AVIATION FUEL PROPERTIES

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HANDBOOK OF AVIATION FUEL PROPERTIES

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FOREWORD

The purpose of this document is to provide a convenient source of information on properties of aviation fuels for reference use. The data presented herein have been compiled by the CRC Aviation Handbook Advisory Group from the latest known sources on each particular subject. Where conflicts arose owing to discrepancies in source material, they have been resolved by decision of the Group. The references cited document the source of information, even though in many cases those references are no longer in print.

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SECTION 1

DESCRIPTION OF FUELS

- FUEL SPECIFICATIONS
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1.1 SPECIFICATIONS

Aviation fuels and fuels for air-breathing missile propulsion are characterized and controlled by specifications. In the case of fuels for aircraft, the specifications are based more upon usage requirements and less upon the detailed chemistry of the fuels. The one composition requirement common to all aviation fuels is that they shall consist completely of hydrocarbon compounds except for specified additives. There are, however, some limits on particular hydrocarbons such as aromatics and olefins primarily due to performance factors. The system demands are still the primary determinants of the requirements and include such items as fluidity, combustion properties, corrosion protection, fuel stability, contaminant limits, additives for various purposes, and other miscellaneous properties. The missile propulsion fuels, unlike the aviation fuels, are primarily controlled by specific chemical composition. In this case, the chemical composition has been tailored to satisfy the system usage demands. Additives are also specified to meet certain requirements. Where applicable, NATO symbols have been included.

1.1.1 Aviation Gasoline (Av Gas)

Specifications for aircraft reciprocating-engine fuels are found in Table 1. There are three grades of fuel—80, 100, and 100LL. In this case, there is no requirement for the and 115/145. The commercial specification as described by ASTM D 910 also covers three grades of fuel—80, 100, and 100LL. In this case, there is no requirement for the 115/145 military fuel, but a Grade 100 of higher lead content is permitted. The low lead, 100LL, is identical in lead content to the 100/130 military grade. The grades are determined primarily by octane or performance number.

1.1.2 Turbine Fuels

Turbine fuels are in extensive use by both military and commercial aircraft. Although similar, military and commercial fuel differences warrant separate specifications.

1.1.2.1 Commercial Turbine Fuels

The specifications for these fuels are found in Table 2. There are two basic fuels included: a kerosene type and a wide-cut (kerosene and naphtha mixture) type. ASTM Jet A fuel is used exclusively in the United States with Jet A-1 being the primary fuel outside the United States. The International Air Transport Association (IATA) guideline specifications are basically the same as ASTM Jet A-1 and Jet B

1.1.2.2 U.S. Military Turbine Fuels

There are several turbine fuels in use by the military services. This is due to the different operational needs of the services, or to specific applications requiring special fuels. The primary fuel for the U.S. Air Force and Army is the wide-cut JP-4 fuel that meets operational requirements and reflects a broad availibility. The U.S. Navy, particularly for carrier safety, relies on JP-5, a high flash-point fuel. JP-7 and Thermally Stable fuels (TS) are used by the Air Force for specific applications in which high thermal stability is required. JP-8 is a kerosene-based fuel very similar to the commercial Jet A-1, and is under consideration by the Air Force as a replacement to JP-4. The specifications for JP-4, JP-5, and JP-8 are found in Table 3. Those for JP-7 and thermally stable kerosene are shown in Table 4.

1.1.3 Missile Fuels

Missile fuels included in this Handbook consist of pure hydrocarbons or mixtures of a few hydrocarbons for use in air-breathing missile engines. These include RJ-4, RJ-5, RJ-6, JP-9, and JP-10.

1.1.3.1 Ramjet Missile Fuels

RJ-4, RJ-5, and RJ-6 are fuels originally developed for ramjet-powered missiles. RJ-4 has been selected by the Navy for the Sea-Launched Turbine-Powered Cruise Missile. RJ-5, a high-density fuel, was originally specified by the Air Force for the Advanced Strategic Air-Launched Missile (ASALM). Due to unsatisfactory low-temperature properties, RJ-5 has been replaced by RJ-6 for use in the ASALM. Specifications for these fuels are found in Table 5.

1.1.3.2 Turbine Missile Fuels

JP-9 was an Air Force fuel which was specified for use in the Air-Launched Cruise Missile (ALCM). JP-10 is a fuel meeting the −65°F Air Force operational requirement, and has replaced JP-9 as the operational fuel for the ALCM. Table 6 outlines the specification requirements for JP-9 and JP-10.

TABLE 1
U.S. MILITARY AND COMMERCIAL AVIATION GASOLINE SPECIFICATIONS

	Issuing Agency:		U.S. Navy			
	Specification:		MIL-G-5572F-Amd. 1 and ASTM D 910 (3)			
	Revision Date:		13 March 1979	1981		
	Grade Designation:		80/87	100/130	115/145	
	Fuel Type:		Av Gasoline	Av Gasoline	Av Gasoline	ASTM
	Color:		Red	Blue (3)	Purple	Test Method
COMPOSITION	Sulfur (wt %)	MAX.	0.05	0.05	0.05	D 1266 or D 2622
	Aromatics (vol %)	MIN.		5.0	5.0	D 936, D 131 or D 2267
VOLATILITY	Distillation					
	Temp. 10% Rec (°C)	MIN. at	75	75	75	D 86
	40% Rec (°C)	MAX. at	75	75	75	
	50% Rec (°C)	MIN. at	105	105	105	
	90% Rec (°C)	MIN. at	135	135	135	
	End Point (°C)	MAX. at	170	170	170	
	Sum. of 10% and 50% Evaporated Temp.	MIN.	135	135	135	
	Residue (vol %)	MAX.	1.5	1.5	1.5	
	Distillation Loss (vol %)	MAX.	1.5	1.5	1.5	
	Gravity, °API		(1)	(1)	(1)	D 287
	Reid Vapor Pressure at 37.8°C, psi (kPa)		5.5-7.0 (38.5-49.0)	5.5-7.0 (38.5-49.0)	5.5-7.0 (38.5-49.0)	D 323 or D 2551
FLUIDITY	Freezing Point, °C	MAX.	−60	−60	−60	D 2386
COMBUSTION	Net Heat of Combustion MJ/kg (Btu/lb)	MIN.	43.5(18,700)	43.5(18,700)	44.0(18,900)	D 240 or D 2382
	or					
	Aniline-Gravity Product	MIN.	7,500	7,500	9,800	D 611 or D 287
	Knock Rating, Lean Mixture Aviation Rating	MIN.	80	100	115	D 2700 (2)
	Knock Rating, Rich Mixture Supercharge Rating	MIN.	87	130	145	D 909
CORROSION	Copper Strip Corrosion (2 hrs at 100°C)	MAX.	1	1	1	D 130
STABILITY	Potential Gum, 16 hr Aging (mg/100 ml)	MAX.	6.0	6.0	6.0	D 873
	Precipitate (mg/100 ml)	MAX.	2.0	2.0	2.0	D 873
CONTAMINANTS	Existent Gum (mg/100 ml)	MAX.	3.0	3.0	3.0	D 381
	Water Reaction					
	Interface Rating	MAX.	2	2	2	D 1094
	Vol. Change (ml)	MAX.	2	2	2	D 1094
ADDITIVES	Tetraethyllead Content, g/liter	MAX.	0.14	0.56	1.28	D 3341, D 2599, or D 2547
	Dye Content					
	Blue Dye (mg/liter)		0.131 MAX.	0.50 to 1.51	0.713 to 1 24	D 2392
	Red Dye (mg/liter)		1.83 to 2.29		0.50 to 0.864	
	Yellow Dye (mg/liter)		–	1.4	–	
OTHER	*NATO Code No.		F-12	F-18	F-22	

NOTES: (1) To be reported, not limited.
(2) Knock values obtained by ASTM Method D 2700 are Motor Octane Numbers. To convert to Aviation Ratings, use Table 2 of ASTM D 910.
(3) Commercial specification ASTM D 910 covers three grades of aviation gasoline: 80,100, and 100 LL. All three grades are essentially identical to their respective military specification, except for freezing point which is -58°C MAX. for the commercial grades instead of the −60°C MAX. requirement in the military grades. The commercial specification for the lead content in 100 LL is the same as that for the military specification 100/130, namely 0.56 g/liter MAX. However, the commercial grade 100 is colored green and has a lead content of 1.12 g/liter MAX.

TABLE 2
COMMERCIAL TURBINE FUEL SPECIFICATIONS

	Issuing Agency:		ASTM		IATA		Test Method	
	Specification:		D 1655		ADD 76-1 (1)			
	Revision Date:		1981	1981	Dec 81			
	Grade Designation:		Jet A (2)	Jet B				
	Fuel Type:		Kerosene	Wide-Cut	Kerosene	Wide-Cut	ASTM	IP
COMPOSITION	Acidity, Total (mg KOH/g)	MAX.	0.1	—	0.1	0.1	D 974 or D 3242	273
	Aromatics (vol %)	MAX.	20 (3)	20 (3)	20 (3)	20 (3)	D 1319	156
	Olefins (vol %)	MAX.	—	—	—	—	D 1319	
	Sulfur, Mercaptan (wt %)	MAX.	0.003	0.003	0.003	0.003	D 1323	104
	or Doctor Test, N = Negative		N	N	N	N	D 484	30
	Sulfur, Total (wt %)	MAX.	0.3	0.3	0.3	0.3	D 1266 D 1552 or D 2622	107
VOLATILITY	Distillation							
	Temp. 10% Rec (°C)	MAX.	204.4		204		D 86	123
	20% Rec (°C)	MAX.		143.3		143		
	50% Rec (°C)	MAX.	Rpt	187.8	Rpt	188		
	90% Rec (°C)	MAX.	Rpt	243.3	Rpt	243		
	Final BP (°C)	MAX.	300		300			
	Residue (vol %)	MAX.	1.5	1.5	1.5	1.5		
	Loss (vol %)	MAX.	1.5	1.5	1.5	1.5		
	Flash Point (°C)	MIN.	37.8		38		D 56	170/34
	Gravity, °API (60°F)		37-51	45-57	37-51	45-57	D 287	
	Relative Density (15.5°C)		0.7753-0.8398	0.7507-0.8017	0.7753-0.8398	0.7507-0.8017	D 1298	160
	Vapor Pressure, 38°C (kPa)	MAX.		21		21	D 323	169
FLUIDITY	Freezing Point (°C)	MAX.	−40 (2)	−50	−47	−50	D 2386	16
	Viscosity @ −20°C (cSt)	MAX.	8	—	8	—	D 445	71
COMBUSTION	Net Heat of Comb. (MJ/kg)	MIN.	42.8	42.8	42.8	42.8	D 2382 or D 1405 (8)	
	Luminometer No.	MIN.	45	45	45	45	D 1740	
	or Smoke Point	MIN.	25	25	25	25	D 1322	
	or Naphthalenes (vol %)	MAX.	3 (4)	3 (4)	3 (5)	3 (5)	D 1840	
CORROSION	Copper Strip (2 hrs @ 100°C)	MAX.	1	1	1	1	D 130	154
STABILITY	JFTOT ΔP (mm Hg)	MAX.	25	25	25	25	D 3241 (9) or	
	JFTOT Tube Color Code	MAX.	<3	<3	<3	<3	D 1660 (9)	197
CONTAMINANTS	Existent Gum (mg/100 ml)	MAX.	7	7	7	7	D 381	131
	Particulates (mg/l)	MAX.	—	—	—	—	D 2276	216
	Water Reaction Interface	MAX.	1b	1b	1b	1b	D 1094	289
	Water Reaction Separation	MAX.	2	2	2	2	D 1094	289
ADDITIVES	Anti-Icing		Agreement	Agreement				
	Antioxidant		Option	Option	Option	Option		
	Corrosion Inhibitor		Agreement	Agreement	Agreement (7)			
	Metal Deactivator		Option	Option	Option	Option		
	Antistatic		Agreement	Agreement	Agreement	Agreement		
OTHER	Electrical Conductivity (pS/m) (6)		50-450	50-450	50-450	50-300	D 2624 or D 3114	274

NOTES: (1) This is not a specification, but Guidance Material.
(2) Jet A-1 is a similar kerosene-type, but Freezing Point is −47°C MAX.
(3) Fuels containing up to 25 vol % aromatics may be shipped if supplier notifies user.
(4) Plus Smoke Point = 20 MIN, but 18 MIN may be shipped if supplier notifies user.
(5) Plus Smoke Point = 20 MIN, but 18 MIN may be shipped if supplier notifies user.
(6) At time, place, and temperature of delivery into aircraft if antistatic additive is used.
(7) Approved corrosion inhibitor to improve fuel lubricity may be added at user's option.
(8) D 2382 is the Referee Method.
(9) Test at 260°C tube temperature. Repeat test at 245°C that meets limits considered to pass; D 1660 is alternative at 149°C preheat 204°C filter temperatures with maximum test limits of 76.2 mm Hg filter ΔP and Code 3 tube rating.

TABLE 3
U.S. MILITARY SPECIFICATIONS FOR TURBINE FUELS

	Issuing Agency:		USAF		USAF	
	Specification:		MIL-T-5624L-Amd. 1		MIL-T-83133A-Amd. 1	
	Revision Date:		16 June 1980		4 April 1980	
	Grade Designation:		JP-4	JP-5	JP-8	Test Method
	Fuel Type:		Wide-Cut	Kerosene	Kerosene	ASTM FTMS 791
COMPOSITION	Acidity, Total (mg KOH/g)	MAX.	0.015	0.015	0.015	D 3242
	Aromatics (vol %)	MAX.	25.0	25.0	25.0	D 1319
	Olefins (vol %)	MAX.	5.0	5.0	5.0	D 1319
	Sulfur, Mercaptan (wt %) (1)	MAX.	0.001	0.001	0.001	D 1323
	Sulfur, Total (wt %)	MAX.	0.4	0.4	0.3	D 1266/D 2887/ D 2622
	Color, Seybolt	MAX.	Report	Report	Report	D 156
VOLATILITY	Distillation					
	Temp. Init. BP (°C)	MAX.	Report	Report	Report	D 86/D 2887
(D 2887 Limits in parentheses)	Temp. 10% Rec (°C)	MAX.	Report	205 (185)	205 (186)	
	20% Rec (°C)	MAX.	145 (130)	Report	Report	
	50% Rec (°C)	MAX.	190 (185)	Report	Report	
	90% Rec (°C)	MAX.	245 (250)	Report	Report	
	Final BP (°C)	MAX.	270 (320)	290 (320)	300 (330)	
	Residue (vol %) (for D 86)	MAX.	1.5		1.5	
	Loss (vol %) (for D 86)	MAX.	1.5		1.5	
	Explosiveness, Percent	MAX.		50		1151 FED STD 791
	Flash Point (°C)	MAX.		60	38	D 93 (2)
	Gravity, °API (15°C)	MAX.	45-57	36-48	37-51	D 1298
	Density, 15°C (kg/m^3)	MAX.	751-802	788-845	775-840	D 1298
	Vapor Pressure (37.8°C), kPa (psi)		14-21 (2.0-3.0)	--		D 323/D 2551
FLUIDITY	Freezing Point, °C (F)	MAX.	−58 (−72)	−46 (−51)	−50 (−58)	D 2386
	Viscosity @ −20°C (cSt)	MAX.	–	8.5	8.0	D 445
COMBUSTION	Aniline-Gravity Product	MIN.	5250	4500		D 1405
	or Net Heat of Comb., MJ/kg (Btu/lb)	MIN.	42.8 (18,400)	42.6 (18,300)	42.8 (18,400)	D 2382/D 3338/ D 240 (3)
	Smoke Point	MIN.	20.0	19.0	19.0	D 1322
	or Hydrogen Content (wt %)	MIN.	13.6	13.5	13.5	D 1018/D 3343/ D 3701 (4)
CORROSION	Copper Strip (2 hrs @ 100°C)	MAX.	1b	1b	1b	D 130
STABILITY	JFTOT ΔP (mm Hg)	MAX.	25	25	25	D 3241 (9)
	JFTOT Tube Color Code	MAX.	< 3	< 3	<3	
CONTAMINANTS	Existent Gum (mg/100 ml)	MAX.	7	7	7	D 381
	Particulates (mg/liter)	MAX.	1	1	1	D 2276 (5)
	Water Reaction Interface	MAX.	1b	1b	1b	D 1094
	Water Separation Index Modified	MIN.	70 (6)	85 (8)	70 (6)	D 2550
	Filtration Time (minutes)	MAX.	15	–		(5)
ADDITIVES	Anti-Icing (vol %)		0.10-0.15	0.10-0.15	0.10-0.15	5330, 5340, 3527 FED STD 791
	Antioxidant		Required (7)	Required (7)	Option	
	Corrosion Inhibitor		Required	Required	Required	
	Metal Deactivator		Option	Option	Option	
	Antistatic		Required		Required	
OTHER	Conductivity (pS/m)		200-600		200-600	D 2624/D 3114
	Service		All	Navy	USAF	
	NATO Code No.		F-40	F-44	F-34; F-35 (10)	

NOTES: (1) The mercaptan sulfur determination may be waived if fuel "Doctor Sweet."
(2) D 56 also applicable to JP-8.
(3) D 3338 only allowed for JP-4 and JP-8.
(4) D 3343 only allowed for JP-4 and JP-8.
(5) Minimum one-gallon sample. Filtration time in accordance with Appendix A of MIL-T-5624L also used for D 2276 particulate.
(6) With all additives except electrical conductivity additive.
(7) If hydrogen treated blend stocks used - Optional if no hydrotreating used.
(8) With all additives except the corrosion inhibitor additive or 70 with all additives present.
(9) Test at 260°C tube temperature.
(10) Same as JP-8 without additives.

TABLE 4
U.S. MILITARY SPECIFICATIONS FOR TURBINE FUELS

	Issuing Agency:		USAF		
	Specification:		MIL-T-38219A - Amd. 2	MIL-T-25524C	
	Revision Date:		26 January 1981	30 January 1981	
	Grade Designation:		JP-7	Th. Stable (TS)	Test Method
	Fuel Type:		Low Volatility	Kerosene	ASTM
COMPOSITION	Acidity, Total (mg KOH/g)	MAX.		.015	D 3242
	Aromatics (vol %)	MAX.	5	5.0 - 20.0	D 1319
	Olefins (vol %)	MAX.		3	D 1319
	Sulfur, Mercaptan (wt %)	MAX.	0.001	0.001	D 3227
	or Doctor Test, N = Negative		N	N	D 484
	Sulfur, Total (wt %)	MAX.	0.1	0.3	D 1266, D 2622 or D 3120
VOLATILITY	Distillation				
	Temp. Init. BP (°C)		182 MIN.	157 (105) MIN.	D 86 or D 2887
(D 2887 limits in parentheses)	10% Rec (°C)		196 MIN.	193 (174) MAX.	
	20% Rec (°C)		206 MIN.		
	50% Rec (°C)		Report	204 (207) MAX.	
	90% Rec (°C)		260 MAX.	238 (250) MAX.	
	Final BP (°C)		288 MAX.	260 (288) MAX.	
	Residue (vol %)		1.5 MAX.	1.5 MAX	D 86
	Loss (vol %)		1.5 MAX.	1.5 MAX.	D 86
	Flash Point (°C)		60 MIN.	43 MIN.	D 56 or D 93
	Gravity, °API (15°C)		44 - 50	46 - 53	D 1298
	Density, 15°C (kg/m^3)		779 - 806	767 - 797	D 1298
	Vapor Pressure @ 149° (kPa)	MAX.	20.7 (1)		
	Vapor Pressure @ 260° (kPa)	MAX.	331 (1)		
FLUIDITY	Freezing Point (°C)	MAX.	−43.5	−53	D 2386
	Viscosity @ −40°C (cSt)	MAX.		12.0	D 445
	Viscosity @ −34.5°C (cSt)	MAX.	15.0		
COMBUSTION	Net Heat of Comb., MJ/kg	MIN.	43.5	42.8	D 240, D 2382 or D 3338
	Luminometer No.	MIN.	75 (2)		D 1740
	Smoke Point	MIN.		25.0	D 1322
	Hydrogen Content (wt %)	MIN.	(2)	14	D 3343
CORROSION	Copper Strip (2 hrs @ 100°C)	MAX.	1b	1b	D 130
THERMAL STABILITY	(JFTOT or Coker)				
	JFTOT TDR	MAX.	12 (3)	12 (4)	D 3241
	JFTOT (mm Hg pressure diff.)	MAX.	25 (3)	25 (4)	D 3241
	Coker, Tube deposit		<3 (5)	<3 (6)	D 1660 (TS only)
	Coker (mm Hg pressure diff.)	MAX.	76 (5)	76 (6)	D 1660 (TS only)
CONTAMINANTS	Existent Gum (mg/100 ml)	MAX.	5.0	5.0	D 381
	Particulate matter (mg/l)				D 2276
	FOB Origin Deliveries	MAX.	.3	.3	(7)
	FOB Destination Deliveries	MAX.	.5	.5	
	WSIM	MIN.	85	Report	D 2550 or D 3948
ADDITIVES	JFA-5 (mg/l)			86 to 11.4	
	Anti-Icing (vol %)		0.10 to 0.15	0.10 to 0.15	FTMS 791, 5327 or 5340
	Antioxidant		Option	Option	
	Metal Deactivator		Option	Option	
	Lubricity (ppm)		200-250		
OTHER	Thermal Precipitation Rating	MAX	B-2 (8)		

NOTES: (1) Vapor pressure test in accordance with Appendix C, MIL-T-38219A.
(2) If Luminometer No. between 70 and 75, fuel acceptable--if hydrogen content is not less than 14.4 wt % as calculated by ASTM D 3343.
(3) Test by D 3241 - Conditions as specified in MIL-T-38219A Amd. 2 and tube rating in Appendix D.
(4) Test by D 3241 - Conditions as specified in MIL-T-25524C.
(5) Research Fuel Coker - Conditions as specified in MIL-T-38219A Amd. 2.
(6) Test by D 1660 - Conditions as specified in MIL-T-25524C.
(7) Minimum sample size of 3.785 liters (1 gal.) shall be filtered.
(8) Test by Appendix B, MIL-T-38219A.

TABLE 5
U.S. MILITARY SPECIFICATIONS FOR MISSILE FUELS

	Issuing Agency:	U.S. Navy	USAF	USAF	
	Specification:	MIL-F-82522A	MIL P (Tentative)	MIL P (Tentative)	
	Revision Date:	8 Oct 71			
	Grade Designation:	RJ 4	RJ-5	RJ-6	Test Method
	Fuel Type:	T-H. Dimer	High Density	High Density	ASTM
COMPOSITION					
wt %	Exo-tetrahydrodi (cyclopentadiene)			36.0 to 42.0	(1)
	Perhydrodi (norbornadiene)		98.5 to 100	58.0 to 64.0	
	Tetrahydromethylcyclopentadiene	100			
	Other Hydrocarbons		1.5 MAX.	1.5 MAX.	
VOLATILITY	Distillation				
	Temp. Init. BP (°C)	204.4			D 86
	5% Rec (°C) MAX.	212.7			
	50% Rec (°C) MAX.	Report			
	90% Rec (°C) MAX.	Report			
	Final BP (°C) MAX.	221.1			
	Residue (vol %) MAX.	1.5			
	Loss (vol %) MAX.	1.0			
	Vapor Pressure, 150°C (kPa)			23	(2)
	Flash Point (°C)	60 - 79.4	95 MIN.	60 MIN.	D 93/D 3243
	Gravity				
	°API (15.6°C)	19.0 - 22.3			D 287
	Specific Gravity (15.6°C/15.6°C)		1.080 MIN.	1.010 - 1.050	D 1298
	Density @ 15°C (kg/m^3)	920 - 940			D 1298
FLUIDITY	Freezing point (°C)	−40 MAX.		−54 MAX.	D 2386 (3)
	Pour point (°C)		−30 MAX.		D 97
	Viscosity, centistokes at °C				D 445
	−54			400 MAX.	
	−18		400 MAX.	40 MAX.	
	−17.8	30.0 MAX.			
	37.8	4.2 MAX.			
COMBUSTION	Net Heat of Combustion				D 240
	MJ/kg (Btu/lb)	42.3 (18,200)	41.3 (17,750) MIN.	41.5 (17,850) MIN.	D 2382
	MJ/m^3 (Btu/gallon)	38,900 (139,450)	44,600 (160,000) MIN.	42,300 (152,000) MIN.	
STABILITY	Potential Gum (mg/100 ml)		6 MAX. (4)		D 873
CONTAMINANTS	Iron (parts per million)		10 MAX.	10 MAX.	(5)
	Existent gum (mg/liter)	30 MAX.	100 MAX.	100 MAX.	D 381
	Particulate matter (mg/liter)	1.0 MAX.	1.0 MAX.	1.0 MAX.	D 2276 (6)
	WSIM	85 MIN. (7)			
ADDITIVES	Antioxidant	Required			
	Anti-Icing (vol %)			0.10 to 0.15	Fed Std 791, Method 5327
OTHER	Bromine Number	1.0 MAX.			D 1159
	Color, Saybolt		+25 MIN.	+25 MIN.	D 156

NOTES: (1) Test procedure outlined in Appendix A Specification.
(2) Test procedure outlined in Appendix C Specification.
(3) For RJ-5 and RJ-6, test procedure outlined in Appendix D Specification.
(4) Use only 50 ml product.
(5) Test procedure outlined in Appendix B Specification.
(6) Use 0.45 μm membrane filter.
(7) A blend of 60% RJ-4 and 40% iso-octane (98 WSIM) shall be used.

TABLE 6
U.S. MILITARY SPECIFICATIONS FOR MISSILE FUELS

	Issuing Agency:	USAF		
	Specification:	MIL-P-87107 B, Amd. 1		
	Revision Date:	23 April 1981		
	Grade Designation:	JP-9	JP-10	
	Fuel Type:	High Density Synthetic Blend	High Density Synthetic	ASTM Standards
COMPOSITION: Chem.	Comp. (wt %)			
	Methylcyclohexane	10 - 12		(1)
	Exo-TH dicyclopentadiene	65 - 70	98.5 - 100	
	H-norbornadiene dimers	20 - 25		
	Other Hydrocarbons	1.5 MAX.	1.5 MAX.	
VOLATILITY	Flash Point (°C)	21 MIN.	55 MIN.	D 93
	Density, kg/m³ at 15°C or	935 - 955	935 - 943	D 1298
	Gravity, °API	16.8 - 20.0	18.5 - 20.0	D 1298
FLUIDITY	Freezing Point (°C)	−54 MAX.	−79 MAX.	(2)
	Viscosity centistokes at			
	−54°C	50 MAX.	37 MAX.	D 445
	−32°C	20 MAX.	14 MAX.	
	−18°C	12 MAX.	9 MAX.	
COMBUSTION	Net Heat of Comb.			
	MJ/kg (Btu/lb)	41.98 (18,500) MIN.	42.10 (18,100) MIN.	D 2382 or
	MJ/m³ (Btu/gal)	39,573 (142,000) MIN.	39,434 (141,500) MIN.	D 240
STABILITY	Change in pressure drop (mm Hg)	10 MAX.	10 MAX.	D 3241 (3)
	Heater tube deposit rating	Code 2 MAX.	Code 2 MAX.	D 3241 (3)
CONTAMINANTS	Iron Content (ppm)	10 MAX.		(4)
	Particulates (mg/liter)	1.0 MAX.	1.0 MAX.	D 2276
ADDITIVES	Anti-Icing (vol %)	0.10 - 0.15	0.10 - 0.15	Fed. Std. 791
	Antioxidants (ppm)	90 - 110	90 - 110	Method 5327
OTHER	Color, Saybolt	+25 MIN.	+25 MIN.	D 156

NOTE: (1) Test procedure outlined in Appendix A Spec. MIL-P-87107A.
(2) Test procedure outlined in Appendix C. Test waived for JP-10.
(3) Test limits and conditions in Spec. MIL-P-87107A.
(4) Test procedure outlined in Appendix B Spec. MIL-P-87107A.

1.2 COMPOSITION OF FUELS

Turbine fuels, unlike missile hydrocarbon fuels, are made up of hundreds of different hydrocarbons. They are, therefore, not specified by chemical composition, but by general property limits. This category includes Jet A, Jet A-1, Jet B, JP-4, JP-5, JP-7, JP-8, and thermally stable fuels. The missile fuels RJ-4, RJ-5, RJ-6, JP-9, and JP-10 are, on the other hand, essentially pure or mixtures of a few pure synthesized hydrocarbon compounds tailored to their operational use with high density as a primary requirement.

1.2.1 Turbine Fuels

Although made up of many different hydrocarbons, the turbine fuels consist of essentially four types of compounds. These hydrocarbons can be grouped into the following series: the paraffins, including isoparaffins; cycloparaffins or naphthenes; aromatics; and olefins. The proportion of each will vary with the types of crude oils from which the final fuel is derived and the refining process used. Figure 1 gives examples of the chemical structures of the above compounds.

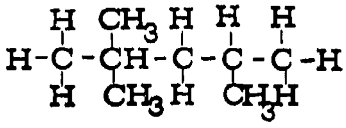
1.2.1.1 Paraffins and Cycloparaffins

Paraffins and cycloparaffins are the major components of turbine fuels. The paraffins consist of singly-bonded chains of carbon in which each carbon atom is fully saturated with hydrogen. They may be straight-chain or branch-chain molecules. This makes for a very stable structure not readily reacting with materials with which they come in contact such as elastomers, paints, and various metals. The high hydrogen-to-carbon ratio gives them high heat release per unit weight, and makes them cleaner burning than other hydrocarbons.

Cycloparaffins have a saturated ring structure which decreases the hydrogen-to-carbon ratio, lowering their heat release per unit weight, but increasing their density. They are also very stable and clean burning. Their primary advantage is that, in general, their freezing points are lower than comparable paraffins with the same number of carbon atoms.

Figure 1
Examples of Hydrocarbon Compound
Types

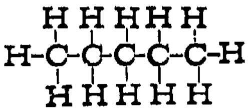
Paraffins



$$\mathrm{H-\underset{H}{\overset{H}{C}}-\underset{CH_3}{\overset{CH_3}{C}}H-\underset{H}{\overset{H}{C}}-\underset{CH_3}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-H}$$

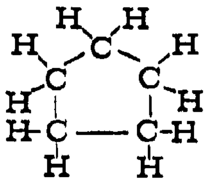
Isooctane

n-Pentane



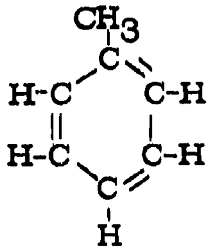
$$\mathrm{H-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-H}$$

Cyclo Paraffin



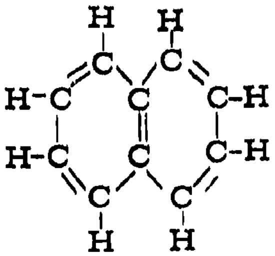
Cyclopentane

Aromatics

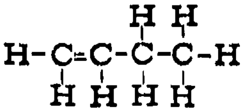


Toluene

Naphthalene



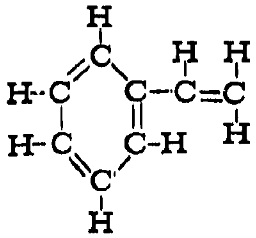
Olefins



$$\mathrm{H-\underset{H}{C}=\underset{H}{C}-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-H}$$

Butylene

Styrene



1.2.1.2 Aromatics

Aromatics are fully-unsaturated six-carbon ring compounds. The six member ring structures may be substituted with paraffin or olefin structures and/or may be coupled to form polynuclear aromatics; e.g., naphthalenes. They have, in general, a higher heat content per unit volume, but a lower heat content per unit weight than the paraffins. They tend to cause swelling effects on rubbers and certain sealants. In addition, they are smoky in burning, and tend to form combustor coke and contribute to high-luminosity flames. Due to these factors, the maximum concentration of aromatics permitted in turbine fuel specifications is 20 to 25 percent by volume. Aromatic content of fuels derived from crude oils is typically 10 to 20 percent.

1.2.1.3 Olefins

The olefins are similar to the paraffin series, but are unsaturated and, therefore, have lower hydrogen-to-carbon ratios. They are the most reactive of the hydrocarbons and are capable of reacting with many materials. For example, they combine with air to form varnish or rubber-like materials, and can react with each other to form polymers of higher molecular weight. The olefins, due to their unstable nature, are not generally found in crude petroleum, but may be formed in large quantities in refinery cracking processes. The specification content of olefins in the final fuel is limited to five percent by volume in order to reduce the formation of gums and polymers which limit the useful life of fuels in storage. Thermal stability of turbine fuels would also be adversely affected by high olefin fuels.

1.2.1.4 Nonhydrocarbon Types

Nonhydrocarbon compounds that may be found in aviation fuels contain sulfur, oxygen, or nitrogen. They are present in low concentrations and do little to contribute to fuel quality but, in the majority of cases, cause problems.

1.2.1.4.1 Sulfur and Sulfur Compounds

Practically all known crude oils contain sulfur in varying amounts. It may be present as free sulfur, mercaptans, sulfides, disulfides, and thiophenes. Free sulfur can be corrosive to certain metals in the fuel system, and therefore, free sulfur is controlled not by weight but by its corrosive effect on copper as determined by the copper strip corrosion test, ASTM D 130. The mercaptans are compounds that contain sulfur, hydrogen, and carbon. They attack cadmium plate and can cause deterioration of some types of synthetic rubbers. The amount of these compounds is, therefore, limited by specification limits, or if the fuel is considered "Doctor Sweet" when tested in accordance with the doctor test of ASTM D 484. The other sulfur compounds are controlled by the total sulfur content limits found in the specifications.

1.2.1.4.2 Gums and Gum Forming Compounds

Gums are high molecular weight compounds containing hydrogen, carbon, oxygen, and usually sulfur and nitrogen. They may occur in refined fuels in either soluble or insoluble forms. They may be produced in storage when the fuel is exposed to air. The formation of gums during storage is accelerated if the stored fuel is exposed to sunlight, elevated temperatures, and contains high concentrations of sulfur compounds.

These gums, when precipitated, can cause filter plugging, sticking and binding of fuel valves and controls, and plugging of metering orifices. Even though the insoluble gums are more deleterious to fuel systems, the soluble type can be expected to cause trouble when thin films of fuel are exposed to air. This fuel then evaporates, leaving gum deposits. Although fuel specifications do not differentiate between soluble and insoluble gums, they do limit the existent and, occasionally, potential gums.

1.2.1.4.3 Water Soluble Materials

Certain materials such as alcohol, sodium soaps, and other water soluble constituents contribute to fuel system corrosion, poor water/fuel separation, filter clogging, and poor performance of filter separators. To control this, a water tolerance test is included in fuel specifications.

