Thermophysical Properties of Materials for Nuclear Engineering: A Tutorial and Collection of Data

IAEA
International Atomic Energy Agency

Thermophysical Properties of Materials For Nuclear Engineering: A Tutorial and Collection of Data

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA 2008

The originating Section of this publication in the IAEA was:

Nuclear Power Technology Development Section
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
A-1400 Vienna, Austria

THERMOPHYSICAL PROPERTIES OF MATERIALS FOR NUCLEAR ENGINEERING:
A TUTORIAL AND COLLECTION OF DATA
IAEA, VIENNA, 2008

IAEA-THPH

ISBN 978–92–0–106508–7

Printed by the IAEA in Austria
November 2008

FOREWORD

Renewed interest in the potential of nuclear energy to contribute to a sustainable worldwide energy mix is strengthening the IAEA's statutory role in fostering the peaceful uses of nuclear energy, in particular the need for effective exchanges of information and collaborative research and technology development among Member States on advanced nuclear power technologies (Articles III-A.1 and III-A.3).

To meet Member States' needs, the IAEA conducts activities to foster information exchange and collaborative research development in the area of advanced nuclear reactor technologies. These activities, implemented with the advice and support of the various technical working groups of the IAEA's Department of Nuclear Energy, include coordination of collaborative research, organization of international information exchange and analyses of globally available technical data and results, with a focus on reducing nuclear power plant capital costs and construction periods while further improving performance, safety and proliferation resistance. In other activities, evolutionary and innovative advances are catalyzed for all reactor lines such as advanced water cooled reactors, high temperature gas cooled reactors, liquid metal cooled reactors and accelerator driven systems, including small and medium sized reactors. In addition, there are activities related to other applications of nuclear energy such as seawater desalination, hydrogen production, and other process heat applications.

Of particular interest is the collection and dissemination of up to date scientific and technical data, also in view of knowledge preservation and transmission the next generation of scientists and engineers.

This publication provides a comprehensive summary of the thermophysical properties data needed in nuclear power engineering, viz. data for nuclear fuels (metallic and ceramic), coolants (gases, light water, heavy water, liquid metals), moderators, absorbers, structural materials. The correlations and equations are given, which are needed for estimation of material properties, including thermodynamic properties (density, enthalpy, specific heat capacity, melting and boiling points, heat of fusion and vapourization, vapour pressure, thermal expansion, surface tension), and transport properties (thermal conductivity and thermal diffusivity, viscosity, integral thermal conductivity, electrical resistivity, and emissivity). The detailed material properties for both solid and liquid states are shown in tabular form. The data on thermphysical properties of saturated vapours of some metals are also given.

The driving force behind this publication was P.L. Kirillov of the Obninsk Institute for Atomic Power Engineering (OIATE). The IAEA would like to express its appreciation to him and to the contributors listed at the end of this publication. The IAEA officer responsible for this publication was A. Stanculescu from the Division of Nuclear Power.

EDITORIAL NOTE

CONTENTS

INTRODUCTION

The knowledge of thermophysical properties of materials is essential for designing nuclear power plants (NPP). The results of the research work on thermophysical properties of materials for the first fifteen years of nuclear power engineering development in the Soviet Union (1950–65) are reviewed in a reference book [1].

In the Obninsk Institute for Atomic Power Engineering (OIATE) some short methodic reference editions on thermophysical properties of materials assigned to students were published in 1987–94 [2–4].

However, it proved to be a pressing-need to prepare a reference edition on thermophysical properties of materials applied in NPP in terms of the present-day knowledge. This collection of data is developed for the benefit of the students majoring in power engineering as a support for the preparation of term papers, diploma projects, resolving problems for various courses in the nuclear power engineering programme.

The subject structure of the publication is in agreement with the content of the IAEA report on 'Thermophysical Properties of Materials for Water Cooled Reactors' [5] and the classification of the Material Properties Database 'MATPORP' of the International Nuclear Safety Center of Argonne National Laboratory (ANL) available on the Internet web site [6]. The methodology of data processing of the SSC RF-IPPE Thermophysical Data Center and the teaching experience of OIATE have been taken into account.

The data presented were obtained by compilation of unclassified publications (more than 290 references) being in the public domain, such as articles in journals, proceedings of international conferences, preprints, monographs, reference books, educational editions, IAEA reports and Internet materials.

Thermophysical properties of materials depend on various factors, such as structure, porosity, thermal treatment, production technology, radiation exposure and other unidentified factors, rather than on temperature alone. This must be considered in solving specific problems.

The collection contains data on the properties of materials for solid and liquid states, including thermodynamic properties (density, enthalpy, specific heat capacity, melting and boiling points, heat of fusion and vapourization, thermal expansion, surface tension) and transport properties (thermal conductivity, integral thermal conductivity, thermal diffusivity, electrical conductivity, viscosity, and emissivity). The tables of thermophysical properties of materials for corresponding temperature ranges were obtained based on the formulas given in the tutorial using Excel and MATHCAD.

The publication consists of six sections and four appendices. The references are given at the end of each section. Section 1 introduces the data on physical constants [7, 8], spectrum of electromagnetic radiation [9], and thermophysical properties of most widely applicable materials under normal conditions (20°C, 0.1 MPa). The comparative characteristics of the thermal conductivity of various substances and metals are presented both as diagrams and in tabulated form.

Section 2 contains the data on nuclear fuel including general performance of fissile materials and selected types of fuel. In this section, the data on thermophysical fuel properties are generalized: metallic (uranium, plutonium, and thorium) and ceramic (uranium dioxide, mixed oxide fuel MOX, uranium nitride and carbide).

In Section 3, thermophysical properties of coolants including some gases, water (H_2O, D_2O), liquid metals, their vapours and alloys (Na, NaK, Pb, PbBi, Li and others) are addressed. The data on the properties of liquid metals and alloys are based on the review [10], properties of

Vapours in Ref. [11]. The properties of light water are based on the tables in Refs [12, 13], the properties of heavy water on Hill's tables [14], which were provided to SSC RF-IPPE by Atomic Energy of Canada Ltd (AECL) under the agreement for mutual scientific and technical cooperation. It was considered unreasonable to include in the tutorial the thermophysical data of high temperature organic coolants, molten salts and other advanced coolants, which have not yet found application in nuclear engineering, in spite of continuing attempts.

Section 4 outlines the characteristics of basic moderators such as graphite, beryllium, and beryllium oxide.

Section 5 is devoted to the properties of neutron absorbers, which are used in control devices and burnable absorbers (boron, boron carbide, AgInCd alloy).

In Section 6, properties of structural materials including metals, a number of traditional alloys and steels used in the power industry and nuclear power engineering are addressed.

In the first appendix to the tutorial, the table on conversion factors of some units is presented. In the next three appendixes, the general data plant of main reactor types (WWER, fast, graphite) are given based on monographs [15, 18, 19] and IAEA reports [16, 17].

1. GENERAL INFORMATION

This Section provides a summary of general data encountered in nuclear engineering.

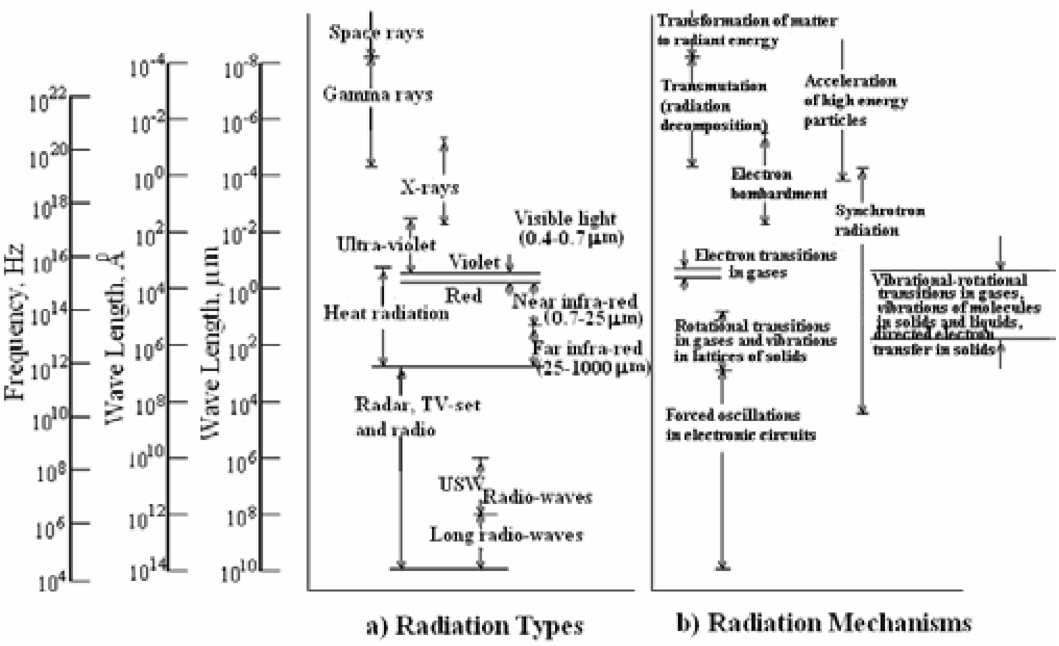


FIG. 1.1. Spectrum of electromagnetic radiations [9].

TABLE 1.1. PHYSICAL CONSTANTS

Property	Value
Speed of light in vacuum	$c = 2.998 \times 10^{8}$ m/s
Gravity constant	$G = 6.672 \times 10^{-11}$ N·m²/kg²
Plank constant	$H = 6.626 \times 10^{-34}$ J·s
	$h/2\pi = 1.055 \times 10^{-34}$ J·s
Avogadro constant	$N_A = 6.022 \times 10^{23}$ mol^{-1}
Faraday constant	F = 96485 C/mol
Universal gas constant	R = 8.314 J/(mol·K)
Boltzmann constant	$k = R/N_A = 1.3807 \times 10^{-23}$ J/K
Stefan-Boltzmann constant	$\sigma_o = 5.670 \times 10^{-8}$ W/(m^2·K^4)
First constant of radiation	$C_1 = 2hc^2 = 3.742 \times 10^{-16}$ W·m^2
Second constant of radiation	$C_2 = hc/k = 0.01439$ m·K
Wien constant	$C_3 = \lambda_{max}\cdot T = 2.8978 \times 10^{-3}$ m·K
Solar constant	S = 1325 W/m^2
Acceleration of gravity (standard)	$g_o = 9.8066$ m/s^2
Proton mass	$m_p = 1.503302 \times 10^{-10}$ J $= 1.672623 \times 10^{-27}$ kg
Neutron mass	$m_n = 1.505374 \times 10^{-10}$ J $= 1.674928 \times 10^{-27}$ kg
Electron mass	$m_e = 8.187241 \times 10^{-14}$ J $= 9.109 \times 10^{-31}$ kg
Electron charge	1.602×10^{-19} C
Ratio m_p/m_e	1836.153
Electron-volt	$1\text{eV} = 1.602 \times 10^{-19}$ J

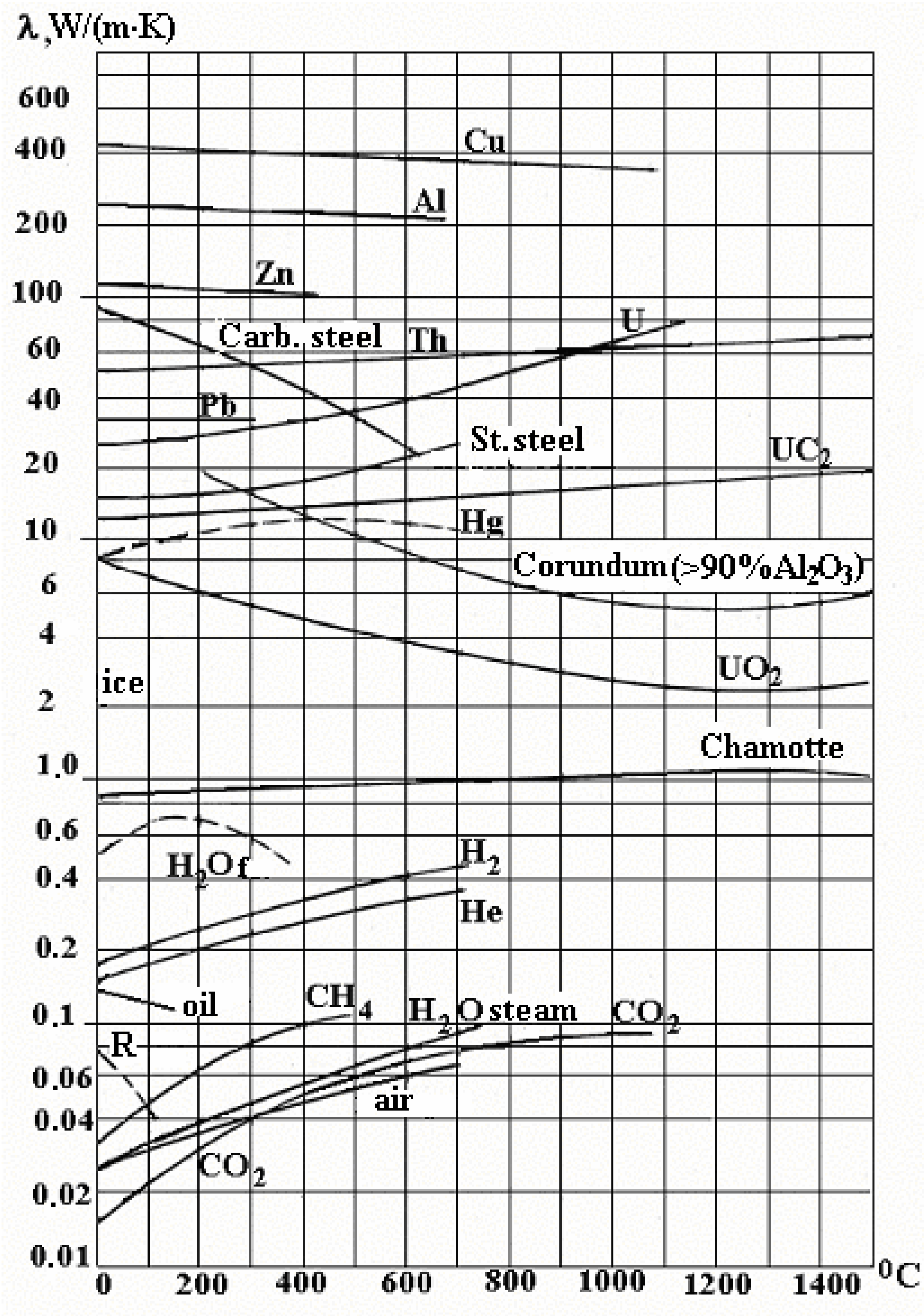


FIG. 1.2. Thermal conductivity of various materials at 0.1 Mpa.

The data on U, UC_2, UO_2 are in Refs [1, 20], on Th and other metals in Refs [21, 22], on steels and industrial materials in Refs [23–25], on gases and liquids at saturation line in Ref. [26].

TABLE 1.2. THERMAL CONDUCTIVITY OF SOLID PURE METALS AT DIFFERENT TEMPERATURES [21, 22, 27]

Temp. K	Thermal conductivity W/(m·K)
Aluminium (Al)	
300	237
400	240
500	236
600	236
700	225
800	218
933.5	208
Beryllium (Be)	
300	200
400	161
500	139
600	126
800	106
1000	91
1200	79
1400	69
Vanadium (V)	
300	30.7
400	31.3
600	33.3
800	35.7
1000	38.2
1200	40.8
1400	43.4
1600	45.9
1800	48.4
2000	50.9
Bismuth (Bi)	
300	7.9
350	7.4
400	7.0
500	6.6
544.6	6.5
Tungsten (W)	
300	174
400	159
600	137
800	125
1000	118
1200	113
1500	107
2000	100
2500	95
3000	91
Hafnium (Hf)	
300	23.0
400	22.3
600	21.3
800	20.8
1000	20.7
1400	21.1
1600	21.5
1900	22.3
-	-

Temp. K	Thermal conductivity W/(m·K)
Iron (Fe)	
300	80.2
400	69.5
500	61.3
600	54.7
800	43.3
1000	32.8
1400	31.2
1500	32.1
Gold (Au)	
300	317
400	311
600	298
800	284
1000	270
1200	255
Cadmium (Cd)	
300	96.8
400	94.7
500	92.0
594.3	88.0
Potassium (K)	
273	104
300	102
336.8	98.5
Cobalt (Co)	
300	71.6
400	98.2
500	111
600	119
800	126
1000	114
1200	92
1500	43.7
-	-
Lithium (Li)	
273	85.9
300	84.7
350	82.8
400	80.4
453.7	77.2
Magnesium (Mg)	
300	156
400	153
500	151
600	149
800	146
923.2	145
Manganese (Mn)	
300	7.8
700	11
800	12
900	13
1000	14

Temp. K	Thermal conductivity W/(m·K)
Copper (Cu)	
300	401
400	393
500	386
600	379
800	366
1000	352
1200	339
Molybdenum (Mo)	
300	138
400	134
600	126
800	118
1000	112
1200	105
1500	98
1800	93
2000	90
2200	88
Sodium (Na)	
273	142
300	141
350	139
371.0	132
Nickel (Ni)	
300	90.7
400	80.2
500	72.2
600	62.7
800	67.6
1000	71.8
1200	76.2
1400	80.4
1500	82.6
Niobium (Nb)	
400	51.7
600	55.2
800	58.4
1000	61.2
1200	63.6
1400	65.4
1600	66.8
1800	68.0
2000	68.9
2200	69.8
Tin (Sn)	
300	66.6
400	62.2
505.1	59.5
-	-
-	-
-	-
-	-
-	-
-	-
-	-

Temp. K	Thermal conductivity W/(m·K)
Platinum (Pt)	
300	71.6
400	71.8
600	73.2
800	75.6
1000	78.7
1200	82.6
1400	87.1
1600	91.9
2000	99.4
Plutonium (Pu) [21]	
300	5.2
400	5.8
450	6.1
500	6.4
550	6.6
600	7.0
700	7.6
800	8.2
900	8.8
1000	9.3
Lead (Pb)	
300	35.3
350	34.7
400	34.0
500	32.8
600.7	31.4
Silver (Ag)	
300	429
400	425
600	412
800	396
1000	379
1200	361
Antimony (Sb)	
300	24.3
400	16.5
500	16.4
600	17.2
700	18.4
800	20
900	24
Tantalum (Ta)	
300	57.5
600	58.6
800	59.4
1000	60.2
1400	61.8
1800	63.4
2000	64.1
2400	65.4
2800	66.4
3200	66.6
-	-
-	-
-	-

Temp. K	Thermal conductivity W/(m·K)
Titanium (Ti)	
300	21.9
400	20.4
600	19.4
800	19.7
1000	20.7
1200	22.0
1400	23.6
1600	25.3
1900	27.9
Thorium (Th) [21]	
300	35.6
400	33.3
500	31.0
600	28.6
800	24.0
1000	19.3
1200	14.4
1500	7.5
Uranium (U) [5]	
300	22.6
400	24.9
600	29.5
800	34.1
1000	38.7
1200	43.3
1400	47.9
Chromium (Cr)	
300	93.7
400	90.9
500	86.0
600	80.7
800	75.6
1000	65.4
1200	61.9
1400	58.8
1600	55.6
Zinc (Zn)	
300	116
400	111
500	107
600	103
692.7	99.3
Zirconium (Zr)	
300	21.2
400	19.6
600	19.0
800	19.9
1000	21.5
1200	23.5
1400	25.9
1600	28.5
1800	31.5
-	-
-	-
-	-
-	-

TABLE 1.3. THERMAL CONDUCTIVITY OF GASES AND VAPOURS λ·(W/m·K) [11, 26]

Gas (Vapour)	Pressure MPa	Temperature °C								
		0	100	200	300	400	500	600	800	1000
Nitrogen (N_2)	0.1	23.9	30.9	37.2	43.0	48.4	53.5	58.4	68.6	79.6
	20.0	34.0	39.4	43.3	48.1	52.4	56.6	61.6	70.7	81.5
	50.0	61.3	54.5	54.7	56.2	59.1	62.9	66.9	74.5	84.3
Ammonia (NH_3)	0.1	21.1	33.9	48.8	65.5	84.0	104	124	–	–
Argon (Ar)	0.1	16.4	21.0	25.4	29.6	33.2	36.5	39.8	45.6	50.8
Hydrogen (H_2)	0.1	169	214	256	290	332	368	403	477	557
	50.0	210	246	282	313	345	380	413	486	567
Helium (He)	0.1	143	174	209	242	270	297	323	372	423
	30.0	160	183	220	251	279	307	329	377	427
Oxygen (O_2)	0.1	24.4	29.8	38.6	45.6	51.3	57.4	63.4	74.5	85.7
	10.0	31.6	36.3	42.4	47.8	53.7	59.7	64.9	75.2	86.5
	30.0	51.9	48.3	51.3	55.1	59.3	64.1	69.1	78.4	88.6
Krypton (Kr)	0.1	8.8	11.7	14.3	16.8	19.0	21.2	23.3	27.1	30.3
Xenon (Xe)	0.1	5.2	7.7	8.6	10.2	11.7	13.1	14.5	17.2	19.7
Methane (CH_4)	0.1	30.4	45.0	62.0	80.1	99.2	–	–	–	–
	5.0	35.4	48.2	64.5	82.1	–	–	–	–	–
	10.0	43.8	52.0	67.1	84.0	–	–	–	–	–
Neon (Ne)	0.1	46.4	57.0	67.2	76.9	86.0	94.8	103	118	–
Carbon oxide (CO)	0.1	23.3	30.1	36.5	42.6	48.5	54.1	59.7	70.1	80.6
Propane (C_3H_8)	0.1	15.0	27.4	41.7	57.9	76.0	95.8	–	–	–
Mercury (Hg)	0.1	–	–	7.02	8.7	10.4	12.0	13.7	17.0	20.2
Sulfur dioxide (SO_2)	0.1	8.4	12.3	16.6	21.2	25.8	30.7	35.8	46.3	57.6
Carbon dioxide (CO_2)	0.1	14.7	22.2	30.2	38.5	46.1	53.3	60.0	72.7	84.6
	5.0	–	26.2	33.0	40.7	48.0	54.9	61.3	73.6	85.4
Carbon tetra Chloride (CCl_4)	0.1	–	8.7	11.6	14.7	17.8	21.2	24.5	–	–
Fluor (F_2)	0.1	24.8	32.5	39.7	46.8	53.5	–	–	–	–
Chlorine (Cl_2)	0.1	7.9	11.4	14.9	18.0	20.8	–	–	–	–

TABLE 1.4. THERMOPHYSICAL PROPERTIES OF MATERIALS [4, 27]

Material	Temperature °C	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6(m^2/c)	Heat permeability* W·s$^{1/2}$/(m^2·K)
Metals and alloys						
Aluminium 99.99	20	2700	945	238	93.4	24700
Beryllium	20	1848	1780	180	54.7	24300
Bronze (84 Cu, 9Zn, 6 Sn, 1 Pb)	20	8800	377	61.7	18.6	14300
Vanadium	50	6120	498	31.0	10.2	9720
Bismuth	20	9800	129	8.4	6.6	3260
Tungsten	20	19000	138	174	66.4	21360
Wood's metal (50 Bi, 25 Pb, 12,5 Cd, 5 Sn)	20	9730	147	12.8	8.96	4280
Gallium	20	5910	371	41	18.7	9480
Duralumin (95 Al, 4,5 Cu, 0,5 Mg)	20	2790	912	165	64.8	20490
Iron	20	7870	456	75	20.9	16400
Gold	20	19290	128	310	125	27700
Iridium	20	22400	133	147	49.3	20900
Indium	20	7280	239	81.8	47.0	11930
Cadmium	100	8640	246	94.2	44.3	14100
Potassium	20	860	760	100	153	8100
Cobalt	20	8780	427	69.1	18.4	16100
Constantan (60Cu, 40 Ni)	20	8900	410	22.6	6.19	9080
Lithium	20	534	3570	85	44.5	12730
Magnesium	20	1740	1050	159	87.0	37190
Copper 99,99	20	8960	385	401	116	37190
Copper 99,8	20	8300	419	386	111	36640
Molybdenum	20	10200	272	147	53.0	20200
Sodium	20	970	1234	130	112	12700
Nickel 99,9	20	8900	450	92	23	19200
Niobium	20	8570	267	52.3	22.9	10900
Nichrome	20	8400	440	13	3.5	6930
(80 Ni, 20 Cr)	700	8130	615	24	4.8	10950
Tin	20	7290	221	62.8	39.0	10100
Palladium	20	11970	242	71.2	24.6	14400
Platinum	20	21500	133	71.2	24.9	14300
Plutonium	20	19840	130	6.7	2.6	4170
Rhenium	20	21020	138	48.1	16.6	11800
Rhodium	20	12500	246	151	49.1	21500
Lead	20	11340	127	35	24.3	7100
Argentum	20	10497	234	418	170	32040
Carbon steel (St. 20)	20	7860	483	52	13.7	14050
Austenitic steel (Kh18N10T)	20	7900	470	14.5	3.9	7340
Low alloyed pearlitic steel (Kh2M)	20	7800	486	10.6	10.6	12300
Tantalum	20	16500	142	57.5	24.5	11600
Titanium	20	4500	522	21.9	9.32	7170
Thorium	25	11720	118	37	26.7	7150
Uranium 99.9	500	18600	174	30	9.26	9850
Chromium	20	7100	474	88.6	26.3	17300
Cesium	20	1870	242	35.9	79.3	4030
Zinc	20	7130	385	113	41.2	17600
Zirconium	70	6500	290	22.7	12.0	6540

TABLE 1.4 (continued)

Material	Temperature °C	Density kg/m^3	Heat capacity J/(kg·K)	Thermal Conductivity W/(m·K)	Thermal diffusivity $10^6(m^2/s)$	Heat permeability* $W \cdot s^{1/2}/(m^2 \cdot K)$
Building and heat-insulating materials (in dry air)						
Asphalt	20	2120	-	0.70	0.19	1590
Concrete	20	2200	879	1.28	0.66	1570
Wood (pine)	20	550	2700	0.16	0.10	472
Reinforced concrete	20	2200	840	1.5	0.81	1660
Red brick	20	1800	890	0.77	0.49	1100
Lime-sand brick	20	1900	840	0.81	0.51	1140
Sand	20	1500	1020	0.50	0.33	875
Cement	20	1900	1130	0.30	0.14	802
Cement mortar	20	1900	800	0.93	0.61	1190
Slag concrete	0	1500	750	0.87	0.77	990
Asbestos fiber	50	470	820	0.11	0.29	210
Asbestos cardboard	20	900	816	0.16	0.22	340
Mineral wool	50	200	920	0.046	0.25	92
Glass-wool	0	200	660	0.037	0.28	70
Slag-wool	25	200	800	0.05	0.31	89
Various materials						
Bakelite	20	1270	1590	0.23	0.114	680
Paper	20	700	1200	0.12	0.14	320
Paper laminate	25	1350	1420	0.23	0.12	664
Granite	20	2750	890	2.9	1.2	2700
Graphite (natural)	20	1700	710	100	0.83	10990
Ground (compact)	20	1900	1150	1.5	0.69	1810
Coal (brown)	20	1200	1260	0.26	0.18	630
Quartz	20	2500	780	1.4	0.72	1650
Ice	0	917	2040	2.25	1.20	2050
Chalk stone	20	2000	880	0.93	0.53	1280
Paraffin	30	925	2260	0.27	0.13	750
Polyvinyl chloride	20	1380	960	0.15	0.113	445
Polystyrene	20	1050	1250	0.14	0.107	430
Polyurethane	20	1200	2090	0.32	0.128	800
Polyethylene	25	930	2500	0.28	0.12	810
White rubber	20	1100	1670	0.16–0.23	0.087–0.095	540–650
Sponge rubber	20	250	2050	0.06	0.12	17
Sulfur	20	2070	720	0.27	0.18	630
Snow (recent)	0	200	2100	0.10	0.24	648
Snow (dense)	0	350	2100	0.35	0.48	507
Window glass	20	2480	800	1.16	0.58	1520
Quartz glass	20	2210	730	1.40	0.87	1500
Lead glass	20	2890	680	0.80	0.40	1250
Laminated cloth	20	1350	1500	0.28	1.38	753
Porcelain ware	25	2200	900	1.0	0.5	1400
Cotton	30	80	1150	0.059	0.63	74

*Heat permeability $$b = \sqrt{\lambda \rho C_p}\ , (W \cdot s^{1/2} m^{-2} \cdot K^{-1}) \qquad (1.1)$$

REFERENCES TO INTRODUCTION AND SECTION 1

1. Chirkin V.S. Thermophysical Properties of Materials for Nuclear Power Engineering/Reference Book. – M.: Atomizdat. 1968 (Russian).
2. Kirillov P.L. Thermophysical Properties of Materials for Nuclear Power Engineering/Recommended practice. – Obninsk: Edition OIATE, 1994 (Russian).

3. Kirillov P.L., Yuriev Yu.S., Bobkov V.P. Reference Book on Thermohydraulic Designs (Nuclear Reactors, Heat exchangers, Steam generators). 2nd rev. and enl. ed. – M.: Energoatomizdat, 1990 (Russian).
4. Kirillov P.L., Bogoslovskaya G.P. Heat and Mass Transfer in Nuclear Power Installations. – M.: Energoatomizdat, 2000 (Russian).
5. Thermophysical Properties of Materials for Water Cooled Reactors/IAEA-TECDOC–949. – Vienna: IAEA, 1997.
6. INSC Material Properties Database. – http://www.insc.anl.gov/matprop/
7. Physical Quantities. Reference book/A.P. Babichev, N.A. Babushkin, A.M. Bratkovsky, et al.; Ed. by I.S. Grigoriev, E.Z. Meilikhov. – M.: Energoatomizdat, 1991 (Russian).
8. International Encyclopedia of Heat and Mass Transfer/Ed. By G.F. Hewitt, G.L. Shires and Y.V. Polezhaev. – New York: CRC Press LLC, 1997.
9. Miakishev G.Ya., Bukhovtsev B.B. Physics/10th ed. – M.: Prosveshcheniye. 1989 (Russian).
10. Kirillov P.L., Deniskina N.B. Thermophysical Properties of Liquid Metal Coolants (Reference Tables and Correlations)/Review, IPPE-0291. – M.: TSNIIAtominform. 2000 (Russian).
11. Handbook of Physical Properties of Liquids and Gases/N.B. Vargaftik, V.K. Vinogradov, V.S. Yargin, 3rd enl. and rev. ed. – N.Y.: Begell House Inc., 1996.
12. ASME Steam Tables for Industrial Use/Based on IAPWS — IF97, CRTD — vol.58. 1999.
13. Alexandrov A.A., Grigoriev B.A. Tables of Thermophysical Properties of Water and Steam/Reference book. –M.: MEI Press, 1999 (Russian).
14. Hill P.G., MacMillan R.D., Lee V. Tables of Thermodynamic Properties of Heavy Water in SI Tables. AECL. 1981.
15. White Book of Nuclear Power Engineering/Edited by Prof. O.E. Adamov. Minatom of Russia. – M.: GUP NIKIET Press, 2001 (Russian).
16. Review of Design Approaches of Advanced Pressurized LWRs/IAEA-TECDOC-861. –Vienna: IAEA, 1996.
17. Fast Reactor Database/IAEA-TECDOC-866. –Vienna: IAEA, 1996.
18. Dollezhal N.A., Emelianov I.Ya. Channel Nuclear Power Reactor. – M.: Atomizdat, 1980 (Russian).
19. Margulova T.Kh. Atomic Power Stations/3rd rev. and enl. ed. – M.: Vysshaya Shkola, 1978; 5th rev. and enl. ed. – M.: IzdAT, 1994 (Russian).
20. Benjamin M.Ma. Nuclear Reactor Materials and Applications, Van Nostrand Reihold Co., 1983.
21. Theoretical Science of Heat Engineering. Heat Engineering Experiment/Reference book Ed. by A.V. Klimenko, V.M. Zorin. 3rd rev. and enl. ed. –. M.: MEI Press. 2001, Book 2nd (Russian).
22. Zinoviev V.E. Thermophysical Properties of Metals at High Temperatures/Reference edition. – M.: Metallurgiya. 1989 (Russian).
23. Smithells C.J. Metal Reference Book/Ed. by S.G. Glazunov. Translated from English (5th ed. London: Publ. Butterworth and Co. Ltd., 1976). – M.: Metallurgiya. 1980 (Russian).
24. Chirkin V.S. Thermal Conductivity of Industrial Materials/2nd ed. – M.: Mashgiz. 1962 (Russian).
25. Thermal Conductivity of Solids/Reference book. Ed. by A.S. Okhotin. – M.: Energoatomizdat. 1984 (Russian).

