CRC Project AV-12-10

Properties of Russian Jet Fuels

November 2011

COORDINATING RESEARCH COUNCIL, INC.

3650 MANSELL ROAD·SUITE 140·ALPHARETTA, GA 30022

The Coordinating Research Council, Inc. (CRC) is a non-profit corporation supported by the petroleum and automotive equipment industries. CRC operates through the committees made up of technical experts from industry and government who voluntarily participate. The four main areas of research within CRC are: air pollution (atmospheric and engineering studies); aviation fuels, lubricants, and equipment performance, heavy-duty vehicle fuels, lubricants, and equipment performance (e.g., diesel trucks); and light-duty vehicle fuels, lubricants, and equipment performance (e.g., passenger cars). CRC's function is to provide the mechanism for joint research conducted by the two industries that will help in determining the optimum combination of petroleum products and automotive equipment. CRC's work is limited to research that is mutually beneficial to the two industries involved, and all information is available to the public.

Properties of Russian Jet Fuels

FINAL REPORT

Prepared for

Coordinating Research Council, Inc.
3650 Mansell Road, Suite 140
Alpharetta, GA 30022

Prepared by

Clifford Moses
Consultant
New Braunfels, Texas

CRC Project No. AV-12-10

November 2011

This page intentionally left blank
for back-to-back printing

Properties of Russian Jet Fuels

EXECUTIVE SUMMARY

The use of the Russian aviation fuel TS-1 has increased significantly over recent years by American and European airlines. The engine and airframe manufacturers depend on knowledge of fuel properties outside the normal specification properties for design issues. Since the knowledge base for TS-1 is insufficient, they have asked the CRC to collect available data and put it into an appropriate format for inclusion in future editions of the CRC Handbook of Aviation Fuel Properties.

Recently, a handbook of Russian fuel properties was made available and relevant chapters translated. This report summarizes data extracted from that report and presents the data superimposed on the appropriate graphs from the CRC Handbook.

The majority of the properties have similar values and temperature functions as those of conventional commercial and military fuels, i.e., Jet A, Jet A-1, and JP-8. Recommendations are made to include these data in the next edition of the CRC Handbook.

The three major exceptions are minimum ignition energy, bulk modulus, and the solubility of gases. The differences in the data may not be due to differences in the fuels so much as either to differences in test methods or the uncertainty of the historical data in the CRC Handbook. Recommendations are made to verify the data in the CRC Handbook on these properties.

To assess the relevance of the data from the Russian Handbook, the density data were compared with density data from field samples of TS-1 for the period of 1993 to 2011. There is good agreement on temperature sensitivity, but the values from the Russian Handbook are about 1% lower than the field average, which were quite consistent from year to year. TS-1 appears to be a more consistent product than Jet A-1 or JP-8 as evidenced by the smaller variation in density among samples each year.

Acknowledgement

The author thanks Mike Farmery of Shell Aviation and Stan Seto of Belcan Engineering Group for obtaining the original copy of the Russian book **The Handbook on Physical, Chemical, and Operational Properties of Jet Fuels** (English translation of title) by Dubrovkin, Malanicheva, Massur, and Fjodorov. Many thanks to Ramaz Kvavilashvili, from DTRA (Defense Threat Reduction Agency), and Anna Kulberg from Belcan Engineering Group for the translations of selected chapters; their knowledge and effort made this work possible. The author also thanks Dr. Tim Edwards of the Air Force Fuels Branch at Wright-Patterson AFB for providing several databases on TS-1 fuel samples. The author also thanks Daniel Baniszewski of DLA Energy for his support with the PQIS (Petroleum Quality Information System) database. Finally, the author thanks Dr. Jean-Philippe Belières of Boeing Commercial Airplanes for his assistance with the section on gas solubility.

Table of Contents

List of Figures

List of Tables

This page intentionally left blank
for back-to-back printing

1. Background

Jet B/JP-4 jet fuels are no longer the high volatility fuels to be used for the design of aircraft and engine fuel systems. These fuels are no longer being produced or used by a vast majority of countries in either military (JP-4) or commercial (Jet B) equipment. The use of these fuels is restricted in many aircraft. New designs of airframe and engine fuel systems will need to be designed and certified to run on the next most volatile aviation kerosene, Russian TS-1 or RT grades of fuel; however, little is known by "Western" designers about the properties of these fuels other than a few specification properties from isolated surveys.

Several years ago, a book entitled **The Handbook on Physical, Chemical, and Operational Properties of Jet Fuels** (English translation of title) by Dubrovkin, Malanicheva, Massur, and Fjodorov, was provided by the Russian Civil Institute of Aviation Motors (CIAM).[1] Much of the book has been translated and made available for review, and has been found to contain pertinent information on the properties of TS-1 and RT fuels that are of design interest. Hereafter, this resource will be termed the Russian Handbook.

2. Objective

The objective of this effort is to provide available pertinent data on the properties of Russian TS-1 and RT fuels in a format suitable for insertion into CRC Report 635, Handbook of Aviation Fuel Properties.[2] Hereafter, this document will be termed the CRC Handbook.

3. Scope

The primary resource for this effort was Физико-Химические и Эксплуатационные Свойства Реактивных Топлив (Translation: Physical, Chemical, and Operational Properties of Jet Fuels). [1] Translations of many of the chapters have been made and provided for the purpose of this effort. In many ways, this handbook of Russian aviation fuels is similar to the CRC Handbook in that a wide variety of bulk thermodynamic and transport properties are given as functions of temperature for typical fuels.

Secondary resources were the Petroleum Quality Information System (PQIS) [3] and data from Lufthansa [4] and the Air Force Petroleum Agency [5]. These sources provided data only as required by fuel specifications, and as such, are limited in scope and then usually only provided for one temperature. The advantage is that these data bases, especially PQIS, are more recent and represent a number of fuel samples in the field. As such, they provide insight on the relevance of the data from the Russian Handbook to more recent products and the variability of properties in these more current fuels.

The data reported herein are limited to properties that are included in the CRC Handbook. Table 1 summarizes the data presented and the sources. The data from the Russian Handbook are presented and compared to the CRC Handbook data in Section 4 of this report. Data on density of fielded fuels from the secondary sources are presented in Section 5.

Table 1. Summary of Data Presented and Resources

Fuel Property	Resource			
	Russian Handbook	PQIS 2010[1]	AFPET[2]	Lufthansa[3]
Density vs T	X			
Specific gravity vs T	calculated	X[4]	X[4]	X[4]
Thermal Expansion vs T	calculated			
Viscosity vs T	X			
Surface tension vs T	X			
Vapor pressure vs T	X			
Specific heat vs T	X			
Thermal conductivity vs T	X			
Heat of vaporization vs T	X			
Dielectric Constant vs T	X			
Flammability limits	X			
Minimum ignition energy	X			
Bulk modulus vs T	X			
Solubility of CO2 vs T	X			
Solubility of air vs T	X			
Solubility of O2 vs T	X			
Solubility of N2 vs T	X			
Solubility of water vs T	X			

Notes: 1. Contains data on TS-1 for the years 2006 – 2011
2. Contains data on TS-1 for the years 2003 – 2005
3. Contains data on TS-1 for the years 1993 – 1999
4. Data available at only one or two temperatures

4. Properties of Russian TS-1 and RT Fuels

TS-1 and RT are two aviation turbine fuels defined by the Russian specification GOST 10227-86 (latest revision). According to a British Airways report, TS-1 is the most widely used jet fuel in the C.I.S. [6] TS-1 is produced by straight atmospheric distillation from a high sulfur crude, half of which is hydrotreated and the other half a straight-run product which may have had mild caustic treatment. RT is a higher quality fuel that can be produced from straight run or hydrotreated kerosene; additives may be included to improve its properties. RT has improved lubricity properties and a wider boiling range. The major distinction between these fuel specifications and Jet A/Jet A-1/JP-8 specifications is the lower minimum flash point of 28°C as compared to 38°C. A comparative table of specifications is provided in the Appendix.

The individual properties from the Russian Handbook will be presented one at a time with a table of the data for TS-1 and RT extracted from the Russian Handbook and a corresponding graph comparing the data to data for fuels in the CRC Handbook, hereafter termed "Western fuels".

4.1. Density, Specific Gravity, and Thermal Expansion of TS-1 and RT

Table 2 presents the data for three related properties, density, specific gravity, and thermal expansion, of TS-1 and RT. These data are compared graphically with CRC Handbook data [2] in Figures 1, 2, and 3, respectively. The data for density were taken from Table 2.2 of the Russian Handbook [1]. Specific gravity was calculated from the density data using the following definition for specific gravity, sg: (Note: the density of water, ρ, at 15.5°C = 999.026 kg/m^3)

$$sg(fuel) = \rho(fuel)/\rho(water\ @\ 15.5°C) \qquad \text{[Eqn. 1]}$$

Thermal expansion is defined as the volume of the fuel relative to its volume at 15.5°C and 0.1 MPa; this is the same as the inverse of the density relative to the density at 15.5°C. The density at 15.5°C was determined from the correlation equation for the least-squares fit to the density data:

$$\text{TS-1:}\quad \rho(T) = -0.7400 \cdot T + 794.00;\quad \rho(15.5) = 782.84\ \text{kg/m}^3 \qquad \text{[Eqn. 2]}$$
$$\text{RT:}\quad \rho(T) = -0.7198 \cdot T + 792.55;\quad \rho(15.5) = 781.39\ \text{kg/m}^3 \qquad \text{[Eqn. 3]}$$

Table 2. Density, ρ, Specific Gravity, sg, and Thermal Expansion, TE of Typical TS-1 and RT Fuels

Temperature	ρ, kg/m^3		sg (calculated)		TE (calculated)	
°C	TS-1	RT	TS-1	RT	TS-1	RT
-60	837.2	835.6	0.8380	0.8364	0.935	0.935
-40	822.8	821.2	0.8236	0.8220	0.951	0.952
-20	808.4	806.8	0.8092	0.8076	0.968	0.969
0	794.0	792.4	0.7948	0.7932	0.986	0.986
20	779.6	778.0	0.7804	0.7788	1.004	1.004
40	765.2	763.6	0.7659	0.7643	1.023	1.023
60	750.8	749.2	0.7515	0.7499	1.043	1.043
80	736.4	736.8	0.7371	0.7375	1.063	1.061
100	722.0	720.4	0.7227	0.7211	1.084	1.085
120	707.6	706.0	0.7083	0.7067	1.106	1.107
140	693.2	631.6	0.6939	0.6923	1.129	1.130
160	678.8	677.2	0.6795	0.6779	1.153	1.154
180	664.4	662.8	0.6650	0.6634	1.178	1.179
200	650.0	648.4	0.6506	0.6490	1.204	1.205

From the data in Table 2 and Figures 1, 2, and 3, the densities of TS-1 and RT are essentially identical, and similarly for the two related properties. This will be seen to be true for almost all the properties, and the observation will not be repeated each time.

Figure 1 shows that TS-1 and RT fuels can be expected to have lower densities than typical Western military and commercial jet fuels, i.e., Jet A, Jet A-1, and JP-8. The density-temperature characteristics of TS-1 and RT are typical of Western jet fuels, i.e., linear with temperature and have about the same slope.

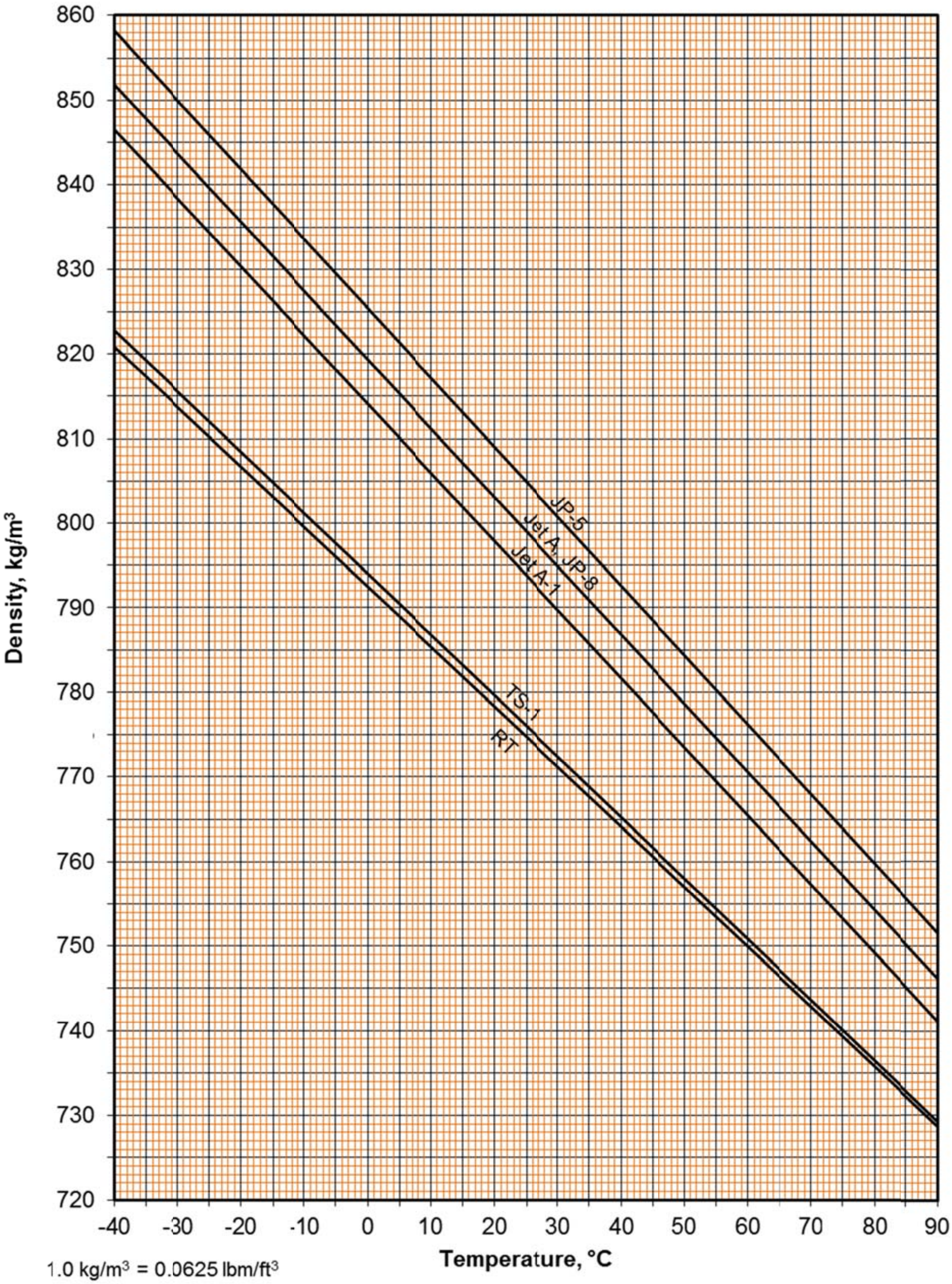


Figure 1. Density of Typical TS-1 and RT Fuels Compared to Data from the CRC Handbook [2]

