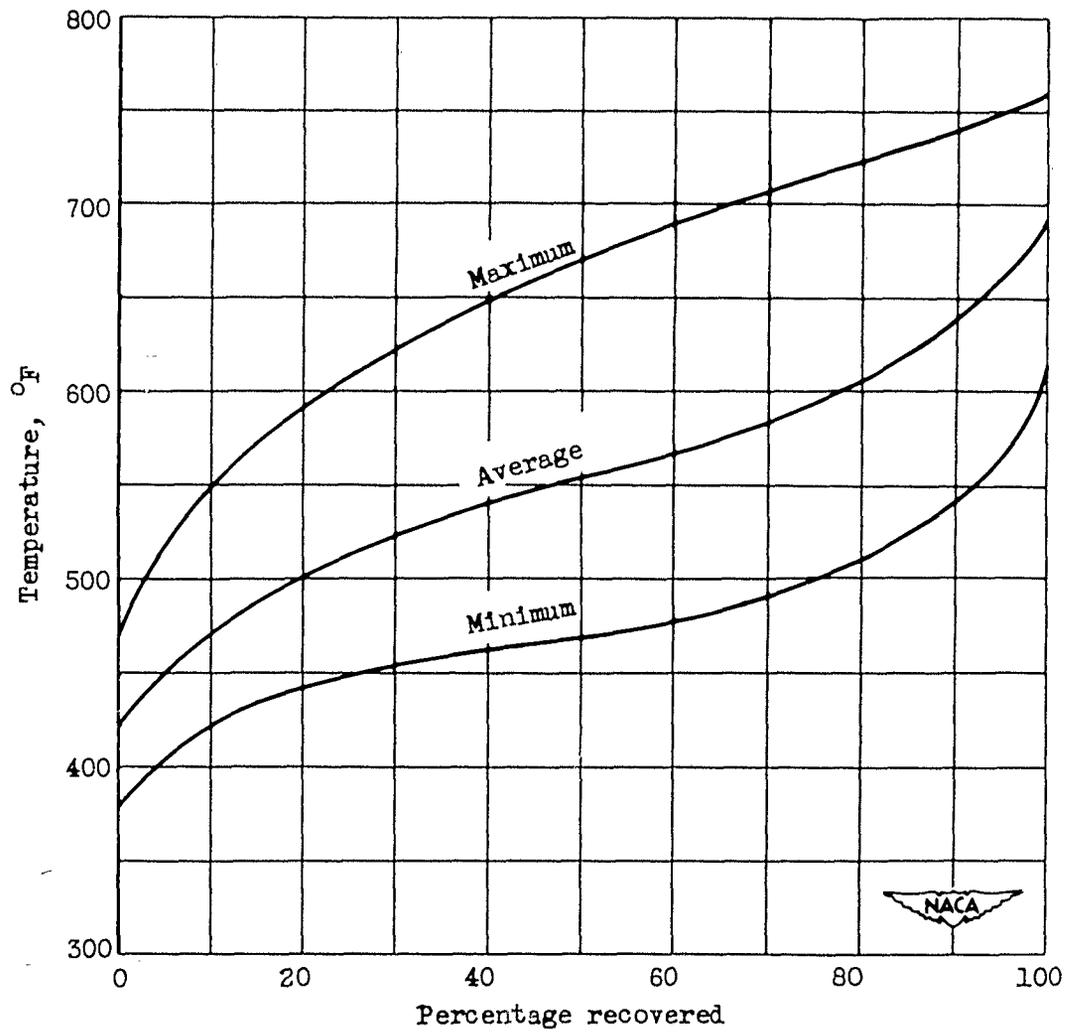
Figure 4. - Variation of A.S.T.M. distillation temperatures for fuel oils.

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(b) Grade 2 fuel oil; 135 samples.

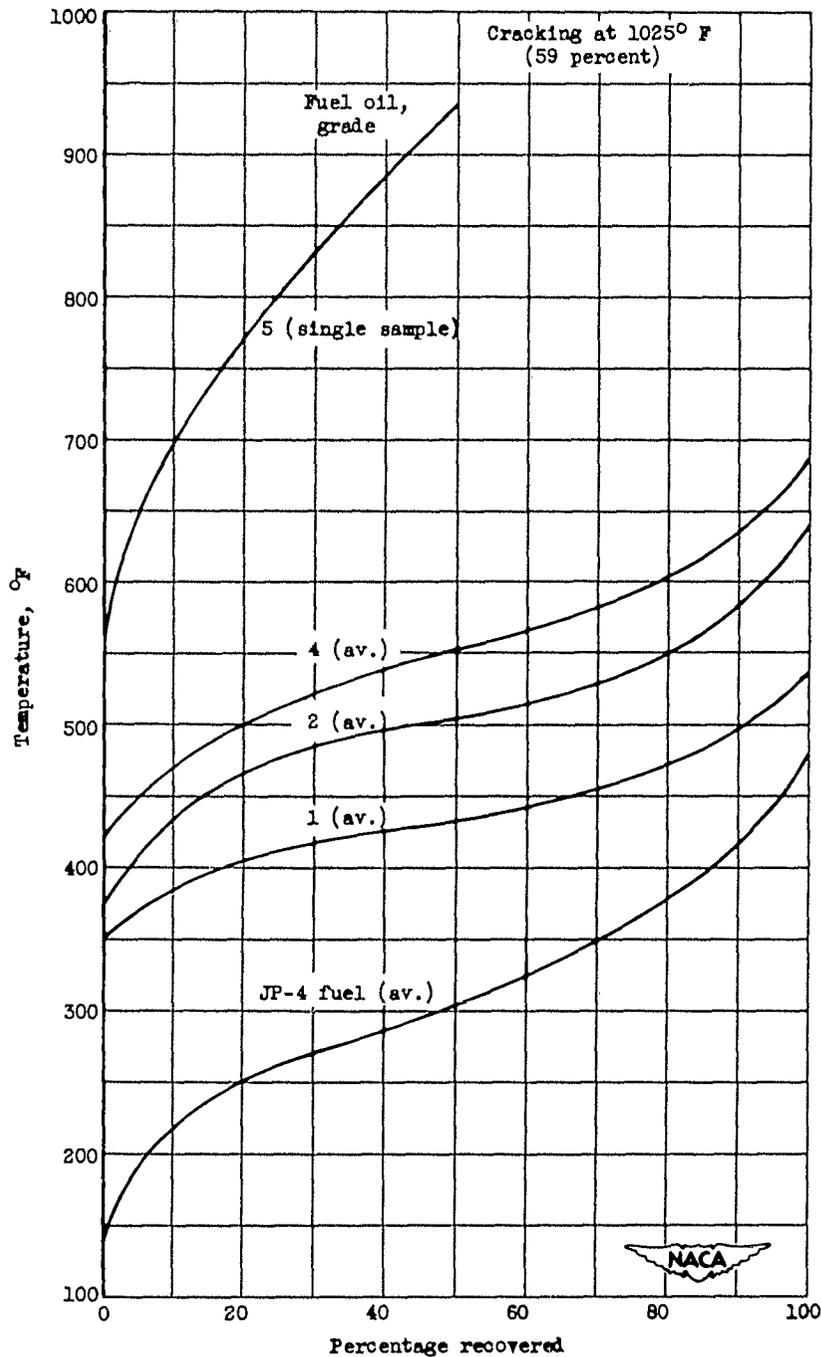
Figure 4. - Continued. Variation of A.S.T.M. distillation temperatures for fuel oils.



(c) Grade 4 fuel oil; 10 samples.

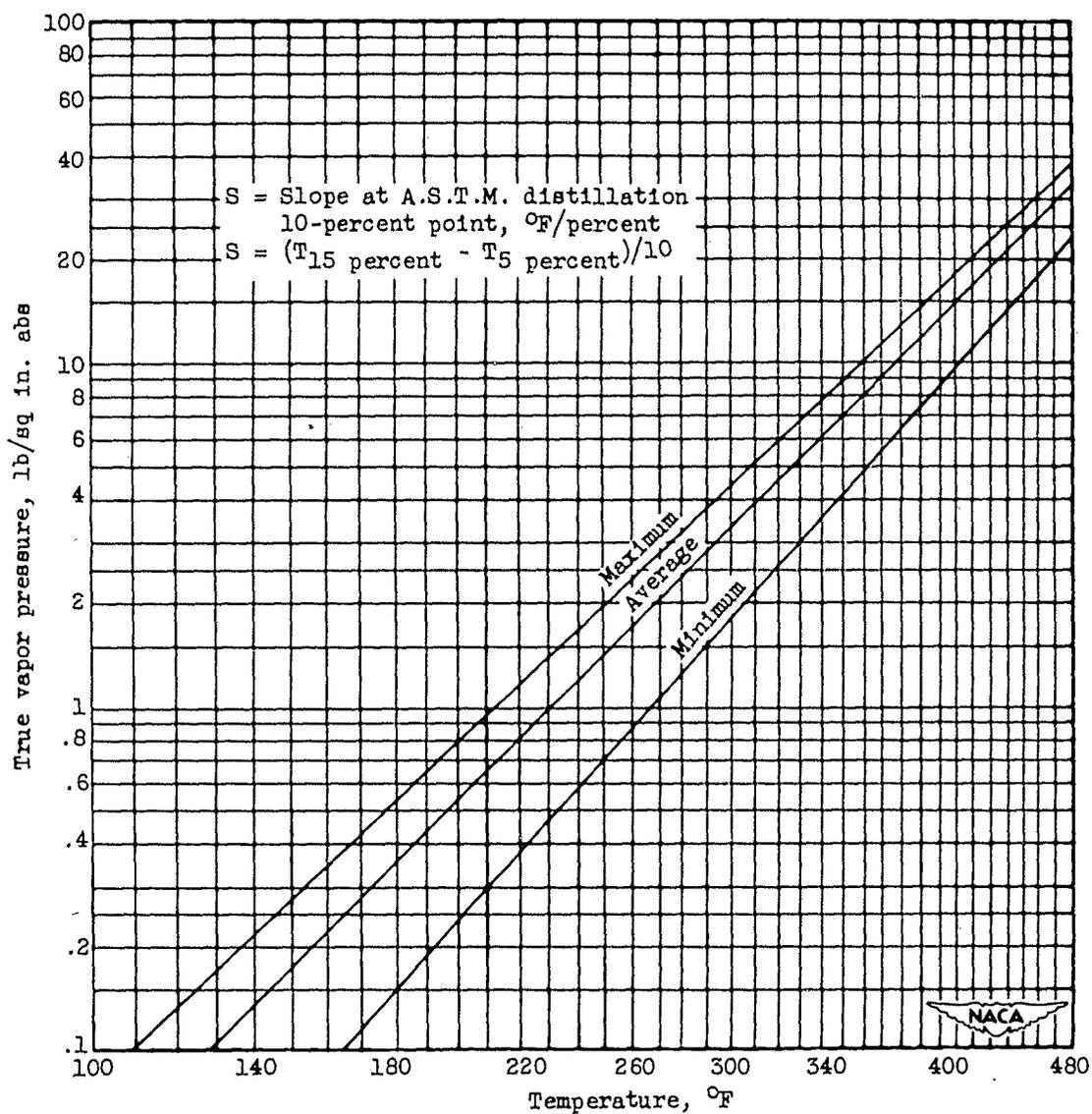
Figure 4. - Continued. Variation of A.S.T.M. distillation temperatures for fuel oils.

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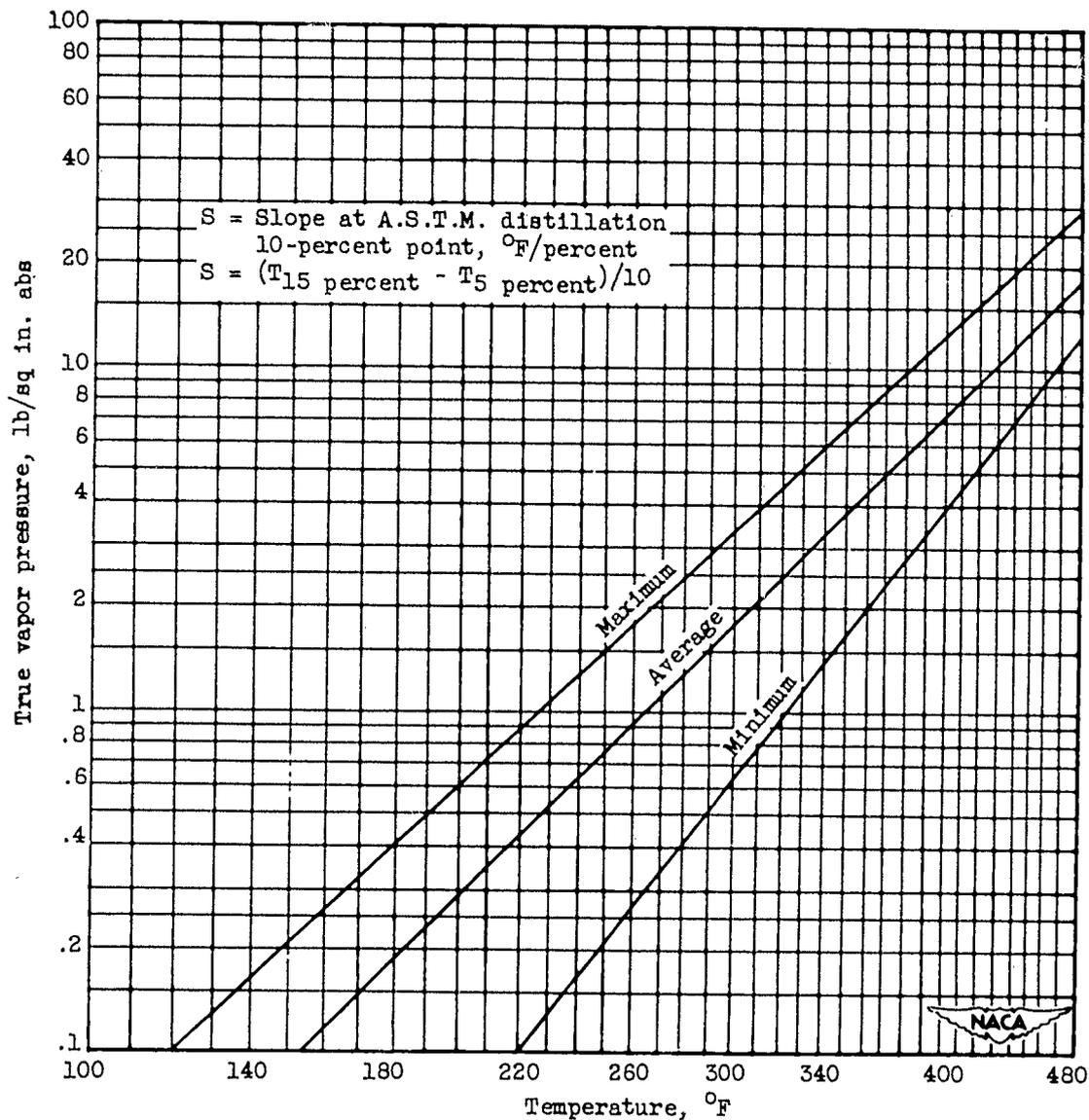
(d) Comparison of several fuels.