26. Vargaftik N.B. Reference Book on Thermophysical Properties of Gases and Liquids. – M.: Nauka, 1972 (Russian).
27. Heat and Mass Transfer. Heat Engineering Experiment/Reference book. Edited by V.A. Grigoriev, V.M. Zorin. – M.: Energoatomizdat, 1982 (Russian).

2. NUCLEAR FUEL

2.1. GENERAL PERFORMANCE OF FISSILE MATERIALS AND NUCLEAR FUEL

Nuclear fuel relates to materials that are capable to release energy in the course of nuclear reactions. They are categorized into fissile materials and fertile materials providing new fuels. Among the first class are the materials of neutron-induced fission. The unique natural material of thermal fission is isotope ^{235}U. Another isotope ^{238}U is fissionable only by fast neutrons (>1–2 MeV). Naturally occurring uranium contains ^{238}U (99.283%) and ^{235}U (0.711%) as well as some other isotopes.

Two natural isotopes ^{238}U and ^{232}Th are fertile materials, because they produce new fissionable materials ^{239}Pu and ^{233}U by absorbing neutrons. The ability of producing new fuel is used in fast neutron reactors the so called breeder reactors [1, 2].

Thus, there are principally three fissionable isotopes important for the nuclear power engineering: a naturally occurring isotope (^{235}U) and two other artificial isotopes (^{239}Pu and ^{233}U) made from ^{238}U and ^{232}Th by neutron capture. The characteristics of thermal neutron fissionable isotopes are presented in Table 2.1 [3].

TABLE 2.1. CHARACTERISTICS OF THERMAL NEUTRON-FISSIONABLE ISOTOPES [3]

Nuclear constants	Isotopes		
	^{233}U	^{235}U	^{239}Pu
Cross-sections in barns (1 barn=10^{-24} cm^2)			
fission, σ_f	529	582	742
capture, σ_c	46	98	270
absorption, σ_a	575	680	1012
Neutron yield			
per fission, ν_f	2.495	2.437	2.891
per capture, ν_c	2.211	2.078	2.079

Nuclear fission is accompanied by energy production proportional to the change of nuclear mass according to the law $E = \Delta mc^2$. The change of Δm is relatively small and is about 0.1% for nucleus ^{235}U. The main fraction of this energy is kinetic energy of fission fragments that converts to heat at their slowdown. The energy distribution between various fission products of one nucleus ^{235}U is given in Table 2.2 [4].

The energy carried away by neutrino is partially compensated by γ ray absorption at radiation capture of fission neutrons by materials. Thus, the energy being released at one nuclear fission is close to 200 MeV or 3.2×10^{-11} J. Total energy released at fission of 1g of the isotope ^{235}U is defined as:

$$E = (1/235) \underset{\text{number}}{\frac{6.02 \times 10^{23}}{\text{Avogadro}}} \times 200 \cdot \underset{\text{conversion coefficient}}{\frac{1.6 \times 10^{-13}}{\text{MeV to J}}} = 8.2 \times 10^{10}\ \text{J} \qquad (2.1)$$

To provide a thermal power of 1 MW per day, 1g of nuclear fuel is used (1 W of power corresponds to 3×10^{10} fissions per second). In thermal-neutron reactors, about 1.2 kg of ^{235}U or 1.5 kg of ^{239}Pu is burnt up per day at a power of 1 MW. The isotope ^{235}U, which is readily fissionable by thermal neutrons, is used in light-water reactors.

TABLE 2.2. ENERGY DISTRIBUTION AT ONE ^{235}U FISSION [4]

Kind of energy	Energy MeV	Integral energy MeV	Character of release
Kinetic energy of fission fragments	165–167	178	Released practically instantly (10^{-12} s)
Kinetic energy of fission neutrons	5		
Prompt gamma energy	6–7		
Energy of β-particles at decay of fission products	6–8	15	Released gradually through decay chains of fission-products
Energy of γ decay of fission products	7–10		
Neutrino energy	10–12		Loss of energy, because of no interaction between neutrino and reactor materials
Total energy	approx. 205		

Owing to the properties of metallic uranium, it is of limited value as a nuclear fuel. It has three allotropic modifications, and considerable changes in volume are observed at phase transitions. Metallic uranium is unstable under the action of water and air. Besides, fission products accumulate in the course of uranium radiation, which results in metal swelling. The most reasonable types of nuclear fuel are uranium dioxide (UO_2) and mixed fuel MOX — (UO_2+PuO_2). These fuels have found wide applications in the nuclear power engineering, although they have low thermal conductivity, which leads to high temperatures and thermal stresses in fuel.

Uranium carbide (UC), uranium nitride (UN) and thorium based fuel are the advanced types of nuclear fuel. As compared with MOX fuel, uranium carbide and mixed carbide fuel (U, Pu)C have higher thermal conductivity, lower linear expansion coefficient and better compatibility with coolant and fuel cladding materials [5, 6].

Plutonium is an artificial element being produced during uranium reactor operation. The isotope ^{239}Pu is the most-used one, which release neutrons at fission (about 2 per one capture, see Table 2.1), that makes it possible to provide nuclear fuel breeding. Plutonium used in reactors is composed of 70% ^{239}Pu and 20% ^{240}Pu. Metallic plutonium is not used as a fuel owing to its low melting point (~913 K), six allotropic modifications, whose conversions are accompanied by volume changes, as well as its chemical activity, possible heating in air and high toxic level. As a fuel, it is preferable to use plutonium dioxide (PuO_2, T_m ~ 2573 K). The properties of PuO_2 are close to those of UO_2. As a rule, mixed fuel MOX (80% UO_2 + 20% PuO_2) is used [7].

Naturally-occurring thorium is composed only of the isotope ^{232}Th, which is not fissionable, but converts to the fissionable isotope ^{233}U at neutron capture as a result of two β decays. The advantage of ^{233}U consists in higher neutron yield per one capture (~2.21 as compared to 2.08 of uranium and plutonium, see Table 2.1), high thermal conductivity and low linear expansion coefficient [4, 8]. Thorium dioxide (ThO_2) and mixed fuel from ThO_2 and UO_2, PuO_2 can be used as fuel. The properties of ThO_2 are similar to those of UO_2 and PuO_2. Thorium is suitable for long-term application owing to its inventory that exceeds uranium reserves several times. The basic properties of fissile materials and nuclear fuels are presented in Table 2.3.

TABLE 2.3. BASIC PROPERTIES OF FISSILE MATERIALS AND NUCLEAR FUEL

Materials [references]	Atomic or molecular mass amu	Density kg/m^3		T_{melt}, K (t_{melt}),°C	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Linear expansion coefficient 10^6(1/K)	Electrical resistivity 10^8(Ω·m) *
		physical	on fission material					
Uranium U [9, 10]	238	19050	19050	1405 (1132)	155 (673 K)	31.2 (673 K)	13.9 (300 K)	35 (298 K)
Plutonium Pu [11, 12]	244	19840	19840	913 (640)	135 (300 K)	6.5 (508 K)	33.9 (400–470 K)	150 (298 K). 102 (673 K)
Thorium Th [13, 14]	232	11720	11720	2023 (1750)	118 (298 K)	54 (298 K)	11.2 (298–473 K)	13–15 (298 K)
Uranium dioxide UO_2 [9, 19]	270	10963	9664	3120 (2850)	328 (1523 K)	2.6 (1523 K) theor. density	9.8 (300 K)	7.32 (300 K)
Plutonium dioxide PuO_2[16, 17]	271	11440	10100	2663 (2390)	344 (1523 K)	2.2 (1500 K)	6.7 (300 K)	–
Thorium dioxide ThO_2 [18, 21]	264	10600	9315	3923 (3650)	266 (1500 K)	3.2 (1500 K)	8.9 (300 K)	6×10^{-5} Ω·m (300 K)
MOX fuel $(U_{0,8}Pu_{0,2})O_2$ [19]	271	11070	9770	3023 (2750)	321 (1523 K)	2.6 (1523 K)	9.1 (300 K)	–
Fuel, $(U_{0,95}Gd_{0,05})O_2$ [20, 20a]	275	10370	8560	2873 (2600)	365 (1500 K)	2.35 (1500 K)	10.5 (300 K)	–
Fuel $(U_{0,8}Th_{0,2})O_2$ [21]	269	10140	8930	3553 (3280)	317 (1500 K)	2.1 (1500 K)	11.0 (700 K)	–
Uranium nitride UN [22, 23, 24]	252	14420	13619	3123 (2850)	238 (1000 K)	20.9 (1000 K)	7.5 (300 K)	146 (300 K)
Plutonium nitride PuN [22, 25]	253	14400	13603	2823 (2550)	239 (1000 K)	15.0 (500 K)	12.5 (300 K)	1000
Uranium carbide UC [22, 26]	250	13630	12970	2793 (2520)	240 (700 K)	23.0 (700 K)	10.5 (300 K)	250
Plutonium carbide PuC [21, 22]	251	13500	12870	1923 (1650)	165 (700 K)	16.0 (300 K)	28 (300 K)	120

* Dimension of electrical resistivity is used for all values, except as stated particularly.

2.2. METALLIC FUEL

2.2.1. Uranium

Uranium is a chemical element that has atomic number 92 and atomic mass 238.03 amu and belongs to the actinide series. Uranium is more widespread than gold, platinum, silver, cadmium, bismuth and mercury. Uranium is heavy, silvery white metal with high density exceeding lead density. It is malleable, ductile metal, which is softer than steel. Uranium is weakly radioactive and slightly paramagnetic. The basic properties of uranium are given in Table 2.4.

Uranium has three allotropic modifications (alpha, beta and gamma); their characteristics are presented in Table 2.5 [27, 34]. The uranium crystals are characterized by strong anisotropy along the symmetry axes of crystals.

The mechanical properties of uranium are shown in Table 2.6 [48]. The β phase of uranium is harder and more brittle than the α phase. Uranium in the γ phase is very soft that influences its processing technology.

TABLE 2.4. BASIC PROPERTIES OF URANIUM UNDER NORMAL CONDITIONS (0.1 MPa; 298 K)

Property	Value
Density (ρ), kg/m^3	19050 [27]
Melting point, K (°C)	1405 (1132) [27]
Boiling point, K (°C)	4018–4400 (3745–4127) [44–48]
Heat of fusion (ΔH_f), kJ/kg kJ/mol acc. to data from Refs [38, 46–48, 131] kJ/mol	36.6–39.1 8.72–9.3 [31–33] 15.5–19.6
Heat ofvapourization (ΔH_{vap}) kJ/kg kJ/mol	2046 487 [31]
Heat capacity, J/(kg·K) J/(mol·K)	116.3 at 293 K 27.67 [31]
Thermal conductivity (λ), W/(m·K)	22.5 [27]
Linear expansion coefficient, 10^{-6} K^{-1} for single crystal [31, 44–48, 131]	13.9 [46] 21–26
Electrical resistivity (ρ_e), 10^{-8} Ω·m acc. to data from Refs [37, 44–48, 131]	21.8 [32] 21–31
Emissivity	0.51 at λ = 67 nm [28]
Sound velocity, m/s	2490–3155 [44–48]
Critical constants [31, 95] Temperature (T_c), K Pressure (P_c), MPa Molar volume (V_c), dm^3/mol Density (ρ_c), kg/m^3	 11630 611 0.045 5290

TABLE 2.5. CHARACTERISTICS OF ALLOTROPIC MODIFICATIONS OF URANIUM [27, 34]

Phase	Stability temperature range, K	Crystal structure, lattice dimensions Å	Density 10^{-3}kg/m^3	Volume change ΔV/v, % [27]	Heat of phase transition, (ΔH)	
					kJ/kg	kJ/mol
α-U	< 942	Orthorhombic, a=2.853 b=5.865 c=4.955	19.05	1.0–1.12	α→β at 938 K	
					12.5	2.98
β-U	942–1049	Tetragonal, a=10.795 b=5.865 c=4.955	18.11	0.6–0.7	β→γ at 1049 K	
					20.0	4.76
γ-U	1049–1408	Face-centered, cubic a=3.525	18.06	-	γ→liquid at 1405.3	
					36.6	8.72

TABLE 2.6. MECHANICAL PROPERTIES OF URANIUM AT 298 K [48]

Property	Value
Brinell hardness	185
Vickers hardness	190
Tensile strength, MPa	615
Modulus of elasticity, GPa	190
Poisson ratio	0.22
Shear modulus of elasticity, GPa	86

2.2.1.1. Properties of solid uranium depending on temperature

Density of uranium is evaluated using following correlations obtained by linear approximation of the data in Refs [27, 41]:

$$\rho\ (kg/m^3) = 19.36 \times 10^3 - 1.03347\ T \text{ at } 273 \le T \le 942\ K\ (\alpha \text{ phase}),$$
$$\rho\ (kg/m^3) = 19.092 \times 10^3 - 0.9807\ T \text{ at } 942 \le T \le 1049\ K\ (\beta \text{ phase}), \quad (2.2)$$
$$\rho\ (kg/m^3) = 18.447 \times 10^3 - 0.5166\ T \text{ at } 1049 \le T \le 1405\ K\ (\gamma \text{ phase}).$$

Heat capacity of uranium in the range of 293–942 K is calculated by expression in Ref. [1]:

$$C_p\ [J/(kg\cdot K)] = 104.82 + 5.3686 \times 10^{-3}\ T + 10.1823 \times 10^{-5}\ T^2. \quad (2.3)$$

At $942 \le T \le 1049$ K $C_p = 176.4$ J/(kg·K);

At $1049 \le T \le 1405$ K $C_p = 156.8$ J/(kg·K) [27].

Thermal conductivity in the range of 293–1405 K is estimated using the correlation obtained by averaging the data of Fig. 4.1.1.3 in Ref. [27] on P.24 to an accuracy of ± 10%:

λ [W/(m·K)] = 22 + 0.023(T – 273) (2.4)

Thermal diffusivity is defined by the formula:

$a \cdot 10^6$ (m^2/s) = $\lambda/C_p\rho$. (2.5)

The properties of solid uranium evaluated by the correlations (2.2–2.5) are given in Table 2.7. At a temperature of 1405 K uranium transfers to liquid state. The properties of liquid uranium at melting point are shown in Table 2.8.

TABLE 2.7. PROPERTIES OF SOLID URANIUM BY CORRELATIONS (2.2–2.5)

Temperature		Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6(m^2/s)
°C	K				
α phase					
20	293	19057	115.1	22.5	10.2
100	373	18975	121.0	24.3	10.6
200	473	18871	130.1	26.6	10.8
300	573	18768	141.3	28.9	10.9
400	673	18664	154.6	31.2	10.8
665	942	18386	200.2	37.4	10.2
β phase					
665	942	18168	177.2	37.4	11.6
700	973	18138	178	38.1	11.8
727	1000	18111	178	38.7	12.0
776	1049	18067	178	39.8	12.4
γ phase					
776	1049	17905	162	39.8	13.7
800	1073	17893	162	40.4	13.9
900	1173	17841	162	42.7	14.5
1000	1273	17789	162	45.0	15.6
1110	1383	17773	162	47.5	16.5

TABLE 2.8. PROPERTIES OF LIQUID URANIUM AT MELTING POINT (1405 K)

Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6(m^2/s)	Dynamic viscosity mPa·s	Kinematic viscosity 10^6(m^2/s)	Surface tension mN/m	Electrical resistivity 10^8(Ω·m)	Spectral emissivity	Volumetric expansion coefficient 10^6/K	Prandtl number
17320	198	13.7	4.2	6.5	0.376	1650	60	0.34 at λ=67 nm	99	0.0935
[50]	[52]	[28]	-	[49]	-	[50]	[36]	[28]	[52]	-

2.2.1.2. Properties of liquid uranium at 0.1 MPa

Density at 1405 ≤ T ≤ 2100 K [50, 52]

$$\rho\ (kg/m^3) = 20332 - 2.146T \qquad (2.6)$$

Heat capacity C_p=198.3 J/(kg·K) [52].

Dynamic viscosity at $T_{melt} \leq T \leq 2973$ K is calculated by the correlation [51]

$$\ln \mu\ (mPa \cdot s) = A + B \cdot \ln T + C/T, \qquad (2.7)$$

where A = – 5.9307, B = 0.6557, C = 4134.

Volumetric expansion coefficient $\beta = 99 \times 10^{-6}$ 1/K [52]

Surface tension at 1405 ≤ T ≤ 2100 K [50]:

$$\sigma\ (mN/m) = 2127 - 0.3365T \pm 10\% \qquad (2.8)$$

Vapour pressure at temperatures 1873 – 2273 K is defined by the formula [53]:

$$\lg P\ (MPa) = 4.701 - \frac{23330}{T}. \qquad (2.9)$$

The properties of liquid uranium according to the correlations (2.6–2.8) are given in Table 2.9, the radiological properties of uranium isotopes in Table 2.10 [40].

TABLE 2.9. PROPERTIES OF LIQUID URANIUM AT 0.1 MPa BY EQUATIONS (2.6–2.8)

Temperature		Density	Surface tension	Kinematic viscosity
°C	K	kg/m^3	mN/m	10^6(m^2/s)
1133	1460	17315	1654	5.76
1200	1473	17171	1632	5.65
1300	1573	16956	1598	4.94
1327	1600	16898	1589	4.77
1400	1673	16742	1565	4.39
1500	1723	16634	1548	4.17
1627	1900	16255	1488	3.56
1700	1973	16098	1464	3.37
1727	2000	16040	1455	3.31
1827	2100	15825	1421	3.10

TABLE 2.10. RADIOLOGICAL PROPERTIES OF URANIUM ISOTOPES [40]

Isotope	Mass number amu*	Concentration in natural uranium, %	Half-life years	Decay energy keV	Decay product
^{232}U	232.04	-	68.9	5414	^{228}Th
^{233}U	233.04	-	159.2×10^3	4909	^{229}Th
^{234}U	234.09	0.0055	245.7×10^3	4859	^{230}Th
^{235}U	235.04	0.711	703.8×10^6	4679	^{231}Th
^{236}U	236.046	-	234.2×10^5	4572	^{232}Th
^{238}U	238.05	99.283	446.8×10^7	4270	^{234}Th

* On the scale ^{12}C

2.2.2. Plutonium

Plutonium is a man-made transuranium element of the actinide series that has atomic number 94 and atomic mass 244.06 amu. Plutonium is silvery gray metal that is formed by slow neutron bombardment of uranium as a result of radioactive neutron capture by the isotope ^{238}U and subsequent two-stage β decay of intermediate products. The mechanism of its formation is the following:

$$_{92}U^{238} \xrightarrow[(n,\gamma)]{} {}_{92}U^{239} \xrightarrow[(-\beta)]{} {}_{93}Np^{239} \xrightarrow[(-\beta)]{} {}_{94}Pu^{239}$$

Plutonium has six crystal modifications (alpha, beta, gamma, delta, delta-prime, epsilon); their properties are presented in Tables 2.12 [37] and 2.13 [36, 139, 140].

TABLE 2.11. BASIC PROPERTIES OF Pu UNDER NORMAL CONDITIONS (0.1 MPa, 298 K)

Property	Value
Density (ρ), kg/m^3	19840 [32]
Melting point, K (°C)	913 (640) [31, 32]
Boiling point, K (°C)	3500 (3230) [33, 131]
Heat capacity, J/mol J/(kg·K)	31.2 [31, 32] 130
Heat of fusion (ΔH_f), kJ/mol kJ/kg	2.8 [31, 32] 117
Heat ofvapourization (ΔH_{vap}), kJ/mol kJ/kg	350 [31, 32] 1464
Thermal conductivity, W/(m·K)	5.2*[32]
Electrical resistivity, 10^{-8} Ω·m	150 [33, 38, 131]
Sound velocity, m/s	2260 [56–59]
Critical constants: [31]	
Temperature (T_c), K	10000
Pressure (P_c), MPa	324
Molar volume (V_c), dm^3/mol	0.081
Density (ρ_c), kg/m^3	2950

* The range of another data on thermal conductivity of Pu is 4.2÷6.74 W/(m·K) according to Refs [33, 38, 56–59].

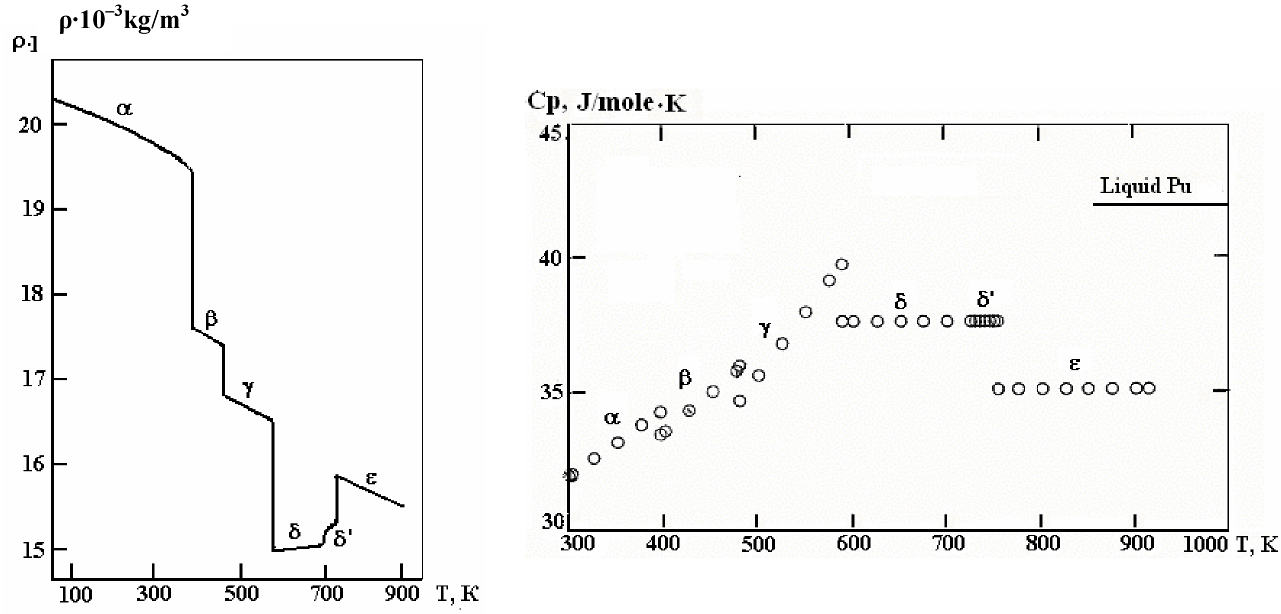
TABLE 2.12. CHARACTERISTICS OF CRYSTAL STRUCTURE AND PHASE TRANSITIONS OF PLUTONIUM [37]

Phase	Crystal structure. Stability temperature range K	Lattice dimensions nm	Temperature of phase transition K (°C)	Heat of phase transition J/mol	Volumetric expansion %
α-Pu	Monoclinic at T < 395	at 294 K a=6.1835 b=4.8244 c=10.973 β=101.81°	α→β 395 (122±2)	3365±41	8.9–9.62
β-Pu	Monoclinic body-centered at 395 < T < 479	at 463 K a=9.284 b=10.463 c=7.859 β=92.13°	β→γ 479 (206±3)	637±63	2.4–2.67
γ-Pu	Rhombic face-centered at 479 < T <5 92	at 506 K a=3.1587 b=5.7862 c=10.162	γ→δ 592 (319±5)	721±84	6.7–6.90
δ-Pu	Face-centered, cubic at 59 2< T < 724	at 593 K a=4.6371	δ→η 724 (451±4)	80±46	(–0.36)–(–0.4)
δ'-Pu	Face-centered, tetragonal at 724 < T < 749	at 738 K a=4.701 b=4.489 c/a=0.955	η→ε 749 (476±5)	1927±84	(–2.16)–(–3.0)
ε-Pu	Body-centered, cubic at 749 < T < 913	at 763 K a=3.6361	ε→melt >913 (639.4)	2933±251	(–0.1)–(0.82)

TABLE 2.13. PROPERTIES OF PLUTONIUM PHASES [8, 102, 103]

Property	Plutonium phases					
	α	β	γ	δ	δ'	ε
Density kg/m^3	19816 at 298 K	17770 at 463 K	17140 at 508 K	15920 at 593 K	16010 at 723 K	16480 at 783 K
Linear expansion coefficient 10$^{6/}$K	46.85±0.05 at 87–373 K	33.86±0.11 at 406–470 K	Mean 34.7±0.7 at 483–583 K along the axes: a= –19.7±0.1 b= +39.5±0.6 c=84.3±1.6	–8.6±0.3 at 593–713 K	–16±28 at 738–758 K along the axes: a=+305±35 b=–659±67	36.5±1.1 at 772–823 K
Heat capacity J/(mol·K)]	32.0–34.3	33.4–36.0	34.8–39.8	37.7	37.4 at 728 K	35 at 773 K
Thermal conductivity W/(m·K)	5.2–6.6	7.87–8.67	8.97–10.5	10.97–12.1	7.72 at 723 K	12.1–12.6 at 783 K
Thermal diffusivity 10^6(m^2/s)	1.78–2.10	3.10–3.31	3.53–3.96	4.40–4.85	-	5.04–5.25
Electrical resistivity 10^8(Ω·m)	142–140	108–108	107–107	100–100	-	114–114
Sound velocity m/s	2200	1500	1100	1000	-	1200–1300

Internal heat generation owing to fission of the Pu^{239} nuclei is equal to (1.923±0.019) × 10^{-3} W/g. The mechanical properties of plutonium at 298 K are presented in Table 2.14 [30]. They essentially depend on temperature varying from high strength and brittleness for α phase to low strength and high ductility for δ phase at 593–723 K. Owing to great changes in volume combined with anisotropy of most crystal phases, there occur internal stresses and defects, which influence on elastic and plastic properties of plutonium.



a) b)

FIG. 2.1. Changes of density (a) [10a] and heat capacity (b) [29] of different plutonium phases depending on temperature.

TABLE 2.14. MECHANICAL PROPERTIES OF PLUTONIUM AT 298 K [59]

Property	Value
Brinell hardness	242
Vickers hardness	250
Tensile strength, MPa	400
Modulus of elasticity, GPa	96.5
Compression strength, MPa	830
Poisson ratio	0.15–0.21
Shear modulus of elasticity, GPa	45

2.2.2.1. Properties of liquid plutonium at 0.1 MPa

Density [141] ρ (kg/m^3) = 16500 ± 80 at melting point.
In the temperature range t = 650 – 950°C, ρ (kg/m^3) = 17567 – 1.451 t.

Heat capacity [138] C_p (J/kg·K) = 177; C_p (kJ/mol·K) = 42.3

Dynamic viscosity of liquid plutonium at melting point is equal to 4.51×10^{-3} Pa·s according to the experimental data in Ref. [60].

The viscosity can be calculated by the correlation $\ln \mu$ (Pa·s) = A + B·lnT +C/T, where A= –2.4909, B = 0.2751, C = 1948 in the range $T_{melt} \le T \le 2313$ K [51].

Thermal conductivity (by estimates) λ (W/(m·K)) ≈ 4.

Volumetric expansion coefficient is of β (1/K) = 50×10^{-6} in Ref. [138].

Surface tension [139] σ (mN/m) = 550 – a (T – T_{melt}) at T < 1200 K. Here a = 0.08 ÷ 0.15.

Vapour pressure of plutonium for the temperatures 1673–2073 K is evaluated by the correlation [29, 53]:

$$\lg P\ (\text{MPa}) = 4.019 - \frac{17587}{T} \quad (2.10)$$

The radiological properties of some plutonium isotopes are presented in Table 2.15 [40].

2.2.3. Thorium

Thorium is a chemical element with atomic number 90 and atomic mass 232.04 amu, which occurs in nature and belongs to the actinide series. When pure, thorium is silvery white, ductile metal. The basic properties of thorium are given in Table 2.16. Thorium has two crystal modifications; their characteristics are presented in Table 2.17 [37]. Metallic thorium is soft, ductile metal similar to platinum. It is easily amenable to processing by cold stretching, swaging and stretch forming. The mechanical properties of thorium at 298 K are given in Table 2.18 [64]. These properties depend on the metal purity and its preprocessing. Such impurities as oxygen, nitrogen and carbon increase thorium strength, carbon providing the largest increase.

TABLE 2.15. RADIOLOGICAL PROPERTIES OF SOME PLUTONIUM ISOTOPES [40]

Isotope	Mass number amu*	Half-life	Decay energy keV	Decay product	Specific activity kBq/g
^{236}Pu	236.05	2.86 years	5867	^{232}U	1.97×10^{10}
^{237}Pu	237.05	45.2 days	220	^{233}U	4.48×10^{11}
^{238}Pu	238.05	87.7 years	5593	^{234}U	6.33×10^{8}
^{239}Pu	239.05	24110 years	5244	^{235}U	2.27×10^{6}
^{240}Pu	240.05	6537 years	5255	^{236}U	8.84×10^{6}
^{241}Pu	241.06	14.4 years	20.8	^{241}Am	3.66×10^{9}
^{242}Pu	242.06	376000 years	4982	^{238}U	1.41×10^{5}
^{243}Pu	243.06	4.95 h	581.5	^{243}Am	6.19×10^{14}

* On the scale ^{12}C.

TABLE 2.16. BASIC PROPERTIES OF THORIUM UNDER NORMAL CONDITIONS (0.1 MPa, 298 K)

Property	Value
Theoretical density, kg/m^3	11720 [32, 61]
Melting point, K (°C)	2023 (1750)
Boiling point, K (°C)	5063 (4790)
Heat capacity, J/(kg·K)	118 [31]
J/(mol·K)	26.23
Heat of fusion (ΔH_f), kJ/kg	69.4 [63]
kJ/mol	16.1
Acc. to data from Refs [31, 61, 62], kJ/mol	13.8–15.6
Heat ofvapourization (ΔH_{vap}) kJ/kg	2330 [31]
kJ/mol	540
Thermal conductivity, W/(m·K)	37 [30]
according to another data [32, 61]	54
Linear expansion coefficient, K^{-1}	11.2 (393 K) [31]
Electrical resistivity, Ω·m	$(13–19) \times 10^{-8}$ [31, 33]
Emissivity	0.38 at λ=67 nm; 1273–1973 K [30]
Sound velocity, m/s	2490 [61]
Critical constants: [31]	
Temperature (T_c), K	14950
Pressure (P_c), MPa	488
Molar volume (V_c), dm^3/mol	0.0723
Density (ρ_c), kg/m^3	3220

TABLE 2.17. CHARACTERISTICS OF THORIUM CRYSTAL STRUCTURE [37]

Phase	Structure	Lattice dimension Å	Temperature range of existence K
α-Th	Face-centered cubic	a=5.086	< 1623
β-Th	Body-centered cubic	a=4.11	1623 < T < 2023

TABLE 2.18. MECHANICAL PROPERTIES OF THORIUM AT 298 K [64]

Property	Value
Vickers hardness	35–114
Tensile strength, MPa	200
Modulus of elasticity, GPa	73.1
Poisson ratio	0.27
Fatigue strength, MPa	97
Shear modulus of elasticity, GPa	28

2.2.3.1. Properties of solid thorium depending on temperature

Density
ρ (kg/m^3) = 11836 – 0.4219 T (2.11)

Heat capacity [43]
for α-Th at T< 1623 K C_p [J/(kg·K)] = – 0.0145T^2 + 3.6384T + 111.95 (2.12)
for β-Th at 1623 K< T < 2023 K C_p [J/(kg·K)] = – 0.2032T^2 + 5.7774T + 145.77 (2.12a)

Thermal conductivity
The data on thermal conductivity of thorium in different references greatly disagree. In Refs [32, 36] and many web sites, the values of 50–54 (W/m K) are found, the temperature range not indicated. In Ref. [134] there are the data on composition and processing of a number of thorium specimens. These data and those in Refs [38, 43, 135, 136] are in an agreement with accuracy of ± 15% and evaluated by the correlation:

λ [W/(m·K)] = 34 + 0.0133 T, (2.13)
where T (K).

The values given in Refs [28, 42, 130] that indicate a considerable decrease of thorium thermal conductivity with increasing temperature up to 10 W/(m·K) at 1773 K, seem to be incorrect.

2.2.3.2. Properties of liquid thorium at $T \geq T_{melt}$

Density [133] ρ = 10500 kg/m^3

Heat capacity C_p = 198 J/(kg·K)

Dynamic viscosity ln μ (Pa·s) = A + B·lnT +C/T,
where A= – 2.9328, B = 0.3075, C = 4504 for the temperature range $T_{melt} \leq T \leq T_{boil}$ [51]. Based on this correlation μ (T_{melt}) = 5.129 × 10^{-3} Pa·s. According to experimental data in Ref. [60], the value of μ at melting point is equal 5.033 × 10^{-3} Pa·s.

Surface tension [133]:
σ (mN/m) = 978 – 0.14 (T – T_{melt}). (2.13)

Vapour pressure of thorium for the temperature range of 2030–2229 K is defined by correlation [53]:

$$\lg P(\text{MPa}) = 4.991 - \frac{28780}{T} \quad (2.14)$$

Twenty five isotopes of thorium are known with mass numbers from 212 to 236, among them only the isotope ^{232}Th occurs in nature. In the course of ^{232}Th decay that includes six stages of α decay and four stages of β decay, thorium turns into stable isotope ^{208}Pb. The radiological properties of the most stable isotopes are given in Table 2.19 [40]. Most of other thorium isotopes have a half-life, which is less than 10 minutes.