1.2.1.4.4 Naphthenic Acid

Naphthenic acids are organic acids which originate from the crude oil, and which may be present in aviation fuels. They can cause corrosion with aluminum and magnesium if water is present. Zinc is rapidly attacked by these acids to form zinc naphthenates which are soluble in the fuel. Naphthenic acid can also form surfactants if it reacts with metals to form soaps which can cause free water to remain in suspension for prolonged periods. This can also cause poor performance of filter separators. Although there is no direct method of limiting the naphthenic acid in the specifications, the total acidity and the Water Separation Index indirectly control this contaminant. Advanced refining techniques in conjunction with clay filters have, for the most part, eliminated this potential problem.

1.2.1.5 Additives

Additives for improving the properties and overcoming particular problems are in some cases required and, in other cases, they are optional. Only officially-approved additives are permitted, and the amount is controlled.

1.2.1.5.1 Antioxidants

The main function of antioxidants is to prevent the formation of gums and peroxides. Heavily hydrotreated fuels have a tendency to form peroxides, and the additive is required. In other fuels, antioxidants are optional.

1.2.1.5.2 Metal Deactivators

Metal deactivators are allowed in all fuels. They are used primarily in those fuels that have been refined by copper sweetening processes. These additives react with soluble copper and other metal compounds, thus preventing undesirable reactions leading to filter-blockage troubles.

1.2.1.5.3 Fuel System Icing Inhibitors

These additives prevent the formation of ice resulting from water coming out of solution at low temperatures and from water condensing in fuel tank ullage. They have also been found to be an effective barrier to microbiological growth. Ethylene glycol monomethyl ether is specified for most military fuels and is permissible in commercial turbine fuels. Diethylene glycol monomethyl ether is specified for use with JP-5.

1.2.1.5.4 Corrosion Inhibitors

These additives are intended to minimize rusting in product pipelines and fuel storage tanks. They have also been found to improve the lubricity of some fuels and are mandatory in certain military fuels for this purpose. The exact composition of these materials is proprietary, but they are controlled by Specification MIL-I-25017.

1.2.1.5.5 Static Dissipator Additives

Static dissipator additives are added to JP-4 and JP-8. They are permitted in most other fuels to raise their electrical conductivity, thereby preventing the buildup of hazardous static charges.

1.2.2 Hydrocarbon Missile Fuels

These fuels are essentially pure synthesized hydrocarbons or mixtures of pure synthetic hydrocarbons. They are compounds of high energy content per unit volume tailored to meet the operational requirements of their assigned system. These fuels are based on bridged ring hydrocarbon structures (which contain high carbon-to-hydrogen ratios) which increase both density and volumetric heat of combustion. The simplest bridged structure which forms the building block for all the hydrocarbon missile fuels is norbornane or bicyclo (2.2.1) heptane. Though never found as such in the final fuels, its structure can be observed as the basic part of each compound. Figure 2 presents the chemical structures of the various high-density fuels.

1.2.2.1 RJ-4

RJ-4 is a mixture of eight isomeric forms produced by the hydrogenation of methylcyclopentadiene dimer. The product, tetrahydromethylcyclopentadiene dimer, or TH Dimer, is a high-density hydrocarbon having substantially more energy per unit volume than kerosene fuels. The mixture of isomers accounts for the ranges in the boiling and freezing temperatures.

1.2.2.2 JP-10

JP-10 has the single chemical structure exo-tetrahydrodi(cyclopentadiene). It is prepared by hydrogenating commercially-available di(cyclopentadiene), which yields the solid material endo-tetrahydrodi(cyclopentadiene). The intermediate endo structure is then isomerized in the presence of a catalyst to produce pure JP-10.

1.2.2.3 RJ-5

RJ-5 is a mixture of hydrogenated dimers of norbornadiene, an unsaturated derivative of the bridged compound norbornane. This high-density fuel is called perhydrodi(norbornadiene). It has the highest energy per unit volume of all the missile fuels, but its high freezing point makes it unusable for many applications.

1.2.2.4 RJ-6

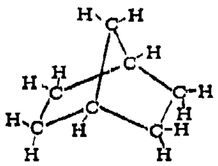
RJ-6 is made up of a mixture of RJ-5 or perhydrodi(norbornadiene) and exo-tetrahydrodi(cyclopentadiene). Exo-tetrahydrodi(cyclopentadiene) is JP-10. Although RJ-6 has a lower volumetric heat of combustion, it has better low-temperature properties than RJ-5.

1.2.2.5 JP-9

JP-9 is a high-density hydrocarbon fuel composed of three different components tailored to have a high volatility permitting proper ignition at low temperatures. It is made up of methylcyclohexane, JP-10 exo-tetrahydrodi(cyclopentadiene), and RJ-5 (H-norbornadiene dimers).

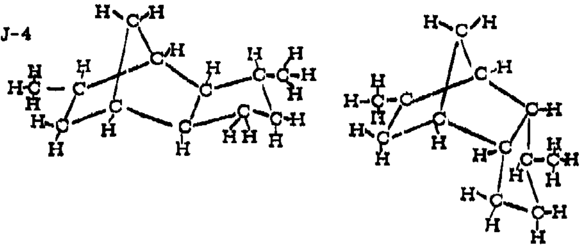
Figure 2
Chemistry of High Density Hydrocarbon Missile Fuels

Building Block



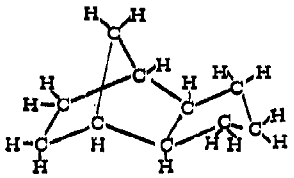
Norbornane

RJ-4



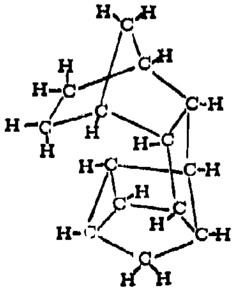
Endo and Exo-Tetrahydrodi (methylcyclopentadiene) (TH Dimer)

JP-10



Exo-Tetrahydrodi (cyclopentadiene)

RJ-5

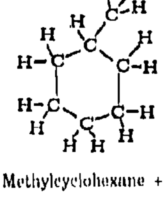


Perhydrodi (norbornadiene)

RJ-6

JP-10 + RJ-5

JP-9



Methylcyclohexane + JP-10 + RJ-5

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1. Exxon Company, USA, *Data Book for Designers—Fuels, Lubricants, and Hydraulic Fluids,* September 1973.

2. M. Shayeson, "Fuels for Aviation Gas Turbine Engines," General Electric Technical Memorandum No. 81-315, May 1981.

3. H. Barnett and R. Hibbard, "Properties of Aircraft Fuels," NACA Technical Note 3276, August 1956.

4. Coordinating Research Council, Inc., *CRC Aviation Handbook—Fuels and Fuel Systems,* NAVAIR 06-5-504, May 1967.

5. G. W. Burdette, H. R. Lander, and J. R. McCoy, "High Energy Fuels for Cruise Missiles," AIAA Paper No. 78-267, June 1978.

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SECTION 2

FUEL PROPERTIES

2.1 FUEL DENSITY

Density is the mass per unit volume relationship of fluids. The relative density, commonly referred to as specific gravity, is usually the ratio of the density of a particular liquid fuel to the density of water at 15.5°C. These relationships are important in the design of aircraft and missiles, since variations in fuel density can have large effects on determining their loaded weight and the range attainable. They are also used in flow calculations, fuel gaging, metering device considerations, fuel loading, thermal expansion of fuels, and fuel tank design.

2.1.1 Density

Density is defined in terms of mass per unit volume at a given temperature. It can be expressed in several mass to volume units with the standard for metric practice defined in terms of kilogram per cubic meter (kg/m^3). Temperature has a marked effect on the density of fuels. As the temperature increases, the density of a fuel decreases. Figure 3 shows the effect of temperature on the density of a number of typical aviation fuels. Figure 4 shows the same effect as it pertains to a number of hydrocarbon missile fuels.

2.1.2 Relative Density (Specific Gravity)

Relative density or specific gravity is dimensionless, since it is a ratio of the density of a substance to the density of a reference substance, namely water. Since density varies with temperature, the temperature of the liquid which is being compared with the reference substance must be given, as well as the temperature of the reference substance. Relative density can also be expressed in terms of API gravity. The following equation gives the relationship between API gravity and relative density:

$$^{\circ}\text{API} = \frac{141.5}{\text{Relative Density } (60^{\circ}\text{F})} - 131.5$$

As in the case of density, the relative density of a fuel decreases with an increase in temperature. Figures 5 through 9 show the effect of temperature on the relative densities of aircraft and missile fuels. Maximum and minimum values are given with typical values derived from inspection data on these fuels.

2.1.3 Thermal Expansion

Another approach in showing the effect of temperature on density is to consider the thermal expansion of a fuel as it is heated. Figure 10 depicts the multiple of volume for aircraft and missile fuels as compared with their volumes at 15.5°C when the temperature is increased. Pressure is specified, since highly elevated pressures tend to depress slightly this volumetric increase.

2.1.4 Unit Mass of Fuels

Figures 11 and 12 provide a general method for determining the appropriate unit mass of aviation gasoline and turbine fuels, respectively, at a given temperature when the relative density at 15.5°C is known.

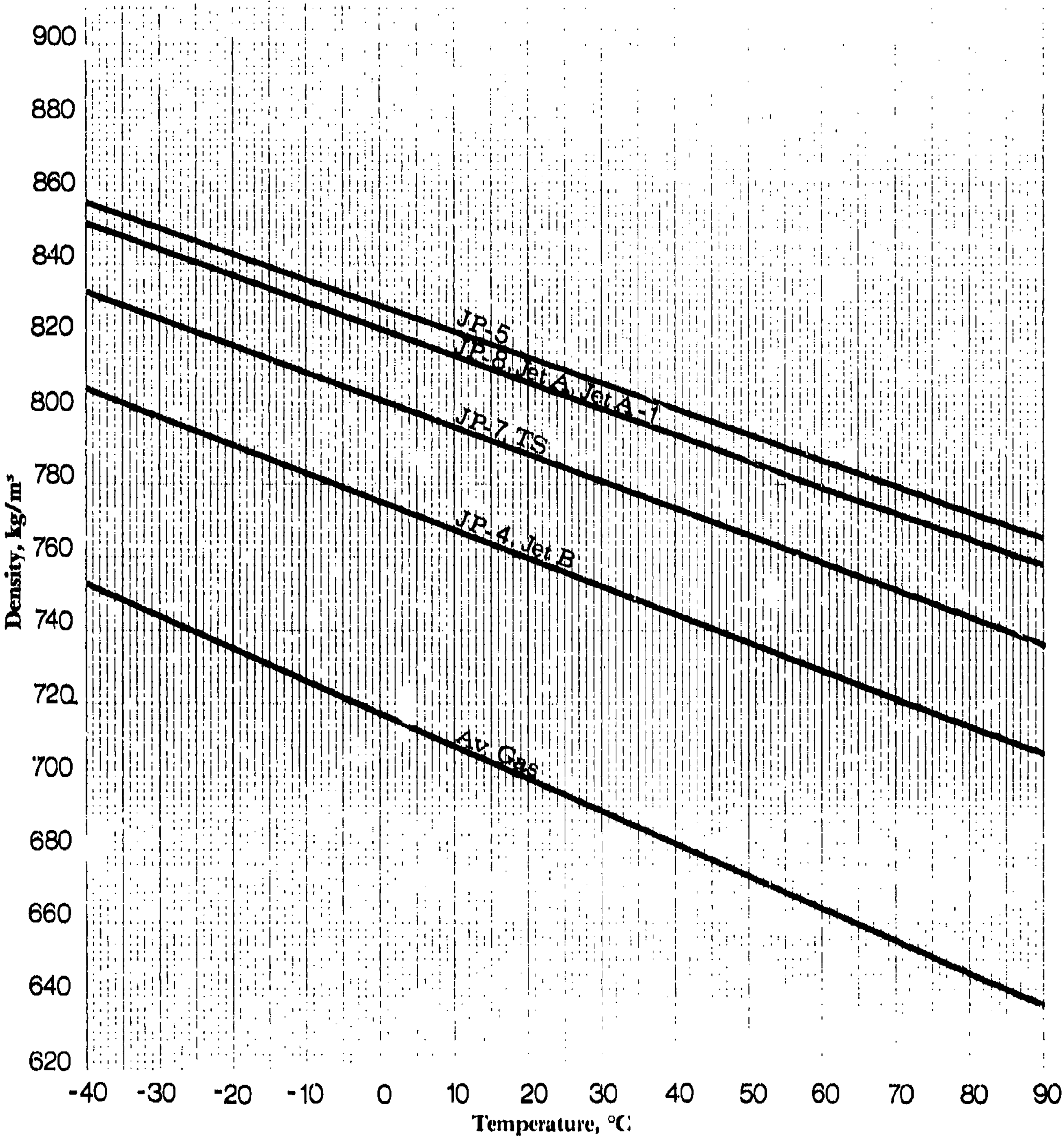

Figure 3
Typical Density vs. Temperature For Aircraft Fuels

1 kg/m³=.0625 lb/ft³

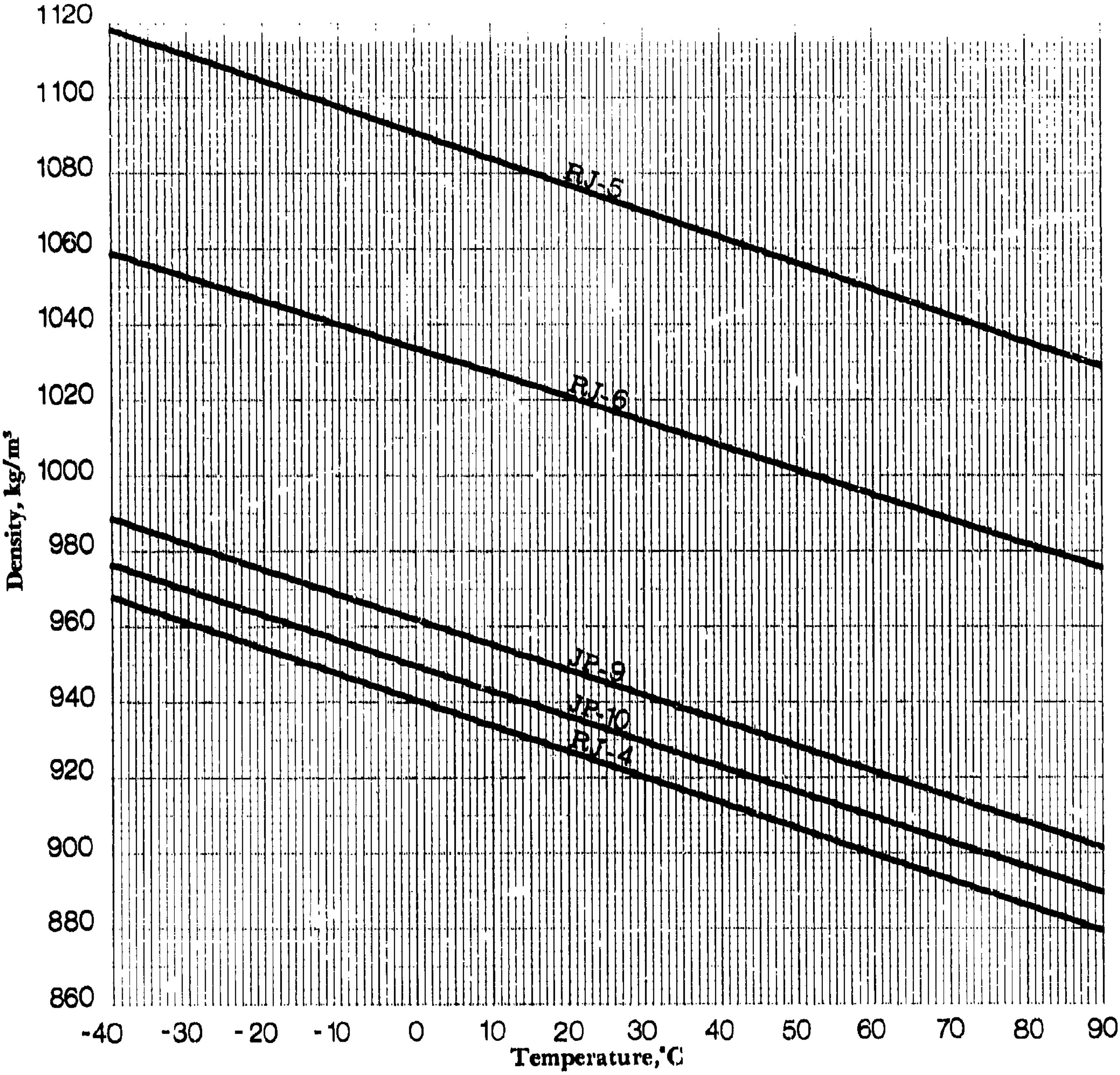

Figure 4
Typical Density vs. Temperature For Missile Fuels

1 kg/m^3 = .0625 lb/ft^3

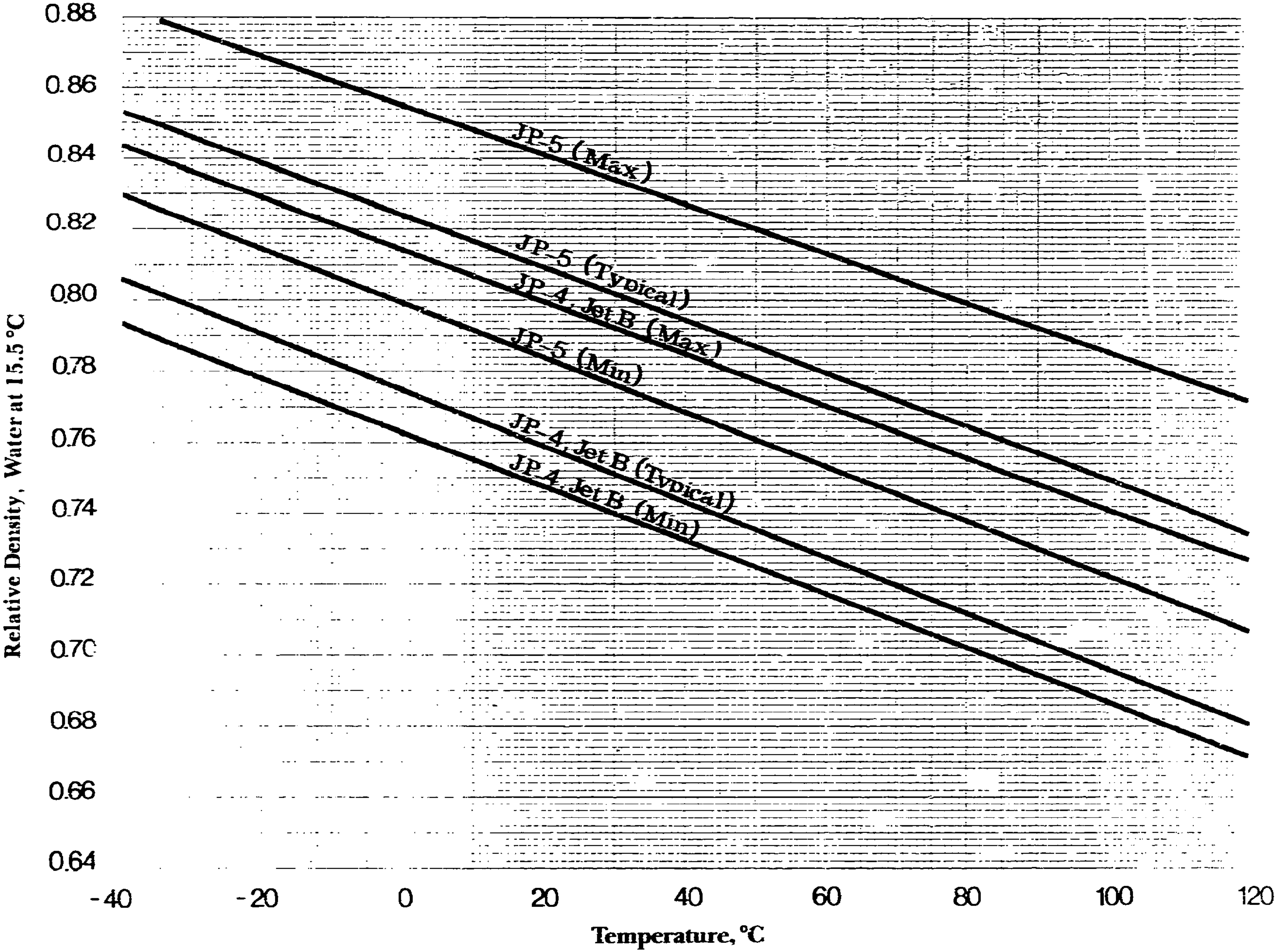

Figure 5
Relative Density vs. Temperature (Max., Min., Typical)

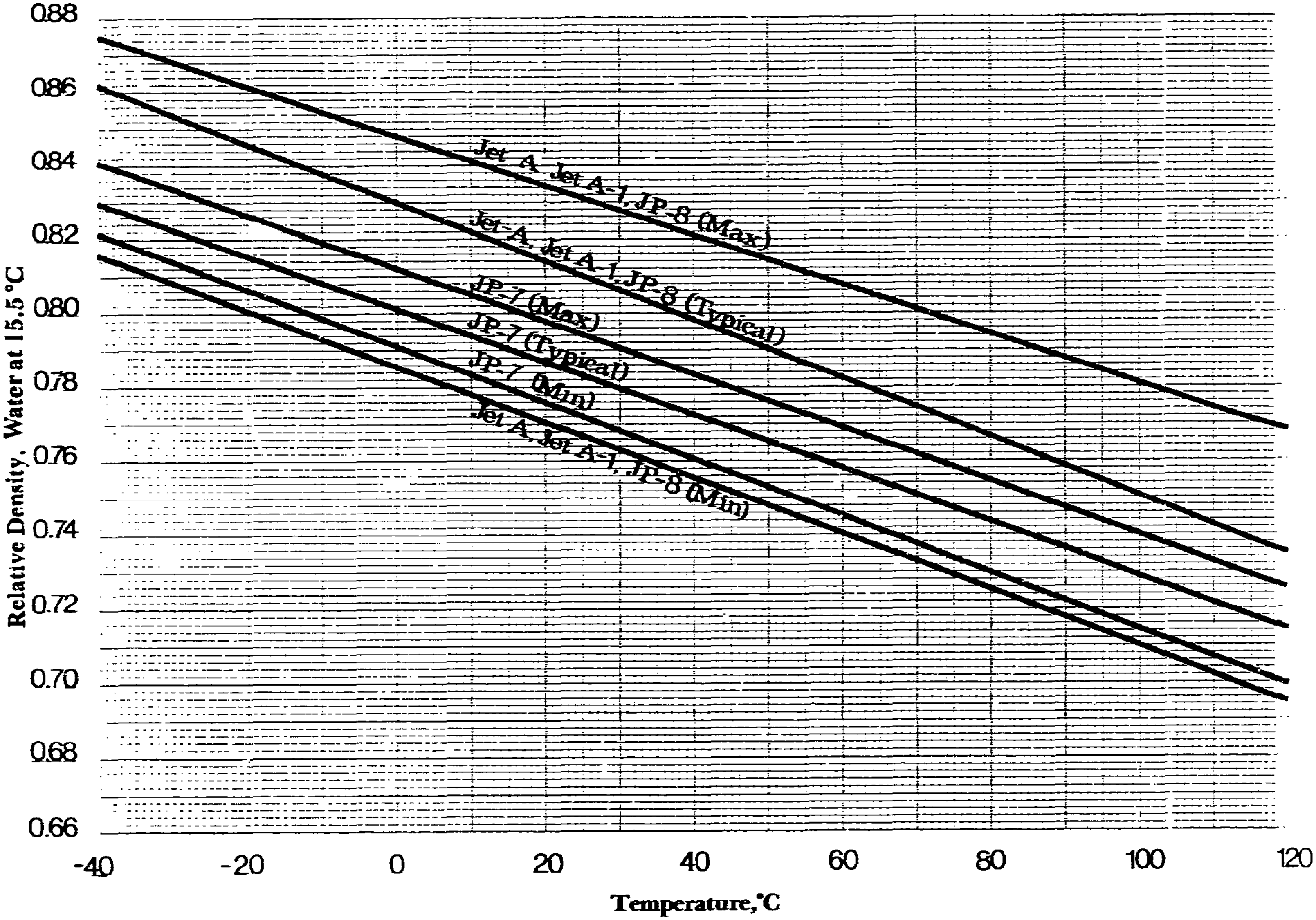

Figure 6
Relative Density vs. Temperature, (Max., Min., Typical)

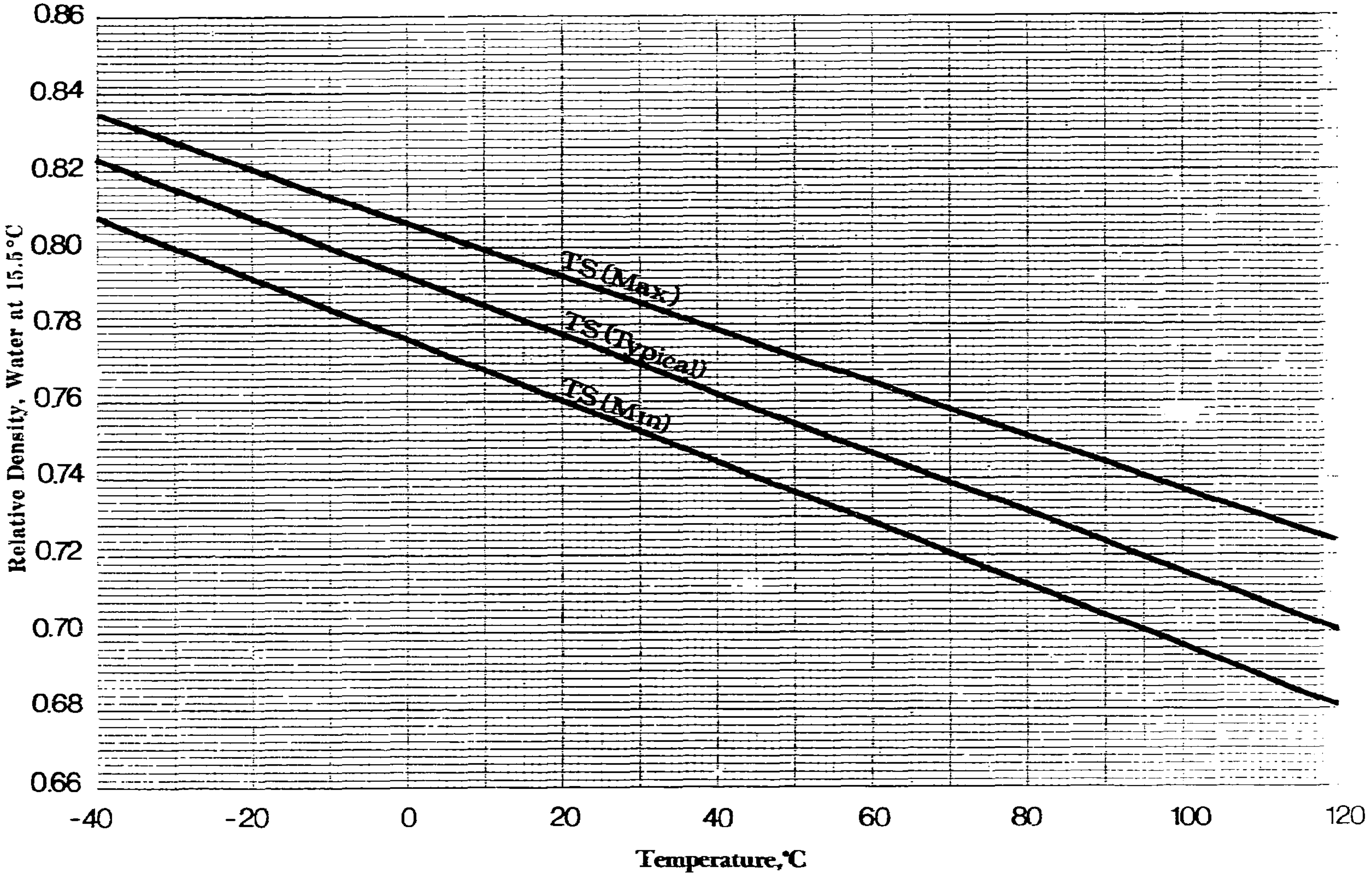

Figure 7
Relative Density vs. Temperature (Max., Min., Typical)

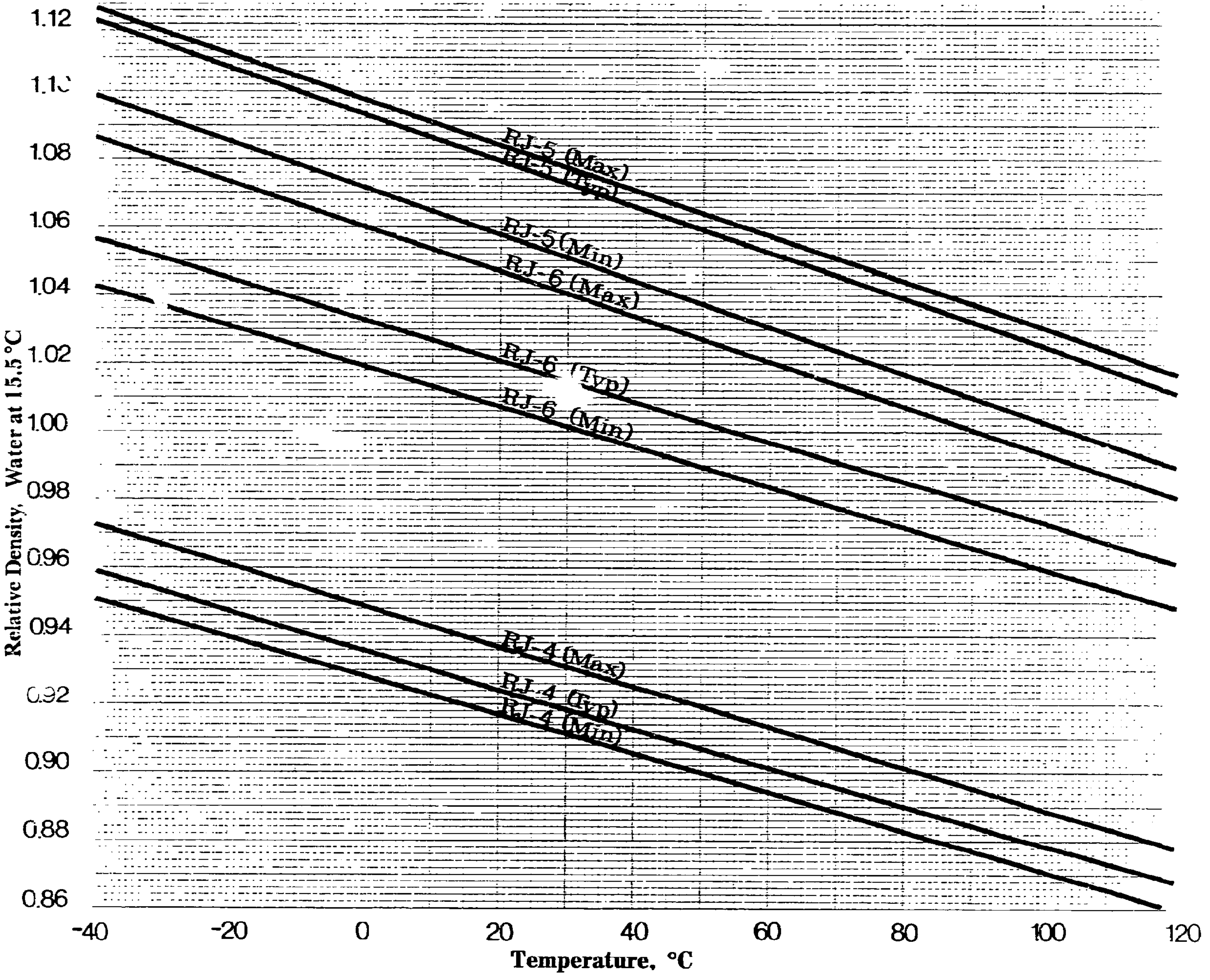

Figure 8

Relative Density vs. Temperature (Max., Min., Typical)

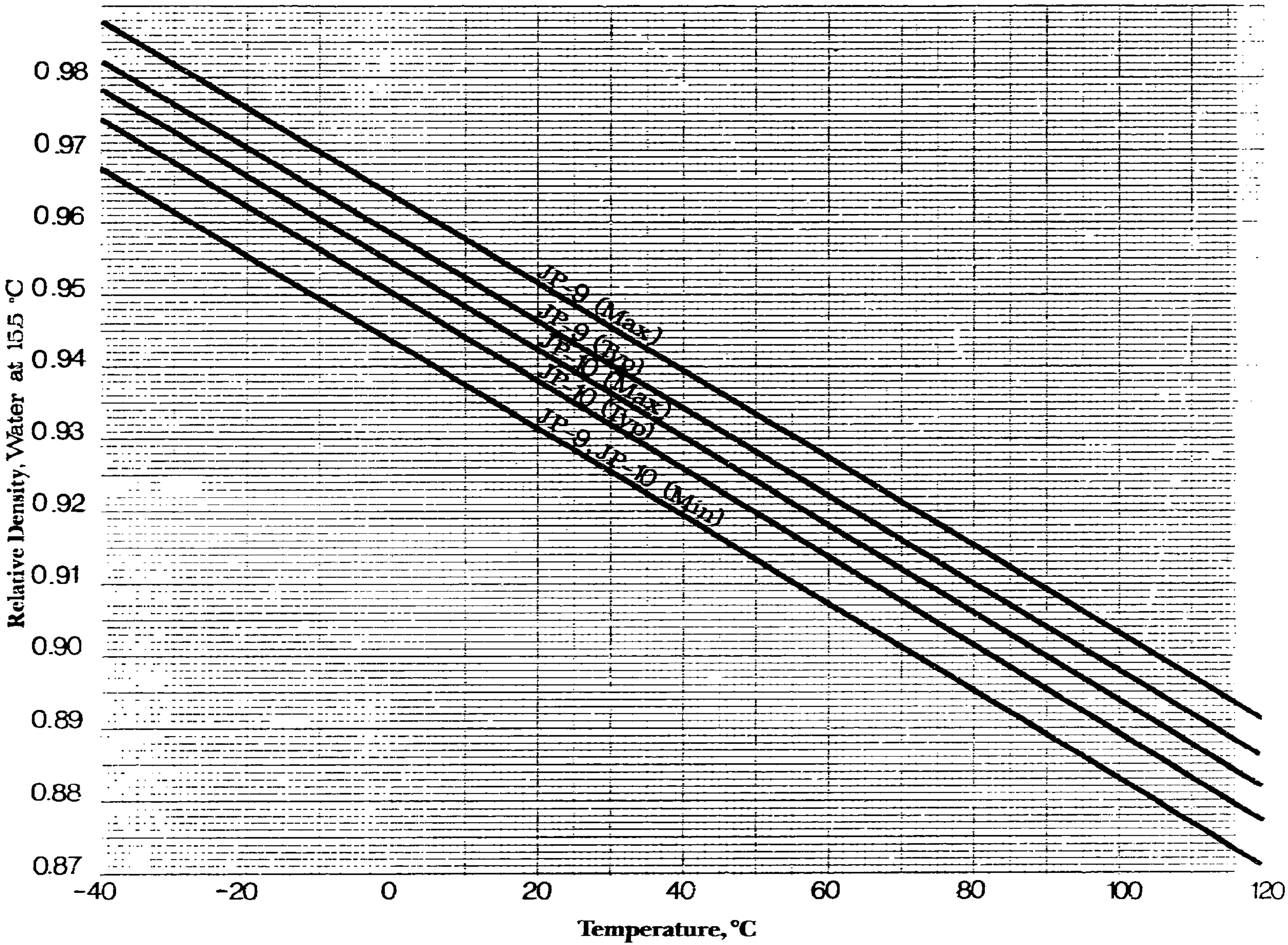

Figure 9
Relative Density vs. Temperature (Max., Min., Typical)