Figure 4. - Concluded. Variation of A.S.T.M. distillation temperatures for fuel oils.



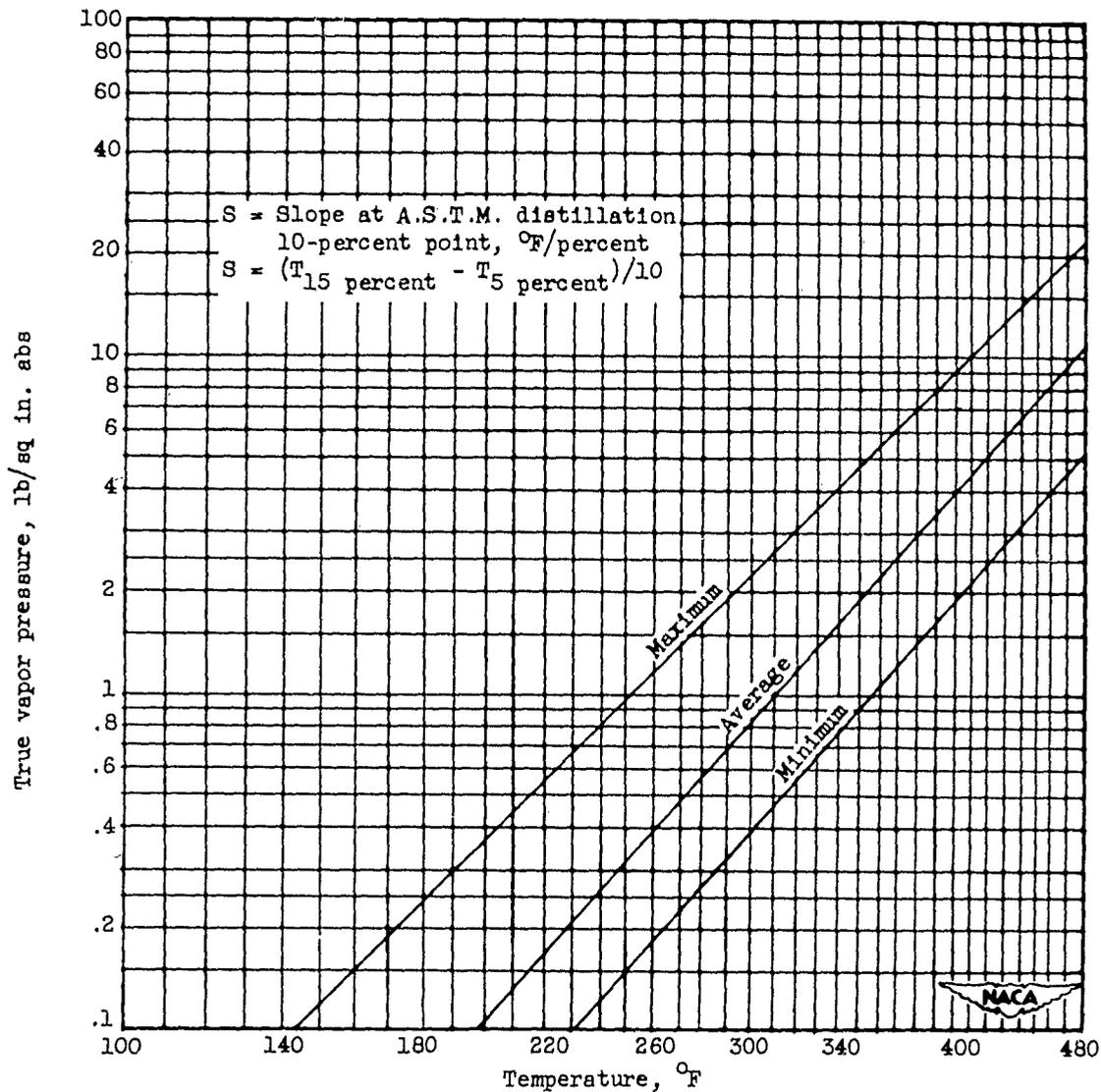
(a) Grade 1 fuel oil; 67 samples.

Figure 5. - Variation of vapor pressure with temperature.

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CE-5 back

(b) Grade 2 fuel oil; 135 samples.

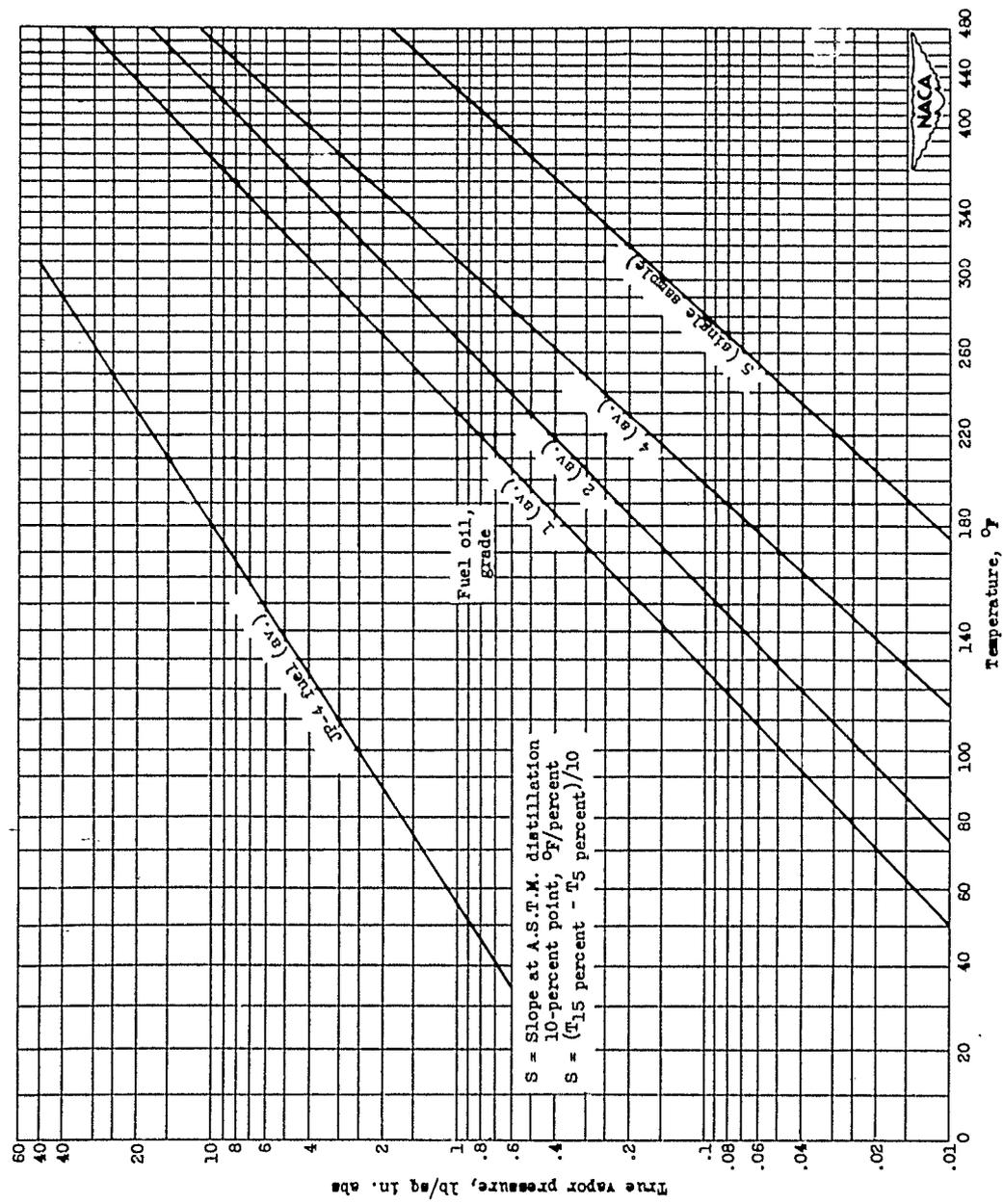
Figure 5. - Continued. Variation of vapor pressure with temperature.



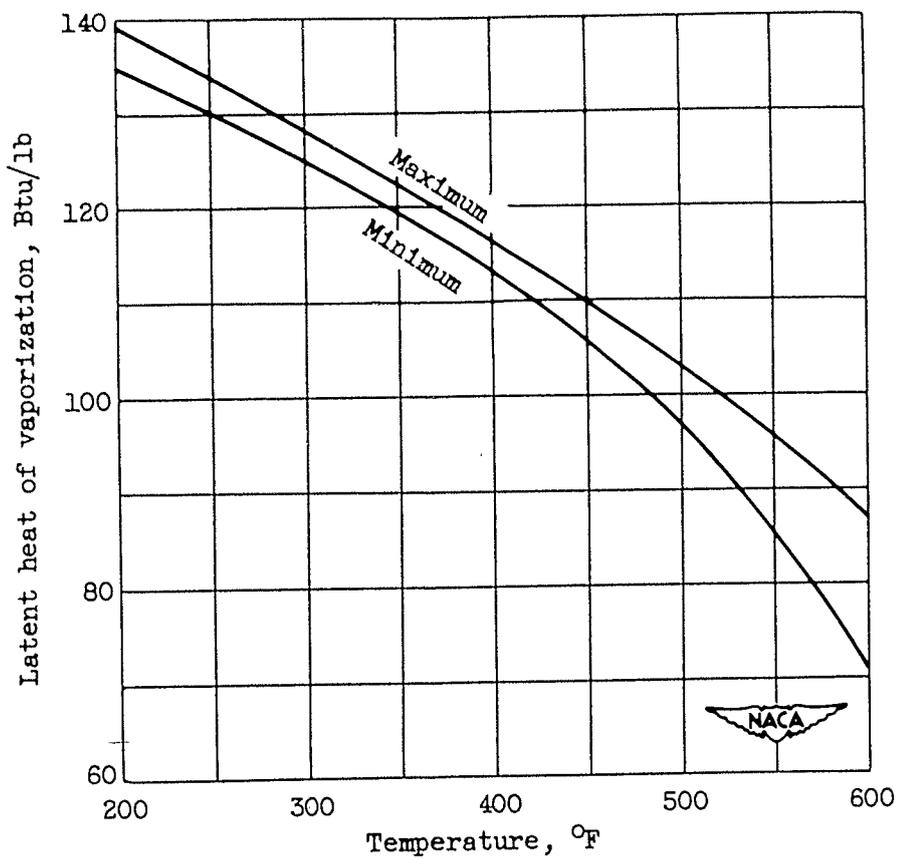
(c) Grade 4 fuel oil; 10 samples.

Figure 5. - Continued. Variation of vapor pressure with temperature.

