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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

FUEL CHARACTERISTICS PERTINENT TO THE DESIGN OF AIRCRAFT FUEL SYSTEMS

SUPPLEMENT I - ADDITIONAL INFORMATION ON MIL-F-7914(AER) GRADE JP-5 FUEL AND SEVERAL FUEL OILS

By Henry C. Barnett and Robert R. Hibbard

INTRODUCTION

Since the release of the first NACA publication on fuel characteristics pertinent to the design of aircraft fuel systems (ref. 1), additional information has become available on MIL-F-7914(AER) grade JP-5 fuel and several of the current grades of fuel oils. In order to make this information available to fuel-system designers as quickly as possible, the present report has been prepared as a supplement to reference 1.

Although JP-5 fuel is of greater interest in current fuel-system problems than the fuel oils, the available data are not as extensive. It is believed, however, that the limited data on JP-5 are sufficient to indicate the variations in stocks that the designer must consider under a given fuel specification.

The methods used in the preparation and extrapolation of data presented in the tables and figures of this supplement are the same as those used in reference 1.

SPECIFICATIONS AND PHYSICAL PROPERTIES OF FUELS

The properties of the various grades of marketed fuel oil are at present controlled by specifications (table I) written for industrial furnace requirements and home heating purposes. These specifications would undoubtedly be altered somewhat if such fuels were applied to aircraft power plants. There is, of course, no means of predicting these alterations; so for the purposes of this discussion the variation of fuel properties under a given specification will be considered in comparison with the existing specifications under which fuel oils are marketed.

The fuel oils are derived from distillate and residual fractions of petroleum and are commonly identified by numbers (table I) corresponding to the various specification requirements. The more conventional uses of the distillate fuels (grades 1 and 2) are for home heating, Diesel engines, and industrial heating, where it is impractical to heat the fuel to improve flow characteristics. Residual fuels (grades 4, 5, and 6) are

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residues from petroleum stills and in marketed form are blended with less viscous materials. These fuels are used in applications where it is feasible to heat the fuel for flow improvement.

The available data on physical properties for numerous samples of fuel oils have been compared, and the variations to be expected are summarized in table II. Data on fuel oils 1, 2, and 4 were compiled from surveys of the U.S. Bureau of Mines (refs. 2, 3, and 4). Data on fuel oils 5 and 6 are quite scarce; therefore, it has been necessary to compare the properties of single samples of these two fuels with averages for the three lower grades. 3102

Inspection data are available for only a few large batches of fuel procured under MIL-F-7914(AER) grade JP-5. Other refineries, however, have supplied inspection data on samples typical of expected large-scale production under the JP-5 specification. All these inspections have been considered equally in order to illustrate the variation in physical properties that may be encountered under the JP-5 specifications. These data, shown in table III, have been made available by the Bureau of Aeronautics, Department of the Navy. Throughout the subsequent discussion it will be apparent that the properties of JP-5 fuel conform closely to those of a grade 1 fuel oil.

Density. - Appreciable variations of density may be encountered under current specifications for fuel oils and JP-5 fuel. This fact is illustrated in figure 1. 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 fuel oil, the deviation is 6.7 percent; and for grade 4 fuel oil, 8.0 percent. The JP-5 fuel (fig. 1(d)) shows a maximum deviation from average of about 5.7 percent. As seen in figures 1(a), (b), and (d), all these deviations could be greater if samples meeting the maximum and minimum limits of the specifications were marketed.

In figure 1(e), the average curves for grades 1, 2, and 4 fuel oil and JP-5 fuel are compared with data for MIL-F-5624A grade JP-4 fuel and data for single samples of grades 5 and 6 fuel oil. The density of the grade 6 fuel oil is about 23 percent higher than that of average JP-4 fuel at 60° F.

Viscosity and pour points. - The variation of viscosity with temperature for the fuel oils and JP-5 fuel is shown in figure 2. Viscosity data (tables II and III) were available at only one temperature (either -40° or 100° F). For this reason the curves were estimated by extension through the known point and in a position parallel to a more accurately established curve for JP-4 fuel in reference 1. All the samples of grades 1 and 2 fuel oils (figs. 2(a) and (b)) fell within the limits of the specifications (table I), but some samples of grade 4 were considerably beyond both upper and lower limits of the specification. Regardless of this condition, the samples were averaged because the original reference sources (refs. 2, 3, and 4) indicated that all these samples had been marketed as grade 4 fuel oil. The viscosity - temperature curves for the various fuels are compared in figure 2(e). It is evident that extremely high viscosities may be encountered with 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 low-temperature extremes of the curves in figure 2 are determined by the pour point. The pour point 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. The relation between pour point and A.S.T.M. distillation end point (fig. 3), however, is no more rigorous than a similar relation for freezing point shown in reference 1. Both relations are subject to the influence of fuel composition, which accounts for the scattering of data in figure 3.

Volatility. - A.S.T.M. distillation curves for four of the fuel oils and JP-5 fuel are presented in figure 4. Some samples of grades 1 and 2 fuel oils and JP-5 fuel are very near the limits permitted by specifications. As in the case of the specific gravity data (fig. 1), the spread between minimum and maximum values of distillation temperature tends to increase as the grade of fuel oil becomes heavier.

In figure 4(e) distillation data for four grades of fuel oil, JP-5 fuel, and JP-4 fuel are compared. All the fuel oils and JP-5 fuel are considerably less volatile than JP-4 fuel as indicated by the high distillation temperatures. Similar data for grade 6 fuel oil were not determined, and the curve for grade 5 fuel oil is incomplete because of cracking of the sample at 1025° F.

The true vapor-pressure - temperature curves for the fuel oils and JP-5 fuel are shown in figure 5. The data for the fuel oils and JP-5 fuel were calculated by the method described in reference 5, and the curve for the JP-4 fuel shown in figure 5(d) is taken from reference 1. Only the average curve for the JP-5 fuel is presented in figure 5 since the differences between the maximum and minimum curves are quite small. The calculated values of vapor pressure for JP-5 fuel are as follows:

Temperature, °F	Vapor pressure, lb/sq in.		
	Max.	Min.	Av.
200	0.52	0.37	0.46
300	3.06	2.51	2.92
400	11.56	10.17	11.48

It is apparent in figure 5 that the volatility of the fuel oils and JP-5 fuel 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.

Latent heat of vaporization. - Latent heats of vaporization for the fuel oils, JP-5 fuel, and JP-4 fuel were calculated by the method described in reference 6. The results are shown in figure 6. Average curves are not shown in figures 6(a), (c), and (d) because of the narrow spread between minimum and maximum limits. A comparison of the fuel oils and JP-5 fuel with JP-4 fuel is made in the following table:

Fuel	Latent heat, Btu/lb									
	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	---	---	---	---
JP-5	141	141	130	131	117	120	102	107	80	91
Grade 1 fuel oil	135	139	125	128	113	116	97	103	71	87
Grade 2 fuel oil	135	142	124	133	113	123	98	113	79	100
Grade 4 fuel oil	145	147	134	139	123	129	111	120	96	110

[a]Data from ref. 1.

Dielectric constant. - In reference 1, the following equation was presented to permit the estimation of the dielectric constant from fuel specific gravity:

$$K = 1.667\rho + 0.785 \tag{1}$$

where:

ρ specific gravity at any temperature

K dielectric constant at the same temperature

This equation was based upon a rather limited number of fuels but was found to represent the data with deviations no greater than ±2 percent. Since the issuance of reference 1, an additional check has been made to determine the extent of application of the equation. Data from references 7 and 8 indicate that the equation applies for paraffinic and cycloparaffinic hydrocarbons over a range of temperatures from -184° to 410° F. The dielectric constants for pure aromatics are somewhat higher than those of paraffins, particularly in the high density range. For this reason it is recommended that equation (1) be used with caution for fuels containing high percentages of aromatics. There is no accurate method to set the limiting value of aromatic concentration for use in this equation; however, on the basis of data available at this time it is suggested that equation (1) be used for estimation of dielectric constants only with fuels containing less than 25 percent (by volume) aromatics.

Equation (1) has been used to estimate the dielectric constants for the fuel oils and JP-5 fuel. The specific gravity curves of figure 1 were used in making these estimates. The results are presented in figure 7.

Flammability limits. - Sea-level flammability temperature limits have been calculated by methods described in reference 1 and 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.
[a]JP-4	-6	34	15	40	49	95	74	46
JP-5	119	141	128	22	195	221	205	26
Grade 1 fuel oil	111	146	124	35	185	226	200	41
Grade 2 fuel oil	116	208	159	92	191	299	241	108
Grade 4 fuel oil	149	233	181	84	229	327	267	98
[b]Grade 5 fuel oil	---	---	335	--	---	---	446	---

[a]Data from ref. 1.

[b]Single sample.

These data follow the trends illustrated for the fuels in reference 1 in that the temperature limits increase as the volatility of the fuels decreases. Also, large differences between minimum and maximum temperature limits may be encountered under a given specification. For grades 2 and 4 fuel oils these differences are of the order of 80° to 110° F.

The lean and rich flammability limits of fuel-air mixtures have also been calculated by methods described in reference 1. These limits are shown in the following table:

Fuel	Lean limit, vol. percent	Rich limit, vol. percent
[a]JP-4		
Min. volatility	0.73	5.27
Max. volatility	.91	6.28
Av. volatility	.81	5.72
JP-5		
Min. volatility	0.60	4.41
Max. volatility	.65	4.84
Av. volatility	.62	4.64
Grade 1 fuel oil		
Min. volatility	0.54	4.22
Max. volatility	.65	4.84
Av. volatility	.60	4.57
Grade 2 fuel oil		
Min. volatility	0.47	3.80
Max. volatility	.62	4.69
Av. volatility	.55	4.24
Grade 4 fuel oil		
Min. volatility	0.42	3.40
Max. volatility	.60	4.49
Av. volatility	.53	4.06
Grade 5 fuel oil		
Single sample	0.2	2.0

[a]Data from ref. 1.

The data in the preceding table are based upon completely vaporized fuel, and the calculations were made by using heats of combustion and molecular weights estimated from A.S.T.M. distillation data and specific gravities from tables II and III.

CONCLUDING REMARKS

Data reported herein supplement reference 1, which contains physical property data on MIL-F-5616 grade JP-1, MIL-F-5624A grade JP-3, and MIL-F-5624A grade JP-4 fuels. Fuels considered in the present report are MIL-F-7914(AER) grade JP-5 fuel and grades 1, 2, 4, 5, and 6 fuel oils. The physical properties included in this study are density, viscosity, pour point, volatility, latent heat of vaporization, dielectric constant, and flammability limits. Data are presented to illustrate the variation of physical properties under existing specifications.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, September 16, 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 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.	90-percent point, max.	End point, max.	100° F		122° F			
									Max.	Min.	Max.	Min.		
1 {A distillate oil intended for vaporizing pot-type burners and other burners requiring this grade of fuel	100 or legal	0	Trace	0.15	----	420	---	625	2.2	1.4	---	--	35	Pass
2 {A distillate oil for general purpose domestic heating for use in burners not requiring grade 1 fuel oil	100 or legal	[d]20	0.10	.35	----	---	675	---	4.3	----	---	--	26	----
4 {An oil for burner installations not equipped with preheating facilities	130 or legal	20	.50	----	0.10	---	---	---	26.4	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	----	----	---	---	---	----	----	638	92	--	----

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

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

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

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

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

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

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

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

[a]Measured at 122° F.

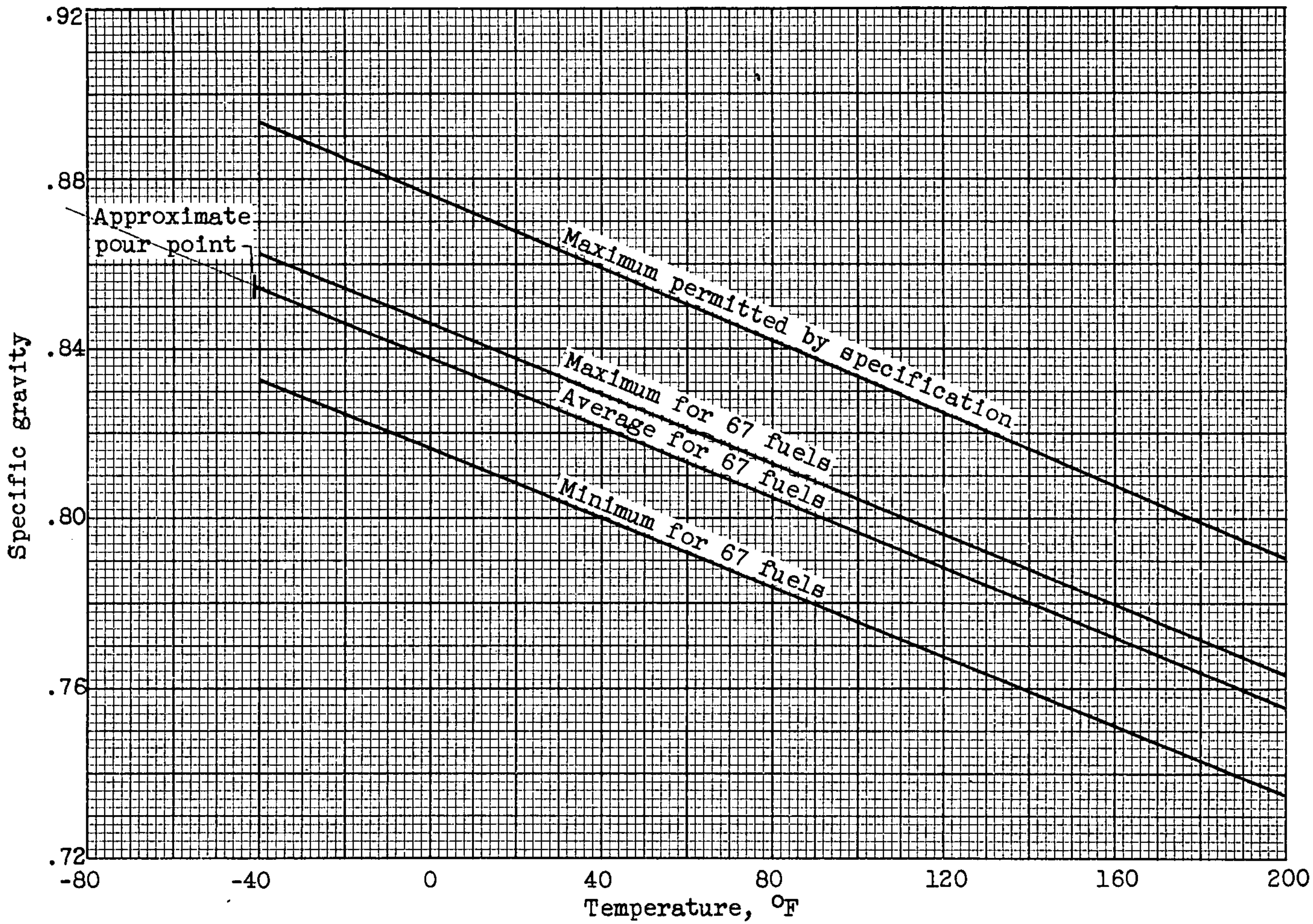
[redacted]