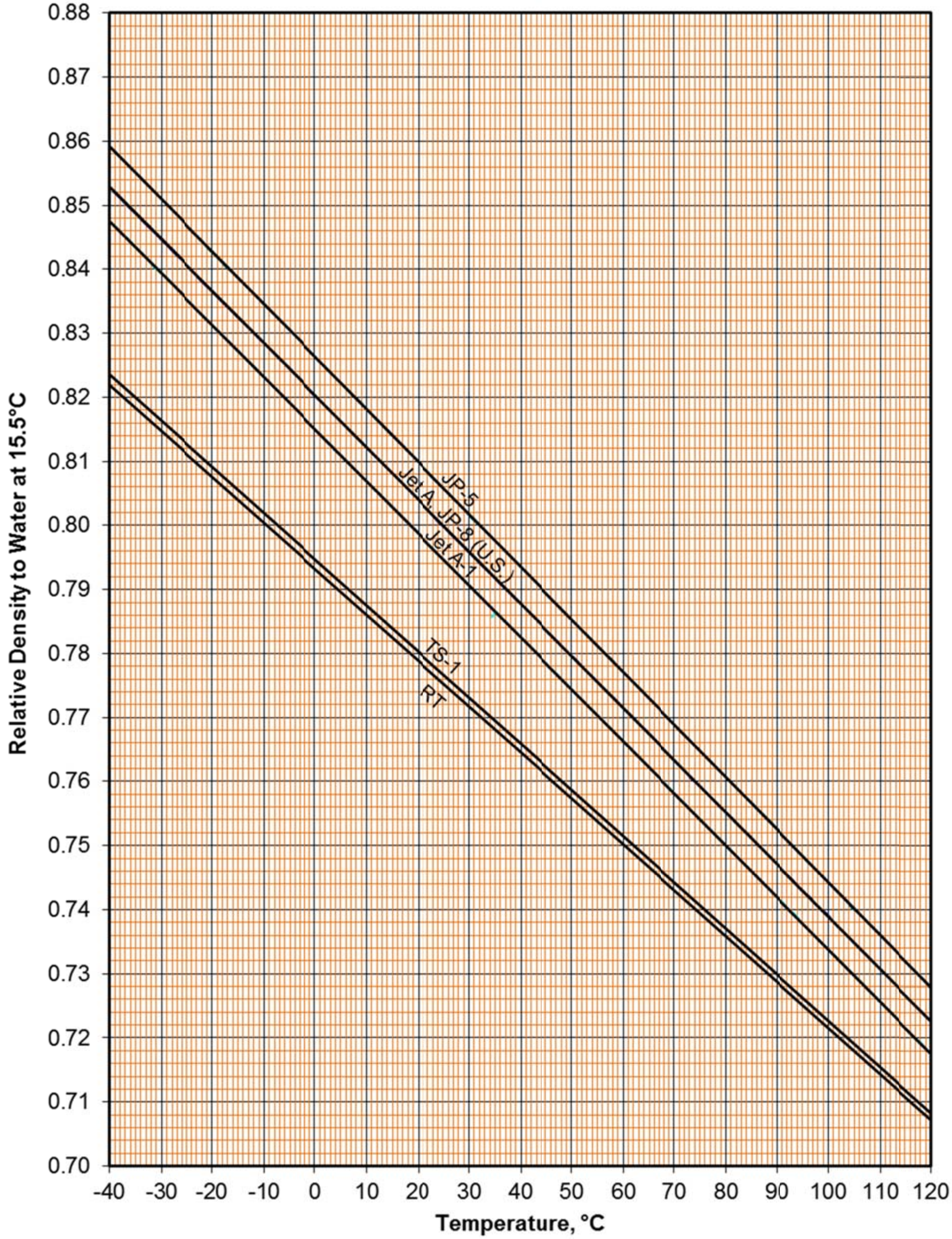


Figure 2. Specific Gravity of Typical TS-1 and RT Fuels Compared to Data from the CRC Handbook [2]

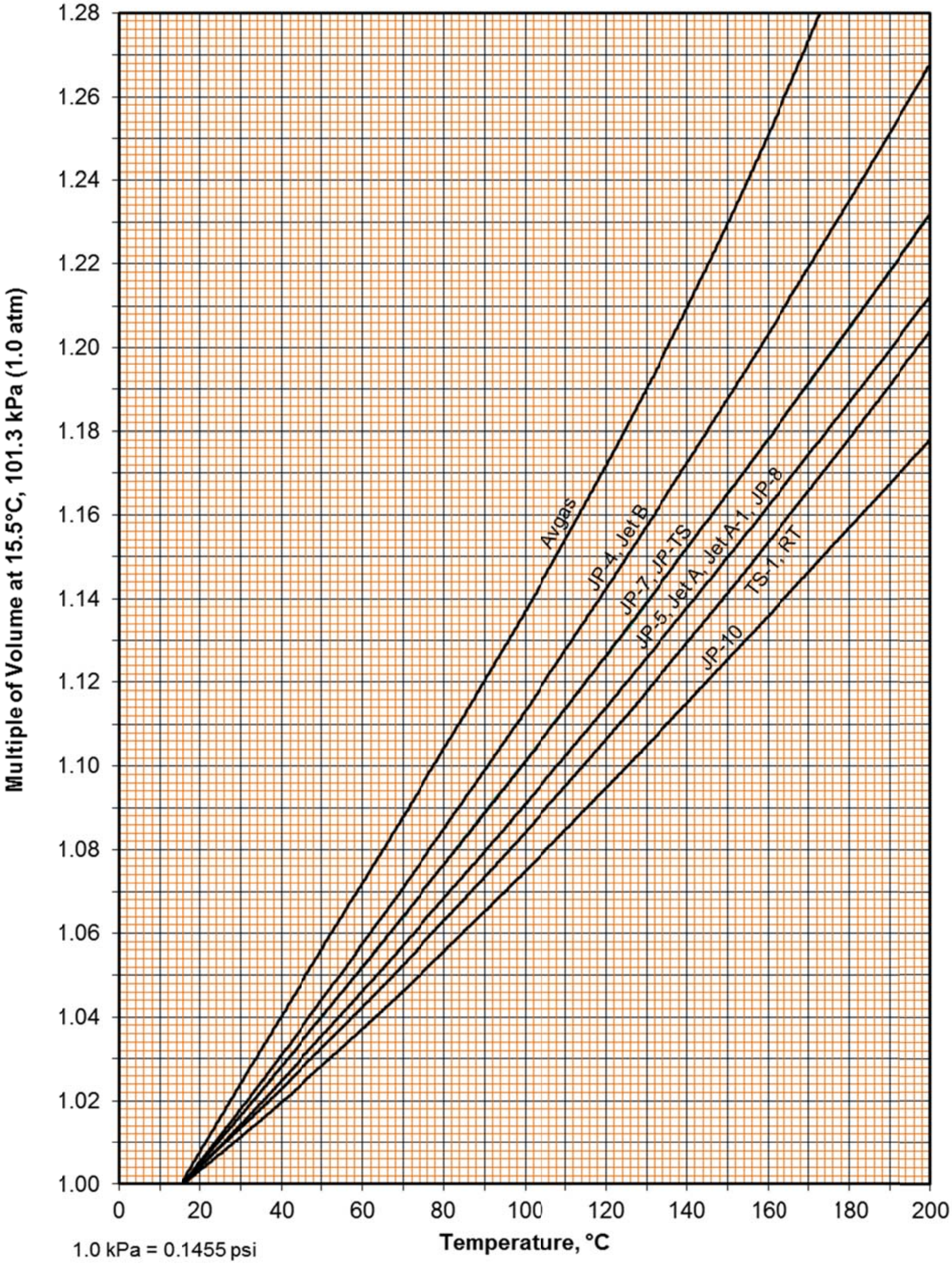


Figure 3. Thermal Expansion of Typical TS-1 and RT Fuels Compared to Data from the CRC Handbook [2]

4.2 Viscosity of TS-1 and RT

Table 3 presents the viscosity characteristics of typical TS-1 and RT fuels extracted from Table 2.21 of the Russian Handbook. Figure 4 compares the viscosity data for typical TS-1 and RT fuels with that of Western fuels. At low temperatures, the viscosity of TS-1 and RT are lower than that of Jet A-1 and Jet A/JP-8/JP-5, which is consistent with the lower density of TS-1 and RT; at higher temperatures the viscosity of TS-1 and RT are about the same as that of these fuels.

Table 3. Viscosity of typical TS-1 and RT Fuels [1]

Temperature, °C	Viscosity, cSt	
	TS-1	RT
-60	13.33	11.45
-50	8.09	7.24
-40	5.42	5.00
-30	3.89	3.68
-20	2.95	2.83
-10	2.32	2.26
0	1.89	1.86
20	1.34	1.34
40	1.01	1.03
60	0.802	0.824
80	0.658	0.682
100	0.555	0.580
120	0.479	0.503
140	0.420	0.443
160	0.373	0.396
180	0.336	0.358
200	0.305	0.327

4.3. Surface Tension of TS-1 and RT

Table 4 presents the data on surface tension for TS-1 and RT fuels extracted from Table 2.31 of the Russian Handbook. Figure 5 compares these data with surface tension data for Western aviation fuels. These data are about 10% lower than the surface tension of Jet A, Jet A-1, and JP-8.

Table 4. Surface Tension, σ, of Typical TS-1 and RT Fuels [1]

Temperature °C	σ, mN/m	
	TS-1	RT
-60	31.77	31.51
-40	29.93	29.71
-20	28.10	27.93
0	26.30	26.17
20	24.53	24.44
40	22.78	22.73
60	21.06	21.05
80	19.37	19.40
100	17.72	17.78
120	16.09	16.19
140	14.50	14.63
160	12.94	13.10

Temperature °C	σ, mN/m	
	TS-1	RT
180	11.43	11.62
200	9.95	10.17
220	8.52	8.76
240	7.14	7.40
260	5.82	6.10
280	4.55	4.85
300	3.36	3.66
320	2.25	2.56
340	1.25	1.54
360	0.405	0.660
380	--	0.136

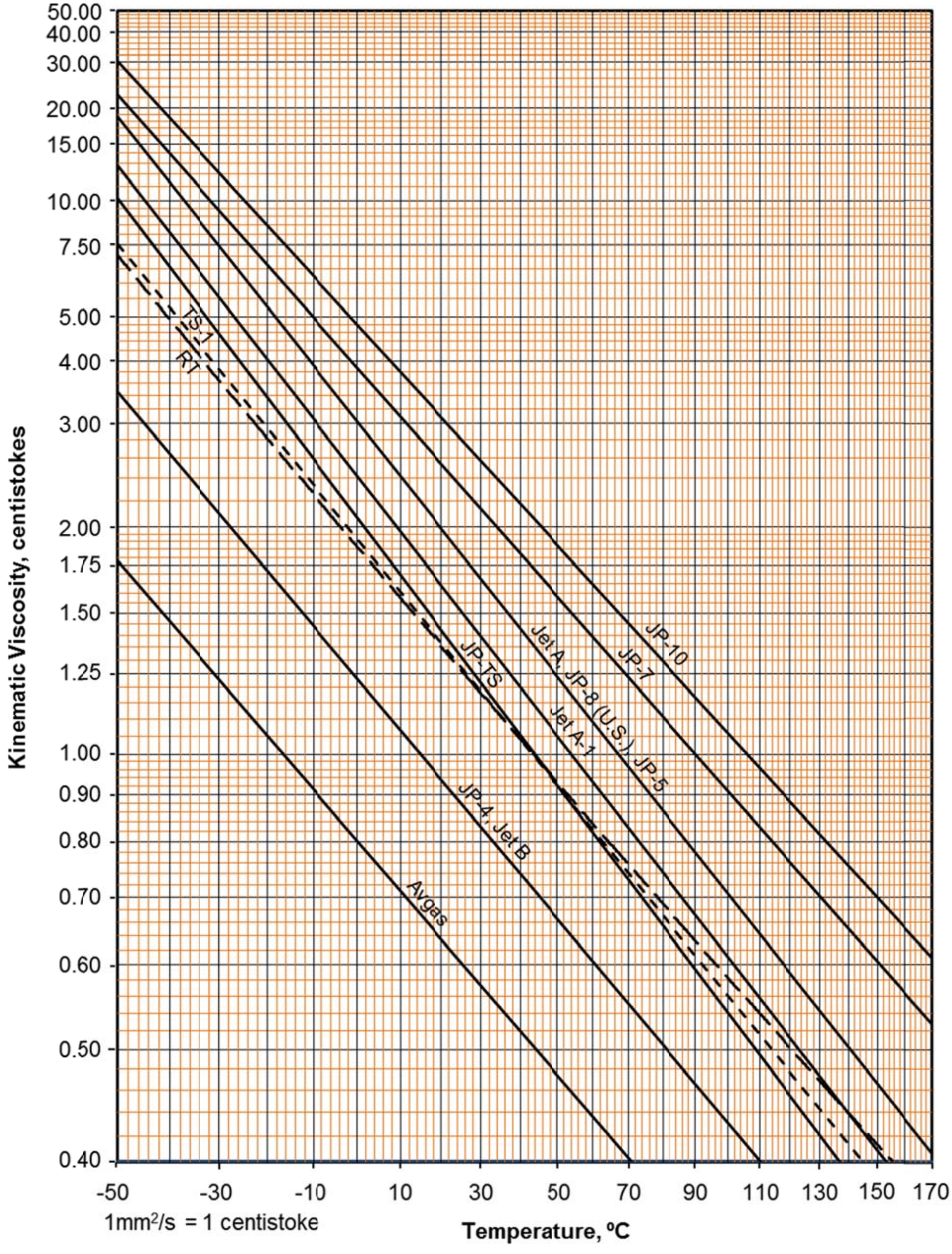


Figure 4. Viscosity of Typical TS-1 and RT Fuels Compared to Data from CRC Handbook [2]

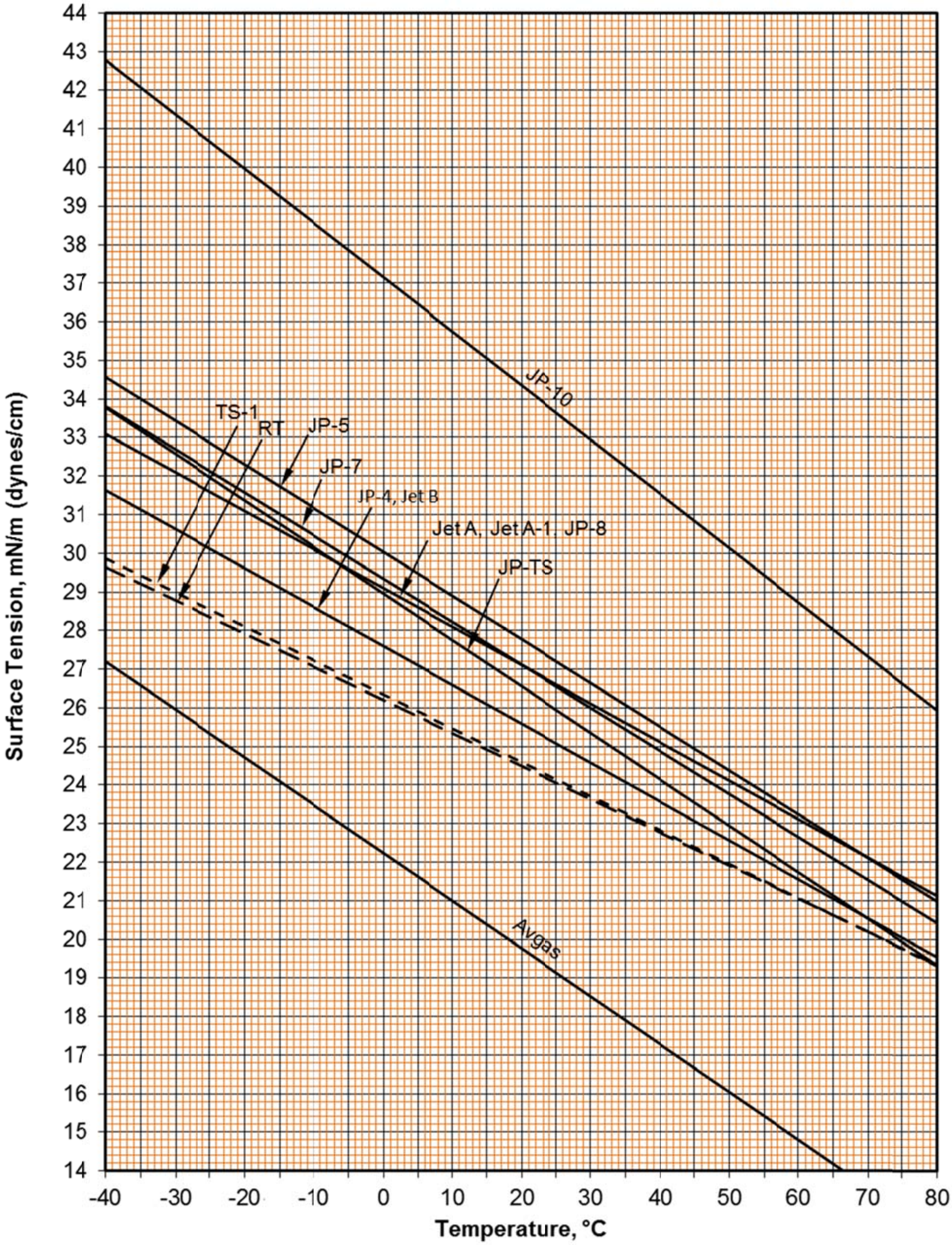


Figure 5. Surface Tension of Typical TS-1 and RT Fuels Compared to Data from the CRC Handbook [2]

4.4. Vapor Pressure of TS-1 and RT

Table 5 presents the data on vapor pressure of TS-1 and RT fuels extracted from Table 2.18 of the Russian Handbook. Figure 6 compares these data for vapor pressure to that of typical aviation turbine fuels from the CRC Handbook. The Russian fuels have vapor pressures about 2 to 3 times that of Jet A, Jet A-1, and JP-8, depending on the temperature.