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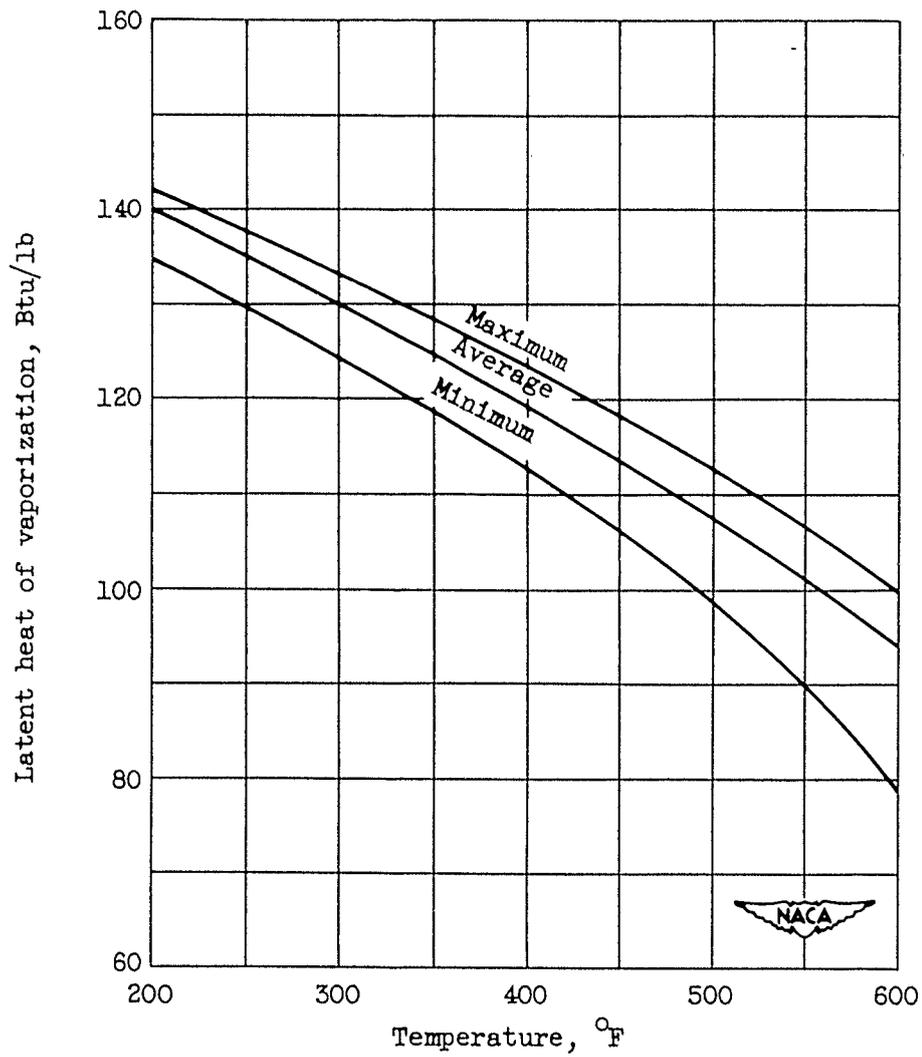


(d) Comparison of several fuels.
 Figure 5. - Concluded. Variation of vapor pressure with temperature.



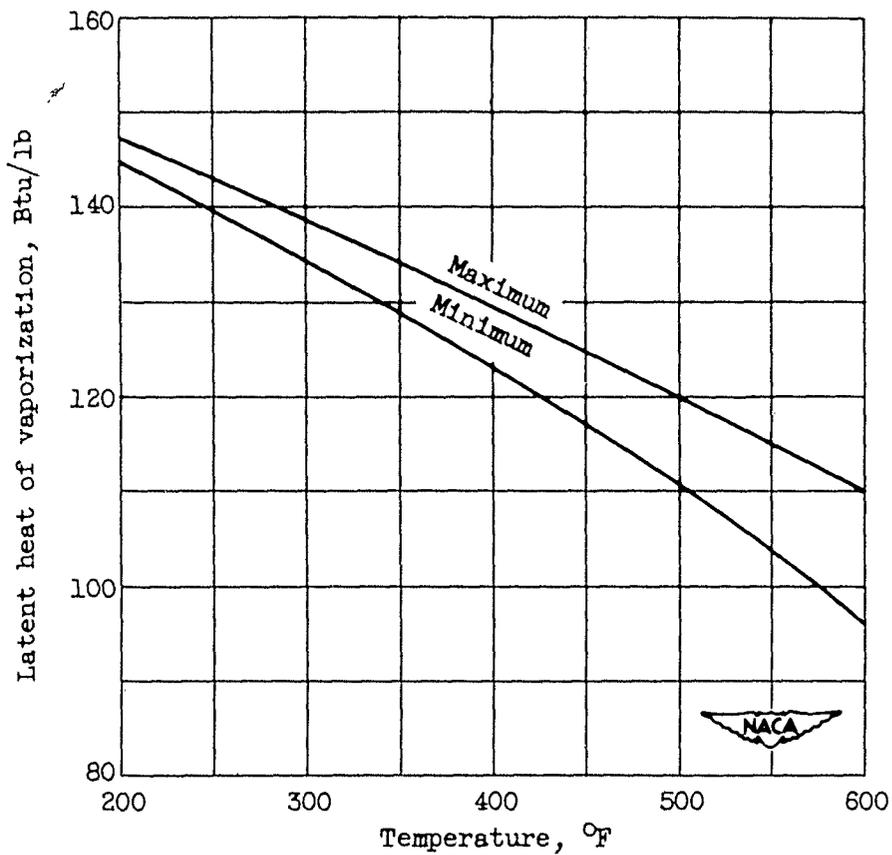
(a) Grade 1 fuel oil; 67 samples.

Figure 6. - Variation of latent heat of vaporization with temperature.



(b) Grade 2 fuel oil; 135 samples.

Figure 6. - Continued. Variation of latent heat of vaporization with temperature.

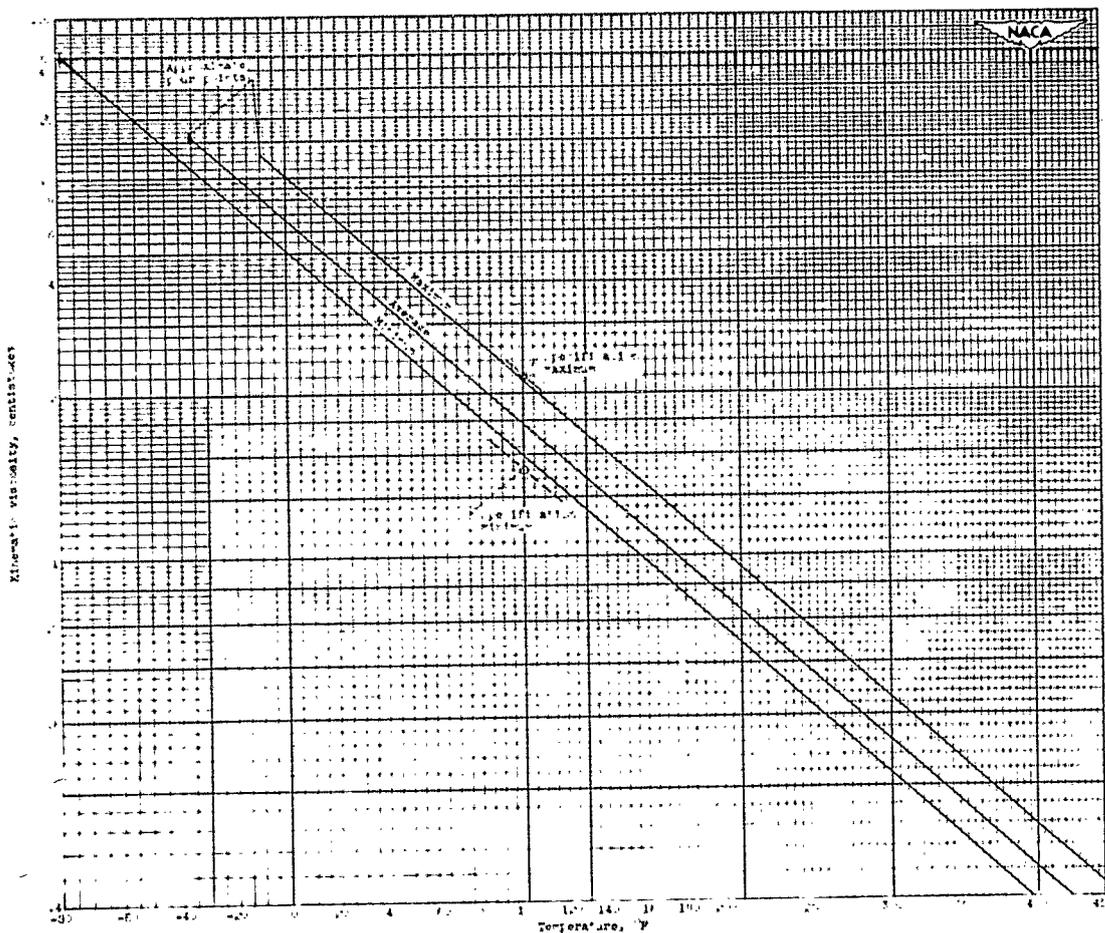


(c) Grade 4 fuel oil; 10 samples.

Figure 6. - Concluded. Variation of latent heat of vaporization with temperature.

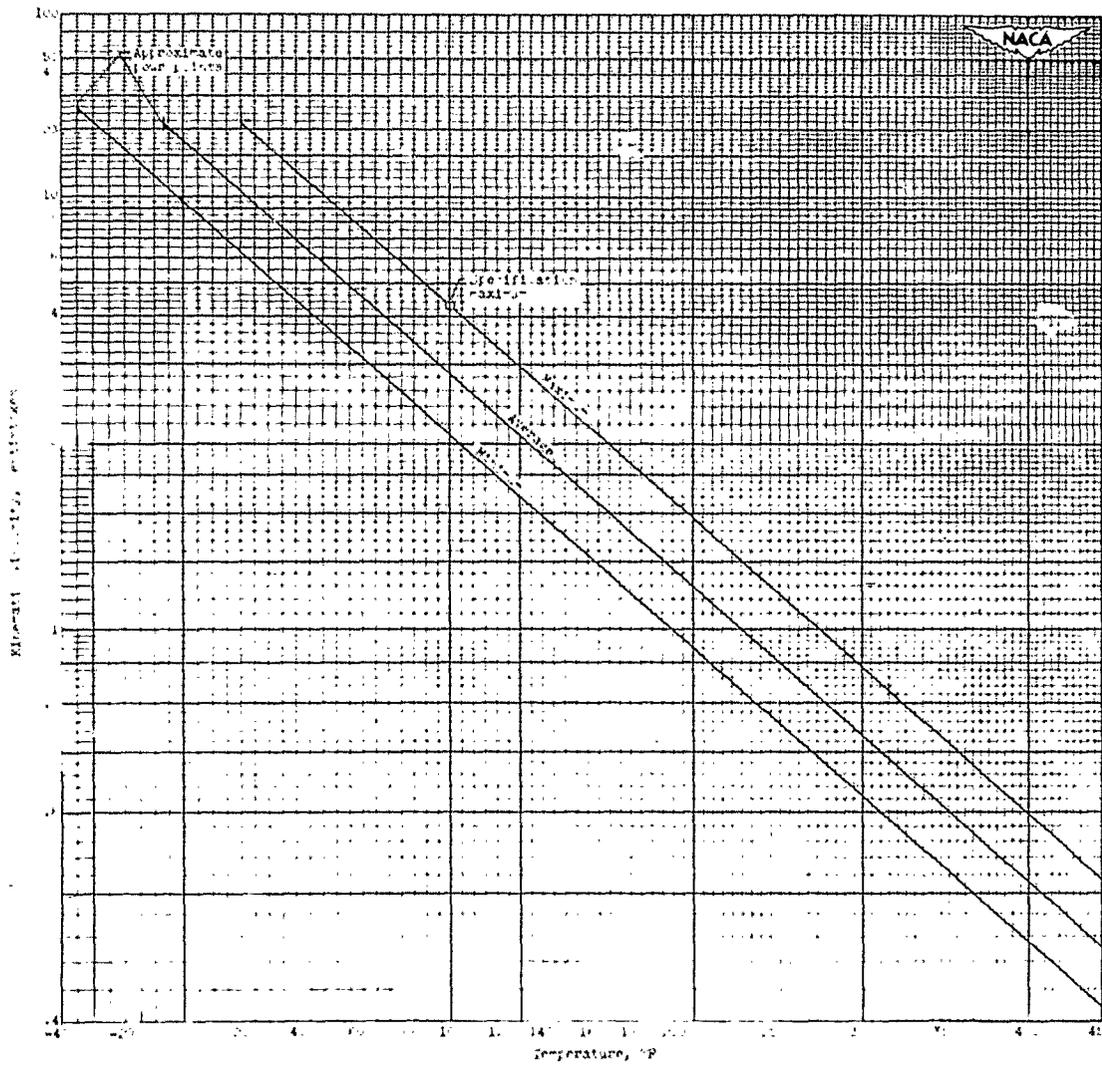
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CE-6



(a) Grade 1 fuel oil; 57 samples.

Figure 7. - Variation of viscosity with temperature.