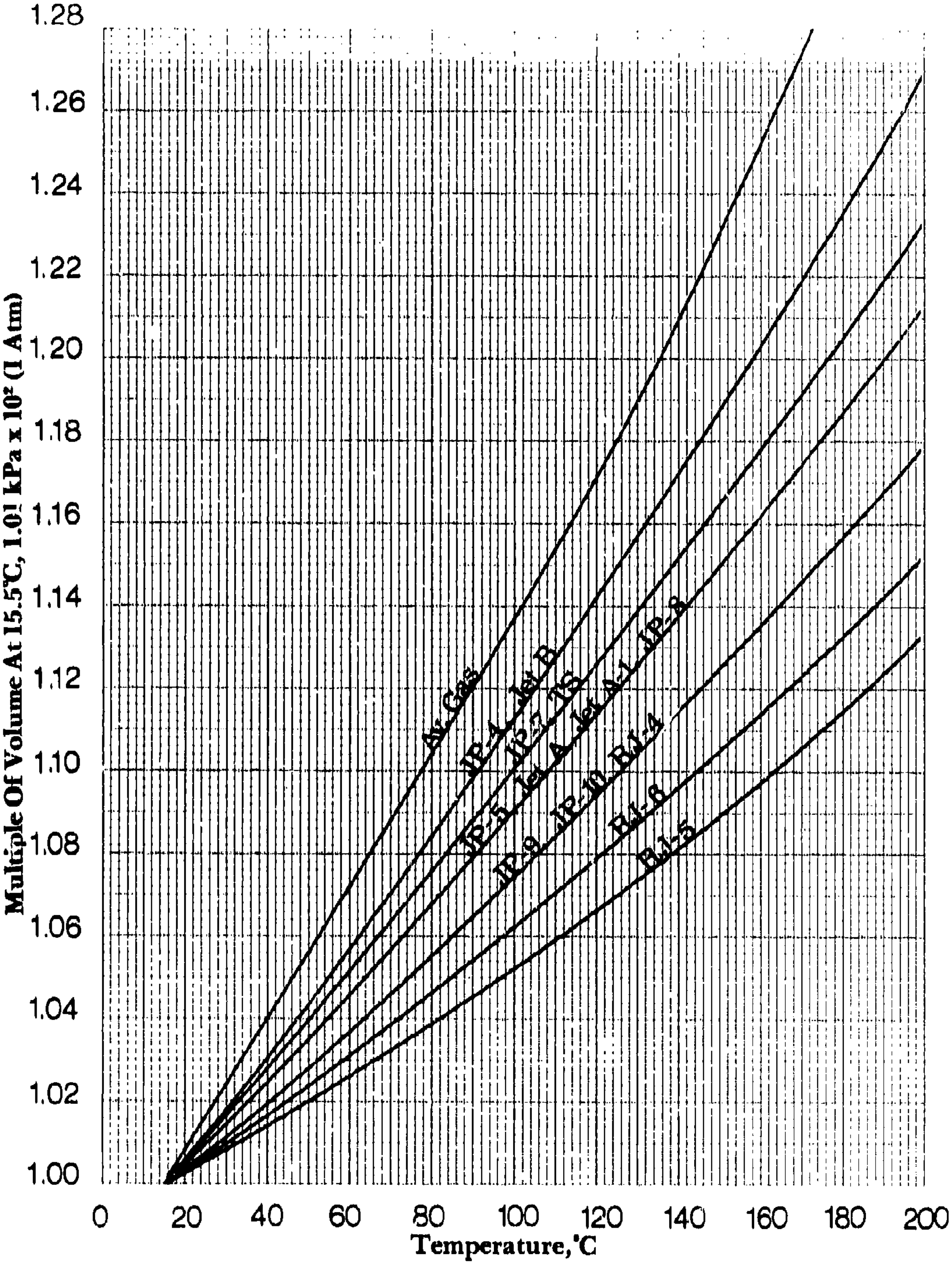

Figure 10
Thermal Expansion

1 Atm. = 1.01 kPa x 10²

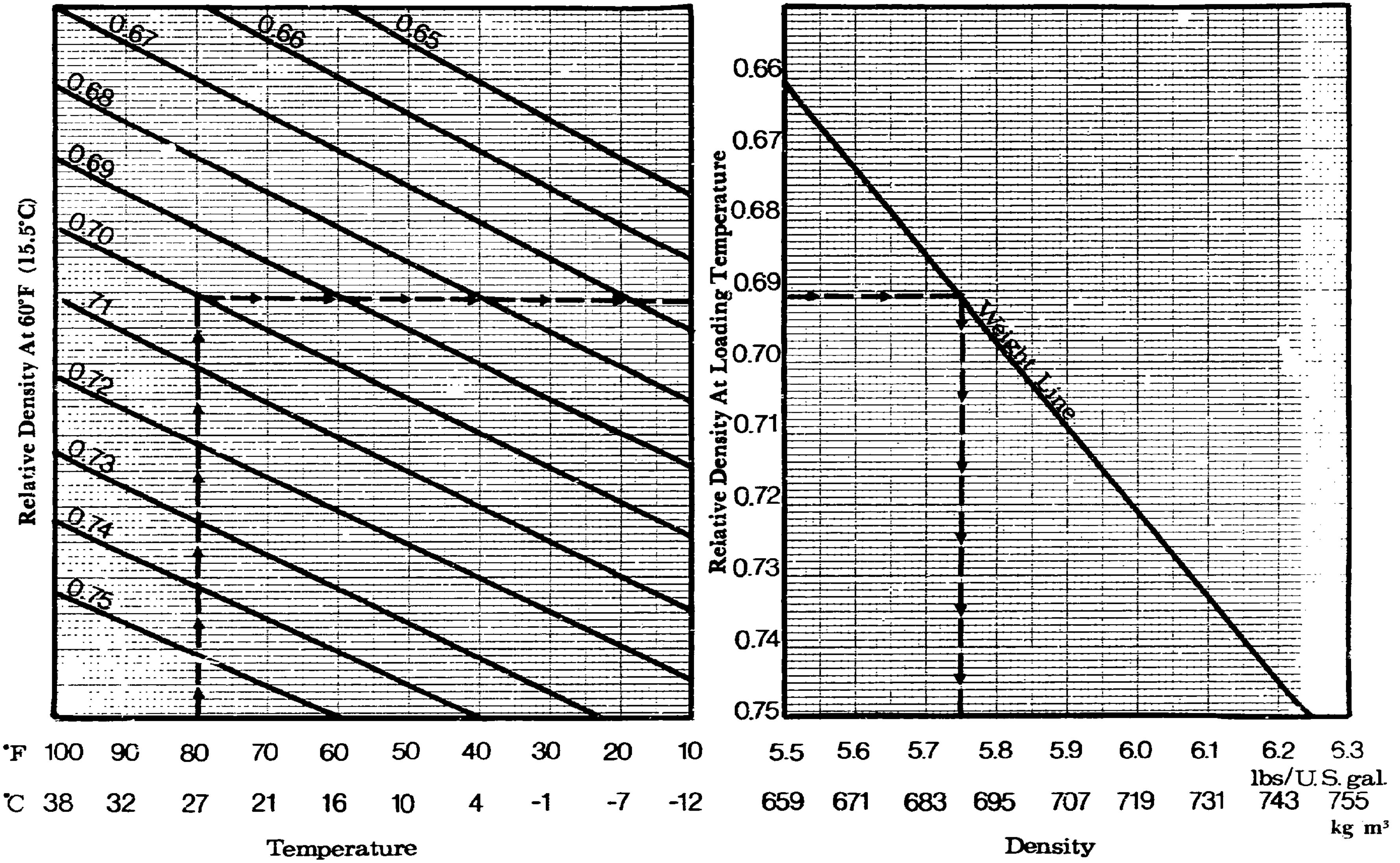

Figure 11
Unit Mass of Aviation Gasoline

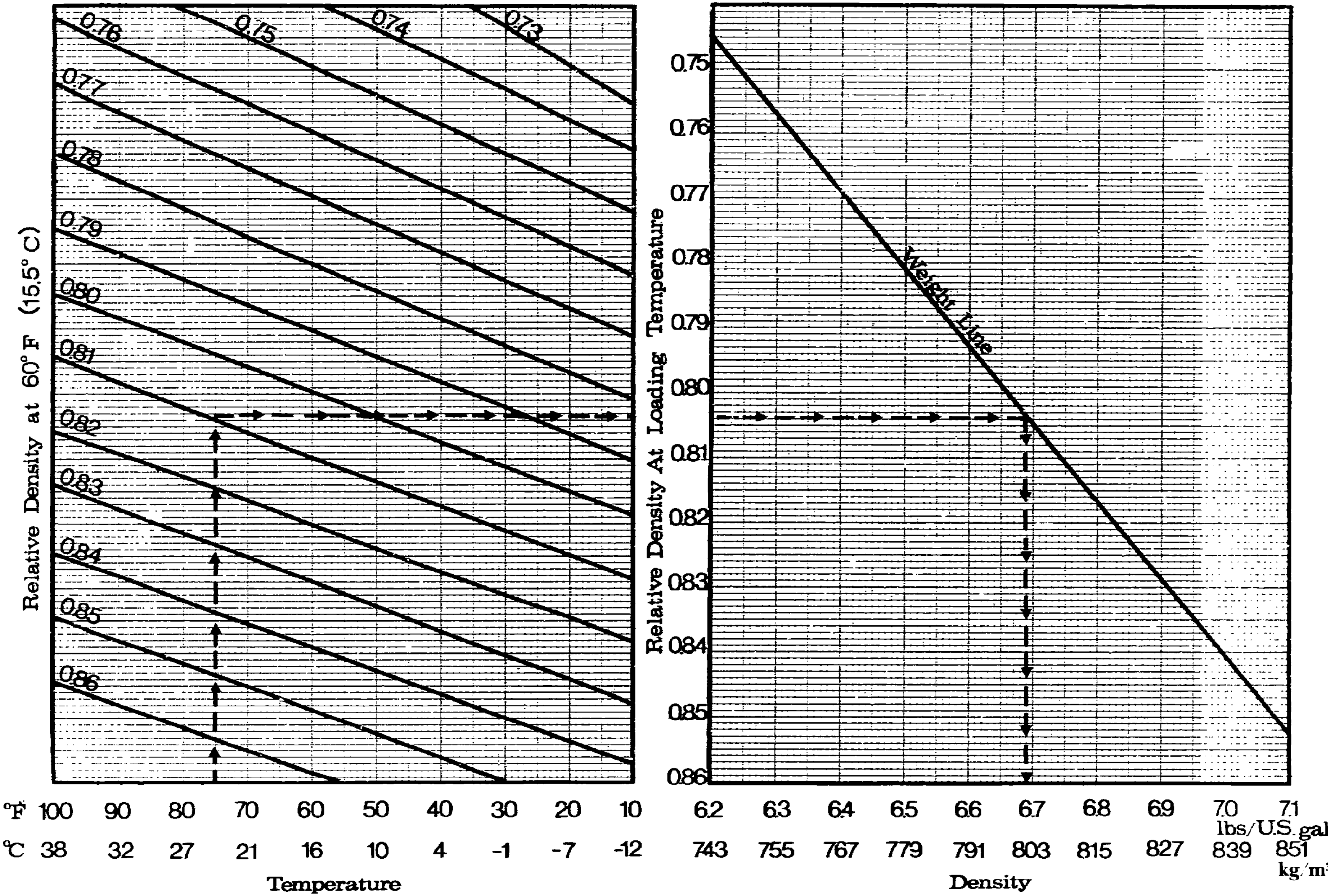

Figure 12
Unit Mass of Turbine Fuels

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5. H. Barnett and R. Hibbard, "Properties of Aircraft Fuels," NACA Technical Note 3276, August 1956.

6. Coordinating Research Council, Inc., *CRC Aviation Handbook—Fuels and Fuel Systems,* NAVAIR 06-5-504, May 1967.

2.2 VISCOSITY

The viscosity of a fluid is a measure of its internal resistance to motion caused by cohesive forces among the fluid molecules. It is of primary interest to the fuel system designer as a prime factor in calculating pressure drops in lines through its relationship to Reynolds number. The cohesive or interaction forces among the molecules appear as shear stresses between the moving layers of fluid. The shear stress at a point divided by the velocity gradient at that point is defined as absolute viscosity. The pascal second is the unit of absolute viscosity specified in the Standard for Metric Practice. In practice, absolute viscosity is used in conjunction with density, particularly in the calculation of Reynolds number. Also, the determination of viscosity is usually done in combination with density as a function of time. This relationship between viscosity and density is defined as kinematic viscosity, the ratio of the absolute viscosity of a fluid to the density with both properties measured at the same temperature and pressure. Kinematic viscosity is usually found in terms of centistokes. In the Standard for Metric Practice, it is defined in terms of square meter per second (m^2/s). One centistoke is equivalent to one mm^2/s.

Viscosity varies considerably with temperature. Lowering the temperature of the fuel has the effect of increasing its viscosity. In fact, many fuel specifications specify maximum viscosity limits at low temperatures to assure pumping and flow capabilities. Figures 13 and 14 give typical kinematic viscosities versus temperature for various aircraft and missile fuels plotted on an ASTM chart modified from ASTM D 341-39. The variation of viscosity with temperature plots on this chart as a straight line. Therefore, viscosities can be extrapolated to any desired temperature by connecting known viscosity points at two different temperatures. Caution must be taken not to extend these extrapolations through phase changes.

Comparison of Figures 13 and 14 shows that missile fuels are generally higher in viscosity at a given temperature than turbine aircraft fuels. This is due to the difference in chemical composition between aircraft and missile fuels. The missile fuels are generally composed of hydrocarbons high in density, such as cyclic paraffins or condensed five- or six-membered ring structures. It is characteristic of such hydrocarbons to exhibit large intermolecular cohesive forces compared with aircraft fuels made up of mostly straight-chain paraffins.

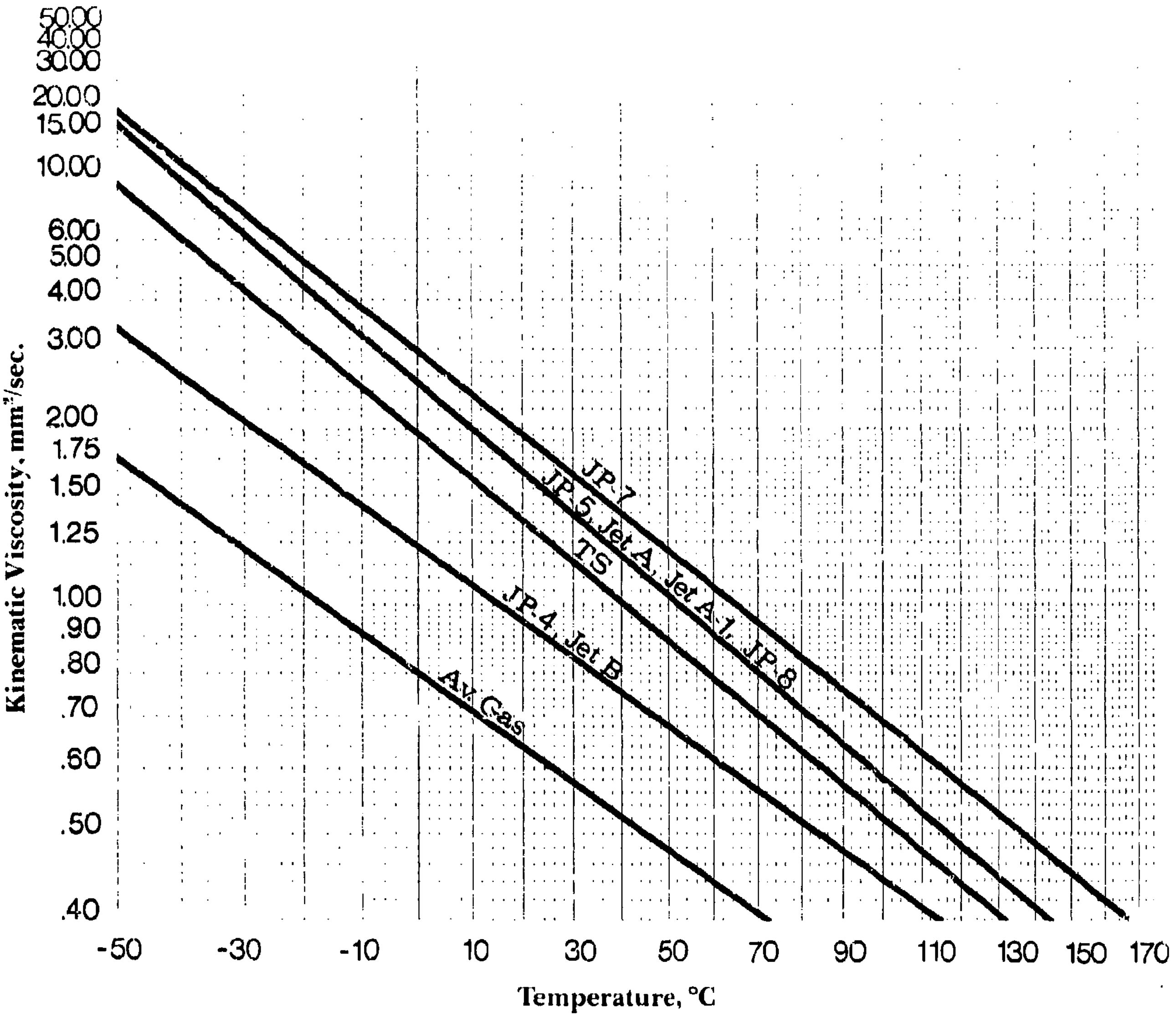

Figure 13
Typical Viscosity vs. Temperature For Aircraft Fuels

1 mm²/s = centistoke

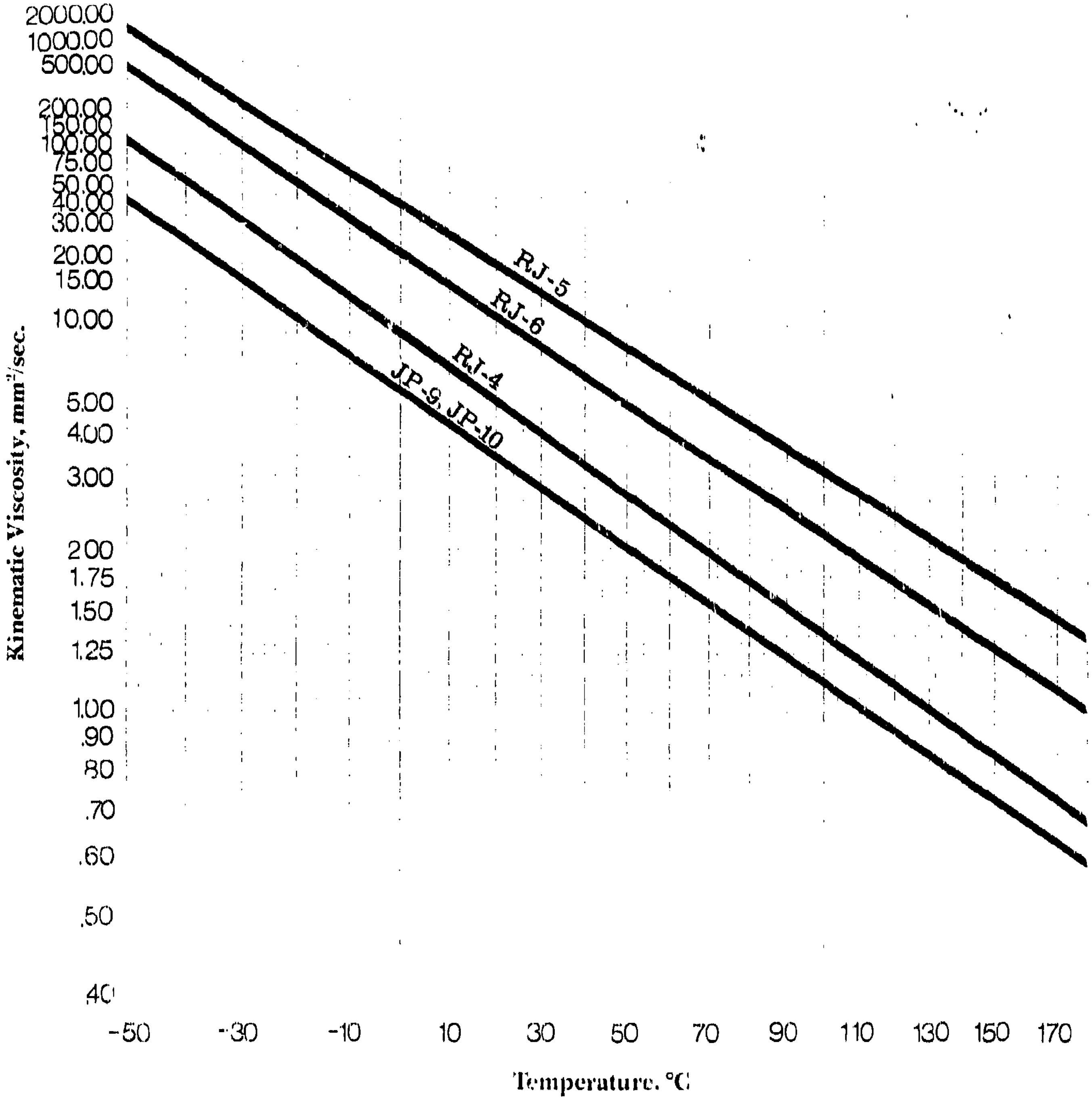

Figure 14
Typical Viscosity vs. Temperature For Missile Fuels

1 mm²/s = centistoke

REFERENCES

1. Exxon Company, USA, *Data Book for Designers—Fuels, Lubricants, and Hydraulic Fluids*, September 1973.

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2.3 SURFACE TENSION

Surface tension is defined as the specific free energy of a liquid surface at interface with another fluid. Values for surface tensions are usually given when the surface of the liquid is in contact with air. It is of importance in gas evolution and solubility, and has a pronounced effect in atomization characteristics of fuels.

Fluids with large cohesive forces among molecules such as water exhibit high surface tensions. Nonpolar fluids such as hydrocarbons have lower internal cohesive forces and lower surface tensions. Surface tensions decrease toward zero as temperature increases and cohesive forces are overcome. At the fluid's critical temperature, surface tension ceases to exist. As found in Reference 2, surface tension can be estimated by using the Ramsey and Shields correlation if density, molecular weight, and the critical temperature of the fluid is known.

The surface tension data for aircraft fuels in Figure 15 has been estimated from the Ramsey and Shields correlation, and shows the reduction of surface tension with increasing temperature. Figure 16 shows higher surface tensions for missile fuels, because of their higher molecular weights and densities. In the correct Standard for Metric Practice, newton per meter (N/m) is specified as the standard unit for surface tension.

Impurities have a very important effect on surface tension, since they cause a reduction on surface tension as does increased temperature. These factors have a major influence on the atomization and ignition of fuel droplets which are favored by low surface tension.

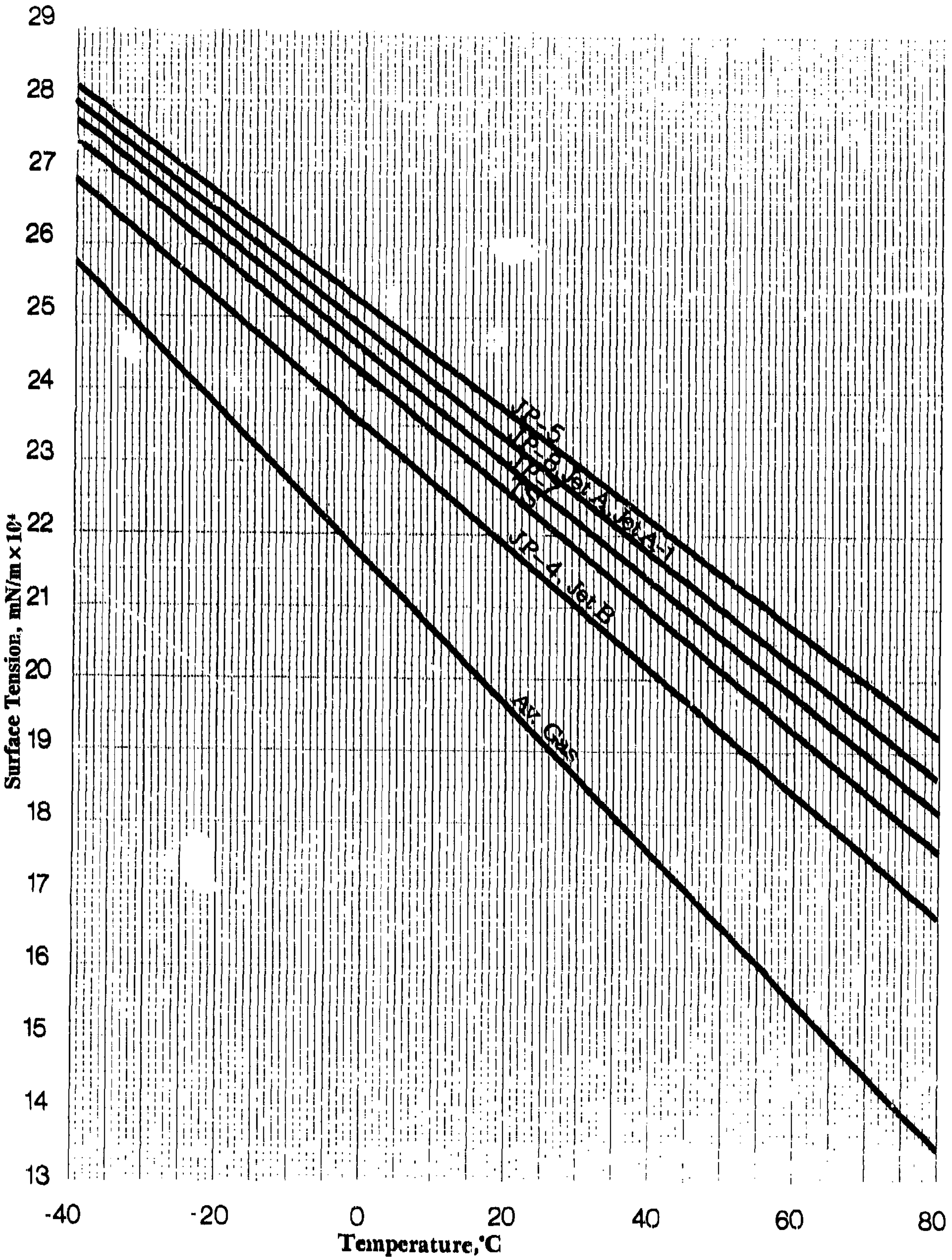

Figure 15
Typical Surface Tension vs. Temperature For Aircraft Fuels

1mN/m = dyne/cm

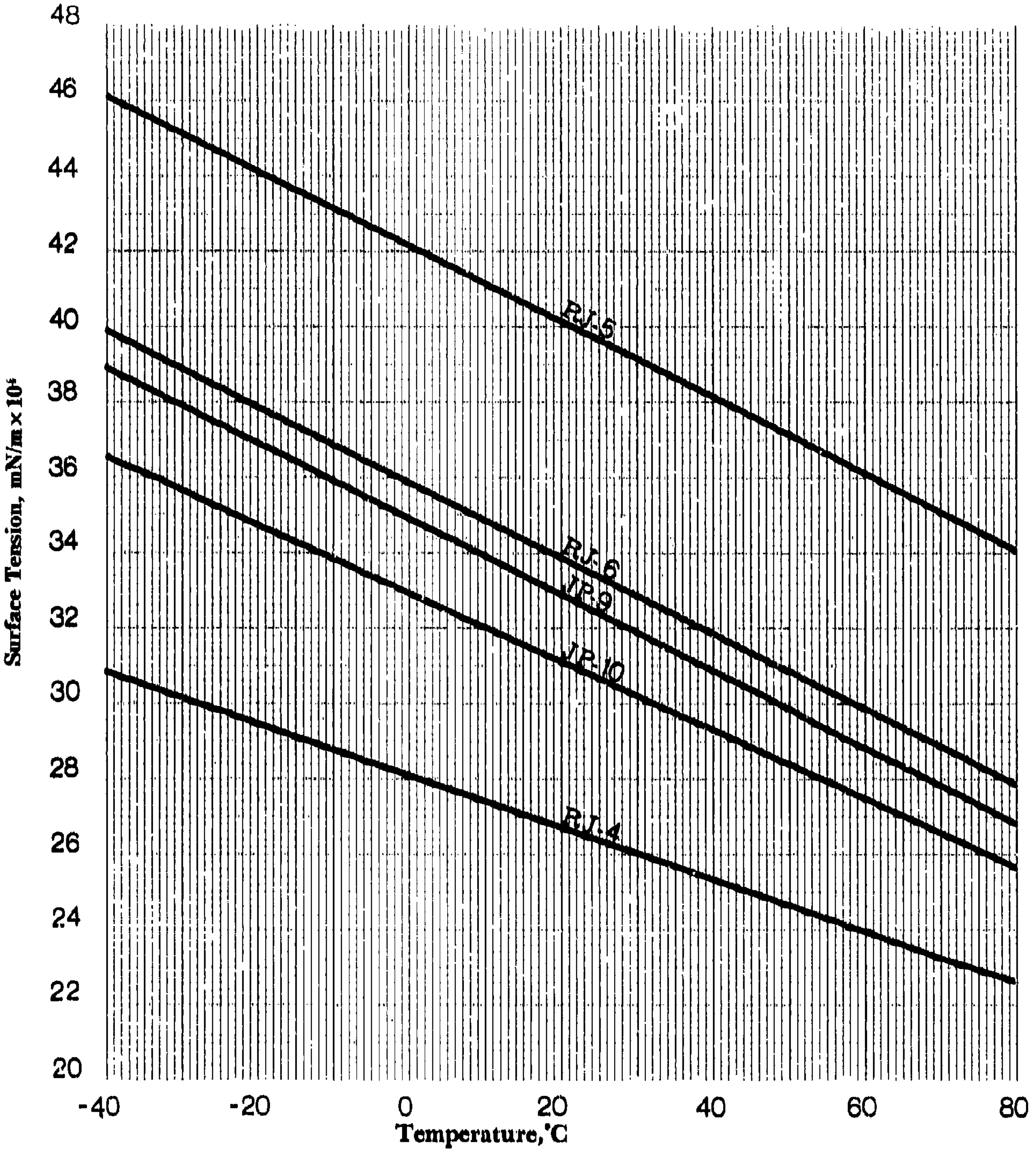

Figure 16
Typical Surface Tension vs. Temperature For Missile Fuels

1mN/m = dyne/cm

REFERENCES

1. Coordinating Research Council, Inc., *CRC Aviation Handbook—Fuels and Fuel Systems,* NAVAIR 06-5-504, May 1967.
2. H. Barnett and R. Hibbard, "Properties of Aircraft Fuels," NACA Technical Note 3276, August 1956.
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2.4 VOLATILITY

Volatility, or tendency to change from liquid to vapor, is a fuel property that affects its ability to vaporize and form a combustible mixture with air. This property determines the pressure exerted by the fuel vapor, which is called the vapor pressure. Volatility is particularly important to the engine and fuel system designer since it affects vapor and entrainment losses, vapor lock effects on pumping, flammability hazards, and engine-starting characteristics.

2.4.1 ASTM Distillation

Fuel volatility is controlled by specification limits derived from distillation data based on the ASTM D 86 test for distillation of petroleum products. ASTM D 2887, the gas chromatography test for boiling-range distribution of petroleum fractions, is a more precise modern method, but it is not yet being widely used. D 2887 separates components of fuel into a wider spectrum of hydrocarbons than D 86 in a manner similar to a fifteen-plate distillation column such as ASTM D 2892 employs. By comparison, the D 86 distillation corresponds to a crude one-plate fractionating device. Nevertheless, D 86 distillation data on volatility can be related to some service performance characteristics.

Figures 17 and 18 give ASTM distillation (ASTM D 86) curves for aircraft fuels based on averaged inspection data for the past three years. Figure 19 depicts the ASTM distillation curve for JP-9 missile fuel. Other missile fuels, being essentially pure chemical entities, are not plotted since they vaporize at a constant temperature.

2.4.2 True Vapor Pressure

The vapor pressure of a fuel is defined as the pressure exerted by its vapors in equilibrium with the liquid at a specific temperature with the absence of air in or over the fuel. In the case of a pure substance, this pressure does not vary with evaporation as long as there is liquid present.

Fairly simple experimental methods, such as the vapor reflux method, can be used to determine the vapor pressure of pure chemicals or simple mixtures of known chemical compositions. This is the case for missile fuels which are either essentially pure compounds or simple mixtures of such compounds.

Aviation fuels, unlike missile fuels, are complex mixtures of many hydrocarbons of different vapor pressures. In this case, evaporization alters the composition of liquid, and the vapor pressure decreases with the amount evaporated. The measure of the amount of this vaporization is the "vapor/liquid ratio" which is the ratio, vapor volume/liquid volume. The "true" vapor pressure of a mixture such as a petroleum fuel is defined as the pressure exerted as this vapor/liquid ratio approaches zero. It is the maximum pressure attainable at a given temperature since the vapor pressure decreases with increasing vapor/liquid ratio. There are several methods available for determining the true vapor pressure of complex hydrocarbon mixtures. These fall into two general categories: the empirical correlation techniques; and the experimental techniques. The experimental techniques, namely gas-liquid chromatography and mass spectrometry, may be used, but are expensive and time-consuming. The empirical correlation techniques are more commonly employed and are based on two general approaches: the derivation from Reid vapor pressure data as determined by ASTM D 323 or the more accurate ASTM D 2551; or the derivation from distillation data as developed by ASTM D 86 in combination with equilibrium flash vaporization calculations or determinations.