TABLE 2.19. RADIOLOGICAL PROPERTIES OF THORIUM ISOTOPES [11]

Isotope	Mass number amu*	Half-life	Decay energy keV
^{227}Th	227.03	18.72 days	6146
^{228}Th	228.03	1.913 years	5520
^{229}Th	229.03	7880 years	5167
^{230}Th	230.03	75380 years	4770
^{231}Th	231.04	25.52 hours	4213
^{232}Th	232.04	1.4×10^{10} years	4082
^{233}Th	233.04	22.3 min	1245
^{234}Th	234.06	24.1 days	273

* On the scale ^{12}C.

At slow neutron radiation, the isotope ^{232}Th turns into fissionable isotope ^{233}U according to the reaction:

$$_{90}Th^{232} + {_0}n^1 \rightarrow {_{90}}Th^{233} \xrightarrow{-\beta} {_{91}}Pa^{233} \xrightarrow{-\beta} {_{92}}U^{233}$$

The isotope ^{233}U is characterized by higher neutron yield per number of absorbed neutrons as compared to other fission materials such as ^{235}U or ^{239}Pu. In combination with one of these isotopes, thorium gives rise of fuel-breeding cycle in thermal-neutron reactors. The thorium cycle is proposed for the use in advanced converter reactors.

2.3. CERAMIC FUEL

2.3.1. Uranium dioxide

Uranium dioxide is a ceramic refractory uranium compound, in many cases used as a nuclear fuel. The basic properties of uranium dioxide are given in Table 2.20.

The crystal lattice of uranium dioxide corresponds to the face-centered cubic lattice of Ca_2F fluoride with the lattice constant a=0.5704 nm [37].

2.3.1.1. Properties of solid uranium dioxide depending on temperature

Density [67]

$$\rho\left(kg/m^3\right) = \rho_0\left(273\right) \cdot K_i^{-3}, \qquad (2.15)$$

where $\rho_0(273)$ (kg/m^3) is the theoretical density of UO_2, K_i are the relative linear thermal expansion coefficients estimated by the Martin correlations [70]:
at $273 \le T \le 923$ K.

TABLE 2.20. BASIC PROPERTIES OF URANIUM DIOXIDE AT 0.1 MPa, 298 K

Property	Value
Molecular mass, amu	270.3
Theoretical density ρ_0, kg/m^3	10960 [41]
Melting point, K (°C)	3120 ± 30 (2850) [27]
Boiling point, K (°C)	3815 (3542) [68]
Heat of fusion ΔH_f, kJ/kg	259 ± 15
kJ/mol	70 ± 4 [65]
Heat ofvapourization ΔH_{vap}, kJ/kg	1530
kJ/mol	413 [68]
Heat capacity, J/(kg·K)	235 [66]
J/(mol·K)	63.7
Thermal conductivity, W/(m·K)	8.68 [67]
Linear expansion coefficient, 1/K	9.75×10^{-6} [67]
Electrical resistivity, Ω·m	7.32×10^{-8} [69]
Total normal emissivity(ε_t)	0.79 [41]

$$K_1 = \frac{L(T)}{L(273)} = 0.99734 + 9.802\times10^{-6}T - 2.705\times10^{-10}T^2 + 4.291\times10^{-13}T^3, \qquad (2.16)$$

at 923 ≤ T ≤ 3120 K

$$K_2 = \frac{L(T)}{L(273)} = 0.99672 + 1.179\times10^{-5}T - 2.429\times10^{-9}T^2 + 1.219\times10^{-12}T^3. \qquad (2.17)$$

Enthalpy and heat capacity. The enthalpy of solid uranium dioxide at 298.15 ≤ T ≤3120 K is defined by correlation [66]:

$$[H(T) - H(298.15K)](kJ/mol) = C_1\theta\left[\left(e^{\theta/T} - 1\right)^{-1} - \left(e^{\theta/298.15} - 1\right)^{-1}\right] + C_2\left[T^2 - (98.15)^2\right] + C_3 e^{-E_a/T} \qquad (2.18)$$

where C_1 = 81.613, θ = 548.68, $C_2 = 2.285 \times 10^{-3}$, $C_3 = 2.360 \times 10^7$, E_a = 18531.7, T (K). The uncertainty of correlation (2.18) is ± 2% in the range from 298.15 to 1800 K, and ± 3% in the range from 1800 to 3120 K. Correlation (2.18) is approximated by polynomial [66]:

$$\begin{aligned}[H(T) - H(298.15K)](kJ/mol) = &-21.1762 + 52.1743\tau + 43.9753\tau^2 - 28.0804\tau^3 + \\ &+ 7.88552\tau^4 - 0.52668\tau^5 + 0.71391\tau^{-1}\end{aligned}, \qquad (2.19)$$

where τ = T/1000, T (K), H (kJ/mol).

As $(\partial H/\partial T)_p = C_p$, after differentiation (2.18) in [66] we obtain,

$$C_p[\text{kJ}/(\text{mol}\cdot\text{K})] = \frac{C_1\theta^2 e^{\theta/T}}{T^2\left(e^{\theta/T}-1\right)^2} + 2C_2T + \frac{C_3E_a e^{-E_a/T}}{T^2}. \qquad (2.20)$$

Equation (2.20) has an uncertainty of ± 3% in the range from 298 to 1800 K and ± 13% at 1800–3120 K. In Ref. [67] the data on UO_2 heat capacity are given in the form of polynomial:

$$C_p[\text{kJ}/(\text{mol}\cdot\text{K})] = 52.1743 + 87.951\tau - 84.2411\tau^2 + 31.542\tau^3 - 2.6334\tau^4 + 0.71391\tau^{-2} \qquad (2.20a)$$

where τ = T/1000, T (K).

Thermal conductivity of solid UO_2 with a density of 95% is estimated by correlation [71]:

$$\lambda\,[\text{W}/(\text{m}\cdot\text{K})] = \frac{100}{7.5408 + 17.692\tau + 3.6142\tau^2} + \frac{6400}{\tau^{5/2}}\exp\left(\frac{-16.35}{\tau}\right) \qquad (2.21)$$

where τ = T/1000, T (K). The uncertainty of correlation (2.21) is +10% in the range from 298.15 to 2000 K and +20% in the range from 2000 to 3120 K.

Taking into account the porosity (λ_p), the thermal conductivity of solid UO_2 can be calculated by the Brandt-Neuer correlation [72]:

$$\lambda_p[\text{W}/(\text{m}\cdot\text{K})] = \lambda_0(1-\alpha p) \qquad (2.22)$$

where α = (2.6 – 0.5τ), p is the UO_2 porosity in volume fractions, λ_0 the UO_2 thermal conductivity with no porosity.

Integral thermal conductivity of solid UO_2 is determined as $\Lambda\,(\text{W/m}) = \int_{293}^{T}\lambda(T)\,dT$. The values of integral thermal conductivity of UO_2 (95% and theoretical density) defined by numerical integration of correlations (2.21, 2.22) using MATHCAD are given in Table 2.21. For uranium dioxide with a density of 95%, the integral thermal conductivity is approximated by the following polynomials: at 323 ≤ T ≤ 623 K with an accuracy of ± 2%

$$(\Lambda)_{UO_2,95\%}(\text{W/m}) = -4211.3\tau^3 + 546.65\tau^2 + 8407\tau - 2402, \qquad (2.23)$$

at 623 ≤ T ≤ 3120 K with an accuracy of ± 1%.

$$(\Lambda)_{UO_2,95\%}(\text{W/m}) = -101.93\tau^4 + 1166.9\tau^3 - 4532.1\tau^2 + 9460.4\tau - 2372.3. \qquad (2.24)$$

For uranium dioxide of theoretical density, integral thermal conductivity is approximated by polynomials:

at 298 ≤ T ≤ 823 K with an accuracy of ± 2%

$$(\Lambda)_{UO_2,100\%}(\text{W/m}) = 3176.8\tau^3 - 9070.2\tau^2 + 13220\tau - 3175, \qquad (2.25)$$

at 823 ≤ T ≤ 3120 K with an accuracy of ± 1%

$$(\Lambda)_{UO_2,100\%}(\text{W/m}) = -115.26\tau^4 + 1318.1\tau^3 - 5157.5\tau^2 + 10746\tau - 2704.3, \qquad (2.26)$$

where τ = T/1000, T (K).

The correlation for calculation of thermal conductivity, which takes into account the deviation from stoichiometric composition for UO_{2+X} of theoretical density, has been developed for a range of 773≤ T ≤ 1773 K [Washington, cit. in Ref. 41]:

$$\lambda[W/(m\cdot K)] = \left(0.035 + 3.47X - 7.26X^{-2} + 2.25\times 10^{-4}T\right)^{-1} + \\ + \left(83.0 - 537X + 7610X^2\right)\times 10^{-12}T^3 , \qquad (2.27)$$

where X is the deviation from stoichiometry; T (K).

Based on (2.27) Martin [73] obtained a correlation for UO_{2+X} of theoretical density in the range of 773≤ T ≤3120 K and 0≤ X ≤0.2:

$$\lambda[W/(m\cdot K)] = \left(0.035 + 3.47X\,\phi - 7.26X^{-2}\,\phi + 2.25\times 10^{-4}T\right)^{-1} + \left(83.0 - 537X\,\phi + 7610X^2\,\phi\right)\times 10^{-12}T, \qquad (2.28)$$

where $\phi = (3120 - T)/1347$.

For calculation of thermal conductivity of irradiated uranium dioxide by the computer codes FRAPCON-3 and FRAPTRAN, the following correlation [45] has been developed based on the modified NFI model:

$$\lambda_{irr}[W/(m\cdot K)] = \frac{1}{A + BT + f(Bu) + [1 - 0{,}9\exp((-0.04Bu))]\,g(Bu)\,h(T)} + \frac{E}{T^2}\exp(-F/T), \qquad (2.29)$$

where Bu is the burnup in terms of GW day/Mt U, f(Bu) = 0.00187 Bu is the function that considers the effect of decay products on crystalline matrix (solution); g(Bu) = 0.00187 $Bu^{0.28}$ is the function that considers the effect of radiation defects; $h(T) = 1/\left(1 + 396e^{-Q/T}\right)$ is the function that considers temperature dependence of annealing from radiation defects; Q = 6380 K is the temperature parameter, A = 0.0452 (m·K)/W, B = 2.46E–4 (m/W), E = 3.59E9 ((W·K)/m), F = 16361 K.

Linear expansion coefficient of solid UO_2 [67],
at 273 ≤ T ≤ 923 K

$$\alpha, 10^{-6}1/K = 9.828\times 10^{-6} - 6.39\times 10^{-10}T + 1.38\times 10^{-12}T^2 - 1.757\times 10^{-17}T^3, \qquad (2.30)$$

at 923 ≤ T ≤ 3120 K

$$\alpha, 10^{-6}1/K = 1.1833\times 10^{-5} - 5.013\times 10^{-9}T + 3.756\times 10^{-12}T^2 - 6.125\times 10^{-17}T^3. \qquad (2.31)$$

The linear expansion coefficient of UO_2 depends on the degree of stoichiometry and the presence of other oxides.

Thermal diffusivity a =$\lambda/C_p\cdot\rho$, m^2/s.

Thermophysical properties of solid uranium dioxide evaluated by correlations (2.15–2.17, 2.19–2.22, 2.30, 2.31) are presented in Table 2.21.

TABLE 2.21. THERMOPHYSICAL PROPERTIES OF SOLID URANIUM DIOXIDE (UO_2) BY EQS (2.15–2.17, 2.19, 2.20a, 2.21, 2.23, 2.24, 2.30, 2.31)

Temperature		Density kg/m^3	Enthalpy H(T)–H(298) kJ/kg	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)		Integral thermal conductivity W/m		Thermal diffusivity 10^6 (m^2/s)		Linear expansion coefficient 10^6/K
°C	K				95% density	theor. density	95% density	theor. density	95% density	theor. density	
25	298	10950	0	235	7.61	8.68	38	44	2.96	3.38	9.76
27	300	10950	0	236	7.59	8.65	53	61	2.94	3.35	9.76
50	323	10950	6	244	7.34	8.35	225	254	2.74	3.12	9.76
100	373	10930	19	260	6.83	7.77	579	659	2.41	2.74	9.77
150	423	10910	32	270	6.38	7.25	909	1034	2.16	2.46	9.79
200	473	10900	45	279	5.98	6.78	1280	1385	1.97	2.23	9.82
250	523	10880	59	285	5.62	6.37	1580	1713	1.81	2.05	9.86
300	573	10870	74	290	5.30	5.99	1780	2022	1.68	1.90	9.90
350	623	10850	88	294	5.01	5.66	2038	2313	1.57	1.77	9.94
400	673	10830	103	297	4.74	5.35	2282	2568	1.47	1.66	10.0
450	723	10820	118	300	4.50	5.07	2513	2849	1.38	1.56	10.1
500	773	10800	134	303	4.28	4.81	2732	3095	1.31	1.47	10.1
550	823	10790	149	305	4.07	4.57	2941	3330	1.24	1.39	10.2
600	873	10770	164	307	3.89	4.36	3140	3553	1.17	1.32	10.3
650	923	10750	180	309	3.71	4.16	3330	3766	1.12	1.25	10.4
700	973	10740	195	311	3.55	3.97	3511	3969	1.06	1.19	10.5
750	1023	10720	211	312	3.40	3.80	3685	4163	1.02	1.13	10.6
800	1073	10700	226	314	3.26	3.64	3851	4349	0.97	1.08	10.7
850	1123	10680	242	315	3.13	3.49	4011	4527	0.93	1.03	10.9
900	1173	10670	258	317	3.01	3.35	4165	4697	0.89	0.99	11.0
950	1223	10650	273	318	2.90	3.22	4312	4861	0.86	0.95	11.2
1000	1273	10630	289	320	2.79	3.10	4455	5019	0.82	0.91	11.4
1050	1323	10610	305	321	2.70	2.99	4592	5171	0.79	0.88	11.6
1100	1373	10590	321	323	2.61	2.88	4724	5318	0.76	0.84	11.9
1132	1405	10580	331	324	2.55	2.82	4807	5409	0.75	0.82	12.1
1150	1423	10570	337	324	2.52	2.79	4853	5460	0.74	0.81	12.1
1200	1473	10560	353	326	2.45	2.70	4977	5597	0.71	0.78	12.4
1250	1523	10540	369	328	2.38	2.62	5098	5730	0.69	0.76	12.7
1300	1573	10520	385	331	2.32	2.55	5215	5859	0.67	0.73	13.0
1350	1623	10490	402	334	2.27	2.49	5330	5985	0.65	0.71	13.3
1400	1673	10470	419	337	2.22	2.43	5442	6108	0.63	0.69	13.7
1450	1723	10450	435	341	2.18	2.38	5552	6299	0.61	0.67	14.0
1500	1773	10430	452	345	2.14	2.34	5659	6347	0.60	0.65	14.4
1550	1823	10410	470	350	2.11	2.31	5776	6463	0.58	0.63	14.8
1600	1873	10380	487	355	2.09	2.28	5871	6577	0.57	0.62	15.2
1650	1923	10360	505	361	2.07	2.26	5975	6691	0.55	0.60	15.6
1700	1973	10330	524	368	2.06	2.25	6078	6803	0.54	0.59	16.1
1750	2023	10310	542	376	2.06	2.24	6181	6915	0.53	0.58	16.6
1800	2073	10280	562	385	2.06	2.24	6284	7027	0.52	0.57	17.0
1850	2123	10260	581	395	2.07	2.24	6388	7139	0.51	0.55	17.5
1900	2173	10230	601	405	2.08	2.25	6491	7252	0.50	0.54	18.1
1950	2223	10200	622	417	2.10	2.27	6596	7365	0.49	0.53	18.6

TABLE 2.21 (continued)

Temperature		Density kg/m^3	Enthalpy H(T)–H(298) kJ/kg	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)		Integral thermal conductivity W/m		Thermal diffusivity 10^6(m^2/s)		Linear expansion coefficient 10^6/K
°C	K				95% density	theor. density	95% density	theor. density	95% density	theor. density	
2000	2273	10170	643	430	2.12	2.29	6702	7479	0.49	0.52	19.1
2050	2323	10140	665	443	2.15	2.32	6808	7594	0.48	0.52	19.7
2100	2373	10110	688	458	2.18	2.35	6917	7710	0.47	0.51	20.3
2150	2423	10080	711	474	2.22	2.38	7027	7829	0.46	0.50	20.9
2200	2473	10050	736	490	2.26	2.42	7138	7949	0.46	0.49	21.5
2250	2523	10020	761	508	2.30	2.47	7252	8071	0.45	0.48	22.1
2300	2573	9982	787	527	2.35	2.51	7369	8195	0.45	0.48	22.8
2350	2623	9948	813	547	2.40	2.56	7487	8322	0.44	0.47	23.4
2397	2670	9912	840	566	2.45	2.61	7601	8444	0.44	0.46	24.1
2400	2673	9912	841	568	2.45	2.61	7608	8452	0.44	0.46	24.1
2450	2723	9876	870	589	2.50	2.67	7732	8584	0.43	0.46	24.8
2500	2773	9839	900	612	2.56	2.72	7859	8718	0.43	0.45	25.5
2550	2823	9801	931	636	2.62	2.78	7988	8856	0.42	0.45	26.2
2600	2873	9762	964	660	2.68	2.84	8120	8997	0.42	0.44	27.0
2650	2923	9722	997	685	2.74	2.91	8256	9141	0.41	0.44	27.7
2700	2973	9681	1032	711	2.80	2.97	8394	9287	0.41	0.43	28.5
2750	3023	9639	1068	738	2.87	3.03	8536	9437	0.40	0.43	29.3
2800	3073	9596	1106	766	2.93	3.10	8681	9591	0.40	0.42	30.1
2827	3100	9573	1127	781	2.97	3.13	8761	9675	0.40	0.42	30.9
2847	3120	9555	1143	792	2.99	3.16	8820	9738	0.40	0.42	30.9

The data on electrical resistivity of solid UO_2 can greatly disagree owing to the manufacturing process and composition of specimens. Uranium dioxide is a semiconductor with mixed conduction and its coefficient of electrical resistivity at 20°C is of 380 ohm·m. Depending on temperature at 300–600 K, electrical resistivity of UO_2 is described by the formula [124, 125]:

$$\rho_e\ (\Omega\cdot m) = 18.04 \exp(1867/T). \qquad (2.32)$$

For UO_{2+x} in the form of single crystal of non-stoichiometric composition at 773 K≤ T≤ 1423 K the formula is proposed in Ref. [126]:

$$1/\rho_e = 3.8 \times 10^{4/}T\ (2 \times)\ (1-2 \times)\ \exp[(-0.30 \pm 0.03\ \text{eV})/kT], \qquad (2.33)$$

where ρ_e – (Ω·m); $k = 1.38 \times 10^{-23}$ J/K = 8.625×10^{-3} eV/K.

Subsequent data in Ref. [132] are evaluated by the formulas:

at 286 K≤ T ≤ 1430 K $$\lg\frac{1}{\rho_e} = 1.9045 - \frac{830.68}{T}, \qquad (2.33\ a)$$

at 1430 K≤ T ≤ 4000 K $$\lg\frac{1}{\rho_e} = 5.2607 - \frac{5662.36}{T}. \qquad (2.33\ b)$$

Total normal emissivity of solid UO_2 [38]
at 1000 < T < 3120 K and a wave length of 630 nm $\varepsilon_t = 0.78 + 1.53 \times 10^{-5} T$. (2.34)

Vapour pressure above solid UO_2 [75]:

$$\lg P\,(Pa) = 66.54 + 4.382 \times 10^{-3} T - 4.41 \times 10^{-7} T^2 - \frac{37090}{T} - 19.07 \lg T \qquad (2.35)$$

The uncertainty of correlation (2.35) is −40%/+60% at 1700 ≤ T ≤3120 K. The values ofvapour pressure calculated by Eq. (2.35) are given in Table 2.22.

TABLE 2.22.VAPOUR PRESSURE P (MPa) ABOVE SOLID UO_2 BY CORRELATION (2.35)

Temperature K	Pressure MPa
1723	3.43×10^{-11}
1773	1.12×10^{-10}
1973	6.74×10^{-9}
2273	7.76×10^{-7}
2673	7.41×10^{-5}
2723	1.18×10^{-4}
2773	1.84×10^{-4}
2823	4.13×10^{-4}
2923	6.23×10^{-4}
2973	9.04×10^{-4}
3023	1.29×10^{-3}
3073	1.82×10^{-3}
3120	2.47×10^{-3}

2.3.1.2. Properties of liquid uranium dioxide

The thermophysical properties of liquid UO_2 are discussed in Refs [76–85].

Density at T_{melt} = 3120 K by estimations in Ref. [76] is 8860 ± 120 kg/m^3
at 3120 ≤ T ≤ 7600 K

$\rho(T)$ kg/m^3 = 8860 − 0.9285 (T − 3120). (2.36)

The uncertainty of correlation (2.36) is ± 1.4% at 3120 K, +1.6% and −2% at 3500 K, +2.2% and −4% at 4500 K, + 3% and −6.3% at 5400 K, + 4.2% and −10% at 6500 K, + 6% and −15.4% at 7600 K.

Enthalpy of liquid UO_2 in terms of J/kg [77]:

$$[H(T) - H(298.15K)](kJ/mol) = 2.9768 \times 10^6 + 0.93087T - 4.9211 \times 10^9 / T \qquad (2.37)$$

The uncertainty of correlation (2.37) is ± 2% at 3120 ≤ T ≤ 3500 K and ± 10% at 3500 ≤ T ≤ 4500 K.

Heat capacity of liquid UO_2 is estimated with an uncertainty of ± 10% at 3120≤T≤ 3500 K and ± 25% at 3500 ≤ T ≤ 4500 K by the correlation [77]:

$$C_p \text{ [J/(kg·K)]} = 0.93087 + 4.921 \times 10^9 T^{-2}. \qquad (2.38)$$

Thermal conductivity of liquid UO_2 was studied in Refs [78–80]. According to recent data of the MATPRO computer code, thermal conductivity of liquid UO_2 is in the range from 2.5 to 3.6 W/(m·K) [81]. The λ value at 3120 ≤ T ≤4500 K is calculated with an uncertainty of ± 40% by the empirical formula

$$\lambda \text{ [W/(m·K)]} = 2.5 + 0.01375(T - 3120). \qquad (2.39)$$

Volumetric thermal expansion coefficient β_0 of liquid UO_2 is determined from correlation [12]:

$$\beta_0(1/K) = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_0 + \beta_T\left(\frac{\partial P}{\partial T}\right)_0 \qquad (2.40)$$

where ρ is density, β_T isothermal compressibility, Pvapour pressure; the subscript 'o' denotes along the saturation line. As the quantity of the second member is very low, the β_0 value is defined by the first member; thus, taking into account the correlation (2.36) we obtain:

$$\beta_0 \text{ (1/K)} = 0.9285/[8860 - 0.9285(T - 3120)]. \qquad (2.41)$$

The uncertainty of the correlation (2.41) is +10% and −12% at 3120 K, +10% and −13% at 3500 K, +12% and −15% at 4500 K.

Thermal diffusivity $a=\lambda/C_p\cdot\rho$.

Dynamic viscosity of liquid UO_2 at 3120 K< T <3400 K is calculated with an uncertainty of ± 25% by correlation [82]:

$$\mu \text{ (mPa·s)} = 0.988 \exp(4620/T). \qquad (2.42)$$

At 3400< T <4000 K the dynamic viscosity of UO_2 is estimated by the extrapolation of formula (2.42) with an uncertainty of ± 50%.

Surface tension of liquid UO_2 with an uncertainty of ± 17% is calculated by formula [54]:

$$\sigma \text{ (mN/m)} = 513 - 0.19 (T - 3120). \qquad (2.43)$$

Normal emissivity at λ=630 nm [41]:

$$\varepsilon_\lambda = 1 - 0.16 \exp[-3.79 \times 10^{-4}(T - 3120) - 3.27 \times 10^{-7}(T - 3120)^2] \qquad (2.44)$$

Vapour pressure [47] at 3120 K ≤ T ≤ 8000 K:

$$\lg P\ (\text{MPa}) = 15.961 - \frac{26974}{T} - 2.76\lg T\,. \qquad (2.45)$$

The uncertainty of correlation (2.45) is $\begin{matrix} -40\% \\ +60\% \end{matrix}$ at 3120 K and $\begin{matrix} -45\% \\ +80\% \end{matrix}$ at 6000 K.
In Refs [76, 84, 85] the following properties of liquid UO_2 at T_{melt}=3120 K are given:

Volumetric expansion coefficient $\beta = 1.05 \times 10^{-4}$ 1/K [76]

Adiabatic compressibility 3.5×10^{-5} 1/MPa [84]

Sound velocity c = 1800 (m/s) [85]

Thermophysical properties of liquid uranium dioxide evaluated by correlations (2.36–2.45) are shown in Table 2.23.

TABLE 2.23. THERMOPHYSICAL PROPERTIES OF LIQUID URANIUM DIOXIDE [76, 86, 96]

Temperature K	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Volumetric expansion coefficient 10^6/K	Dynamic viscosity mPa·s	Surface tension mN/m	Normal emissivity ε	Sound velocity m/s	Vapour pressure Pa
3120	8870	511	3	1.09E-04	4.34	513	0.84	1897	3.98E03
4000	8126	399	(15)	9.50E-05	3.14	346	0.91	1716	1.47E05
5000	7354	372	(20)	1.08E-04	2.49	-	0.98	1582	2.33E06
6000	6533	416	-	1.34E-04	2.13	-	0.99	1407	2.02E07
7000	5680	524	-	1.81E-04	1.91	-	1.0	1211	1.12E08
8000	4876	851	-	2.83E-04	1.76	-	1.0	1080	3.88E08

2.3.1.3. Evaluation of critical constants

The critical temperature of material (T_c) can be preliminarily estimated based on semiempirical correlations, for example:

Guldberg's rule for ionic compounds [87]:

$$T_c = T_{boil}/0.54. \qquad (2.46)$$

where T_{boil} is the normal boiling temperature, K.

Watson's correlation [88],

$$T_e/T_c = 0.283(M/\rho_{boil})^{0,18}, \qquad (2.47)$$

where ρ_{boil} is material's density at boiling point, M molecular weight, T_e transient temperature, at whichvapour density is M/22400g/cm^3. Based on correlation (2.47) the T_c value is calculated as:

$$T_c = T_e / [0.283(M/\rho_{boil})]^{0,18} . \quad (2.48)$$

The T_e value relates to normal boiling temperature by the correlation:

$$\ln T_e = 9.8(T_e/T_{boil}) - 4.2 \quad (2.49)$$

Correlation (2.49) is solved approximately by the Newton method [89].

The critical temperature of UO_2 defined by correlations (2.46, 2.48) is equal to 7052 K and 9306 K, respectively. The compressibility factor Z_c is calculated by the formula $Z_c = \frac{P_c (V_m)_c}{R T_c}$, where P_c is the critical pressure, MPa; $(V_m)_c$ is the critical molar volume, cm^3/mol; R is the universal gas constant [88].

The critical constants of uranium dioxide are calculated based on various theoretical models including different equations of state of UO_2. The data on critical constants of UO_2 are presented in Table 2.24.

The problem of discrepancy between the data on critical constants of UO_2 is analyzed in Refs [86, 95].

TABLE 2.24. CRITICAL CONSTANTS OF URANIUM DIOXIDE

Author, year, theory	Critical constants				
	Temperature T_c K	Pressure P_c MPa	Molar volume $(V_m)_c$ cm^3/mol	Density ρ_c g/cm^3	Compressibility factor Z_c
Menzies,1996 cit. in Ref. [91] principle of corresponding state	8000	200	90	3.14	0.27
Browning, 1978 [92] significant structure theory in view of UO_2 dissociation	8840 9138	142.4 158	158 153	1.71 1.76	0.31 0.316
Mistura, 1985 [93] solid sphere perturbation theory	7567	140.9	156	1.73	0.35
Fisher, 1989 [84] theory of essential structures	10600	158	173.1	1.56	0.31
Iosilevski et al., 2001 [94, 95] chemical model based on thermodynamic perturbation theory	10120	965	103	2.61	0.32
Azad, 2005 [86] generalization of experimental data, equation of state	10500	219	107	2.51	0.27

Taking into account the scattering of the afore cited data, the following values of critical constants of UO_2 are recommended for estimations: T_c = 10400 K, P_c = 200 MPa, $(V_m)_c$ = 126 cm^3/mol, ρ_c = 2.15 g/cm^3.

2.3.2. Plutonium dioxide

PuO_2 is ceramic fuel that makes it possible to achieve burnups of 10% of heavy atoms, used in the reactors of types BR-5, IBR-2, etc. Basic properties of plutonium dioxide at 0.1 MPa, 298 K [31, 32] are as follows:

Molecular mass, amu	276.045
Theoretical density ρ_0 (kg/m^3)	11460
Melting point, K (°C)	2663 ± 20 (2390)
Boiling point, K (°C)	3600 (3327)
Heat of fusion ΔH_f (kJ/kg)	255
Heat ofvapourization ΔH_{vap} (kJ/kg)	1365
Heat capacity C_p (J/(kg·K))	240
Thermal conductivity λ [W/(m·K)]	6.3
Linear expansion coefficient $\alpha \cdot 10^6$(1/K)	7.8

The crystal structure of PuO_2 is a face-centered cubic lattice of CaF_2 type:
a = 0.5396 ± 0.005 nm. The expansion of lattice parameter in the range of 298–1550 K is described by correlation [102]:

$$a\ (\text{nm}) = 0.53943 \pm 0.00007 + (4.7 \pm 0.3) \times 10^{-6}\ (T - 298) + (8 \pm 2) \times 10^{-10}\ (T - 298)^2. \quad (2.50)$$

TABLE 2.25. THE VALUES OF TRUE LINEAR THERMAL EXPANSION COEFFICIENT OF PuO_2 [103]

Temperature		Linear expansion coefficient 10^{-6} K^{-1}
K	°C	
373	100	8.06
473	200	9.42
573	300	9.87
673	400	10.20
773	500	10.97
873	600	11.48
973	700	12.54
1073	800	12.70
1173	900	12.70
1273	1000	14.40

Taking into account the scattering of data in Refs [102, 103] on *linear thermal expansion coefficient* of PuO_2, they can be approximated by correlation:

$$\alpha \cdot 10^{-6}\,(K^{-1}) = 5.74 + 7.04 \times 10^{-3}\,T. \qquad (2.51)$$

Enthalpy of PuO_2 is calculated by correlation [27]:
at $\tau \le 0.856$

$$(H_u)_{PuO_2}\,(J/mol) = -32481 + 228656\tau + 43346\tau^2 - 11270\tau^3 + 987.72\tau^4 + 1970.7\tau^5 + 744.21\tau^{-1} \qquad (2.52)$$

at $\tau > 0.856$

$$(H_u)_{PuO_2}\,(J/mol) = 352544\tau - 109876 \qquad . \qquad (2.52a)$$

where $\tau = T/T_{melt} = T/3023$ is the reduced temperature.

Heat capacity. In Ref. [27] the following correlation is recommended:

$$C_{p_{PuO_2}}\,[J/(kg \cdot K)] = \frac{347.4 \times 571^2 \exp\left(\frac{571}{T}\right)}{T^2\left[\exp\left(\frac{571}{T}\right) - 1\right]^2} + 3.95 \times 10^{-4}\,T + \frac{3.860 \times 10^7 \times 1.967 \times 10^5}{RT^2}\exp\left(-\frac{1.965 \times 10^5}{RT}\right) \qquad (2.53)$$

where R is the universal gas constant = 8.3141 J/(mol·K).

In Ref. [102] a simpler correlation is proposed, which after its transformation from mole heat capacity to mass one has the following form:

$$C_p\,[J/(kg \cdot K)] = -\,4.243 \times 10^{-6}\,T^2 + 2.366 \times 10^{-3}\,T + 293.1. \qquad (2.54)$$

Thermal conductivity. The data on thermal conductivity of PuO_2 used in Ref. [2] are approximated by the correlation:

$$\lambda\,[W/(m \cdot K)] = 8.441 \; - 7.445\,T + 2.236 \times 10^{-6}\,T^2. \qquad (2.55)$$

The thermal conductivity of PuO_2 as a function of density (at porosity up to 10%) is defined by the correlation:

$$\lambda = \lambda_0\left(1 - 2.5\frac{\rho_0 - \rho_f}{\rho_f}\right). \qquad (2.56)$$

where λ_0 is the thermal conductivity at ρ_0.