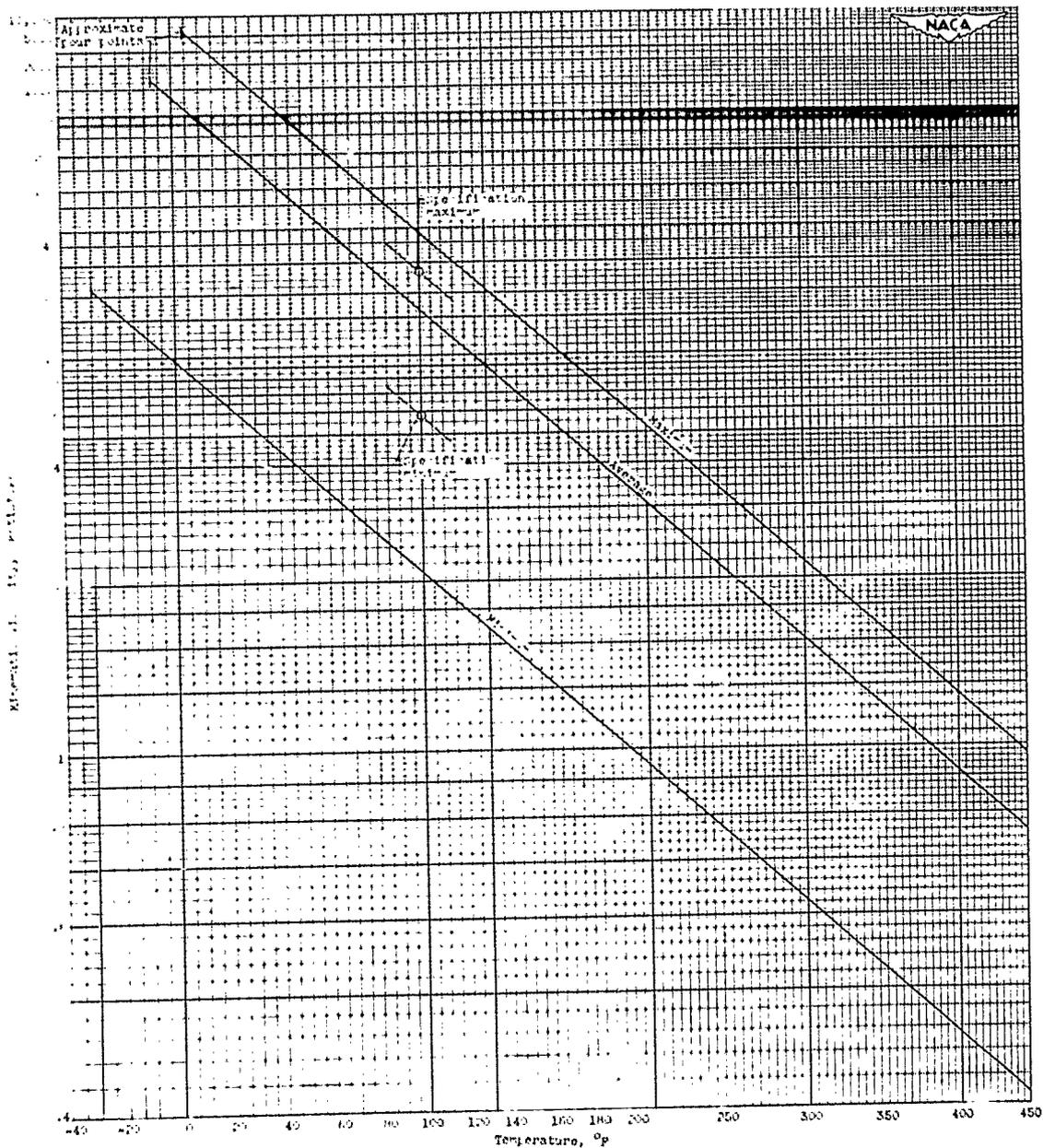


(b) Grade 2 fuel oil; 134 samples.

Figure 7. - Continued. Variation of viscosity with temperature.

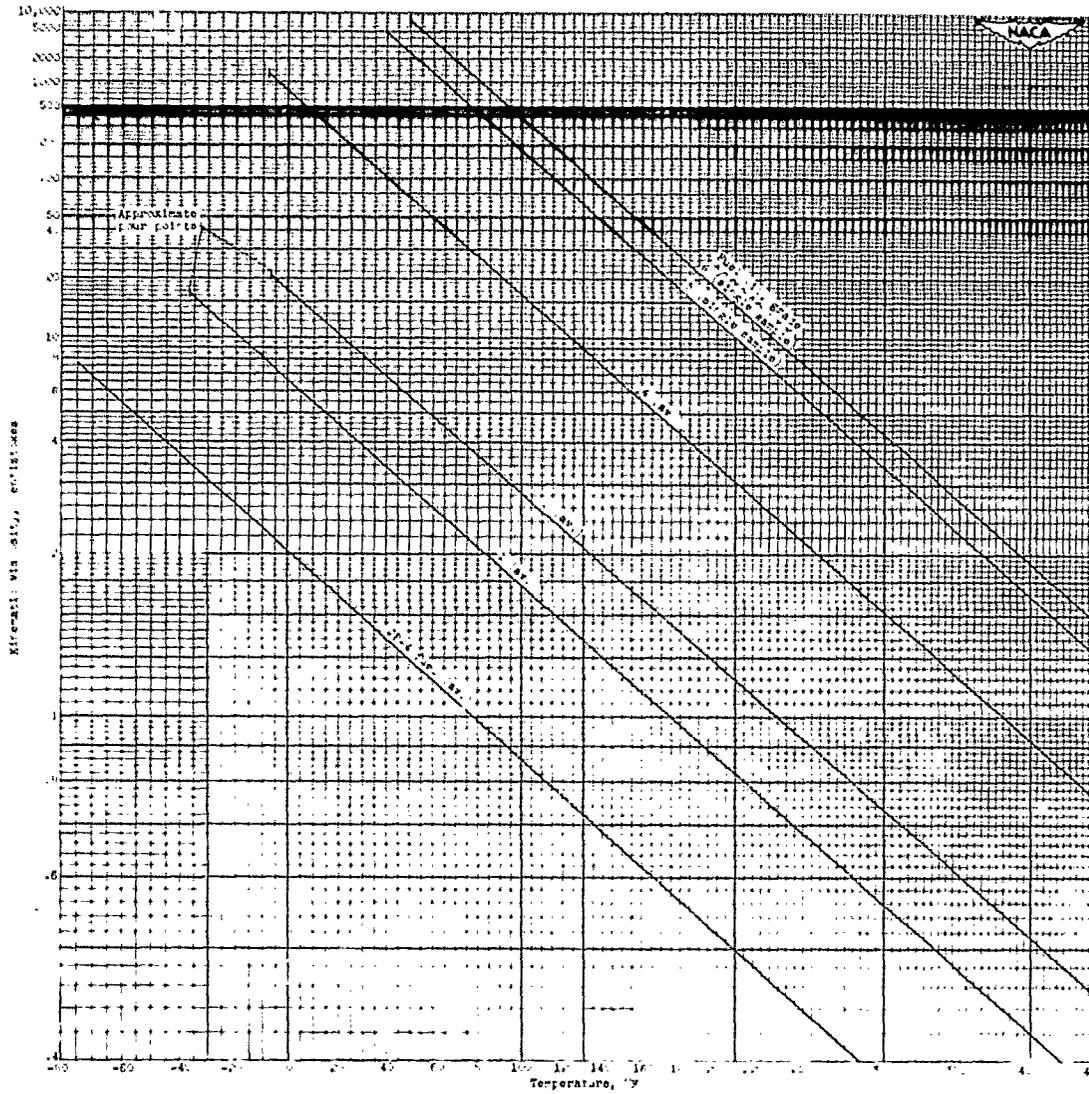
3023

CE-6 back



(c) Grade 4 fuel oil; 15 samples.

Figure 7. - Continued. Variation of viscosity with temperature.



(d) Comparison of several fuels.

Figure 7. - Concluded. Variation of viscosity with temperature.

3023

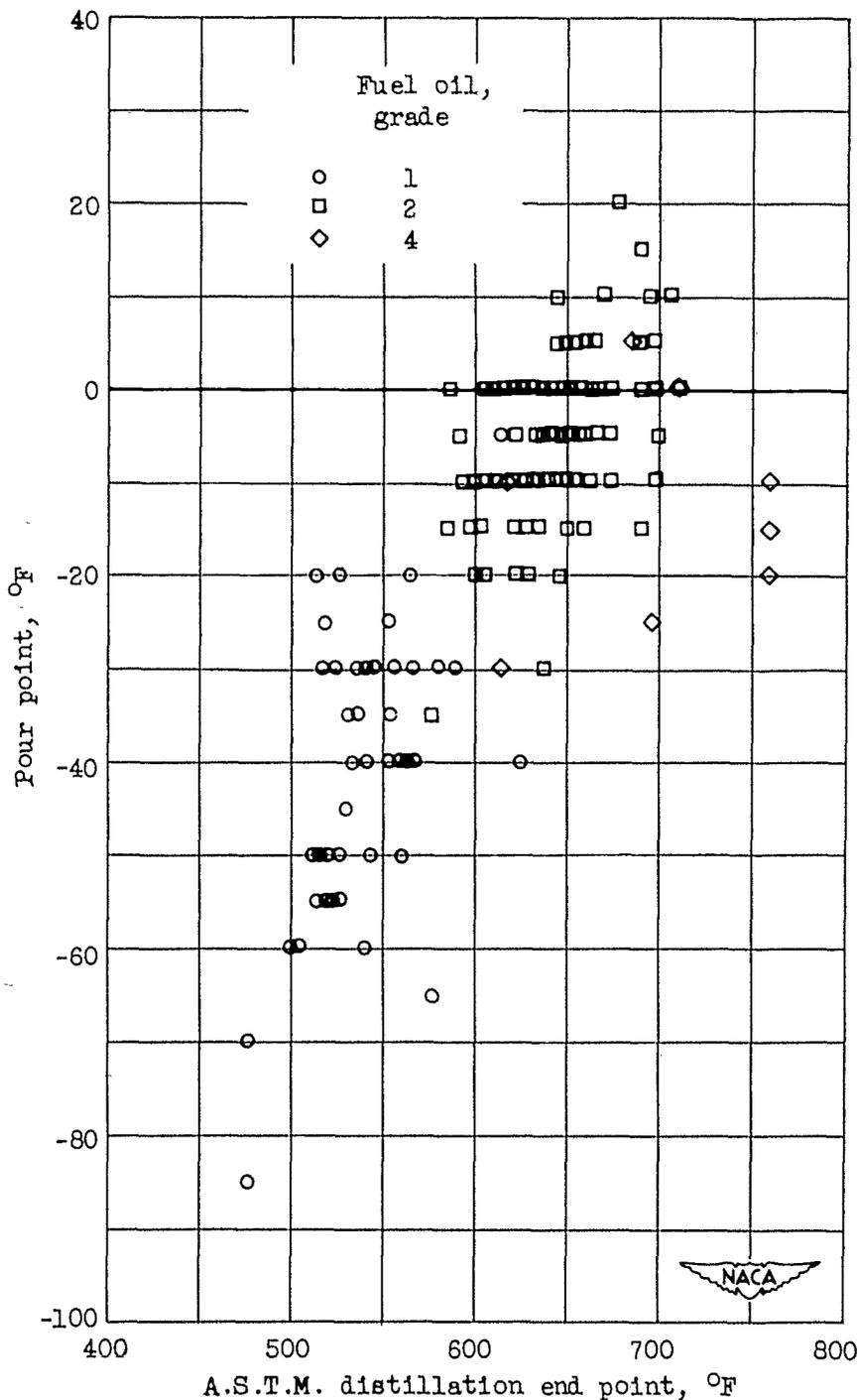


Figure 8. - Variation of pour point with A.S.T.M. distillation end point.

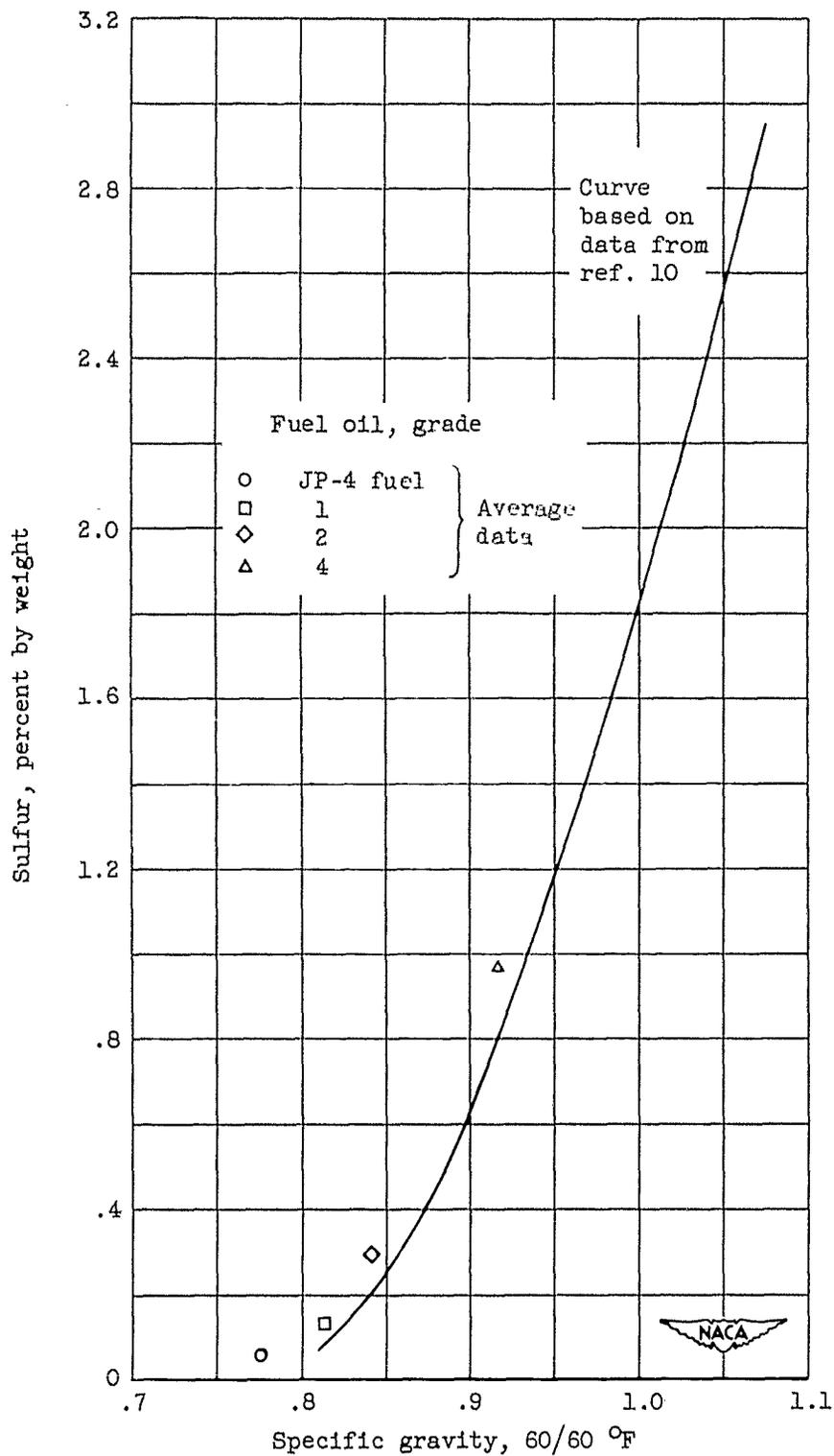


Figure 9. - Sulfur content of several fuels.