Derivation of true vapor pressure by the Reid method is found in Reference 1, pages 48 through 109. This method is limited to vapor pressures up to 20 psi. It is also not directly applicable to petroleum fuels of low volatility such as JP-5 and JP-7 in which flash-point temperatures, as measured by ASTM D 93, are used instead of Reid vapor pressures. The above reference includes the flash-point approach along with the determination of changes in true vapor pressure with temperature over a range of vapor-to-liquid ratios.

Distillation data derived from ASTM D 86 is used for determining true vapor pressure by the Edmister technique found in ASTM D 2889, and the British Petroleum method described in Reference 5. A combination of these above methods using experimentally determined equilibrium flash vaporization by the vapor reflux method is found in the JP-7 specification MIL-T-38219A (USAF), Appendix C. The Edmister technique is recommended in Reference 5 for vapor pressures up to 316°C, but is not reliable for fuels having a boiling range of less than 37.8°C (100°F) between 10 percent and 90 percent distilled temperatures. This includes low-volatility fuels such as JP-5 and JP-7. The British Petroleum method and the JP-7 specification method do not have the limitations that are present with the other empirical methods, and are recommended for precise true vapor pressure determinations when high accuracy is required.

True vapor pressure curves derived from Reid vapor pressure data for aircraft fuels are found in Figure 20, except for JP-5 and JP-7 whose vapor pressures were determined using the JP-7 specification method. For missile fuels, Figure 21 gives vapor pressure curves derived experimentally.

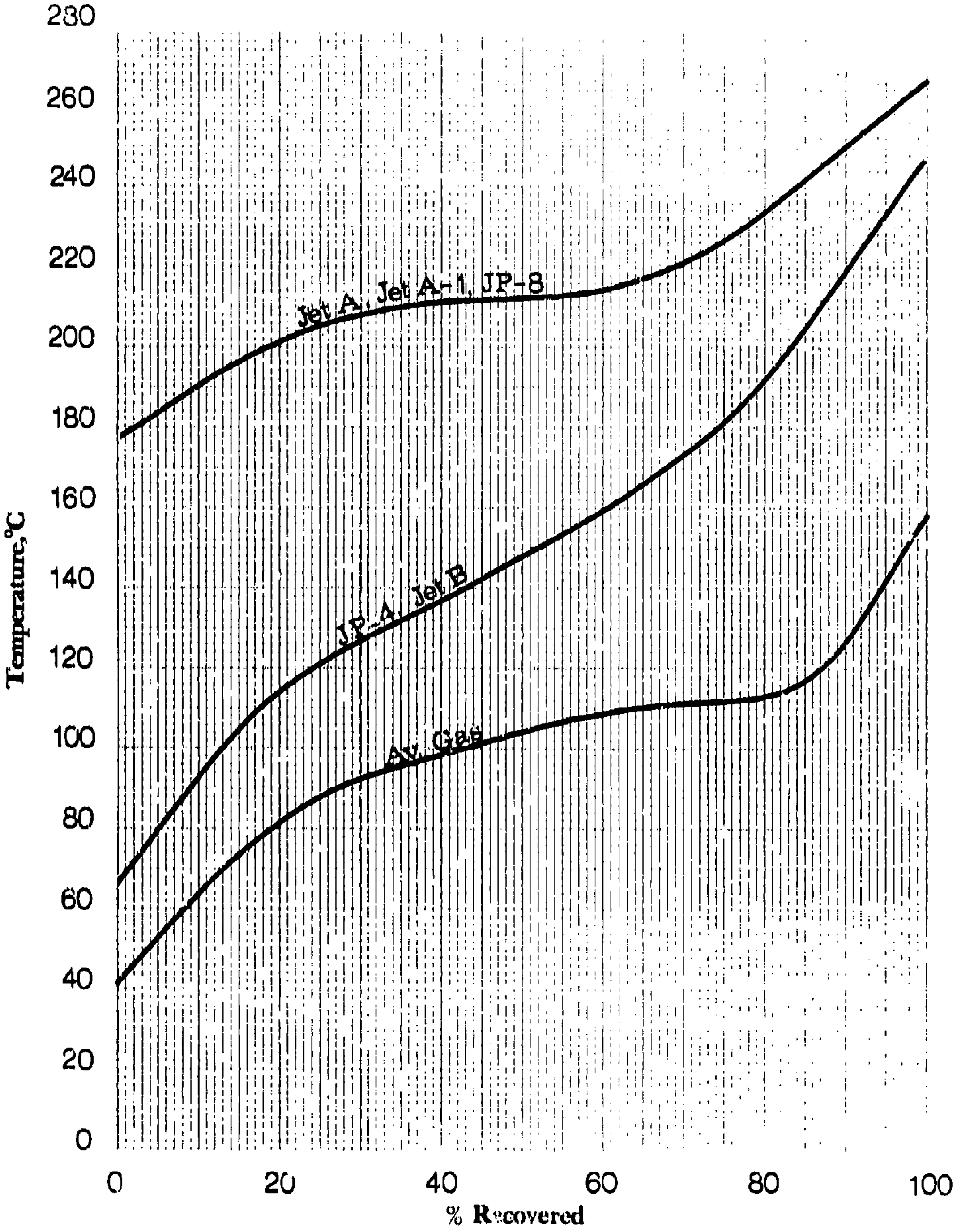

Figure 17
Typical Distillation Curves - ASTM D 86

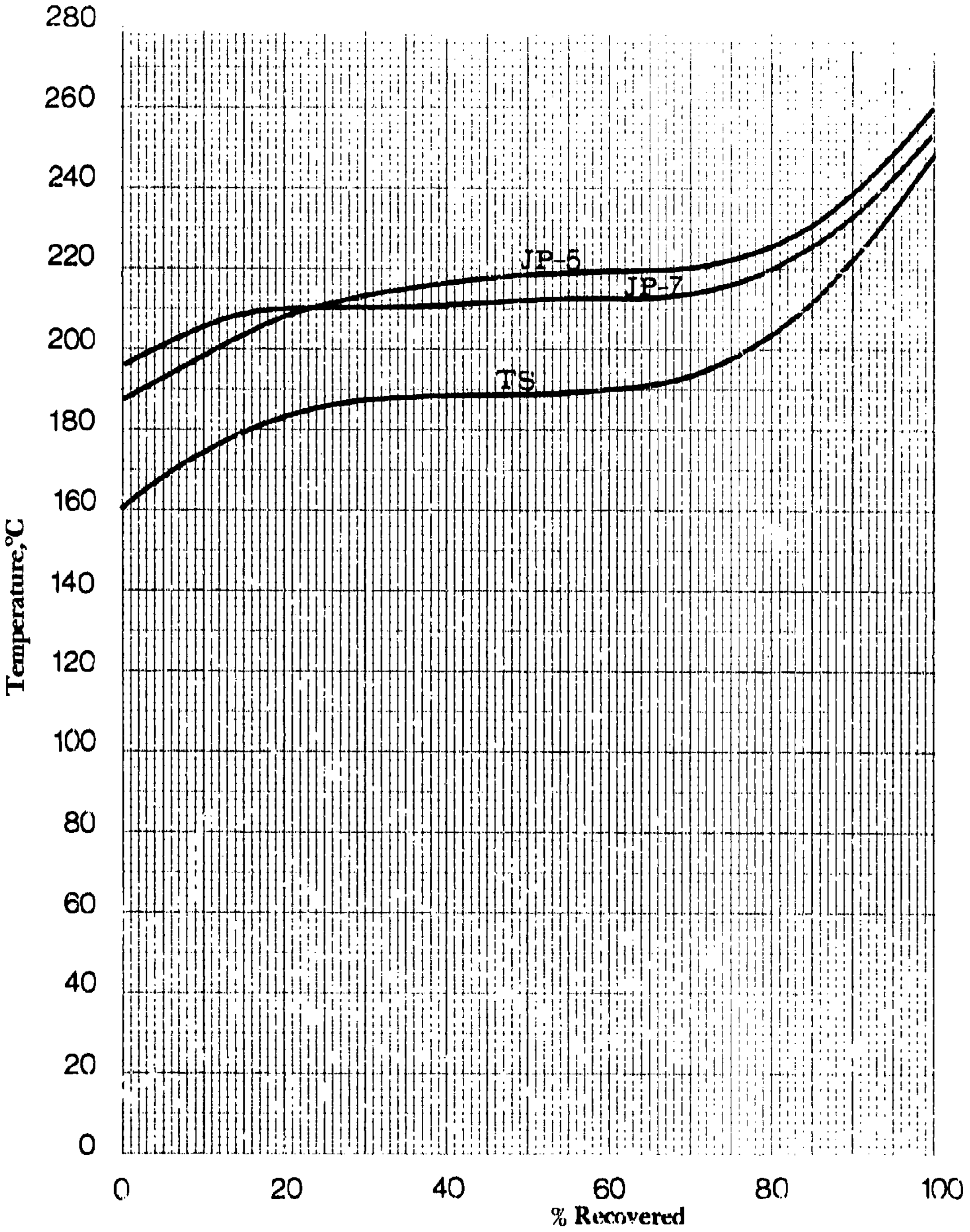

Figure 18
Typical Distillation Curves - ASTM D 86

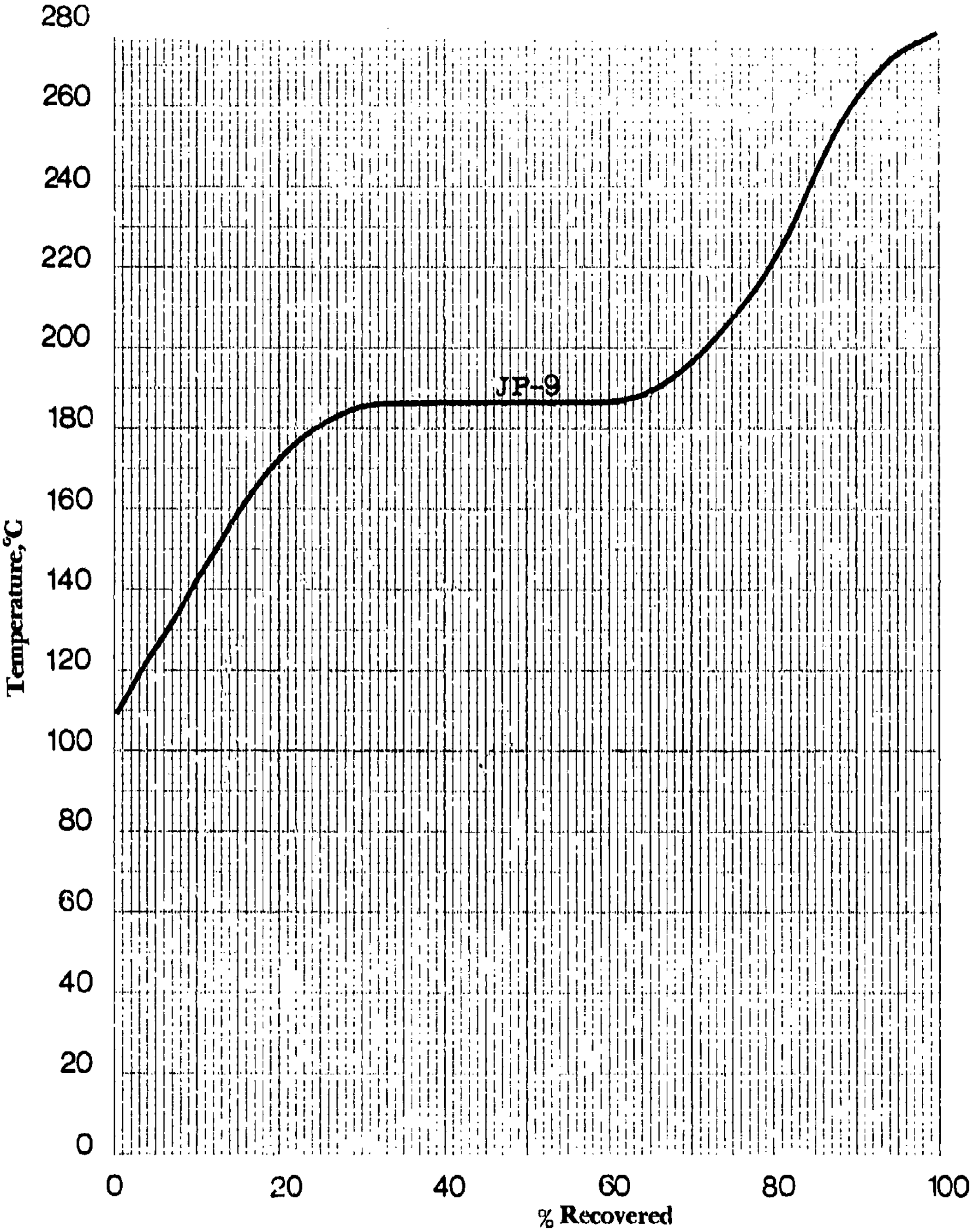

Figure 19
Typical Distillation Curves - ASTM D 86

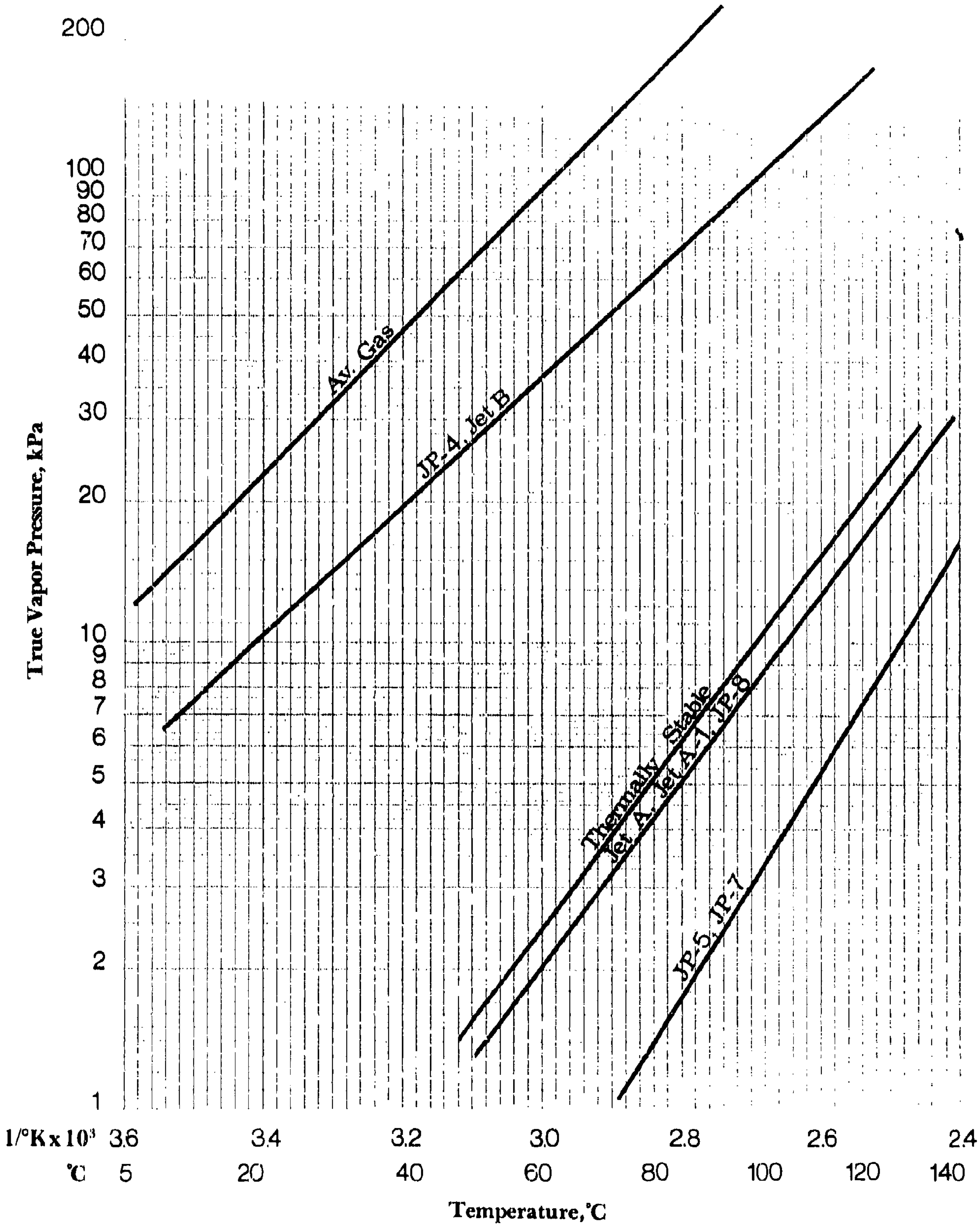

Figure 20
Vapor Pressure - Aircraft Fuels

1 kPa = .145 psi

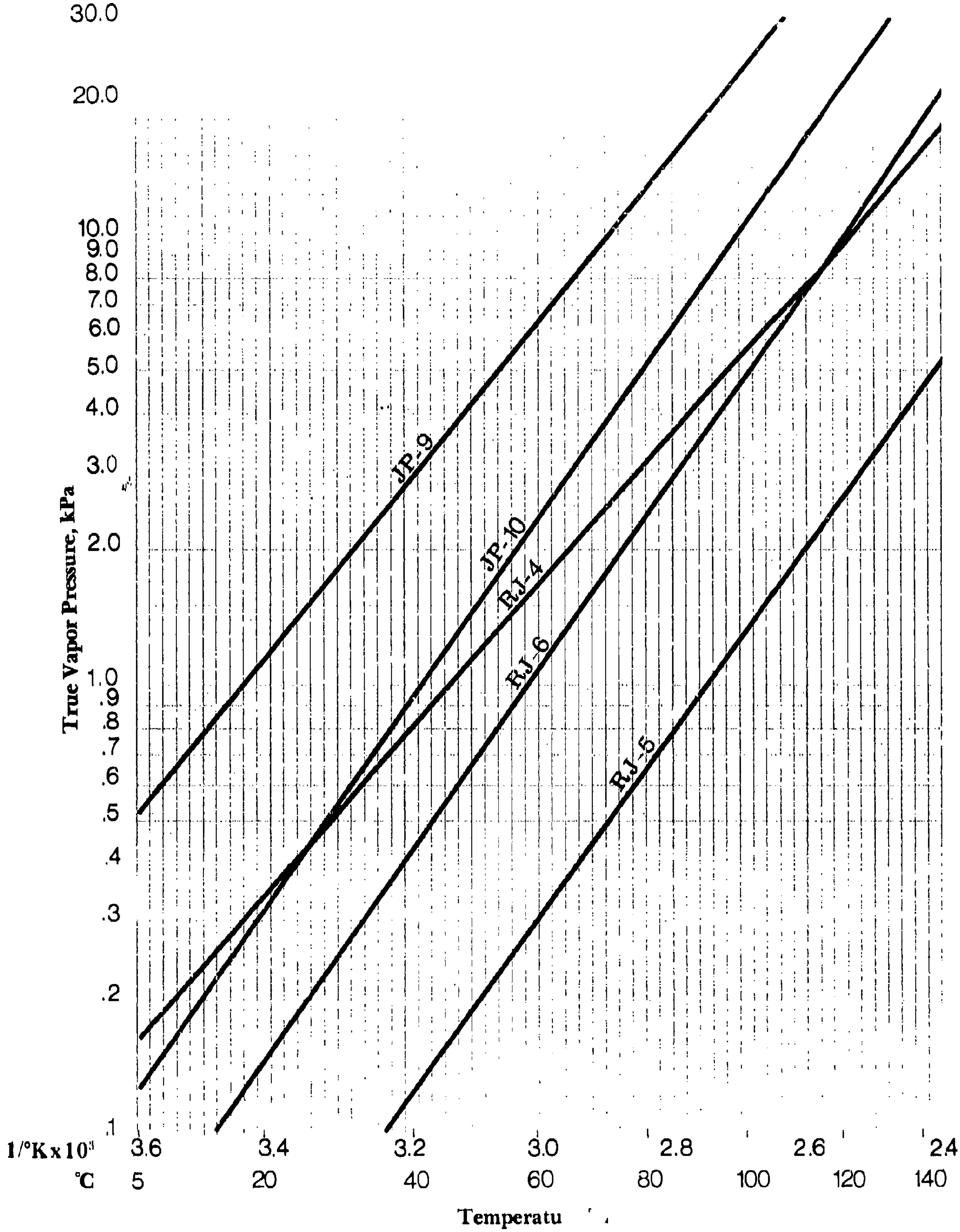

Figure 21
Vapor Pressure - Missile Fuels

1 kPa =.145 psi

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1. Coordinating Research Council, Inc., *CRC Aviation Handbook—Fuels and Fuel Systems*, NAVAIR 06-5-504, pages 48-109, May 1967.

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2.5 LOW-TEMPERATURE PROPERTIES

The low-temperature properties of fuels must be controlled to insure adequate and reliable system operation both in flight and on the ground. Basic fuel properties such as freezing point and viscosity are important factors in a fuel's pumpability. In addition, the formation of solid materials can cause flow restrictions. The low-temperature properties of fuels also have a profound effect on the availability of fuels and, therefore, must not be overly restrictive.

In view of the above, the optimal low-temperature criteria for fuels should be based on some direct means of insuring fuel pumpability at the temperatures to which the systems and fuels will be exposed. This approach has been attractive due to the ability of dry uncontaminated hydrocarbon fuels, particularly fuel types made up of complex mixtures, to be pumpable below their so called "freeze point." The freeze point determined under ASTM D 2386 is the temperature at which the visible solid fuel particles disappear on warming, the dry fuel having been chilled until crystals appear. Extensive efforts at developing a suitable pumpability test have not resulted in specification requirements based on pumpability due to the many variables encountered in such tests. The low-temperature characteristics of fuels are, therefore, rather arbitrarily controlled by the freezing point and viscosity limits at −20°C for those fuels which may be marginal from a flow standpoint at the lower temperatures. Table 7 tabulates freeze point and viscosity values for typical fuels.

TABLE 7
LOW-TEMPERATURE PROPERTIES OF AVIATION FUELS

	JP-4	JP-5	JET A	JET A-1	JET B	JP-7	JP-8	THERMALLY STABLE
FREEZE POINT, °C								
Specification Limit, Max	−58	−46	−40	−47	−50	−43.5	−50	−53.3
Typical Value	−62	−49	−45	−51	−62	−44	−54	−57
VISCOSITY, mm^2/s								
Specification Limits, Max	—	8.5@-20°C	8.0@-20°C	8.0@-20°	—	8.0@-20°C	8.0@-20°C	12@-40°C
Typical Value	1.75@-20°C	4.4@-20°C	5.0@-20°C	5.0@-20°C	1.8@-20°C	5.5@-20°C	5.0@-20°C	7@-40°C

LOW-TEMPERATURE PROPERTIES OF MISSILE FUELS

	RJ-4	RJ-5	RJ-6	JP-9	JP-10
FREEZE POINT, °C					
Specification Limit, Max	−40	−29	−54	−54	−79
Typical Value	−40	−18		−54	−79
VISCOSITY, mm^2/s					
Specification Limits, Max	120@-40°C	2,000@-40°C	140@-40°C	50@-54°C 20@-32°C 12@-18°C	37@-54°C 14@-32°C 9@-18°C
Typical Values	60@-40°C	2,000@-40°C	140@-40°C	42@-54°C 10@-32°C 6.5@-18°C	34@-54°C 14@-32°C 8.5@-18°C

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2. K. Ruh, K. Cuddlingtons, W. Dukek, and T. Shei, "Summary Report on Low Temperature Pumpability of Turbine Fuels," American Society for Testing and Materials, Research Division VII, Section E, May 1979.

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2.6 THERMAL PROPERTIES

Thermal properties of fuels include those properties of a fuel which are involved in heat-energy transfer to and from the fuel, the heat released or absorbed in the change of state of a fuel, and the heat released in the combustion of the fuel. These properties include specific heat, thermal conductivity, enthalpy, heat of vaporization, and net heat of combustion. These properties play an important role in the design of an aircraft system, and are essential to the performance of the system.

2.6.1 Specific Heat

The specific heat of a fuel is the amount of heat-energy transferred into or out of a unit mass of the fuel when increasing or decreasing its temperature. In fuel system analysis, specific heats are used in the calculation of heat-transfer, as the fuel is used as a coolant or as a heat sink. Specific heat is given in terms of kilo joules per kilogram Kelvin (kJ/kg·K) in the ASTM Standard for Metric Practice.

Figures 22 and 23 give the specific heats of aircraft fuels and missile fuels plotted against temperature. These data were derived from experimental and calculated methods. The experimental data were developed using a differential scanning calorimeter, while the bulk of the determinations were calculated from a correlation published by J. B. Maxwell using averaged fuel gravity and distillation data.

2.6.2 Thermal Conductivity

The thermal conductivity of a fuel is that thermal property of a fuel which controls the rate at which heat can flow by conduction through that fuel.

In the ASTM Standard for Metric Practice, it is expressed in terms of watt per meter Kelvin (W/m·K). It is extensively used in heat-transfer calculations when fuel is heated in heat exchangers, when it is used as a heat sink, when fuel is heated or cooled in flight or on the ground, or whenever there is a temperature gradient within the fuel.

In Figure 24, the thermal conductivity is plotted as a function of temperature for hydrocarbon fuels. This curve is based on experimental data developed for JP-4, JP-5, JP-7, JP-8, Jet A, Jet A-1, Jet B, and RJ-6. The accuracy of values obtained from this chart should be within 10 percent of actual values.

2.6.3 Enthalpy

Enthalpy is the heat-energy required to bring a fuel from one reference state to another state; therefore, it is a function of the integral of the specific heat between the two states, and any latent heat of vaporization that was required in the interval. Enthalpy is quantified in terms of kilo joule per kilogram (kJ/kg) in the ASTM Standard for Metric Practice.

Figures 25 and 26 are enthalpy diagrams for typical JP-4 and JP-5, respectively. In these figures, the saturated liquid curve represents the heat that can be absorbed in the liquid phase alone, and the saturated vapor curves represent the heat absorbed to completely vaporize the fuel. The intermediate area represents partial vaporization, whereas the curves above this saturated vaporization line represent super-heated vapor. The line of constant pressure provides the pressure relationship to determine the state of vaporization of the fuel for the addition of a given amount of heat.

2.6.4 Heat of Vaporization

The heat of vaporization is the amount of heat added to vaporize a unit weight of a liquid at a constant pressure below the critical point. As the pressure increases, the heat of vaporization decreases; and at the critical point, the heat of vaporization becomes zero. The heat of vaporization can be calculated at sea-level pressure by the use of equations in Reference 5. At other temperatures and pressures, a general method outlined in Reference 6 must be used. Figure 27 is a plot of the heat of vaporization of various fuels versus temperature in kilo joules per kilogram (kJ/kg).

2.6.5 Heat of Combustion (Specific Energy)

The energy stored in fuel is released as heat when a unit weight is burned in a bomb-type calorimeter under controlled conditions to produce gaseous carbon dioxide and liquid water containing sulfuric and nitric acids. The gross heat of combustion or specific energy of the fuel in terms of mega joules per kilogram (MJ/kg) or Btu per pound (Btu/lb) is calculated from the rise of temperature after suitable corrections are made. In an aircraft gas turbine, the product water from combustion leaves in the vapor phase; hence, the heat of vaporization of water as determined from the hydrogen content of the fuel is subtracted from the gross heat of combustion to determine net heat of combustion, the proper basis for comparison of aircraft fuels.

2.6.5.1 Net Heat of Combustion of Aircraft Fuels

The net heat of combustion per unit weight is an important factor in aircraft performance. Empirical methods ASTM D 1405 and D 3338 are used to calculate the heat of combustion of some aircraft fuels. Experimental methods ASTM D 240 and D 2382 can also be used and are specifically required in some specifications. In the ASTM Standard for Metric Practice, the heat of combustion is quantified in mega joules per kilogram (MJ/kg).

Figure 28 presents typical net heat of combustion ranges for the various aircraft fuels. Where available, typical values are given.

2.6.5.2 Net Heat of Combustion of Missile Fuels

The heat of combustion per unit volume is an important factor as applied to missile performance. Experimental methods ASTM D 240 and D 2382 are used to determine the basic values in terms of heat release per unit volume depending upon the density of a particular fuel. In the ASTM Standard for Metric Practice, the volumetric heating value is quantified in terms of mega joules per cubic meter (MJ/m^3).

Figure 29 presents typical net heat of combustion ranges per unit volume for the various missile fuels.