Vapour pressure of PuO_2 [102, 142],

$$\lg P\ (\text{atm}) = 8.072 \pm 0.239 - \frac{29240 \pm 530}{T}.. \qquad (2.57)$$

For more detailed data see in Refs [143, 144].

Dynamic viscosity of liquid PuO_2 at T_{melt} is 32 centipoise ±25%.

Surface tension of liquid PuO_2 at T_{melt} is 523 dyn/cm ±15%.

Hemispherical emissivity of PuO_2 is defined by the correlation:

$$\varepsilon = 0.548 + 1.65 \times 10^{-4}T. \qquad (2.58)$$

2.3.3. Mixed oxide fuel MOX – (U, Pu)O_2

The term 'MOX' derived from 'mixed oxides' relates to the nuclear fuel manufactured from uranium and plutonium oxides ($UO_2 + PuO_2$). The concentration of plutonium in MOX fuel is equal from 3 to 10%. In the course of analysis of MOX fuel thermophysical properties, fuel of stoichiometric composition $(U_{0.8}Pu_{0.2})O_2$ is usually considered, where 0.8 and 0.2 are the molar fractions of UO_2 and PuO_2. The basic properties of MOX fuel $(U_{0.8}Pu_{0.2})O_2$ are presented in Table 2.26.

TABLE 2.26. BASIC PROPERTIES OF MOX FUEL – $(U_{0.8}PU_{0.2})O_2$

Property	Value
Molecular mass, amu	271.2
Density, kg/m^3	11074 at 298 K [89]
Solidus temperature (T_S), K (°C)	3002 (2729) [98]
Liquidus temperature (T_L), K (°C)	3041 (2768) [98]
Melting point, K (°C)	3023 [101]
Boiling point, K (°C)	3811 (3538) [101]
Heat of fusion, kJ/kg	285.3 [27]
Heat ofvapourization, kJ/mol	413.5 [68]
Heat capacity, J/(kg·K)	240 at 298 K [27]
Thermal conductivity, W/(m·K)	7.82 at 298 K for MOX of 95% density [100]
Linear expansion coefficient, 1/K	9.4×10^{-6} at 300 K [Table 2.28]

2.3.3.1. Properties of solid MOX fuel – (U, Pu) O_2 depending on temperature

Density of MOX fuel is evaluated by the correlation [89, 90],

$$\rho\ (\text{kg/m}^3) = 11080\ [1 + 2.04 \times 10^{-5}(T - 273) + 8.7 \times 10^{-9}(T - 273)^2]^{-1}. \qquad (2.59)$$
$$\rho\ (\text{kg/m}^3) = 10970 - 490y\ (y - \text{mole fractions of } PuO_2). \qquad (2.59a)$$

Solidus/liquidus temperature (T_S)/(T_L) of MOX fuel of stoichiometric composition is estimated by the Adamson correlations [98]:

$$T_S\,(K) = 3120.0 - 655.3y + 336.4y^2 - 99.9y^3, \quad (2.60)$$
$$T_L\,(K) = 3120.0 - 388.1y - 30.4y^2\,. \quad (2.60a)$$

where y is the PuO_2 content in molar fractions. The standard deviation of correlations (2.60, 2.60a) is of ± 30 K.

Based on Eq. (2.59), the density of MOX fuel is 9889 kg/m^3 at T_S and 9865 kg/m^{3}at T_L.

Enthalpy of MOX fuel in terms of J/mol is calculated by the sum of enthalpies of its components in the ratio from their molar fractions $(H_u)_{MOX} = (H_u)_{UO_2}\,0{,}8 + (H_u)_{PuO_2}\,0{,}2$, where H_u = H(T) − H(298.15) [27]. The value $(H_u)_{UO_2}$ is calculated by Eq. (2.19). The enthalpy of PuO_2 is evaluated by Eqs (2.50, 2.53).

Heat capacity of MOX fuel can be estimated from the sum of heat capacities of its components in the ratio of molar fractions $(C_p)_{MOX} = (C_p)_{UO_2}\,0.8 + (C_p)_{PuO_2}\,0.2$ [27]. In this case, correlation (2.20) (see Table 2.21) is used to calculate heat capacity of uranium dioxide, and correlation (2.54) for plutonium dioxide.

Thermal conductivity of MOX fuel with 95% density of the theoretical one is calculated by the relation [100]:

$$\lambda_{MOX,95\%}\left[W/(m\cdot K)\right] = \left[1.528\sqrt{X+0.00931} - 0.1055 + 2.885\times10^{-4}\,T\right]^{-1} + 76.38\times10^{-12}\,T^3, \quad (2.61)$$

where X is the degree of fuel nonstoichiometry (X = 2 − O/M, dimensionless quantity). In a generalized form, the thermal conductivity of MOX fuel (U, Pu)O_{2-X} is estimated by formula in Ref. [100]:

at 500 K <T< T_{melt}

$$\lambda\,\left[W/(m\cdot K)\right] = \left(\frac{1}{A+BT} + CT^3\right)\cdot F(P), \quad (2.62)$$

where $A = F(x,u)\left[(m\cdot K)/W\right] = 1.528\sqrt{x+0.00931} - 0.1055 + 0.44u\,.$ (2.63)

Here u is the burnup in fractions (dimensionless quantity), B = 2.885 × 10^{-4}m/W, C = 76.38 × 10^{-12} W/(m·K^4) and function F(P) is found from the formula (P porosity in fractions):

$$F(P) = \frac{1}{0.864}\cdot\frac{1-P}{1+2P}\,. \quad (2.64)$$

Based on Eqs (2.61–2.64), the thermal conductivity of MOX fuel (U, Pu)O_{2-X} of theoretical density (P = 0) is calculated as $\lambda_{MOX,100\%} = \lambda_{MOX,95\%}\cdot 1.4907$. This approach gives, however, conservative values of $\lambda_{MOX,100\%}$, for example, 11.7 and 3.9 W/(m·K), for temperatures 25°C and 1000°C respectively, as compared with the well known experimental data in Ref. [100].

The values of the ratio $\lambda_{MOX,95\%}$ to $\lambda_{MOX,100\%}$ were found by the Brandt-Neuer relation (see Eq. (2.22)), namely:

$$\lambda_{MOX,100\%} = \lambda_{MOX,95\%} / \{1 - [(2.6 - 0.5/T) \cdot 0.05]\} \qquad (2.65)$$

The value of $\lambda_{MOX,95\%}$ is less than the thermal conductivity of UO_2 of theoretical density by about 7–10% (by the Harding estimation approximately by 5% [27]). The thermal conductivity of superstoichiometric MOX fuel $(U, Pu)O_{2+X}$ of theoretical density in the range of $773 < T < 3120 - 470y$, $0 \leq X \leq 0.12$ according to Ref .[73] is evaluated as:

$$\lambda[W/(m \cdot K)] = [0.037 + 1.67x + 2.37 \times 10^{-4} T]^{-1} + 78.9 \times 10^{-12} T^3 \qquad (2.66)$$

where y is the PuO_2 content in molar fractions.

Integral thermal conductivity in terms of W/m of MOX fuel both of 95% and theoretical density was evaluated as $\Lambda = \int_{273}^{T} \lambda(T)\, dt$ by numerical integration of Eqs (2.61, 2.65).

Thermal diffusivity of MOX fuel in terms of m^2/s is calculated as $a = \lambda / C_p \rho$.

The thermophysical properties of MOX fuel of stoichiometric composition $(U_{0.8}Pu_{0.2})O_2$ in solid state according to correlations (2.55, 2.58–2.61, 2.65) are presented in Table 2.27.

Linear expansion coefficient of MOX fuel can be evaluated by the sum of linear expansion coefficients of their components in the ratio of their molar fractions $(\alpha)_{MOX} = (\alpha)_{UO_2} 0.8 + (\alpha)_{PuO_2} 0.2$ [27]. The values of the linear expansion coefficient of UO_2 calculated by correlations (2.30, 2.31) are given in Table 2.21.

The calculated values α for stoichiometric PuO_2 (Eq. (2.51)) and MOX fuel are given in Table 2.28.

The thermophysical properties of MOX fuel of stoichiometric composition *in liquid state* are accepted in Ref. [27] to be the same as the properties of liquid uranium dioxide (see Table 2.24)

2.3.4. Uranium mononitride

Uranium nitride (UN) is the advanced nuclear fuel for fast reactors with respect to safety improvement and efficiency of reactors. Uranium mononitride is characterized by high concentration of uranium, high melting point and thermal conductivity, increased radiation resistance and good compatibility with structural materials [104, 105]. Advanced types of nitride fuels for actinide transmutation are discussed in Ref. [106]. The basic properties of uranium mononitride are presented in Table 2.29.

TABLE 2.27. THERMOPHYSICAL PROPERTIES OF MOX FUEL — STOICHIOMETRIC COMPOSITION $(U_{0.8}Pu_{0.2})O_2$ IN SOLID STATE BY CORRELATIONS (2.55, 2.58–2.61, 2.65)

Temperature		Density kg/m^3 MOX	Enthalpy [(H(T)–H(298)] kJ/kg		Heat capacity J/(kg/K)		Thermal conductivity W/(m/K)		Integral thermal conductivity W/m		Thermal diffusivity 10^6 (m^2/s)	
°C	K		PuO_2	MOX	PuO_2	MOX	MOX 95% density	MOX of theor. density	MOX 95% density	MOX of theor. density	MOX 95% density	MOX of theor. density
25	298	11074	0	0	258	240	7.82	8.91	39	45	2.95	3.36
50	323	11068	0	4	270	249	7.40	8.43	300	262	2.68	3.06
100	373	11056	7	16	287	265	6.69	7.61	581	662	2.28	2.59
150	423	11044	18	29	299	276	6.10	6.93	901	1025	2.00	2.28
200	473	11031	29	42	308	285	5.61	6.37	1194	1357	1.79	2.03
250	523	11018	41	56	315	291	5.20	5.89	1464	1663	1.62	1.84
300	573	11004	54	70	320	296	4.84	5.47	1714	1947	1.49	1.68
350	623	10990	66	84	324	300	4.53	5.11	1948	2211	1.37	1.55
400	673	10975	79	99	328	303	4.26	4.80	2168	2459	1.28	1.44
450	723	10960	92	113	330	306	4.02	4.53	2375	2692	1.20	1.35
500	773	10945	105	128	332	309	3.81	4.28	2571	2913	1.13	1.27
550	823	10929	118	143	334	311	3.62	4.07	2756	3121	1.07	1.20
600	873	10912	131	158	336	313	3.45	3.87	2933	3320	1.01	1.14
650	923	10895	144	173	337	315	3.30	3.70	3102	3509	0.96	1.08
700	973	10878	158	188	338	316	3.17	3.54	3264	3690	0.92	1.03
750	1023	10861	171	203	339	317	3.05	3.40	3419	3864	0.88	0.99
800	1073	10843	184	218	340	319	2.94	3.28	3569	4031	0.85	0.95
850	1123	10824	198	233	340	320	2.84	3.16	3714	4192	0.82	0.91
900	1173	10805	211	248	341	322	2.75	3.06	3853	4347	0.79	0.88
950	1223	10786	224	264	342	323	2.67	2.97	3989	4498	0.77	0.85
1000	1273	10767	238	279	342	324	2.60	2.88	4121	4644	0.74	0.83
1050	1323	10747	251	294	343	325	2.54	2.81	4249	4787	0.73	0.80
1100	1373	10726	264	310	343	327	2.48	2.74	4375	4925	0.71	0.78
1150	1423	10706	278	325	343	328	2.43	2.68	4497	5061	0.69	0.76
1200	1473	10685	291	341	344	330	2.39	2.63	4618	5194	0.68	0.75
1250	1523	10663	304	356	344	331	2.35	2.59	4736	5324	0.66	0.73
1300	1573	10641	318	372	344	334	2.31	2.55	4853	5453	0.65	0.72
1350	1623	10619	331	388	345	336	2.29	2.51	4968	5579	0.64	0.70
25	298	11074	0	0	258	240	7.82	8.91	39	45	2.95	3.36
1500	1773	10551	371	436	346	345	2.23	2.44	5306	5950	0.61	0.67
1550	1823	10527	384	453	346	349	2.22	2.43	5417	6072	0.60	0.66
1600	1873	10503	397	469	346	353	2.22	2.42	5529	6193	0.60	0.65
1650	1923	10479	411	486	347	358	2.22	2.42	5639	6314	0.59	0.64
1700	1973	10455	424	504	347	364	2.22	2.42	5751	6435	0.58	0.64
1750	2023	10430	437	521	348	370	2.23	2.42	5862	6556	0.58	0.63
1800	2073	10405	450	539	348	378	2.24	2.43	5974	6676	0.57	0.62
1850	2123	10379	464	558	349	386	2.26	2.45	6086	6794	0.56	0.61
1900	2173	10354	477	576	350	394	2.28	2.47	6200	6922	0.56	0.60
1950	2223	10328	490	596	351	404	2.30	2.49	6314	7046	0.55	0.60
2000	2273	10301	503	615	352	414	2.33	2.51	6430	7171	0.55	0.59
2050	2323	10275	516	636	353	425	2.36	2.54	6547	7297	0.54	0.58
2100	2373	10248	529	656	354	437	2.40	2.58	6666	7425	0.53	0.57
2150	2423	10221	543	678	356	450	2.44	2.62	6787	7558	0.53	0.57
2200	2473	10193	556	700	357	463	2.48	2.66	6910	7687	0.52	0.56
2250	2523	10166	569	722	359	478	2.53	2.71	7035	7821	0.52	0.55
2300	2573	10138	582	746	361	494	2.58	2.76	7163	7958	0.51	0.55
2350	2623	10110	710	793	363	510	2.63	2.81	7293	8097	0.51	0.54
2397	2670	10083	730	818	365	526	2.69	2.87	7418	8230	0.51	0.54
2400	2673	10081	731	819	366	528	2.69	2.87	7426	8239	0.51	0.54
2450	2723	10053	752	847	368	545	2.75	2.93	7562	8384	0.50	0.54
2500	2773	10024	774	875	371	564	2.82	3.00	7701	8532	0.50	0.53
2550	2823	9995	795	904	374	584	2.89	3.07	7843	8684	0.49	0.53
2600	2873	9965	816	934	377	603	2.96	3.14	7989	8839	0.49	0.52
2650	2923	9936	837	965	380	624	3.04	3.22	8139	8998	0.49	0.52
2729	3002	9889	870	1017	386	659	3.17	3.35	8384	9258	0.49	0.51
2750	3023	9876	879	1031	388	668	3.20	3.39	8451	9329	0.48	0.51
2768	3041	9865	887	1043	389	676	3.24	3.42	8509	9390	0.48	0.51

TABLE 2.28. LINEAR THERMAL EXPANSION COEFFICIENT OF STOICHIOMETRIC PuO_2 AND MOX FUEL

Temperature		Linear expansion coefficient 10^6/K		
		PuO_2		MOX fuel
°C	K	experimental [102]	calculated (Eq. 2.51)	
27	300	-	7.9	9.4
50	323	-	8.0	9.4
100	373	7.47	8.4	9.5
200	473	8.13	9.1	9.7
300	573	9.90	9.8	9.9
400	673	9.90	10.5	10.1
500	773	10.20	11.2	10.3
600	873	11.20	11.9	10.6
700	973	11.40	12.6	10.9
800	1073	11.20	13.3	11.2
900	1173	11.62	14.0	11.6
1000	1273	12.33	14.7	12.1
1100	1373	-	15.4	12.6
1200	1473	-	16.1	13.1
1300	1573	-	16.8	13.8
1400	1673	-	17.5	14.5
1500	1773	-	18.2	15.2

TABLE 2.29. BASIC PROPERTIES OF URANIUM MONONITRIDE AT 0.1 MPa, 298 K

Property	Value
Molecular mass, amu	252
Theoretical density ρ°, kg/m^3	14300 [107]
Melting point, K (°C)	3123 (2850 ± 30) [108]
	At nitrogen pressure $P_{N2} \geq 0.25$ MPa
Heat capacity, J/(kg·K)	190
J/(mol·K)	48 [110]
Thermal conductivity, W/(m·K)	13.0 [109]
Linear expansion coefficient, 1/K	7.52×10^{-6} [107]
Electrical resistivity, Ω·m	1.46×10^{-6} [109]

2.3.4.1 Properties of uranium mononitride depending on temperature

Melting point as a function ofvapour pressure [Pa] of nitrogen over UN at $10^{-8} \leq P_{N2} \leq 7.5 \times 10^5$ is defined by formula [107]:

$$T_{m,} (K) = 3055 \cdot P_{N2}^{0.02832}. \quad (2.67)$$

Uranium mononitride melts congruently only at high values of partial pressure of nitrogen P_{N2}, at low values of P_{N2} UN decomposes, UN(s)→U(liq) + 0.5 N_2(gas) [112].

Partialvapour pressures of nitrogen and uranium over UN are calculated by the correlations [110]:

at $1400 \leq T \leq 3170$ K lgP_{N2} (Pa) = $6.8216 + 1.882 \times 10^{-3}T - 23543.4/T$, (2.68)

at $1400 \leq T \leq 2400$ K lgP_U (Pa) = $11.9654 - 5.137 \times 10^{-4}T - 26616.1/T$. (2.69)

Total Vapour pressure above UN is evaluated by the sum of partial pressures of P_{N2} and P_U vapours, because the $P_{UN(gas)}$ value is very low. The values of vapour pressures are given in Table 2.30.

TABLE 2.30. PARTIAL PRESSURES OF NITROGEN AND URANIUM VAPOURS, TOTAL PRESSURE ABOVE UN [110]

Temperature		Partial pressure Pa		Total pressure Pa
°C	K	N_2	U	
1127	1400	4.41×10^{-8}	1.73×10^{-8}	6.14×10^{-8}
1200	1473	4.12×10^{-7}	1.39×10^{-7}	5.51×10^{-7}
1300	1573	6.60×10^{-6}	1.74×10^{-6}	8.33×10^{-6}
1400	1673	7.99×10^{-5}	1.59×10^{-5}	9.57×10^{-5}
1427	1700	1.50×10^{-4}	2.75×10^{-5}	1.78×10^{-4}
1500	1773	7.66×10^{-4}	1.11×10^{-4}	8.77×10^{-4}
1527	1800	1.36×10^{-3}	1.81×10^{-4}	1.54×10^{-3}
1600	1873	6.04×10^{-3}	6.26×10^{-4}	6.67×10^{-3}
1627	1900	1.02×10^{-2}	9.65×10^{-4}	1.12×10^{-2}
1700	1973	4.04×10^{-2}	2.9×10^{-3}	4.33×10^{-2}
1800	2073	2.34×10^{-1}	1.16×10^{-2}	2.46×10^{-1}
1900	2173	1.21×10^{0}	4.03×10^{-2}	1.25×10^{0}
2000	2273	5.57×10^{0}	1.24×10^{-1}	5.69×10^{0}
2027	2300	8.29×10^{0}	1.64×10^{-1}	8.45×10^{0}
2100	2373	2.35×10	3.42×10^{-1}	2.38×10
2127	2400	3.41×10	4.43×10^{-1}	3.46×10

Theoretical density of UN at 298 ≤ T ≤ 2523 K [107],

$\rho\ (kg/m^3) = 14420 - 0.2779T - 4.897 \times 10^{-5}T^2$. (2.70)

Parameter of crystal lattice of UN at 298 ≤ T≤ 2523 K [107],

a (A°) = 4.879 + 3.264 × 10–5T + 6.889 × 10–9T2. (2.71)

Heat capacity of UN at 298 ≤ T≤ 2523 K [110],

$$C\ [kJ/(mol \cdot K)] = 0.2029(\theta/T)^2 \frac{\exp(\theta/T)}{[\exp(\theta/T)-1]^2} + 3.766 \times 10^{-5}T + \frac{1.048 \times 10^9}{T^2}\exp\left(\frac{-18081}{T}\right), \quad (2.72)$$

where θ = 365.7 K is the Einstein temperature [109].

Thermal conductivity of UN is estimated from the empirical correlation obtained by approximation of the data in Refs [113, 114] with an accuracy of ± 3% at 273 ≤ T ≤ 1300 K and ± 6% at 1700 ≤ T≤ 2300 K,

$\lambda\ [W/(m \cdot K)] = 1.41 \times T^{0.39}$. (2.73)

Thermal conductivity of UN in view of porosity is calculated by formula [109]:

$\lambda\ [W/(m \cdot K)] = 1.864 \cdot e^{-2.14\ P}\ T^{0.361}$, (2.74)

where P is the porosity in volume fractions. The thermal conductivity of UN decreases with increasing porosity (Table 2.31).

TABLE 2.31. THERMAL CONDUCTIVITY OF UN DEPENDING ON POROSITY [109]

Temperature K	Porosity in volume fractions					
	0.01	0.02	0.04	0.06	0.08	0.1
	Thermal conductivity W/(m·K)					
298	14.3	14.0	13.4	12.8	12.3	11.8
273	15.5	13.5	13.0	12.4	11.9	11.4
573	18.1	17.7	16.9	16.2	15.6	14.9
873	21.0	20.6	19.7	18.9	18.1	17.3
1273	24.1	23.6	22.6	21.7	20.7	19.3
1773	27.2	26.9	25.5	24.4	23.4	22.4
2300	29.8	29.2	28.0	26.8	25.7	24.6

Integral thermal conductivity $\Lambda(W/m) = \int_{293}^{T} \lambda(T)\,dt$ of uranium nitride was evaluated by numerical integration of correlation (2.73) using the MATHCAD program.

Thermal diffusivity of UN is found as a $(m^2/s) = \lambda/C_p \times \rho$.

Linear expansion coefficient of UN is calculated by the correlation:

at $298 \le T \le 2523$ K [107] α (1/K) = $7.096 \times 10^{-6} + 1.409 \times 10^{-9}$ T. (2.75)

Thermophysical properties of uranium mononitride estimated by correlations (2.70–2.73, 2.75) are presented in Table 2.32.

TABLE 2.32. THERMOPHYSICAL PROPERTIES OF URANIUM MONONITRIDE BY CORRELATIONS (2.70–2.73, 2.75)

Temperature		Density kg/m^3	Crystal lattice parameter nm	Heat capacity J/(kg·K)	Thermal conductivity W/(mK)	Integral thermal conductivity W/m	Thermal diffusivity 10^6(m^2/s)	Linear expansion coefficient 10^6/K
°C	K							
25	298	14330	0.489	190	13.0	64.8	4.78	7.52
100	373	14310	0.489	201	14.2	1806	4.94	7.62
200	473	14278	0.490	211	15.6	2831	5.17	7.76
300	573	14245	0.490	218	16.8	4450	5.40	7.90
400	673	14211	0.491	223	17.9	6184	5.64	8.04
500	773	14176	0.491	228	18.9	8021	5.84	8.19
577	850	14148	0.491	232	19.6	9501	5.96	8.29
600	873	14140	0.492	233	19.8	9954	6.00	8.33
700	973	14103	0.492	237	20.6	11975	6.17	8.47
727	1000	14093	0.492	238	20.9	12536	6.22	8.51
800	1073	14065	0.493	241	21.4	14079	6.32	8.61
900	1173	14027	0.493	246	22.2	16261	6.43	8.75
1000	1273	13987	0.494	250	22.9	18517	6.55	8.89
1100	1373	13946	0.494	255	23.6	20843	6.64	9.03
1200	1473	13904	0.495	260	24.3	23236	6.72	9.17
1300	1573	13862	0.495	266	24.9	25693	6.76	9.31
1400	1673	13818	0.496	273	25.5	28213	6.76	9.45
1427	1700	13806	0.496	275	25.7	28902	6.76	9.49
1500	1773	13773	0.496	281	26.1	30790	6.74	9.59
1527	1800	13761	0.497	284	26.2	31946	6.71	9.63
1600	1873	13728	0.497	292	26.6	33246	6.65	9.74
1627	1900	13715	0.497	295	26.8	34147	6.62	9.77
1700	1973	13681	0.498	305	27.2	36117	6.51	9.86
1800	2073	13633	0.498	320	27.7	38862	6.35	10.02
1900	2173	13585	0.499	338	28.2	41660	6.15	1.016
2000	2273	13535	0.500	359	28.7	44507	5.91	10.30
2027	2300	13522	0.500	365	28.9	45285	5.85	10.34

Electrical resistivity of UN is estimated at 298 ≤ T ≤ 1600 K by the formula in Ref. [109]:

$$\rho_e \times 10^{-8}\ (\Omega\cdot m) = 71.49\ e^{2.14\ P}\ T^{0.125}, \qquad (2.76)$$

where P is the porosity in volume fractions. The values of electrical resistivity of UN of theoretical density are given in Table 2.33.

Mechanical properties of uranium mononitride are given in Table 2.34. They were calculated at UN density in the range of 70 ≤ ρ ≤ 100% of the theoretical density and the temperature of 298 ≤ T ≤ 1473 K [111].

Modulus of elasticity (E):

$$E\ (MPa) = 0.258\rho^{3.002}(1 - 2.375 \times 10^{-5}T), \qquad (2.77)$$

Shear modulus (G):

$$G\ (MPa) = 1.44 \times 10^{-2}\rho^{3.446}(1 - 2.375 \times 10^{-5}T), \qquad (2.78)$$

2.3.5. Uranium carbide

Uranium carbide (UC) as a nuclear fuel for fast reactors has an advantage as compared with UO_2 owing to a higher density of fissile material (1.34 times) and thermal conductivity (2.6 times). The basic properties of UC are presented in Table 2.35.

TABLE 2.33. ELECTRICAL RESISTIVITY OF UN OF THEORETICAL DENSITY $_e$ (Ω·m) [109]

Temperature		Electrical resistivity
°C	K	10^6 Ωm
25	298	1.46
27	300	1.46
100	373	1.50
200	473	1.54
300	573	1.58
400	673	1.61
600	873	1.67
800	1073	1.71
1000	1273	1.75
1200	1473	1.78
1300	1573	1.79
1327	1600	1.80

TABLE 2.34. MECHANICAL PROPERTIES OF URANIUM MONONITRIDE AT DENSITY OF % OF THE THEORETICAL DENSITY

Temp. K	Density kg/m^3	Modulus of elasticity GPa				Shear modulus GPa			
		70%	80%	90%	100%	70%	80%	90%	100%
298	14413	267.98	400.12	569.84	781.84	896.51	1420.4	2131.4	3064.4
300	14412	267.94	400.06	569.75	781.71	896.34	1420.1	2131.0	3063.9
320	14407	267.49	399.40	568.81	780.42	894.71	1417.5	2127.1	3058.3
373	14392	266.31	397.64	566.30	776.98	890.35	1410.6	2116.8	3043.4
473	14362	264.06	394.27	561.50	770.40	882.01	1397.4	2097.0	3014.8
573	14332	261.76	390.84	556.62	763.70	873.53	1384.0	2076.8	2985.9
673	14301	259.43	387.35	551.66	756.89	865.0	1370.3	2056.3	2956.4
773	14269	257.06	383.81	546.61	749.97	856.14	1356.4	2035.4	2926.4
873	14236	254.65	380.22	541.49	742.95	847.24	1342.3	2014.3	2896.0
973	14201	252.21	376.57	536.30	735.82	838.22	1328.0	1992.8	2865.2
1000	14192	251.54	375.58	534.88	733.88	835.76	1324.1	1987.0	2856.8
1073	14166	249.73	372.87	531.03	728.59	829.07	1313.5	1971.1	2833.9
1173	14130	247.22	369.12	525.69	721.27	819.81	1298.8	1949.1	2802.2
1273	14093	244.68	365.33	520.29	713.85	810.43	1284.0	1926.8	2770.2
1373	14055	242.10	361.49	514.82	706.34	800.95	1269.0	1904.2	2737.8
1473	14016	239.50	357.60	509.28	698.75	791.36	1253.8	1881.4	2705.0

TABLE 2.35. BASIC PROPERTIES OF URANIUM CARBIDE AT 0.1 MPa, 298 K

Property	Value
Molecular mass, amu	250
Theoretical density (ρ_0), kg/m^3	13630 [116]
Melting point, K (°C)	2638 ± 165 (2365 ± 165) [117] 2780 ± 25 [35]
Boiling point, K	4691 [118] 4866 [97]
Heat capacity, J/(kg·K) J/(mol·K)	200 50 [120]
Heat of fusion, kJ/kg kJ/mol	195.6 48.9 [119]
Heat of vapourization, kJ/kg kJ/mol	~2120 ~530 at T_b [120]
Thermal conductivity, W/(m·K)	25.3 [82]
Linear expansion coefficient, 1/K	10.1×10^{-6} [115]
Electrical resistivity, Ω·m	72.7×10^{-8} [115]

The crystal lattice of uranium carbide is similar to that of NaCl (face-centered cubic). The excess of uranium over superstoichiometric quantity results in free metallic uranium at crystal boundaries. As a consequence, the fuel properties may be deteriorated due to carbonization of fuel element cladding [35].

2.3.5.1. Properties of uranium carbide depending on temperature

Density of UC is defined by the following correlation:

$$\rho(T)\ (kg/m^3) = 13630\ (1 - 3.117 \times 10^{-5} T - 3.51 \times 10^{-9} T^2), \qquad (2.79)$$

where T is temperature, K. This correlation has been derived based on the experimental data in Refs [115, 116] that were obtained by measurement of linear expansion coefficient in the temperature range from 0 to 2800°C.

The analysis of data in Refs [121, 122] results in the correlation, which gives more severe decrease of UC density with temperature:

$$\rho(T)\ (kg/m^3) = 13500\ (1 - 2.13 \times 10^{-5} T - 2.04 \times 10^{-8} T^2), \qquad (2.80)$$

Values of UC *heat capacity* have been obtained by the differentiation of function $f(T) = H_0 - H_{295}$ at $298 \le T \le 2838$ K presented in Ref. [120].

$$C_p\ (J/(kg\ K)) = 0.2397 - 5.068 \times 10^{-6}\ T + 1.7604 \times 10^{-8}\ T^2 - 3488.1/T^2. \qquad (2.81)$$

Thermal conductivity of UC depends on the composition, porosity (P), temperature, manufacturing process, and other factors [37, 43, 116]. In some cases, the data in different references have two-fold disagreement. The effect of porosity is described by the correlation:

$$\lambda(t, P) = \lambda(t)\ [(1 - P)/(1 + P)], \qquad (2.82)$$

where P is the porosity in volume fractions.

With zero porosity in the temperature range from 50 to 2300°C, the thermal conductivity is estimated by the empirical correlations [37]:

for 50 – 700°C $\lambda\ [W/(m\ K)] = 21.7 - 3.04 \times 10^{-3}\ t + 3.61 \times 10^{-6}\ t^2$. (2.83)

for 700 — 2300°C $\lambda\ [W/(m\ K)] = 20.2 + 1.48 \times 10^{-3}\ t$. (2.84)

Here, t (°C).

Integral thermal conductivity $\Lambda(t)\,(W/m) = \int_{20}^{t} \lambda(t)dt$ of uranium carbide is evaluated by numerical integration of Eqs (2.83, 2.84) using the MATHCAD program.

Thermal diffusivity $a = \lambda/C_p\,\rho$, m^2/s.

Linear expansion coefficient of UC is calculated according to Ref. [115] in the range from 0 to 2000°Cwith an uncertainty of ±15% by the correlation:

$$\alpha\ (1/°C) = 1.007 \times 10^{-5} + 1.17 \times 10^{-9}t. \quad (2.85)$$

Electrical resistivity of UC is defined with an uncertainty of ± 15% according to Ref. [116]:

$$\rho_e \times 10^8\ (\Omega\cdot m) = 69.3 + 0.138\ t - 2.56 \times 10^{-5}\ t^2, \quad (2.86)$$

where t (°C).

The data in Ref. [137] apparently relating to a higher purity UC of theoretical density are estimated by formula:

$$\rho_e\cdot 10^8\ (\Omega\cdot m) = 32.9 + 0.159\ T - 2.68 \times 10^{-5}\ T^2, \quad (2.87)$$

where T (K).

Thermophysical properties of solid UC estimated by Eqs (2.79–2.87) are presented in Table 2.36.

In Ref. [128] the data on UC eVapouration are given; on the basis of these data vapour *pressure above solid UC* at $1600 \le T \le 2780$ K is estimated by following correlation:

$$\lg P\ (MPa) = 7.824 - 35700/T \quad (2.88)$$

2.3.5.2. Properties of liquid uranium carbide depending on temperature

Density of liquid UC at $T_{melt} < T < T_{boil}$ is evaluated according to Refs [115, 119]:

$$\rho\ (kg/m^3) = (12000 - 6.25 \times 10^{-4}\ T) \pm 200, \quad (2.89)$$

where T (K).

Vapour pressure above liquid UC above melting point at $2780 \le T \le 6270$ K is described by correlation [118] (see Table 2.38):

$$\lg P\ (MPa) = 8.622 - 32860/T - 0.715 \lg T \quad (2.90)$$

The critical constants of uranium carbide have a slight scattering with the exception of density (see Table 2.39).