Table 5. Vapor Pressure, Pv, of Typical TS-1 and RT Fuels [1]

Temperature	Pv, kPa	
°C	TS-1	RT
20	0.920	1.115
40	2.350	2.705
60	**5.365**	5.990
80	11.15	11.78
100	21.44	21.86
120	38.56	38.02
140	65.52	62.73
160	106.0	98.82
180	162.7	149.6
200	238.1	218.6

Temperature	Pv, kPa	
°C	TS-1	RT
220	337.7	309.7
240	466.1	497.2
260	628.1	575.1
280	828.2	757.7
300	1071	979.4
320	1362	1244
340	1704	1556
360	2103	1919
380	-	2336

4.5. Specific Heat of TS-1 and RT

Table 6 presents the data on specific heat for TS-1 and RT fuels extracted from Table 3.4 of the Russian Handbook. Figure 7 compares these data with specific heat data for Western aviation turbine fuels. These data are essentially the same as the specific heat of Jet A, Jet A-1, and JP-8.

Table 6. Specific Heat, Cp, of Typical TS-1 and RT Fuels [1]

Temperature		Cp, kJ/kgK	
K	°C	TS-1	RT
210	-63	1.708	1.697
220	-53	1.741	1.730
230	-43	1.808	1.764
240	-33	1.842	1.798
250	-23	1.878	1.833
260	-13	1.913	1.869
270	-3	1.949	1.905
280	7	1.986	1.941
290	17	2.023	1.978
300	27	2.061	2.016
310	37	2.099	2.053
320	47	2.137	2.091

Temperature		Cp, kJ/kgK	
K	°C	TS-1	RT
330	57	2.137	2.130
340	67	2.175	2.169
350	77	2.214	2.208
360	87	2.254	2.247
370	97	2.293	2.287
380	107	2.333	2.327
390	117	2.373	2.367
400	127	2.414	2.408
410	137	2.455	2.449
420	147	2.496	2.490
430	157	2.538	2.532
440	167	2.580	2.575

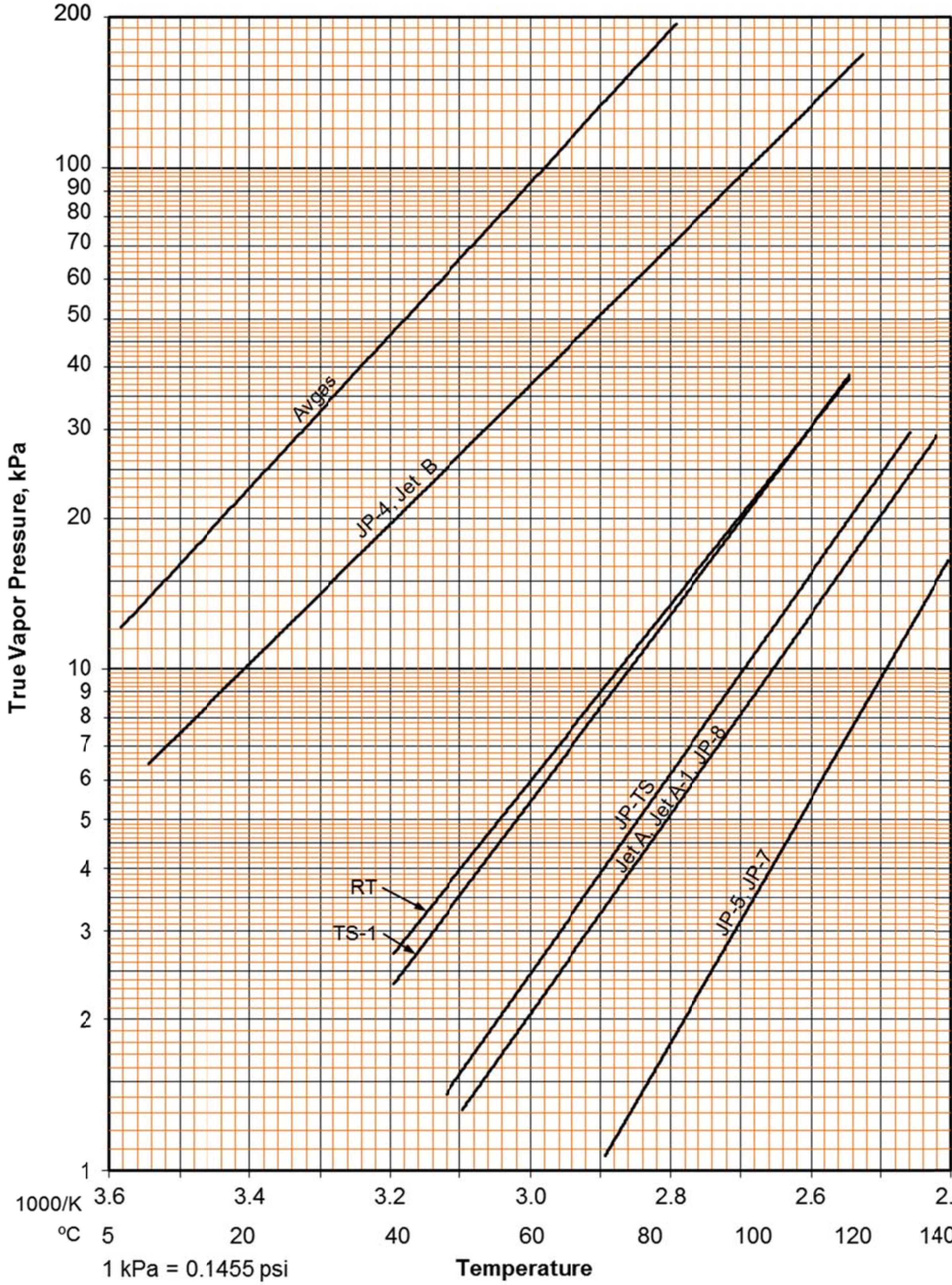


Figure 6. True Vapor Pressure of Typical TS-1 and RT Fuels Compared to Data from the CRC Handbook [2]

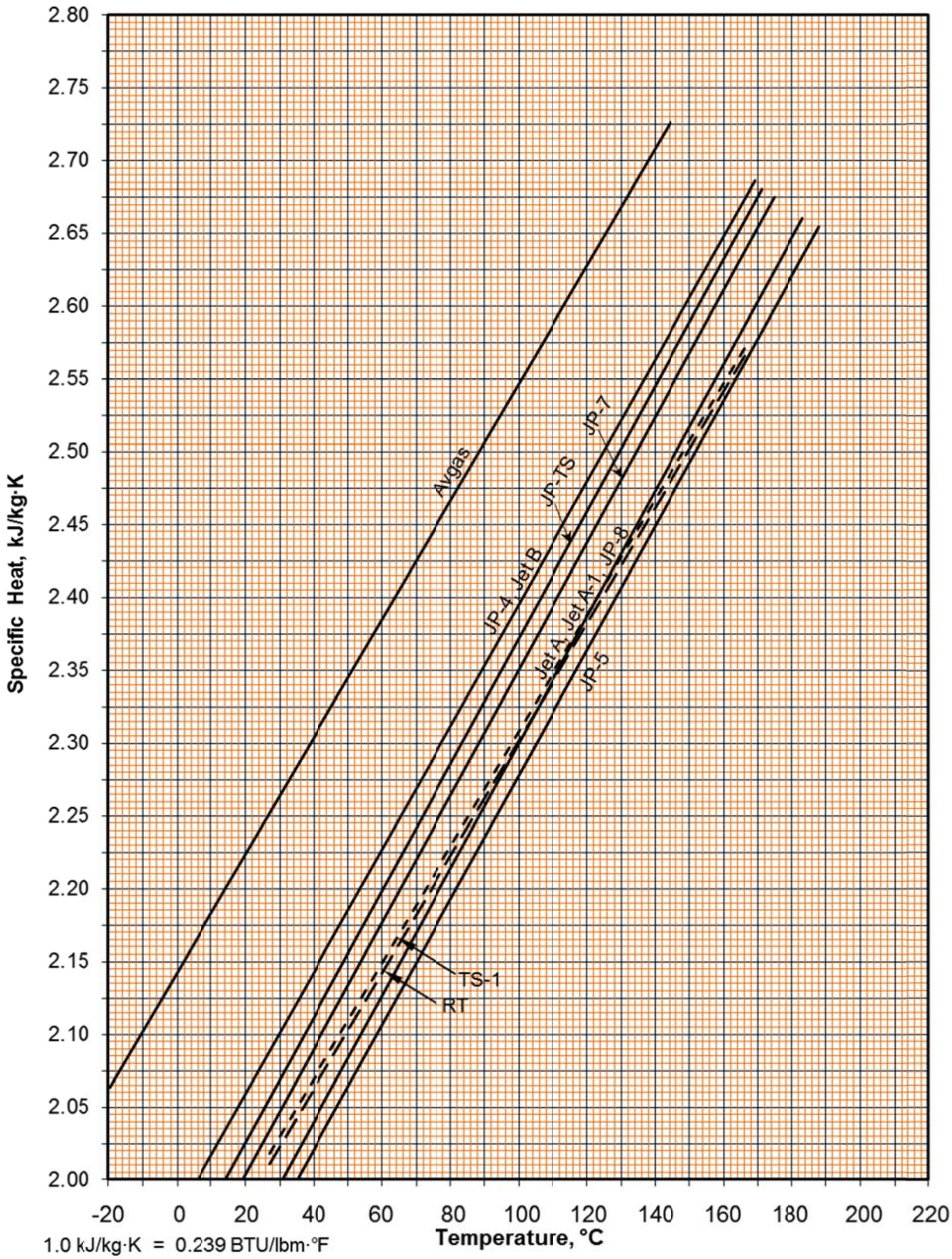


Figure 7. Specific Heat of Typical TS-1 and RT Fuels Compared to Data from the CRC Handbook [2]

4.6. Thermal Conductivity of TS-1 and RT

Table 7 presents the data on thermal conductivity for TS-1 and RT fuels extracted from Table 2.25 of the Russian Handbook. Figure 8 compares these data with thermal conductivity data for Western aviation turbine fuels. The conductivity data of the Russian fuels are about 10% less than the CRC data for Jet A, Jet A-1, and JP-8.

Table 7. Thermal Conductivity, k, of Typical TS-1 and RT Fuels [1]

Temperature °C	k, W/mK	
	TS-1	RT
-60	0.1263	0.1263
-40	0.1230	0.1231
-20	0.1198	0.1199
0	0.1166	0.1167
20	0.1134	0.1135
40	0.1102	0.1103
60	0.1069	0.1071

Temperature °C	k, W/mK	
	TS-1	RT
80	0.1037	0.1039
100	0.1005	0.1006
120	0.0973	0.0974
140	0.0941	0.0942
160	0.0908	0.0910
180	0.0876	0.0878
200	0.0844	0.0845

4.7. Heat of Vaporization

Table 8 presents the data on heat of vaporization for TS-1 and RT fuels extracted from Table 2.25 of the Russian Handbook. Figure 9 compares these data with heat of vaporization data for Western aviation turbine fuels. There are no data for heat of vaporization of Jet A, Jet A-1, and JP-8 in the CRC Handbook with which to compare the Russian fuel data.

Table 8. Heat of Vaporization, H_{vg}, of TS-1 and RT Fuels [1]

Temperature °C	H_{vg}, kJ/kg	
	TS-1	RT
-60	390	385
-40	383	378
-20	375	371
0	368	363
20	360	356
40	351	348
60	343	339
80	334	331
100	324	322
120	315	312
140	305	302
160	294	292

Temperature °C	H_{vg}, kJ/kg	
	TS-1	RT
180	283	281
200	271	270
220	258	257
240	244	244
260	228	230
280	212	214
300	192	196
320	168	175
340	141	149
360	98.8	114
380	-	33.7

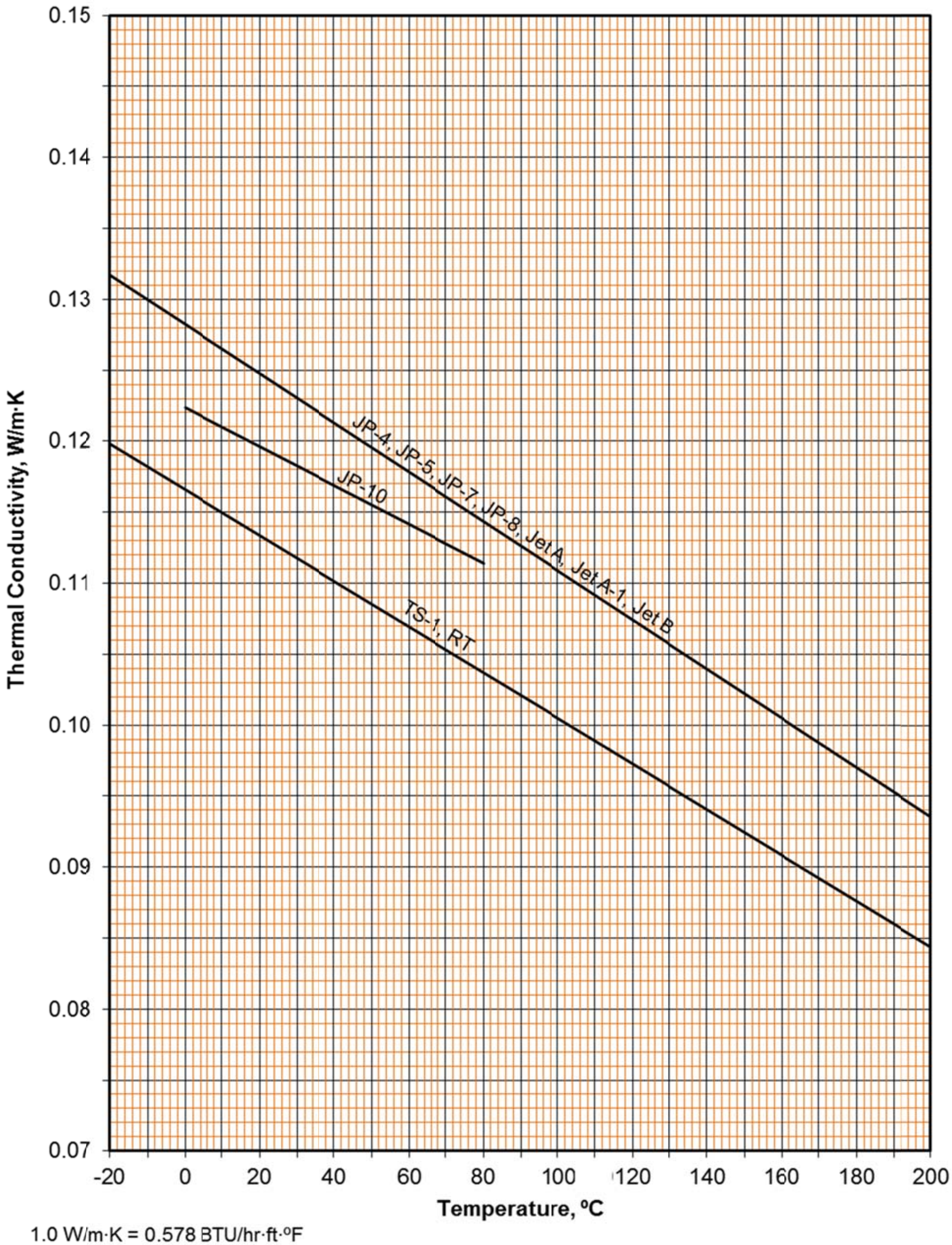


Figure 8. Thermal Conductivity of Typical TS-1 and RT Fuels Compared to Data from the CRC Handbook [2]