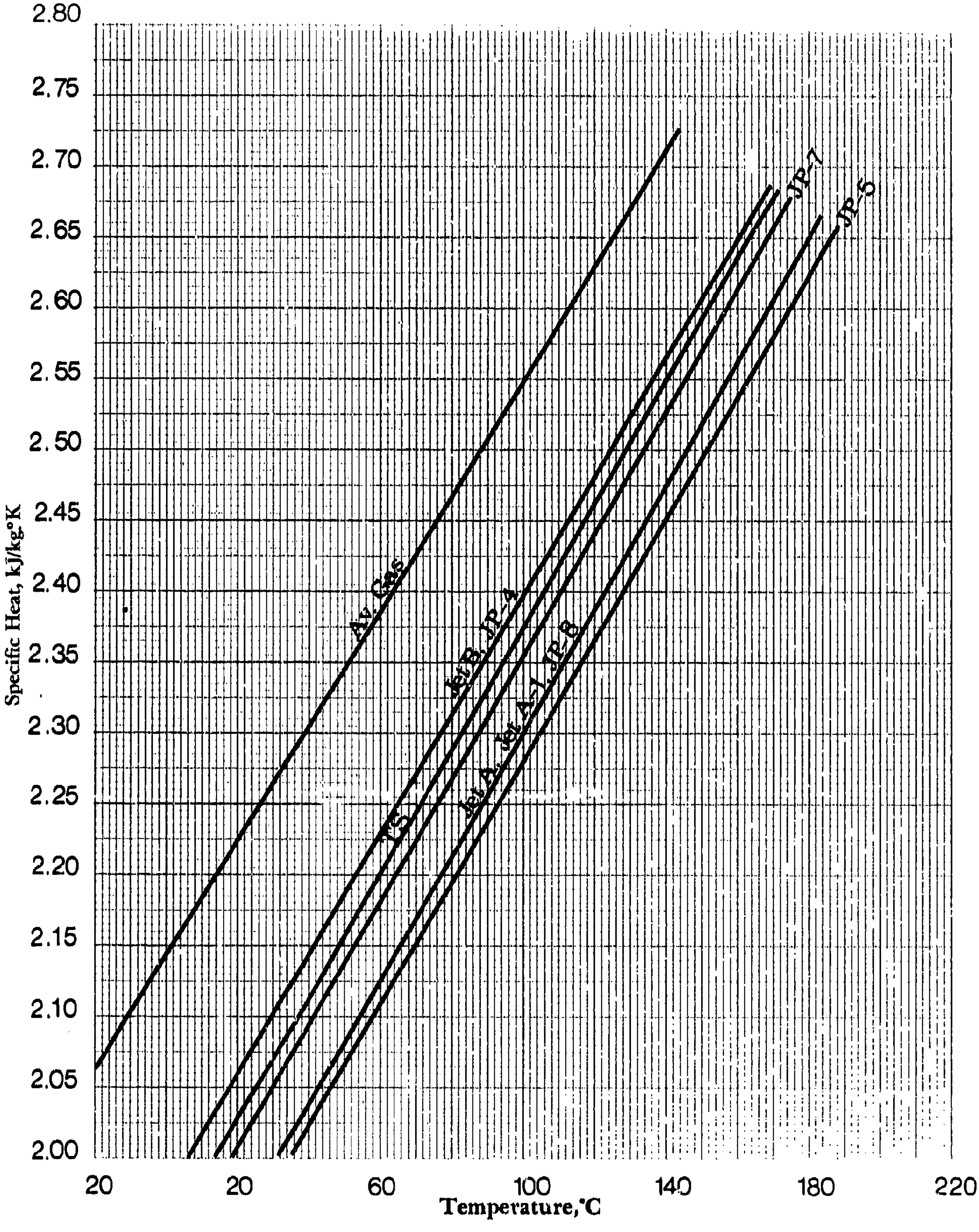

Figure 22
Typical Specific Heat vs. Temperature for Aircraft Fuels

1 kJ/kg • °K = .239 Btu/lb. • °F

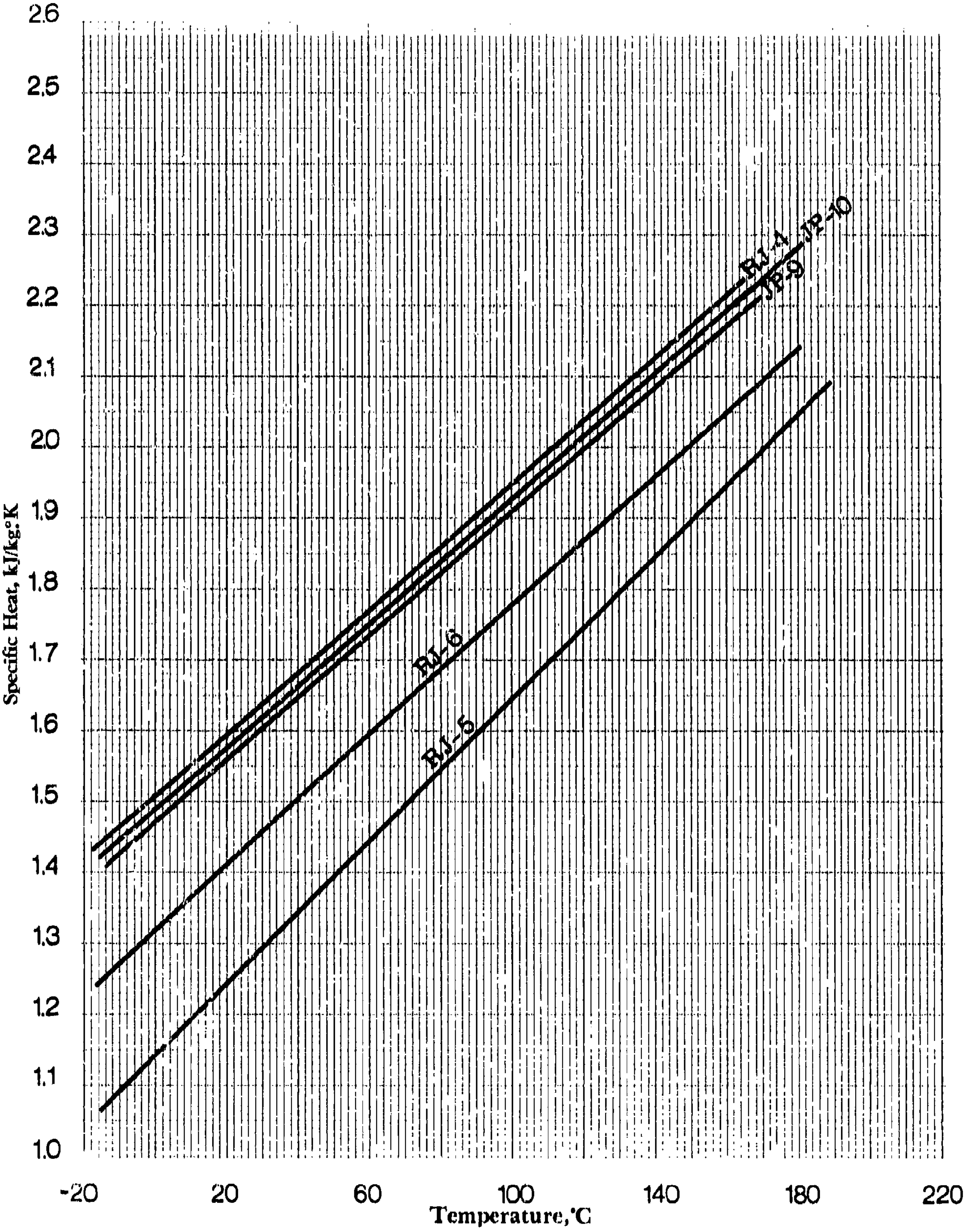

Figure 23
Typical Specific Heat vs. Temperature for Missile Fuels

1 kJ/kg • °K = .239 Btu/lb • °F

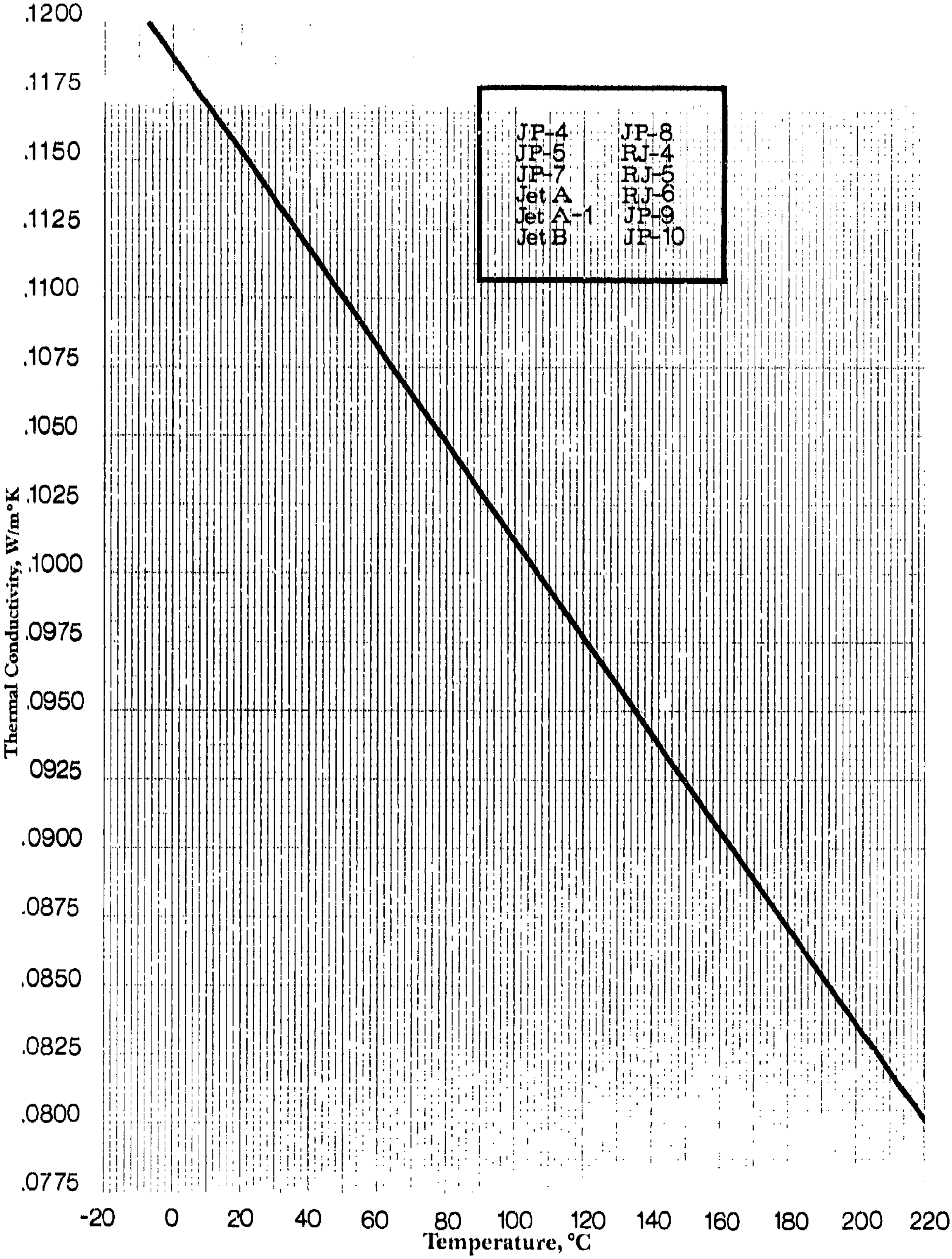

Figure 24
Thermal Conductivity of Hydrocarbon-Based Fuels

1 W mK = .578 Btu ft (h • ft^2 • F)

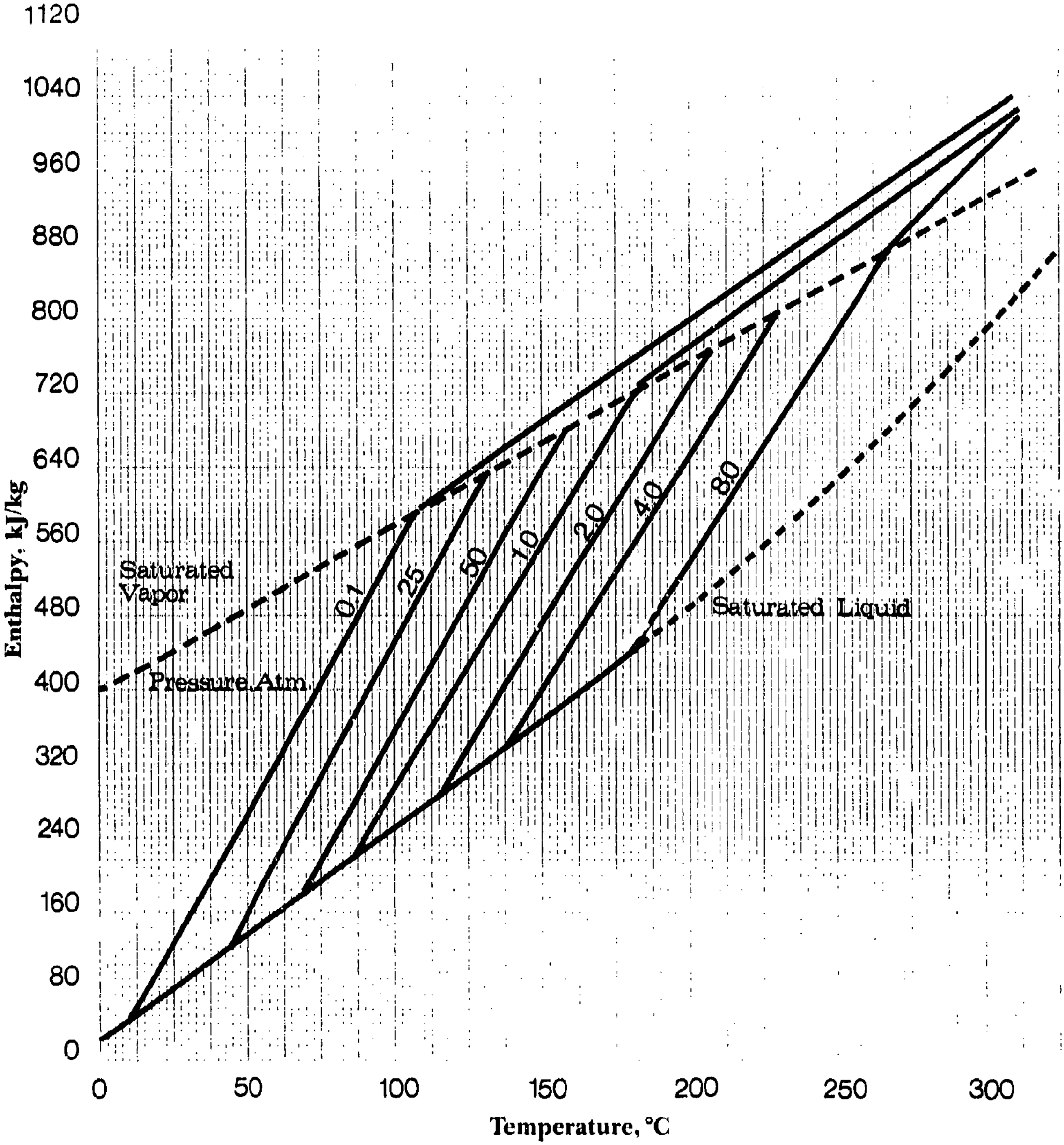

Figure 25
Enthalpy Diagram, JP-4

1 kJ/kg = .43 Btu/lb

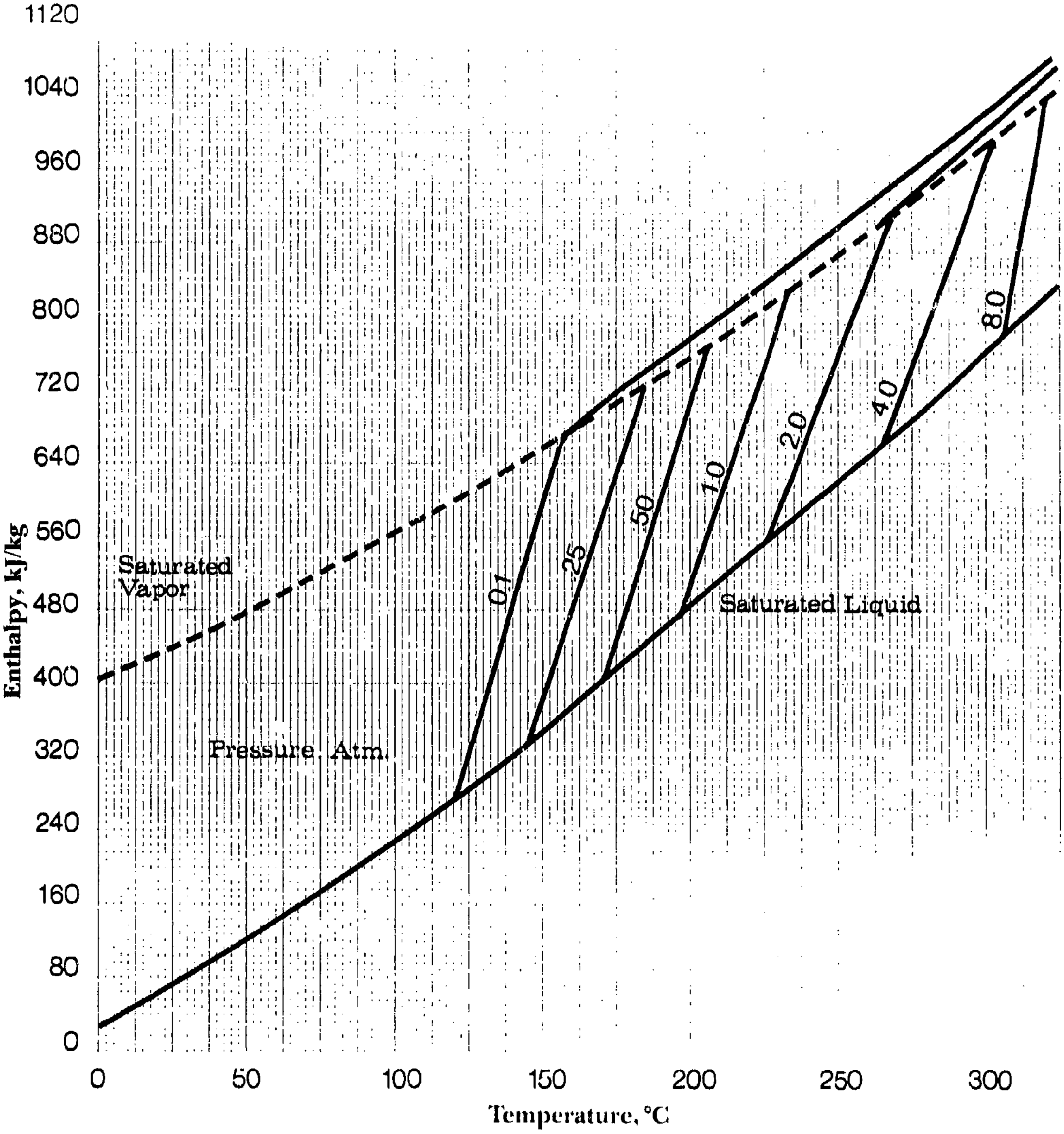

Figure 26
Enthalpy Diagram, JP-5

1 kJ/kg = .43 Btu/lb

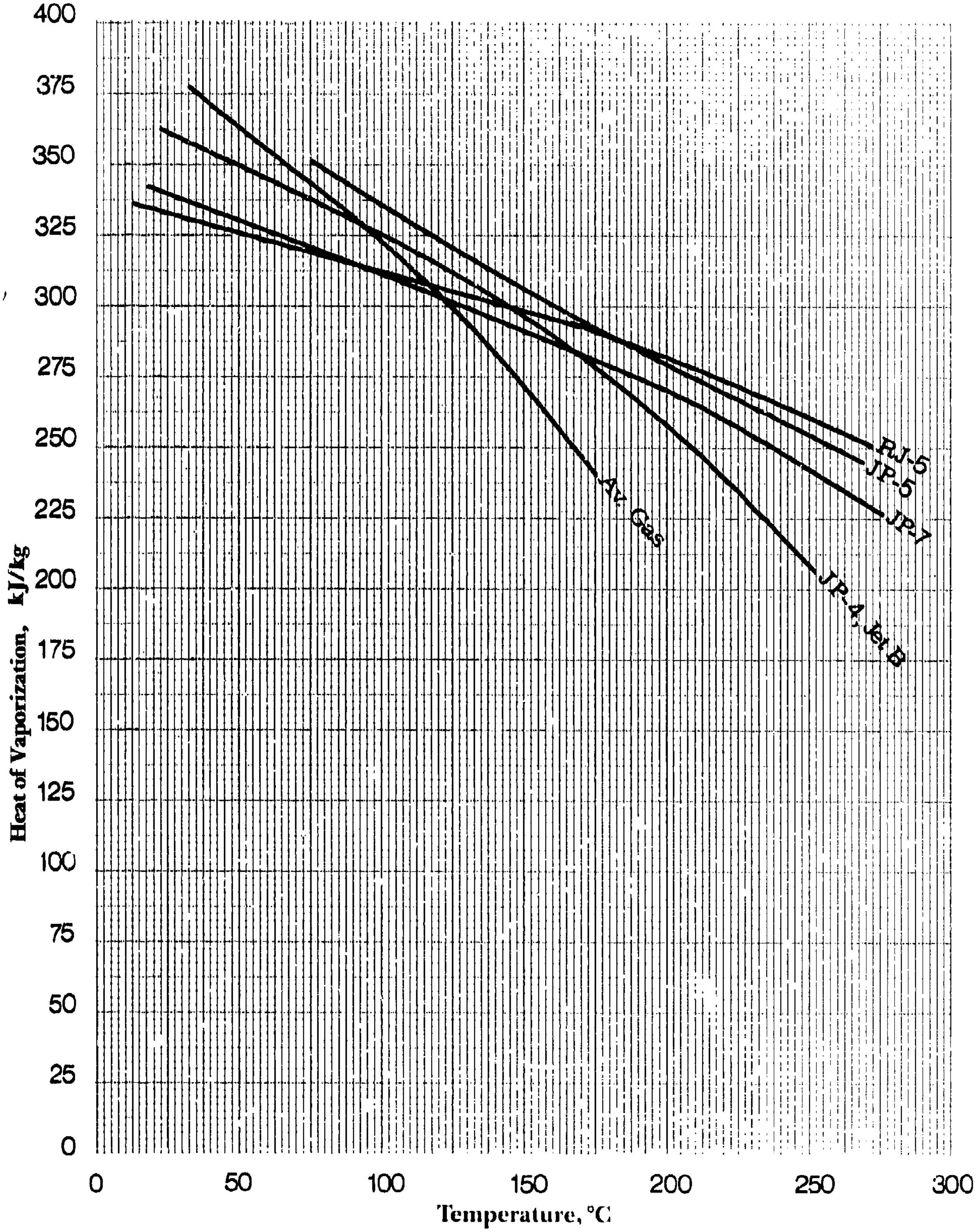

Figure 27
Heats of Vaporization For Various Hydrocarbons at 1 Atm.

1 kJ/kg = .43 Btu/lb

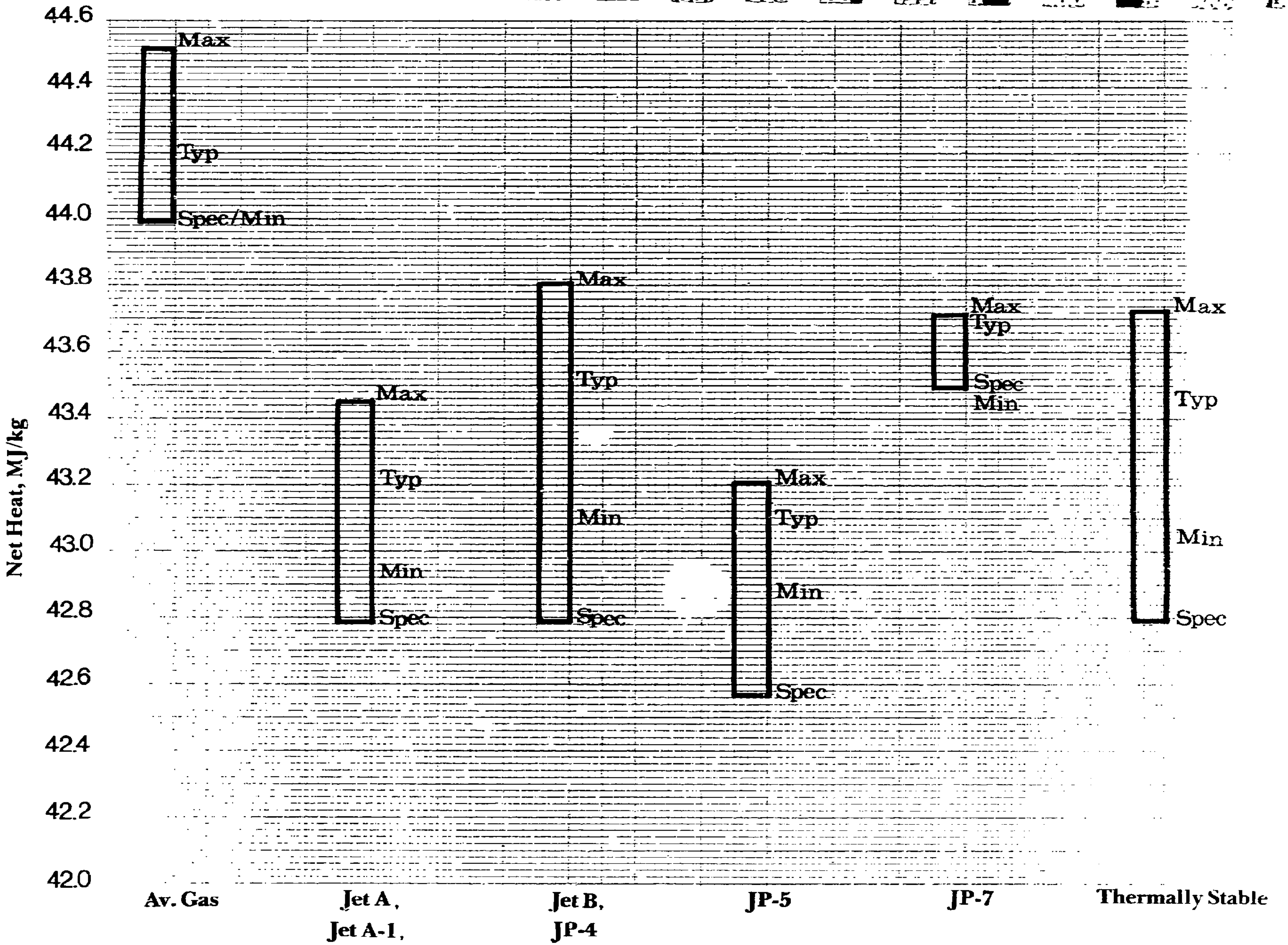

Figure 28
Net Heat of Combustion - Aircraft Fuels

1 MJ kg = 430 Btu lb

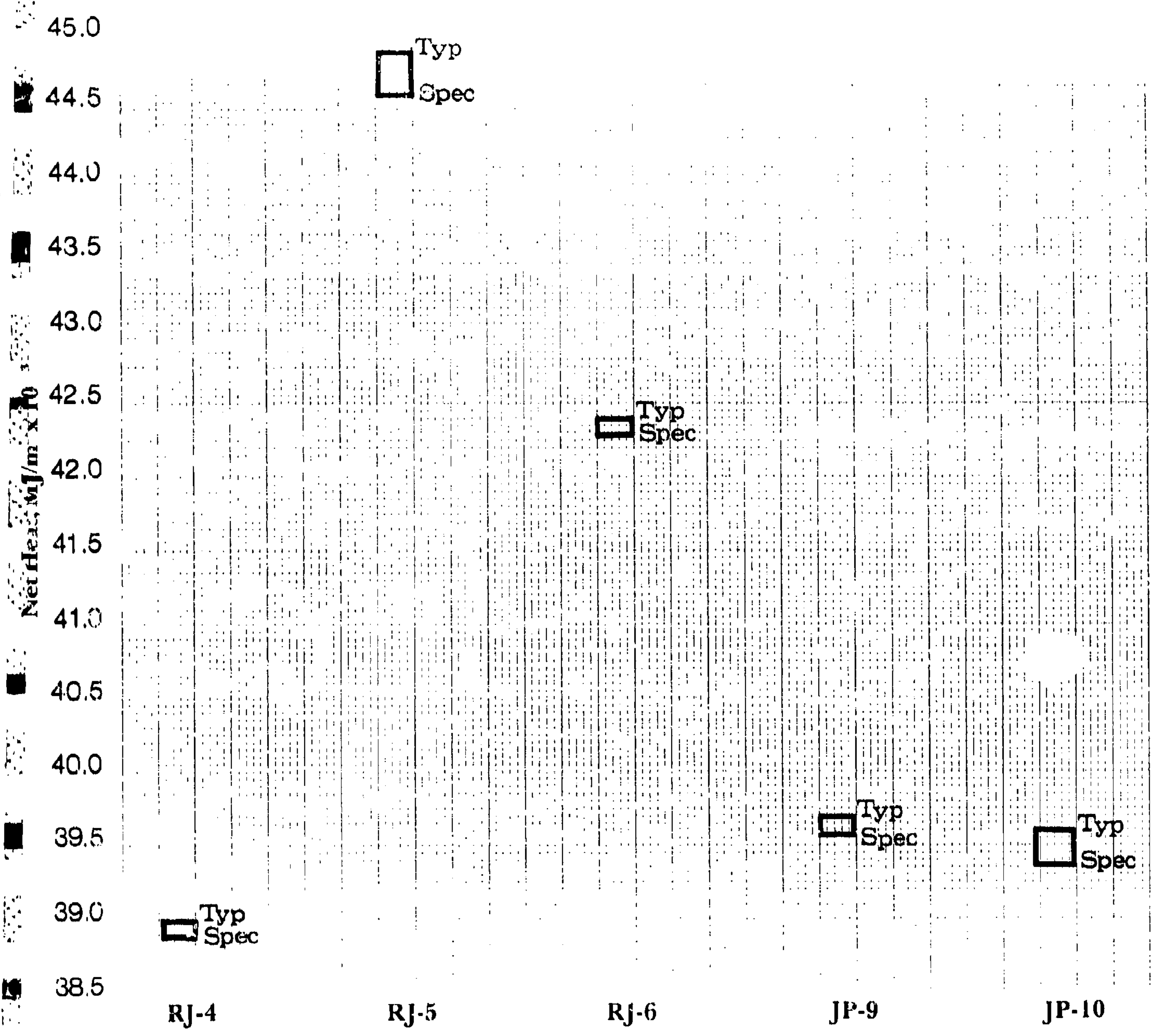

Figure 29
Net Heat of Combustion per Unit Volume - Missile Fuels

1 MJ/m^3 = 3.59 Btu/gal.

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1. F. N. Hodgson, W. Scribner, and A. M. Kenner, "Environmental Degradation of Fuels, Fluids, and Related Materials for Aircraft," Monsanto Research Corporation, AFAPL-TR-74-8, Volume 2, March 1974.

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2.7 ELECTRICAL CHARACTERISTICS

Fuels have electrical characteristics that are important to aircraft and fuel system designers. These characteristics become evident in the manner in which a fuel reacts to the flow of an electrical current. Of major importance is the conductivity of a fuel which plays a primary role in the electrostatic charge buildup in a fuel as it flows through a system. The dielectric properties relate to the way a fluid varies the capacitive reactance of a pair of parallel electrodes, and is the key to the design of fuel gages.

2.7.1 Dielectric Constant (Permittivity)

The dielectric constant of a fuel is experimentally determined by establishing the ratio of the electrical capacitance of a device filled with the fuel as compared with the electrical capacitance of the same device when filled with air. Measurements of the dielectric constant of a fuel at various temperatures show that the dielectric constant is a linear function of temperature, decreasing with increasing temperature and varying with the applied frequency. Figures 30 and 31 give the relationship between dielectric constant versus temperature for the various aircraft and missile fuels. The data presented are at 400 Hz, which is the most used frequency in commercial and military aircraft. This indicates that fuel gages based on this fuel property must be calibrated for the particular fuel being measured.

2.7.2 Electrical Conductivity

Pure hydrocarbons and mixtures of hydrocarbons such as fuels are essentially nonconductors of electricity. In practice, however, they always contain trace amounts of materials which increase their conductivity to a lesser or greater extent, depending upon the chemical nature and the concentration of the impurities. In most cases, the conductivity of the fuels is still very low. In any event, this low conductivity is the fundamental property that can cause a very hazardous situation to arise in handling flowing fuels.

A fuel when flowing tends to become electrically charged due to a shearing mechanism called "charge separation." This phenomenon can cause the development of high levels of electrostatic charges within the fuel which cannot be dissipated due to the low conductivity of the fuel. These free charges can build up to levels high enough to cause static discharges through the vapors in tanks. Depending upon the composition of the vapor phase, ignition may occur. The phenomena are highly complex and involve a multitude of variables depending upon the system and conditions being encountered. Such factors as high contact areas encountered in filter separators, relaxation time required for charge dissipation, fuel system design, protruding devices in flow channels, impurity levels in the fuel, and many other factors influence the degree of hazard. At the root of the problem, however, is the fundamental low conductivity of fuels which in most cases is in the range of 0.1 to 5.0 pS/m, even with trace impurities present.

Although devices have been developed in an effort to decrease and measure the charge buildup in fuels, the most successful approach has been the introduction of an additive to increase the overall conductivity of the fuel. A minimum of 50 pS/m is considered to furnish adequate conductivity for handling safety. The maximum limit of 600 pS/m is set low enough to prevent malfunctions of fuel quantity gages. Fuels will generally show decreased conductivities at lower temperatures. Due to this factor, most fuels are treated with enough additive to produce a conductivity of 175 to 200 pS/m at 15.5°C, so that they will still retain conductivities of at least 50 pS/m at lower temperatures. Figure 32 shows the change in conductivity versus temperature for typical JP-4 and JP-8, with and without additives.

A complete review of the generation and dissipation of electrostatic charge with a selected literature survey can be found in Reference 1.