TABLE 2.36. THERMOPHYSICAL PROPERTIES OF SOLID UC

Temperature		Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Integral thermal conductivity W/m	Thermal diffusivity 10^6(m^2/s)	Linear expansion coefficient 10^6/K	Electrical resistivity 10^8(Ω·m)
°C	K							
25	298	13500	200	25.3	127	9.34	10.1	72.7
100	373	13460	215	24.5	1991	8.44	10.2	82.8
200	473	13420	226	23.6	4392	7.81	10.3	95.9
300	573	13370	232	23.1	6728	7.46	10.4	108.4
400	673	13320	237	23.0	9030	7.29	10.5	120.4
500	773	13270	240	23.1	11332	7.25	10.7	131.9
600	873	13220	244	23.6	13666	7.31	10.8	142.9
700	973	13170	248	24.4	16065	7.48	10. 9	153.4
800	1073	13120	252	25.6	18560	7.74	11.0	163.3
900	1173	13070	255	27.0	21186	8.09	11.1	172.8
1000	1273	13010	260	28.8	23974	8.53	11.2	181.7
1100	1373	12960	264	30.9	26957	9.03	11.4	190.1
1200	1473	12900	269	33.4	30167	9.62	11.5	198.0
1300	1573	12840	274	36.1	33638	10.27	11.6	205.4
1400	1673	12790	279	39.2	37402	10.98	11.7	212.3
1500	1773	12730	285	42.6	41491	11.75	11.8	218.7
1600	1873	12670	291	46.4	45936	12.58	11.9	224.6
1700	1973	12610	297	50.4	50775	13.46	12.1	229.9
1800	2073	12550	304	54.8	56036	14.38	12.2	234.8
1900	2173	12490	311	59.6	61752	15.34	12.3	239.1
2000	2273	12420	318	64.6	67957	16.33	12.4	242.9
2100	2373	12350	326	70.0	74683	17.36	12.5	246.2
2200	2473	12290	334	75. 7	81963	18.42	12.6	249.0
2300	2573	12220	343	81.7	89828	19.51	12.8	251.3

TABLE 2.37. VAPOUR PRESSURE ABOVE SOLID UC [128]

Temperature		Pressure MPa
°C	K	
1600	1973	4.0×10^{-12}
1700	1973	3.8×10^{-11}
1800	2073	6.8×10^{-11}
2000	2273	2.9×10^{-10}
2300	2573	6.8×10^{-7}
2507	2780	7.5×10^{-6}

TABLE 2.38. VAPOUR PRESSURE OVER UC ABOVE THE MELTING POINT [118]

Temperature		Pressure MPa
°C	K	
2507	2780	2.2×10^{-6}
2600	2873	5.1×10^{-6}
2700	2973	1.2×10^{-5}
3227	3500	5.0×10^{-4}
4000	4273	2.2×10^{-2}
4418	4691	9.8×10^{-2}
5727	6000	2.8
6000	6273	4.6

TABLE 2.39. CRITICAL CONSTANTS OF URANIUM CARBIDE

Author, year Theory	Critical constants			
	T_c K	P_c MPa	$(V_m)_c$ cm^3/mol	ρ_c g/cm^3
Ohse, 1980 [118] The significant structure theory	9300	180	219	1.14
Giggli, 1981 [119] The significant structure theory	8890	158.4	190	1.32
Joseph, 1989 [129] Principle of corresponding states	9777	198	112	2.23

REFERENCES TO SECTION 2

1. Rahn F.J., Adamantiades A.G., Kenton J.E., Braun C. A Guide to Nuclear Power Technology. – N.Y., John Wiley & Sons. 1984.
2. Walter A.E., Reynolds A.B. Fast Breeder Reactors. – N.Y., Pergamon Press, 1981.
3. Abagian L.P. et al. Group Constants for Designing of Reactors and Shielding/Reference book. – M.: Energoizdat, 1981 (Russian).
4. Ursu I. Fizica si Tehnologia Materialelar Nucleare.- Bucuresti: Publ. Acad. Romania. 1982.
5. Gerasimov V.V., Monakhov A.S. Materials for Nuclear Engineering/2nd revised and augmented edition. –M.: Energoatomizdat, 1982 (Russian).
6. Materials for Nuclear Engineering/Ed. by A.B. McIntosh, T.J. Heal.: Temple Press Ltd. 1960.
7. “Plutonium, 1960”/Proc. “The Metal Plutonium” Conf., Univ. Chicago Press. 1960. – London: Cleaver-Hume Press Ltd. 1961.
8. Plutonium/In “Rare Metals Handbook”, Ed. by C.A. Hampel, 2-ed edition. – London: Reinhold Publ. Co Ltd. 1965.
9. Thermophysical Properties of Materials for Water Cooled Reactors/Report IAEA-TECDOC-949.–Vienna: IAEA, 1997.

10. Uranium.– http://www.fact-index.com./u/ur/uranium.html
11. Emelianov V.S., Evtyukhin A.I. Metallurgy of Nuclear Fuel. Properties and Basics of Technology of Uranium, Thorium and Plutonium/2nd rev. and enl. ed.– M.: Atomizdat, 1968 (Russian).
12. General Information on Element Plutonium.– http://www.efunda.com/materials/elements/element-info.cfm?Element_ID=Pu
13. Thorium. – http://www.fact-index.com./t/th/thorium.html
14. Thorium Physical Properties. – http://www.qivx.com/ispt/elements/ptw_090.php
15. Chirkin V.S. Thermophysical Properties of Materials for Nuclear Engineering.– M.: Atomizdat, 1968 (Russian).
16. Golovnin I.S. Properties of Plutonium Dioxide as Nuclear Fuel. – *Atomnaia Energiya*, 2000, Vol. 89, No. 2, PP. 117–128 (Russian).
17. Zaimovsky A.S., Kalashnikov V.V., Golovnin I.S. Fuel Elements of Nuclear Reactors. – M.: Atomizdat, 1966 (Russian).
18. Kotelnikov R.B. et al. High-Temperature Nuclear Fuel/2nd ed.– M.: Atomizdat, 1978 (Russian).
19. Juan J., et al. A Review of MOX and UO_2 Fuels. –*Journal of Nuclear Materials*, 2001, Vol. 299, No. 3, PP. 181–198.
20. Ho S., Radford K. Structural Chemistry of Solid in the UO_2-Gd_2O_3 System. – *Nuclear Technology*, 1986, Vol. 73, No 3, PP. 350–360.
20a. Une K., Oguma M. Thermodynamic Properties of Urania-Gadolinia Solid Solution in 700–1000 ^{o}C. –*Journal of Nuclear Materials*, 1982, Vol. 110, PP. 215–222.
21. Loeven E.P., McDonald P.E., Hohorst J. Recommended Thorium Materials Properties to FRACON-3. *Proc. Int. Top. Meet. Top Fuel-2000*, Apr. 10–13, ANS, USA.
22. Samsonov G.V., Vinnitsky I.M. High-Melting Compounds/Reference book, 2nd ed.– M.: Metallurgiya, 1976 (Russian).
23. Hayes S.L. Material Property Correlations for Uranium Mononitride. IV. Thermodynamic Properties. – *Journal of Nuclear Materials*, 1990, Vol. 171, No. 2–3, PP. 300–318.
24. Hayes S.L. Material Property Correlations for Uranium Mononitride. III. Transport properties. – *Journal of Nuclear Materials*, 1990, Vol. 171, No. 2–3, PP. 289–299.
25. Plutonium: Compound Data [Plutonium Nitride]. – http://www.webelements.com/elements/text/Pu
26. Frost B.R.T. Nuclear Fuel Elements.– Oxford: Pergamon Press, 1982.
27. Thermophysical Properties of Materials for Water Cooled Reactors/IAEA-TECDOC-949.– Vienna: IAEA, 1997.
28. Chirkin V.S. Thermophysical Properties of Materials for Nuclear Power Engineering/Reference book. – M.: Atomizdat. 1968 (Russian).
29. Thermodynamic Properties of Inorganic Substances/Handbook. Ed. by A.P. Zefirov. – M.: Atomizdat, 1965 (Russian).
30. Rare Metals Handbook/Ed. by C.A. Hampel. 2-ed. – London: Reinhold Publ. Co Ltd., 1965.
31. Thermodynamic Properties of Individual Substances/Ed. by V.P. Glushko, L.V. Gurvich et al. 3rd rev. and enl. ed. –M.: Nauka, 1982, Vol. IV, Book 2 (Russian).
32. Physical Quantities. Reference book/A.P. Babichev, N.A. Babushkin, A.M. Bratkovsky, et al.; Ed. by I.S. Grigoriev, E.Z. Meilikhov. – M.: Energoatomizdat, 1991 (Russian).
33. Physical Encyclopedia ed. by A.M. Prokhorov. — M.: Bolshaia Rossiiskaia Entsiklopedia Publ., 1998. (Uranium — Vol.5, P.236; Thorium — Vol.5, P.138; Plutonium — Vol.3, P.640) (Russian).

34. Zaimovsky A.S., Kalashnikov V.V., Golovnin I.S. Fuel Elements of Nuclear Reactors. – M.: Atomizdat, 1966 (Russian).
35. Frost B.R.T. Nuclear Fuel Elements.– Oxford: Pergamon Press, 1982.
36. Zinoviev V.E. Thermophysical Properties of Metals at High Temperatures/Reference edition. – M.: Metallurgiya. 1989 (Russian).
37. Ursu I. Fizica si Tehnologia Materialelar Nucleare. – Bucuresti: Publ. Acad. Romania. 1982.
38. Materials for Nuclear Engineering/Ed. by A.B. McIntosh, T.J. Heal. –London: Temple Press Ltd. 1960.
39. Söderlind P. Ambient Pressure Phase Diagram of Plutonium: a Unified Theory for α-Pu and δ-Pu.. –*Europhysics. Letters*., 2001, Vol. 55, No 4, P. 525.
40. Golashvili T.V., Chechev V.P., Lbov A.A. Handbook of Nuclides.– M.: CNIIatominform, 1995 (Russian).
41. Fink J.K., Petri M.C. Thermophysical Properties of Uranium Dioxide/Report ANL/Re-97/2.-Argonne: Argonne National Laboratory, 1997.
42. Washington A.B.G. Preferred Values for the Thermal Conductivity of Sintered Ceramic Fuel for Fast Reactor Use/UKAEA Authority TRG-Report-2236 (D), 1973 (Cit. by [44]).
43. Oggianu S.M. Kazimi M.S. A Review of Properties of Advanced Nuclear Fuels/MTI-NFC-TR-021. – Cambridge, USA, 2000. – http://web.mit.edu ned/www.resources/reports NFC021.pdf (85 PP.).
44. Uranium. – http://www.fact-index.com./u/ur/uranium.html
45. Melting and Boiling Temperatures. – http://www.physik.tu-muenchen.de/~gammel/matpack/html/Nuclear/Elements/meltboil.htm
46. Uranium. Thermal Properties. – http://webelememnts.com/ webelements/elements/text/u/heat.html
47. Uranium. – http://www.qivx.com/ispt/elements/ptw-092php
48. Uranium/The Online Materials Database. – http://www.matweb.com/
49. Ofte D. Viscosities of the Liquid Uranium, Gold and Lead.– *Journal of Nuclear Materials*, 1967, Vol. 22, P. 28.
50. Shpilrain E.E., Fomin V.A., Kachalov V.V. Density and Surface Tension of Liquid Uranium.– *Teplofizika Vysokikh Temperatur*, 1988, Vol. 26, No. 5, PP. 892–900 (Russian).
51. Postovalov V.G., Romanov E.P. et al. Theory of Transfer in Liquid Metals. Calculation of Dynamic Viscosity.– *Teplofizika Vysokikh Temperatur*, 2003, Vol. 41, No. 6, PP. 860–869 (Russian).
52. Mulford R.N.R., Sheldon R.I. Density and Capacity of Liquid Uranium at High Temperatures.– *Journal of Nuclear Materials*, 1998, Vol. 154, PP. 268–275.
53. Thermodynamics of Nuclear Materials/Coll. Papers, Vienna, IAEA, 1962.
54. Plutonium/In “Rare Metals Handbook”, Ed. by C.A. Hampel 2-ed, Reinhold Publ. Co Ltd, London, 1965.
55. Sandenaw T.A., et al. The Heat Capacity of Plutonium Metal Below 420 K/In “Plutonium, 1960” Cleaver-Hume Press Ltd, London, 1960. Proc. “The Metal Plutonium” Conf., Univ. Chicago Press, 1961.
56. General Information on Element Plutonium. – http://www.efunda.com/ materials/elements/element-info.cfm?Element_ID=Pu
57. Plutonium — htpp://encyclopedia/thefreedictionary.com.
58. Heat Transfer/Phase Change Models. – http://www.lanl.gov/telluride/workshop=2003/Presentations/HeatTransfer.pdf (8 PP.).

59. Plutonium/The Online Materials Database. – http://www.matweb.com/
60. Cavalier G./In book: The Physical Chemistry of Metallic Solutions and Intermetallic Compounds.–London: Her Majesty's Office, 1959, Vol. 2, 4 D, P. 2.
61. Thorium.– http://www.brainyencyclopedia.com/encyclopedia/t/th/thorium.html
62. Thorium Physical Properties.– http://www.qivx.com/ispt/elements/ptw_090.php
63. Thorium. – http://www.fact-index.com./t/th/thorium.html
64. Thorium/The Online Materials Database. – http://www.matweb.com/
65. Enthalpy of Fusion of Uranium Dioxide. Recommendation. – http://www.insc.anl.gov/matprop/uo2/hfusuo2.pdf (3 PP.)
66. Enthalpy and Heat Capacity of Solid Uranium Dioxide. – http://www.insc.anl.gov/matprop/uo2/ent-hc/liquid/hcpluo2.pdf (28 PP.).
67. Fink J.K. Thermophysical Properties of Uranium Dioxide. – *Journal of Nuclear Materials*, 2000, Vol. 279, No. 1, PP. 1–18.
68. Breitung W., Reil K.O. Vapor Pressure Measurements on Liquid Uranium Oxide and (U, Pu) Mixed Oxide. – *Nuclear Science and Engineering*, 1989, Vol. 101, No. 1, PP. 26–40.
69. Meek T., Hu M., Haire M.J. Semiconductive Properties of Uranium Oxides/*Proc. of Symp. On Waste Management-2001*, USA, Tuscon, Arizona, Febr. 25–March 1, 2001. – http://web.ead.anl.gov/uranium/pdf/WM01Semicond.pdf
70. Martin D.G. The Thermal Expansion of Solid UO_2 and Mixed Oxides — A Review and Recommendations. – *Journal of Nuclear Materials*, 1988, Vol. 152, PP. 9–101.
71. Thermal Conductivity and Thermal Diffusivity of Solid UO_2. – http://www.insc.anl.gov/matprop/uo2/thcsuo2.pdf (30 PP.)
72. Brandt R., Neuer G. Thermal Conductivity and Thermal Radiation Properties of UO_2. – *Journal of Non-Equilibrium Thermodynamics*, 1970, Vol. 1, PP. 3–23.
73. Martin D.G. A Re-appraisal of the Thermal Conductivity of UO2 and Mixed (U, Pu) Oxide Fuels (Review Paper). – *Journal of Nuclear Materials*, 1982, Vol. 110, PP. 73–94.
74. Lanning D.D., Beyer C.E. Revised UO2. Thermal Conductivity for Frapcon-3 NRC fuel performance codes. – *Transactions of. ANS*, 2002, Vol. 86, PP. 285–286.
75. Ackerman R.J., Rauh E.G., Rand M.H. A Re-determination and Re-assessment of the Thermodynamics of Sublimation of Uranium Dioxide/*Proc. of Int. Symp. on Thermodynamics of Nuclear Materials*. 1979. –Vienna: IAEA, 1980, Vol. 1, PP. 11–27.
76. Breitung W., Reil K.O. The Density and Compressibility of Liquid (U, Pu)-mixed Oxide. – *Nuclear Science and Engineering*, 1990, Vol. 105, No. 3, PP. 205–217.
77. Enthalpy and Heat Capacity of Liquid UO_2. – http://www.insc.anl.gov/matprop/uo2/ent-hc/liquid/hcpluo2.pdf (28 PP.).
78. Kim C.S. et al. Measurement of Thermal Diffusivity of Molten UO_2/*Proc. of 7th Symp. on Thermophysical Properties*. Part A., Cezairliyan. –New York, ASME, 1977, PP. 336–343.
79. Otter C., Damien D. Measure de la Diffusivite Thermique of UO_2 Fondu. – *High Temperatures-High Pressures*, 1984, Vol. 16, No. 1, PP. 1–6.
80. Tasman H.A. et al. Measurement of Thermal Conductivity of Liquid UO_2.– *High Temperatures-High Pressures*, 1983, Vol. 15, No. 4, PP. 419–431.
81. Thermal Conductivity and Diffusivity of Liquid UO_2. – http://www.insc.anl.gov/matprop/uo2/cond liquid/wkliqm.php
82. Woodley R.E. The Viscosity of Molten Uranium Dioxide. – *Journal of Nuclear Materials*, 1974, Vol. 50, No. 1, PP. 103–106.

83. Schins H. On the Surface Tension of Liquid UO2 – *Journal of Nuclear Materials*, 1978, Vol.78, PP.215–216.
84. Fischer E.A. A New Evaluation of the Urania Equation of State Based on Recent Vapour Pressure Measurements. – *Nuclear Science and Engineering*, 1989, Vol. 10, No. 2, PP. 97–116.
85. Azad A.A., Gausan S. An Approach for the Prediction of Temperature Dependence of Sonic Velocity Application to Liquid Alkali Metals and Molten UO_2. – *Journal of Nuclear Materials*, 1986, Vol. 139, PP. 91–96.
86. Azad A.A. Refinement in the Ultrasonic Velocity Data and Estimation of the Critical Parameters for Molten Uranium Dioxide. – *Journal of Nuclear Materials*, 2005, Vol. 341, No 1, PP. 53–61.
87. Sladkov I.B. Estimation of Critical Temperature Using the Guldberg Generalized Rule. – *Zhurnal Fizicheskoi Khimii*, 1984, Vol. 58, No. 8, PP. 2057–2059 (Russian).
88. Dharmadurai G. On Estimation of Critical Temperatures of Fast Reactor Fuels. – *Nuclear Engineering and Design*, 1982, Vol. 73, No. 3, PP. 287–291.
89. Chawla T.C. et al. Thermophysical Properties of Mixed Oxide Fuel and Stainless Steel Type 316 for Use in Transition Phase Analysis. – *Nuclear Engineering and Design*, 1981, Vol. 67, No.1, PP. 57–54.
90. Carabajo J.G. et al. A Review of the Therphysical Properties of MOX and UO_2 Fuels. – *Journal of Nuclear Materials*, 2001, Vol. 299, No. 3, PP. 181–198.
91. Kapil S.K. Evaluation of the Thermodynamic Critical Constants for Uranium Dioxide. – *Journal of Nuclear Materials*, 1976, Vol. 60, No. 2, PP. 158–160.
92. Browning P. et al. The Equation of State of Oxide Nuclear Fuels: the Thermodynamic Properties of Urania and Plutonia. – *Revue Internationale des Hautes Temperatures et des Refrectaires*, 1978, Vol. 15, No. 4, PP. 333–346.
93. Mistura L.A Perturbed Hard Core Equation of State for Oxide Nuclear Fuels. – *Journal of Nuclear Materials*, 1985, Vol. 135, No. 1, PP. 94–104.
94. Iosilevski I., Hyland R.G., Ronchi C, Yakub E. Equation of State of UO_2.– *International Journal of Thermophysics*, 2001, Vol. 22, No. 4, PP. 1253–1264.
95. Iosilevski I., Gryaznov V. Uranium Critical Point Problem. – *Journal of Nuclear Materials*, 2005, vol. 344, No 1–3, PP. 30–35.
96. Iosilevski I., Hyland R.G., Ronchi C, Yakub E., in: *The Proc. of the 14-th Symp. on Thermophysical Properties*, Boulder, CO, 25–30 June 2000, P.1. (Cit. by 56a).
97. Ronchi C. Equation of State of Uranium Dioxide. – Springer Verlag. 2004. 356 PP. (ISBN 3-540-22122-0).
98. Solidus/Liquidus of Uranium-Plutonium Dioxide. — http://www.insc.anl.gov/matprop/MOX/soliupo2.pdf
99. Morita K., Fischer E.A., Thurnay K. Thermodynamic Properties and Equations of State for Fast Reactor Safety Analysis. Part II. Properties of Fast Reactor Materials. – *Nuclear Engineering and Design*, 1981, Vol. 183, PP. 193–211.
100. Philipponneau Y. Thermal Conductivity of (U, Pu)O2–x Mixed Oxide Fuel. – *Journal of Nuclear Materials*, 1992, Vol. 188, PP. 194–197.
101. Maschek W. et al. Safety Aspects of Oxide Fuels for Transmutation and Utilization in Accelerator Driven Systems. – *Journal of Nuclear Materials*, 2003, Vol. 320, No. 3, PP. 147–155.
102. Golovnin I.S. Properties of Plutonium Dioxide as a Nuclear Fuel. – *Atomnaia Energiia*, 2000, Vol. 89, No. 2, PP. 117–128 (Rus).
103. "Plutonium, 1960" Cleaver-Hume Press Ltd, London, 1960. *Proc.* "The Metal Plutonium" Conf., Univ. Chicago Press, 1961, P. 299.

104. Rogozkin B.D., Stepennova N.M., Proshkin A.A. Moninitride Fuel for Fast Reactors. – *Atomnaia Energiia*, 2003, Vol. 95, No. 3, PP. 208–221 (Russian).
105. Rogozkin B.D. et al. Thermochemical Stability, Radiation Tests, Manufacture and Regeneration of Mononitride Fuel. – *Atomnaia Energiia*, 2003, Vol. 95, No. 6, PP. 428–438 (Russian).
106. Thetford R., Mignanelli M. The Chemistry and Physics of Modeling Nitride Fuels for Transmutation. – *Journal of Nuclear Materials*, 2003, Vol. 320,PP. 44–53.
107. Hayes S.L. Material Property Correlations for Uranium Mononitride. I. Physical Properties. – *Journal of Nuclear Materials*, 1990, Vol. 171, No. 2–3, PP. 262–270.
108. Olson W.M., Mulford R.N.R. The Decomposition Pressure and Melting Point of Uranium Mononitride. – *The Journal of Physical Chemistry*, 1963, Vol. 67, No. 4, PP. 952–954.
109. Hayes S.L. Material Property Correlations for Uranium Mononitride. III. Transport Properties. – *Journal of Nuclear Materials*, 1990, Vol. 171, No. 2–3, PP. 289–299.
110. Hayes S.L. Material Property Correlations for Uranium Mononitride. IV. Thermodynamic Properties. – *Journal of Nuclear Materials*, 1990, Vol. 171, No. 2–3, PP. 300–318.
111. Hayes S.L. Material Property Correlations for Uranium Mononitride. II. Mechanical Properties. – *Journal of Nuclear Materials*, 1990, Vol. 171, No. 2–3, PP. 271–288.
112. Prins G., Gordfunke E.H.P. Investigations on Uranium Carbonitrides. III. Nitrogen Vapour Pressure and Thermodynamic Properties. – *Journal of Nuclear Materials*, 1980, Vol. 89, No. 2–3, PP. 221–228.
113. Ross S.B., El-Genk M.S. Thermal Conductivity Correlation for Uranium Nitride Fuel between 10 and 1923 K. – *Journal of Nuclear Materials*, 1998, Vol. 151, No. 3, PP. 318–326.
114. Takahashi Y. et al. Uranium Mononitride: Heat Capacity and Thermal Conductivity from 298 to 1000 K. – *Journal of Nuclear Materials*, 1971, Vol. 38, No. 3, PP. 303–308.
115. Kotelnikov R.B. et al. High Temperature Nuclear Fuel/2nd ed.– M.: Atomizdat, 1978 (Russian).
116. Preusser T. Modeling of Carbide Fuel Rod. – *Nuclear Technology*, 1982, Vol. 57, PP. 343–371.
117. Nickerson G.M., Kastenberg W.E. Preliminary Assessments of Carbide Fuel Pins During Mild Overpower Transients in LMFBRs. – *Nuclear Engineering and Design*, 1976, Vol. 36, P. 209.
118. Ohse R.W. et al. Equation of State Studies of Fast Breeder Oxide and Carbide Fuels by Dynamic Pulse Heating Techniques and Prediction of Their Critical Point Date by Various Theoretical Models. –*High Temperature-High Pressure*, 1980, Vol. 13, No. 1, PP. 35–78.
119. Giggli G et al. The Equation of State of Liquid Uranium Monocarbide: an Application of the Significant Structure Theory. – *Journal of Nuclear Materials*, 1981, Vol. 98, No. 1–2, PP. 35–46.
120. Storms E. Carbides/In “Thermodynamics of Nuclear Materials”, IAEA, Vienna: 1966. – 1980, Vol. 1, P. 309.
121. Nicols R. Uran/Ch.2 In “Materials for Nuclear Engineering”, Ed. by A.B. McIntosh, T.J. Heal, Temple Press Ltd, London, 1960.
122. Samsonov G.V., Vinnitsky I.N. Refractory Compounds/Handbook.– M.: Metallurgiia, 1976 (Russian).

123. Krzhizhanovsky R.E. Thermophysical Properties of Non-metallic Materials (Carbides)/Reference book. –Leninigrad: Energiia, 1974 (Russian).
124. Krzhizhanovsky R.E., Shtern Z.Yu. Thermophysical Properties of Non-metallic Materials (Oxides)/Reference book. — Leninigrad: Energiia, 1973 (Russian).
125. Cherepanov A.M., Trekhsvaitsky S.G. High Refractory Materials and Products from Oxides. –M.: Metallurgizdat, 1964.
126. Aronson S., Rulli J.E., Schaner B.E. Electrical Properties of Nonstoichiometric Uranium Dioxide. *Journal Chemical Physics*, 1961, v. 35, No 4, pp. 1382–1388.
127. Mukaybo T. et al. Variation of Specific Heat Capacity of UC and UC2/Cit. from: Nuclear Material Thermodynamics Symposium. – *Atomnaia Energiia*, 1963, V. 15, No. 4, p. 350.
128. Andrievsky R.A. et al. Study of Evaporation of Uranium Carbide, Nitride and Carbonitrides. *Atomnaia Energiia*, 1969, V. 26, No. 6, pp. 494–498
129. Joseph M. et al. Studies on Equation of State of Mixed Carbide Fuels. – *Journal of Nuclear Materials*, 1989, v. 168, No3, p. 220–227
130. Theoretical Science of Heat Engineering. Thermotechnical Experiment./Handbook in 4 Volumes ed. by A.V. Klimenko, V.M. Zorin. –M.: MEI Press. 2001 (Russian).
131. Emsley J. The Elements/2-ed..- Oxford Publ. Clarendon Press, 1991.
132. Gmelin Handbook, 1979; Cit. by Meek Th., Semiconductivity Properties of UO2, Symp. Waste Management, Feb. 25 — March 1, 2001, Tucson, Ar., USA.
133. Smithells C.J., Metals Reference Book/5-th ed.- London: Publ. Butterworth and Co. Ltd. 1980.
134. Thermal Conductivity of Solids/Handbook ed. by A.S. Okhotin. – M.: Energoatomizdat, 1984 (Russian).
135. Thorium: Physico-Chemical Properties of its Compounds and Alloys. IAEA, Vienna, 1975.
136. Benjamin M.Ma. Nuclear Reactor Materials and Applications. – N.Y., Van Nostrand Reihold Co, 1983.
137. Lewis H.D., Kerrisk J.F. Electrical and Thermal Transport Properties of Uranium and Plutonium Carbides (a Review of the Literature)/Report LA-6096, 1976.
138. Boivineau M. What's New on Plutonium Up to 4000K? – *Journal of Nuclear Materials*, 2001, Vol. 297, PP. 97–106.
139. Rohr W.G. Liquid Plutonium — A Review of Physical Properties. – *Nuclear Applic*., 1967, Vol. 3, No 9, PP. 550–555.
140. Carter W.C. Thermodynamics of Materials 3.00 fall 2002. — Depart. of Materials Sci. & Eng., Massachusetts Inst. of Technology.
141. Emelianov V.S., Evtyukhin A.I. Metallurgy of Nuclear Fuel. Properties and Manufacturing Science of Uranium, Thorium and Plutonium/2nd rev. and enl. ed. – M.: Atomizdat, 1968 (Russian).
142. Mulford R.N.R. In Coll. Papers "Plutonium 1960".– Cleaver Hume Press, Ltd. London, 1960.
143. Kulikov I.S. Thermodynamics of PuO_2 System. – *Atomnaia Energiia*, 1988, Vol. 65, No. 4, PP. 265–268 (Russian).
144. Kulikov I.S. Thermodynamics of Oxides/Handbook. – M.: Metallurgiia, 1986 (Rus).

3. COOLANTS

3.1. GASES

The thermophysical properties of dry air and helium are presented in Tables 3.1 and 3.2, respectively.

3.1.1. Air

TABLE 3.1. THERMOPHYSICAL PROPERTIES OF DRY AIR AT P = 0.0981 MPa [1]

Temperature °C	Density kg/m^3	Heat capacity kJ/(kg·K)	Thermal capacity 10^2 [W/(mK)]	Dynamic viscosity 10^6(Pa·s)	Thermal diffusivity 10^6(m^2/s)	Kinematic viscosity 10^6 (m^2/s)	Prandtl number
–50	1.532	1.00	2.05	14.53	13.4	9.49	0.71
–20	1.350	1.00	2.28	16.15	16.8	11.97	0.71
0	1.251	1.00	2.44	17.19	19.4	13.75	0.71
10	1.207	1.00	2.51	17.69	20.7	14.66	0.71
20	1.166	1.00	2.58	18.19	22.0	15.61	0.71
30	1.127	1.00	2.65	18.68	23.4	16.58	0.71
40	1.091	1.00	2.72	19.16	24.8	17.57	0.71
50	1.057	1.00	2.79	19.63	26.3	18.58	0.71
60	1.026	1.01	2.86	20.10	27.6	19.60	0.71
70	0.996	1.01	2.92	20.56	29.2	20.65	0.71
80	0.967	1.01	2.99	21.02	30.6	21.74	0.71
90	0.941	1.01	3.06	21.47	32.2	22.82	0.71
100	0.916	1.01	3.12	21.90	33.6	23.91	0.71
120	0.869	1.01	3.24	22.77	36.9	26.21	0.71
140	0.827	1.02	3.37	23.61	40.0	28.66	0.71
160	0.789	1.02	3.49	24.44	43.3	31.01	0.71
180	0.754	1.02	3.62	25.24	46.9	33.49	0.71
200	0.722	1.03	3.74	26.01	50.6	36.03	0.71
250	0.6530	1.03	4.06	27.91	60.0	42.75	0.71
300	0.5960	1.05	4.37	29.71	70.0	49.87	0.71
350	0.5482	1.06	4.64	31.42	80.0	57.33	0.72
100	0.5075	1.07	4.91	33.09	90.6	65.22	0.72
500	0.4418	1.09	5.45	36.15	113	81.85	0.72
600	0.3912	1.11	5.98	39.05	137	99.86	0.73
700	0.3510	1.13	6.47	41.74	162	118.95	0.73
800	0.3183	1.16	7.00	44.29	190	139.18	0.73
900	0.2916	1.17	7.40	46.68	216	160.14	0.74
1000	0.2683	1.18	7.84	48.99	247	182.67	0.74
1100	0.2487	1.20	8.26	51.20	277	205.94	0.74
1200	0.2319	1.21	8.66	53.36	309	230.17	0.74

3.1.2. Helium

The isobaric heat capacity of helium in the range of temperatures and pressures under considerations can be accepted to be constant and be C_p = 5.193 kJ/(kg·K).