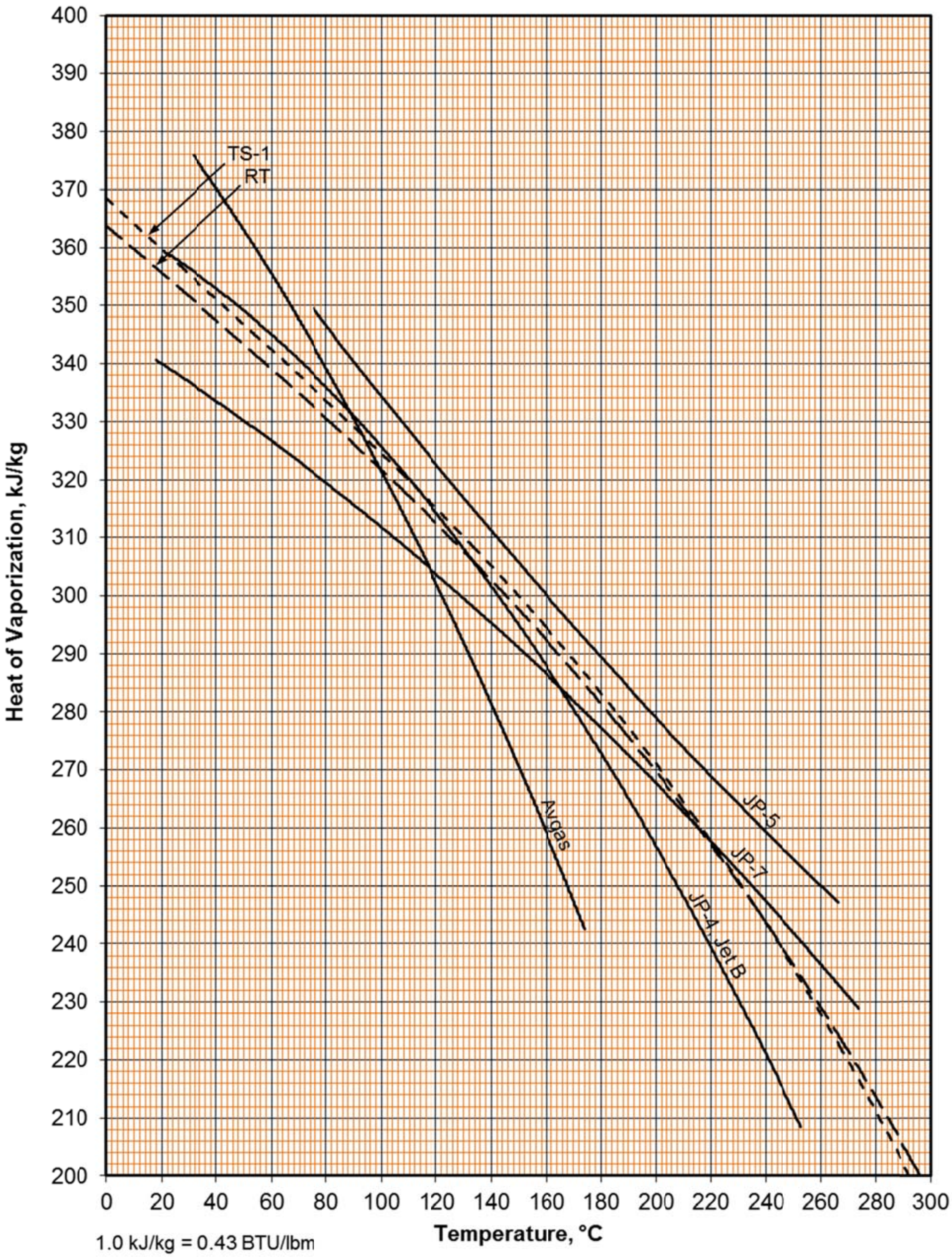


Figure 9. Heat of Vaporization of Typical TS-1 and RT Fuels Compared to Data from the CRC Handbook [2]

4.8. Dielectric Constant

Table 9 presents the data on the dielectric constant of TS-1 and RT fuels extracted from Table 2.67 of the Russian Handbook. Figure 10 compares these data with data on dielectric constant for Western fuels.

Table 9. Dielectric Constant, κ, of TS-1 and RT Fuels [1]

Temperature °C	κ	
	TS-1	RT
-60	2.214	2.200
-20	2.150	2.136
20	2.088	2.078
60	2.030	2.021
100	1.974	1.966
140	1.920	1.910

4.9. Flammability Limits

In Figure 11, the flammability limits for TS-1 are superimposed on the graph of static flammability limits from the CRC Handbook. There are no data to present for the flammability limits of TS-1; this figure was copied from Figure 4.23 of the Russian Handbook and rescaled to fit the CRC graph. The limits are less than that of Jet A/Jet A-1/JP-8 because the minimum flash point of TS-1 is 28°C compared to 38° for the other fuels and the maximum freezing point is lower so TS-1 is a lighter fuel as was seen earlier in the density comparison of Figure 1.

4.10. Minimum Ignition Energy

The Russian Handbook does not provide specific data on minimum ignition energy; instead, it states that the minimum ignition energy of jet fuel from capacitive discharge has a range of Q_0 = 0.20 – 0.25 mJ at the standard conditions of 20°C and 0.1 MPa. Temperature and pressure effects are given by Equation 4.36 in the Russian Handbook as follows:

$$\boldsymbol{Q_{T,P} = Q_0 \left(\frac{273}{T}\right)^3 \left(\frac{0.1}{P}\right)^2} \qquad \text{[Eqn. 4]}$$

where $Q_{T,P}$ is the minimum ignition energy in mJ at T(K) and P(MPa). [Note: It seems possible that the value 273 should be 293 since that is the equivalent of the reference temperature, 20°C.]

Table 10 presents calculated values of minimum ignition energy for a range of temperatures at 0.1 MPa using this equation. These calculated values are compared to the minimum ignition data of Western fuels in Figure 12. The calculated values for the Russian fuels are significantly less than the CRC data – much less than even the JP-4/Jet B data. The noted difference of 273K versus 293K could not account for this as the variation would only be 20 to 25%. The translation of the Russian Handbook provided does not describe the condition of the fuel-air mixture, i.e., whether they are vaporized and premixed or if the fuel is sprayed into the air. The air is stagnant, so presumably the fuel is sprayed into the air as it is in the CRC Handbook. However, minimum ignition energy for fuel sprays into quiescent air depends heavily on the droplet size [7], so a difference in the spray conditions could be a reasonable explanation.

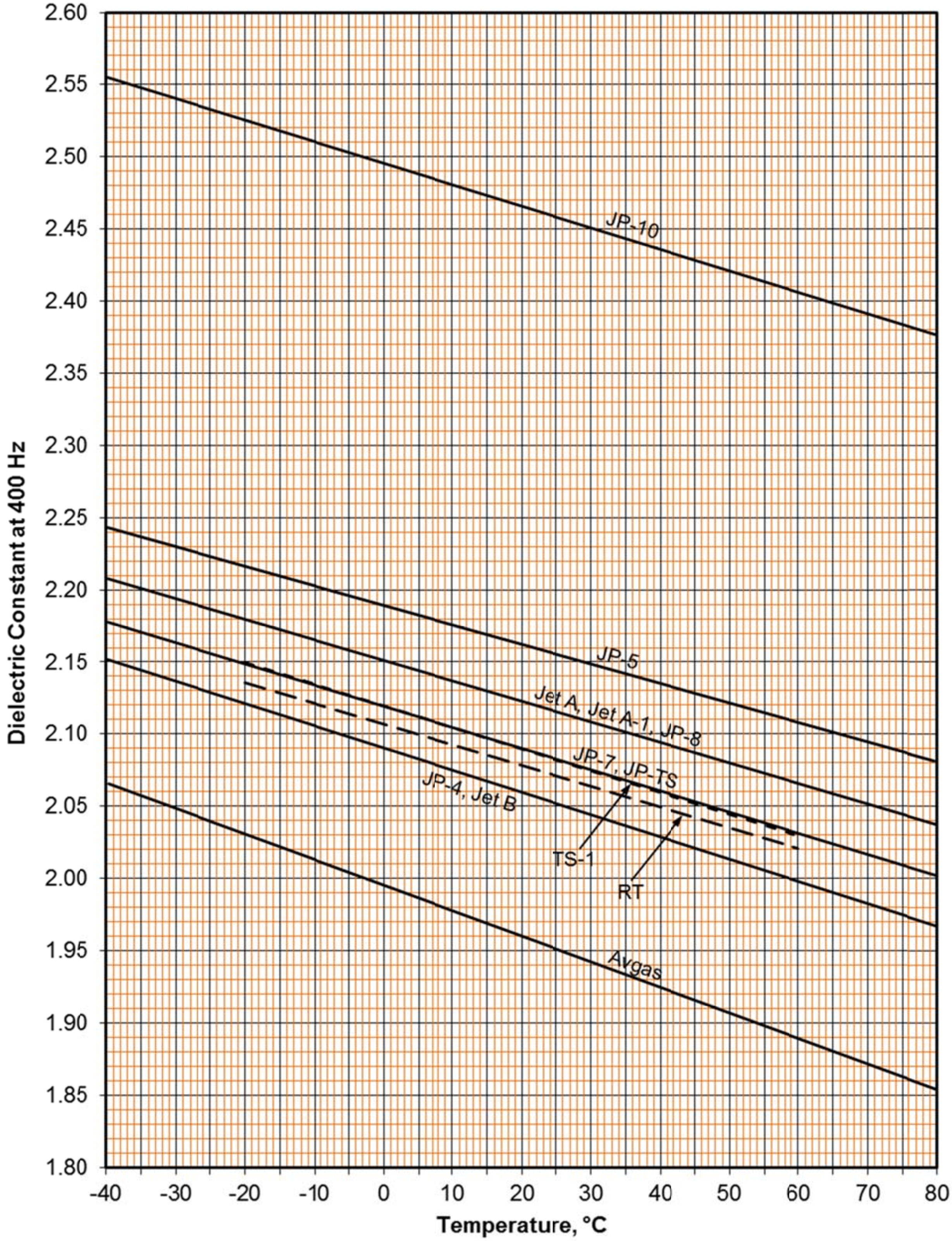


Figure 10. Dielectric Constant of Typical TS-1 and RT Fuels Compared to Data from the CRC Handbook [2]

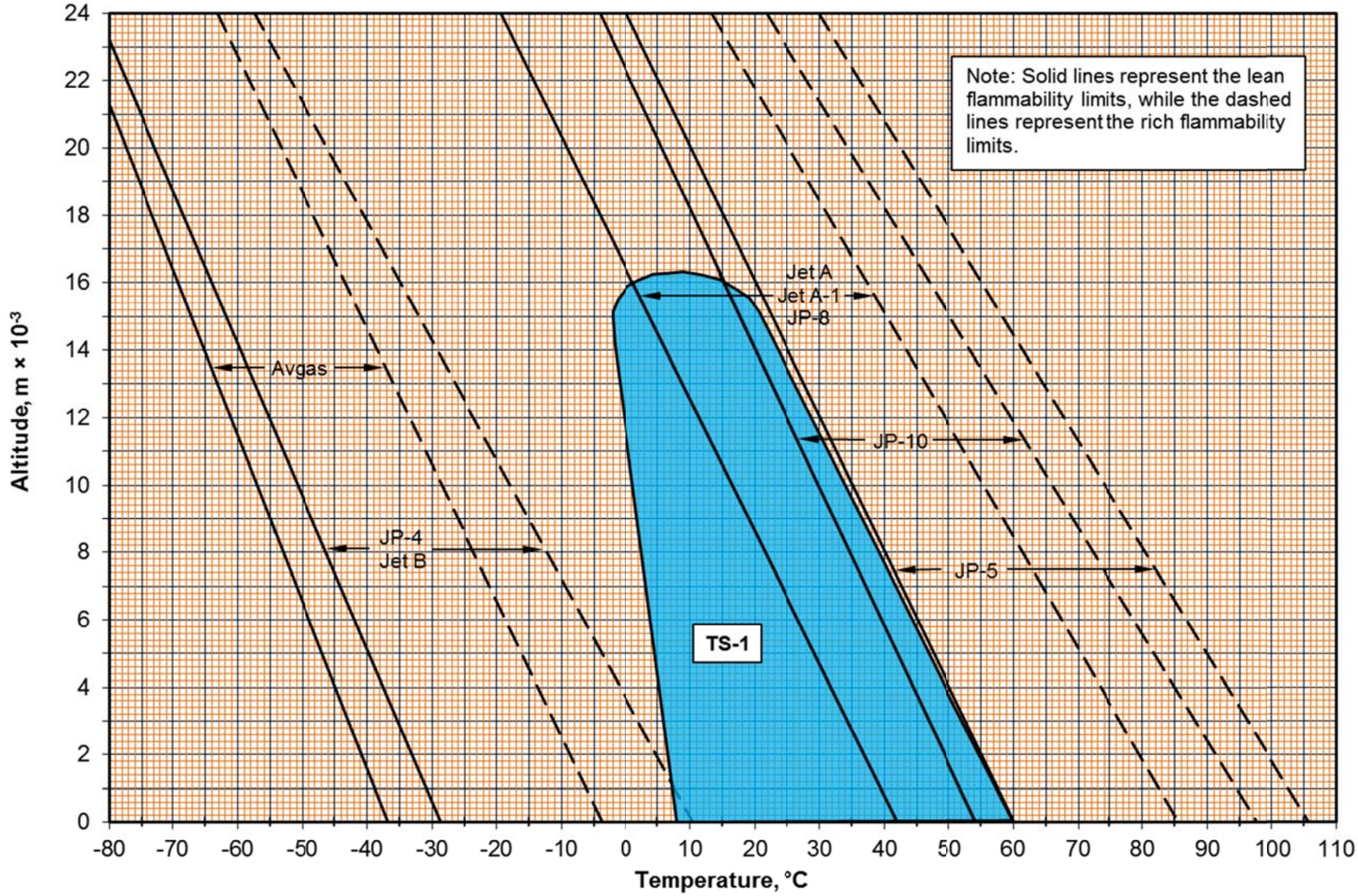


Figure 11. Flammability Limits vs. Altitude for Typical TS-1 Fuel Compared to Data from the CRC Handbook [2]

Table 10. Calculated Values of Minimum Ignition Energy of Russian Fuels at 0.1 MPa

Fuel Temperature		Minimum Ignition Energy, mJ	
°C	K	Q_0 = 0.20	Q_0 = 0.25
-20	253	0.31	0.39
-10	263	0.28	0.35
0	273	0.25	0.31
10	283	0.22	0.28
20	293	0.20	0.25
30	303	0.18	0.23
40	313	0.16	0.21

4.11. Bulk Modulus

The Russian Handbook does not provide data on bulk modulus per se; however it does provide data on acoustic velocity. The acoustic velocity in liquids, *c*, is defined as:

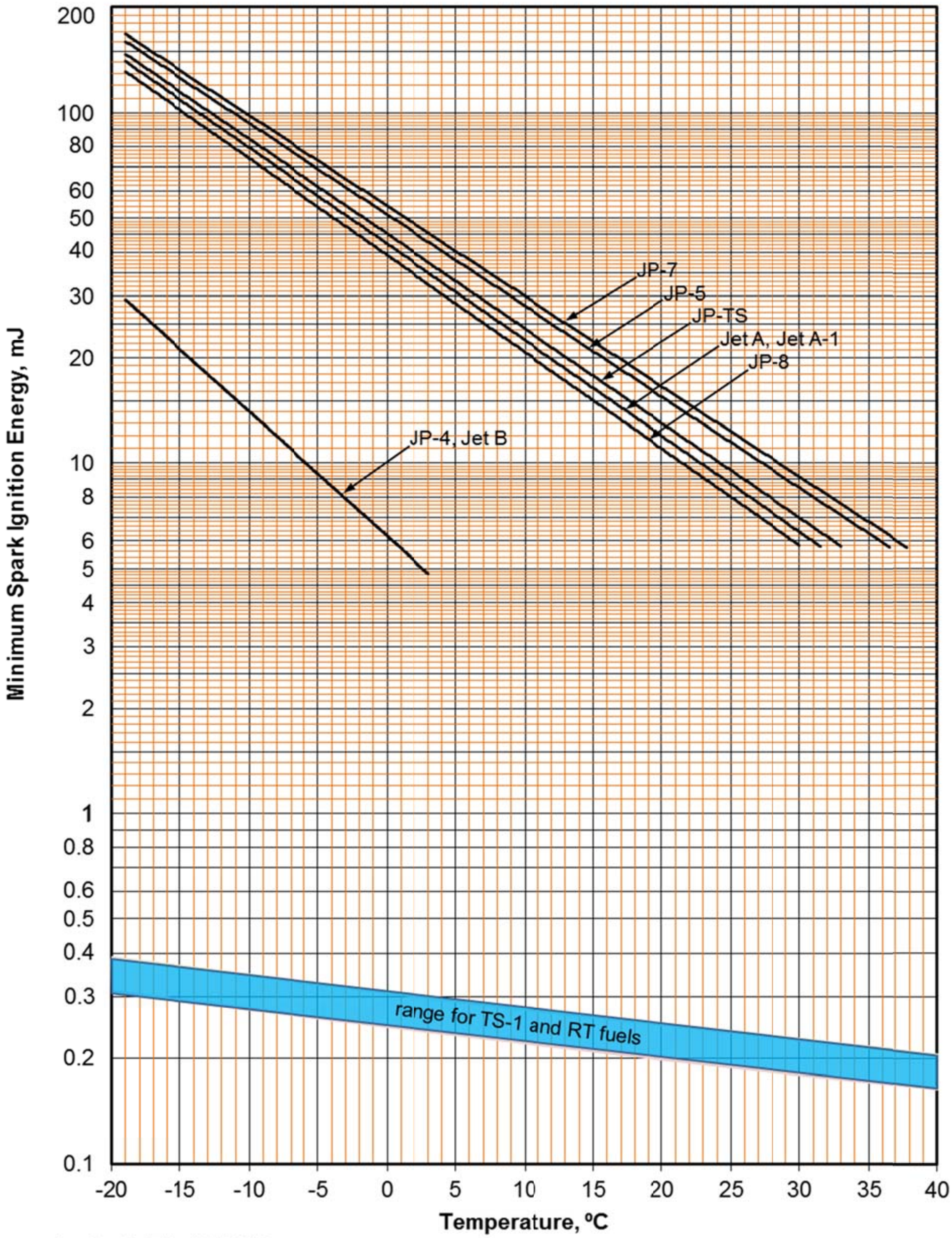
$$c = \sqrt{E_s/\rho} \qquad \text{[Eqn. 5]}$$

Where E_s is the isentropic bulk modulus, in Pa, and ρ is the density of the liquid, in kg/m^3. [8]

Table 11 presents the data on acoustic velocity for TS-1 and RT fuels at two pressures, 0.1 and 10.0 MPa, extracted from Table 2.32 of the Russian Handbook. Density was given earlier in Table 2. The calculated values for bulk modulus are also presented in Table 11; it is assumed that the density was not appreciably changed by the pressure change. Figure 13 compares these data with data on bulk modulus for Western jet fuels. The data for the Russian fuels are much lower than the CRC Handbook data for kerosene-type fuels. Also, the pressure effect is not as great with the Russian data, although it is directionally the same. The reason for the difference is not obvious. The lower density does not account for the difference since the CRC Handbook data for bulk modulus of JP-4 are also higher than the TS-1 and RT data. Both sets of data are identified as being isentropic bulk modulus as opposed to one being isothermal bulk modulus. It is not known if the fuels were de-aerated.

Table 11. Acoustic Velocity and Bulk Modulus of Typical TS-1 and RT Fuels

Temperature °C	Density, kg/m^3		Acoustic velocity, m/s				Bulk Modulus (calculated), MPa			
			0.1 MPa		10 Mpa		0.1 MPA		10 MPa	
	TS-1	RT	TS-1	RT	TS-1	RT	TS-1	RT	TS-1	RT
-60	837.2	835.6	1557	1532	1569	1543	2030	1961	2061	1989
-40	822.8	821.2	1452	1429	1465	1441	1735	1677	1766	1705
-20	808.4	806.8	1358	1336	1371	1349	1491	1440	1520	1468
0	794.0	792.4	1273	1252	1287	1266	1287	1242	1315	1270
20	779.6	778.0	1195	1176	1210	1191	1113	1076	1141	1104
40	765.2	763.6	1123	1105	1139	1121	965	932	993	960
60	750.8	749.2	1056	1039	1074	1056	837	809	866	835
80	736.4	736.8	994	978	1013	997	728	705	756	732
100	722.0	720.4	935	920	956	941	631	610	660	638
120	707.6	706.0	880	865	902	888	548	528	576	557
140	693.2	631.6	826	813	851	838	473	457	502	486
160	678.8	677.2	775	762	803	790	408	393	438	423



1.0 mJ = 9.478×10^{-7} BTU

Figure 12. Minimum Spark Ignition Energy of Typical TS-1 and RT Fuels at 1 atm Compared to Data from the CRC Handbook [2]

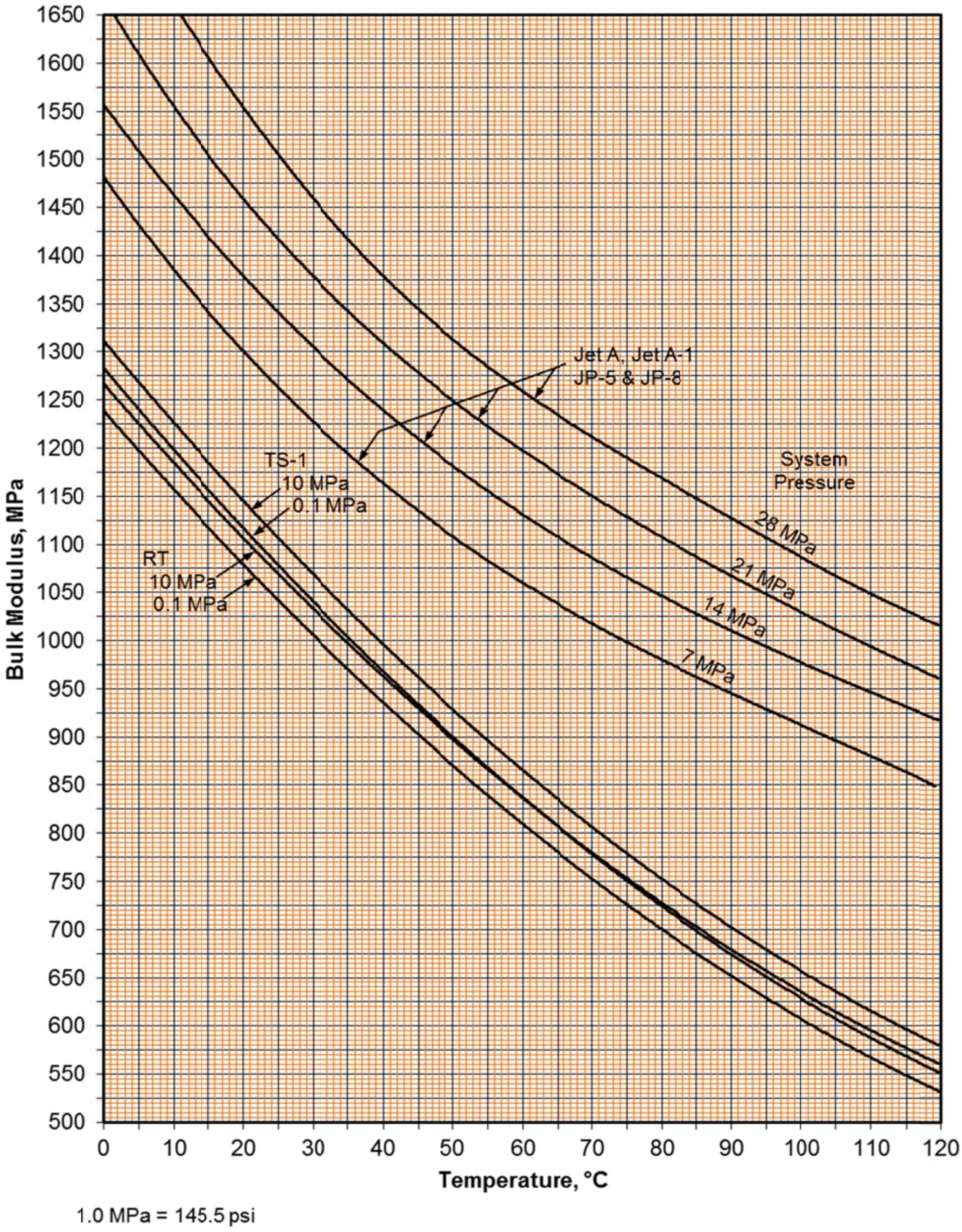


Figure 13. Bulk Modulus vs. Temperature & Pressure for Typical TS-1 and RT Fuels Compared to Data from the CRC Handbook [2]

4.12 Solubility of Gases, Air, Nitrogen, Oxygen, and Carbon Dioxide, in Typical TS-1 and RT Fuels

According to the Russian Handbook, the solubility of gasses in fuels decreases with increases in viscosity, surface tension, and density; the presence of aromatics increases the solubility of gases as does the presence of water.

The Russian Handbook does not provide data tables of gas solubility coefficients as functions of temperature as it does with most of the other properties addressed above. Instead, the Bunsen solubility coefficients for air, nitrogen, oxygen, and CO_2 are provided for several Russian fuels at 20°C and 0.1 MPa. An empirical equation is then given to calculate the coefficient at other temperatures.

The Bunsen solubility coefficient, α, is the volume of a gas, normalized to the standard conditions of 1 atm pressure (101.32 kPa) and a temperature of 0°C, that can be dissolved into 1 m^3 of fuel. It differs from the Ostwald solubility coefficient, L, used in the CRC Handbook by simple temperature and pressure corrections since the Ostwald coefficient does not correct the volume of dissolved gas to standard conditions. Table 12 presents the Bunsen solubility coefficients for air, nitrogen, oxygen, and CO_2 in jet fuels at 20°C and 0.1 MPa taken from Table 1.16 of the Russian Handbook. Equation 6, taken from equation 1.7 of the Russian Handbook, gives the empirical temperature correlation that is said to be within 1% of experimental values for gases over the temperature range -20 to 40°C. This correlation is valid for gases with critical temperatures less than 180K; thus, this equation is not valid for CO_2, which has a critical temperature of 304K. Figure 1.18 in the Russian Handbook graphs the Bunsen coefficient for CO_2 as a function of temperature for RT fuel. Equation 7 gives the conversion from the Bunsen coefficient to the Ostwald coefficient.

Table 12. Bunsen Solubility Coefficients, α_{20}, for TS-1 and RT at T = 20°C and P = 0.1 MPa

Fuel	Air	N_2	O_2	CO_2
TS-1	0.191	0.170	0.272	1.73
RT	0.193	0.171	0.274	1.74

$$\boldsymbol{\alpha = \alpha_{20}\left(\frac{T(K)}{293}\right)^{0.445}} \qquad \text{[Eqn. 6]}$$

$$\boldsymbol{L = \alpha\left(\frac{T(K)}{273}\right)\left(\frac{0.1}{P(MPa)}\right)} \qquad \text{[Eqn. 7]}$$

Table 13 presents the values of the Bunsen and Ostwald solubility coefficients, α and L, for air, nitrogen, and oxygen for TS-1 and RT calculated using the data from Table 12 and Equations 6 and 7 over the range of validity. These results for the Ostwald coefficients are compared with the corresponding solubility data from the CRC Handbook in Figures 14, 15 and 16. The graph lines for the two fuels are combined since they differ by 1% or less. The Ostwald coefficients for air, nitrogen, and oxygen for the Russian fuels are similar to the CRC data except that they are on the order of 30 to 50% higher than expected; from a purely density consideration, the line for the Russian fuels would be expected to lie between that of JP-4/Jet B and Jet A/Jet A-1/JP-8.

Table 13. Bunsen and Ostwald Gas Solubility Coefficients for Typical TS-1 and RT Fuels (Calculated According to the Russian Handbook)

Temp. °C	Bunsen Coefficient (Russian Handbook), α						Ostwald Coefficient (Russian Handbook), L					
	Air		N_2		O_2		Air		N_2		O_2	
	TS-1	RT	TS-1	RT	TS-1	RT	TS-1	RT	TS-1	RT	TS-1	RT
-20	0.179	0.181	0.159	0.160	0.255	0.257	0.154	0.156	0.138	0.138	0.220	0.222
0	0.185	0.187	0.165	0.166	0.264	0.266	0.172	0.174	0.153	0.154	0.246	0.247
20	0.191	0.193	0.170	0.171	0.272	0.274	0.191	0.193	0.170	0.171	0.272	0.274
40	0.197	0.199	0.175	0.176	0.280	0.282	0.210	0.212	0.187	0.188	0.299	0.301

After reviewing these results, Boeing staff identified deficiencies in the Russian approach due to the lack of consideration of density and vapor pressure in Equation 6. They recommended the use of ASTM D3827 for calculating solubility coefficients of gases in petroleum liquids based on the density and vapor pressure characteristics of the fuel. [9] Calculations were made accordingly by Jean-Philippe Belières and Todd Erickson of Boeing to determine both the Bunsen and Ostwald coefficients for air, nitrogen, and oxygen in both TS-1 and RT. [10] Table 14 provides these data. These Ostwald coefficients are also included in the graphs of Figure 14, 15, and 16; again the data for TS-1 and RT are combined into one line. The calculated solubility coefficients for nitrogen and air are closer in value to the CRC Handbook than the Russian data, but have somewhat different temperature functions. As with the Russian data, the calculated coefficient for oxygen are much higher at lower temperatures than would be expected based on density.

Table 14. Bunsen and Ostwald Gas Solubility Coefficients for Typical TS-1 and RT Fuels (Calculated According to ASTM D3827) [9,10]

Temp. °C	Bunsen Coefficient (ASTM D3827), α						Ostwald Coefficient (ASTM D3827), L					
	Air		N_2		O_2		Air		N_2		O_2	
	TS-1	RT	TS-1	RT	TS-1	RT	TS-1	RT	TS-1	RT	TS-1	RT
-20	0.149	0.150	0.102	0.103	0.274	0.275	0.139	0.140	0.095	0.095	0.254	0.255
0	0.154	0.155	0.110	0.110	0.264	0.266	0.155	0.155	0.110	0.110	0.265	0.267
20	0.157	0.157	0.115	0.116	0.254	0.255	0.170	0.171	0.125	0.126	0.276	0.277
40	0.157	0.157	0.119	0.119	0.243	0.243	0.184	0.185	0.140	0.140	0.285	0.286
60	0.154	0.153	0.120	0.119	0.228	0.227	0.198	0.199	0.155	0.155	0.294	0.294
80	0.145	0.144	0.116	0.115	0.207	0.206	0.211	0.212	0.169	0.169	0.301	0.302
100	0.129	0.126	0.105	0.105	0.177	0.177	0.224	0.224	0.183	0.183	0.308	0.309
120	0.101	0.102	0.084	0.085	0.135	0.136	0.235	0.236	0.196	0.196	0.315	0.315
140	0.057	0.062	0.048	0.052	0.075	0.080	0.246	0.247	0.209	0.209	0.321	0.321