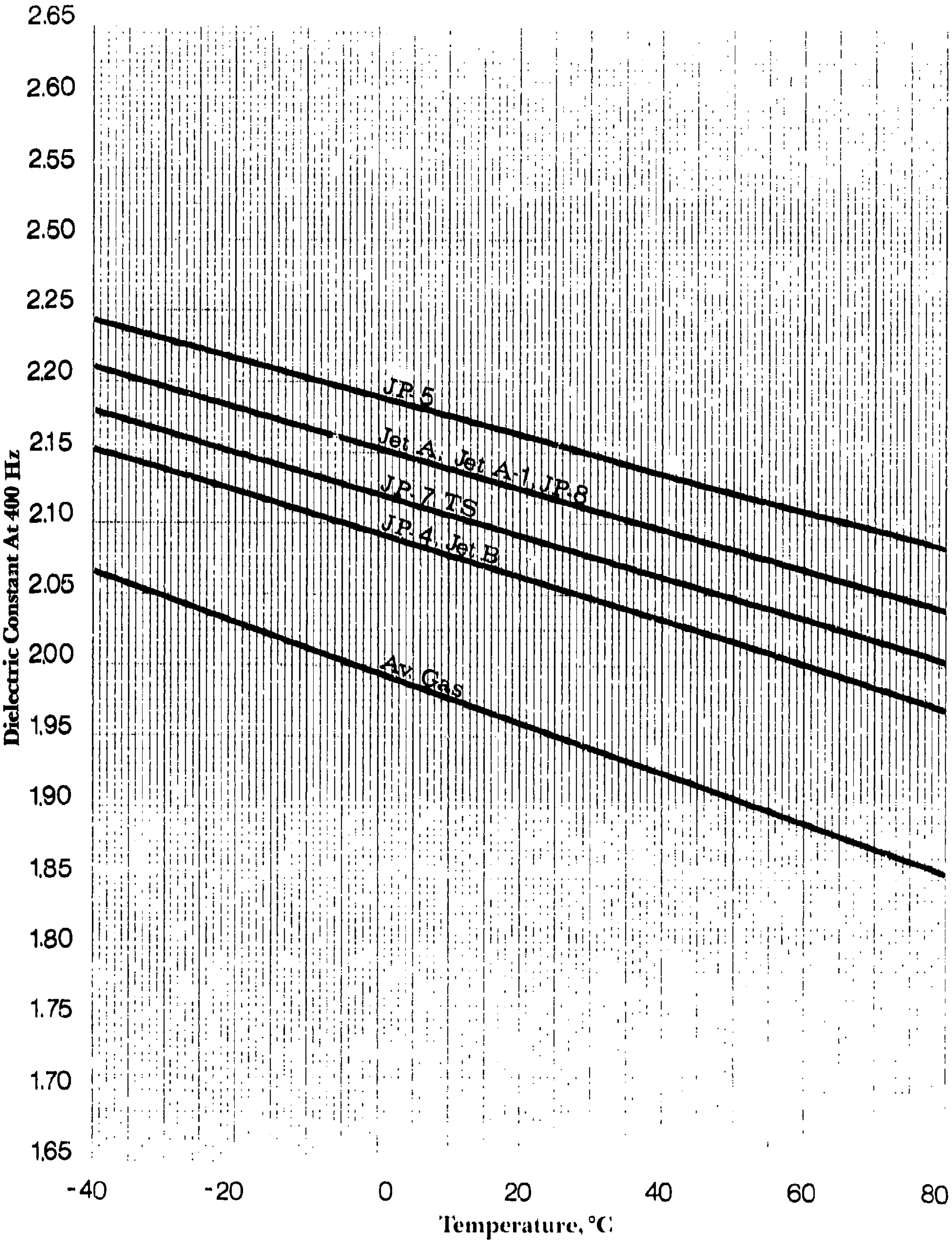

Figure 30
Dielectric Constant vs. Temperature For Typical Aircraft Fuels

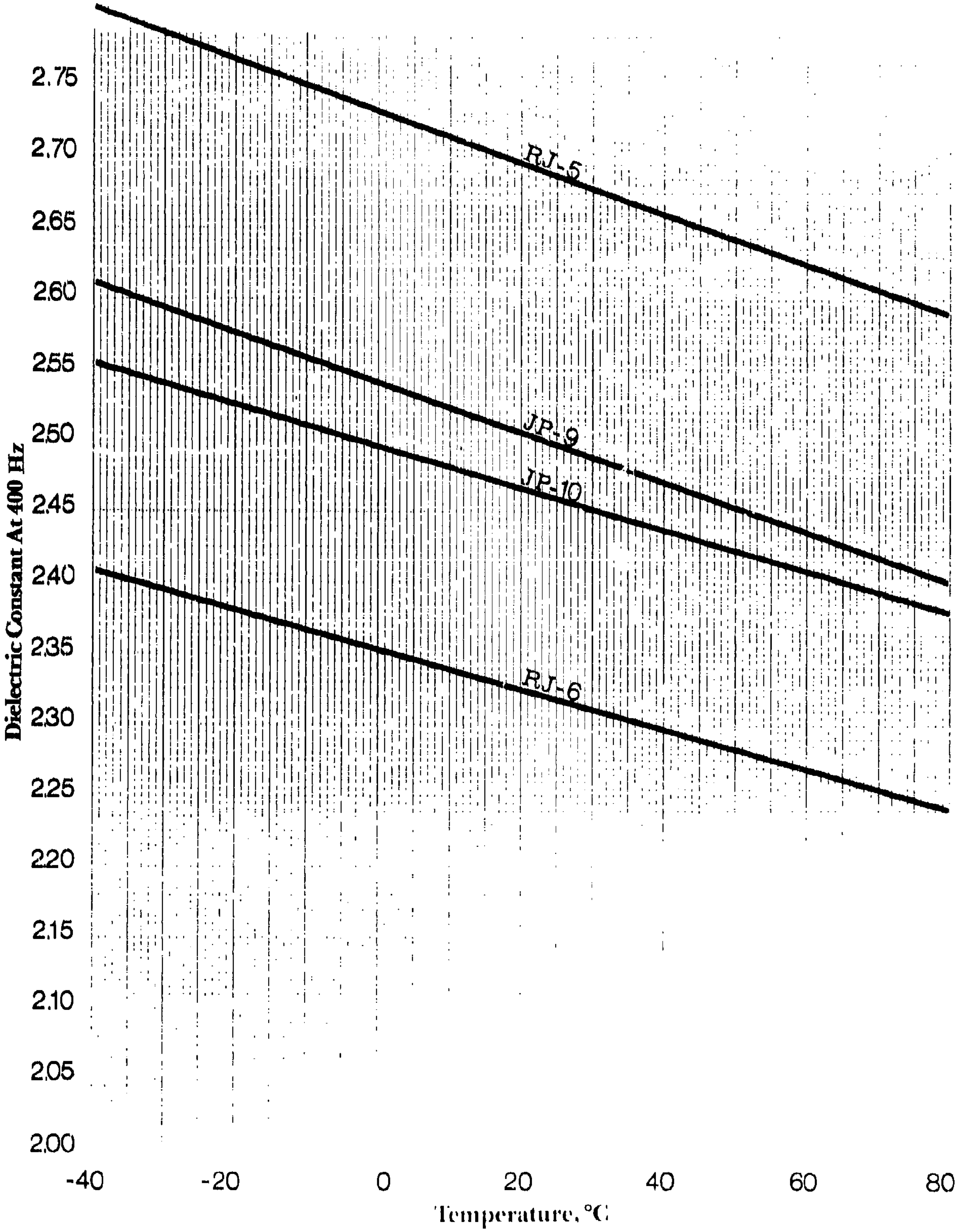

Figure 31
Dielectric Constant vs. Temperature For Typical Missile Fuels

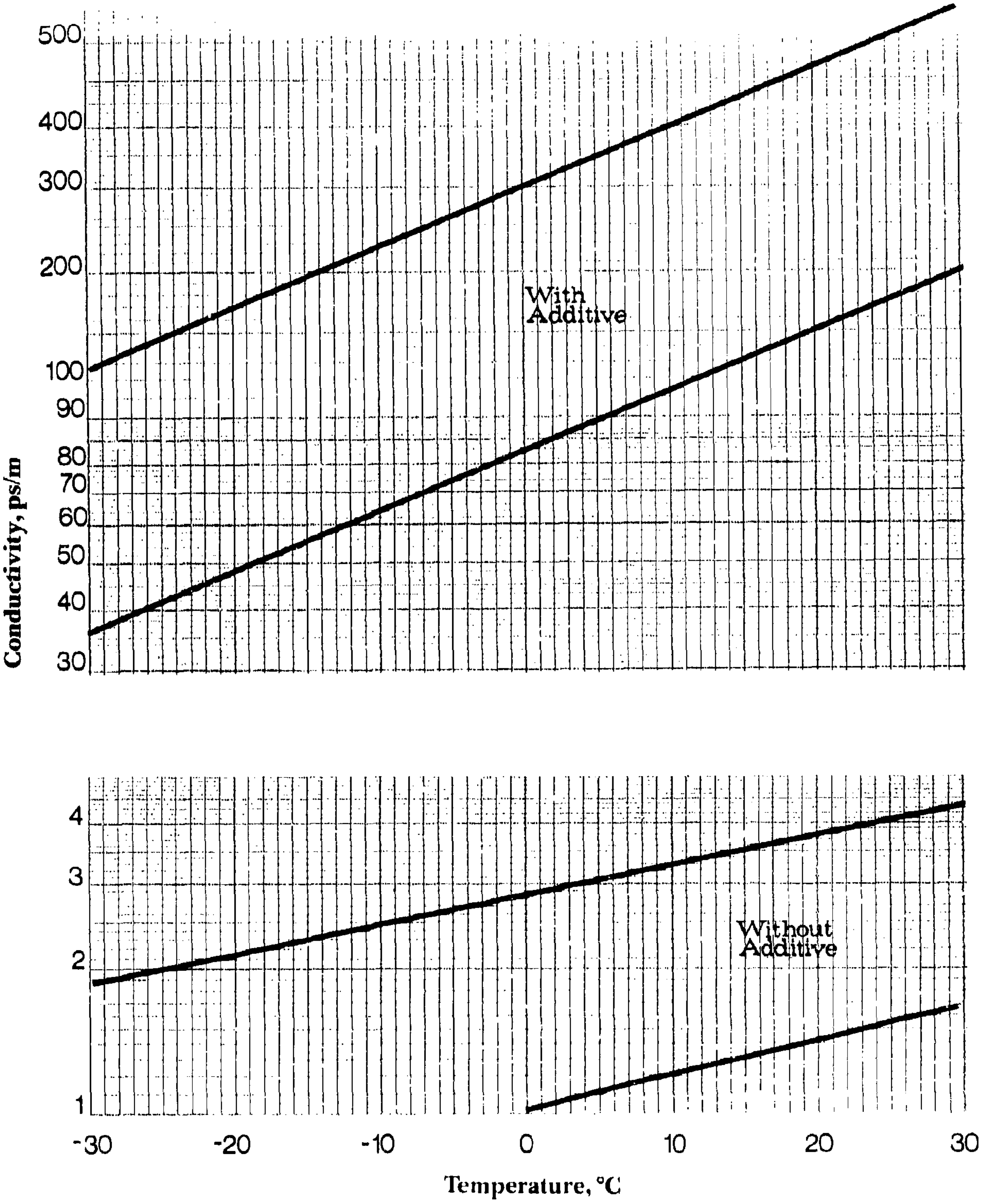

Figure 32
Typical Range of Conductivity vs. Temperature for Aircraft Fuels

REFERENCES

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2.8 FLAMMABILITY AND IGNITION CHARACTERISTICS

The combustion properties of fuels have been studied extensively due to their importance in the safety aspects of system design and performance of propulsion devices. The basic ingredients necessary for combustion are fuel vapor, air, and an ignition source. In actuality, a multitude of variables and influencing factors must be taken into consideration. A complete review of this subject is beyond the scope of this report, and only selected data are presented. The goal of this report is mainly to establish relationships among the various fuels. The data should be used with caution, since each specific situation may have other factors which must be considered. Extensive literature references are found in the referenced documents, which cover many of the influences of non-equilibrium conditions and system design effects.

Table 8 presents typical flammability and ignition properties of aircraft fuels which are measures of the relative fire hazards of the fuels. These values are typical, and vary significantly within the same fuel specification. Table 9 gives typical flammability and ignition properties of missile fuels.

2.8.1 Flammability Limits Versus Altitude

Self-sustained combustion occurs within certain ranges of fuel vapor-air ratios which are a function of temperature and pressure. Therefore, at any given pressure or altitude, a particular fuel will have a lean (lower) flammability temperature limit; and at a higher temperature, a rich (upper) flammability limit. Outside these limits, combustion will not occur if the system is in equilibrium with no spray or mist present. Figure 33 gives the flammability temperature limits for various fuels versus altitude in meters.

2.8.2 Flash Point

Flash point is the best known and most widely used flammability property for the evaluation of the flammability hazard of combustible liquids. It is an important criterion for the fire-hazard rating of these liquids. A number of methods have been developed for the determination of flash point, which are based on placing a sample of the liquid being tested in a cup and heating at a constant rate. A small flame is directed into the cup at intervals, and the lowest temperature at which the vapor of the sample ignites is taken as the flash point. The methods used are classified either as closed-cup (closed to the atmosphere and exposed only at the moment of application of the test flame), or open-cup (open to the atmosphere). Usually, flash points obtained by closed-cup methods are lower and more reliable than those obtained by open-cup methods. Figure 34, using the closed-cup ASTM Method D 93 for flash point determinations, illustrates the fact that very small quantities of a volatile fuel such as Jet B reduces the flash point of a low-volatility Jet A fuel in a nonlinear manner. For example, a 10-percent addition of Jet B to Jet A reduces the flash-point temperature of Jet A by 30°C.

TABLE 8
TYPICAL FLAMMABILITY AND IGNITION PROPERTIES OF AIRCRAFT FUELS

PROPERTY	AV GAS 100/130	JP-4 JET B	JET A JP-8	JP-5	JP-7
Distillation Range (°C)	40-148	61-239	167-266	182-258	189-251
Magnitude of Distillation Range (°C)	108	178	99	76	62
Reid Vapor Pressure, 38°C (kPa)	46	18	1.4	0.6	
Net Heat of Combustion					
By Weight (kJ/kg)	44,150	43,570	43,240	43,050	43,682
By Volume (MJ/m^3)	31,130	33,190	35,060	35,200	39,700
Flammability Conc. Limits[1] (Vol. %)					
Lower ("lean") Limit	1.2	1.3	0.6	0.6	0.6
Upper ("rich") Limit	7.0	8.0	4.7	4.6	4.6
Flammability Temperature Limits[1] (°C)					
Lower ("lean") Limit[2] (1 atm)	−44	−23	53	64	60
Upper ("rich") Limit (1 atm)	−12	18	77	102	100
Autoignition Temperature (°C)[1] (1 atm)	443	246	238	241	241
Minimum Electric Spark Ignition Energy (mJ)[1]	0.20	0.20	0.20	0.20	0.20
Approximate Burning Velocity[1] (m/s)	0.3-0.6	0.3-0.6	0.3-0.6	0.3-0.6	0.3-0.6

[1] Fuel vapors in air.

[2] Tag closed - cup flash-point data. Experimental flash points are generally higher than limit data.

TABLE 9
TYPICAL FLAMMABILITY AND IGNITION PROPERTIES OF MISSILE FUELS

PROPERTY	RJ-4	RJ-5	RJ-6	JP-9	JP-10
Distillation Range (°C)	207-221	260-285	182-285	99-295	182
Magnitude of Distillation Range (°C)	14	25	103	186	0
Net Heat of Combustion					
By Weight (kJ/kg)	42,182	41,300	41,792	42,087	42,100
By Volume (MJ/m^3)	39,600	44,900	42,400	39,700	39,600
Autoignition Temperature (°C)	329	234	232	250	245
Flash Point (°C)	71	104	61	23	53

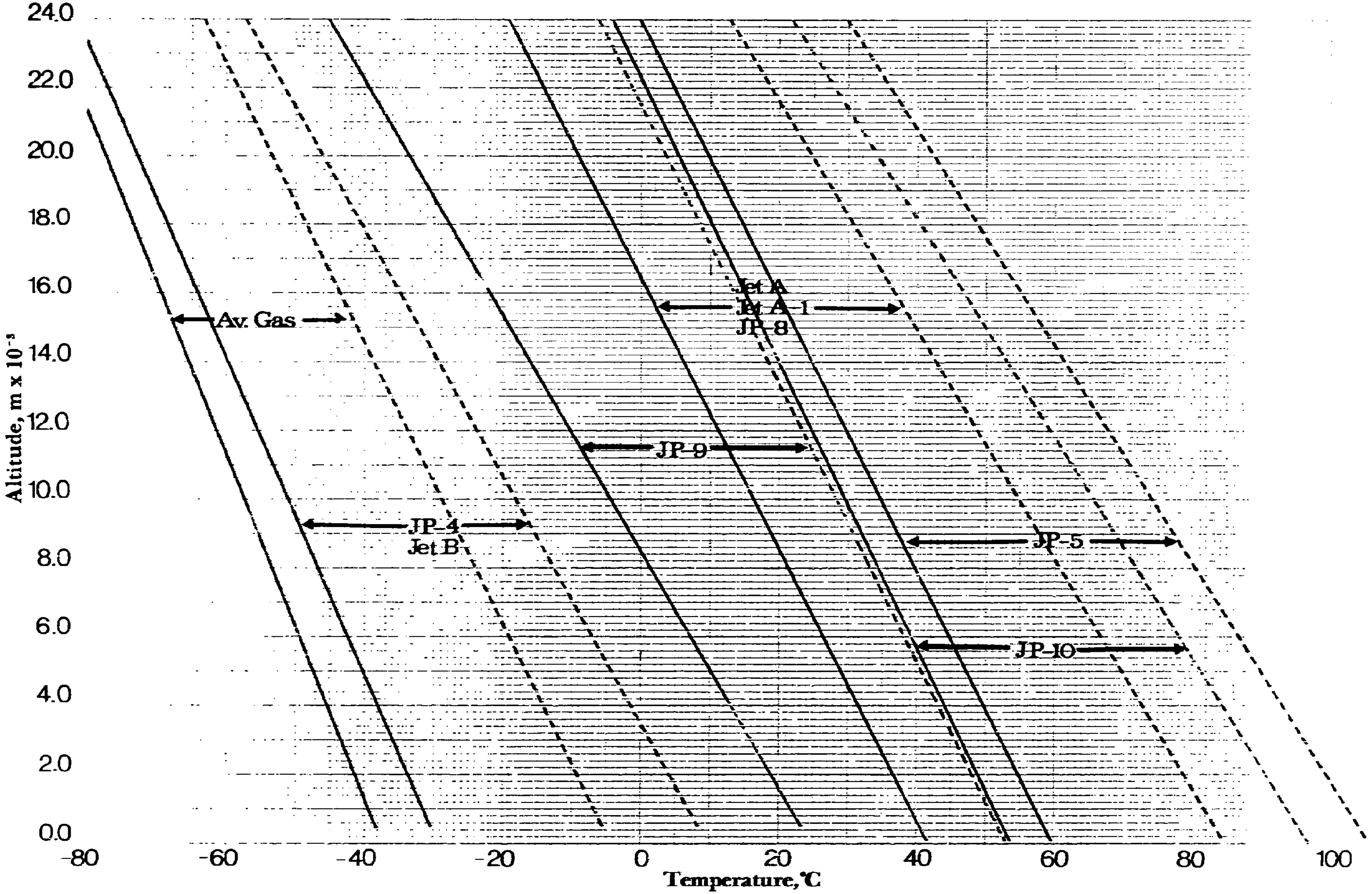


Figure 33
Fuels Flammability Limits vs. Altitude

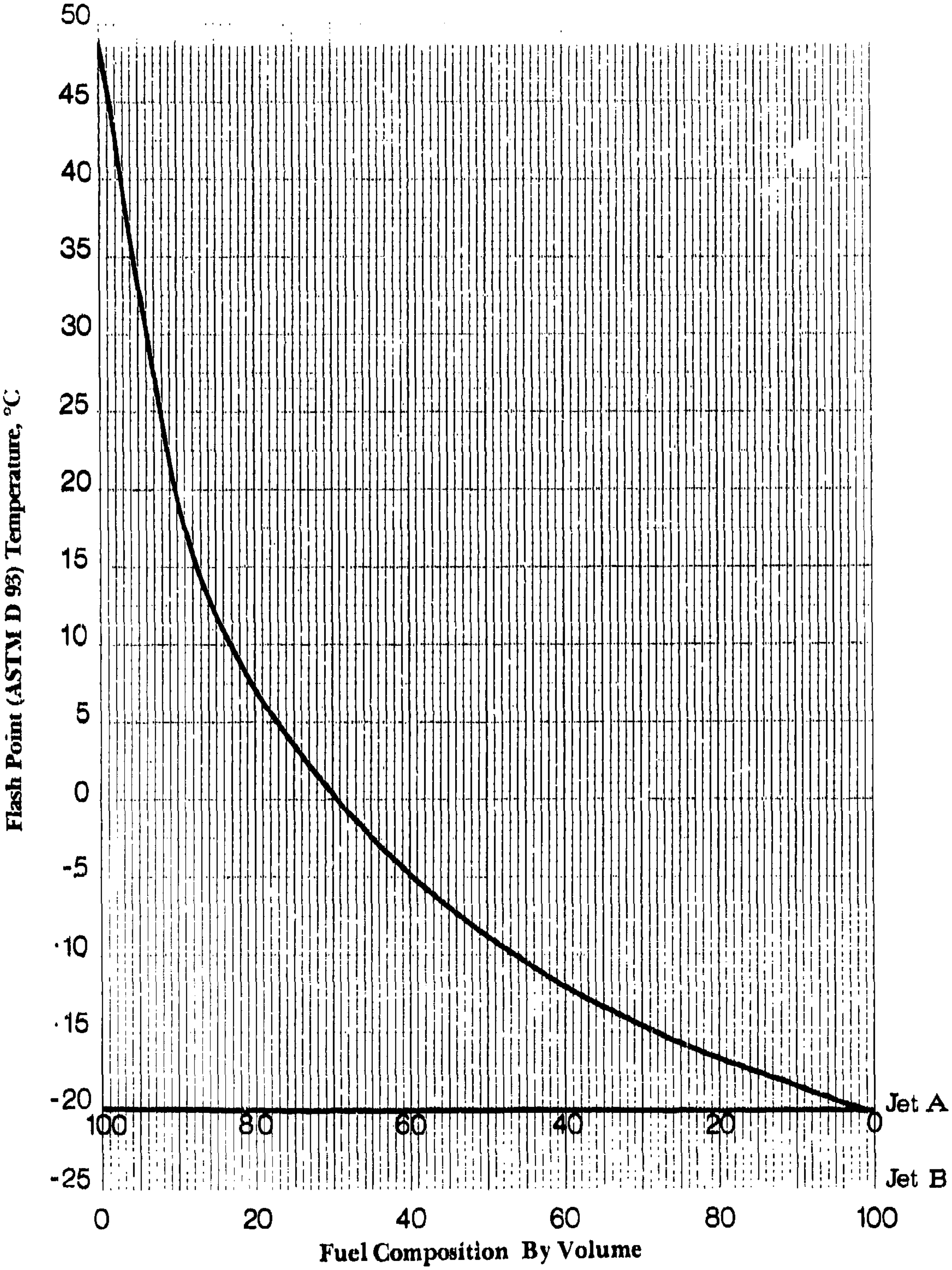


Figure 34
Flash Point of Jet A and Jet B Blends

2.8.3 Effects of Dynamics on Flammability Limits

Equilibrium conditions for the determination of flammability limits must only be used for comparative purposes. In actual practice, tank movement or flow through nozzles will affect these limits by the formation of mists and droplets. Figure 35 depicts the change of the equilibrium limits due to a sloshing situation in a tank. Here, pressure rises due to ignition which occurred at temperatures well below the equilibrium flammability limits. The rich limits are not affected, however, since dynamic situations only add fuel to an already-rich condition.

2.8.4 Effect of Air Release on Flammability Limits

At sea-level conditions, fuels normally contain a quantity of dissolved air. Since oxygen has higher solubility than nitrogen, as the pressure is decreased with increased altitude, oxygen-rich gas is released into the vapor phase over the tank. This additional oxygen will increase the rich flammability markedly. The lower limit is for all practical purposes unchanged. This effect is depicted in Figure 36 for certain aircraft fuels.

2.8.5 Minimum Spark Ignition Energy of Fuels

The minimum amount of energy required for a spark discharge to ignite an optimum hydrocarbon fuel/air mixture under ideal conditions is 0.20 millijoules (mJ). The optimum fuel/air mixture is normally found at a point on the rich side near the stoichiometric point; ideal conditions refer to glass-flanged metal electrodes at a gap of about 0.4 cm. As conditions depart from an ideal state, the energy requirements increase. Thus, changing the fuel/air mixture, the electrode geometry, or the gap distance will increase the amount of energy required for ignition. Likewise, if the fuel is present in the form of a mist or spray as opposed to a vapor, the ignition energy requirements will increase. On the other hand, an increase in the oxygen concentration of the air, such as found in aircraft ullage at altitude, will decrease the amount of energy required for ignition.

The minimum ignition energy for sprays of aircraft fuels are given in Figure 37. This indicates that the spark ignition energy required to ignite a spray of fuel varies with the temperature and is dependent upon the volatility of the fuel in question. Other variables come into effect such as the configuration of the nozzle delivering the spray, and pressure on the fuel which determines the droplet sizes in the spray.

These data, therefore, should not be taken as absolute for all spray devices, and are only presented to give relative values. Laboratory data with premixed air spray mixtures give much lower ignition energy values, but are still in the same relative order and spread. The data for Jet B and Jet A were determined experimentally with the balance estimated from flash-point data. For all practical purposes, all the aircraft fuels covered, except Jet B and JP-4, fall into the same ignition level requirement for ignition. Figure 38 presents estimates based on flash-point data for missile fuels and, again, should only be used from a relative standpoint.

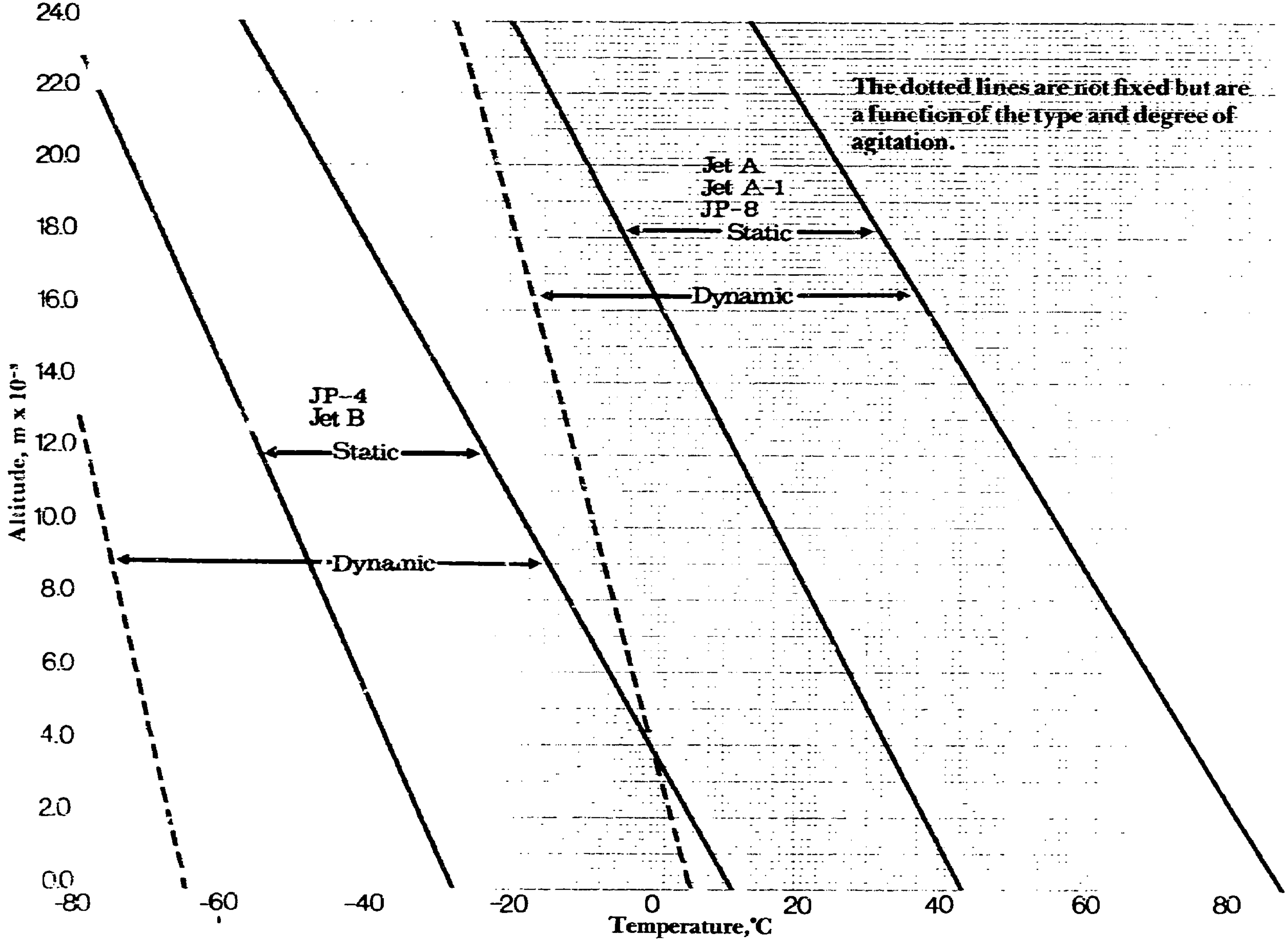


Figure 35

Effect of Tank Dynamics On The Relative Flammability Limits of JP-4, Jet B, and Jet A, A-1, JP-8

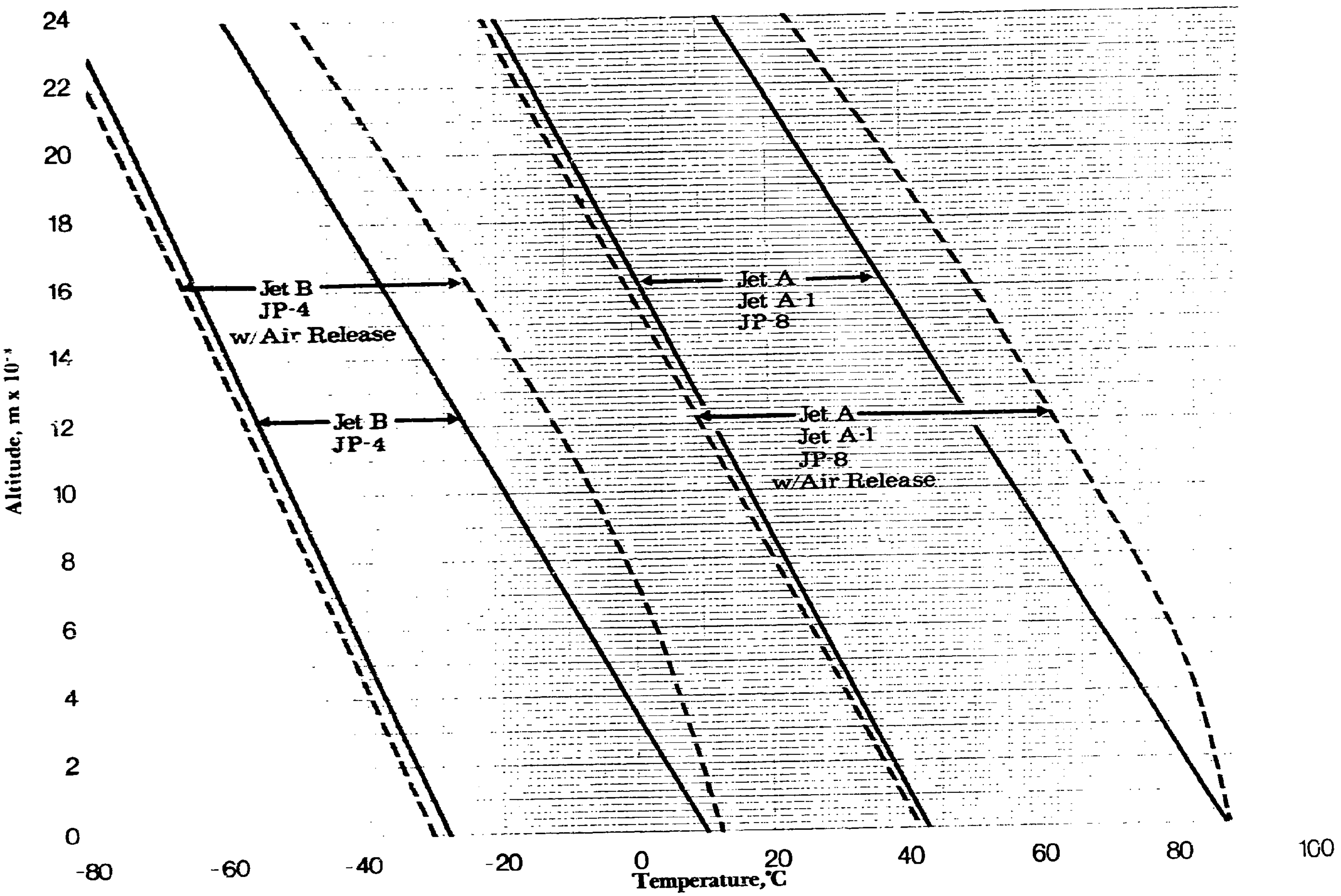


Figure 36
Effect Of Air Release On Flammability Limits of JP-4, Jet B and Jet A, A-1, JP-8

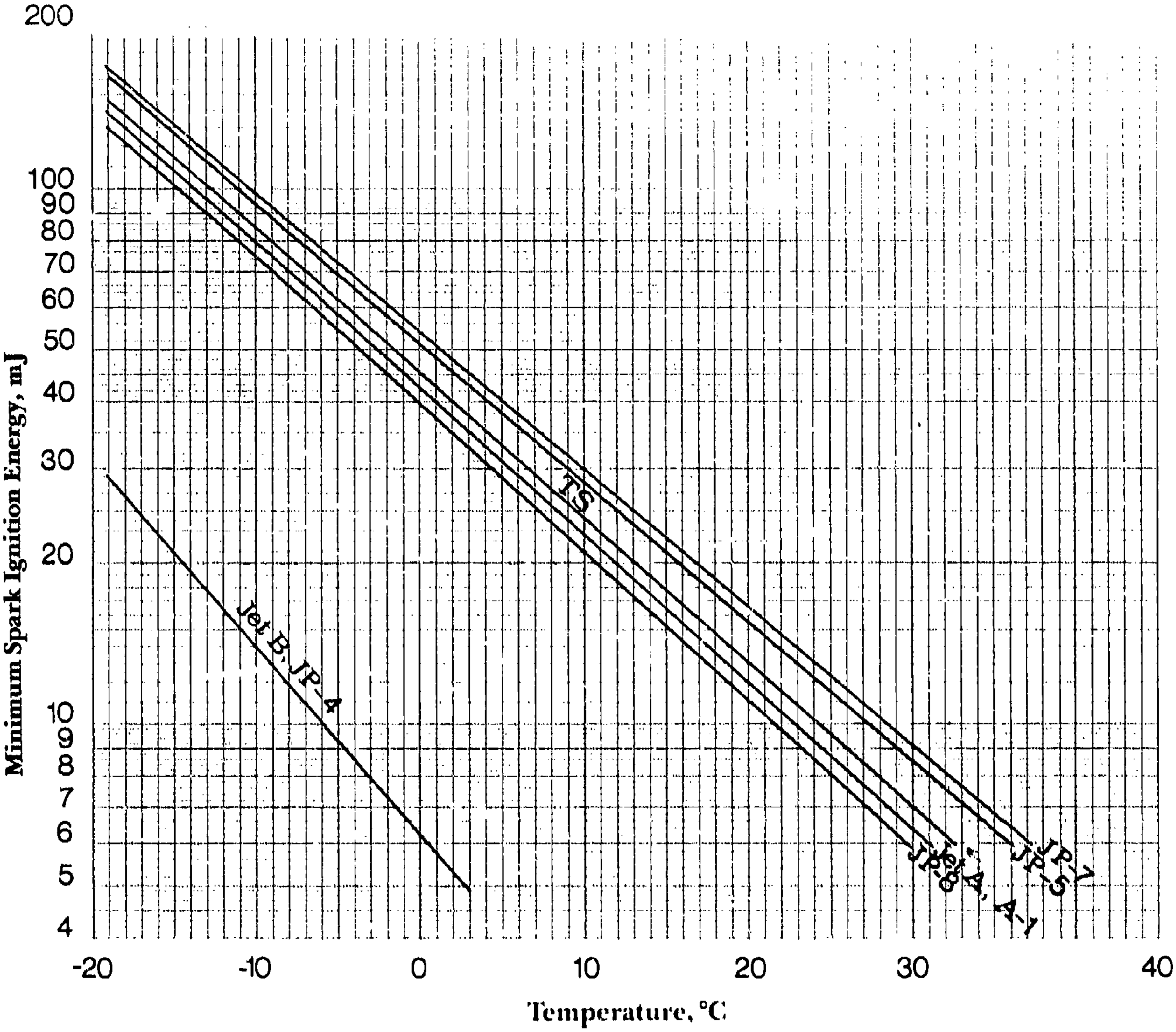


Figure 37
Minimum Spark Ignition Energy at 1 Atm. Pressure For Aircraft Fuel Sprays

1 mJ 9.478 x 10^{-7}Btu

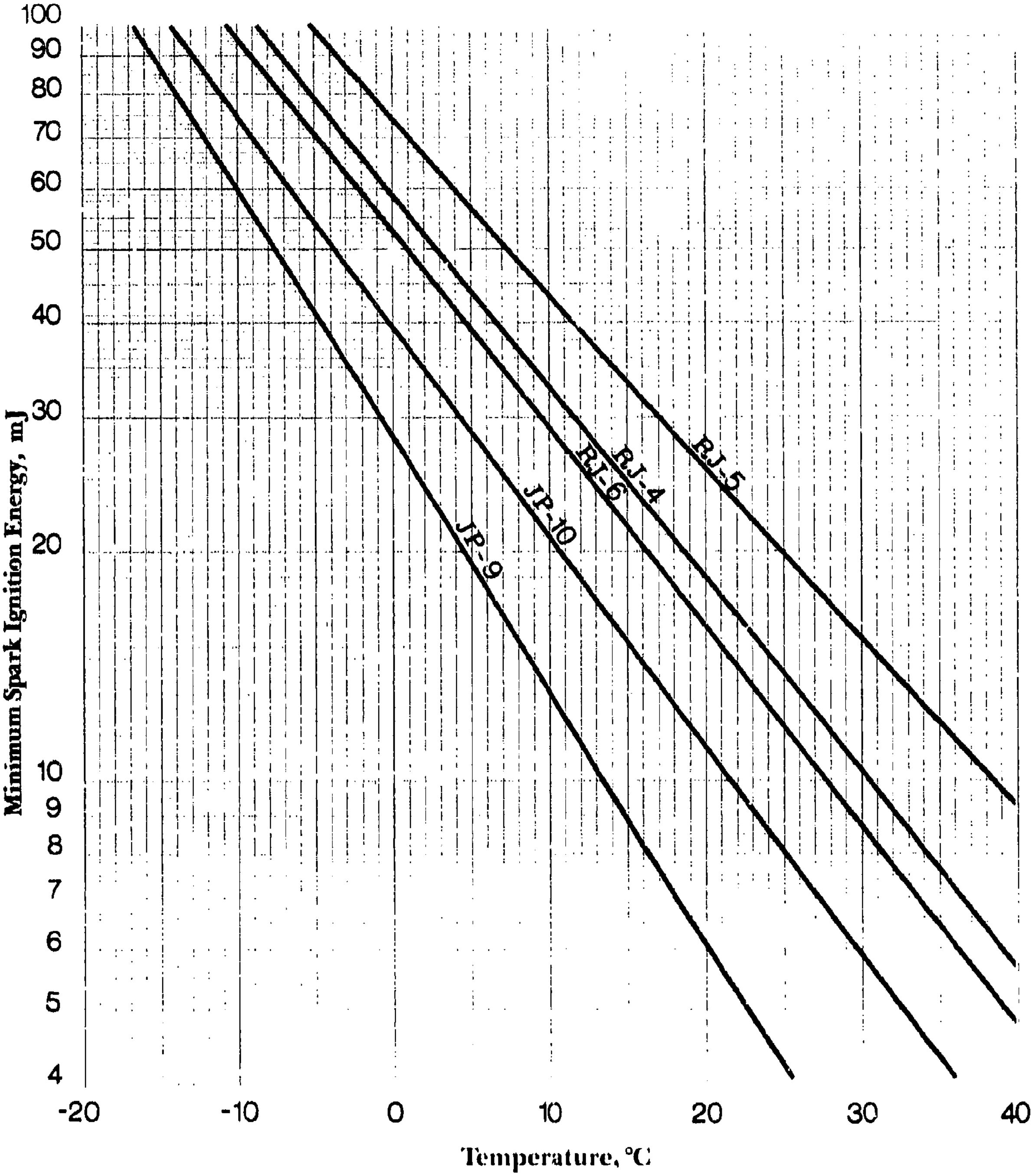


Figure 38
Minimum Spark Ignition Energy at 1 Atm. Pressure For Missile Fuel Sprays

1 mJ = 9.478 x 10^{-7}Btu

2.8.6 Autoignition Temperature

The autoignition temperature (AIT) of a fuel, frequently called the spontaneous ignition temperature (SIT), is that temperature at which fuel vapors will ignite in air at atmospheric pressure, even though an external source of ignition is not present. Laboratory AIT values are determined by heating the fuel vapors in a flask. Hot surface ignition temperatures (where the fuel is vaporized on a hot surface) is similar in concept, but ignition temperatures so obtained are higher than AIT values. The AIT for highly volatile fuels such as aviation gasoline is about 200°C higher than for lower volatility fuels such as JP-8 and JP-5. Figure 39 reveals that AIT increases for Av gas as pressure is reduced below one atmosphere, which is characteristic of high altitude flight. Figure 40 illustrates that the AIT of JP-4 also rises with reduced pressures, but the particular autoignition temperature observed is a function of the size of the test flask, and is also complicated by the existence of "cool flame" reactions which lack sufficient energy to cause true ignition to occur. Much of the data in Figures 39 and 40 were obtained with ASTM D 2155, a method now cancelled and replaced with ASTM E 659, which uses a larger flask considered more reliable in producing AIT data.