TABLE III. - SPECIFICATIONS AND PROPERTIES OF MIL-F-7914(AER) GRADE JP-5 FUEL

	Specifications	Properties			
		Number of fuels averaged	Min.	Max.	Arithmetic av.
A.S.T.M. distillation D86-52, °F					
Percentage evaporated					
Initial point		7	335	374	357
10	410(max)	20	378	411	391
50		12	414	444	427
90		15	456	527	476
End point	550(max)	17	488	560	511
Residue, percent	1.5(max)	17	0.5	1.5	0.8
Loss, percent	1.5(max)	15	0	1.0	0.6
Freezing point, °F	-40(max)	12	-80	-40	-52
Aromatics, percent by volume	25.0(max)	19	13.3	22.0	17.1
Bromine number	30.0(max)	19	0.5	5.0	2.3
Total sulfur, percent by weight	0.5(max)	17	0.044	0.48	0.17
Mercaptan sulfur, percent by weight	0.005(max)	10	0.0002	0.0017	0.0011
Air-jet residue, mg/100 ml	10.0(max)	5	1.0	3.8	2.2
Accelerated gum, mg/100 ml	20.0(max)	14	0.8	12.0	4.6
Heat of combustion, Btu/lb[a]	18,300(min)	--	18,400	18,600	18,500
Aniline-gravity constant	>4200	15	4728	6601	5484
Gravity					
Specific, 60/60° F	0.780-0.850	18	0.808	0.842	0.827
°A.P.I.	50-35	18	43.6	36.6	39.5
Viscosity at -40° F, centistokes	20.0(max)	8	12.6	18.7	16.6
Flash point, °F	140(min)	8	142	159	149

[a]Estimated from gravity.

[redacted]



(a) Grade 1 fuel oil.

Figure 1. - Variation of specific gravity with temperature.

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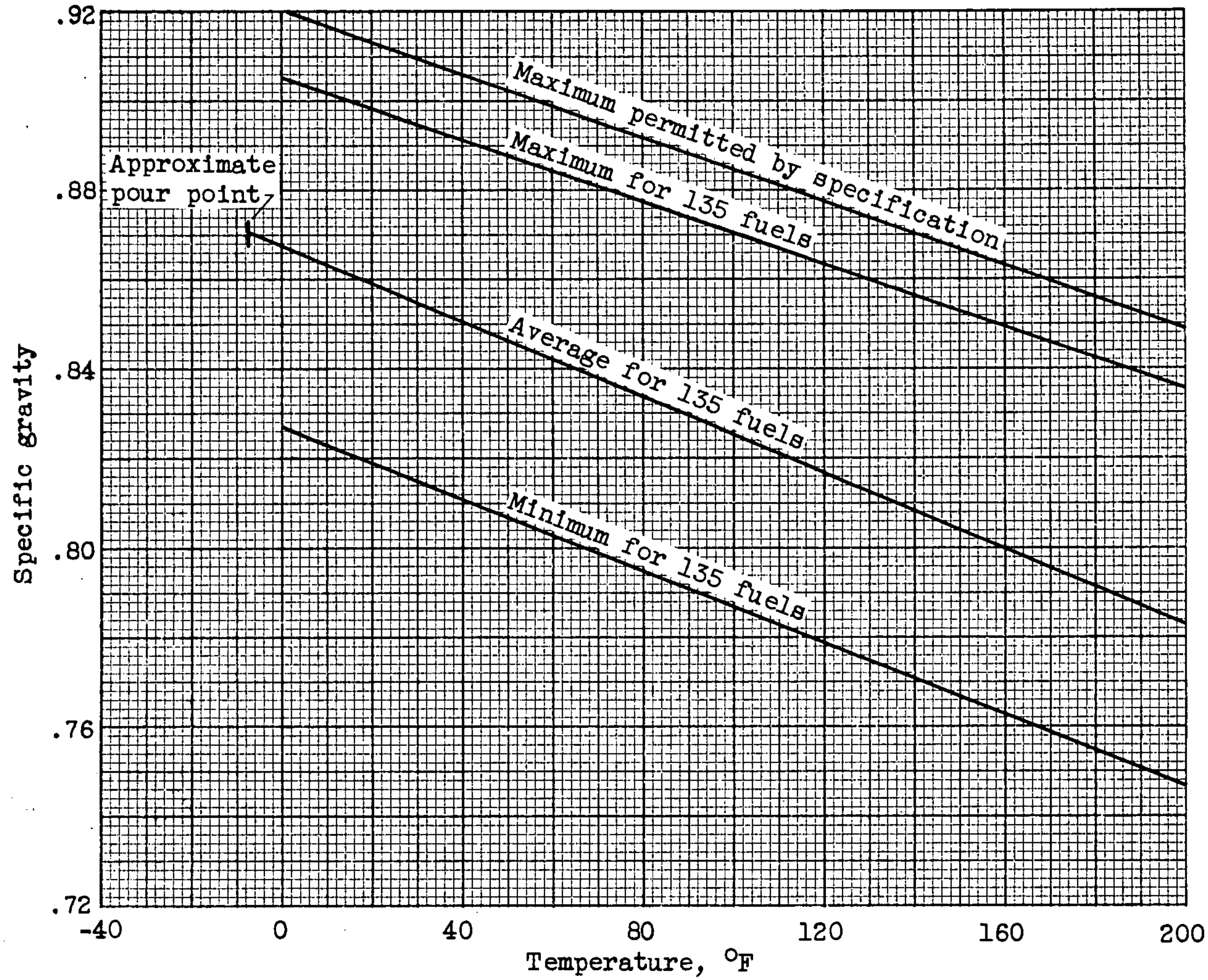

(b) Grade 2 fuel oil.

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

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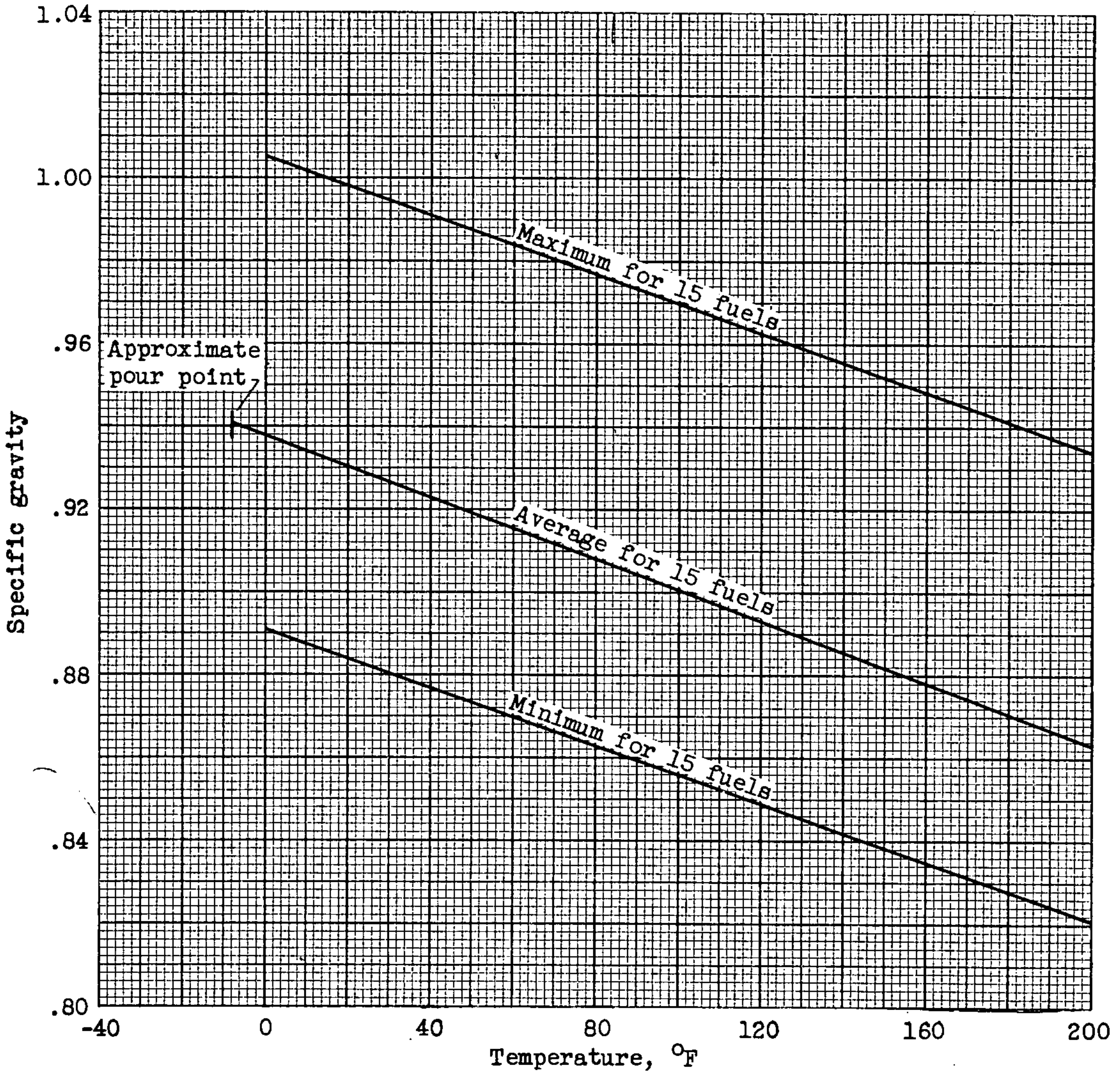
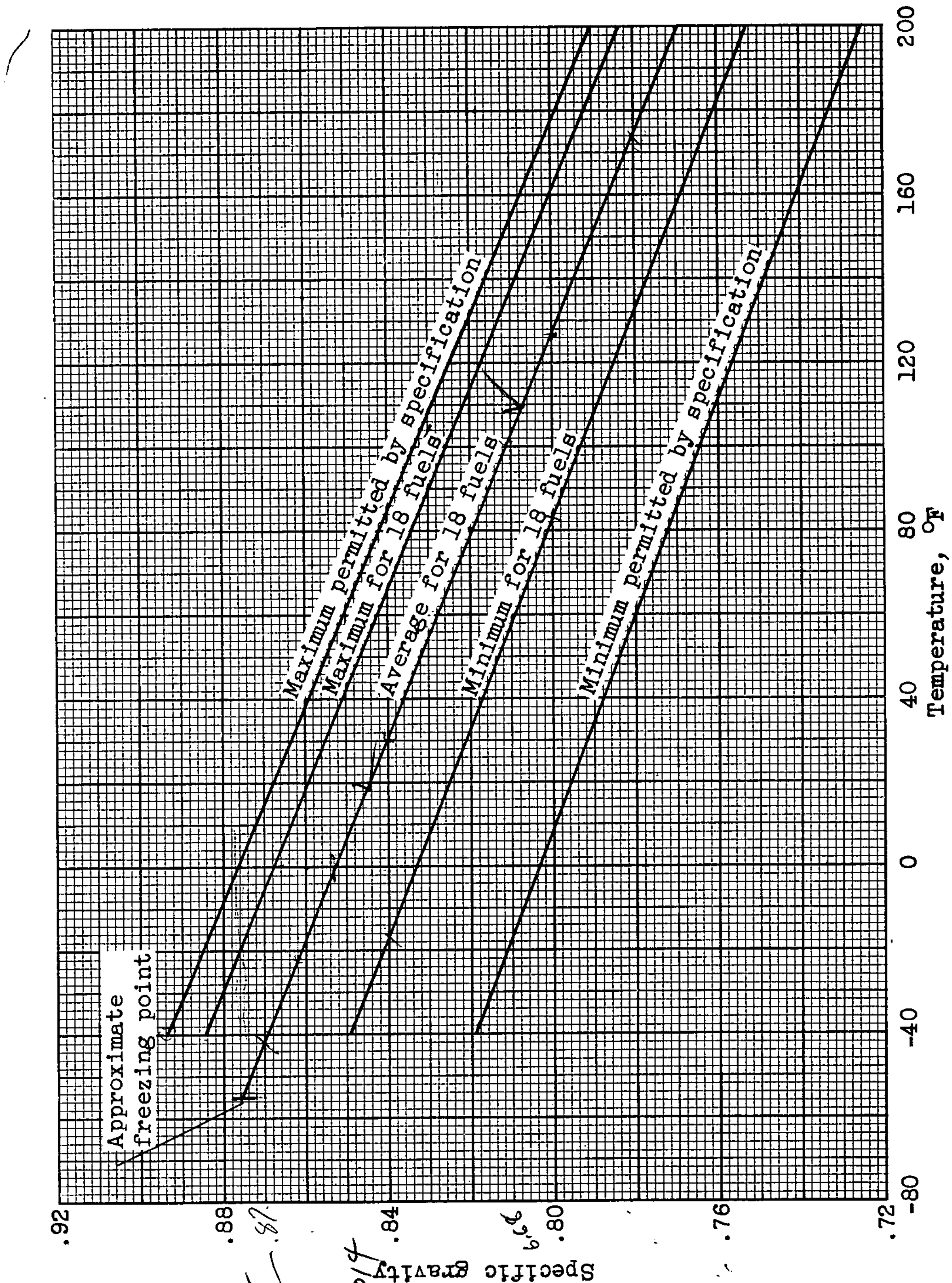


(c) Grade 4 fuel oil.