TABLE 3.2. THERMODYNAMIC AND THERMOPHYSICAL PROPERTIES OF HELIUM [2]

Temp. °C	P = 1 × 10^5 Pa					P = 5 × 10^5 Pa				
	Density kg/m^3	Enthalpy kJ/kg	Thermal conductivity W/(m·K)	Dynamic viscosity mPa·s	Prandtl number	Density kg/m^3	Enthalpy kJ/kg	Thermal conductivity W/(m·K)	Dynamic viscosity 10^6 (Pa·s)	Prandtl number
100	0.1290	519.6	179.0	22.92	0.665	0.6439	520.9	179.1	22.92	0.665
150	0.1137	779.3	196.1	24.93	0.660	0.5679	780.6	196.2	24.93	0.660
200	0.1017	1039	212.6	26.87	0.656	0.5080	1040	212.7	26.37	0.656
250	0.09200	1299	228.6	28.75	0.653	0.4595	1300	223.7	28.75	0.653
300	0.08398	1558	244.1	30.57	0.650	0.4195	1560	244.2	30.57	0.650
350	0.07724	1818	259.3	32.35	0.648	0.3859	1819	259.3	32.35	0.643
400	0.07150	2078	274.0	34.09	0.646	0.3573	2079	274.1	34.09	0.646
450	0.06656	2337	288.3	35.79	0.645	0.3326	2338	288.4	35.79	0.644
500	0.06226	2597	302.3	37.45	0.643	0.3111	2598	302.3	37.45	0.643
550	0.05848	2856	315.7	39.08	0.643	0.2922	2858	315.8	39.08	0.643
600	0.05513	3116	328.8	40.68	0.642	0.2775	3117	328.8	40.68	0.642
650	0.05214	3376	341.3	42.26	0.643	0.2606	3377	341.3	42.26	0.643
700	0.04946	3635	353.3	43.80	0.644	0.2472	3637	353.4	43.80	0.644
750	0.04705	3895	365.0	45.33	0.645	0.2351	3896	365.0	45.33	0.645
800	0.04486	4155	376.2	46.83	0.646	0 2242	4156	376.2	46.83	0.646
850	0.04286	4414	387.1	48.31	0.648	0.2142	4416	387.2	48.31	0.648
900	0.04103	4674	397.8	49.77	0.650	0.2051	4675	397.9	49.77	0.650
1000	0.03781	5193	418.8	52.64	0.653	0.1890	5194	418.8	52.64	0.653
1100	0.03506	5713	439.4	55.44	0.655	0.1722	57I4	439.4	55.44	0.655
100	1.285	522.5	179.2	22.92	0.664	2.562	525.8	179.5	22.92	0.663
150	1.134	782.2	169.3	24.93	0.660	2.261	785.4	196.6	24.93	0.659
200	1.015	1042	212.8	26.87	0.656	2.024	1045	213.0	26.87	0.655
250	0.9179	1301	228.8	28.75	0.653	1.831	1305	229.0	28.75	0.652
300	0.8381	156	244.3	30.57	0.650	1.672	1564	244.5	30.57	0.649
350	0.7710	1821	259.4	32.35	0.648	1.539	1824	259.6	32.35	0.647
400	0.7139	2080	274.2	34.09	0.646	1.425	1083	274.3	34.09	0.645
450	0.6646	2340	288.5	35.79	0.644	1.327	2343	288.6	35.79	0.644
500	0.6217	2600	302.4	37.45	0.643	1.242	2603	302.5	37.45	0.643
550	0.5840	2859	315.9	39.08	0.642	1.166	2862	316.0	39.08	0.641
600	0.5506	3119	328.9	40.68	0.642	1.100	3122	329.0	40.68	0.642
650	0.5208	3379	341.1	42.26	0.643	1.040	3382	341.5	42.26	0.643
700	0.4941	3638	353.4	43.80	0.644	0.9871	3641	353.6	43.80	0.643
750	0.4700	3898	365.1	45.33	0.645	0.9390	3901	365.2	45.33	0.645
800	0.4481	4157	376.3	46.83	0.646	0.8954	4160	376.4	46.83	0.646
850	0.4282	4417	387.2	43.31	0.648	0.8556	4420	387.3	48.31	0.648
900	0.4100	4677	397.9	49.77	0.650	0.8192	4680	398.0	49.77	0.649
1000	0.3778	5196	413.8	52.64	0.653	0.7550	5189	418.9	52.64	0.653
1100	0.3503	5715	439.4	55.44	0.655	0.7001	5718	439.5	55.44	0.655

TABLE 3.2. (continued)

Temp. °C	$P = 4 \times 10^6$ Pa					$P = 6 \times 10^6$ Pa				
	Density kg/m^3	Enthalpy kJ/kg	Thermal conductivity W/(m·K)	Dynamic viscosity mPa·s	Prandtl number	Density kg/m^3	Enthalpy kJ/kg	Thermal conductivity W/(m·K)	Dynamic viscosity mPa·s	Prandtl number
100	5.086	532.3	180.2	22.93	0.661	7.575	538.7	180.8	22.93	0.659
150	4.494	791.8	197.1	24.93	0.656	6.699	798.3	197.7	24.94	0.655
200	4.025	1051	213.5	26.87	0.653	6.005	1058	214.0	26.88	0.652
250	3.645	1311	229.4	23.75	0.649	5.441	1317	229.9	28.75	0.649
300	3.330	1571	244.9	30.57	0.649	4.971	1577	2453	30.58	0.647
350	3.066	830	260.0	32.35	0.641	4.580	1836	260.4	32.36	0.645
400	2.840	2090	274.7	34.09	0.644	4.244	2096	275.0	34.09	0.644
450	2.645	2349	289.0	35.79	0.643	3.955	2355	289.3	35.79	0.642
500	2.475	2609	302.8	37.45	0.641	3.702	2615	303.1	37.45	0.642
550	2.326	2868	316.3	39.08	0.642	3.479	2875	316.6	39.08	0.641
600	2.194	3128	329.3	40.68	0.642	3.282	3134	329.5	40.68	0.641
650	2.076	3388	341.8	42.6	0.642	3.106	3394	342.0	42.26	0.642
700	1.970	3647	353.8	43.80	0.642	2.948	3653	354.0	43.81	0.643
750	1.874	3901	365.4	45.33	0.644	2.805	3913	365.6	45.33	0.644
800	1.7ε7	4166	376.6	46.83	0.645	2.675	4171	376.8	46.83	0.645
850	1.708	4426	387.5	48.3	0.646	2.557	443	387.7	48.31	0.648
900	1.636	4685	398.2	49.77	0.650	2.449	4691	398.4	49.77	0.649
1000	1.508	5204	419.1	52.64	0.652	2.258	5210	419.3	52.64	0.651
1100	1.398	5724	439.7	55.44	0.655	2.094	5729	439.8	55.44	0.655
100	10.03	545.2	181.5	22.94	0.656	12.45	551.7	182.2	22.96	0.654
150	8.877	804.7	198.3	24.95	0.653	11.03	811.2	198.9	24.96	0.652
200	7.963	1064	214.5	26.88	0.651	9.900	1071	215.1	26.89	0.649
250	7.219	1324	230.4	28.76	0.648	8.980	1330	230.8	28.77	0.647
300	6.602	1503	245.8	30.58	0.646	8.217	1590	246.2	30.59	0.645
350	6.083	1843	260.8	32.36	0.644	7.573	1849	261.2	32.37	0.644
400	5.639	2102	275.4	34.10	0.643	7.023	2108	275.8	34.10	0.642
450	5.255	2362	289.6	35.79	0.642	6.557	2368	290.0	35.80	0.641
500	4.921	2621	303.5	37.46	0.641	6.132	2627	303.8	37.46	0.640
550	4.626	2881	316.9	39.09	0.641	5.766	2887	317.2	39.09	0.640
600	4.364	3140	329.8	40.69	0.641	5.441	3146	330.1	40.69	0.640
650	4.131	3400	342.3	42.25	0.641	5.151	3406	342.5	42.26	0.641
700	3.921	3659	354.3	43.81	0.642	4.890	3665	354.5	43.81	0.642
750	3.732	3919	365.8	45.33	0.644	4.655	3924	366.1	45.33	0.643
800	3.560	4178	377.0	46.83	0.645	4.441	4184	377.3	46.84	0.645
850	3.403	4437	187.9	48.31	0.647	4.245	4443	388.1	48.32	0.646
900	3.259	4697	398.6	49.77	0.648	4.067	4703	398.7	49.77	0.648
1000	3.005	5216	419.5	52.64	0.652	3.751	5222	419.7	52.64	0.651
1100	2788	5732	440.0	55.44	0.654	3.480	5740	440.2	55.44	0.654

3.2. WATER (H_2O)

The thermophysical properties of water and steam (see Tables 3.3–3.8) are taken in Refs [3, 4]. Critical constants of water [Ref. 3, p. 23], and are as follows;

Pressure, MPa	22.064
Temperature, °C	373.946
Specific volume, m^3/kg	0.003106
Specific enthalpy, kJ/kg	2087.5
Specific entropy, kJ/(kg·K)	4.4120

TABLE 3.3. THERMOPHYSICAL PROPERTIES OF SATURATED WATER

Temp. rature °C	Pressure Pa	Density kg/m^3	Enthalpy kJ/kg	Heat capacity kJ/(kg·K)	Specific heat kJ/kg	Thermal conductivity 10^3W/(m·K)	Dynamic viscosity 10^4(Pa·s)	Kinematic viscosity $10^6(m^2/s)$	Thermal diffusivity $10^7(m^2/s)$	Prandtl number	Surface tension 10^3N/m
0.00	6.1170×10^{2}	999.8	0.00	4.220	2500.9	562.0	17.920	1.7920	1.332	13.456	75.70
5.00	8.7260×10^{2}	999.9	21.02	4.206	2489.1	572.0	15.220	1.5220	1.360	11.191	74.90
10.00	1.2282×10^{3}	999.7	42.02	4.196	2477.2	581.9	13.080	1.3080	1.387	9.432	74.20
15.00	1.7057×10^{3}	999.1	62.98	4.189	2465.4	600.6	11.380	1.1390	1.435	7.937	73.50
20.00	2.3392×10^{3}	998.2	83.92	4.185	2453.5	599.5	10.000	1.0020	1.435	6.981	72.70
25.00	3.1697×10^{3}	997.0	104.84	4.182	2441.7	607.2	8.883	0.8910	1.456	6.118	71.90
30.00	4.2467×10^{3}	995.6	125.75	4.180	2429.8	614.9	7.958	0.7993	1.478	5.410	71.20
35.00	5.6286×10^{3}	994.0	146.64	4.179	2417.9	621.7	7.184	0.7227	1.497	4.829	70.50
40.00	7.3844×10^{3}	992.2	167.54	4.179	2406.0	628.5	6.529	0.6581	1.516	4.341	69.60
45.00	9.5944×10^{3}	990.2	188.44	4.179	2394.0	632.0	5.967	0.6026	1.527	3.946	68.70
45.81	1.0000×10^{4}	989.8	191.81	4.179	2392.1	635.4	5.884	0.5945	1.536	3.870	68.60
50.00	1.2351×10^{4}	988.0	209.34	4.180	2382.0	640.4	5.480	0.5546	1.551	3.577	67.90
55.00	1.5761×10^{4}	985.7	230.24	4.181	2369.9	645.6	5.053	0.5126	1.567	3.272	67.10
60.00	2.0000×10^{4}	983.2	251.40	4.183	2357.5	651.0	4.677	0.4757	1.583	3.005	66.20
65.00	2.5010×10^{4}	980.5	270.31	4.185	2346.4	655.2	4.343	0.4429	1.597	2.774	65.40
69.13	3.0000×10^{4}	978.3	289.23	4.188	2335.3	658.5	4.094	0.4185	1.607	2.604	64.70
70.00	3.1201×10^{4}	977.7	293.02	4.188	2333.1	659.5	4.045	0.4137	1.611	2.569	64.50
75.00	3.8595×10^{4}	974.8	313.97	4.191	2320.6	663.2	3.778	0.3875	1.623	2.387	63.60
75.86	4.0000×10^{4}	974.3	317.57	4.192	2318.5	663.9	3.735	0.3834	1.626	2.358	63.40
80.00	4.7415×10^{4}	971.8	334.95	4.196	2308.1	666.9	3.540	0.3643	1.635	2.227	62.70
81.32	5.0000×10^{4}	971.0	340.48	4.197	2304.7	667.5	3.481	0.3585	1.638	2.189	62.50
85.00	5.7867×10^{4}	968.6	355.95	4.200	2295.4	669.9	3.326	0.3434	1.647	2.085	61.80
85.93	6.0000×10^{4}	968.0	359.84	4.201	2293.0	670.4	3.288	0.3397	1.649	2.060	61.60
89.93	7.0000×10^{4}	965.3	376.68	4.205	2282.7	672.9	3.136	0.3249	1.658	1.960	60.80
90.00	7.0182×10^{4}	965.3	376.97	4.205	2282.6	673.0	3.134	0.3247	1.658	1.958	60.80
93.49	8.0000×10^{4}	962.9	391.64	4.209	2273.5	674.6	3.012	0.3128	1.664	1.879	60.10
95.00	8.4609×10^{4}	961.9	398.02	4.211	2269.6	675.3	2.962	0.3079	1.667	1.847	59.80
96.69	9.0000×10^{4}	960.7	405.13	4.213	2265.2	676.1	2.908	0.3027	1.670	1.812	59.50
99.61	1.0000×10^{5}	958.7	417.44	4.217	2257.5	677.6	2.819	0.2940	1.676	1.754	59.00
100.00	1.0142×10^{5}	958.3	419.10	4.217	2256.5	677.7	2.807	0.2929	1.677	1.747	58.90
105.00	1.2080×10^{5}	950.9	440.23	4.223	2243.1	679.5	2.669	0.2807	1.692	1.659	57.90
110.00	1.4338×10^{5}	947.1	461.36	4.230	2229.7	681.2	2.545	0.2687	1.700	1.580	57.00

TABLE 3.3. (continued)

Temp. rature °C	Pressure Pa	Density kg/m^3	Enthalpy kJ/kg	Heat capacity kJ/(kg·K)	Specific heat kJ/kg	Thermal conductivity 10^3W/(m·K)	Dynamic viscosity 10^4(Pa·s)	Kinematic viscosity 10^6(m^2/s)	Thermal diffusivity 10^7(m^2/s)	Prandtl number	Surface tension 10^3N/m
115.00	1.6918×10^5	943.1	482.55	4.229	2216.0	682.4	2.432	0.2579	1.711	1.507	56.00
120.00	1.9867×10^5	943.0	503.80	4.246	2202.1	683.6	2.330	0.2471	1.707	1.447	54.90
120.21	2.0000×10^5	939.1	504.70	4.246	2201.6	683.7	2.326	0.2477	1.715	1.445	54.60
125.00	2.3222×10^5	934.8	525.10	4.260	2188.0	684.2	2.236	0.2392	1.718	1.392	54.00
130.00	2.7026×10^5	931.8	546.40	4.274	2173.7	684.8	2.148	0.2305	1.720	1.341	52.90
133.53	3.0000×10^5	930.5	561.50	4.284	2163.4	684.8	2.089	0.2245	1.718	1.307	52.30
135.00	3.1320×10^5	926.1	567.80	4.287	2159.1	684.8	2.065	0.2230	1.725	1.293	52.00
140.00	3.6150×10^5	922.8	589.20	4.286	2144.2	684.8	1.984	0.2150	1.731	1.242	50.90
143.61	4.0000×10^5	921.7	604.70	4.309	2133.3	684.6	1.927	0.2091	1.724	1.213	50.10
145.00	4.1563×10^5	917.0	610.70	4.312	2129.1	684.3	1.904	0.2076	1.731	1.200	49.90
150.00	4.7610×10^5	915.2	632.30	4.310	2113.7	683.8	1.823	0.1992	1.733	1.149	48.70
151.84	5.0000×10^5	912.2	640.20	4.328	2107.9	683.0	1.784	0.1956	1.730	1.130	48.40
155.00	5.4342×10^5	908.6	653.90	4.336	2097.9	682.8	1.742	0.1917	1.733	1.106	47.70
158.83	6.0000×10^5	907.4	670.50	4.345	2085.6	682.0	1.696	0.1869	1.730	1.081	46.90
160.00	6.1814×10^5	902.5	675.60	4.338	2081.9	681.8	1.683	0.1865	1.741	1.071	46.60
165.00	7.0000×10^5	897.4	697.30	4.360	2065.4	680.3	1.630	0.1816	1.739	1.045	45.50
170.00	7.9205×10^5	897.4	719.20	4.369	2048.7	678.7	1.582	0.1763	1.731	1.018	44.40
170.41	8.0000×10^5	897.0	721.00	4.375	2047.3	678.6	1.579	0.1760	1.729	1.018	44.30
175.00	8.9245×10^5	892.3	741.20	4.388	2031.6	676.6	1.538	0.1724	1.728	0.997	43.30
175.36	9.0000×10^5	891.9	742.70	4.389	2030.3	676.5	1.535	0.1721	1.728	0.996	43.20
179.89	1.0000×10^6	887.2	762.70	4.403	2014.4	674.7	1.497	0.1687	1.727	0.977	42.20
180.00	1.0026×10^6	887.0	763.20	4.406	2014.0	674.6	1.496	0.1687	1.726	0.977	42.20
185.00	1.1233×10^6	881.6	785.30	4.420	1996.1	672.0	1.457	0.1653	1.725	0.958	41.10
190.00	1.2550×10^6	876.1	807.60	4.447	1977.7	669.5	1.419	0.1620	1.718	0.943	40.00
195.00	1.3986×10^6	870.5	829.90	4.459	1958.9	666.4	1.382	0.1588	1.717	0.925	38.80
198.30	1.5000×10^6	866.6	844.70	4.474	1946.3	664.3	1.359	0.1568	1.713	0.915	38.00
200.00	1.5547×10^6	864.7	852.40	4.494	1939.7	663.3	1.347	0.1558	1.707	0.913	37.70
205.00	1.7240×10^6	858.7	875.00	4.506	1919.9	659.7	1.313	0.1529	1.705	0.897	36.60
210.00	1.9074×10^6	852.7	897.70	4.548	1899.6	656.2	1.279	0.1500	1.692	0.886	35.40
212.38	2.0000×10^6	849.8	908.60	4.547	1889.8	654.3	1.264	0.1487	1.693	0.878	34.90
215.00	2.1055×10^6	846.5	920.60	4.563	1878.8	652.2	1.248	0.1474	1.688	0.873	34.40
220.00	2.3193×10^6	840.2	943.60	4.611	1857.4	648.2	1.217	0.1448	1.673	0.866	33.10
223.96	2.5000×10^6	835.1	962.00	4.625	1840.1	644.5	1.193	0.1428	1.669	0.856	32.10
225.00	2.5494×10^6	833.8	966.80	4.633	1835.4	643.6	1.187	0.1424	1.666	0.854	31.90
230.00	2.7968×10^6	827.1	990.20	4.683	1812.8	639.1	1.159	0.1401	1.650	0.849	30.70
233.86	3.0000×10^6	821.9	1008.40	4.705	1794.9	635.1	1.138	0.1385	1.642	0.843	29.70
235.00	3.0622×10^6	820.3	1013.80	4.716	1789.5	634.0	1.132	0.1380	1.639	0.842	29.50
240.00	3.3467×10^6	813.3	1037.50	4.767	1765.5	628.9	1.106	0.1360	1.622	0.838	28.40
241.00	3.4059×10^6	812.0	1042.30	4.773	1760.7	627.7	1.101	0.1356	1.620	0.837	28.10
242.56	3.5000×10^6	809.7	1049.80	4.789	1753.0	625.9	1.093	0.1350	1.614	0.836	27.70
245.00	3.6509×10^6	806.2	1061.50	4.814	1740.8	623.3	1.081	0.1341	1.606	0.835	27.20
250.00	3.9759×10^6	798.9	1085.70	4.865	1715.3	617.8	1.058	0.1324	1.590	0.833	26.00
250.36	4.0000×10^6	798.3	1087.40	4.874	1713.5	617.4	1.056	0.1323	1.587	0.834	25.90
255.00	4.3227×10^6	791.4	1110.10	4.930	1689.0	622.6	1.036	0.1309	1.596	0.820	24.80

TABLE 3.3. (continued)

Temp. rature °C	Pressure Pa	Density kg/m³	Enthalpy kJ/kg	Heat capacity kJ/(kg·K)	Specific heat kJ/kg	Thermal conductivity 10^3W/(m·K)	Dynamic viscosity 10^4(Pa·s)	Kinematic viscosity 10^6(m²/s)	Thermal diffusivity 10^7(m²/s)	Prandtl number	Surface tension 10^3N/m
257.44	4.5000×10^6	787.6	1122.10	4.961	1675.9	608.7	1.025	0.1301	1.558	0.835	24.20
260.00	4.6921×10^6	783.6	1134.80	4.981	1661.8	605.6	1.015	0.1295	1.552	0.835	23.70
263.94	5.0000×10^6	777.4	1154.50	5.050	1639.7	600.5	0.999	0.1285	1.530	0.840	22.60
265.00	5.0851×10^6	775.7	1159.80	5.066	1633.7	599.0	0.994	0.1281	1.524	0.841	22.40
270.00	5.5000×10^6	767.5	1184.90	5.141	1604.8	595.6	0.975	0.1270	1.509	0.842	21.30
275.00	5.9463×10^6	767.5	1210.70	5.222	1574.4	585.0	0.957	0.1247	1.460	0.854	20.00
275.59	6.0000×10^6	759.0	1213.70	5.232	1570.8	584.1	0.954	0.1257	1.471	0.855	19.90
280.00	6.4165×10^6	758.0	1236.70	5.290	1543.2	577.7	0.939	0.1239	1.441	0.860	19.00
280.86	6.5000×10^6	750.3	1241.20	5.324	1537.7	576.4	0.936	0.1248	1.443	0.865	18.60
285.00	6.9145×10^6	748.7	1263.00	5.401	1510.7	568.8	0.921	0.1230	1.407	0.875	17.70
285.83	7.0000×10^6	741.2	1267.40	5.417	1505.1	568.7	0.918	0.1238	1.416	0.874	17.60
290.00	7.4416×10^6	739.7	1289.80	5.490	1476.8	562.0	0.904	0.1222	1.384	0.883	16.70
290.54	7.5000×10^6	731.9	1292.70	5.511	1473.1	561.2	0.902	0.1232	1.391	0.886	16.60
295.00	8.0000×10^6	730.9	1317.10	5.605	1441.5	553.5	0.887	0.1214	1.351	0.898	15.50
299.27	8.5000×10^6	722.2	1340.70	5.700	1410.3	500.7	0.873	0.1209	1.216	0.994	14.50
300.00	8.5877×10^6	722.2	1344.80	5.750	1404.8	544.9	0.870	0.1205	1.312	0.918	14.40
303.35	9.0000×10^6	713.6	1363.70	5.850	1379.2	538.8	0.859	0.1204	1.291	0.933	13.60
305.00	9.2092×10^6	712.1	1373.10	5.900	1366.3	535.7	0.853	0.1198	1.275	0.939	13.10
307.25	9.5000×10^6	705.2	1386.00	5.980	1348.4	530.4	0.845	0.1198	1.258	0.953	12.70
310.00	9.8647×10^6	701.7	1402.00	6.090	1325.9	526.5	0.835	0.1190	1.232	0.966	12.10
311.00	1.0000×10^7	696.8	1407.90	6.140	1317.6	524.5	0.832	0.1194	1.226	0.974	11.90
314.61	1.0500×10^7	690.7	1429.30	6.320	1286.9	517.2	0.818	0.1184	1.185	1.000	11.10
315.00	1.0556×10^7	688.4	1439.80	6.410	1271.5	516.4	0.817	0.1187	1.170	1.014	11.00
318.08	1.1000×10^7	680.1	1450.30	6.500	1256.1	510.1	0.805	0.1184	1.154	1.026	10.30
320.00	1.1284×10^7	671.8	1462.10	6.540	1238.6	506.4	0.798	0.1188	1.153	1.031	9.86
321.44	1.1500×10^7	667.1	1470.90	6.680	1225.3	503.4	0.792	0.1187	1.130	1.051	9.60
324.68	1.2000×10^7	663.5	1491.30	6.870	1194.3	496.3	0.779	0.1174	1.089	1.078	8.90
325.00	1.2051×10^7	655.2	1493.40	6.890	1191.1	495.7	0.777	0.1186	1.098	1.080	8.80
327.82	1.2500×10^7	654.3	1511.50	7.060	1163.0	489.6	0.765	0.1169	1.060	1.103	8.10
330.00	1.2858×10^7	646.8	1525.70	7.190	1140.5	484.8	0.756	0.1169	1.042	1.121	7.70
330.86	1.3000×10^7	640.8	1531.40	7.210	1131.5	482.8	0.752	0.1174	1.045	1.123	7.50
333.81	1.3500×10^7	638.4	1551.20	7.270	1099.6	476.0	0.738	0.1156	1.026	1.127	7.00
335.00	1.3707×10^7	629.8	1559.30	7.510	1086.3	473.2	0.733	0.1164	1.000	1.163	6.70
336.67	1.4000×10^7	626.3	1570.90	7.620	1067.2	469.2	0.724	0.1156	0.983	1.176	6.40
339.45	1.4500×10^7	621.2	1590.50	7.780	1034.3	362.7	0.711	0.1144	0.750	1.525	5.70
340.00	1.4600×10^7	612.4	1594.40	8.110	1027.6	461.4	0.708	0.1156	0.929	1.244	5.63
342.16	1.5000×10^7	610.7	1610.20	8.490	1000.7	455.9	0.696	0.1140	0.879	1.296	5.20
344.79	1.5500×10^7	603.5	1629.90	8.950	966.4	449.5	0.682	0.1130	0.832	1.358	4.80
345.00	1.5540×10^7	594.4	1631.40	8.990	963.6	449.0	0.681	0.1146	0.840	1.364	4.70
347.36	1.6000×10^7	593.6	1649.70	9.490	931.1	442.9	0.668	0.1125	0.786	1.431	4.10
350.00	1.6500×10^7	585.0	1669.70	10.120	894.9	436.6	0.652	0.1115	0.738	1.511	3.67
352.29	1.7000×10^7	574.7	1690.00	10.850	857.4	430.8	0.638	0.1110	0.691	1.607	3.20
354.67	1.7500×10^7	565.2	1710.80	11.700	818.4	424.5	0.623	0.1102	0.642	1.717	2.80

TABLE 3.3. (continued)

Temp. rature °C	Pressure Pa	Density kg/m^3	Enthalpy kJ/kg	Heat capacity kJ/(kg·K)	Specific heat kJ/kg	Thermal conductivity 10^3W/(m·K)	Dynamic viscosity 10^6(Pa·s)	Kinematic viscosity 10^6(m^2/s)	Thermal diffusivity 10^6(m^2/s)	Prandtl number	Surface tension mN/m
355.00	1.7570×10^7	554.7	1713.70	11.860	812.7	423.8	0.621	0.1120	0.644	1.738	2.74
356.99	1.8000×10^7	553.2	1732.00	13.540	777.5	419.5	0.607	0.1097	0.560	1.959	2.30
359.26	1.8500×10^7	543.6	1754.00	14.520	734.4	414.0	0.592	0.1089	0.524	2.076	1.90
360.00	1.8666×10^7	531.9	1761.50	14.870	719.5	412.0	0.587	0.1104	0.521	2.119	1.88
361.47	1.9000×10^7	527.8	1776.90	15.720	688.5	409.0	0.576	0.1091	0.493	2.214	1.52
363.63	1.9500×10^7	519.3	1801.10	18.430	638.9	405.3	0.560	0.1078	0.423	2.546	1.19
365.00	1.9822×10^7	496.1	1817.60	21.500	604.5	404.0	0.550	0.1109	0.379	2.927	1.08
365.75	2.0000×10^7	490.4	1827.10	23.760	584.3	404.2	0.544	0.1109	0.347	3.198	0.95
367.81	2.0500×10^7	473.0	1855.90	32.590	522.3	411.8	0.528	0.1116	0.267	4.179	0.68
369.83	2.1000×10^7	452.1	1889.40	45.800	448.2	417.6	0.512	0.1133	0.202	5.615	0.40
370.00	2.1043×10^7	450.0	1892.70	47.100	440.9	418.0	0.510	0.1133	0.197	5.747	0.39
371.00	2.1296×10^7	436.6	1913.30	64.100	394.3	433.0	0.502	0.1150	0.155	7.431	0.27
372.00	2.1553×10^7	419.9	1938.50	101.200	336.1	462.0	0.493	0.1174	0.109	10.799	0.16
373.00	2.1813×10^7	395.8	1974.10	231.000	253.2	534.0	0.485	0.1225	0.062	20.980	0.06

TABLE 3.4. THERMOPHYSICAL PROPERTIES OF SATURATED STEAM

Temp. rature °C	Pressure Pa	Density kg/m^3	Enthalpy kJ/kg	Heat capacity kJ/(kg·K)	Specific heat kJ/kg	Thermal conductivity 10^3W/(m·K)	Dynamic viscosity 10^6(Pa·s)	Kinematic viscosity 10^6(m^2/s)	Thermal diffusivity 10^6(m^2/s)	Prandtl number
0	6.1170×10^2	0.00485	2500.9	1.888	2500.9	16.5	9.22	1901	1802	1.05
5	8.7260×10^2	0.00680	2510.1	1.892	2489.1	16.8	9.32	1371	1306	1.05
10	1.2282×10^3	0.00941	2519.2	1.896	2477.2	17.2	9.46	1005	964	1.04
15.0	1.7057×10^3	0.0128	2528.4	1.903	2465.4	17.5	9.60	747.7	716	1.04
20.0	2.3392×10^3	0.0173	2537.5	1.906	2453.5	18.0	9.73	562.1	546	1.03
25.0	3.1697×10^3	0.0231	2546.5	1.913	2441.7	18.4	9.89	428.7	417	1.03
30.0	4.2467×10^3	0.0304	2555.6	1.918	2429.8	18.7	10.01	329.2	321	1.03
35.0	5.6286×10^3	0.0397	2564.6	1.925	2417.9	19.3	10.18	256.6	253	1.02
40	7.3844×10^3	0.0512	2573.5	1.932	2406.0	19.5	10.31	201.2	197	1.02
45	9.5944×10^3	0.0656	2582.5	1.938	2394.0	19.8	10.48	159.9	156	1.02
45.81	1.0000×10^4	0.0682	2583.9	1.939	2392.1	20.0	10.51	154.2	151	1.02
50	1.2351×10^4	0.0831	2591.3	1.948	2382.0	20.3	10.62	127.7	125	1.02
55	1.5761×10^4	0.1045	2600.1	1.954	2369.9	20.7	10.79	103.2	101	1.02
60	1.9946×10^4	0.1304	2608.8	1.966	2357.7	21.1	10.93	83.81	82.3	1.02
65.0	2.5041×10^4	0.1614	2617.5	1.973	2343.0	21.6	11.10	68.75	67.8	1.02
69.13	3.0000×10^4	0.1913	2624.6	1.982	2335.3	21.8	11.23	58.72	58.6	1.02
70	3.1201×10^4	0.1984	2626.1	1.987	2333.1	22.0	11.26	56.75	55.8	1.02
75	3.8595×10^4	0.2422	2634.6	1.997	2320.6	22.7	11.42	47.16	46.9	1.02
75.86	4.0000×10^4	0.2504	2636.1	1.999	2318.5	22.8	11.45	45.72	45.5	1.02
80	4.7415×10^4	0.2937	2643.0	2.012	2308.1	22.9	11.59	39.47	38.8	1.02
81.32	5.0000×10^4	0.3086	2645.2	2.014	2304.7	23.2	11.63	37.68	37.3	1.02
85	5.7867×10^4	0.3539	2651.3	2.025	2295.4	23.5	11.75	33.20	32.8	1.02
85.93	6.0000×10^4	0.3661	2652.9	2.028	2293.0	23.6	11.78	32.18	31.8	1.02
89.93	7.0000×10^4	0.4228	2659.4	2.041	2282.7	23.9	11.91	28.17	27.7	1.02

TABLE 3.4. (continued)