In practice, as one designs for safety, consideration must be given to all the parameters involved such as fuel temperature, pressure, flow velocity, size or length of hot surfaces, obstructions, and insulation effects. Generally, the temperature of all surfaces on which a flammable fluid may impinge should be below its minimum autoignition temperature.

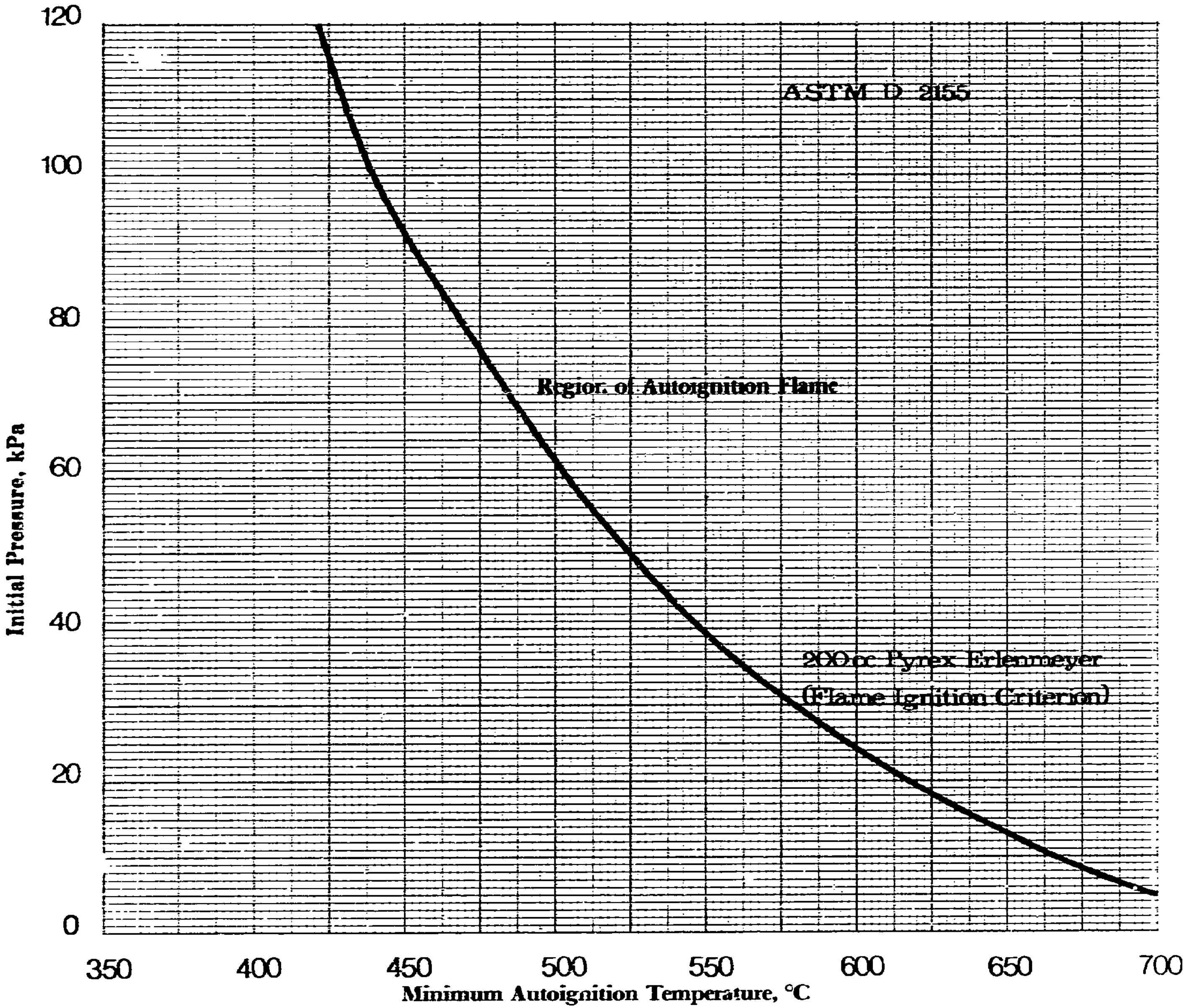
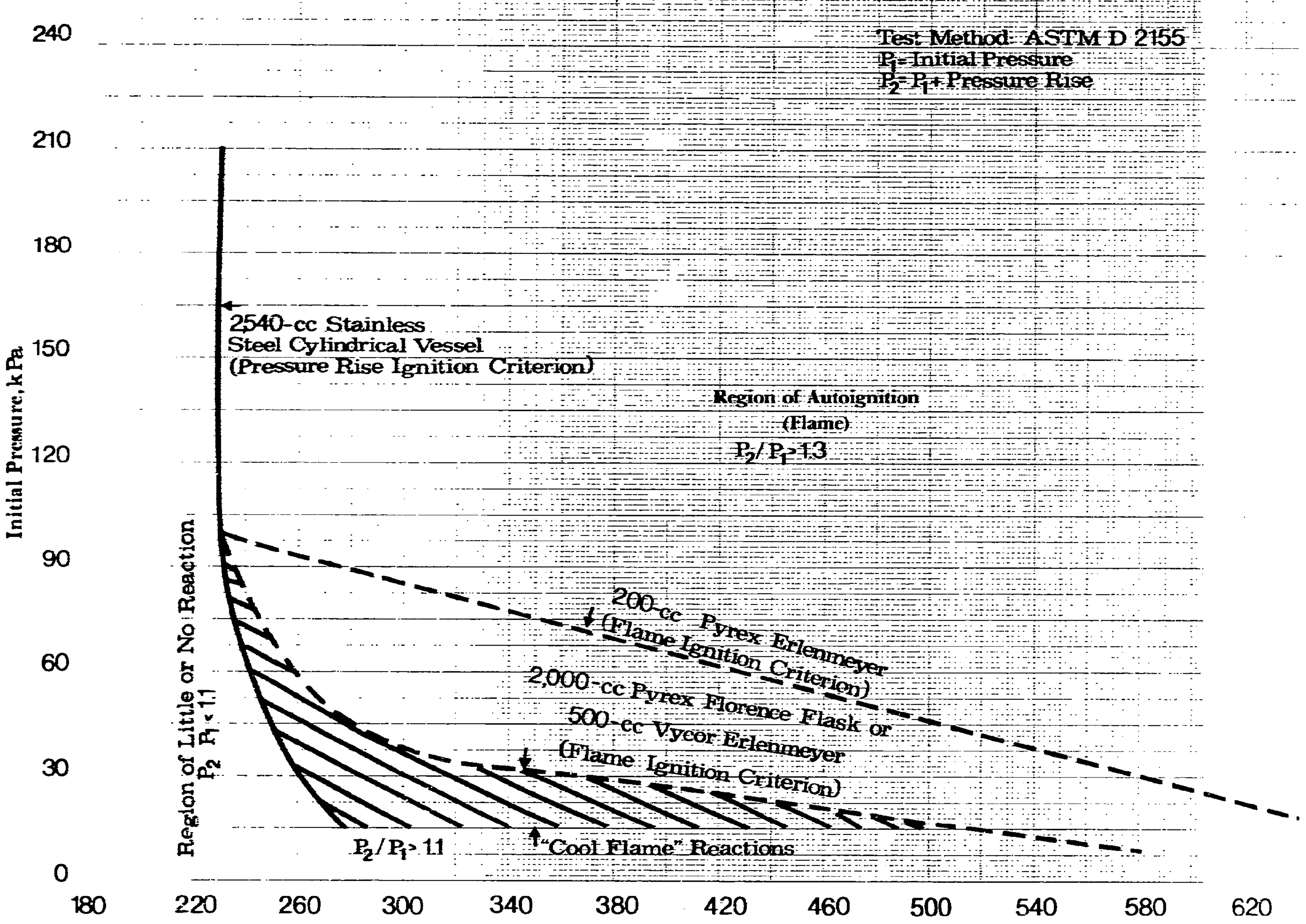


Figure 39
Autoignition Temperature - Av. Gas

1 kPa = 9.86 x 10^{-3} Atm.



1 kPa = 9.86×10^{-3} Atm.

Figure 40

Autoignition Temperature - Turbine Fuels

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2.9 BULK MODULUS

The compressibility of a fluid is the decrease in the volume of a fixed amount of the fluid when pressure is applied to that fluid. The measure of this compressibility is called the bulk modulus of the fluid. It is defined by the following differential equation:

$$\text{bulk modulus} = -v\left(\frac{dp}{dv}\right)$$

The units of bulk modulus are those of unit force per unit area. A fluid with a high bulk modulus shows a small change in volume for a given change in pressure and, therefore, is difficult to compress.

When a fuel is used to activate hydraulic equipment, a high bulk modulus of the fuel is desirable to make a responsive system. There are two kinds of bulk moduli. The first is defined at constant temperature and is called the isothermal bulk modulus. It is used when a relatively slow compression process takes place. The second is called the adiabatic bulk modulus and applies to conditions in which sudden changes in pressure are exerted on the fuel. It is used in calculating reaction speeds of servomechanisms and the forces acting on pump components. The isothermal and adiabatic bulk moduli are related through the expression:

$$\frac{BS}{BT} = \gamma$$

where:

BS = adiabatic bulk modulus
BT = isothermal bulk modulus

$\gamma = \frac{C_p}{C_v} \approx 1.15$ for jet fuels

Bulk moduli can be calculated from P-V-T measurements or determined directly from ultrasonic velocity measurements. The P-V-T measurements method is mostly used under isothermal conditions. The ultrasonic velocity method yields the adiabatic bulk modulus directly, and is a more accurate method since it is dependent upon the quantities being measured rather than their derivatives. Figures 41 and 42 show the adiabatic bulk moduli for JP-4, Jet B, JP-5, Jet A, Jet A-1 and JP-8 versus pressure and temperature.

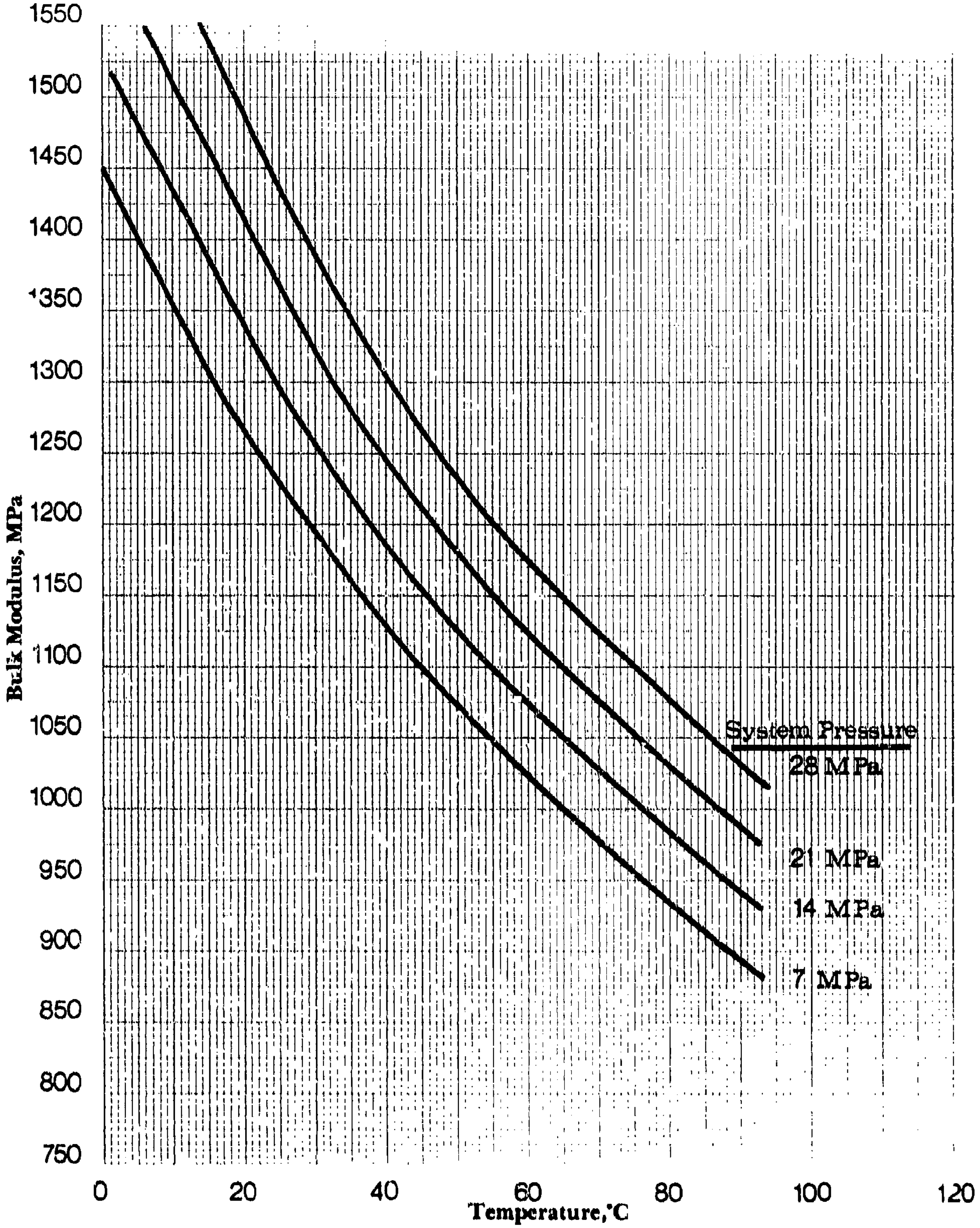

Figure 41
Bulk Modulus vs. Temperature and Pressure For Typical JP-4 and Jet B

1MPa = 145 psi

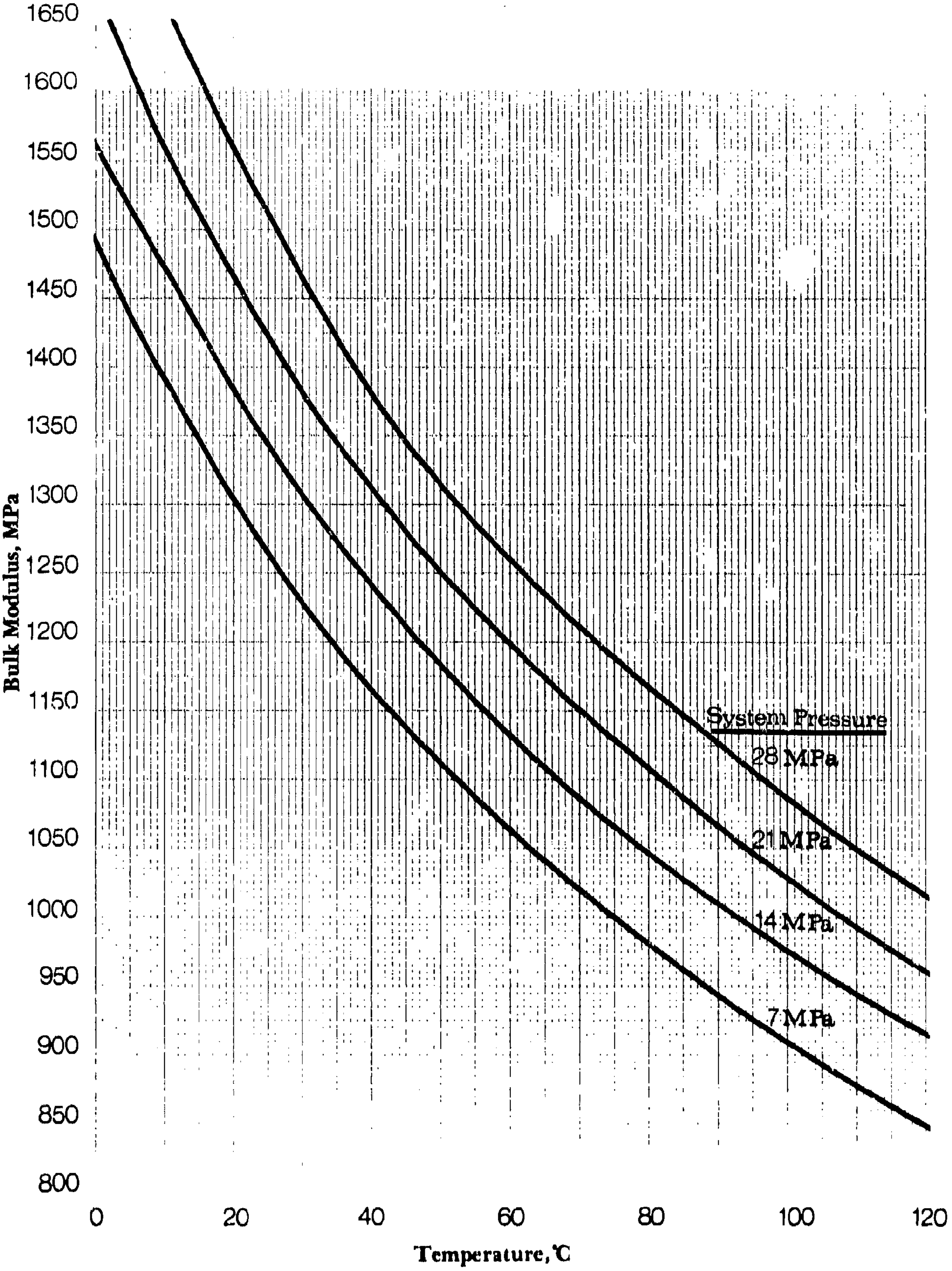

Figure 42
Bulk Modulus vs. Temperature and Pressure For Typical JP-5, Jet A, Jet A-1, JP-8

1 MPa = 145 psi

REFERENCES

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2.10 SOLUBILITY OF GASES

The solubility of gases in fuels is of high importance to the proper design of fuel systems and their components. High evolution of gases during climb can cause loss of fuel due to decreased pressure. In pumping fuel, gas phase separation can occur leading to vapor lock or cavitation problems. There are several variables which affect the solubility of gases in fuels including temperature, pressure, nature of fuel, and the gas itself. The Ostwald Coefficient is defined as the volume of gas dissolved in one volume of solvent, the gas volume being measured at the conditions of solution. This coefficient is independent of pressure. Figures 43 through 45 give the typical solubility of air, CO_2, O_2, and N_2 in aviation fuels. Figure 46 gives the typical solubility of air in missile fuels. Carbon dioxide, unlike the other gases, decreases in solubility with increasing temperature, and the solubility of this gas is very high.

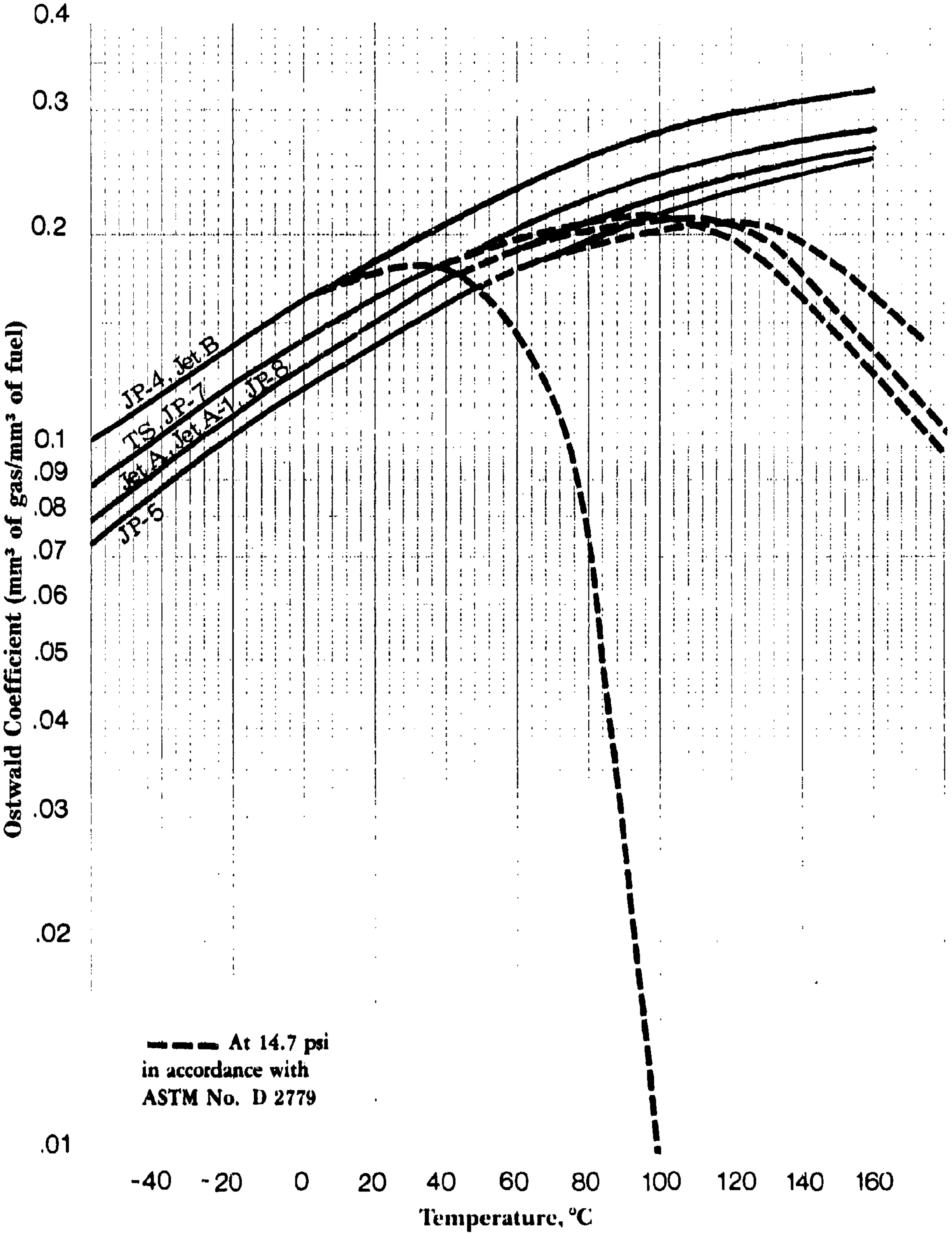

Figure 43
Solubility of Air in Aviation Fuels

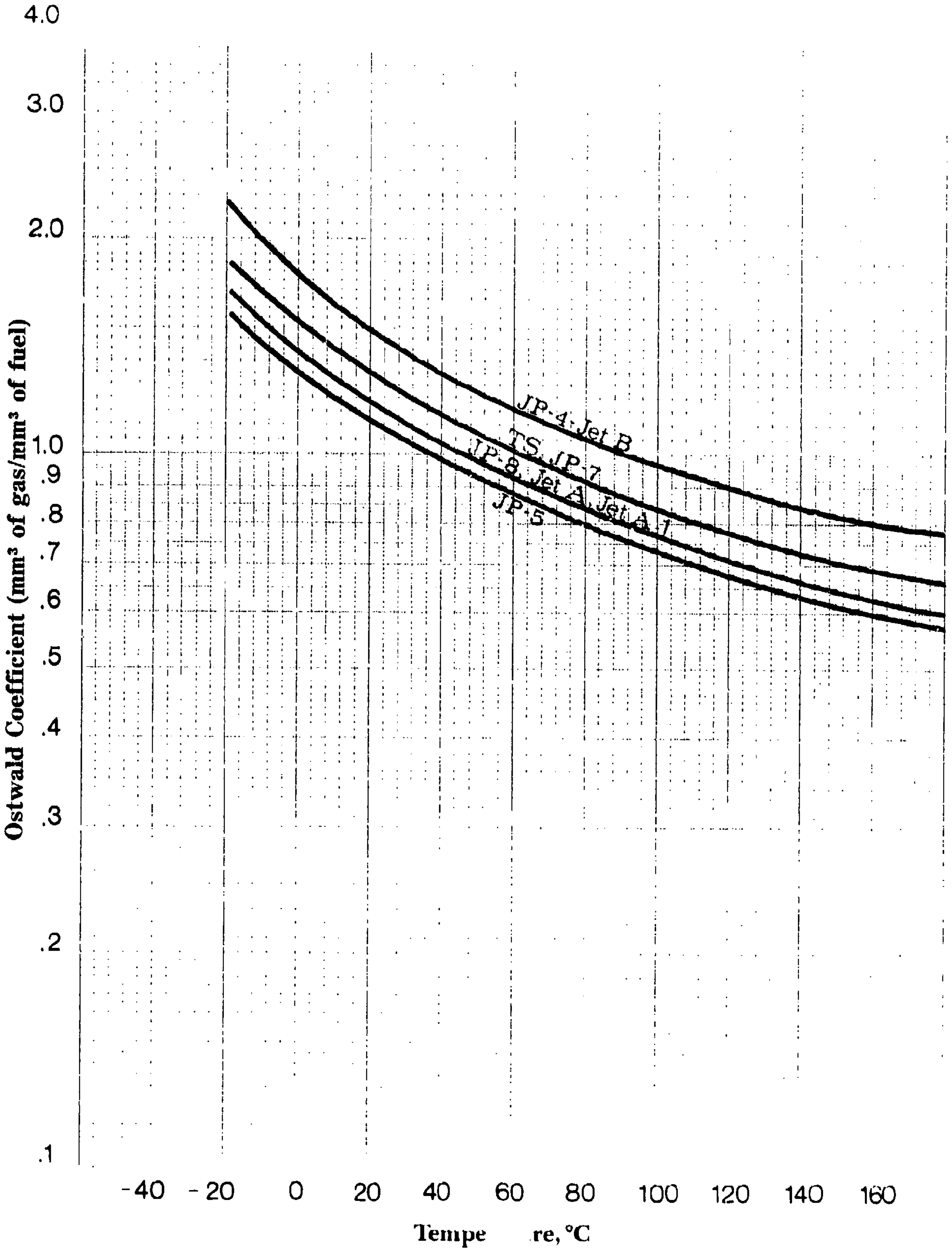

Figure 44
Solubility of CO_2 in Aviation Fuels

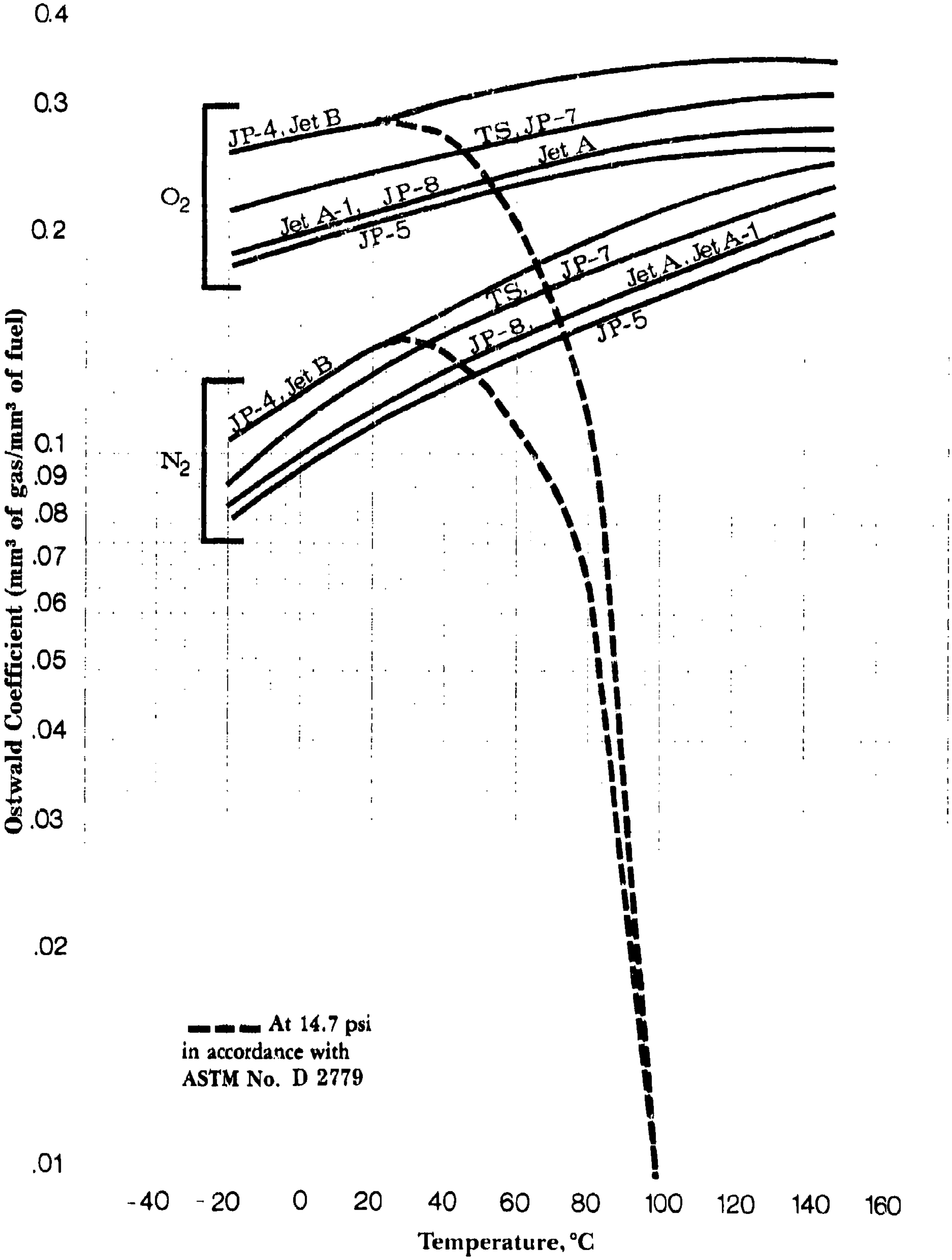

Figure 45
Solubility of O_2, N_2 in Aviation Fuels

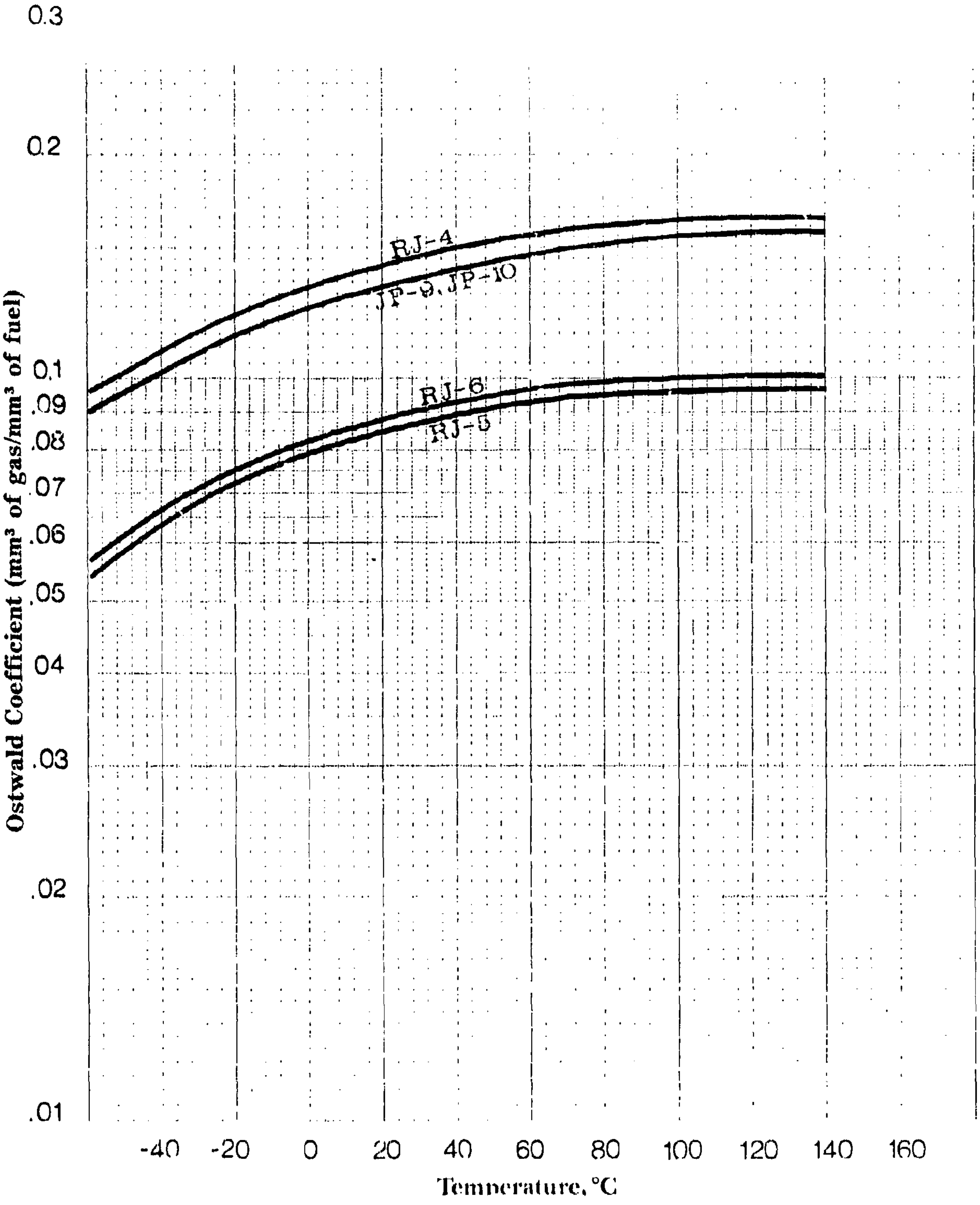

Figure 46
Solubility of Air in Missile Fuels

REFERENCES

1. F. N. Hodgson and J. Tobias, "Analysis of Aircraft Fuels and Related Materials," Monsanto Research Corporation/U.S. Air Force, AFAPL-TR-79-2016, March 1979.