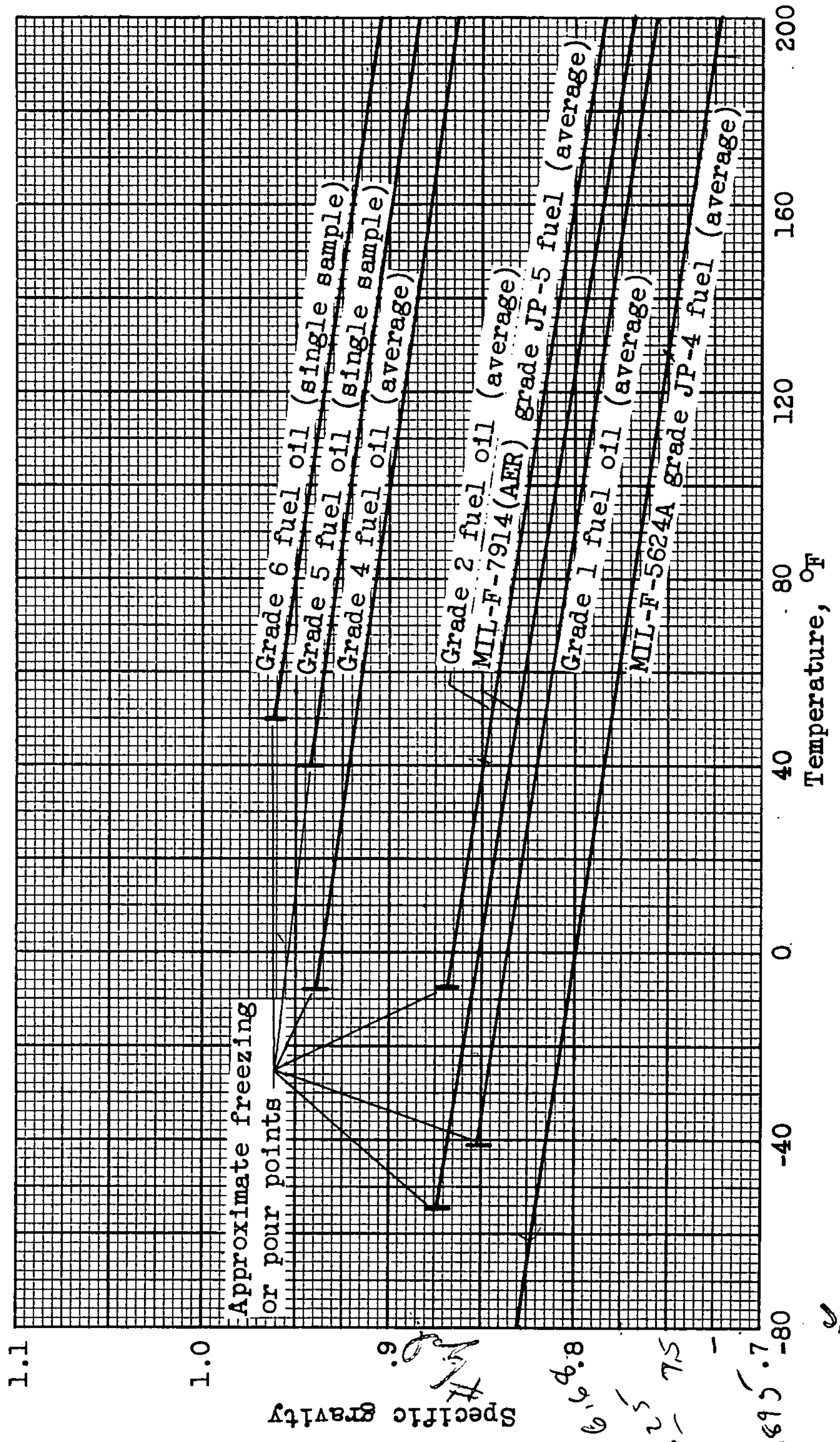
Figure 1. - Continued. Variation of specific gravity with temperature.



(d) MIL-F-7914(AER) grade JP-5 fuel.

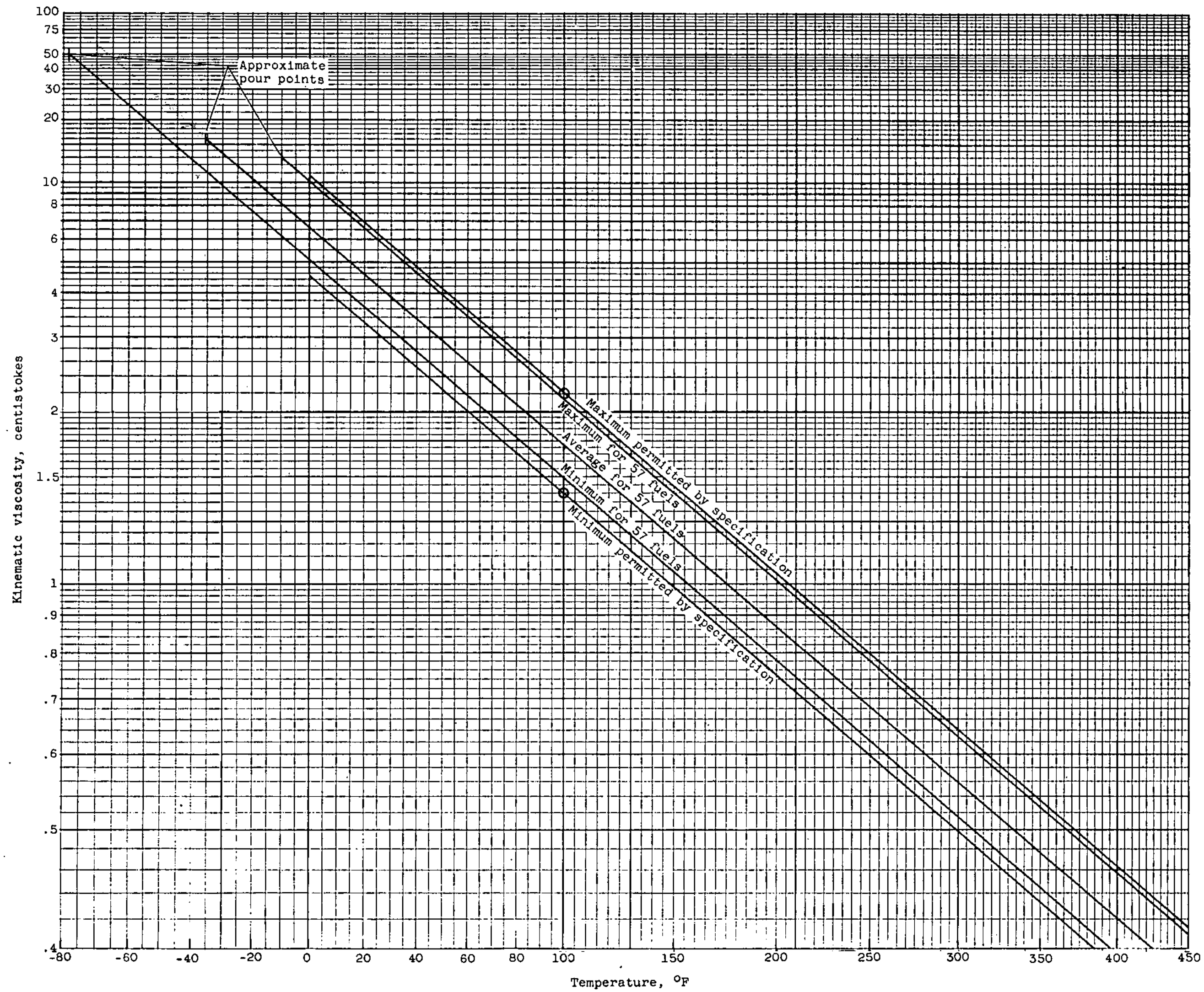
Figure 1. - Continued. Variation of specific gravity with temperature.

[redacted]



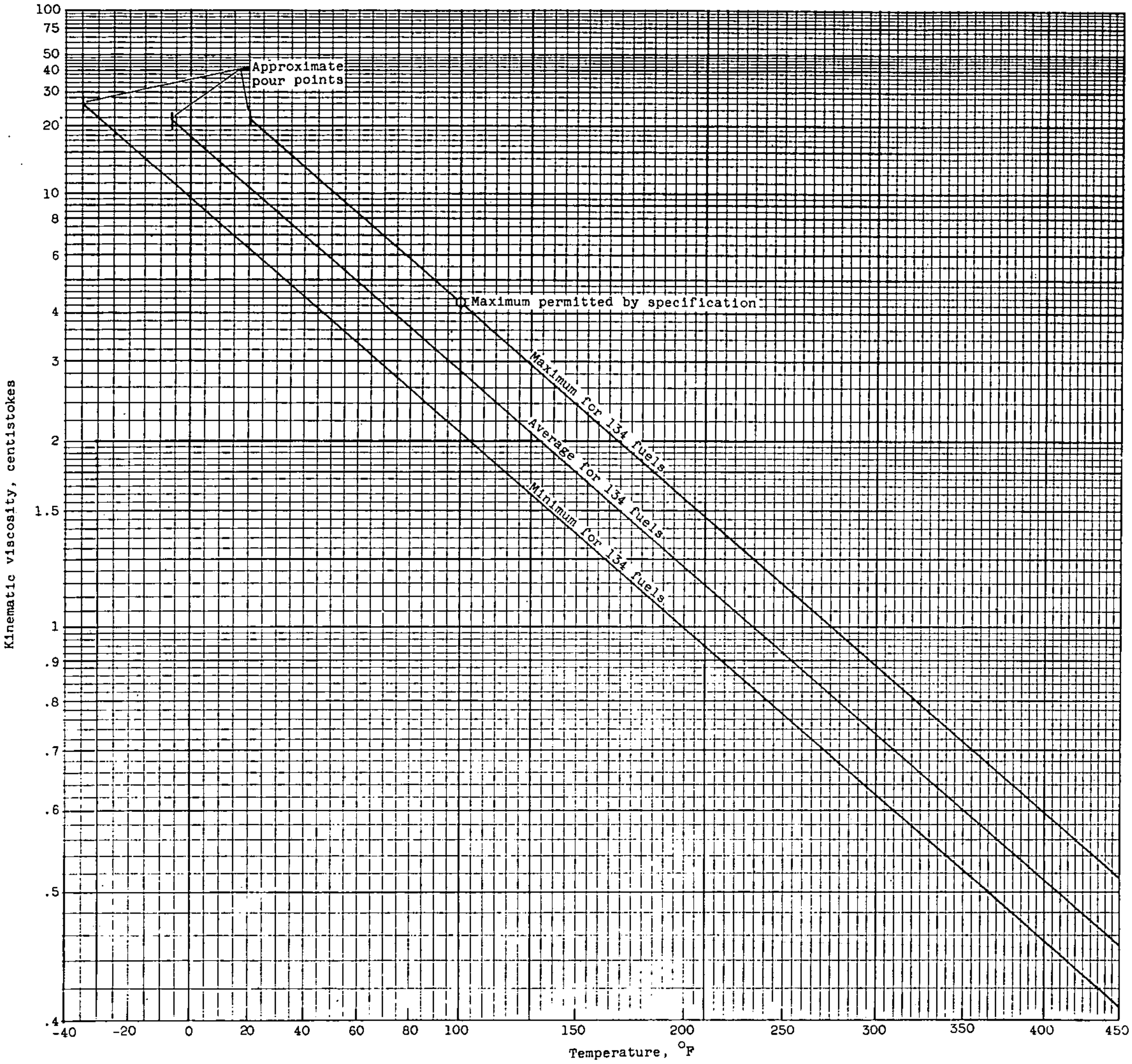
(e) Comparison of several fuels.

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



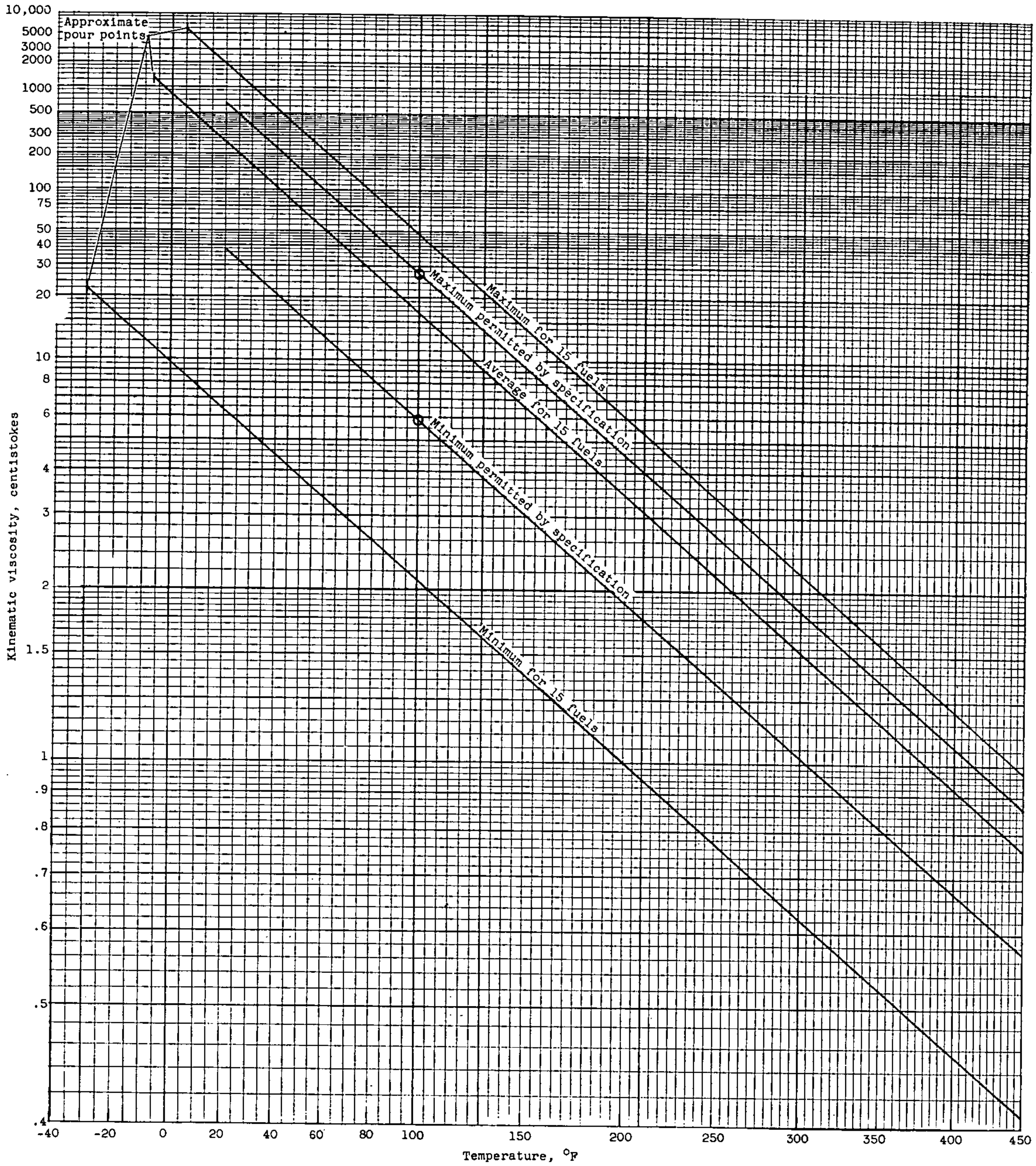
(a) Grade 1 fuel oil.