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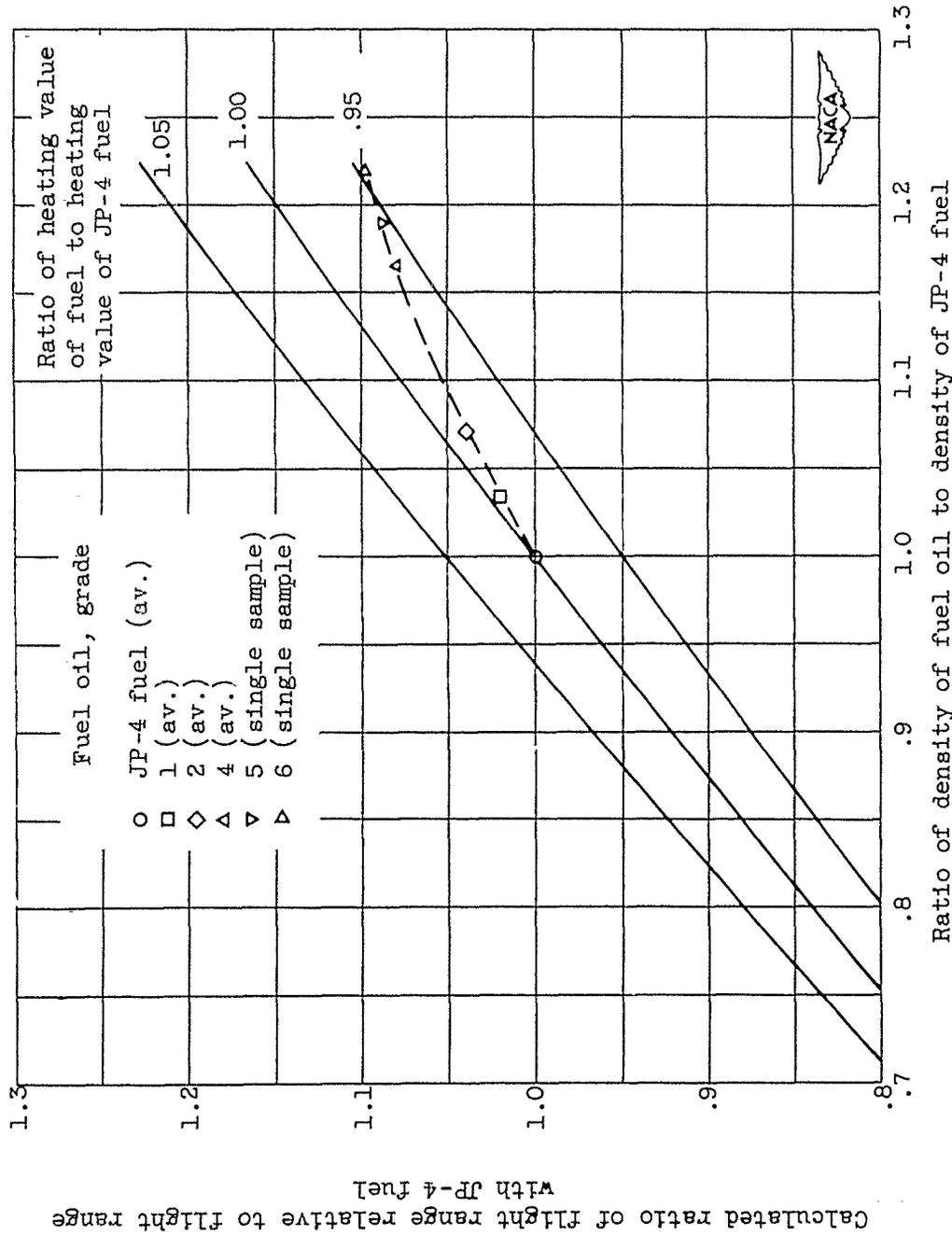


Figure 10. - Calculated range ratio for fixed-volume airplane.
Fuel weight/gross weight = 0.4.

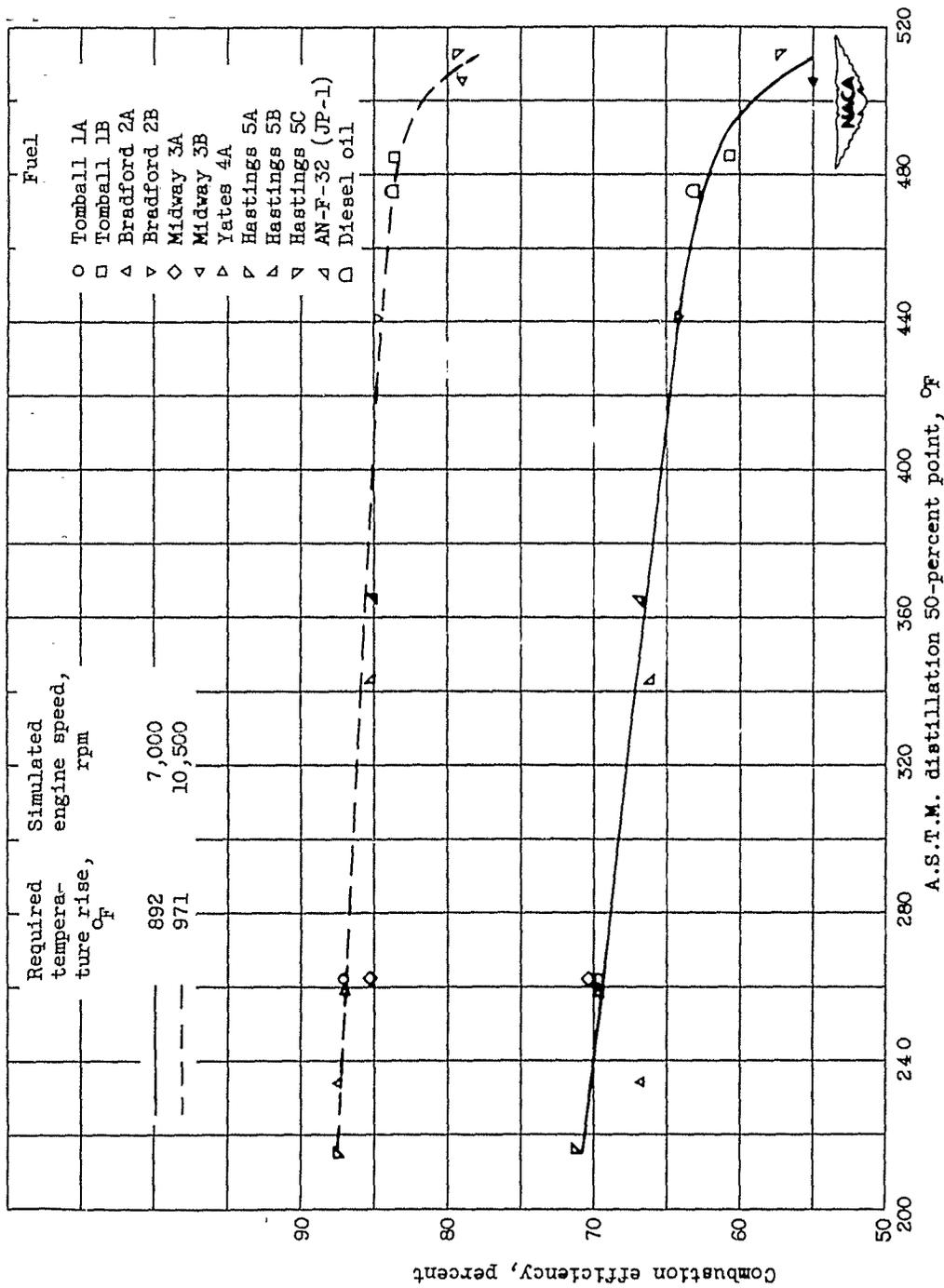


Figure 11. - Effect of volatility on combustion efficiency in single-tubular turbojet combustor at simulated altitude of 40,000 feet.

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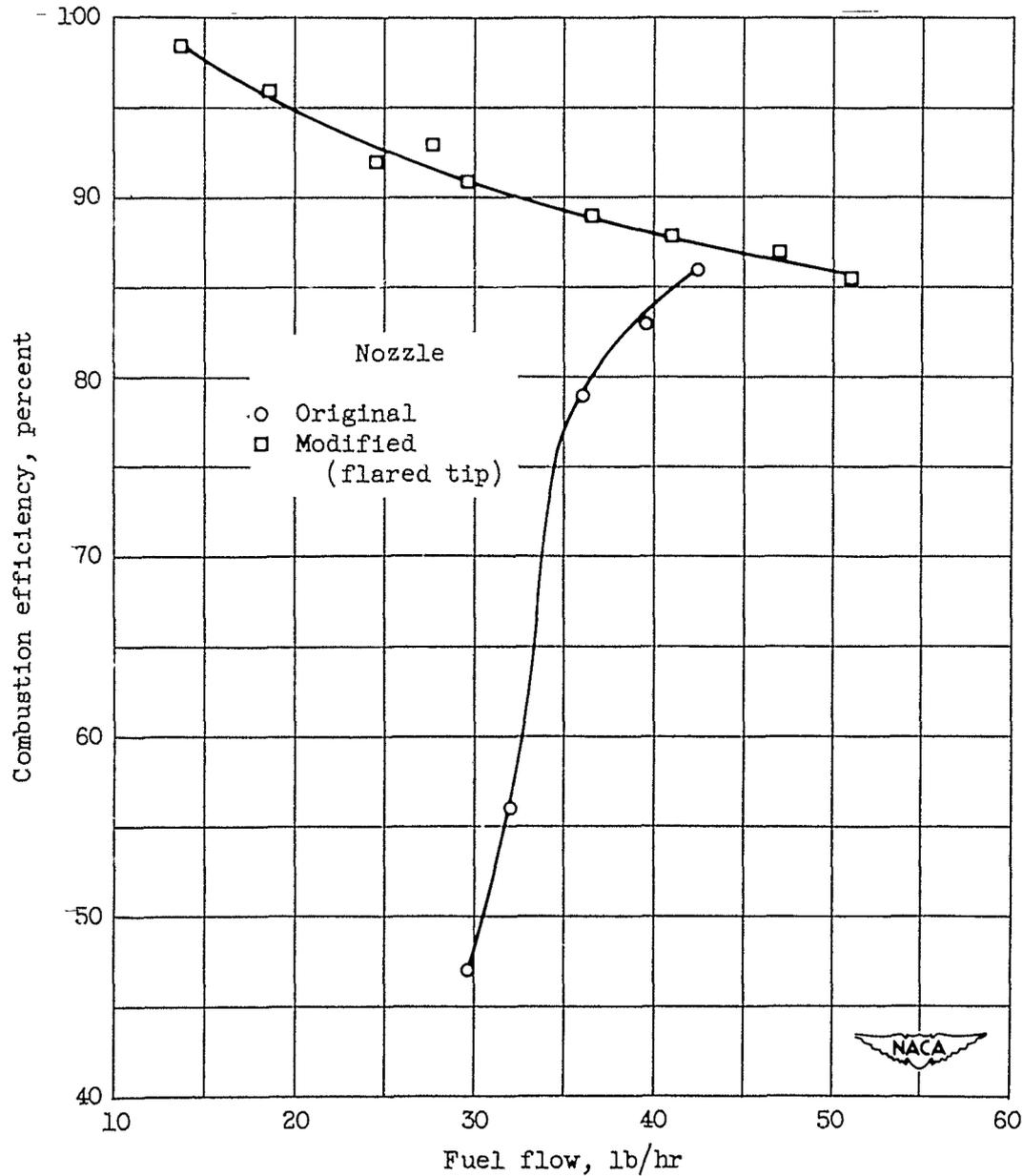
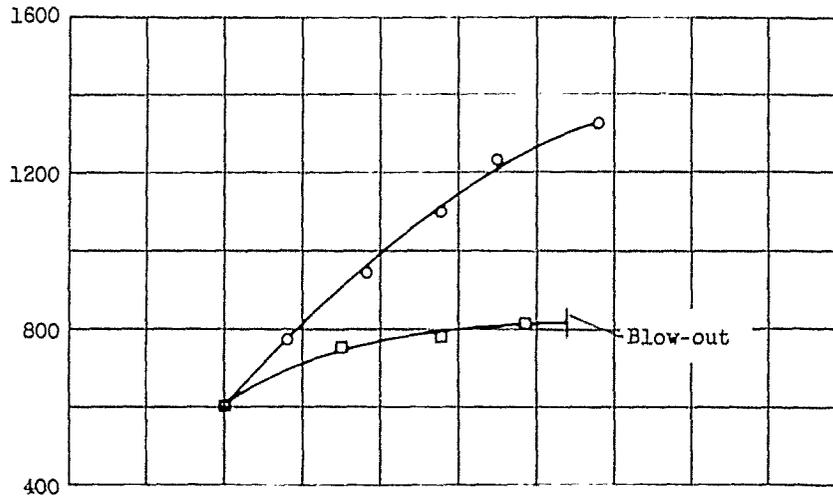
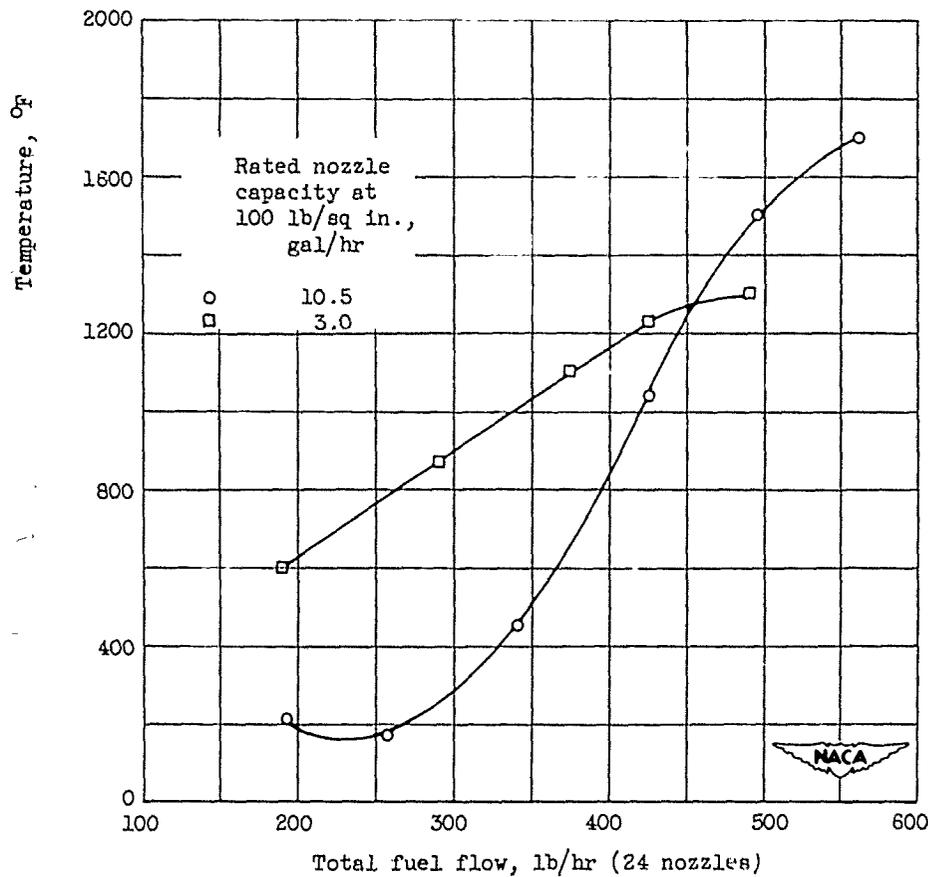