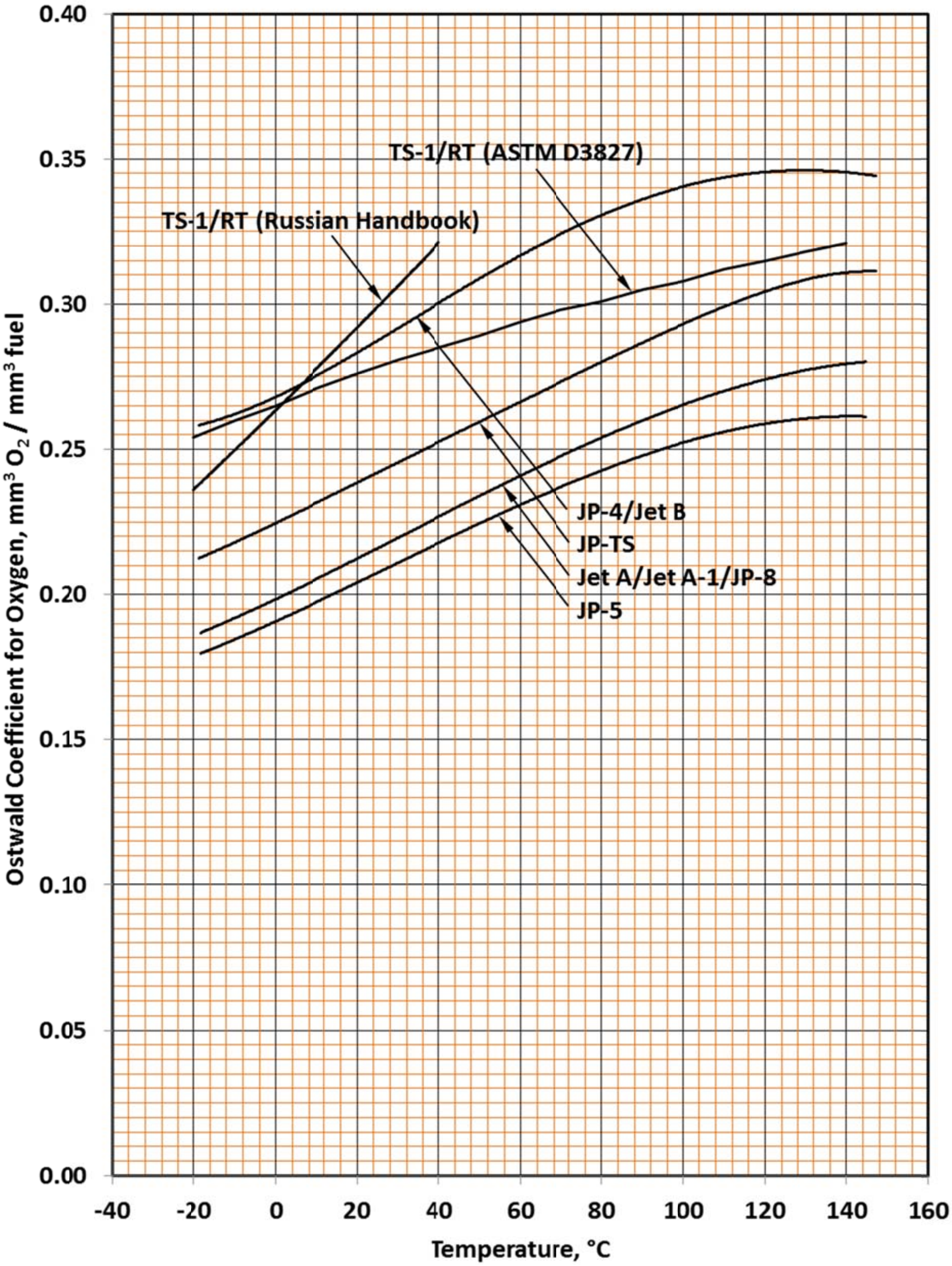


Figure 14. Solubility of Oxygen in Typical TS-1 and RT Compared to CRC Handbook Data [2] and ASTM D3827 [9,10]

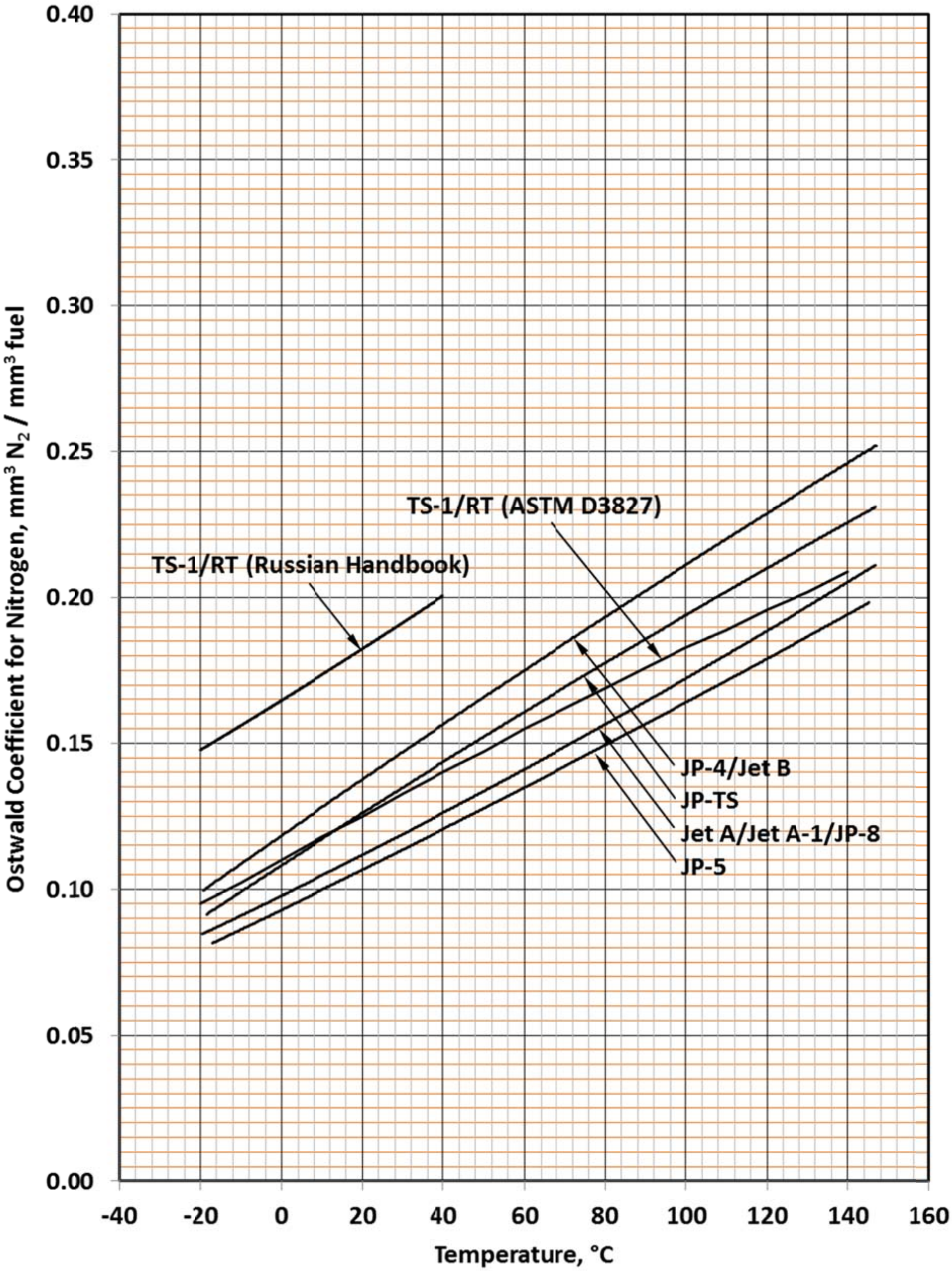


Figure 15. Solubility of Nitrogen in Typical TS-1 and RT Compared to CRC Handbook Data [2] and ASTM D3827 [9,10]

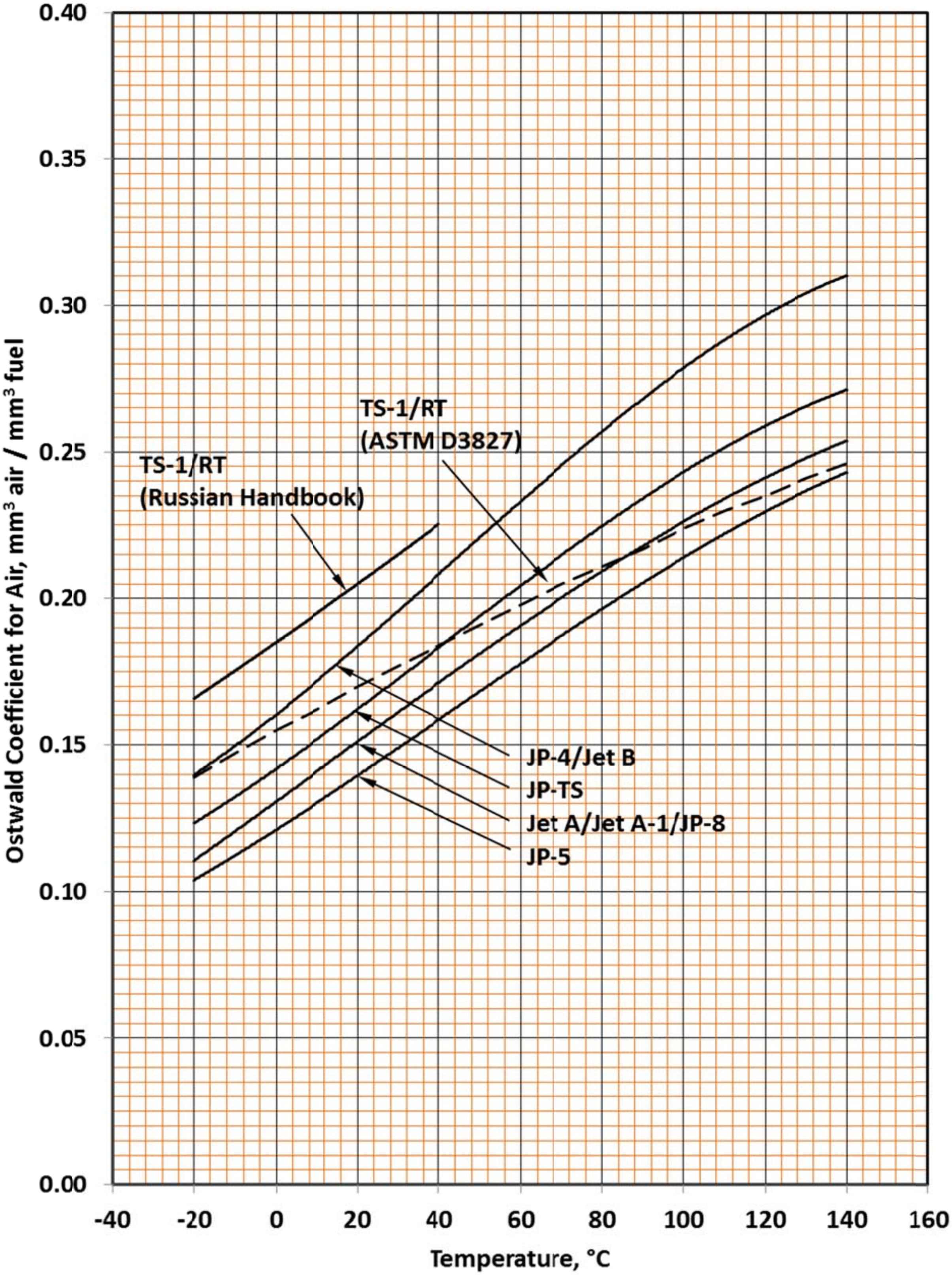


Figure 16. Solubility of Air in Typical TS-1 and RT Compared to CRC Handbook Data [2] and ASTM D3827 [9,10]

As previously noted, Equation 6 is not valid for CO_2. The Russian Handbook does not provide a correlation such as Equation 6 for CO_2, but Figure 1-15 in that Handbook is a graph of the Bunsen coefficient vs. temperature for RT fuels. Table 15 presents the solubility values taken from that graph as well as the corresponding Ostwald coefficients calculated using Equation 7. Figure 17 compares these data with the CO_2 solubility data from the CRC Handbook. Although both sets of data show that the solubility of CO_2 decreases with temperature, the shapes of the curves are quite different. These data also suggest that an experimental project to verify the solubility of relevant gases is warranted.

Table 15. Bunsen and Ostwald Solubility Coefficients for CO_2 in Typical RT Fuel

Temperature °C	Bunsen Coefficient, α	Ostwald Coefficient, L
-38.5	2.23	1.85
-20	1.96	1.69
0	1.58	1.47
20	1.28	1.28
40	1.00	1.07
60	0.80	0.89

4.13 Water Solubility

The solubility of water in fuel depends upon several fuel factors as well as environmental conditions. Water solubility increases with aromatic content and decreases with higher boiling range fuels. On the environmental side, water solubility increases with pressure, temperature, and humidity of the air above the fuel. Equation 1.3 in the Russian Handbook provides the following equation for water solubility in fuel:

$$g^*_{H_2O} = g^*_0 \varphi \left(\frac{P}{P_0}\right)\left(\frac{T}{T_0}\right)^n \qquad \text{[Eqn. 8]}$$

where $g^*_{H_2O}$ = maximum solubility of water in the fuel at the specified condition, m%

g^*_0 = maximum solubility of water in the fuel at the reference condition of φ=1.0 (100% humidity), P_0 = 0.1 MPa, and T_0 = 293K

P = air pressure above the fuel, MPa

T = temperature of the air and fuel, K

φ = humidity of air above the fuel

n = constant depending on the fuel

For TS-1 and RT, g^*_0 = 0.00865 m%, and n = 11.5.

Table 16 presents the solubility of water in TS-1 and RT fuels extracted from Table 1.15 of the Russian Handbook which were calculated from Equation 8. Figure 18 compares these data with water solubility data for Western aviation turbine fuels. [Note: the m% data in Table 16 were converted to vol% by multiplying by the specific gravity of TS-1 as given in Table 1.] The data on water solubility for the Russian fuels is in general agreement with the CRC data although the curve has a somewhat different shape. The position of the Russian data relative to the CRC data is difficult to judge because of the relative positions of the CRC data for various fuel types.

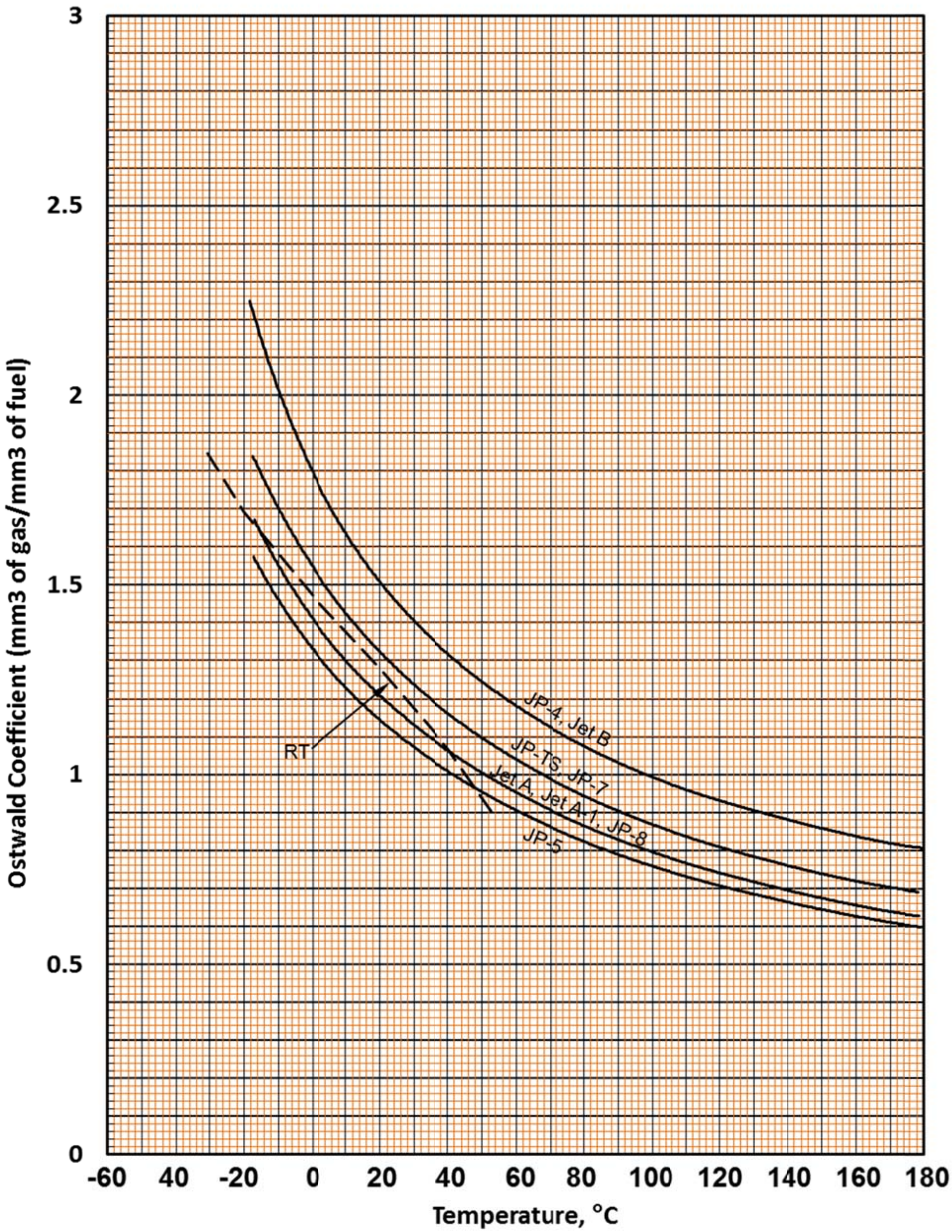


Figure 17. Solubility of CO2 in Typical RT Fuel Compared to Data from CRC Handbook [2]

Table 16. Water Solubility in Typical TS-1 and RT Fuels

Temp. °C	Solubility, m%	Solubility, v%
-10	0.00250	0.00200
-5	0.00315	0.00215
0	0.00384	0.00305
5	0.00473	0.00374
10	0.00581	0.00457
15	0.00710	0.00557
20	0.00865	0.00676
25	0.01051	0.00818
30	0.01273	0.00988
35	0.01536	0.01188
40	0.01849	0.01426
45	0.02218	0.01706
50	0.02654	0.02036
60	0.03767	0.02878

4.14. Summary of Comparison of Russian Fuel Data with CRC Data

Most of the thermal-physical properties of the Russian fuels are very similar in value and temperature function as the fuels in the CRC Handbook of Aviation Fuel Properties. The notable exceptions are:

- Minimum ignition energy
- Bulk modulus
- Solubility of gases

The data for minimum spark energy for the Russian fuels is about two orders of magnitude lower than the CRC data for Jet A/Jet A-1/JP-8. Volatility is not the answer because the Russian data is much less than even the CRC data for JP-4/Jet B. The difference could be due to a difference in test apparatus or spray quality, which is not known.