Figure 2. - Variation of viscosity with temperature.



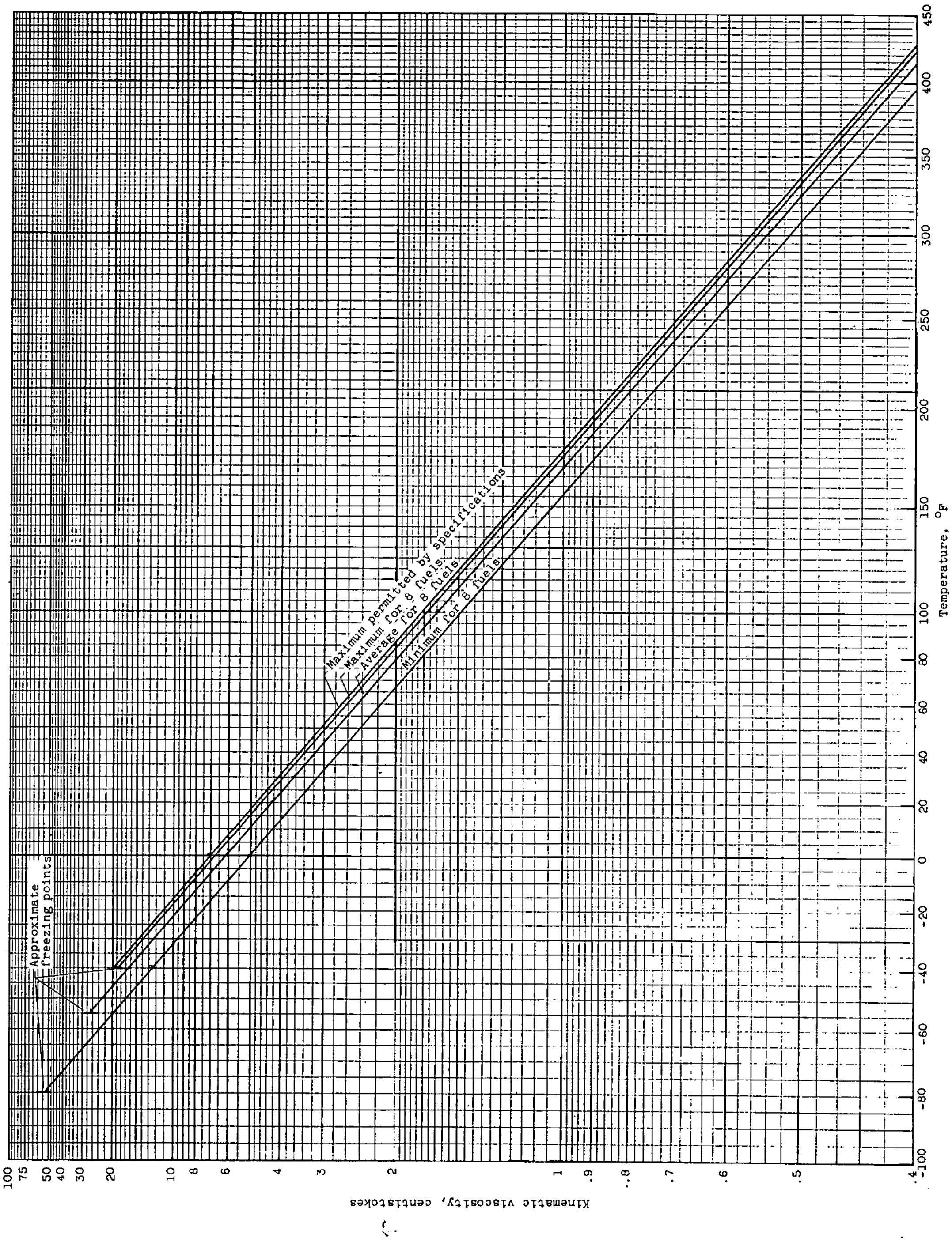
(b) Grade 2 fuel oil.

Figure 2. - Continued. Variation of viscosity with temperature.



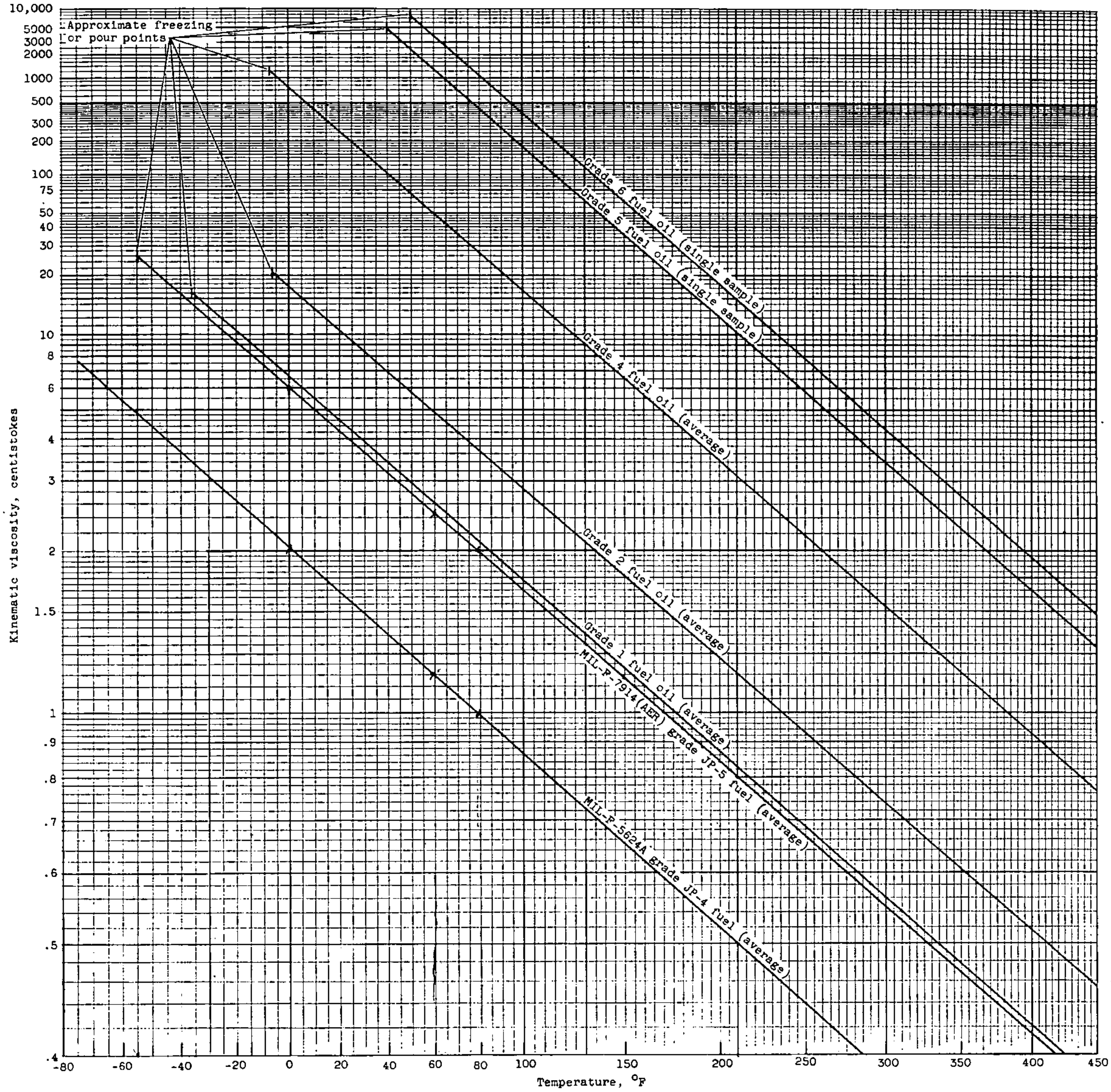
(c) Grade 4 fuel oil.

Figure 2. - Continued. Variation of viscosity with temperature.



(d) MIL-F-7914(AER) grade JP-5 fuel.

Figure 2. - Continued. Variation of viscosity with temperature.



(e) Comparison of several fuels.

Figure 2. - Concluded. Variation of viscosity with temperature.

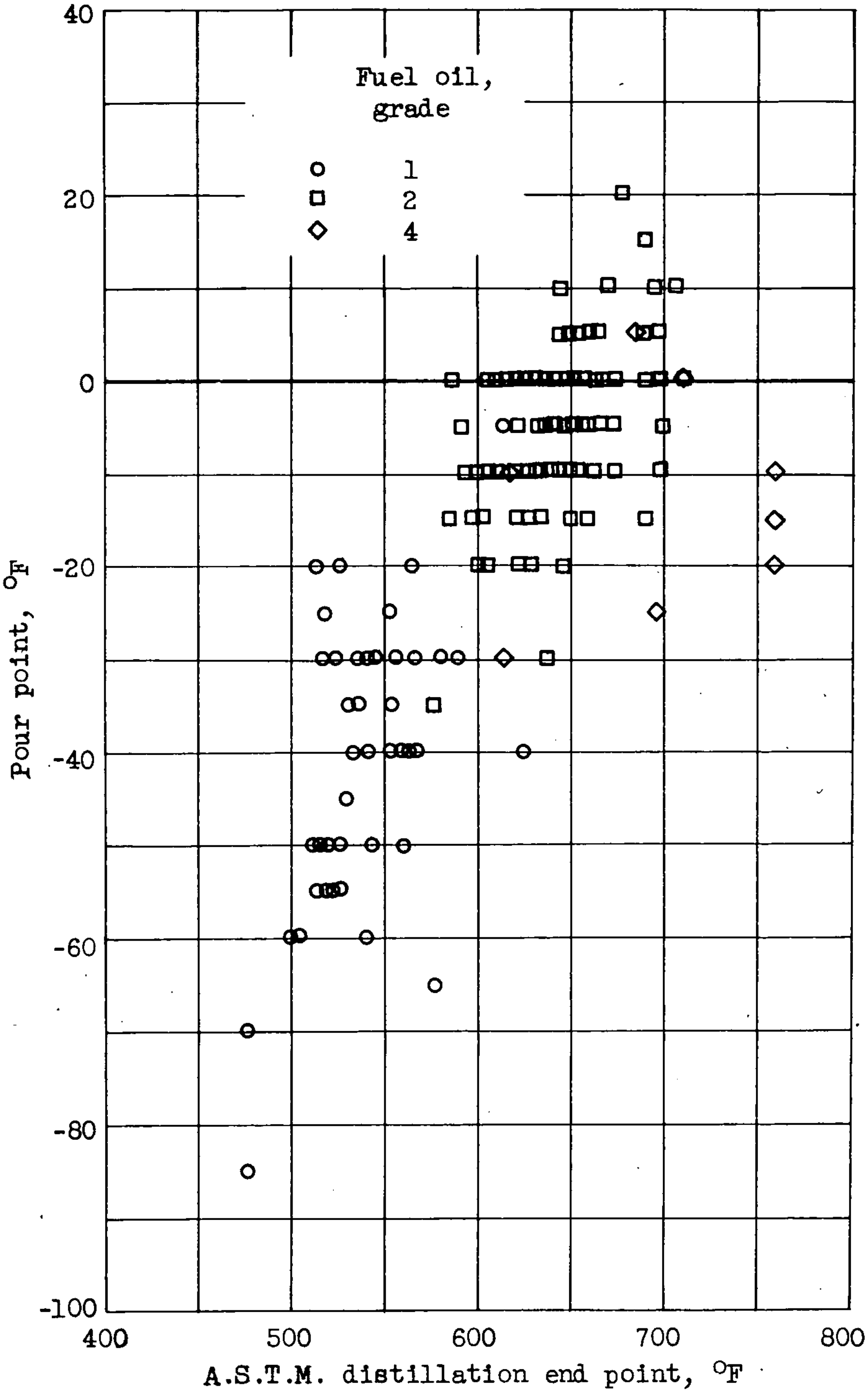
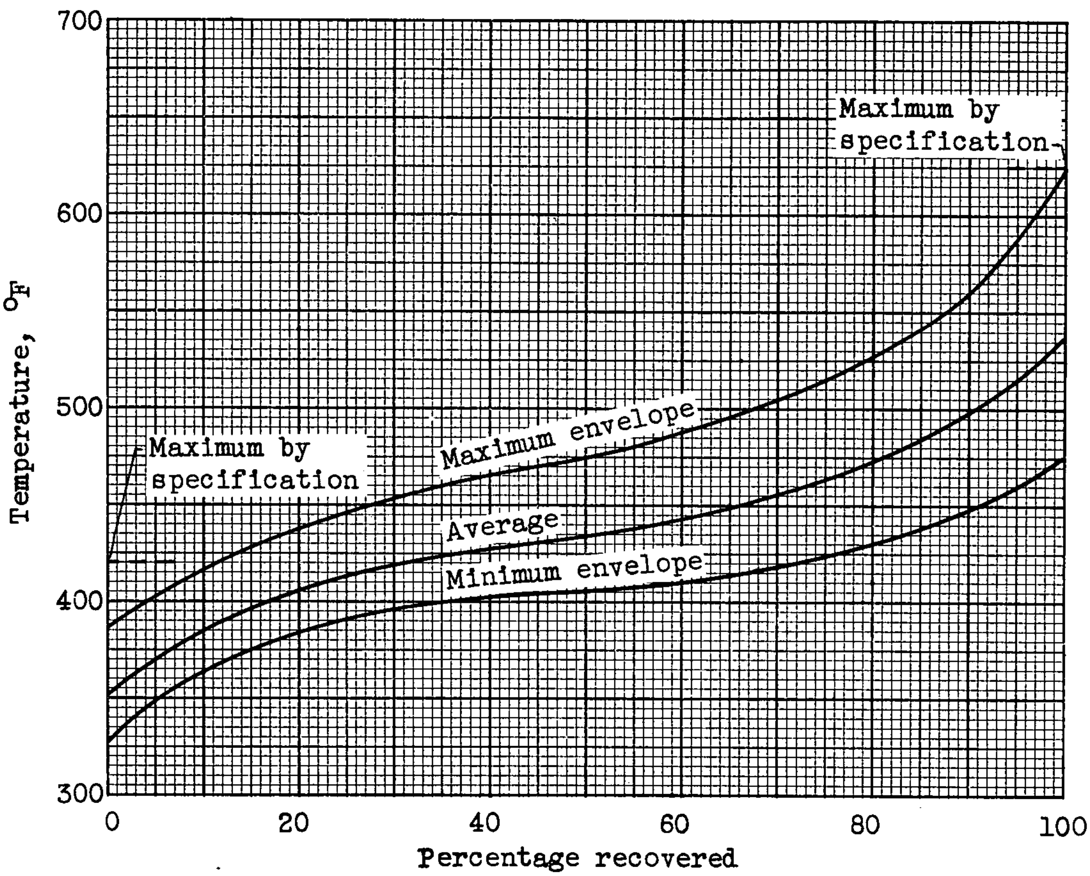
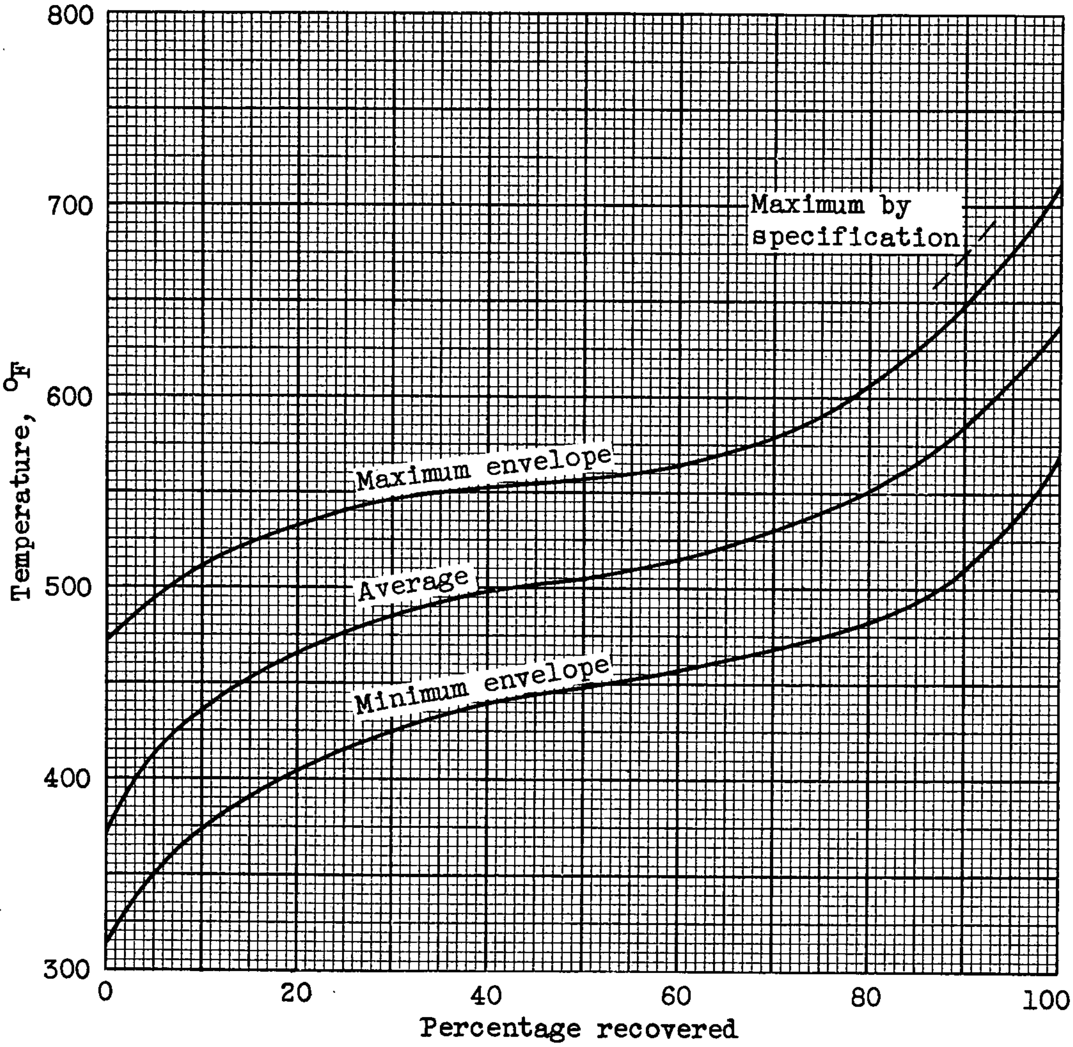