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2.11 SOLUBILITY OF WATER

The quantity of water dissolved in aircraft fuels is determined by the partial pressure of water in the vapor space above the fuel. When this vapor space is saturated with water at a given temperature, i.e., 100 percent relative humidity, the water dissolved in fuel at equilibrium will reflect the saturation values shown in Figures 47 and 48. At relative humidity values less than 100 percent, the amount of water dissolved in fuel will be correspondingly less than saturation values in accordance with Henry's Law.

Because of the sensitivity of water solubility to temperature, it is evident that a drop of 10°C in fuel temperature when that fuel is water-saturated will create from 15 to 25 ppm of undissolved or "free water." It is difficult to visually detect "free water" at levels below 30 ppm; and several tests, including ASTM D 3240, are used to detect levels from 5 to 30 ppm.

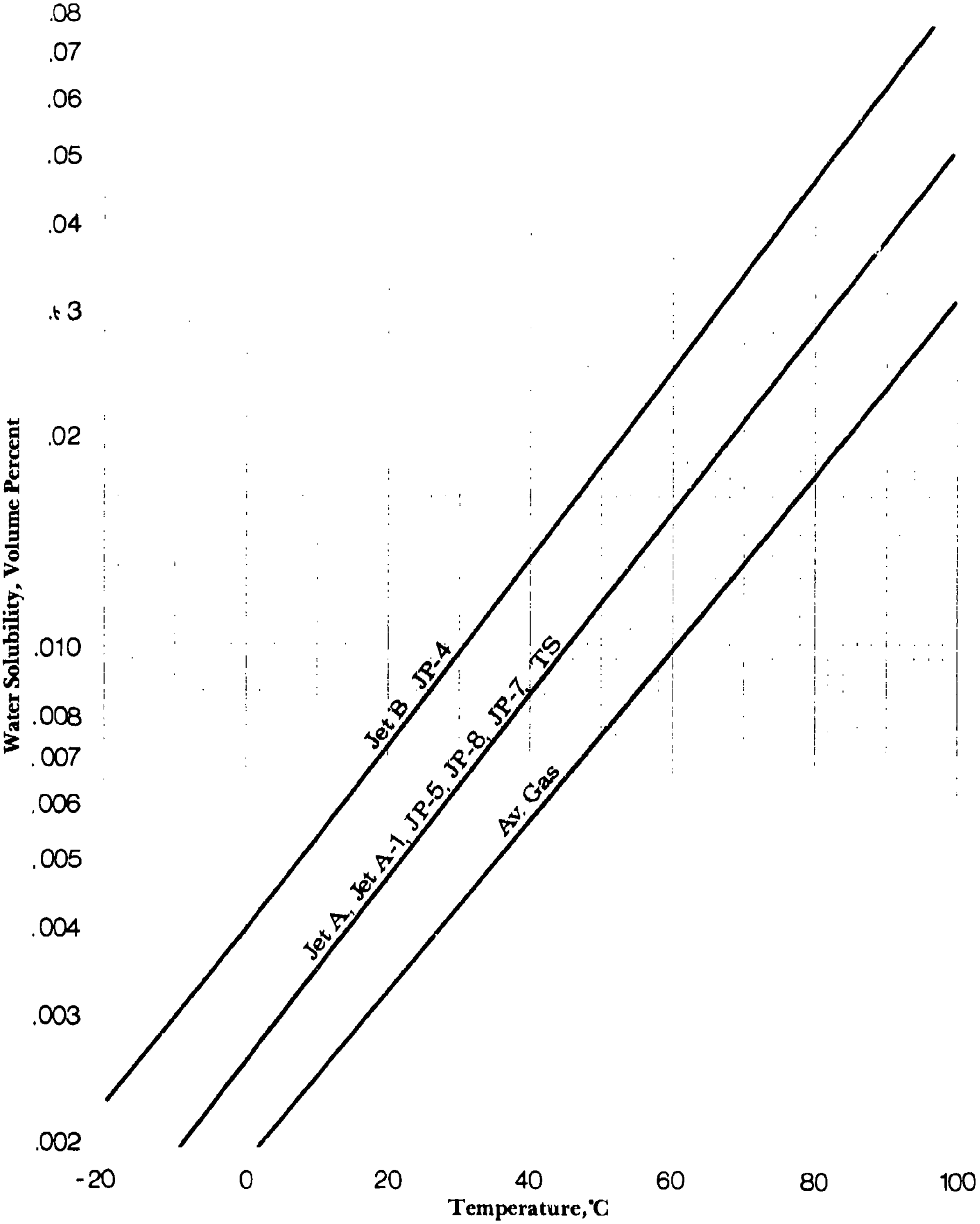

Figure 47
Water Solubility vs. Temperature For Aircraft Fuels

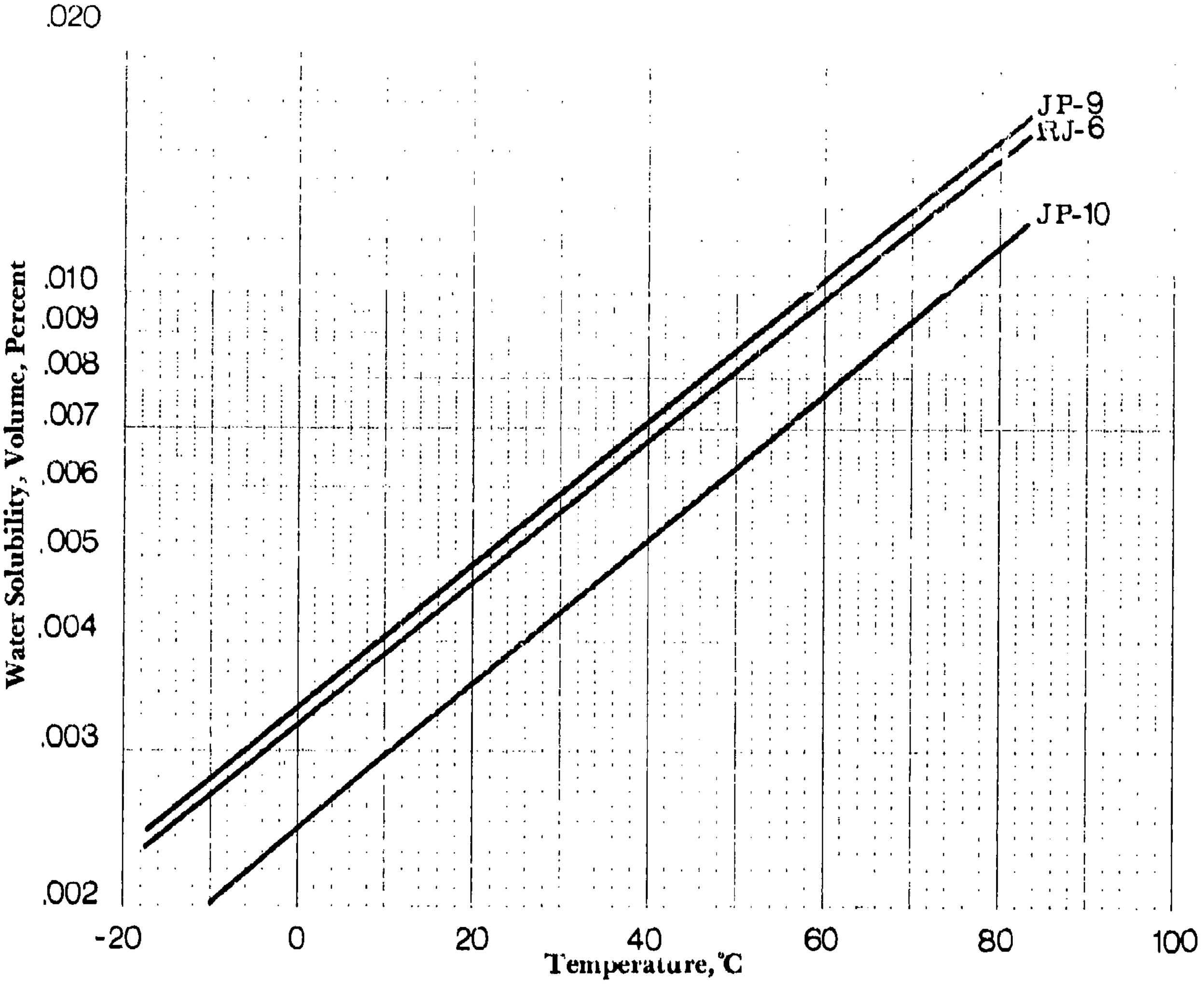

Figure 48
Water Solubility vs. Temperature For Missile Fuels

REFERENCES

1. F. N. Hodgson and J. Tobias, "Analysis of Aircraft Fuels and Related Materials," Monsanto Research Corporation/U.S. Air Force, AFAPL-TR-79-2016, March 1979.

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2.12 THERMAL OXIDATION STABILITY

The high-temperature stability of a fuel is a characteristic of that fuel which describes its tendency to resist breakdown at high temperatures to form undesirable degradation products. Of major importance in this degradation process are the trace contaminants found in fuels. Minimizing these contaminants is an effective method of improving stability. As higher temperatures are encountered, the basic stability of the hydrocarbons themselves comes into play. Long-time, high-temperature exposure increases the thermal stresses on the fuel and its tendency to form deposits.

The stability of fuels is of high importance to the design of jet engines, particularly to the fuel system designer. Fuel is often used as a heat sink to cool the oil in an engine or to cool avionics and other equipment. Breakdown of the fuel can cause decreased heat transfer from the oil to the fuel with resulting degradation of the oil. In other parts of the engine system, deposits and gum formation can cause performance degradation. In high Mach-number applications, aerodynamic heating can break down fuel in the tankage, forming undesirable deposits. A detailed review of these phenomena will be found in Reference 1.

2.12.1 Test Devices

Due to the variety of crude sources and the differences in refining processes, as well as the different stress environments to which a jet fuel is exposed, deposits form by many mechanisms. Simple laboratory test procedures are therefore not applicable for predicting fuel stability, and extensive efforts have been expanded to develop complex simulators to predict this fuel characteristic. These devices range from laboratory static test devices to complete system simulators.

2.12.1.1 ASTM-CRC Fuel Coker (ASTM Method D 1660)

After extensive efforts, the ASTM-CRC Fuel Coker was established as a specification test for thermal stability. In this test, fuel is pumped over a preheater tube and through a heated sintered 20-micron filter. Controlled variables include the temperature of the fuel out of the preheater tube, pressure, filter temperature, fuel flow rate, and test duration. Fuel performance is rated by the visual appearance and color of deposits on the preheater tube and the pressure drop across the filter. Table 10 includes the ASTM-CRC Coker parameters versus the specification requirements for some aircraft fuels.

2.12.1.2 Jet Fuel Thermal Oxidation Tester (JFTOT) (ASTM Method D 3241)

Along with technical improvements, the Jet Fuel Thermal Oxidation Tester (JFTOT) was developed to simplify the ASTM-CRC Fuel Coker procedure. In this procedure, the maximum preheater tube temperature is controlled throughout the test, rather than the fuel temperature as in the Coker. Fuel is displaced by a floating piston pressured by nitrogen, avoiding possible contamination by the pump. Sample size has been reduced from over 19 liters (5 gallons) to about 600 ml, and the test duration has been cut from five hours to 2.5 hours. Several studies have compared the JFTOT with the ASTM-CRC Coker. While the ratings are comparable, there can be significant differences in the pressure drop ratings of the JFTOT against the ASTM-CRC Fuel Coker. The JFTOT method is required in the following specifications: JP-4, JP-5, JP-8, JP-9, JP-10, and thermally stable turbine fuel. A modified JFTOT procedure is an alternate test for JP-7 fuel. Table 10 includes the JFTOT parameters versus the specification requirements for the above fuels.

2.12.1.3 Research Coker

The very stable fuel JP-7 used for high-temperature operations cannot be evaluated in the standard ASTM-CRC Coker, since this device cannot provide the temperatures required. A higher temperature apparatus, termed the Research Coker, was developed to stress fuels at these higher temperatures. In addition, to simulate supersonic operation in which the fuel is heated in aircraft tanks to high temperatures before it is used in the engine, the Research Coker incorporates a heated reservoir. JP-7 requires fuel to be tested in the Research Coker at a reservoir temperature of 149°C (300°F), a preheater-out temperature of 260°C (500°F), and a filter temperature of 316°C (600°F). The flow rate is 2.7 kg (6 pounds) per hour for five hours.

2.12.2 Effect of Deoxygenation

Jet fuel will normally contain forty to fifty parts-per-million of air, which is the equilibrium amount present at atmospheric pressure and room temperature. Dissolved molecular oxygen takes part in complex free-radical chain reactions which result in the formation of sediments, gum, and deposits at elevated temperatures. This indicates that the high-temperature oxidation stability of fuels could be improved by the removal of dissolved oxygen from a fuel.

Extensive programs have been conducted to study the effect of deoxygenation on deposit formation. In general, the removal of air from a fuel does markedly reduce the deposit formation with all fuels except those of the poorest quality. It was found that two deposit formation processes occur: the first, a lower temperature deposit formation process, involves molecular oxygen; and the second, a higher temperature pyrolysis process, is independent of oxygen. With stable hydrocarbons, deoxygenation greatly reduces low-temperature liquid phase deposit formation rates, and significant rates of deposit formation do not occur until higher temperatures. Deoxygenated fuels are also more thermally stable in the presence of contaminants and metal catalyzing surfaces than normal air-saturated fuels.

To date, no operational application has required the use of deoxygenation to minimize deposit formation. Fuels of high stability, such as JP-7 and thermally stable fuels, have been specified for very high-speed application without undue problems. In addition, aircraft and engine systems can do much in their design to minimize the problem. This approach seems at the present to be much more cost effective than the use of deoxygenation procedures.

2.12.3 Effect of Soluble Metals on Deposit Formation

Soluble metals are believed to be present in fuels in the form of acid salts or organic complexes. They are picked up in fuels during transit by the reaction of the fuels with certain metal surfaces. Some metals are highly reactive toward fuels and are a source of soluble metals. Copper, zinc, lead, and cadmium will react with fatty acids in fuels to form acid salts. Table 11 is an example of fuel stability degradation due to different soluble metals, namely copper, iron, and zinc. The breakpoint of each of the six JP-5 fuels is shown before any metal addition. The amount of each separate metal required to degrade each fuel to a breakpoint level of 260°C is then recorded. This shows that copper is the most detrimental of the three soluble metals shown here using the least amount of metal addition to reduce the breakpoint to 260°C. Iron follows copper in activity, with zinc taking the most metal addition to reach the same breakpoint level.

2.12.4 Effect of Metal Surfaces on Thermal Stability

Certain metal surfaces have been found that catalyze the degradation of fuels. This is very important in the design of aircraft fuel systems, particularly where high temperatures are encountered as in heat exchangers. Copper and its alloys such as brass seem to be the least attractive of the metals from this standpoint. Other metals and alloys such as titanium vanadium alloys, beryllium, lead, tungsten, tungsten alloys, zinc, nickel, silver, L-605 alloy, 1015 steel, and 304 stainless steel were found to decrease fuel stability. Metals and metal alloys that had little or no affect on fuel stability included 446 stainless steel, 6061 aluminum, nickel 200, 316 stainless steel, Inconel 600, and Hastelloy C. Additional information is found in Reference 1.

2.12.5 Effect of Fuel Additives on Deposit Formation

There are two broad categories of fuel additives: those which may reduce operational difficulties due to thermal degradation of fuels (antioxidants, metal deactivators, metal passivators, dispersants); and those added for other purposes (corrosion inhibitors, lubricity additives, anti-icing additives, anti-static additives). In practice, only one fuel, Thermally Stable Fuel (MIL-T-25524), specifies an additive containing a dispersant to increase its thermal stability. In all other cases, fuels as currently produced are of satisfactory quality without the use of additives from a thermal stability standpoint. The concentrations of all other additives are controlled by specification to preclude a degradation of the thermal stability of each fuel.

TABLE 10
FUEL THERMAL STABILITY REQUIREMENTS

Test Devices and Conditions	Specification Requirements									
ASTM-CRC Coker Research Coker - JP-7*	JP-7	TS	JP-4	JP-5	JP-8	Jet A	Jet A-1	Jet B	JP-9	JP-10
Reservoir Temp, °C	149									
Preheater Temp, °C	260	232								
Filter Temp, °C	316	238								
Fuel Flow, kg/h	2.7	2.7								
(lb/h)	(6)	(6)								
Pressure Rise, Pa	10,000	10,000								
(mmHg)	(76.2)	(76.2)								
Time of Test, min	300	300								
Preheater Deposit Code, max	<3	<3								
JFTOT										
Preheater Temp, °C	355	335	260	260	260	260	260	260	300	300
Fuel Flow, ml/min	3	3	3	3	3	3	3	3	3	3
Pressure Rise, Pa	3325	3325	3325	3325	3325	3325	3325	3325	1333	1333
(mmHg)	(25)	(25)	(25)	(25)	(25)	(25)	(25)	(25)	(10)	(10)
Time of Test, min	300	150	150	150	150	150	150	150	150	150
Preheater Deposit Code, max	12TDR**	12TDR**	<3	<3	<3	<3	<3	<3	<2	<2

*Research Coker only used for JP-7
**Tube Deposit Rating

TABLE 11
EFFECTS OF METAL CONCENTRATION ON THERMAL STABILITY AT 260°C

	Breakpoint Temp, °C Before Metal Addition	Threshold Metal Concentration, parts/billion, for Soluble Metals		
Fuel		Copper or	Iron or	Zinc
A	271	74	136	
B	268	99	165	
C	282	105	154	250
D	279	89	151	200
E	282	50	145	250
F	296	100	152	420

Determined by JFTOT ASTM D 3241

REFERENCES

1. Coordinating Research Council, Inc., "Thermal Oxidation Stability of Jet Fuels—A Literature Survey," CRC Report No. 509, April 1979.

2. American Society for Testing and Materials, *1981 Annual Book of ASTM Standards,* Petroleum Products and Lubricants, Parts 23 and 25.

3. Coordinating Research Council, Inc., *CRC Aviation Handbook—Fuels and Fuel Systems,* NAVAIR 06-5-504, May 1967.

SECTION 3

USER PROBLEMS

3.1 FUEL CONTAMINANTS

Contaminants can be introduced into jet fuels during the refining process, and particularly in the transfer of the fuel from the refinery to the aircraft. The fuel specification controls the fuel as produced by the refinery, and insures a satisfactory product from the standpoint of impurities. During the transfer process, water, rust, dust particles, and micro-organisms are the major contaminants that can be added into the fuels. Good housekeeping, both in transfer equipment and storage facilities, is most important in this case. Added protection is provided by the use of filter separators capable of efficiently removing excess water and solid particles. The coalescing capability of the filter separators is protected by specification requirements limiting materials detrimental to the ability of filter separators to perform their functions.

Contamination can also occur in the aircraft, usually due to the ability of the fuel to absorb soluble gases and water. The following discussion deals with these contaminants which cannot be controlled prior to their introduction into the aircraft.

3.1.1 Gas Contamination

The solubility of gases in aviation fuels must be considered in the design of aircraft systems. They can cause various difficulties including fuel pump cavitation, vapor lock, fuel expulsion from vents during ascent due to outgassing, and added hazard by oxygen enrichment of the vapor phase in aircraft tanks. The only solution to the above problems is to design aircraft systems capable of safely adapting to the escaping gases based on data previously presented in paragraph 2.10.

3.1.2 Water Contamination

Water contamination in an aircraft system can stem from two sources. First, the fuel introduced to the aircraft contains soluble water which is not removed by filter separators. Even though the amount is small, as shown in Figure 47, it is a potential problem since it comes out of solution at low temperatures often encountered in long, high-altitude flights. This water may accumulate in the bottom of fuel tanks, or may form ice crystals which can plug filters in fuel systems. The second source of water contamination is excess water generated in the cold fuel tanks after prolonged high-altitude flights. On descent, warm, moist air entering the cold tanks condenses water in the tanks which ends up in the tank bottoms or possibly as ice crystals in the fuel.

3.1.2.1 Excess Water

Excess water in a fuel system usually is found in aircraft tank bottoms. It is, therefore, important that this water be removed as often as possible through the drain plugs designed in the system. Traps or pockets which cannot be drained must be avoided in the design of the system. Even with this precaution, however, in very cold climates water bottoms can be frozen and therefore cannot be drained. In this case, it is possible to carry large dead weights of ice in the tanks and have severe problems during thaw periods. Some relief from excess water has been incorporated in filter design and by the use of fuel heaters to melt any ice formed before it is introduced into the engine. Also, small jet pumps located in low or undrainable places in the tank and discharging near the inlet of the main boost pumps have proven to be effective in removing water via the engine. The use of a particular anti-icing additive has proven to be a most effective method for solving this problem for the U.S. Air Force.

3.1.2.2 Dissolved Water

The solubility of water in fuels versus temperature is shown in Figures 47 and 48. It is a basic property of the fuel, and this water cannot be extracted by the use of water separators. The water can come out of solution at lower temperatures in the form of very fine droplets, and also is one of the sources of excess water in tank bottoms. Although the amounts are small, the crystals that are formed can cause filter plugging unless properly designed. The anti-icing additives have been formulated to protect the system from this problem.

3.1.2.3 Fuel System Icing Inhibitors

A fuel system anti-icing additive, ethylene glycol monomethyl ether (EGME), conforming to MIL-I-27686 Amd. 2 has been found to be highly effective in controlling icing difficulties due to both free and dissolved water in JP-4, JP-8, JP-9, and JP-10. It is also specified in military high-density fuels RJ-5 and RJ-6. It may also be used in most commercial specifications with agreement between supplier and purchaser. A higher molecular weight product, diethylene glycol monomethyl ether (DIEGME), conforming to MIL-I-85470 (AS) is required in JP-5 because of the tendency of EGME to lower the flash point of the base fuel by about 4°C. This flash-point depression does not occur with DIEGME and makes it easier for refiners to blend JP-5 to a 60°C minimum flash point.

Both additives, after extensive testing, have been found to be not only highly effective as anti-icing additives, but do not in most cases affect other required properties of fuels. Both additives are prone to oxidation instability unless inhibited, and can form active by-products which lower the water separation rating of fuels.

3.1.3 Microbiological Growth

Microbiological growth has, from time to time, caused major fuel contamination problems. It has been found that hydrocarbons, particularly straight-chain compounds, are a prime source of food for certain types of microorganisms. Using the fuel as a nutrient and propagating at the fuel/water interface, they form slime and large mats of matter. These lead to a variety of problems in fuels and aircraft systems.

3.1.3.1 Effects of Fuel Systems

In aircraft fuel-handling systems, and in aircraft fuel systems themselves, microbiological growth can cause plugging of filters. They contribute to the surfactant problem, which causes poor water coalescing in filter/separator equipment. They have been identified as the cause of aircraft fuel probe fouling and engine fuel pump seizing. The most serious problem, wing tank corrosion, has been related to the interplay among water, rust, surfactants, and these microorganisms.

3.1.3.2 Remedies

Microbiological growth, due to its dependence upon water and other fuel contaminants, is most effectively controlled by "good housekeeping," both in the fuel-handling system and in the aircraft itself. If contamination does occur, there are effective biocides for treating water bottoms in storage facilities. In aircraft themselves, water should be drained from tankage at frequent intervals.

3.1.3.3 Role of Fuel System Icing Inhibitor

The jet fuel anti-icing additives have demonstrated biocidal control in service. It has not been suggested that these additives be a substitute for "good housekeeping," but as an added protection against microorganism contamination. By virtue of being already approved for and compatible with materials of aircraft construction, they provide a single means of biocidal control in all elements of fuel handling and storage.

3.1.4 Solid Contaminants

Solid contaminants are a continual threat to fuel quality. Even though fuel specifications have strict restrictions on solid content, this only guarantees that fuel leaving the refinery is satisfactory for use. During its journey from the refinery to the aircraft, it can be exposed to solid contamination in a variety of ways. These solid contaminants may be in various forms such as rust from handling systems or dirt brought in from the atmosphere through vents. There is also the possibility of solid contamination produced by microbiological growth.

The primary protection against solid contaminants is "good housekeeping" which entails continual awareness. Protective measures include pipeline and tank coatings or linings, and the requirement for corrosion inhibitors in the fuels. The aircraft and the engine are also protected from excessive contamination by the use of filters. In addition, it is required by specification that the engine be designed with the ability to tolerate fairly high levels of contamination. This has been achieved not only through improved engine filters, but by design of engine fuel controls less sensitive to dirt particles.

3.1.4.1 Separation of Solids from Fuels

Contamination can be introduced into fuels in spite of all precautions. The methods for removing solid contaminants from the fuel are settling and filtration. Settling is an effective procedure if the fuel can be retained in storage tanks for a period of time. The rate of settling is a function of the size and density of the particles and the viscosity of the fuels. Figure 49 illustrates the rate at which rust and water will settle out of various fuels depending upon the particle size of the contaminants.

Filtration is accomplished at various points in the transfer of the fuel and just prior to introduction into the aircraft. Extensive development has resulted in highly efficient and reliable filter separators if maintained and operated properly. An extensive bibliography pertaining to this equipment is found in the references.

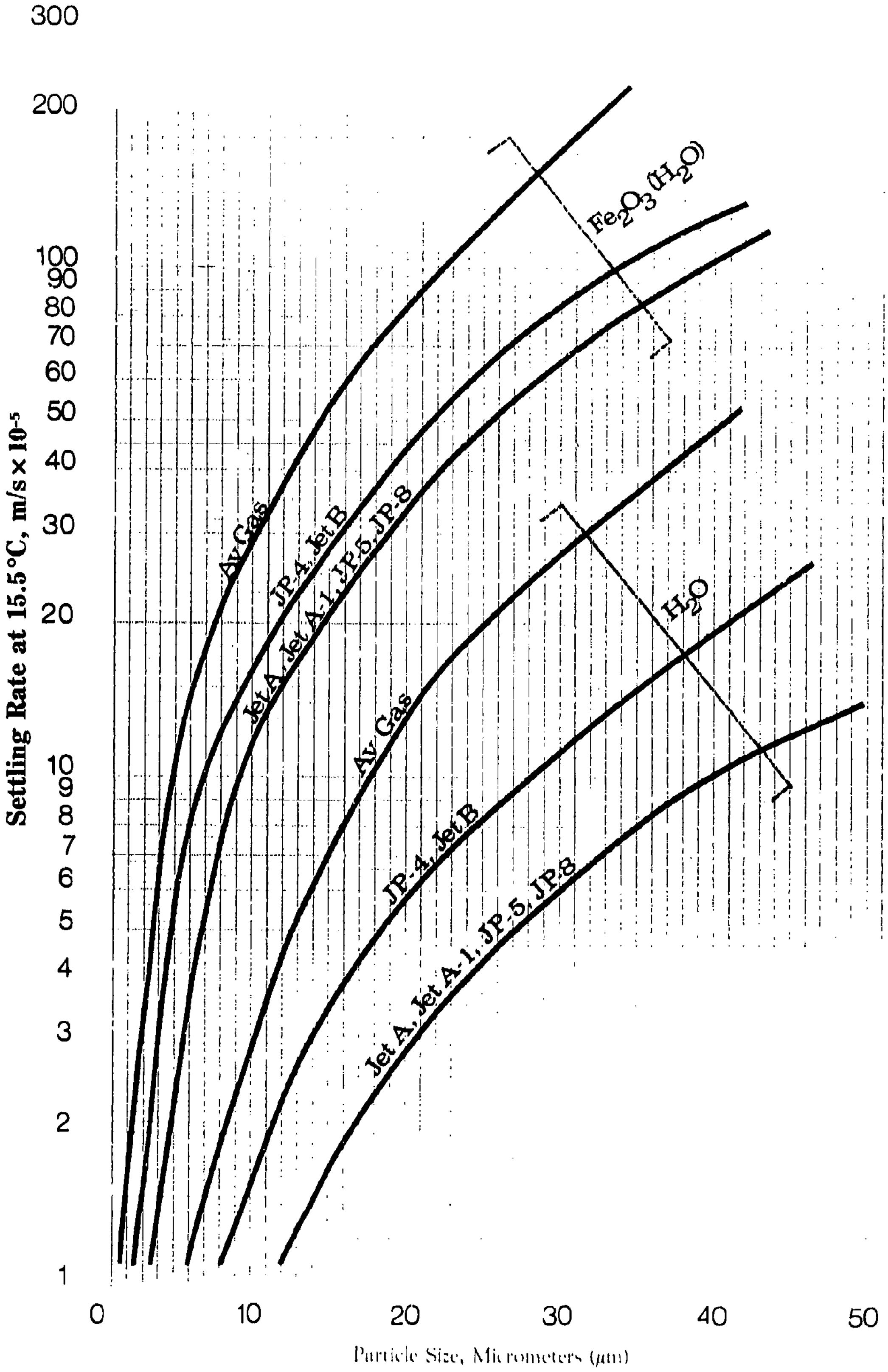

Figure 49
Separation of Contaminants - Water and Rust

1 m/s x 10^{-5} = .118 ft./hr.

3.2 FUEL LUBRICITY

The lubrication properties of jet fuels are important in rubbing surfaces such as engine controls, servo valves, pump bearings, gear and piston-type pumps. The low viscosity of jet fuels (less than 2.0 cs at 37.8°C or 100°F) will, in many cases, prevent sustaining a hydrodynamic film and cause successful lubrication to depend upon boundary lubricants in fuel that adsorb on the rubbing surfaces to form protective films. High temperature encountered at high speeds and in advanced performance engines reduce the viscosity of jet fuels and reduce the adsorption tendency of boundary lubricants. Lack of lubrication results in increased wear rates or high friction that can lead in some cases to adhesion and scuffing of rubbing metal parts.

The high friction and wear rates that characterize poor boundary lubrication derive from surface oxidation reactions; in the complete absence of oxygen and water, a fuel that lacks boundary lubricants shows no wear or high-friction tendencies. Fuels contain natural boundary lubricants in trace amounts which are primarily polar compounds of oxygen, nitrogen, or sulfur, but may also be multi-ring aromatics. Such polar compounds form films on metal and protect against corrosion, thus improving boundary lubrication. Under severe refining conditions, these natural lubricants in fuel are removed; hence, a fuel that has been refined to remove trace materials to a high level of thermal stability is apt to become poor in lubricity. The lubrication properties of fuels can be improved by adding a corrosion inhibitor meeting Specification MIL-I-25017. Most of the approved corrosion inhibitors are excellent lubricity agents and are usually not detrimental to thermal stability and to the ability of filter separators to work effectively.

Corrosion and boundary lubrication of rubbing surfaces are not only a function of fuel lubricity properties, but also of the metallurgy of the system. It is the practice to test advanced materials used in pumps and engine controls using a fluid of poor lubrication quality; such a fluid can be made by severe refining, and maintained in its desired lubricity condition by constantly removing any oxidized species that form during recirculation in the presence of air (an absorbant such as clay is commonly used for this purpose). Oxidation products are polar species that tend to be lubricity agents, and would therefore give a misleading impression of the capabilities of specific metallurgy under test. A laboratory test under development by the CRC called the Ball-on-Cylinder Lubricity Test is used to monitor test fluids and to test the lubricity properties of fuels.

3.3 MATERIAL COMPATIBILITY

Proper materials selection for use with hydrocarbon fuels is required in the design of fuel-handling equipment and the aircraft and engine fuel system. Noncompatible metals result in degradation of the fuel, while the fuel may attack nonmetals and gaskets to destroy their function as well as degrading the fuel itself.

3.3.1 Metals

The following lists categorize metals that are satisfactory for use with hydrocarbon aircraft and missile fuels, and those that are not recommended:

Satisfactory	Unsatisfactory
Aluminum and all its alloys	Bronze
Carbon Moly Steel	Nickel
½ to 3% Ni Steel	Copper
4 to 6% Chr. Moly Steel	Zinc
300 Series Stainless Steel	Cadmium
400 Series Stainless Steel	Brass
Monel	

3.3.2 Packing and Gasket

The following materials are recommended for use for packing and gasket applications with aircraft and missile hydrocarbon fuels:

- Nylon
- Kel-F
- Trithene
- Polyethylene
- Buna N (linear compound MJ-70)
  for JP-4, JP-8 only
- Fluorothene A
- Vinylite
- Teflon
- Fluorel
- Viton

The choice of material depends upon the temperature level of the application.

3.3.3 Lubricants

Lubricants used in conjunction with fuel system components such as pumps and controls may come in contact with the fuel being transferred. The following lubricants are recommended for use in fuel systems handling aircraft and hydrocarbon missile fuels:

- Molykote
- Fluorolubes
- MIL-G-6032 Grease
- Electrofilm Graphite Coating

3.4 TOXICITY

Hydrocarbon fuels are generally not considered highly toxic materials, and under normal situations, medical surveillance and special tests are not required on a periodic basis. However, these materials should be handled with caution, since overexposure can have harmful effects. The high-density hydrocarbon missile fuels have not been completely investigated to date from the standpoint of toxicity, but all indications are that they are very similar in this respect to the other hydrocarbon aircraft fuels. More detailed information is found in Reference 8.

REFERENCES

1. H. Barnett and R. Hibbard, "Properties of Aircraft Fuels," NACA Technical Note 3276, August 1956.

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6. A. R. Garabrant, "Lubricity of JP-5 and Diesel Fuels," Exxon Research and Engineering Company, U.S. Army Materials Report No. GRU.1PD.74, December 1974.

7. Coordinating Research Council, Inc., "Microbiological Aircraft Fuel Tank Contamination—A Bibliography," CRC Report No. 469, July 1974.

8. U.S. Department of Health, Education, and Welfare, *Occupational Diseases,* revised edition, June 1977.

APPENDIX A

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M. P. Dunnam was engaged, with support from the U.S. Air Force, as a consultant to the Group in the preparation of this Handbook.

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