The data for bulk modulus of the Russian fuels is lower than the CRC data in the range of 10 to 40%, depending upon the temperature, with the greater difference being at higher temperatures.

The approach provided in the Russian Handbook for determining solubility coefficients for air, oxygen, and nitrogen yields results that are higher than the CRC data for a typical Jet A/Jet A-1/JP-8. The gas solubility coefficients for TS-1/RT are expected to be slightly higher due to the lower density of the Russian fuels, but the Russian coefficients are even higher than the CRC values for JP-4/Jet B. Solubility coefficients calculated according to ASTM D3827 yield values much closer to the CRC Handbook values, but the temperature sensitivities are less. The Russian data for solubility constant for carbon dioxide has a much different temperature function than the CRC data although the values are about the same.

These areas of difference are important to safety, functionality, and operations. Since the history and test procedures of both the Russian and CRC data are unknown, it would be worthwhile to conduct test programs on representative fuels to verify or correct these data for the CRC Handbook.

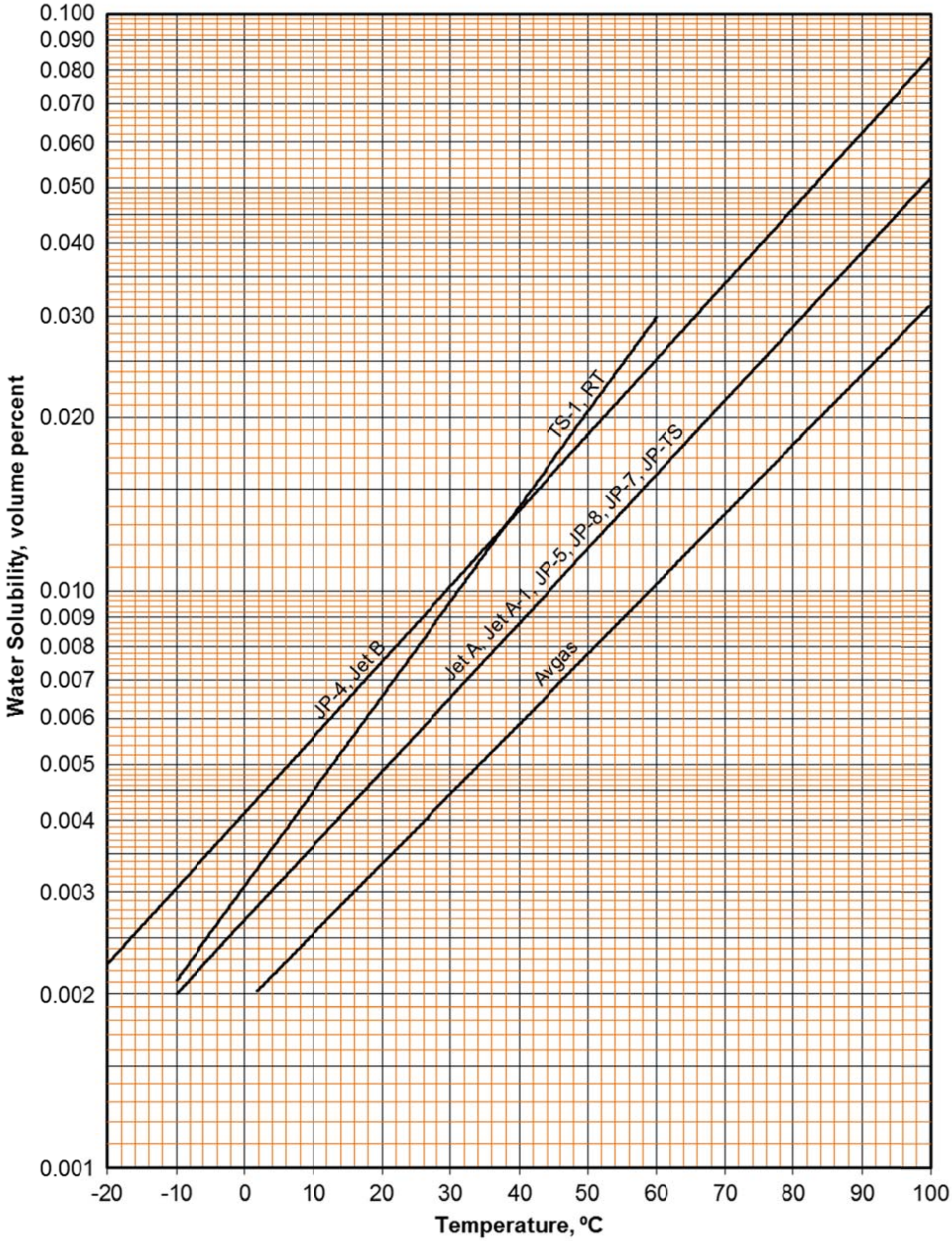


Figure 18. Solubility of Water in Typical TS-1 and RT Fuels Compared to Data from CRC Handbook [2]

5. RELEVANCE OF DATA IN RUSSIAN HANDBOOK

Since the Russian Handbook was published in 1985, before the collapse of the Soviet Union, it is worth considering the relevance of the data to current aviation fuels, both TS-1 and Jet A-1/JP-8. This will be examined first by comparing the density data of TS-1 from the Russian Handbook with that of several recent databases of TS-1 properties from 1993 to 2011. The historic yearly average density for TS-1 will be compared to that of JP-8 and Jet A-1 from the PQIS database for the years 2001 to 2010. Then histograms of density data for TS-1, JP-8, and Jet A-1 for the year 2010 will be presented as means of comparing variability.

The TS-1 data for these comparisons come from four sources:

1. A collection of 24 Lufthansa lab reports from Azerbaijan for the years 2003 – 2006 but mostly from 1995;
2. A collection of 226 data records from Lufthansa from a number of airports around the FSU (Former Soviet Union) and PRC (Peoples Republic of China) for the years 1994 to 1999;
3. A collection of 40 lab reports from AFPET (Air Force Petroleum Office) for the years 2003 to 2006; and
4. A collection of 343 data records from the PQIS data base for the years 2006 to 2011.

The first 3 sets of TS-1 data were provided by Dr. Tim Edwards of the Air Force Fuels Branch at Wright-Patterson AFB and were used in his report of TS-1, "TS-1 Fuel Property Analysis", AFRL-PR-WP-TR-2006-2139. The fourth set of data and the 2011 data for JP-8 and Jet A-1 came from the 2010 PQIS report. Note that all of these data sets are based on reporting specification properties. Density was generally reported at only one temperature either 15°C or 20°C. A large number of the data records in the PQIS data base reported density at both temperatures. The average difference was 3.7 kg/m^3. This value was used to adjust all of the density data that was provided at only 15°C to get a consistent data set at 20°C.

Figures 19 – 22 present histograms generated from the four data sets of TS-1 identified above covering a span of 19 years, although there are no data available for the years 2000 to 2002. Note that these are presented in terms of number of samples each year; while the PQIS data base provides data on sample volumes, the other data bases do not. Although the TS-1 samples came from a number of locations scattered across Eastern Europe and Central Asia, there is a relatively small variation in the density of the samples.

Figure 23 shows the historical averages of density for TS-1 from the data sets above, along with that of JP-8 and Jet A-1 from the PQIS data base. The average density of TS-1 has been quite consistent over the period of 19 years with an increase of about 1% for the years 2008 and 2009. On average it is a little over 1% above the value given by the Russian Handbook. Fuel properties which correlate with density can be expected to vary accordingly from the results presented in this report. For reference, the average density of TS-1 is similar to that of Jet A-1 but about 1½% less than that of JP-8.

Figure 24 compares histograms of the density of TS-1 with JP-8 and Jet A-1 for the year 2010 using data from the PQIS database. The density of TS-1 has less variation than that of the other

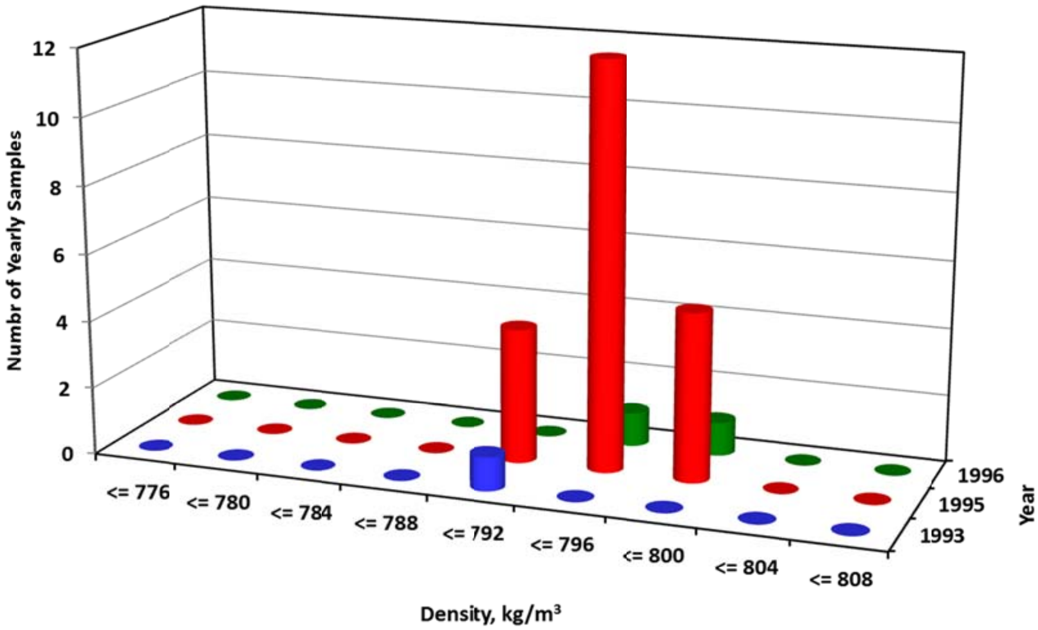


Figure 19. Density of TS-1 Samples from Azerbaijan During 1993 to 1996 [4]

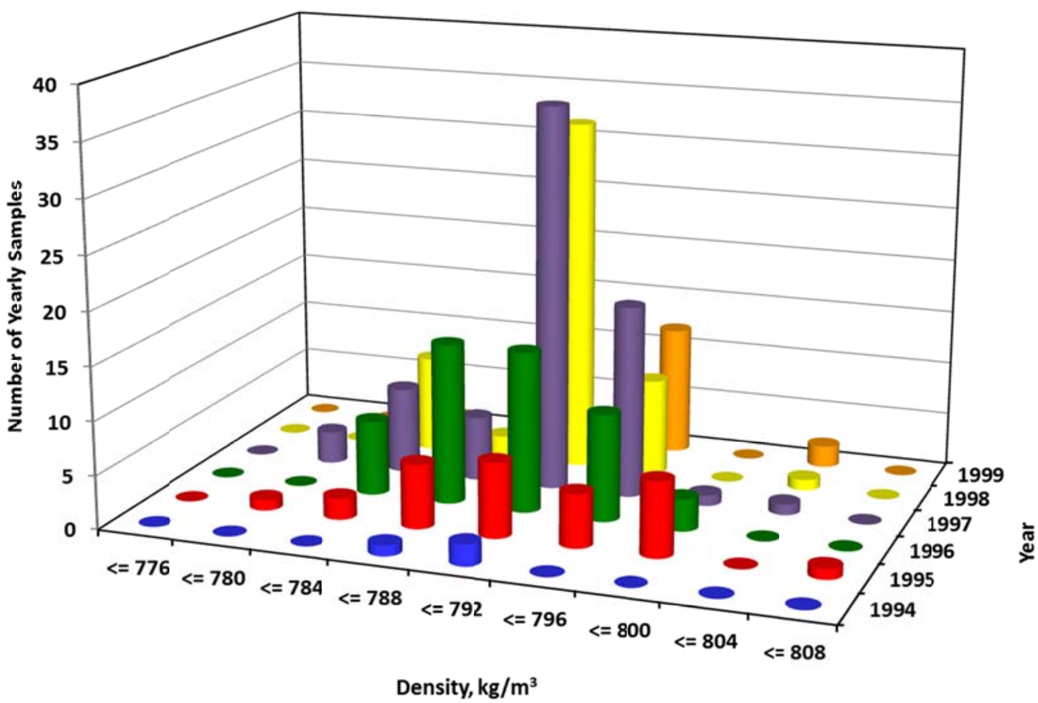


Figure 20. Density of TS-1 Samples from FSU and PRC during 1994 to 1999 [4]

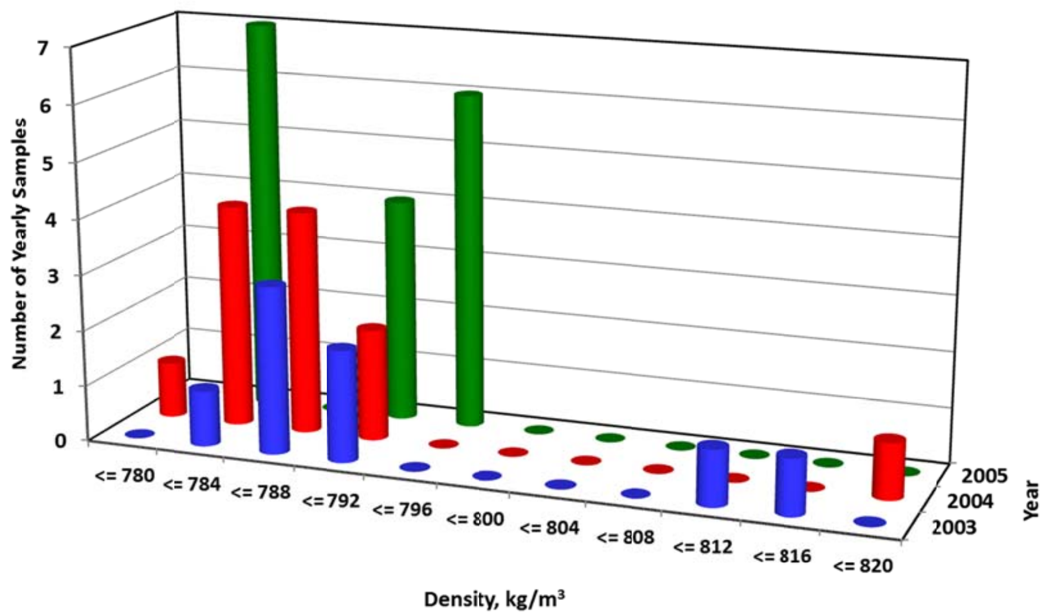


Figure 21. Density of TS-1 Samples for the Period 2003 to 2006 [5]