Figure 3. - Variation of pour point with A.S.T.M. distillation end point.



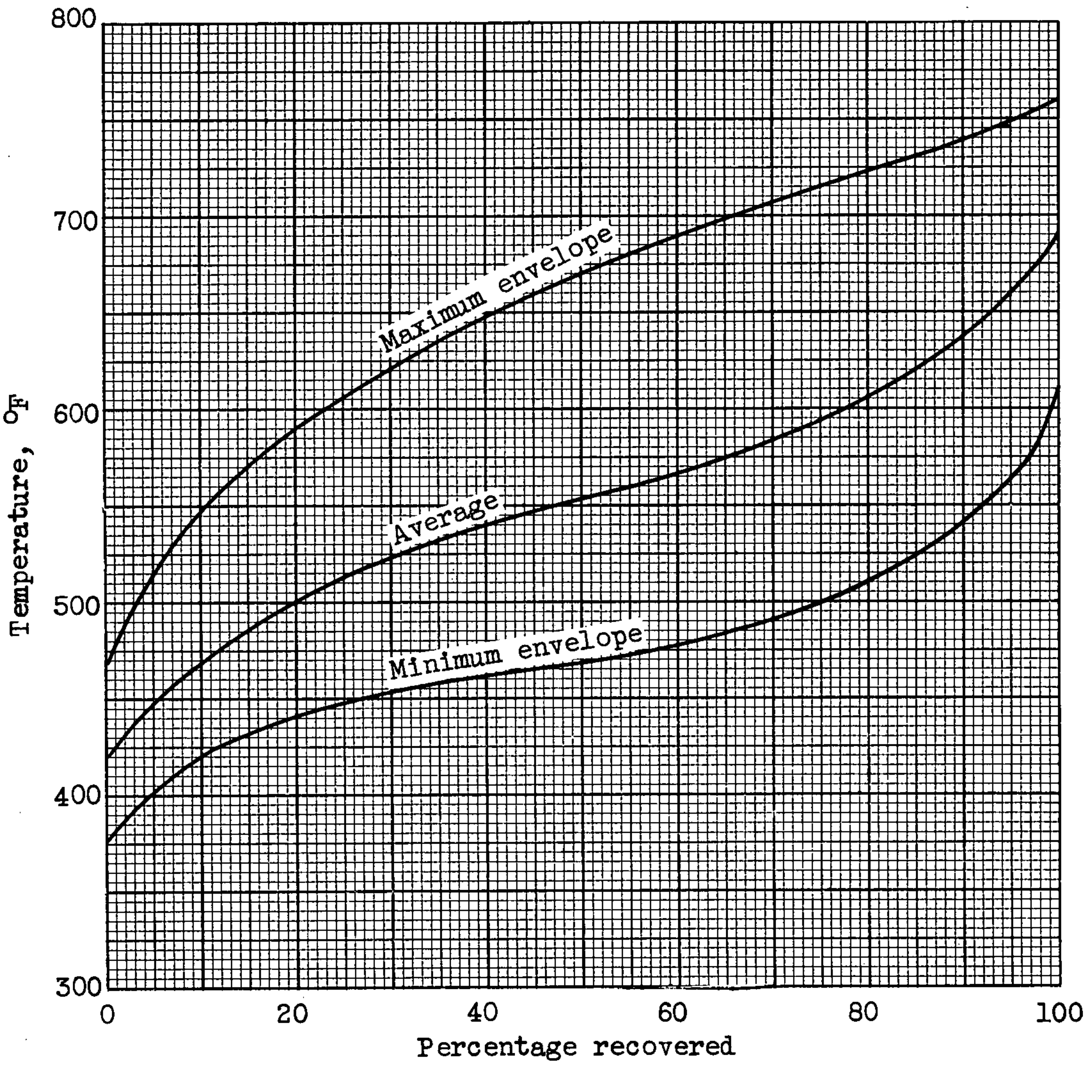
(a) Grade 1 fuel oil.

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



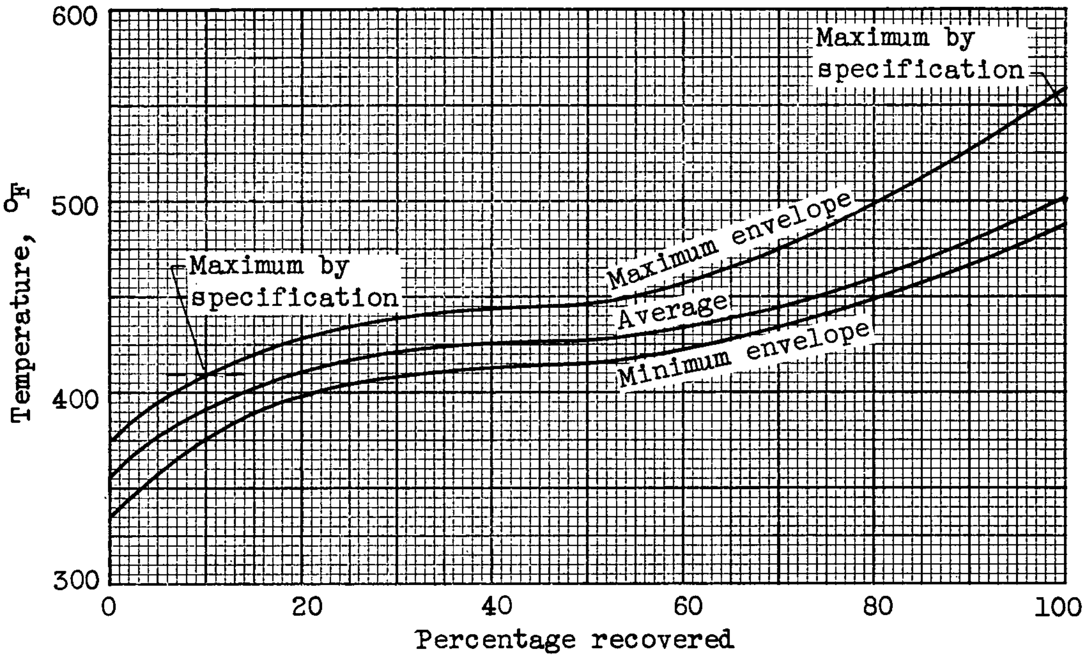
(b) Grade 2 fuel oil.

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



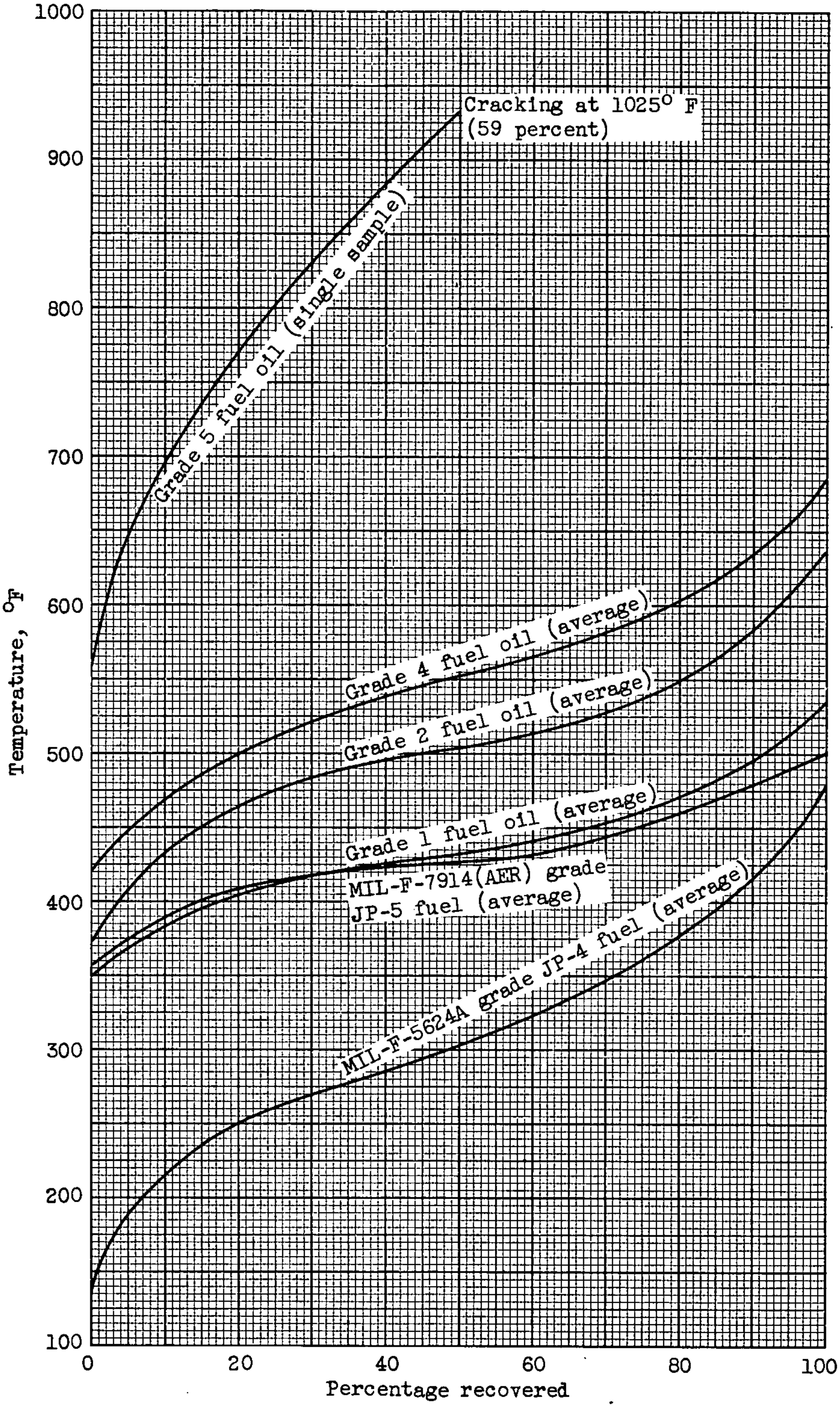
(c) Grade 4 fuel oil.