Figure 12. - Effect of fuel-nozzle design on performance. Fuel, kerosene; simulated altitude, 45,000 feet; 100-percent rated engine speed; tubular combustor.



(a) Gasoline.



(b) Diesel oil.

Figure 13. - Temperature rise with gasoline and with Diesel oil. Annular combustor; inlet pressure, 9.2 pounds per square inch; inlet temperature, 240° F; inlet velocity, 200 feet per second.

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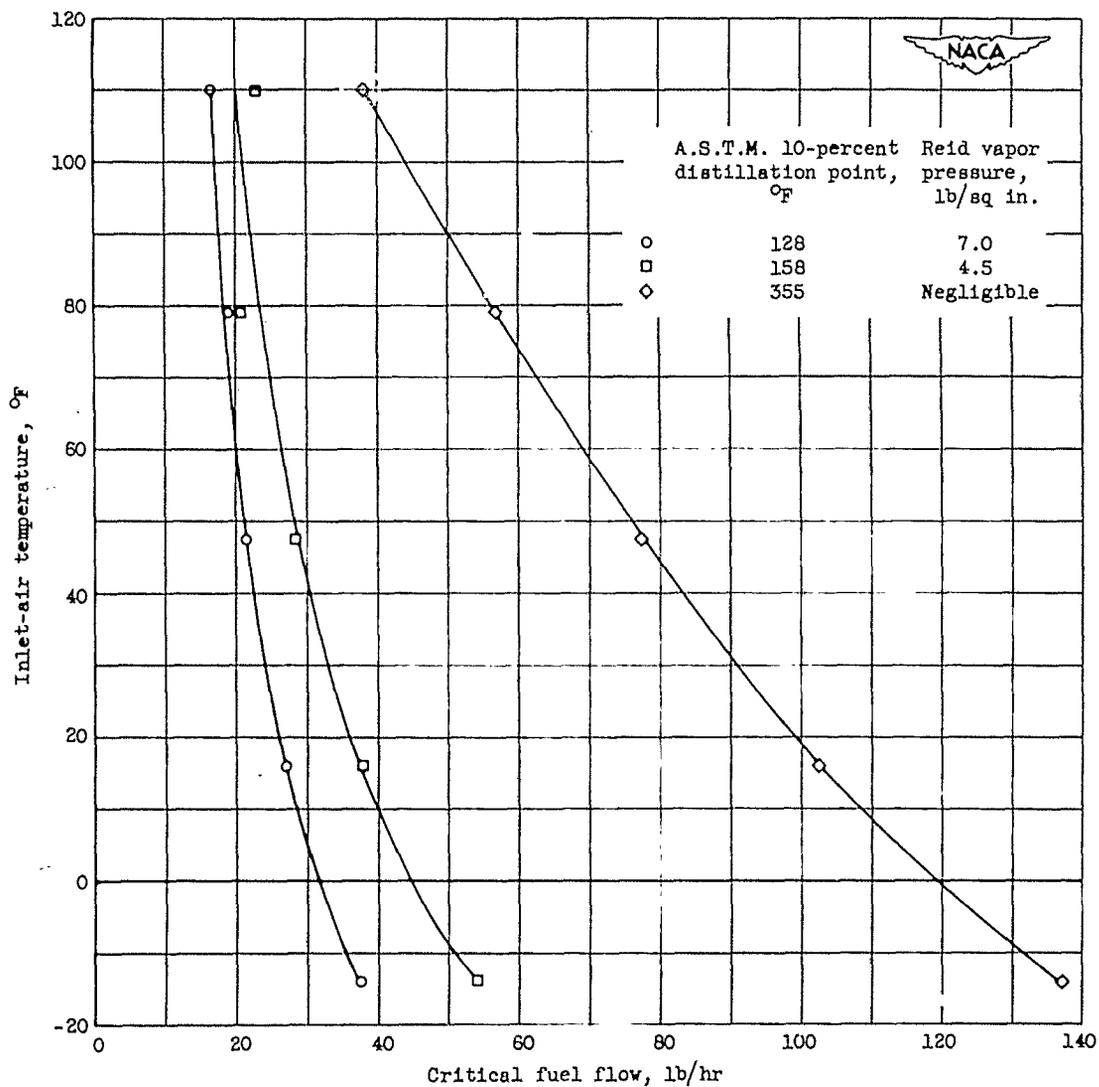


Figure 14. - Effect of inlet-air temperature on fuel flow required for ignition in combustor. Engine speed, 1600 rpm; Mach number, 0; sea level.

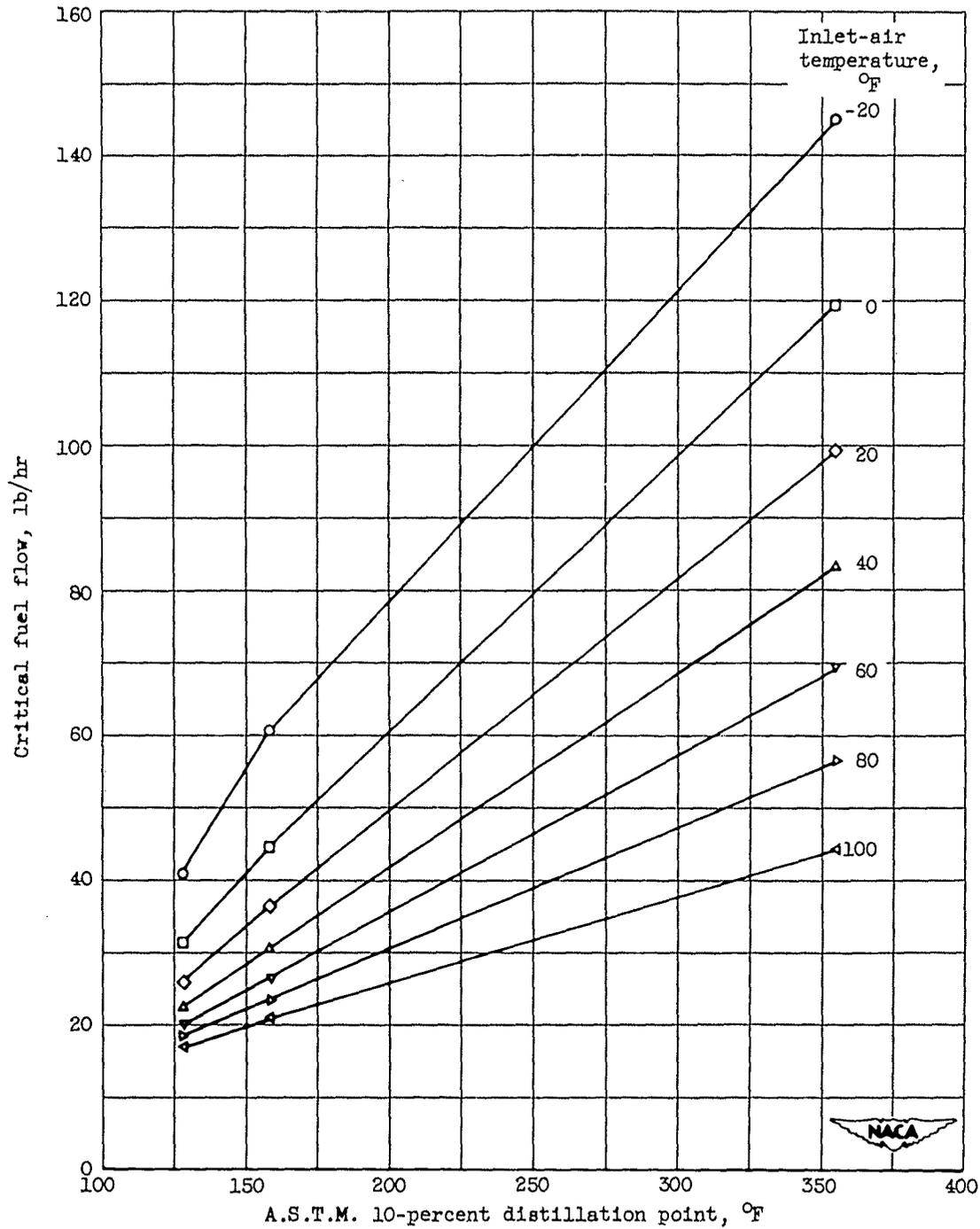


Figure 15. - Variation of critical fuel flow for ignition with fuel volatility. Single combustor; engine speed, 1600 rpm; flight Mach number, 0; sea level.

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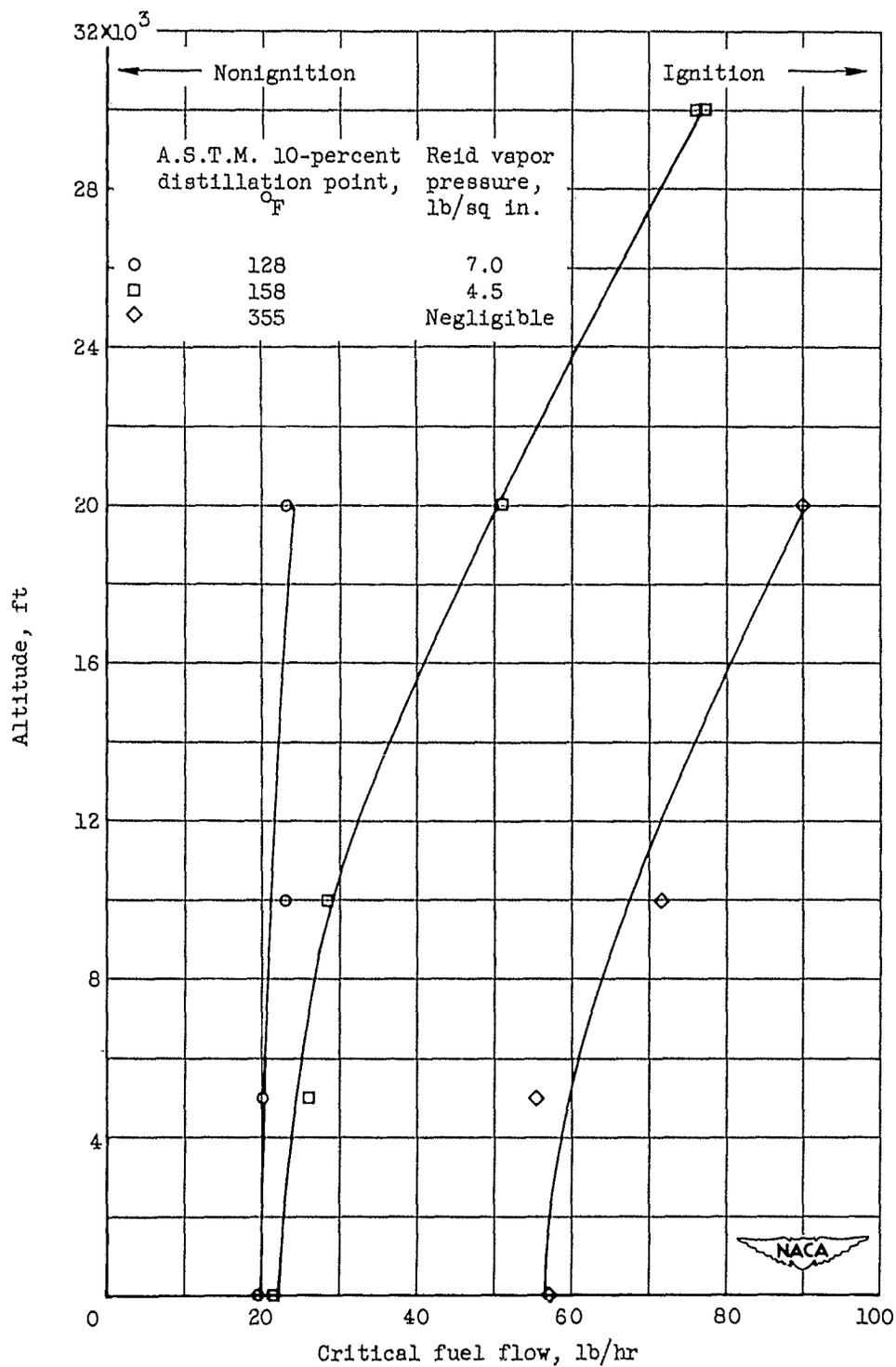


Figure 16. - Effect of altitude on fuel flow required for ignition in combustor. Engine speed, 1600 rpm; Mach number, 0.