Temp. rature °C	Pressure Pa	Density kg/m^3	Enthalpy kJ/kg	Heat capacity kJ/(kg·K)	Specific heat kJ/kg	Thermal conductivity 10^3W/(m·K)	Dynamic viscosity 10^6(Pa·s)	Kinematic viscosity $10^6(m^2/s)$	Thermal diffusivity $10^6(m^2/s)$	Prandtl number
90	7.0182×10^4	0.4239	2659.5	2.042	2282.6	24.0	11.93	28.14	27.5	1.02
93.49	8.0000×10^4	0.4791	2665.2	2.054	2273.5	24.3	12.03	25.11	24.7	1.02
95	8.4609×10^4	0.5049	2667.6	2.060	2269.6	24.4	12.08	23.93	23.5	1.02
96.69	9.0000×10^4	0.5349	2670.3	2.066	2265.2	24.6	12.14	22.70	22.3	1.02
99.61	1.0000×10^5	0.5903	2674.9	2.076	2257.5	24.7	12.23	20.72	20.2	1.03
100	1.0142×10^5	0.5981	2675.6	2.077	2256.5	24.8	12.27	20.51	20.0	1.03
105	1.2090×10^5	0.7050	2683.4	2.101	2243.2	25.3	12.59	17.86	17.5	1.04
110	1.4338×10^5	0.8269	2691.1	2.121	2229.7	25.8	12.61	15.25	14.7	1.04
115	1.6918×10^5	0.9653	2698.6	2.150	2216.0	26.4	12.76	13.22	12.7	1.04
120	1.9867×10^5	1.1220	2705.9	2.174	2202.1	27.0	12.95	11.54	11.1	1.04
120.21	2.0000×10^5	1.1290	2706.2	2.179	2201.6	27.1	12.94	11.46	10.9	1.04
125	2.3222×10^5	1.2985	2713.1	2.208	2188.0	27.4	13.11	10.10	9.56	1.05
130	2.7026×10^5	1.4968	2720.1	2.237	2173.7	28.1	13.30	8.886	8.39	1.06
133.53	3.0000×10^5	1.6507	2724.9	2.264	2163.4	28.4	13.42	8.130	7.60	1.06
135	3.1320×10^5	1.7188	2726.9	2.275	2159.1	28.6	13.47	7.837	7.31	1.07
140	3.6150×10^5	1.9665	2733.4	2.311	2144.2	29.4	13.64	6.936	6.47	1.07
143.61	4.0000×10^5	2.1627	2738.1	2.340	2133.3	29.6	13.78	6.372	5.85	1.08
145	4.1563×10^5	2.2421	2739.8	2.352	2129.1	29.8	13.83	6.168	5.65	1.08
150	4.7610×10^5	2.5478	2745.9	2.396	2113.7	30.8	13.99	5.491	5.05	1.09
151.84	5.0000×10^5	2.6681	2748.1	2.411	2107.9	30.7	14.07	5.273	4.77	1.10
155	5.4342×10^5	2.8860	2751.8	2.440	2097.9	31.1	14.17	4.910	4.42	1.10
158.83	6.0000×10^5	3.1688	2756.1	2.477	2085.6	31.7	14.30	4.513	4.04	1.11
160	6.1814×10^5	3.2592	2757.4	2.492	2081.9	32.2	14.33	4.397	3.96	1.11
164.95	7.0000×10^5	3.6662	2762.7	2.539	2065.6	32.6	14.50	3.955	3.50	1.12
165	7.0082×10^5	3.6703	2762.8	2.540	2065.4	32.6	14.50	3.951	3.50	1.13
170	7.9205×10^5	4.1217	2767.9	2.599	2048.7	33.8	14.68	3.562	3.16	1.13
170.41	8.0000×10^5	4.1609	2768.3	2.601	2047.3	33.8	14.68	3.528	3.12	1.13
175	8.9245×10^5	4.6168	2772.7	2.652	2031.6	34.2	14.84	3.214	2.79	1.14
175.36	9.0000×10^5	4.6540	2773.0	2.656	2030.3	34.3	14.85	3.191	2.77	1.14
179.89	1.0000×10^6	5.1454	2777.1	2.712	2014.4	35.0	15.00	2.915	2.51	1.15
180	1.0026×10^6	5.1584	2777.2	2.716	2014.0	35.4	15.02	2.912	2.53	1.15
185	1.1233×10^6	5.7498	2781.4	2.778	1996.1	35.9	15.18	2.640	2.25	1.17
190	1.2550×10^6	6.3947	2785.3	2.846	1977.7	37.2	15.37	2.404	2.04	1.18
195	1.3986×10^6	7.0967	2788.9	2.918	1958.9	37.8	15.52	2.187	1.83	1.19
198.30	1.5000×10^6	7.5930	2791.0	2.968	1946.3	38.5	15.64	2.060	1.71	1.20
200	1.5547×10^6	7.8604	2792.1	2.990	1939.7	39.1	15.71	1.999	1.66	1.20
205	1.7240×10^6	8.6889	2794.9	3.070	1919.9	39.9	15.87	1.826	1.50	1.22
210	1.9074×10^6	9.5877	2797.4	3.150	1899.6	41.1	16.06	1.675	1.36	1.23
212.38	2.0000×10^6	10.042	2798.4	3.203	1889.8	41.6	16.13	1.606	1.29	1.24
215	2.1055×10^6	10.561	2799.4	3.250	1878.8	42.2	16.23	1.537	1.23	1.25
220	2.3193×10^6	11.614	2801.1	3.328	1857.4	43.3	16.41	1.413	1.12	1.26
223.96	2.5000×10^6	12.508	2802.0	3.415	1840.1	44.4	16.55	1.323	1.04	1.27
225	2.5494×10^6	12.753	2802.3	3.435	1835.4	44.6	16.59	1.301	1.02	1.28

TABLE 3.4. (continued)

Temp. rature °C	Pressure Pa	Density kg/m^3	Enthalpy kJ/kg	Heat capacity kJ/(kg·K)	Specific heat kJ/kg	Thermal conductivity 10^3W/(m·K)	Dynamic viscosity 10^6(Pa·s)	Kinematic viscosity $10^6(m^2/s)$	Thermal diffusivity $10^6(m^2/s)$	Prandtl number
230	2.7968×10^6	13.984	2803.0	3.528	1812.8	45.7	16.76	1.199	0.926	1.29
233.86	3.0000×10^6	15.002	2803.3	3.613	1794.9	47.0	16.91	1.127	0.867	1.30
235	3.0622×10^6	15.314	2803.3	3.637	1789.5	47.3	16.95	1.107	0.849	1.31
240	3.3460×10^6	16.748	2803.1	3.755	1765.5	48.3	17.12	1.022	0.768	1.33
241	3.4059×10^6	17.047	2803.0	3.772	1760.7	49.0	17.18	1.008	0.762	1.33
242.56	3.5000×10^6	17.525	2802.7	3.809	1753.0	49.4	17.23	0.983	0.740	1.33
245	3.6509×10^6	18.295	2802.3	3.868	1740.8	50.2	17.32	0.947	0.709	1.33
250	3.9759×10^6	19.964	2801.0	4.012	1715.3	51.2	17.49	0.876	0.639	1.37
250.36	4.0000×10^6	20.088	2800.9	4.028	1713.5	51.8	17.53	0.873	0.640	1.36
255	4.3227×10^6	21.768	2799.1	4.141	1689.0	53.3	17.70	0.813	0.591	1.38
257.44	4.5000×10^6	22.696	2798.0	4.216	1675.9	54.1	17.79	0.784	0.565	1.39
260	4.6921×10^6	23.708	2796.6	4.308	1661.8	54.3	17.87	0.754	0.532	1.42
263.94	5.0000×10^6	25.349	2794.2	4.430	1639.7	56.3	18.04	0.712	0.501	1.44
265	5.0851×10^6	25.806	2793.5	4.468	1633.7	56.7	18.08	0.701	0.492	1.45
270	5.5000×10^6	28.074	2789.7	4.655	1604.6	57.8	18.27	0.651	0.442	1.47
275	5.9463×10^6	30.516	2785.1	4.860	1574.4	60.3	18.47	0.605	0.407	1.49
275.59	6.0000×10^6	30.817	2784.6	4.885	1570.8	60.5	18.49	0.600	0.402	1.49
280	6.4165×10^6	33.167	2779.8	5.070	1543.2	61.8	18.70	0.564	0.368	1.53
280.86	6.5000×10^6	33.636	2778.8	5.125	1537.7	62.5	18.86	0.561	0.363	1.55
285	6.9145×10^6	36.023	2773.7	5.329	1510.7	64.2	18.99	0.527	0.334	1.58
285.83	7.0000×10^6	36.523	2772.6	5.372	1505.1	64.5	19.02	0.521	0.329	1.58
290	7.4416×10^6	39.124	2766.6	5.580	1476.8	66.4	19.15	0.489	0.304	1.61
290.54	7.5000×10^6	39.479	2765.8	5.627	1473.1	66.5	19.19	0.486	0.299	1.62
295	8.0000×10^6	42.499	2758.6	5.888	1441.6	68.4	19.38	0.456	0.273	1.67
299.27	8.5000×10^6	45.600	2751.0	6.157	1410.3	70.3	19.58	0.429	0.250	1.70
300	8.5877×10^6	46.168	2749.6	6.220	1404.8	71.8	19.65	0.426	0.250	1.70
303.35	9.0000×10^6	48.804	2742.9	6.497	1379.2	73.8	19.80	0.406	0.233	1.74
305	9.2092×10^6	50.150	2739.4	6.634	1366.3	74.9	19.89	0.397	0.225	1.76
307.25	9.5000×10^6	52.083	2734.4	6.824	1348.4	76.4	20.02	0.384	0.215	1.79
310	9.8647×10^6	54.526	2727.9	7.050	1325.9	78.3	20.20	0.370	0.204	1.82
311	1.0000×10^7	55.463	2725.5	7.158	1317.6	79.0	20.24	0.365	0.199	1.83
314.61	1.0500×10^7	58.928	2716.1	7.513	1286.9	81.7	20.48	0.348	0.185	1.88
315	1.0556×10^7	59.312	2715.1	7.554	1283.4	82.1	20.50	0.346	0.183	1.89
318.08	1.1000×10^7	62.539	2706.4	7.901	1256.1	84.6	20.72	0.331	0.171	1.94
320	1.1284×10^7	64.599	2700.7	8.160	1238.6	86.4	20.84	0.323	0.164	1.97
321.44	1.1500×10^7	66.225	2696.2	8.331	1225.3	87.7	20.96	0.316	0.159	1.99
324.68	1.2000×10^7	70.077	2685.6	8.808	1194.3	91.0	21.21	0.303	0.147	2.05
325	1.2051×10^7	70.472	2684.5	8.859	1191.1	91.3	21.23	0.301	0.146	2.06
327.82	1.2500×10^7	74.074	2674.5	9.341	1163.0	94.4	21.46	0.290	0.136	2.12
330	1.2858×10^7	77.042	2666.2	9.740	1140.5	97.0	21.60	0.280	0.129	2.17
330.86	1.3000×10^7	78.186	2662.9	9.931	1131.5	98.0	21.71	0.278	0.126	2.20
333.81	1.3500×10^7	82.508	2650.8	10.58	1099.6	101.7	21.96	0.266	0.117	2.28
335	1.3707×10^7	84.388	2645.6	10.87	1086.3	103.4	22.07	0.262	0.113	2.32

TABLE 3.4. (continued)

Temp. rature °C	Pressure Pa	Density kg/m³	Enthalpy kJ/kg	Heat capacity kJ/(kg·K)	Specific heat kJ/kg	Thermal conductivity 10^3W/(m·K)	Dynamic viscosity 10^6(Pa·s)	Kinematic viscosity 10^6(m²/s)	Thermal diffusivity 10^6(m²/s)	Prandtl number
336.67	1.4000×10^7	87.032	2638.1	11.30	1067.2	106.0	22.22	0.255	0.108	2.37
339.45	1.4500×10^7	91.743	2624.8	12.07	1034.3	110.8	22.47	0.245	0.100	2.45
340	1.4600×10^7	92.764	2622.1	12.24	1027.6	111.8	22.55	0.243	0.098	2.47
342.16	1.5000×10^7	96.712	2610.9	12.92	1000.7	116.0	22.79	0.236	0.093	2.54
344.79	1.5500×10^7	101.93	2596.2	13.93	966.4	121.7	23.10	0.227	0.086	2.64
345	1.5540×10^7	102.35	2595.0	14.02	963.6	122.2	23.13	0.226	0.085	2.65
347.36	1.6000×10^7	107.43	2580.8	15.04	931.1	127.8	23.43	0.218	0.079	2.76
350	1.6500×10^7	113.62	2563.6	16.64	892.7	134.6	23.82	0.210	0.071	2.95
352.29	1.7000×10^7	119.47	2547.4	18.04	857.4	140.5	24.15	0.202	0.065	3.10
354.67	1.7500×10^7	126.15	2529.1	20.17	818.4	148.9	24.57	0.195	0.059	3.33
355	1.7570×10^7	127.13	2526.4	20.71	812.7	151.7	24.65	0.194	0.058	3.37
356.99	1.8000×10^7	133.35	2509.5	22.84	777.5	159	25.02	0.188	0.052	3.59
359.26	1.8500×10^7	141.20	2488.4	26.13	734.4	172.3	25.53	0.181	0.047	3.87
360	1.8666×10^7	143.97	2481.0	27.57	719.5	176.6	25.73	0.179	0.044	4.02
361.47	1.9000×10^7	149.86	2465.4	31.81	688.5	188.1	26.08	0.174	0.039	4.41
363.63	1.9500×10^7	159.57	2440.0	38.04	638.9	205.2	26.70	0.167	0.034	4.95
365	1.9822×10^7	166.50	2422.1	42.00	604.5	217.7	27.21	0.163	0.031	5.25
365.75	2.0000×10^7	170.68	2411.4	49.71	584.3	224.1	26.75	0.157	0.026	5.93
367.81	2.0500×10^7	183.89	2378.2	70.89	522.3	244.6	27.51	0.150	0.019	7.97
369.83	2.1000×10^7	200.48	2337.6	91.65	448.2	266.6	28.78	0.144	0.015	9.89
370	2.1043×10^7	202.14	2333.6	93.40	440.9	309.0	29.70	0.147	0.016	8.97
371	2.1296×10^7	213.13	2307.5	124.9	394.3	346.0	30.5	0.143	0.013	11.0
371.80	2.1500×10^7	223.91	2282.6	177.2	349.8	390	30.76	0.137	0.007	14.0
372	2.1553×10^7	227.38	2274.6	190.3	336.1	403.0	31.6	0.139	0.009	14.9
373	2.1813×10^7	248.82	2227.3	404.0	253.2	504.0	33.2	0.133	0.005	26.2

TABLE 3.5. ISOBARIC HEAT CAPACITY OF WATER AND STEAM

Temp. °C	Isobaric heat capacity [kJ/(kg·K)] at pressure (MPa)													
	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10	20	50	75	100
Water	4.179	4.183	4.197	4.216	4.247	4.315	4.405	4.562	5.032	6.127	23.20	-	-	-
Steam	1.941	1.966	2.016	2.076	2.175	2.413	2.715	3.190	4.438	7.147	45.68	-	-	-
0	4.220	4.220	4.220	4.219	4.219	4.217	4.215	4.210	4.196	4.172	4.129	4.022	3.956	3.906
10	4.196	4.196	4.196	4.195	4.195	4.194	4.192	4.188	4.177	4.160	4.126	4.042	3.988	3.945
20	4.185	4.185	4.185	4.185	4.184	4.184	4.182	4.179	4.170	4.155	4.127	4.056	4.008	3.969
25	4.182	4.182	4.182	4.182	4.182	4.181	4.179	4.176	4.168	4.154	4.128	4.061	4.016	3.978
30	4.180	4.180	4.180	4.180	4.180	4.179	4.178	4.175	4.167	4.154	4.130	4.066	4.022	3.985
40	4.179	4.179	4.179	4.179	4.178	4.178	4.176	4.174	4.167	4.155	4.133	4.073	4.032	3.996
50	1.927	4.180	4.180	4.180	4.179	4.179	4.177	4.175	4.168	4.157	4.136	4.080	4.040	4.005
60	1.912	4.183	4.183	4.183	4.183	4.182	4.181	4.179	4.172	4.161	4.141	4.086	4.047	4.0)2
70	1.907	1.940	4.188	4.188	4.188	4.187	4.186	4.184	4.178	4.167	4.147	4.093	4.054	4.019
80	1.905	1.930	4.196	4.196	4.195	4.195	4.194	4.191	4.185	4.174	4.154	4.100	4.061	4.026
90	1.905	1.925	1.990	4.205	4.205	4.204	4.203	4.201	4.194	4.184	4.163	4.108	4.068	4.033
100	1.906	1.922	1.973	2.074	4.216	4.216	4.215	4.212	4.206	4.194	4.173	4.117	4.076	4.040
110	1.907	1.921	1.963	2.040	4.230	4.230	4.228	4.226	4.219	4.207	4.185	4.127	4.084	4.047

TABLE 3.5. (continued)

Temp. °C	Isobaric heat capacity [kJ/(kg·K)] at pressure (MPa)													
	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10	20	50	75	100
120	1.910	1.921	1.956	2.019	4.246	4.246	4.244	4.242	4.234	4.222	4.199	4.137	4.093	4.055
130	1.913	1.922	1.952	2.004	2.123	4.264	4.263	4.260	4.252	4.239	4.214	4.149	4.103	4.063
140	1.916	1.924	1.949	1.993	2.090	4.286	4.284	4.281	4.273	4.258	4.232	4.163	4.114	4.072
150	1.920	1.927	1.948	1.986	.2.067	4.310	4.309	4.305	4.296	4.281	4.252	4.177	4.126	4.081
160	1.924	1.930	1.949	1.980	2.049	2.318	4.337	4.333	4.323	4.306	4.274	4.194	4.139	4.092
170	1.929	1.934	1.950	1.977	2.036	2.250	4.369	4.365	4.353	4.334	4.300	4.212	4.153	4.103
180	1.934	1.938	1.952	1.976	2.026	2.205	2.712	4.401	4.388	4.367	4.328	4.232	4.169	4.115
190	1.938	1.942	1.954	1.975	2.019	2.171	2.529	4.443	4.428	4.404	4.361	4.255	4.186	4.129
200	1.944	1.947	1.958	1.976	2.014	2.145	2.429	4.491	4.474	4.447	4.398	4.281	4.205	4.144
220	1.954	1.957	1.965	1.979	2.009	2.108	2.310	2.949	4.590	4.553	4.489	4.341	4.250	4.179
240	1.965	1.968	1.974	1.985	2.009	2.086	2.238	2.648	4.749	4.697	4.608	4.417	4.306	4.221
260	1.977	1.979	1.984	1.993	2.012	2.073	2.191	2.491	4.976	4.897	4.769	4.512	4.373	4.271
280	1.989	1.990	1.995	2.002	2.018	2.067	2.160	2.389	3.635	5.193	4.991	4.631	4.455	4.331
300	2.001	2.002	2.006	2.012	2.025	2.066	2.141	2.320	3.171	5.682	5.317	4.782	4.553	4.400
320	2.013	2.014	2.017	2.023	2.034	2.068	2.130	2.273	2.903	5.747	5.849	4.974	4.669	4.478
340	2.026	2.026	2.029	2.034	2.043	2.072	2.124	2.242	2.727	4.389	6.924	5.220	4.801	4.562
360	2.038	2.039	2.041	2.045	2.054	2.079	2.123	2.221	2.606	3.732	11.460	5.562	4.960	4.654
380	2.051	2.052	2.054	2.057	2.065	2.086	2.124	2.207	2.520	3.347	10.221	6.053	5.162	4.774
400	2.064	2.065	2.067	2.070	2.076	2.095	2.128	2.200	2.459	3.096	6.360	6.778	5.395	4.892
420	2:077	2.078	2.079	2.082	2.088	2.105	2.134	2:196	2.415	2.922	4.982	7.864	5.681	5.025
440	2.091	2.091	2.093	2.095	2.100	2.115	2.141	2.196	2.383	2.796	4.257	9.16	6.011	5.178
460	2.104	2.104	2.106	2.108	2.113	2.126	2.149	2.198	2.360	2.704	3.806	9.578	6.337	5.336
480	2.118	2.118	2.119	2.121	2.125	2.138	2.158	2.202	2.344	2.635	3.501	8.609	6.582	5.477
500	2.131	2.132	2.133	2.135	2.138	2.149	2.168	2.207	2.333	2.583	3.284	7.309	6.658	5.576
520	2.145	2.145	2.146	2.148	2.151	2.162	2.179	2.214	2.326	2.544	3.125	6.213	6.524	5.615
540	2.159	2.159	2.160	2.162	2.165	2.174	2.189	2.221	2.322	2.513	3.005	5.414	6.226	5.588
560	2.173	2.173	2.174	2.175	2.178	2.187	2.201	2.230	2.321	2.490	2.912	4.837	5.837	5.495
580	2.187	2.187	2.188	2.189	2.192	2.200	2.213	2.239	2.321	2.473	2.839	4.413	5.425	5.351
600	2.201	2.201	2.202	2.203	2.205	2.213	2.224	2.249	2.324	2.460	2.781	4.097	5.051	5.171
620	2.215	2.215	2.216	2.217	2.219	2.226	2.237	2.259	2.328	2.451	2.735	3.856	4.712	4.977
640	2.229	2.229	2.230	2.231	2.233	2.239	2.249	2.270	2.332	2.444	2.698	3.667	4.427	4.734
660	2.243	2.244	2.244	2.245	2.247	2.253	2.262	2.281	2.338	2.440	2.668	3.515	4.191	4.532
680	2.258	2.258	2.258	2.259	2.261	2.266	2.275	2.292	2.345	2.438	2.644	3.391	3.992	4.358
700	2.272	2.272	2.272	2.273	2.275	2.280	2.287	2.303	2.353	2.438	2.625	3.288	3.824	4.191
720	2.286	2.286	2.287	2.287	2.289	2.293	2.300	2.315	2.361	2.439	2.610	3.203	3.682	4.032
740	2.300	2.300	2.301	2.301	2.303	2.307	2.314	2.327	2.369	2.442	2.598	3.132	3.563	3.888
760	2.314	2.314	2.315	2.315	2.317	2.320	2.327	2.339	2.378	2.445	2.589	3.072	3.465	3.764
780	2.328	2.328	2.329	2.329	2.331	2.334	2.340	2.352	2.388	2.450	2.582	3.023	3.383	3.661
800	2.344	2.344	2.344	2.345	2.346	2.349	2.354	2.365	2.397	2.454	2.578	2.981	3.316	3.576

TABLE 3.6. DYNAMIC VISCOSITY OF WATER AND STEAM

Temp. °C	Dynamic viscosity [μPa·s] at pressure (MPa)												
	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10	20	50	75	100
Water	587.6	466.0	348.6	282.9	231.6	180.1	150.2	126.1	100.0	81.8	56.2	-	-	-
Steam	10.5	10.9	11.6	12.3	13.0	14.1	15.0	16.1	18.0	20.3	27.5	-	-	-
0	1791.8	1791.7	1791.7	1791.5	1791.3	1790.5	1789.3	1786.8	1779.5	1767.9	1746.6	1696.5	1668.8	1652.0
10	1306.0	1306.0	1305.9	1305.9	1305.8	1305.4	1304.9	1303.8	1300.7	1295.7	1286.6	1266.4	1256.7	1252.7
20	1001.6	1001.6	1001.6	1001.6	1001.6	1001.4	1001.2	1000.8	999.6	997.7	994.4	988.4	987.2	989.3
25	890.1	890.1	890.1	890.1	890.1	890.0	889.9	889.6	889.0	888.0	886.4	884.5	885.9	889.7
30	797.4	797.4	797.4	797.3	797.3	797.3	797.3	797.2	796.9	796.6	796.2	797.2	800.4	805.4
40	653.0	653.0	653.0	653.0	653.0	653.0	653.1	653.1	653.4	653.9	655.0	659.7	665.0	671.4
50	10.6	546.8	546.8	546.9	546.9	546.9	547.0	547.2	547.7	548.6	550.6	557.2	563.5	570.6
60	10.9	466.4	466.4	466.4	466.4	466.5	466.6	466.8	467.5	468.6	471.0	478.6	485.4	492.6
70	11.3	11.3	403.9	403.9	403.9	404.0	404.1	404.4	405.1	406.4	409.0	417.0	423.9	431.1
80	11.6	11.6	354.3	354.4	354.4	354.5	354.6	354.9	355.6	357.0	359.6	367.8	374.7	381.7
90	12.0	12.0	11.9	314.4	314.4	314.5	314.7	314.9	315.7	317.1	319.7	327.9	334.7	341.5
100	12.3	12.3	12.3	12.3	281.8	281.9	282.0	282.3	283.1	284.4	287.1	295.1	301.7	308.4
110	12.7	12.7	12.7	12.6	254.7	254.8	254.9	255.2	256.0	257.3	260.0	267.8	274.3	280.7
120	13.1	13.1	13.1	13.0	232.1	232.1	232.3	232.5	233.3	234.6	237.2	244.9	251.2	257.4
130	13.5	13.5	13.4	13.4	13.3	213.0	213.1	213.3	214.1	215.4	218.0	225.5	231.6	237.6
140	13.8	13.8	13.8	13.8	13.7	196.6	196.7	197.0	197.7	199.0	201.5	208.9	214.8	220.6
150	14.2	14.2	14.2	14.2	14.1	182.5	182.6	182.8	183.6	184.9	187.3	194.6	200.4	206.0
160	14.6	14.6	14.6	14.6	14.5	14.4	170.3	170.6	171.3	172.6	175.0	182.1	187.8	193.3
170	15.0	15.0	15.0	15.0	14.9	14.8	159.6	159.9	160.6	161.8	164.2	171.2	176.8	182.1
180	15.4	15.4	15.4	15.4	15.3	15.2	15.0	150.4	151.1	152.4	154.8	161.7	167.1	172.3
190	15.8	15.8	15.8	15.8	15.7	15.6	15.5	142.0	142.7	143.9	146.3	153.2	158.5	163.7
200	16.2	16.2	16.2	16.2	16.1	16.1	15.9	134.4	135.2	136.4	138.8	145.6	150.9	155.9
220	17.0	17.0	17.0	17.0	17.0	16.9	16.8	16.5	122.2	123.5	125.9	132.7	137.9	142.8
240	17.8	17.8	17.8	17.8	17.8	17.7	17.6	17.4	111.3	112.6	115.2	122.1	127.3	132.1
260	18.6	18.6	18.6	18.6	18.6	18.6	18.5	18.3	101.8	103.2	105.9	113.1	118.4	123.2
280	19.5	19.5	19.5	19.5	19.4	19.4	19.3	19.2	18.8	94.7	97.7	105.4	110.8	115.6
300	20.3	20.3	20.3	20.3	20.3	20.2	20.2	20.1	19.8	86.5	90.1	98.5	104.1	109.1
320	21.1	21.1	21.1	21.1	21.1	21.1	21.0	21.0	20.7	20.7	82.5	92.2	98.2	103.3
340	22.0	22.0	22.0	22.0	21.9	21.9	21.9	21.8	21.7	21.7	74.2	86.2	92.8	98.2
360	22.8	22.8	22.8	22.8	22.8	22.8	22.7	22.7	22.6	22.6	62.8	80.3	87.7	93.4
380	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.5	23.5	23.6	25.8	74.3	82.8	89.0
400	24.5	24.5	24.5	24.5	24.4	24.4	24.4	24.4	24.4	24.5	26.0	68.0	78.0	84.8
420	25.3	25.3	25.3	25.3	25.3	25.3	25.3	25.3	25.2	25.4	26.7	61.2	73.2	80.7
440	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.3	27.4	53.9	68.5	76.8
460	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	27.0	27.2	28.2	47.4	64.6	73.0
480	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	28.0	29.0	43.0	59.6	69.4
500	28.6	28.6	28.6	28.6	28.6	28.6	28.6	28.6	28.7	28.9	29.8	40.5	55.8	66.1
520	29.4	29.4	29.4	29:4	29.4	29.4	29.4	29.4	29.5	29.8	30.7	39.3	52.6	63.0
540	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.4	30.6	31.5	38.8	50.2	60.3
560	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.1	31.2	31.4	32.3	38.7	48.5	58.0
580	31.8	31.8	31.8	31.8	31.8	31.8	31.8	31.9	32.0	32.3	33.1	38.8	47.3	56.2
600	32.6	32.6	32.6	32.6	32.6	32.6	32.6	32.7	32.8	33.1	33.9	39.1	46.6	54.7

TABLE 3.6. (continued)

Temp. °C	Dynamic viscosity [μPa·s] at pressure (MPa)													
	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10	20	50	75	100
620	33.4	33.4	33.4	33.4	33.4	33.4	33.4	33.5	33.6	33.9	34.7	39.5	46.1	53.6
640	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.3	34.4	34.7	35.5	40.0	46.0	52.7
660	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.1	35.2	35.5	36.3	40.5	45.9	52.2
680	35.8	35.8	35.8	35.8	35.8	35.8	35.8	35.9	36.0	36.3	37.1	41.1	46.1	51.8
700	36.6	36.6	36.6	36.6	36.6	36.6	36.6	36.6	36.8	37.1	37.8	41.6	46.3	51.6
720	37.3	37.3	37.3	37.3	37.3	37.3	37.4	37.4	37.6	37.8	38.6	42.2	46.6	51.5
740	38.1	38.1	38.1	38.1	38.1	38.1	38.1	38.2	38.3	38.6	39.4	42.9	46.9	51.5
760	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	39.1	39.4	40.1	43.5	47.3	51.7
780	39.6	39.6	39.6	39.6	39.6	39.6	39.7	39.7	39.9	40.1	40.9	44.1	47.8	51.9
800	40.4	40.4	40.4	40.4	40.4	40.4	40.4	40.5	40.6	40.9	41.6	44.7	48.2	52.1

TABLE 3.7. THERMAL CONDUCTIVITY OF WATER AND STEAM

Temp. °C	Thermal conductivity [mW/(m·K)] at pressure (MPa)													
	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10	20	50	75	100
Water	635.7	650.8	667.8	677.6	683.6	683.6	674.7	654.4	600.5	524.5	403.7	-	-	-
Steam	19.9	21.1	23.0	24.8	27.0	31.0	35.4	41.6	55.6	79.0	226.5	-	-	-
0	562.0	562.0	562	562.0	562.1	562.3	562.6	563.2	564.9	567.8	573.6	590.3	603.5	616.0
10	581.9	581.9	581.9	582.0	582.0	582.2	582.5	583.0	584.7	587.5	593.0	608.8	621.4	633.4
20	599.5	599.5	599.5	599.5	599.6	599.7	600.0	600.6	602.2	604.8	610.1	625.4	637.5	649.1
25	607.5	607.5	607.5	607.5	607.6	607.7	608.0	608.5	610.1	612.7	617.9	633.0	645.0	656.4
30	615.0	615.0	615.0	615.0	615.1	615.2	615.5	616.0	617.6	620.2	625.3	640.2	652.1	663.4
40	628.6	628.6	628.6	628.6	628.7	628.8	629.1	629.6	631.1	633.7	638.8	653.5	665.1	676.3
50	20.3	640.5	640.5	640.5	640.6	640.7	641.0	641.5	643.0	645.6	650.6	665.2	676.8	687.8
60	21.0	650.8	650.8	650.8	650.9	651.0	651.3	651.8	653.3	655.9	661.0	675.5	687.1	698.1
70	21.8	21.9	659.6	659.6	659.7	659.8	660.1	660.6	662.2	664.8	669.8	684.5	696.1	707.2
80	22.6	22.7	667.0	667.0	667.0	667.2	667.5	668.0	669.6	672.2	677.4	692.2	703.9	715.1
90	23.4	23.5	23.6	673.0	673.1	673.2	673.5	674.1	675.7	678.3	683.6	698.7	710.5	721.8
100	24.3	24.3	24.4	24.8	677.8	678.0	678.3	678.8	680.5	683.2	688.6	704.0	716.0	727.5
110	25.1	25.1	25.2	25.5	681.3	681.5	681.8	682.3	684.1	686.9	692.4	708.2	720.5	732.1
120	26.0	26.0	26.1	26.3	683.6	683.8	684.1	684.7	686.4	689.4	695.1	711.3	723.8	735.7
130	26.8	26.8	26.9	27.1	27.6	684.9	685.2	685.9	687.7	690.7	696.6	713.3	726.2	738.4
140	27.7	27.7	27.8	27.9	28.4	685.0	685.3	685.9	687.8	691.0	697.1	714.3	727.7	740.2
150	28.6	28.6	28.7	28.8	29.2	683.9	684.2	684.9	686.9	690.2	696.5	714.4	728.2	741.0
160	29.5	29.5	29.6	29.7	30.0	31.4	682.1	682.8	684.9	688.3	695.0	713.6	727.8	741.0
170	30.4	30.4	30.5	30.6	30.8	32.0	678.9	679.6	681.8	685.4	692.4	711.8	726.5	740.2
180	31.4	31.4	31.4	31.5	31.7	32.7	35.4	675.4	677.7	681.5	688.9	709.1	724.5	738.6
190	32.3	32.3	32.3	32.4	32.6	33.4	35.6	670.1	672.6	676.6	684.4	705.6	721.6	736.2
200	33.2	33.3	33.3	33.4	33.5	34.2	36.1	663.8	666.4	670.7	678.9	701.3	717.9	733.2
220	35.2	35.2	35.2	35.3	35.4	36.0	37.3	41.5	650.9	655.8	665.2	690.2	708.4	724.9
240	37.2	37.2	37.2	37.3	37.4	37.8	38.8	41.8	630.9	636.7	647.5	675.8	696.0	714.0
260	39.2	39.2	39.2	39.3	39.4	39.8	40.6	42.8	606.0	613.0	625.8	658.4	681.0	700.8
280	41.3	41.3	41.3	41.4	41.5	41.8	42.5	44.2	53.7	584.0	599.7	637.8	663.3	685.2
300	43.4	43.4	43.4	43.5	43.6	43.9	44.5	46.0	53.0	548.1	568.3	614.0	643.0	667.4
320	45.6	45.6	45.6	45.7	45.7	46.0	46.6	47.8	53.5	74.7	530.4	586.8	620.3	647.6
340	47.8	47.8	47.8	47.9	47.9	48.2	48.7	49.8	54.5	69.8	483.1	556.0	595.1	625.9

TABLE 3.7. (continued)