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



(d) MIL-F-7914(AER) grade JP-5 fuel.

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



(e) Comparison of several fuels.

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

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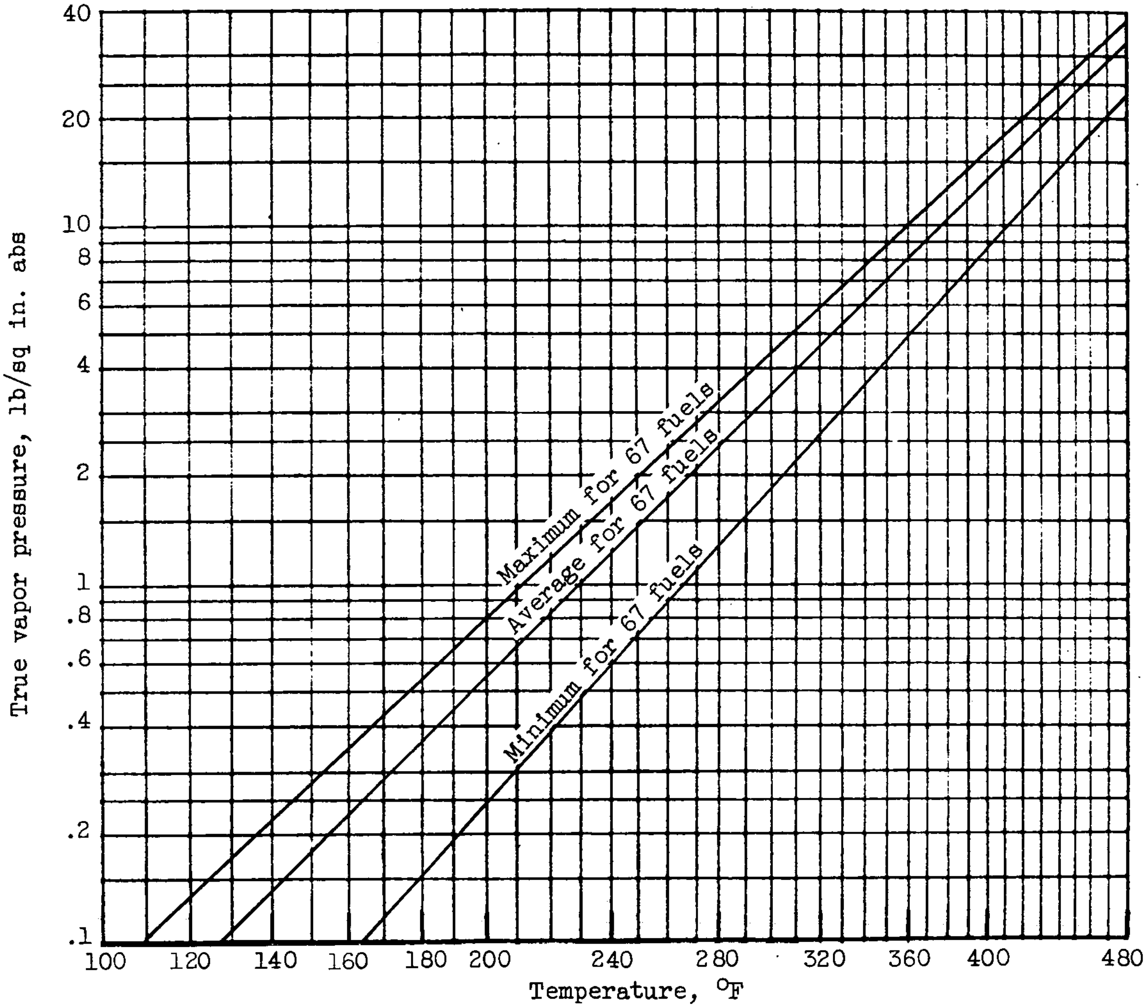
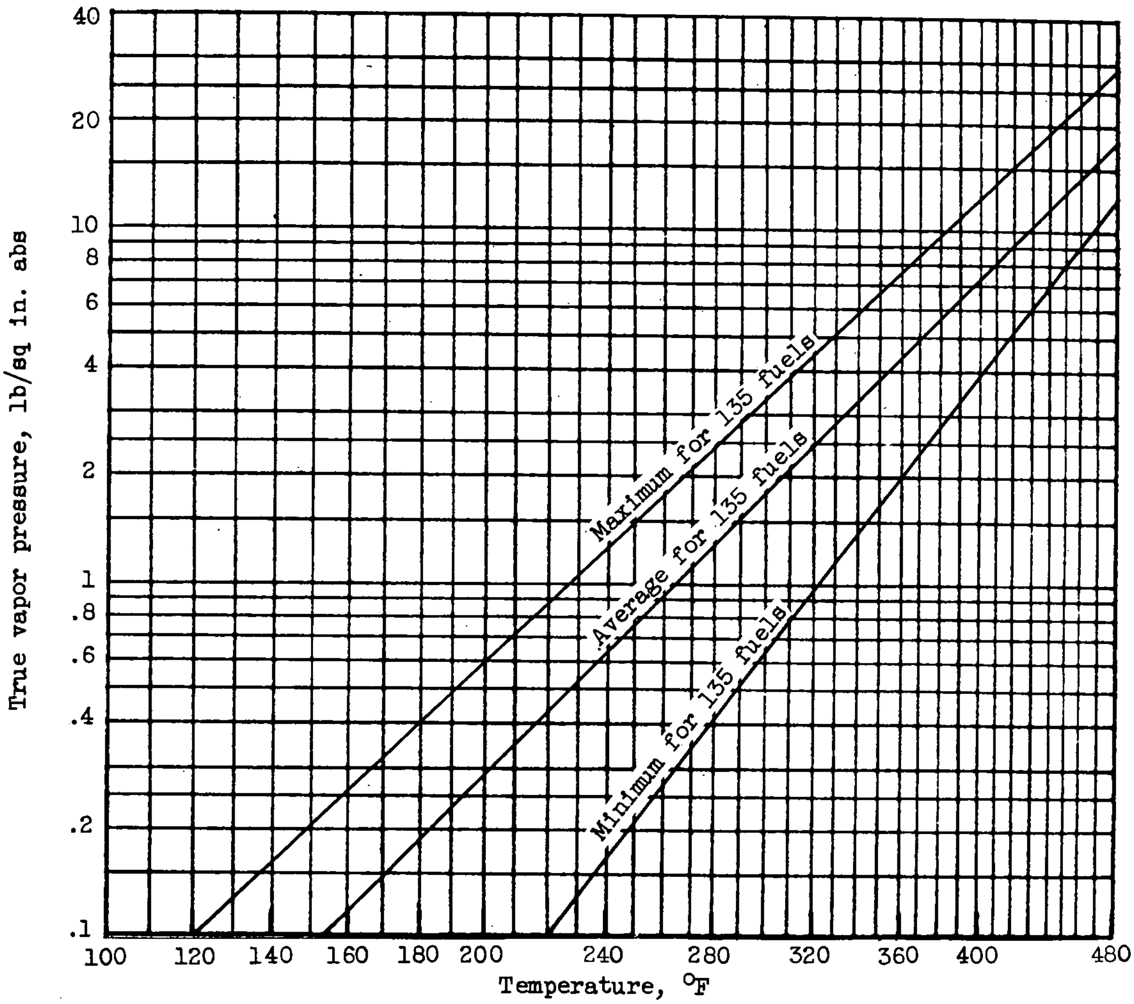


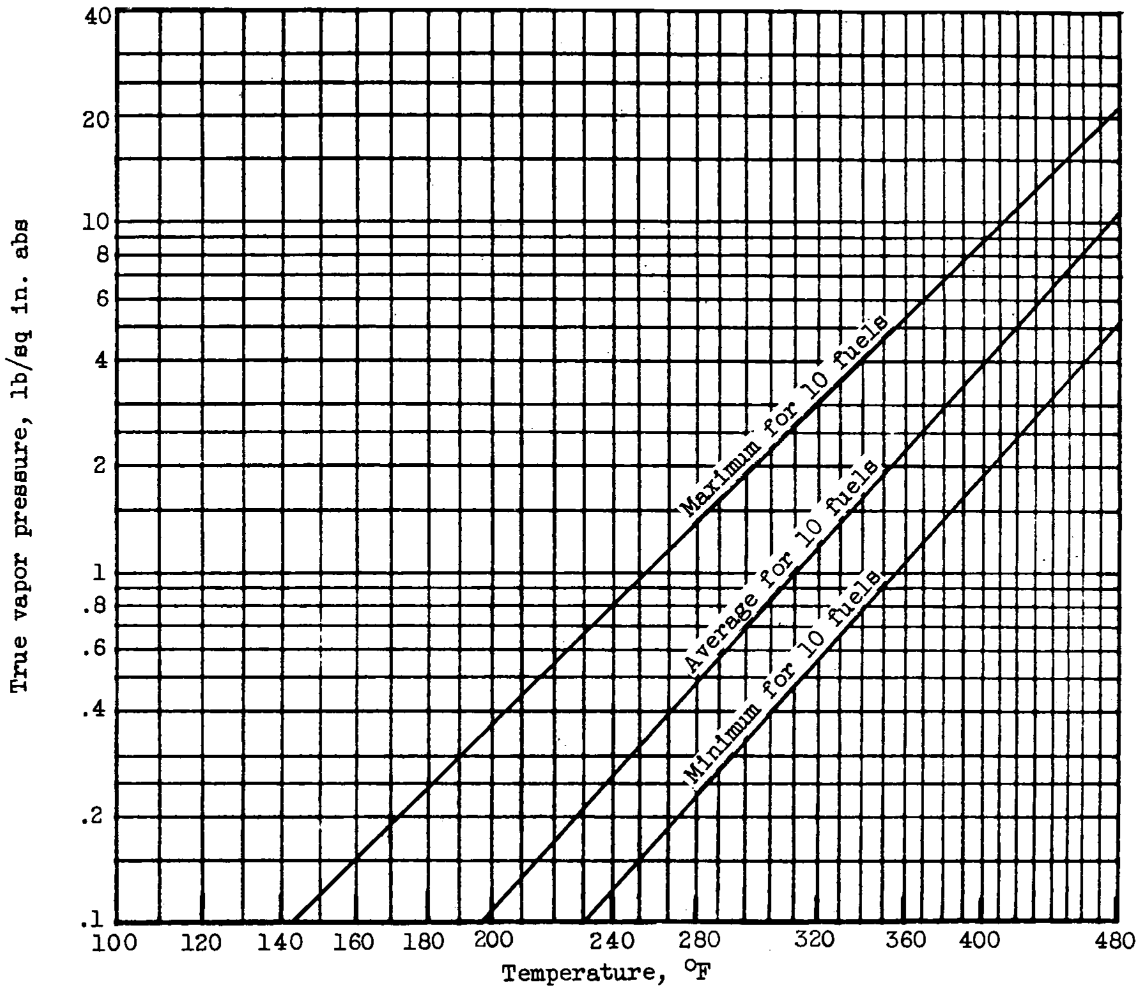
(a) Grade 1 fuel oil.

Figure 5. - Variation of vapor pressure with temperature. Calculated data.



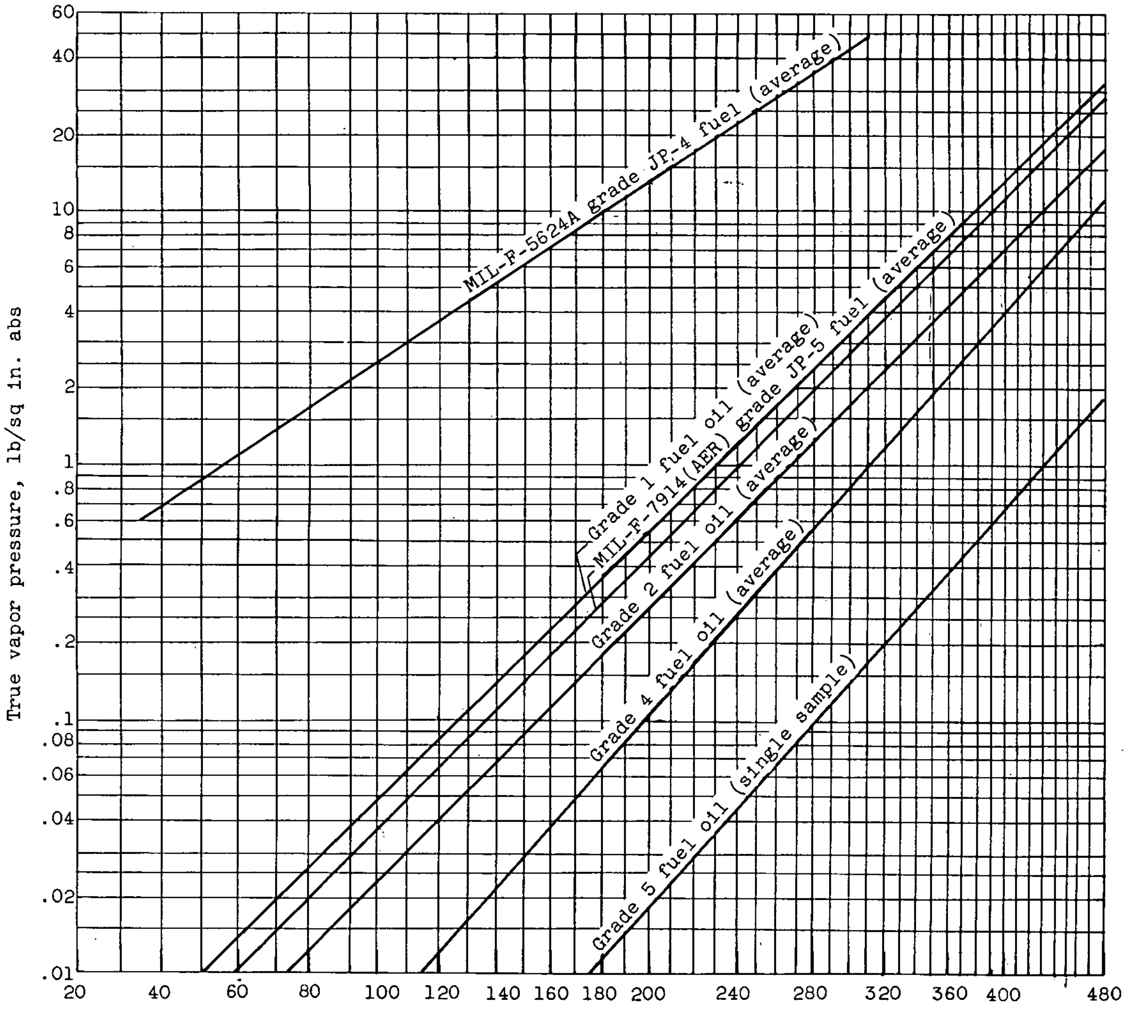
(b) Grade 2 fuel oil.