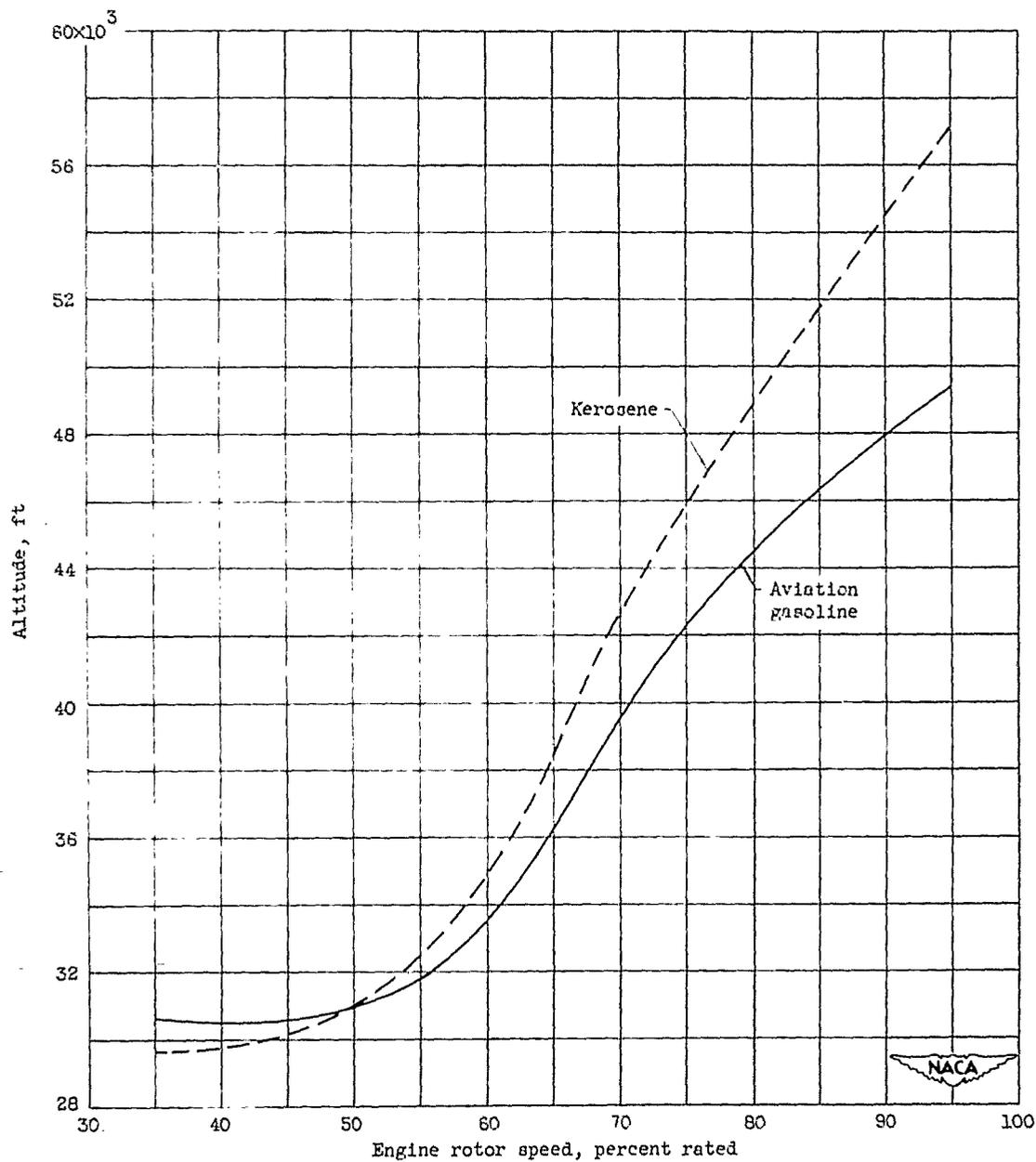


Figure 17. - Altitude operational limits for two fuels. Annular combustor; Mach number, 0.

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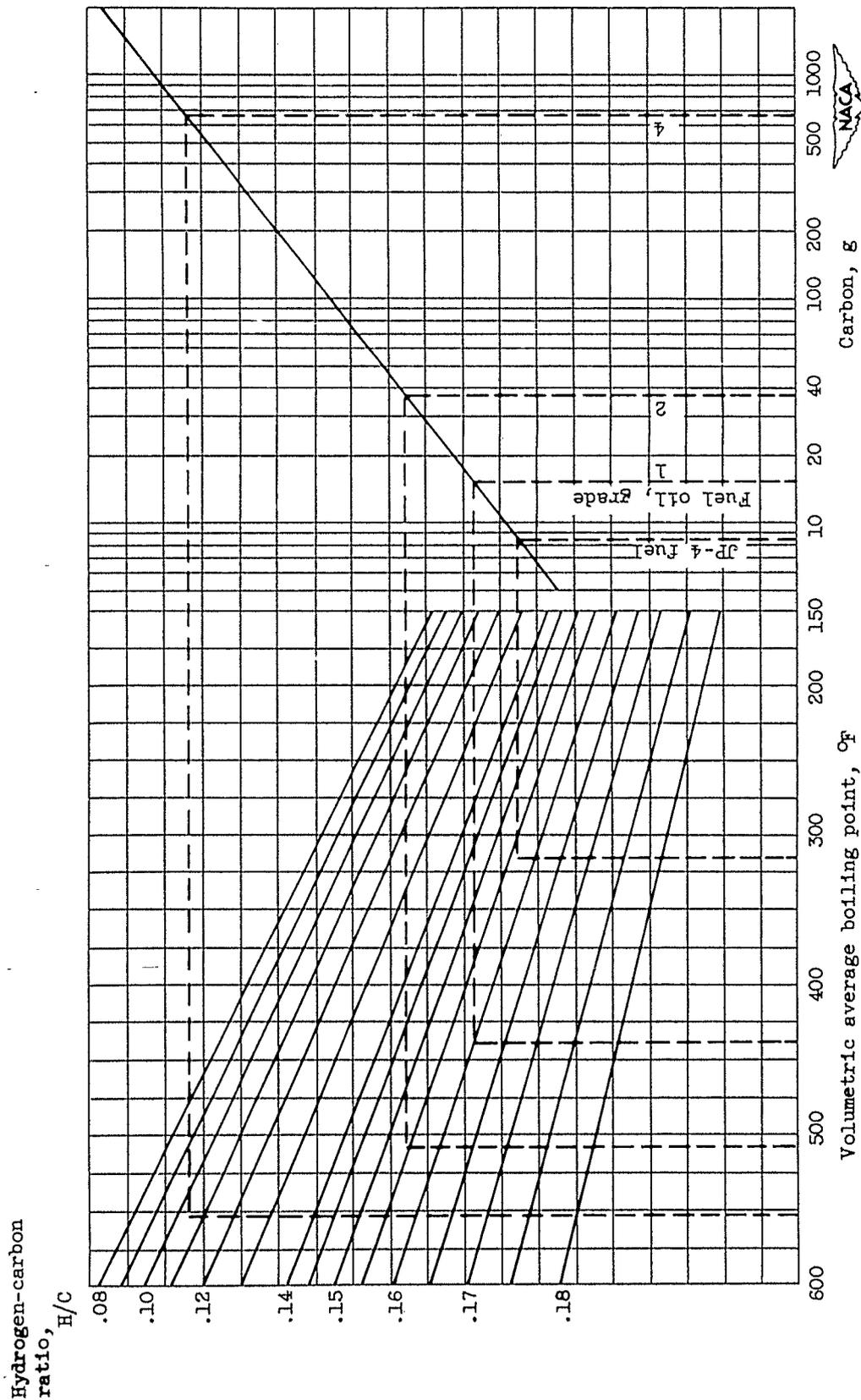


Figure 18. - Estimated carbon deposition of several fuels. Annular combustor; inlet-air total pressure, 40 inches of mercury absolute; inlet-air total temperature, 100° F; fuel flow, 157.5 pounds per hour; fuel-air ratio, 0.0175; running time, 2 hours.

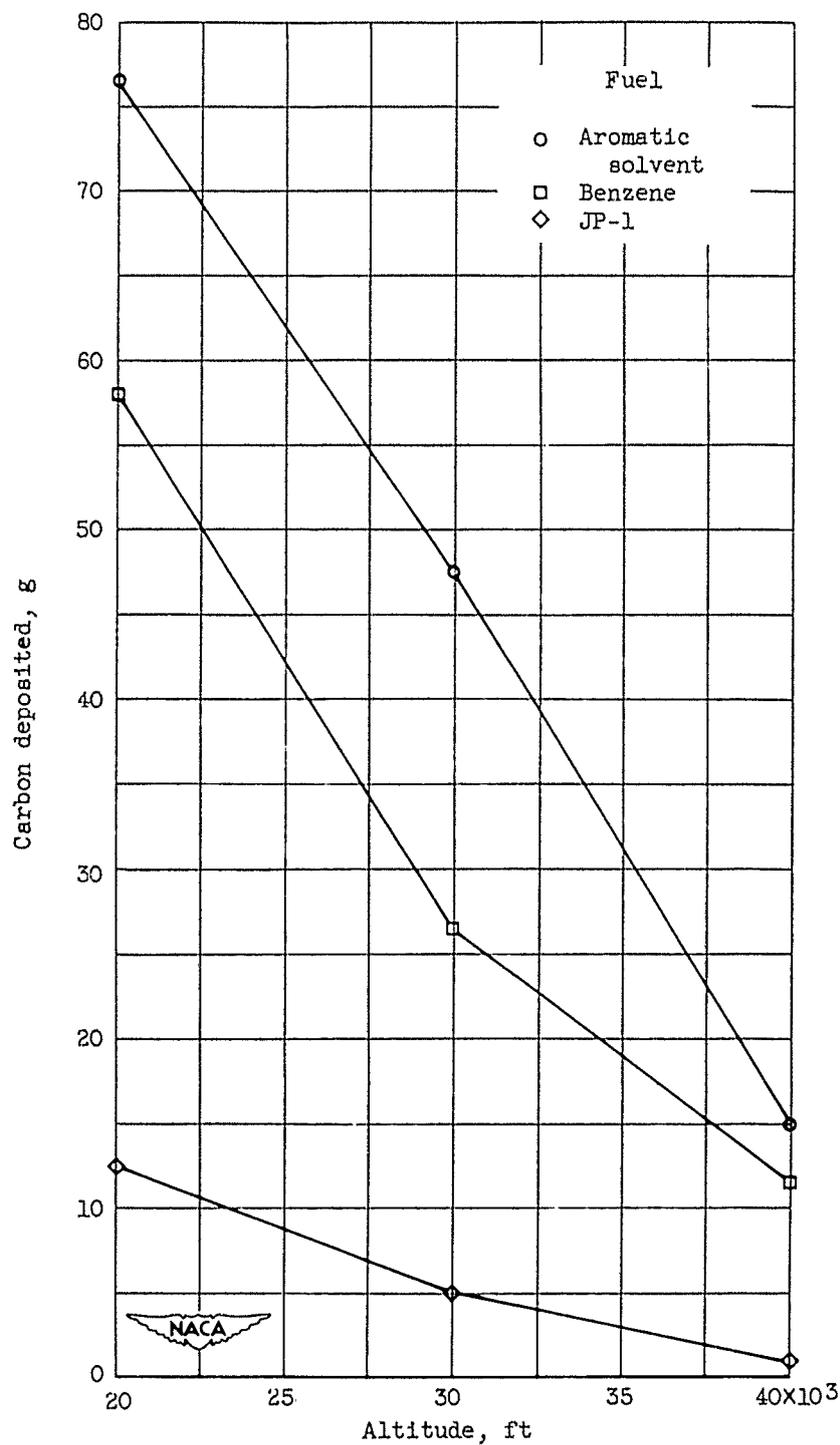


Figure 19. - Effect of altitude on carbon deposition. Annular combustor; rated engine speed; running time, $1\frac{1}{4}$ hours.