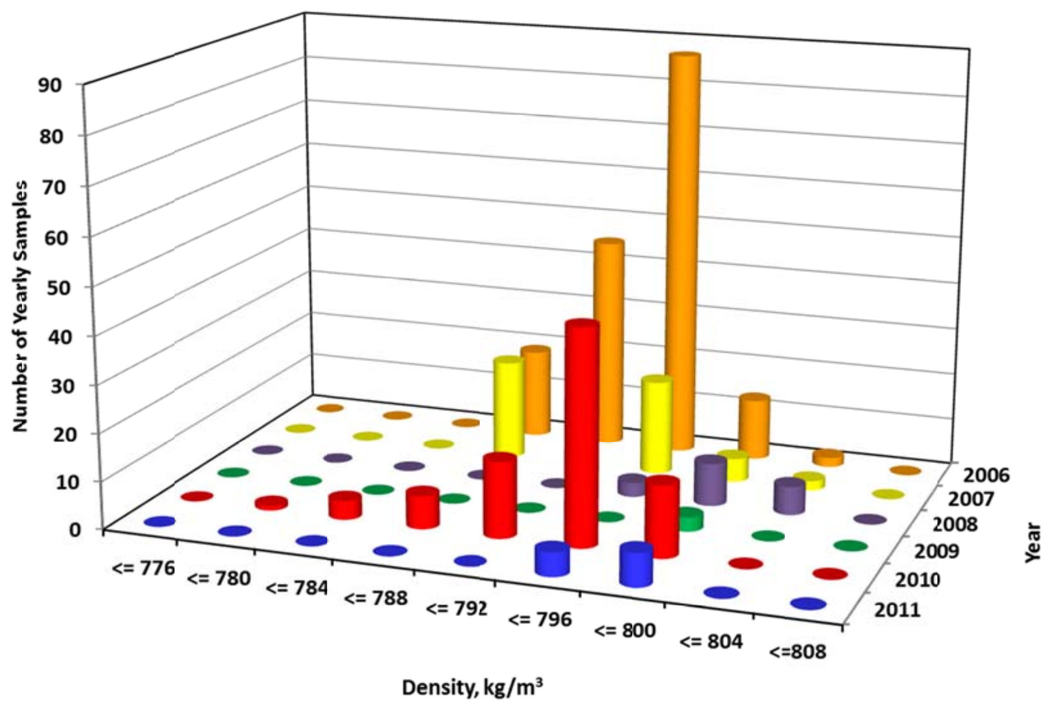


Figure 22. Density of TS-1 Samples for the Period 2006 to 2011 [3]

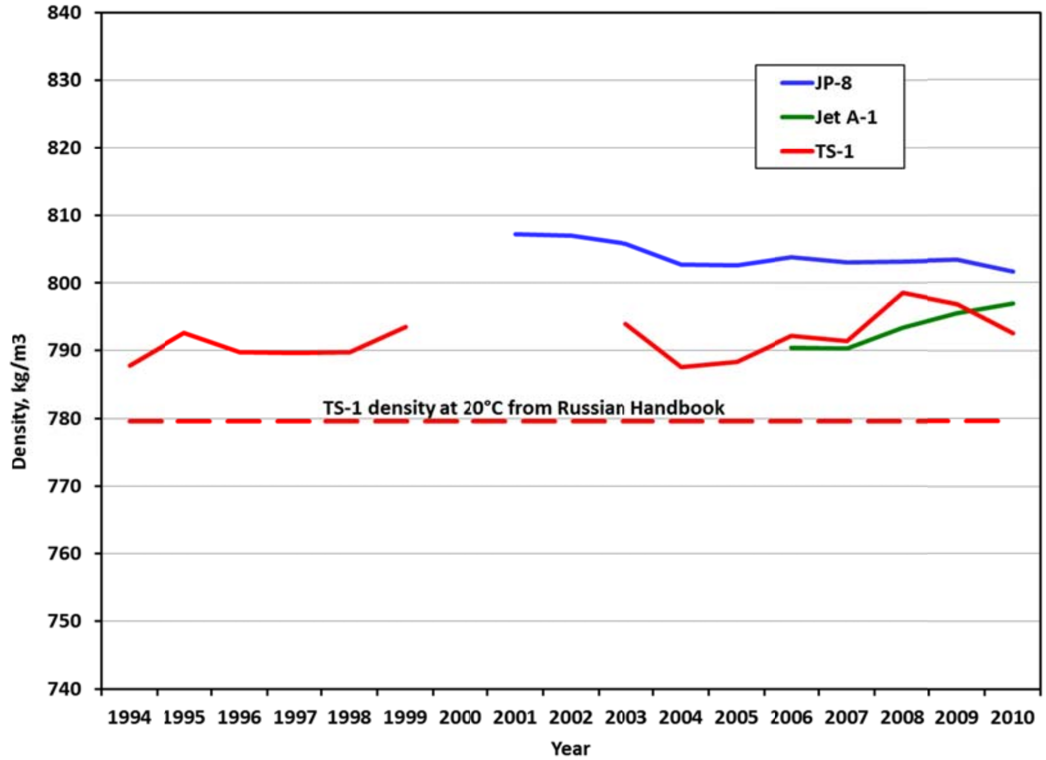


Figure 23. Historical Average Densities of TS-1, JP-8, and Jet A-1 [3]

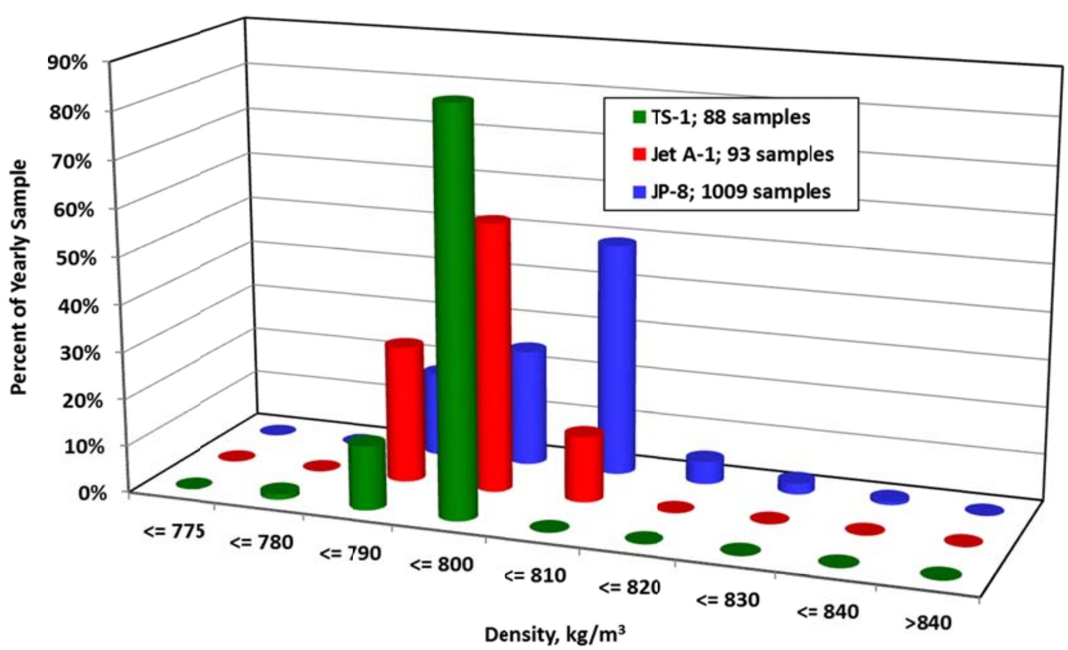


Figure 24. Density Histograms for TS-1, Jet A-1, and JP-8 for the Year 2010 [3]

two fuels, 85% of the samples having density between 790 and 800 kg/m^3. This is consistent with the histograms presented in Figures 19 – 22 in which essentially all of the samples of TS-1 had densities between 780 and 800 kg/m^3. It is reasonable to expect that most other bulk physical properties of TS-1 will be more consistent than those of JP-8 and Jet A-1.

6.0 CONCLUSIONS

The data extracted from the Physical-Chemical and Operational Properties of Jet Fuels are generally quite consistent with the data from the CRC Handbook of Aviation Fuel Properties for the bulk physical properties. The temperature sensitivity of each was essentially the same as for the fuel data in the CRC Handbook. The values were considered consistent with the lower density and the lower minimum flash point of TS-1 and RT fuels compared to Jet A/Jet A-1/JP-8. The only significant exceptions were the minimum ignition energy, bulk modulus, and solubility of gases. For all practical purposes, the differences in property values between TS-1 and RT are considered to be insignificant.

The data for minimum ignition energy was much lower than could be accounted for by higher volatility and lower viscosity, i.e., better atomization, since the data for TS-1 were more than an order of magnitude less than the CRC data for JP-4. One distinct possibility is a difference in the test apparatus and/or conditions. These are very important to ignition but are not known for either set of data.

The gas solubility coefficients for air, oxygen, and nitrogen determined from the Russian Handbook are higher than expected, even accounting for the lower density compared to Jet A/Jet A-1/JP-8. The solubility coefficients for these gases in TS-1/RT calculated according to ASTM D3827 seem more in line with the CRC Handbook values, although the temperature sensitivity is less. The Russian data for the solubility coefficient of carbon dioxide has a much different temperature function than the CRC data although the values are about the same and, unlike the solubility of the other gases, decrease with temperature, as expected.

Using density as a guide, TS-1 appears to have been a very consistent product during the period of 1993 to 2011; the average density has not changed more than about 1% during this period. Moreover, within each year, almost all of the fuel samples have densities within ±1% of the average. This is a narrower spread in density than Jet A-1 and JP-8.

Finally, using density as a guide, the Russian Handbook appears to give a fair representation of the properties of TS-1. On average, the densities of products in the field were about 1% higher than the value given by the Russian Handbook. Fuel properties which correlate with density can be expected to vary accordingly from the results presented in this report. For reference, the average density of TS-1 is similar to that of Jet A-1 but about 1½% less than that of JP-8.

7. RECOMMENDATIONS

Data on the following properties of TS-1 and RT are sufficiently consistent with those of the CRC Handbook to be included in the next edition of that Handbook:

- Density
- Specific gravity
- Thermal expansion
- Viscosity
- Surface tension
- Vapor pressure
- Specific heat
- Thermal conductivity
- Heat of vaporization
- Dielectric constant
- Flammability limits

Since the properties of TS-1 and RT are so close and well within the apparent variations of field values of TS-1, the data should be combined into single graphs when included in the CRC Handbook.

Experimental programs are recommended to collect data on the following fuel properties for a TS-1 and several fuels meeting Jet A, Jet A-1, JP-8, and JP-5 specifications:

- Minimum ignition energy
- Bulk modulus
- Solubility of air, oxygen, nitrogen, and carbon dioxide

These properties are important to safety and operations of aircraft. These data will verify which set of data are correct for these properties and can be used to provide appropriate corrections for the next edition of the CRC Handbook.

Data to verify the solubility of water would also be worthwhile if funds are available.

REFERENCES

1. *Handbook of Aviation Fuel Properties—2004 Third Edition*, CRC Report No. 635, Coordinating Research Council, Inc., Alpharetta, GA 30022.

2. N.F. Dubrovkin, V.G. Malanicheva, Ju. P. Massur, and E.P. Fjodorov, *Физико-химические и эксплуатационные свойства реактивных топлив* [Trans: *Physical, Chemical and Operational Properties of Jet Fuels]*. Moscow Chemistry, Moscow (1988).

3. *Petroleum Quality Information System Fuels Data,(PQIS) 2010 Annual Report*, Defense Logistics Agency Energy, Ft. Belvoir, VA, pqis@dla.mil.

4. TS-1 database from Lufthansa provided by Dr. Tim Edwards as used in his report TS-11 Fuel Property Analysis, Air Force Report AFRL-PR-WP-TR-2006-2139, April 2006.

5. TS-1 database from the Air Force Petroleum Office provided by Dr. Tim Edwards as used in his report "TS-1 Fuel Property Analysis", Air Force Report AFRL-PR-WP-TR-2006-2139, April 2006.

6. Russian Jet Fuel, British Airways Report BAKCFM5/AJH/23OCT95.

7. Lefebvre, A.H. and Ballal, D.R., *Gas Turbine Combustion*, *Third Ed*., ISBN 978-1-4200-8604-1, CRC Press, Boca Raton, FL, 2010.

8. *Marks' Standard Handbook for Mechanical Engineers – 10th edition*, Chapter 3.3: Mechanics of Fluids, McGraw-Hill, New York, 1996.

9. ASTM D3827, "Standard Test Method for Estimation of Solubility of Gases in Petroleum and Other Organic Liquids", ASTM International, West Conshohocken, PA, 2009. Available at www.astm.org.

10. Belières, Jean-Philippe, personal communication by email, September 15, 2011

APPENDIX

Table A-1. Fuel Specifications for TS-1 and RT Compared to JP-8/Jet A-1[1]

Property	JP-8/Jet A-1				TS-1 (first grade)[5]		RT	
	ASTM Method	min.	max.	GOST Method	min.	max.	min.	max.
Total acid number (mg KOH/g)[2]	D3242		0.015	5985		0.7[2]		0.2 – 0.7[2]
Aromatics (vol %)	D1319		25.0	52063 (6994)		20 (22)		20 (22)
Sulfur, Mercaptan (mass %)	D3227		0.002[3]	17323		0.003		0.003
Sulfur, Total (mass %)	D4294 et al		0.30	19121		0.25		0.1
Distillation	D86			2177				
Initial Boiling Point (°C)		Report				150	135	155
10% Recovery (°C)			205			165		175
20% Recovery (°C)		Report				-		-
50% Recovery (°C)		Report				195		225
90% Recovery (°C)		Report				230		270
98% Recovery (°C) (TS-1)		-				250		280
Final Boiling Point (°C)			300			-		-
Residue (vol %)			1.5			1.5		1.5
Loss (vol %)			1.5			1.5		1.5
Flash Point (°C)	D56, D3828	38.0		6356		28[4]		28[4]
Density (kg/L @ 15°C)	D4052 et al	0.775	0.840		-		-	
Density (kg/L @ 20°C) (TS-1)		-	-	3900	0.775		0.775	
Freezing Point (°C)	D2386 et al		-47	-		-		-
Chilling temperature (°C)			-	5066		-60[6,7]		-55[6,7]
Viscosity (mm^2/s @ -20°C)	D445		8.0	33	-	8	-	8
Viscosity (mm^2/s @ 20°C)		-	-		1.25	-	1.25	-
Net Heat of Combustion (MJ/kg)	D3338 et al	42.8		11065	42.9		43.12	
Cetane Index (calculated)	D976 et al	Report						
Hydrogen Content (mass %)	D3701 et al	13.4						
Smoke Point (mm)	D1322	25.0		4338	25		25	
Naphthalenes (vol %)	D1840		3.0	17749		[4]		1.5
Thermal Stability (JFTOT @ 260°C								
Change in pressure drop	D3241		25					
Deposit rating			<3					
Existent gum (mg/100 mL)	D381		7.0	1567		5		4
Particulate Matter (mg/L)	D5452 et al		1.0					
Filtration Time (minutes)	D83133/App B		15					
Water Separation Index (rating)	D3948 et al	70						
Ash Quantity (mass %)				1461		0.003		0.003
Resins (mg/100mL)						5		

Notes:
1. Caution should be used in comparison of methods and values: reader is advised to refer to Section 8 of IATA Guidance Material for Aviation Turbine Fuels (6th ed.)
2. Units for GOST specification are [mg KOH/100cm^3]; acid number for TS-1 and RT would meet ASTM specification if converted to [mg KOH/g]
3. Mercaptan sulfur: 0.003 max for Jet A-1
4. Cells highlighted in yellow don't meet JP-8/Jet A-1 specification requirements
5. GOST 10227 (latest revision) lists two grades for TS-1: Premium Grade and First Grade; First Grade is the more widely available at major airports.
6. GOST 10227 allows a -50°C freeze point in some climatic regions.
7. GOST 5066 chilling temperature is approximately 3°C lower than ASTM D2386.