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



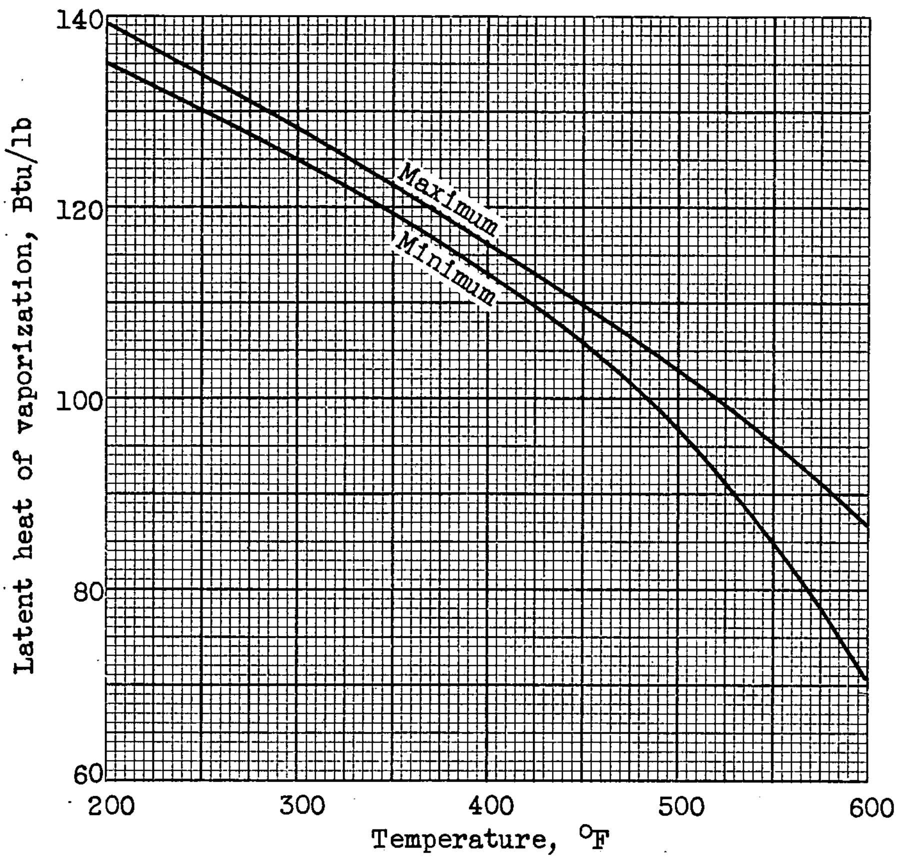
(c) Grade 4 fuel oil.

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



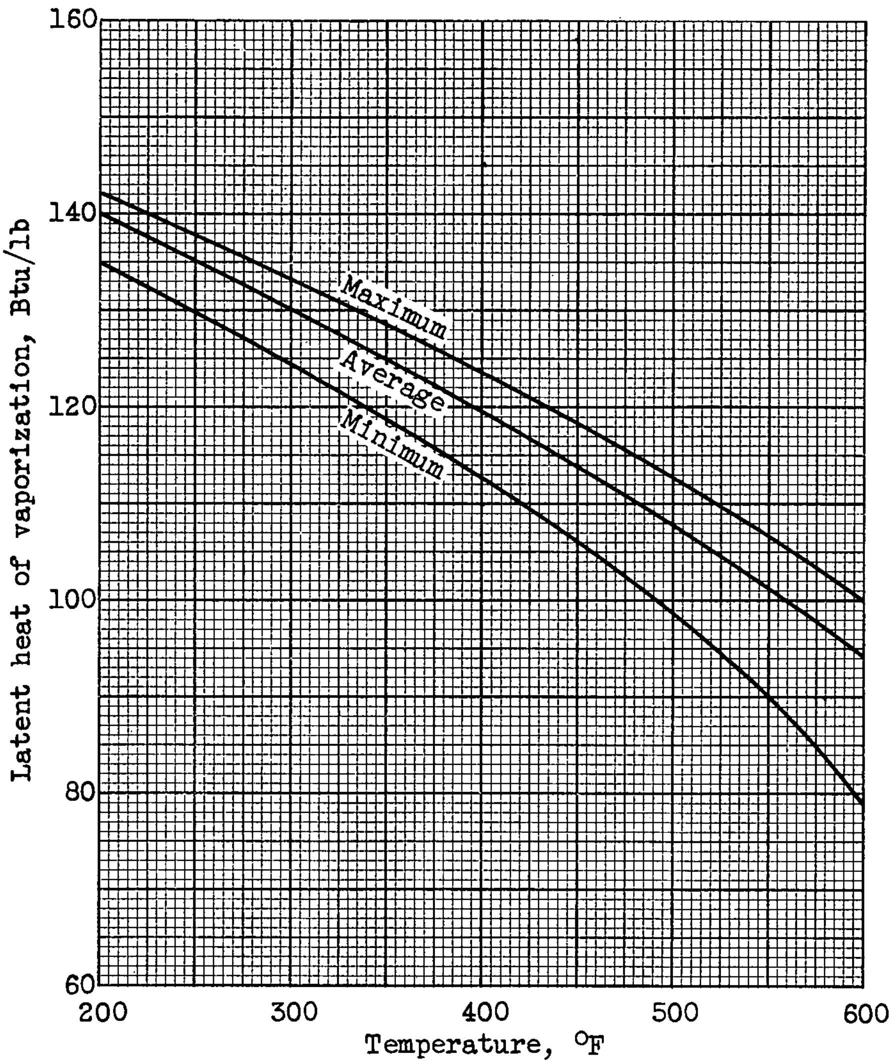
(d) Comparison of several fuels.

Figure 5. - Concluded. Variation of vapor pressure with temperature. Calculated data.



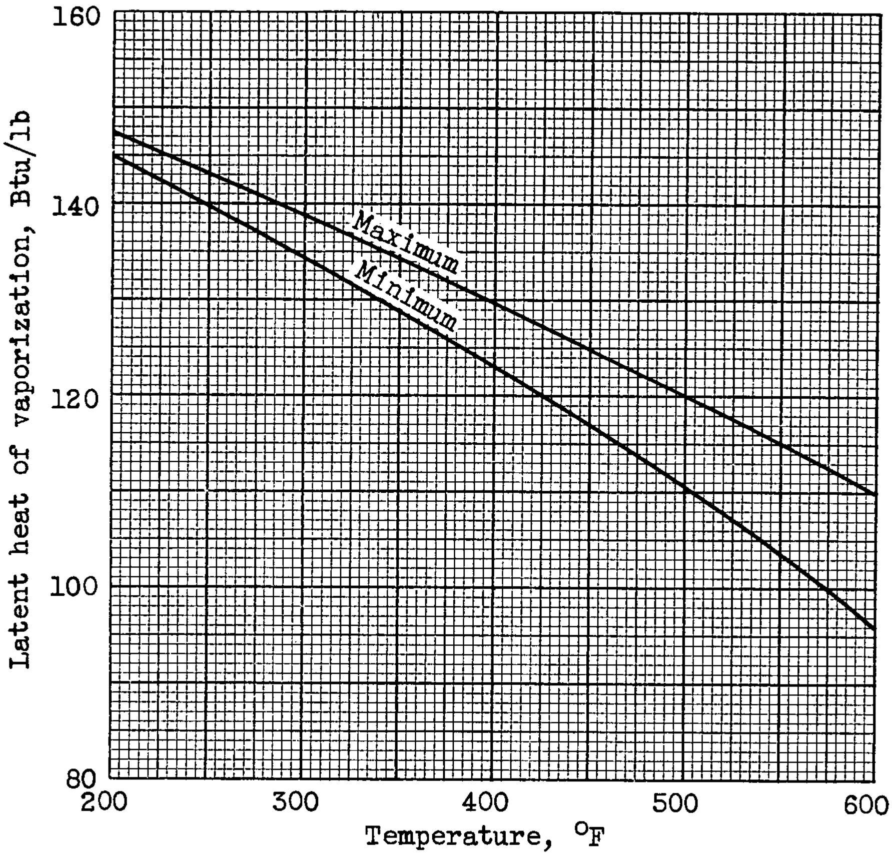
(a) Grade 1 fuel oil.

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



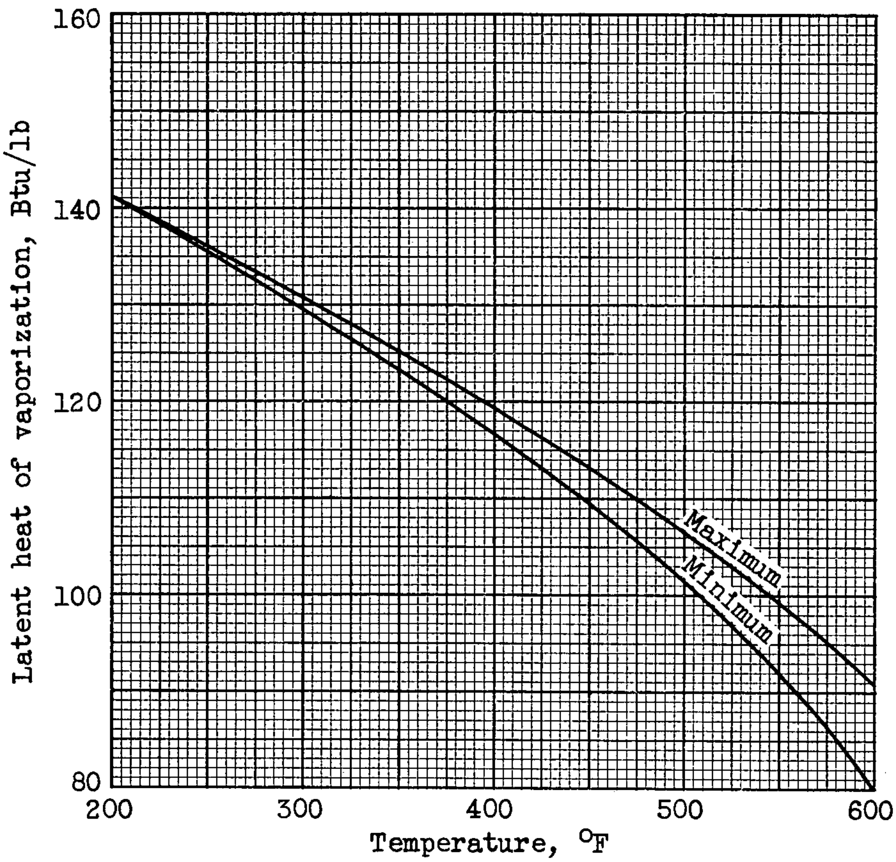
(b) Grade 2 fuel oil.

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



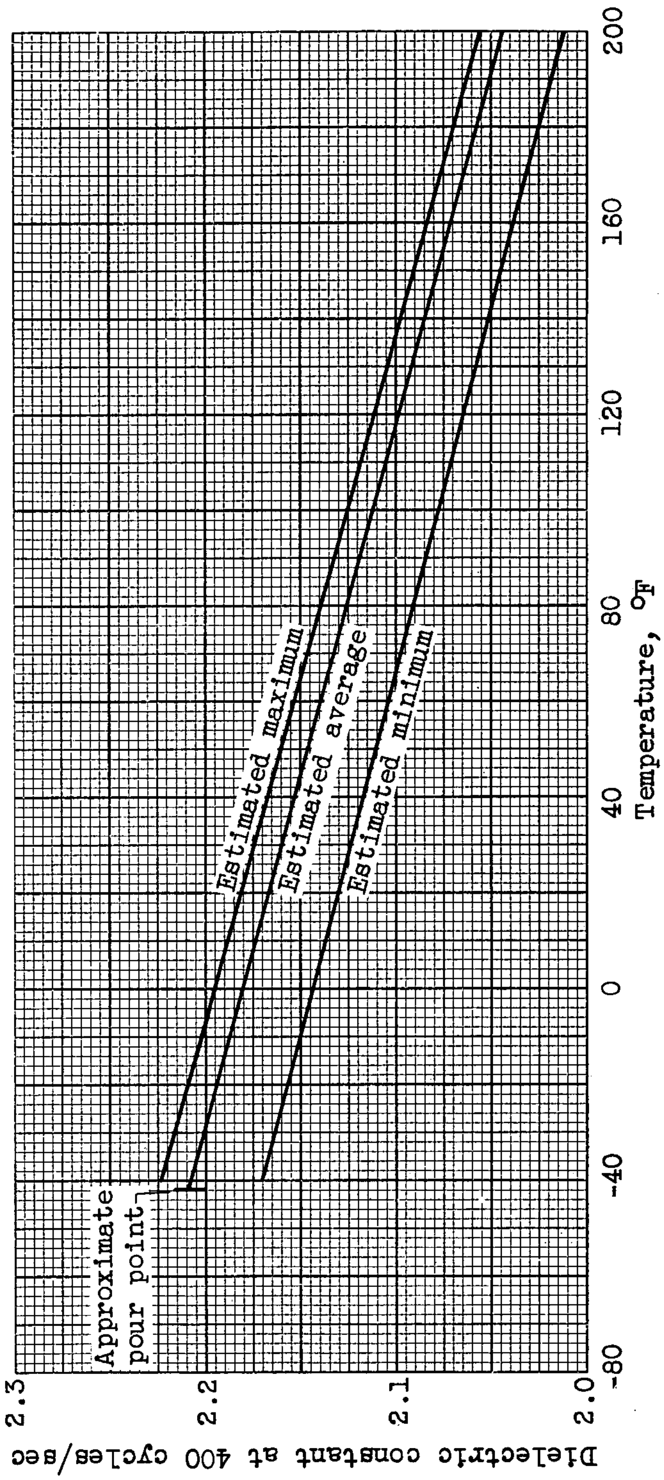
(c) Grade 4 fuel oil.