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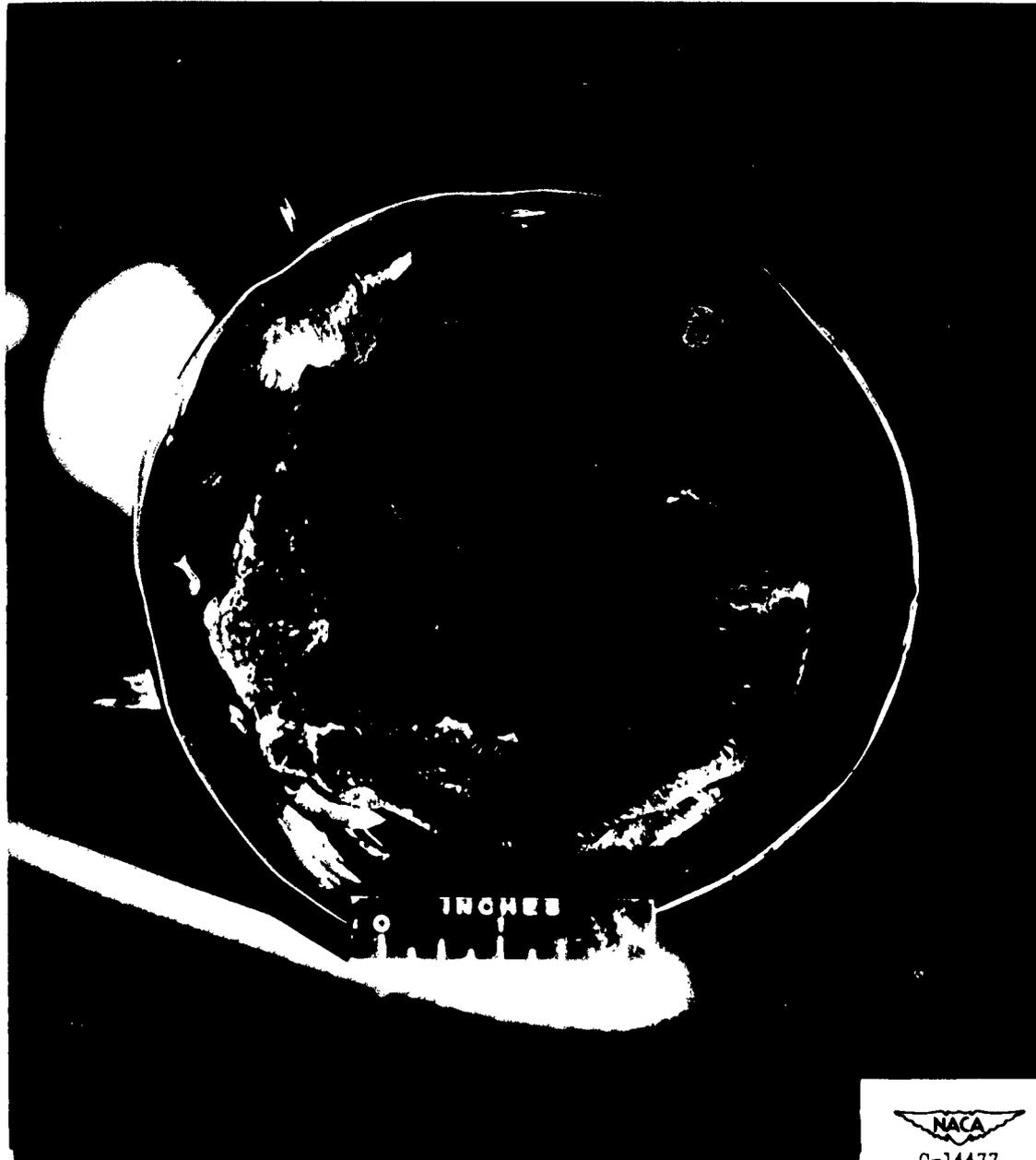


Figure 20. - Carbon deposit after 2-hour run with Diesel fuel at sea-level conditions.

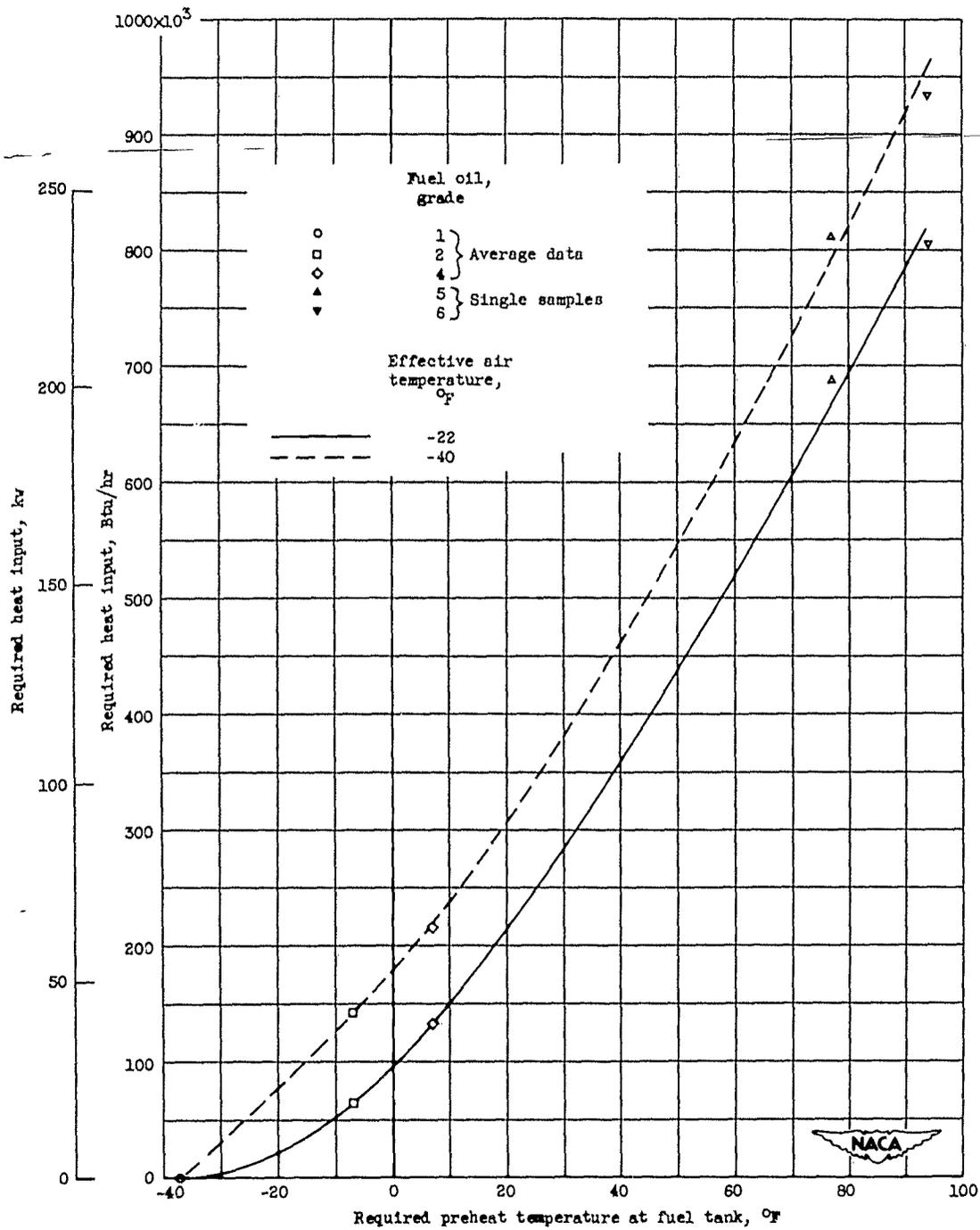


Figure 21. - Required heat input at tank to maintain fuel in pumpable condition, that is, above pour point and below viscosity of 500 centistokes.

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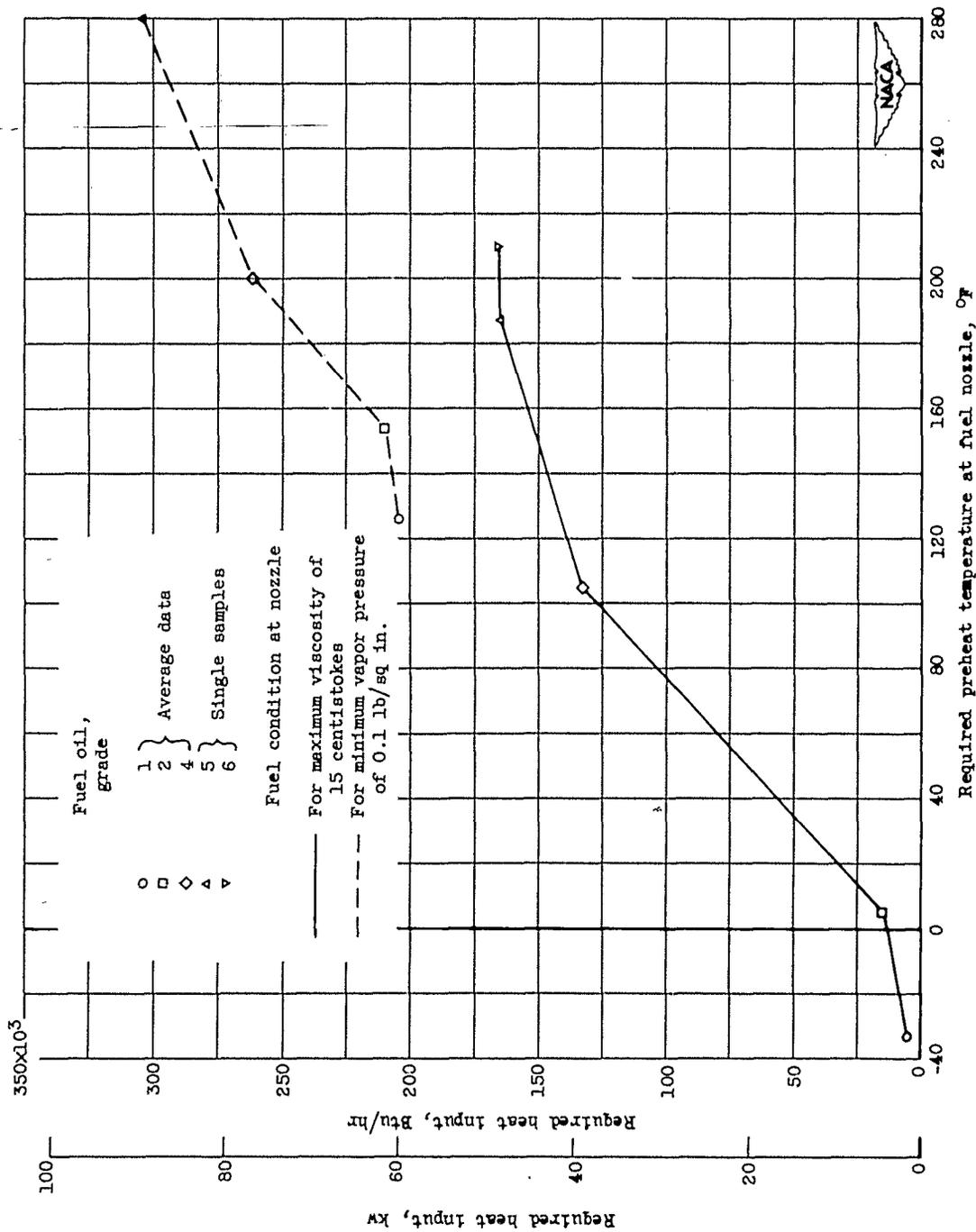
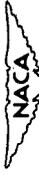


Figure 22. - Required heat input between fuel tank and injection nozzle.

<p>NACA RM E53H05 National Advisory Committee for Aeronautics. CONSIDERATIONS IN THE ADAPTATION OF LOW-COST FUELS TO GAS-TURBINE-POWERED COMMERCIAL AIRCRAFT. Henry C. Barnett and Richard J. McCafferty. October 1953. 59p. diags., photo., 2 tabs. (NACA RM E53H05) CONFIDENTIAL</p> <p>In recent months interest has increased in the possible use of distillate and residual fuel oils as fuels for commercial gas-turbine aircraft. However, the use of such fuels entails the solution of many problems pertaining to fuel physical properties and combustion characteristics. This report reviews some of these problems and discusses the status of current knowledge in relation to their solution. The fuel combustion characteristics considered in this study are ignition, combustion efficiency, combustion stability, and carbon deposition. In addition the effects of distillate and residual fuels on exhaust deposits and corrosion are discussed. Preliminary calculated</p> <p>Copies obtainable from NACA, Washington (over)</p>	<p>CONFIDENTIAL SECURITY INFORMATION</p> <ol style="list-style-type: none"> 1. Fuels (3. 4) 2. Physical and Chemical (3. 4. 2) 3. Fuels - Turbine Engines, Ram Jets, and Pulse Jets (3. 4. 3. 2) 4. Operating Problems, General (7. 10) <p>I. Barnett, Henry C. II. McCafferty, Richard J. III. NACA RM E53H05</p> <p style="text-align: center;"> CONFIDENTIAL</p>	<p>NACA RM E53H05 National Advisory Committee for Aeronautics. CONSIDERATIONS IN THE ADAPTATION OF LOW-COST FUELS TO GAS-TURBINE-POWERED COMMERCIAL AIRCRAFT. Henry C. Barnett and Richard J. McCafferty. October 1953. 59p. diags., photo., 2 tabs. (NACA RM E53H05) CONFIDENTIAL</p> <p>In recent months interest has increased in the possible use of distillate and residual fuel oils as fuels for commercial gas-turbine aircraft. However, the use of such fuels entails the solution of many problems pertaining to fuel physical properties and combustion characteristics. This report reviews some of these problems and discusses the status of current knowledge in relation to their solution. The fuel combustion characteristics considered in this study are ignition, combustion efficiency, combustion stability, and carbon deposition. In addition the effects of distillate and residual fuels on exhaust deposits and corrosion are discussed. Preliminary calculated</p> <p>Copies obtainable from NACA, Washington (over)</p>	<p>CONFIDENTIAL SECURITY INFORMATION</p> <ol style="list-style-type: none"> 1. Fuels (3. 4) 2. Physical and Chemical (3. 4. 2) 3. Fuels - Turbine Engines, Ram Jets, and Pulse Jets (3. 4. 3. 2) 4. Operating Problems, General (7. 10) <p>I. Barnett, Henry C. II. McCafferty, Richard J. III. NACA RM E53H05</p> <p style="text-align: center;"> CONFIDENTIAL</p>
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