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



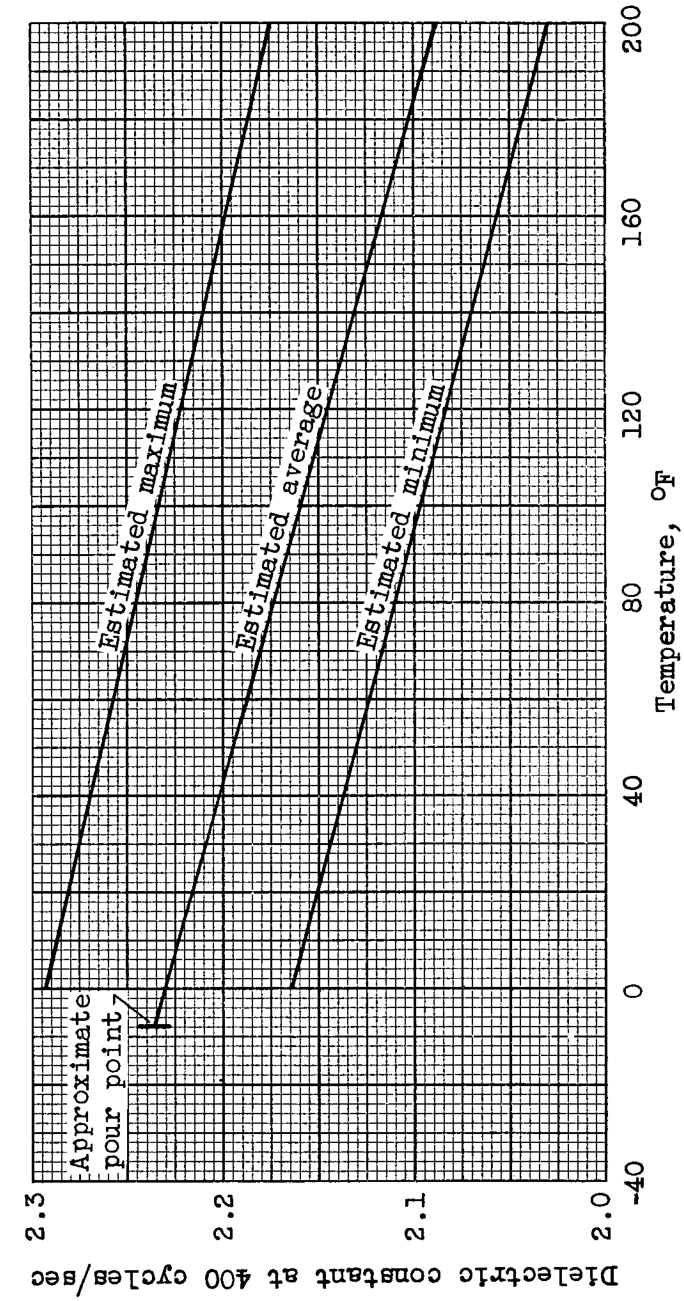
(d) MIL-F-7914(AER) grade JP-5 fuel.

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



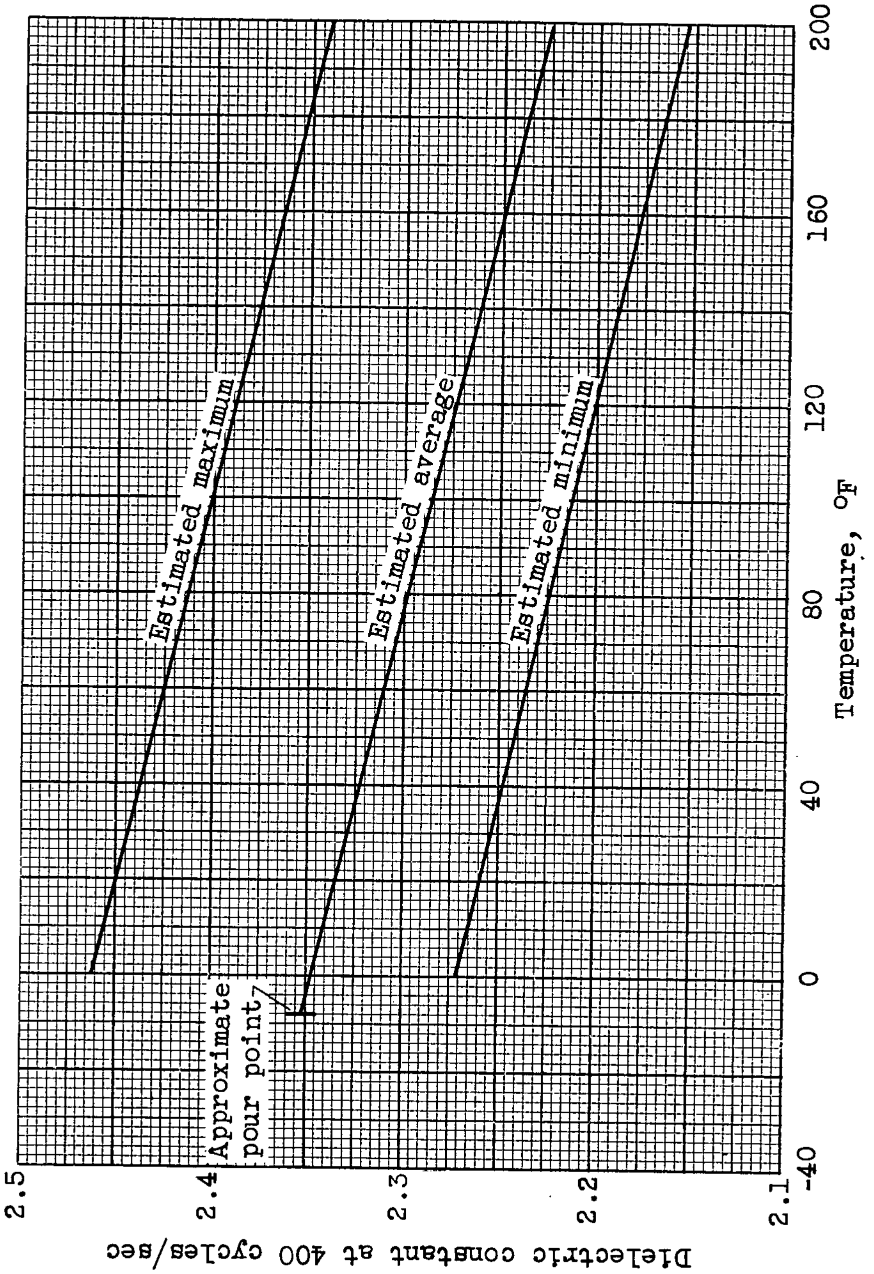
(a) Grade 1 fuel oil.

Figure 7. - Variation of dielectric constant with temperature.



(b) Grade 2 fuel oil.

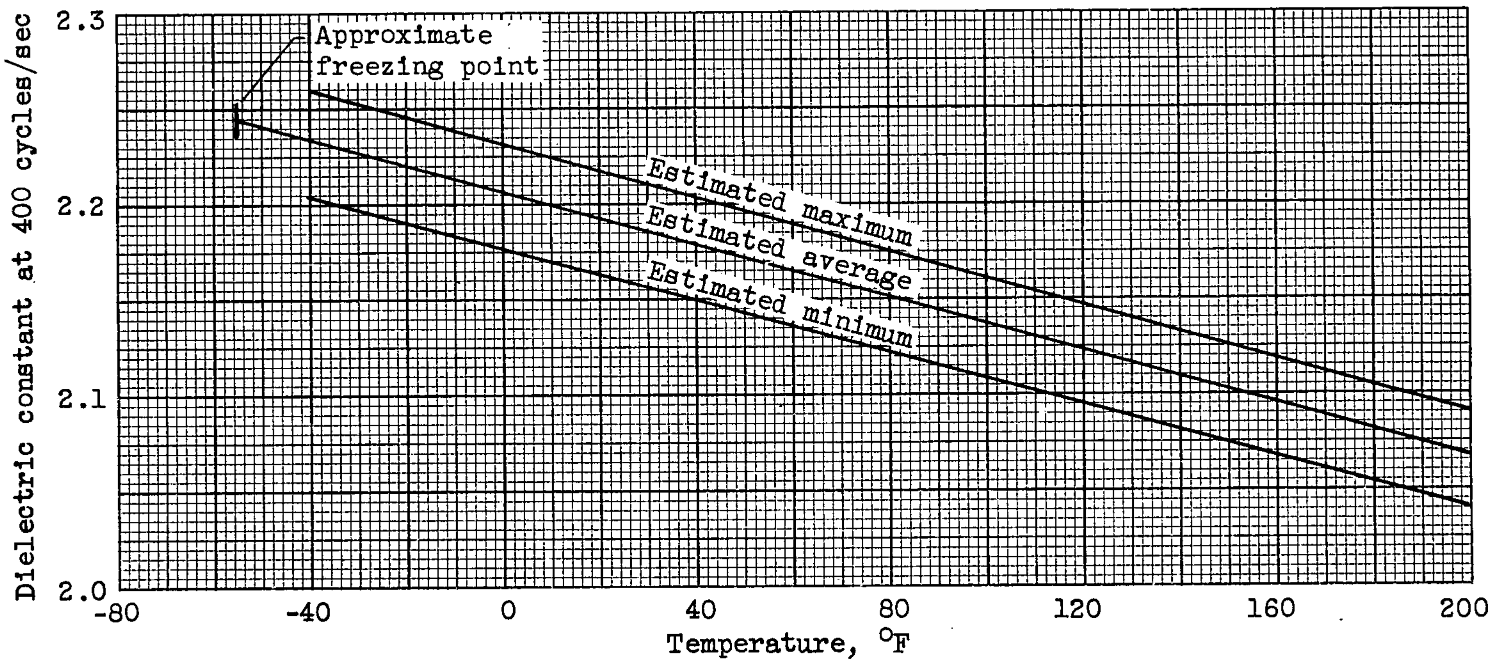
Figure 7. - Continued. Variation of dielectric constant with temperature.



(c) Grade 4 fuel oil.

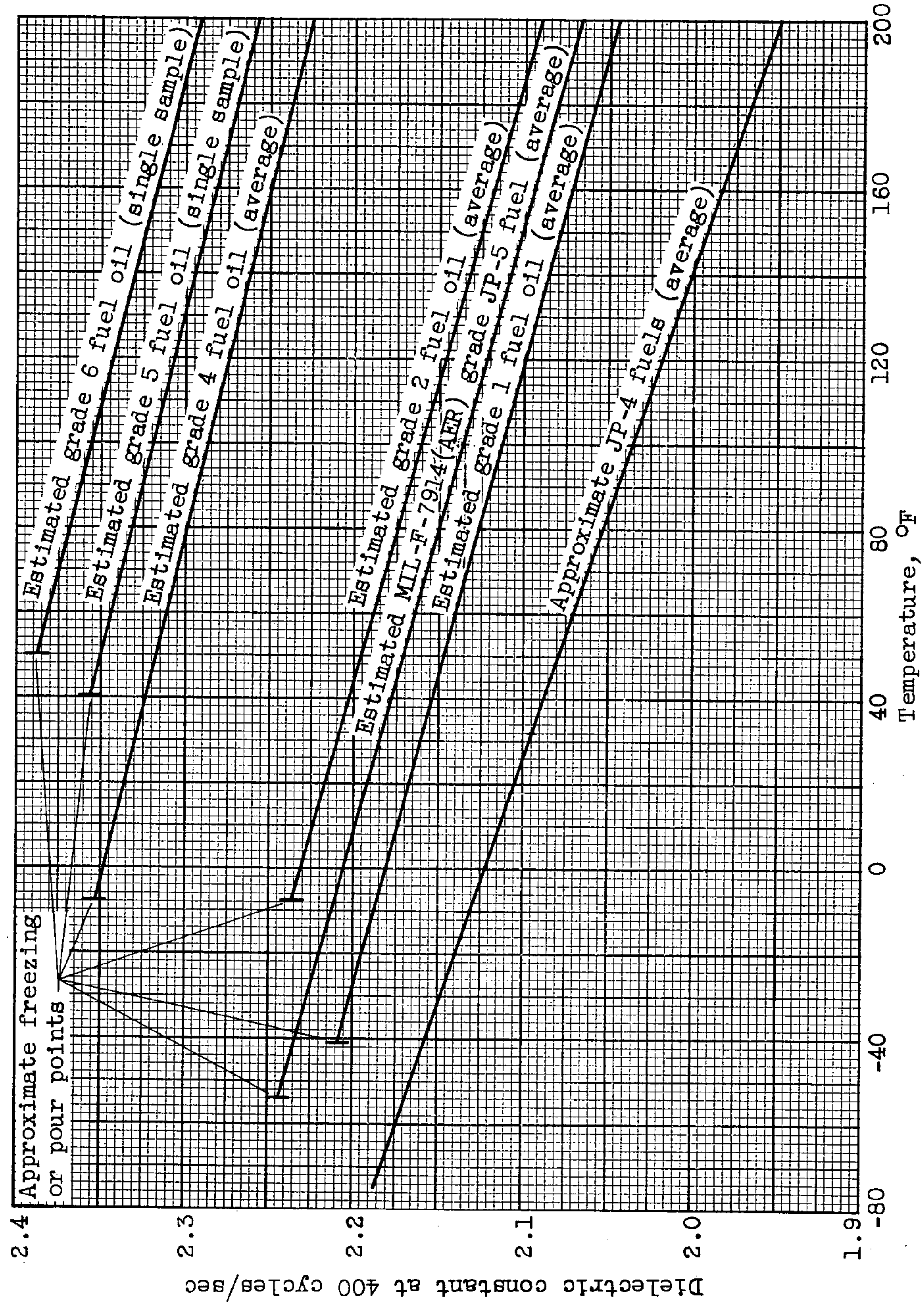
Figure 7. - Continued. Variation of dielectric constant with temperature.

[redacted]



(d) MIL-F-7914(AER) grade JP-5 fuel.

Figure 7. - Continued. Variation of dielectric constant with temperature.



(e) Comparison of several fuels.

Figure 7. - Concluded. Variation of dielectric constant with temperature.