Temp. °C	Thermal conductivity [mW/(m·K)] at pressure (MPa)													
	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10	20	50	75	100
360	50.0	50.0	50.1	50.1	50.2	50.4	50.9	51.9	56.0	67.7	419.8	521.1	567.4	602.3
380	52.3	52.3	52.3	52.4	52.5	52.7	53.1	54.1	57.6	66.7	129.4	481.7	537.2	576.9
400	54.6	54.7	54.7	54.7	54.8	55.0	55.4	56.3	59.5	67.2	103.4	438.3	504.7	550.0
420	57.0	57.0	57.0	57.1	57.2	57.4	57.8	58.6	61.6	68.3	94.6	391.5	470.4	521.9
440	59.4	59.4	59.4	59.5	59.5	59.8	60.1	60.9	63.7	69.7	90.8	342.0	434.7	492.7
460	61.9	61.9	61.9	61.9	62.0	62.2	62.6	63.3	65.9	71.4	89.1	289.0	398.9	463.1
480	64.3	64.3	64.4	64.4	64.5	64.7	65.0	65.8	68.2	73.3	88.7	240.3	363.9	433.5
500	66.8	66.8	66.9	66.9	67.0	67.2	67.5	68.2	70.6	75.3	89.1	205.5	330.9	404.8
520	69.4	69.4	69.4	69.4	69.5	69.7	70.0	70.7	73.0	77.5	90.0	182.8	300.6	377.7
560	74.6	74.6	74.6	74.6	74.7	74.9	75.2	75.8	77.9	82.0	92.7	158.5	251.4	329.9
580	77.2	77.2	77.2	77.2	77.3	77.5	77.8	78.4	80.5	84.3	94.4	152.0	233.4	309.6
600	79.8	79.9	79.9	79.9	80.0	80.1	80.4	81.0	83.0	86.8	96.2	147.7	219.2	291.7
620	82.5	82.5	82.6	82.6	82.6	82.8	83.1	83.7	85.6	89.2	98.2	144.8	208.2	276.2
640	85.2	85.3	85.3	85.3	85.4	85.5	85.8	86.4	88.2	91.7	100.3	142.9	199.8	263.0
660	88.0	88.0	88.0	88.0	88.1	88.2	88.5	89.1	90.9	94.3	102.5	141.9	193.3	252.0
680	90.7	90.7	90.8	90.8	90.8	91.0	91.3	91.8	93.6	96.9	104.7	141.4	188.3	242.7
700	93.5	93.5	93.5	93.6	93.6	93.8	94.0	94.6	96.3	99.5	107.0	141.4	184.5	235.0
720	96.3	96.3	96.3	96.4	96.4	96.6	96.8	97.4	99.0	102.1	109.4	141.8	181.7	228.7
740	99.1	99.1	99.2	99.2	99.2	99.4	99.6	100.2	101.8	104.8	111.8	142.5	179.6	223.5
760	102.0	102.0	102.0	102.0	102.1	102.2	102.5	103.0	104.6	107.5	114.3	143.5	178.2	219.3
780	104.8	104.8	104.8	104.9	104.9	105.1	105.3	105.8	107.4	110.2	116.8	144.6	177.2	215.9
800	107.7	107.7	107.7	107.7	107.8	107.9	108.2	108.6	110.2	113.0	119.3	145.9	176.7	213.2

TABLE 3.8. PRANDTL NUMBERS OF WATER AND STEAM

Temp. °C	Prandtl numbers at pressure (MPa)													
	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10	20	50	75	100
Water	3.86	2.99	2.19	1.76	1.44	1.14	0.98	0.88	0.84	0.96	3.23	-	-	-
Steam	1.02	1.02	1.02	1.03	1.04	1.09	1.15	1.24	1.44	1.83	5.54	-	-	-
0	13.45	13.45	13.45	13.45	13.44	13.43	13.41	13.36	13.22	12.99	12.57	11.56	10.94	10.47
10	9.42	9.42	9.42	9.41	9.41	9.40	9.39	9.37	9.29	9.17	8.95	8.41	8.07	7.80
20	6.99	6.99	6.99	6.99	6.99	6.99	6.98	6.96	6.92	6.85	6.73	6.41	6.21	6.05
25	6.13	6.13	6.13	6.13	6.13	6.12	6.12	6.11	6.07	6.02	5.92	5.67	5.52	5.39
30	5.42	5.42	5.42	5.42	5.42	5.42	5.41	5.40	5.38	5.34	5.26	5.06	4.94	4.84
40	4.34	4.34	4.34	4.34	4.34	4.34	4.34	4.33	4.31	4.29	4.24	4.11	4.03	3.97
50	1.01	3.57'	3.57	3.57	3.57	3.57	3.57	3.56	3.55	3.53	3.50	3.42	3.36	3.32
60	1.00	3.00	3.00	3.00	3.00	3.00	3.00	2.99	2.99	2.97	2.95	2.89	2.86	2.83
70	0.99	1.00	2.56	2.56	2.56	2.56	2.56	2.56	2.56	2.55	2.53	2.49	2.47	2.45
80	0.98	0.99	2.23	2.23	2.23	2.23	2.23	2.23	2.22	2.22	2.21	2.18	2.16	2.15
90	0.97	0.98	1.01	1.96	1.96	1.96	1.96	1.96	1.96	1.96	1.95	1.93	1.92	1.91
100	0.97	0.98	0.99	1.03	1.75	1.75	1.75	1.75	1.75	1.75	1.74	1.73	1.72	1.71
110	0.97	0.97	0.99	1.01	1.58	1.58	1.58	1.58	1.58	1.58	1.57	1.56	1.55	1.55
120	0.96	0.97	0.98	1.00	1.44	1.44	1.44	1.44	1.44	1.44	1.43	1.42	1.42	1.42
130	0.96	0.96	0.97	0.99	1.03	1.33	1.33	1.33	1.32	1.32	1.32	1.31	1.31	1.31
140	0.96	0.96	0.97	0.98	1.01	1.23	1.23	1.23	1.23	1.23	1.22	1.22	1.21	1.21

TABLE 3.8. (continued)

Temp. °C	Prandtl numbers at pressure (MPa)													
	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10	20	50	75	100
150	0.96	0.96	0.97	0.98	1.00	1.15	1.15	1.15	1.15	1.15	1.14	1.14	1.14	1.13
160	0.95	0.96	0.96	0.97	0.99	1.06	1.08	1.08	1.08	1.08	1.08	1.07	1.07	1.07
170	0.95	0.95	0.96	0.97	0.99	1.04	1.03	1.03	1.03	1.02	1.02	1.01	1.01	1.01
180	0.95	0.95	0.96	0.96	0.98	1.03	1.15	0.98	0.98	0.98	0.97	0.96	0.96	0.96
190	0.95	0.95	0.95	0.96	0.97	1.02	1.10	0.94	0.94	0.94	0.93	0.92	0.92	0.92
200	0.95	0.95	0.95	0.96	0.97	1.01	1.07	0.91	0.91	0.90	0.90	0.89	0.88	0.88
220	0.94	0.95	0.95	0.95	0.96	0.99	1.04	1.17	0.86	0.86	0.85	0.83	0.83	0.82
240	0.94	0.94	0.95	0.95	0.96	0.98	1.02	1.10	0.84	0.83	0.82	0.80	0.79	0.78
260	0.94	0.94	0.94	0.94	0.95	0.97	1.00	1.07	0.84	0.82	0.81	0.78	0.76	0.75
280	0.94	0.94	0.94	0.94	0.95	0.96	0.98	1.04	1.28	0.84	0.81	0.77	0.74	0.73
300	0.94	0.94	0.94	0.94	0.94	0.95	0.97	1.01	1.18	0.90	0.84	0.77	0.74	0.72
320	0.93	0.93	0.93	0.94	0.94	0.95	0.96	1.00	1.13	1.59	0.91	0.78	0.74	0.71
340	0.93	0.93	0.93	0.93	0.94	0.94	0.95	0.98	1.08	1.36	1.06	0.81	0.75	0.72
360	0.93	0.93	0.93	0.93	0.93	0.94	0.95	0.97	1.05	1.25	1.71	0.86	0.77	0.72
380	0.93	0.93	0.93	0.93	0.93	0.93	0.94	0.96	1.03	1.18	2.04	0.93	0.80	0.74
400	0.92	0.92	0.92	0.92	0.93	0.93	0.94	0.95	1.01	1.13	1.60	1.05	0.83	0.75
420	0.92	0.92	0.92	0.92	0.92	0.93	0.93	0.95	0.99	1.09	1.40	1.23	0.88	0.78
440	0.92	0.92	0.92	0.92	0.92	0.92	0.93	0.94	0.98	1.05	1.29	1.44	0.95	0.81
460	0.92	0.92	0.92	0.92	0.92	0.92	0.93	0.93	0.97	1.03	1.20	1-.57	' 1.02	0.84
480	0.91	0.91	0.91	0.91	0.92	0.92	0.92	0.93	0.96	1.01	1.15	1.54	1.08	0.88
500	0.91	0.91	0.91	0.91	0.91	0.91	0.92	0.93	0.95	0.99	1.10	1.44	1.12	0.91
520	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.92	0.94	0.98	1.07	1.34	1.14	0.94
540	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.92	0.93	0.97	1.04	1.25	1.14	0.96
560	0.90	0.90	0.90	0.90	0.90	0.91	0.91	0.91	0.93	0.96	1.01	1.18	1.13	0.97
580	0.90	0.90	0.90	0.90	0.90	0.90	0.91	0.91	0.92	0.95	1.00	1.13	1.10	0.97
600	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.91	0.92	0.94	0.98	1.09	1.07	0.97
620	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.91	0.93	0.97	1.05	1.04	0.97
640	0.89	0.89	0.89	0.89	0.90	0.90	0.90	0.90	0.91	0.92	0.96	1.03	1.02	0.95
660	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.90	0.91	0.92	0.95	1.00	1.00	0.94
680	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.90	0.91	0.94	0.98	0.98	0.93
700	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.90	0.91	0.93	0.97	0.96	0.92
720	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.90	0.90	0.92	0.95	0.94	0.91
740	0.88	0.88	0.88	0.88	0.88	0.88	0.89	0:89	0.89	0.90	0.91	0.94	0.93	0.90
760	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.89	0.90	0.91	0.93	0.92	0.89
780	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.89	0.89	0.90	0.92	0.91	0:88
800	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.89	0.90	0.91	0.90	0.87

3.3. HEAVY WATER (D_2O)

The values of t (°C), P (kPa), H (kJ/kg) and r (kJ/kg) for heavy water at saturation are taken from the Hill's tables [5]. The values ρ (kg/m^3) are defined from the relation $\rho=1/V$, where V (m^3/kg) is the specific volume presented in the Hill's tables. The values of C_p [kJ/(kg·K)], $\mu\cdot10^4$ (Pa·s) and $\lambda\cdot10^3$ [W/(m·K)] are calculated by means of the computer code presented on the Web site of University of Athens [6]. The values of $\nu\cdot10^6$ (m^2/s), $a\cdot10^7$ (m^2/s), Pr are evaluated by the formulas: $\nu = \mu/\rho$, $a = \lambda/(C_p\cdot\rho)$, $Pr = \nu/a$.

TABLE 3.9. THERMOPHYSICAL PROPERTIES OF HEAVY WATER (D_2O) AT SATURATION

Temp. °C	Pressure kPa	Density kg/m^3	Enthalpy kJ/kg	Specific heat kJ/kg	Heat capacity kJ/kg·K	Dynamic viscosity 10^4(Pa s)	Kinematic viscosity $10^6(m^2/s)$	Thermal diffusivity $10^7(m^2/s)$	Thermal conductivity 10^3W/(m·K)	Prandtl number	Surface tension 10^3N/m
3.80	0.660	1105.46	0.00	2327.7	4.2107	20.871	1.8880	1.213	564.5	15.568	74.77
4.61	0.700	1105.58	3.40	2321.6	4.2147	20.204	1.8275	1.215	566.0	15.045	74.65
5.00	0.720	1105.58	5.06	2320.6	4.2160	19.965	1.8058	1.215	566.5	14.856	74.61
9.63	1.000	1105.95	24.60	2308.9	4.2302	16.995	1.5367	1.227	574.0	12.525	73.97
10.00	1.026	1105.95	26.18	2307.9	4.2314	16.991	1.5363	1.227	574.2	12.521	73.92
14.56	1.400	1105.83	45.48	2296.2	4.2388	14.558	1.3165	1.240	581.3	10.616	73.28
15.00	1.442	1105.83	47.36	2295.1	4.2393	14.367	1.2992	1.241	581.9	10.467	73.22
20.00	1.999	1105.34	68.57	2282.3	4.2425	12.461	1.1273	1.255	588.6	8.982	72.50
20.01	2.000	1105.34	68.50	2282.3	4.2425	12.459	1.1272	1.255	588.7	8.979	72.50
25.00	2.737	1104.48	89.78	2269.4	4.2425	10.951	0.9915	1.269	594.8	7.811	71.77
26.50	3.000	1104.12	96.15	2265.5	4.2421	10.551	0.9556	1.274	596.6	7.502	71.54
30.00	3.702	1103.27	110.99	2256.5	4.2404	9.718	0.8808	1.283	600.4	6.863	71.02
31.32	4.000	1102.90	116.57	2253.1	4.2995	9.431	0.8551	1.269	601.8	6.738	70.82
35.00	4.950	1101.69	132.19	2243.7	4.2367	8.700	0.7897	1.297	605.6	6.086	70.25
35.18	5.000	1101.69	132.93	2243.2	4.2365	8.667	0.7867	1.298	605.7	6.062	70.24
38.42	6.000	1100.59	146.66	2234.8	4.2335	8.102	0.7361	1.307	608.8	5.634	69.72
40.00	6.549	1099.99	153.36	2230.8	4.2318	7.848	0.7135	1.311	610.2	5.443	69.47
43.69	8.000	1098.42	168.99	2221.2	4.2278	7.305	0.6650	1.321	613.4	5.035	68.89
45.00	8.575	1097.94	174.51	2217.9	4.2263	7.128	0.6492	1.324	614.4	4.903	68.74
47.93	10.000	1096.61	186.90	2210.3	4.2228	6.755	0.6160	1.332	616.6	4.626	68.20
50.00	11.121	1095.65	195.63	2205.0	4.2202	6.512	0.5944	1.337	618.2	4.445	67.86
51.50	12.000	1094.93	201.95	2201.1	4.2183	6.344	0.5794	1.341	619.3	4.331	67.62
54.59	14.000	1093.37	214.97	2193.1	4.2143	6.022	0.5508	1.348	621.3	4.085	67.12
55.00	14.289	1093.14	216.71	2192.1	4.2138	5.981	0.5471	1.349	621.6	4.054	67.04

TABLE 3.9. (continued)

Temp. °C	Pressure kPa	Density kg/m^3	Enthalpy kJ/kg	Specific heat kJ/kg	Heat capacity kJ/kg·K	Dynamic viscosity 10^4(Pa s)	Kinematic viscosity $10^6(m^2/s)$	Thermal diffusivity $10^7(m^2/s)$	Thermal conductivity 10^3W/(m·K)	Prandtl number	Surface tension 10^3N/m
57.32	16.000	1091.94	226.47	2186.1	4.2107	5.760	0.5275	1.355	623.0	3.893	66.65
59.77	18.000	1090.63	236.79	2179.7	4.2074	5.538	0.5078	1.361	624.4	3.732	66.23
60.00	18.200	1090.51	237.77	2179.1	4.2071	5.518	0.5060	1.361	624.6	3.717	66.20
62.00	20.000	1089.44	246.18	2174.0	4.2045	5.350	0.4911	1.366	625.6	3.596	65.85
64.05	22.000	1088.26	254.79	2168.6	4.2017	5.187	0.4766	1.371	626.7	3.478	65.53
65.00	22.297	1087.67	258.79	2166.2	4.2004	5.114	0.4702	1.373	627.2	3.425	65.34
67.71	26.00	1086.01	270.16	2159.2	4.1968	4.915	0.4526	1.379	628.4	3.283	64.87
70.00	28.80	1084.72	279.78	2153.2	4.1938	4.757	0.4385	1.384	629.4	3.170	64.47
70.92	30.00	1084.13	283.64	2150.8	4.1926	4.696	0.4332	1.386	629.8	3.126	64.31
73.79	34.00	1082.25	295.66	2143.3	4.1889	4.514	0.4171	1.392	630.9	2.997	63.80
75.00	35.82	1081.43	300.74	2140.2	4.1873	4.441	0.4107	1.394	631.3	2.946	63.58
77.60	40.00	1079.80	311.61	2133.4	4.1840	4.290	0.3973	1.399	632.2	2.839	63.12
80.00	44.23	1078.17	321.67	2127.1	4.1811	4.159	0.3857	1.404	632.9	2.747	62.69
80.95	46.00	1077.47	325.64	2124.6	4.1800	4.108	0.3813	1.406	633.1	2.712	62.51
82.99	50.00	1076.08	334.16	2119.3	4.1776	4.004	0.3721	1.410	633.7	2.640	62.14
85.00	54.23	1074.69	342.56	2114.0	4.1753	3.906	0.3635	1.413	634.1	2.572	61.77
87.54	60.00	1072.85	353.17	2107.3	4.1725	3.788	0.3531	1.418	634.6	2.491	61.31
90.00	66.07	1071.01	363.44	2100.8	4.1699	3.679	0.3435	1.422	635.0	2.416	60.85
91.50	70.00	1069.86	369.67	2096.9	4.1684	3.616	0.3380	1.425	635.3	2.373	60.57
95.00	79.98	1067.24	384.28	2087.6	4.1651	3.474	0.3255	1.430	635.7	2.276	59.91
95.01	80.00	1067.24	384.31	2087.5	4.1651	3.474	0.3255	1.430	635.7	2.276	59.91
98.17	90.00	1064.85	397.48	2079.1	4.1624	3.354	0.3150	1.435	635.9	2.195	59.31
100.00	96.25	1063.38	405.11	2074.2	4.1610	3.288	0.3092	1.437	636.0	2.151	59.96
101.05	100.00	1062.47	409.48	2071.4	4.1603	3.251	0.3060	1.439	636.0	2.127	58.76

TABLE 3.9. (continued)

Temp. °C	Pressure kPa	Density kg/m^3	Enthalpy kJ/kg	Specific heat kJ/kg	Heat capacity kJ/kg·K	Dynamic viscosity 10^4(Pa s)	Kinematic viscosity $10^6(m^2/s)$	Thermal diffusivity $10^7(m^2/s)$	Thermal conductivity 10^3W/(m·K)	Prandtl number	Surface tension 10^3N/m
103.71	110.00	1060.33	420.53	2064.2	4.1585	3.162	0.2982	1.443	636.1	2.067	58.24
105.00	115.17	1059.32	425.92	2060.7	4.1577	3.119	0.2944	1.444	636.0	2.039	57.99
106.17	120.00	1058.31	430.77	2057.6	4.1570	3.082	0.2912	1.446	636.0	2.014	57.77
108.46	130.00	1058.65	440.33	2051.4	4.1559	3.011	0.2844	1.445	635.9	1.968	57.32
110.00	137.06	1058.54	446.72	2047.2	4.1552	2.965	0.2801	1.446	635.8	1.938	57.02
110.62	140.00	1054.63	449.29	2045.5	4.1550	2.947	0.2794	1.451	635.8	1.926	56.89
114.58	160.00	1051.19	465.73	2034.6	4.1537	2.835	0.2697	1.455	635.4	1.853	56.11
115.00	162.27	1050.86	467.50	2033.5	4.1536	2.824	0.2687	1.455	635.3	1.846	56.03
118.15	180.00	1048.11	480.58	2024.7	4.1532	2.741	0.2615	1.459	634.9	1.793	55.40
119.81	190.00	1046.57	487.51	2020.1	4.1531	2.699	0.2579	1.460	634.6	1.766	55.06
120.00	191.10	1046.46	488.29	2019.6	4.1531	2.694	0.2574	1.460	634.6	1.763	55.03
121.41	200.00	1045.15	494.14	2015.7	4.1531	2.660	0.2545	1.461	634.3	1.742	54.74
124.41	220.00	1042.43	506.63	2007.2	4.1535	2.589	0.2484	1.464	633.7	1.697	54.13
125.00	224.10	1041.88	509.08	2005.6	4.1536	2.575	0.2471	1.464	633.5	1.688	54.01
127.20	240.00	1039.83	518.22	1999.3	4.1541	2.526	0.2429	1.465	633.0	1.658	53.36
129.81	260.00	1037.34	529.06	1991.9	4.1551	2.469	0.2380	1.466	632.0	1.623	53.03
130.00	261.50	1037.24	529.87	1991.4	4.1552	2.465	0.2377	1.467	632.3	1.620	52.99
131.65	280.00	1035.09	539.84	1984.9	4.1563	2.419	0.2337	1.468	631.6	1.592	52.52
134.56	300.0	1032.84	548.86	1978.2	4.1577	2.372	0.2297	1.469	630.9	1.563	52.04
135.00	303.9	1032.42	550.68	1977.0	4.1579	2.364	0.2290	1.469	630.8	1.558	51.95
136.75	320.0	1030.72	557.97	1971.9	4.1592	2.330	0.2261	1.470	630.2	1.538	51.58
138.83	340.0	1028.70	566.64	1965.8	4.1609	2.291	0.2227	1.471	629.5	1.514	51.15
140.00	351.7	1027.54	571.51	1962.3	4.1619	2.269	0.2208	1.471	629.1	1.501	50.90
140.82	360.0	1026.69	574.90	1959.9	4.1627	2.255	0.2196	1.471	628.8	1.493	50.73

TABLE 3.9. (continued)

Temp. °C	Pressure kPa	Density kg/m^3	Enthalpy kJ/kg	Specific heat kJ/kg	Heat capacity kJ/kg·K	Dynamic viscosity 10^4(Pa s)	Kinematic viscosity 10^6(m^2/s)	Thermal diffusivity 10^7(m^2/s)	Thermal conductivity 10^3W/(m·K)	Prandtl number	Surface tension 10^3N/m
142.71	380.0	1024.80	582.81	1954.3	4.1646	2.221	0.2167	1.471	628.0	1.473	50.33
144.53	400.0	1022.91	590.40	1948.9	4.1665	2.190	0.2141	1.472	627.3	1.455	49.94
145.00	405.3	1022.39	592.36	1947.5	4.1671	2.182	0.2134	1.472	627.1	1.450	49.85
146.28	420.0	1021.14	597.69	1943.7	4.1678	2.161	0.2116	1.472	626.6	1.437	49.57
147.96	440.0	1019.37	604.71	1938.6	4.1707	2.133	0.2092	1.472	625.8	1.422	49.21
149.58	460.0	1017.71	611.48	1933.7	4.1729	2.107	0.2070	1.472	625.1	1.407	48.87
150.00	465.3	1017.29	613.24	1932.4	4.1735	2.100	0.2064	1.472	624.9	1.403	48.78
151.14	480.0	1016.05	618.02	1928.9	4.1752	2.083	0.2050	1.472	624.4	1.393	48.53
152.66	500.0	1014.40	624.36	1924.2	4.1755	2.059	0.2030	1.473	623.7	1.379	48.20
154.12	520.0	1012.86	630.49	1919.7	4.1798	2.037	0.2011	1.472	623.0	1.367	47.89
155.00	532.3	1011.94	634.17	1917.0	4.1812	2.024	0.2000	1.471	622.5	1.359	47.70
155.54	540.0	1011.33	636.45	1915.3	4.1822	2.016	0.1993	1.471	622.2	1.355	47.58
156.92	560.0	1009.90	642.23	1911.0	4.1846	1.996	0.1976	1.471	621.5	1.344	47.28
158.27	580.0	1008.37	647.86	1906.8	4.1870	1.997	0.1980	1.470	620.8	1.334	46.99
159.57	600.0	1006.95	653.33	1902.7	4.1894	1.959	0.1945	1.470	620.1	1.324	46.70
160.00	606.7	1006.54	655.13	1901.3	4.1903	1.953	0.1940	1.470	619.9	1.320	46.61
160.84	620.0	1005.63	658.67	1898.7	4.1919	1.942	0.1931	1.470	619.5	1.314	46.43
162.08	640.0	1004.22	663.87	1894.7	4.1944	1.925	0.1917	1.469	618.8	1.305	46.15
163.29	660.0	1002.91	668.95	1890.9	4.1996	1.909	0.1903	1.468	618.1	1.297	45.89
164.47	680.0	1001.60	673.91	1887.1	4.1994	1.894	0.1891	1.468	617.4	1.288	45.63
165.00	689.2	1001.00	676.15	1885.4	4.2000	1.887	0.1885	1.468	617.1	1.284	45.51
165.20	700.0	1000.30	678.76	1883.4	4.2020	1.879	0.1878	1.467	616.7	1.280	45.38
166.75	720.0	999.00	683.50	1879.7	4.2045	1.865	0.1867	1.467	616.1	1.273	45.13
167.85	740.0	997.71	688.15	1876.1	4.2071	1.851	0.1855	1.466	615.4	1.265	44.88

TABLE 3.9. (continued)

Temp. °C	Pressure kPa	Density kg/m^3	Enthalpy kJ/kg	Specific heat kJ/kg	Heat capacity kJ/kg·K	Dynamic viscosity 10^4(Pa s)	Kinematic viscosity $10^6(m^2/s)$	Thermal diffusivity $10^7(m^2/s)$	Thermal conductivity 10^3W/(m·K)	Prandtl number	Surface tension 10^3N/m
168.93	760.0	996.51	692.70	1872.6	4.2097	1.837	0.1843	1.466	614.8	1.258	44.64
169.98	780.0	995.32	697.15	1869.1	4.2123	1.825	0.1834	1.465	614.1	1.252	44.41
170.00	780.3	995.22	697.23	1869.1	4.2123	1.824	0.1833	1.465	614.1	1.251	44.41
171.02	800.0	994.04	701.52	1865.7	4.2149	1.812	0.1823	1.464	613.5	1.245	44.18
172.03	820.0	992.95	705.81	1862.4	4.2175	1.800	0.1813	1.463	612.8	1.239	43.95
173.03	840.0	991.77	710.02	1859.1	4.2201	1.788	0.1803	1.463	612.2	1.233	43.73
174.00	860.0	990.59	714.15	1855.8	4.2227	1.777	0.1794	1.462	611.5	1.227	43.51
174.96	880.0	989.51	718.21	1852.6	4.2253	1.766	0.1785	1.461	610.9	1.221	43.30
175.00	880.8	989.41	718.37	1852.5	4.2254	1.766	0.1785	1.461	610.9	1.221	43.30
175.90	900.0	988.34	722.20	1849.4	4.2279	1.756	0.1777	1.461	610.3	1.216	43.09
176.83	920.0	987.26	726.12	1846.3	4.2305	1.745	0.1768	1.460	609.7	1.211	42.88
177.74	940.0	986.19	729.98	1843.2	4.2332	1.735	0.1759	1.459	609.0	1.206	42.67
178.19	960.0	985.61	733.78	1840.1	4.2358	1.725	0.1750	1.457	608.4	1.201	42.47
179.51	980.0	984.06	737.52	1837.1	4.2384	1.716	0.1744	1.457	607.8	1.197	42.28
180.00	981.2	983.48	739.58	1835.5	4.2399	1.711	0.1740	1.457	607.5	1.194	42.17
180.38	1000.0	982.99	741.20	1834.2	4.2410	1.707	0.1737	1.457	607.2	1.192	42.08
182.07	1040.0	980.97	748.39	1828.3	4.2463	1.689	0.1722	1.455	606.0	1.183	41.70
183.71	1080.0	978.95	755.38	1822.6	4.2516	1.672	0.1708	1.453	604.8	1.175	41.33
184.52	1100.0	978.00	758.81	1819.6	4.2542	1.663	0.1700	1.452	604.3	1.171	41.14
185.00	1112.2	977.33	760.87	1818.1	4.2558	1.659	0.1697	1.452	603.9	1.169	41.03
186.09	1140.0	975.99	765.51	1814.3	4.2595	1.648	0.1689	1.451	603.1	1.164	40.79
187.62	1180.0	974.09	772.05	1808.8	4.2648	1.633	0.1676	1.449	601.9	1.157	40.44
188.37	1200.0	973.14	775.25	1806.2	4.2674	1.625	0.1670	1.448	601.4	1.153	40.27
190.00	1244.5	971.16	782.25	1800.3	4.2733	1.609	0.1657	1.446	600.1	1.146	39.89

TABLE 3.9. (continued)

Temp. °C	Pressure kPa	Density kg/m^3	Enthalpy kJ/kg	Specific heat kJ/kg	Heat capacity kJ/kg·K	Dynamic viscosity 10^4(Pa s)	Kinematic viscosity 10^6(m^2/s)	Thermal diffusivity 10^7(m^2/s)	Thermal conductivity 10^3W/(m·K)	Prandtl number	Surface tension 10^3N/m
190.56	1260.0	970.40	784.64	1798.3	4.2753	1.604	0.1653	1.445	599.7	1.144	39.77
191.97	1300.0	968.62	790.71	1793.2	4.2806	1.591	0.1643	1.444	598.6	1.138	39.44
193.35	1340.0	966.84	796.64	1788.2	4.2859	1.578	0.1632	1.442	597.5	1.132	39.12
194.70	1380.0	965.16	802.45	1783.2	4.2911	1.566	0.1623	1.440	596.4	1.127	38.81
195.00	1388.9	964.79	803.72	1782.1	4.2923	1.563	0.1620	1.440	596.2	1.125	38.75
195.37	1400.0	964.23	805.30	1780.8	4.2938	1.560	0.1618	1.439	595.9	1.124	38.66
197.31	1460.0	961.72	813.69	1773.6	4.3017	1.542	0.1603	1.437	594.3	1.116	38.21
198.58	1500.0	960.06	819.15	1768.9	4.3070	1.531	0.1595	1.435	593.2	1.112	37.92
200.00	1546.0	958.22	825.29	1763.5	4.3130	1.519	0.1585	1.432	592.0	1.107	37.59
203.10	1650.0	954.11	838.70	1751.8	4.3267	1.493	0.1565	1.428	589.4	1.096	36.87
204.53	1700.0	952.20	844.93	1746.3	4.3332	1.481	0.1555	1.425	588.1	1.091	36.54
205.00	1716.6	951.57	846.97	1744.3	4.3354	1.477	0.1552	1.425	587.7	1.090	36.43
207.30	1800.0	948.41	856.99	1735.5	4.3463	1.459	0.1538	1.420	585.5	1.083	35.90
209.96	1900.0	944.73	868.59	1725.1	4.3595	1.438	0.1522	1.416	583.3	1.075	35.28
210.00	1901.5	944.73	868.76	1724.9	4.3597	1.438	0.1522	1.416	583.2	1.075	35.27
212.51	2000.0	941.18	879.75	1714.9	4.3726	1.418	0.1507	1.412	580.9	1.067	34.68
214.96	2100.0	937.73	890.52	1705.0	4.3857	1.400	0.1493	1.407	578.6	1.061	34.10
215.00	2101.5	937.73	890.68	1704.8	4.3859	1.400	0.1493	1.407	578.6	1.061	34.10
217.33	2200.0	934.40	900.93	1695.3	4.3989	1.383	0.1480	1.402	576.3	1.056	33.55
220.00	2317.5	930.58	912.73	1684.3	4.4143	1.364	0.1466	1.397	573.7	1.050	32.92
223.95	2500.0	924.81	930.27	1667.6	4.4384	1.336	0.1445	1.454	569.8	1.041	31.98
225.00	2550.1	923.28	934.93	1663.1	4.4451	1.329	0.1439	1.386	568.7	1.039	31.74
228.04	2700	918.70	948.49	1650.0	4.4650	1.309	0.1425	1.379	565.6	1.033	31.02
230.00	2800	915.75	957.28	1641.4	4.4784	1.297	0.1416	1.374	563.5	1.031	30.55

TABLE 3.9. (continued)

Temp. °C	Pressure kPa	Density kg/m^3	Enthalpy kJ/kg	Specific heat kJ/kg	Heat capacity kJ/kg·K	Dynamic viscosity 10^4(Pa s)	Kinematic viscosity 10^6(m^2/s)	Thermal diffusivity 10^7(m^2/s)	Thermal conductivity 10^3W/(m·K)	Prandtl number	Surface tension 10^3N/m
233.75	3000	910.00	974.14	1624.8	4.5052	1.273	0.1399	1.365	559.5	1.025	29.66
235.00	3069	908.02	979.79	1619.1	4.5145	1.265	0.1393	1.362	558.2	1.023	29.36
237.31	3200	904.40	990.27	1608.1	4.5323	1.251	0.1383	1.355	555.6	1.021	28.81
240.00	3357	900.17	1002.48	1596.2	4.5538	1.235	0.1372	1.348	552.7	1.018	28.17
240.71	3400	899.04	1005.74	1592.9	4.5597	1.231	0.1369	1.346	551.9	1.017	28.00
243.96	3600	893.73	1020.61	1577.6	4.5874	1.212	0.1356	1.337	548.2	1.013	27.22
245.00	3666	892.06	1025.37	1572.6	4.5965	1.206	0.1352	1.334	547.0	1.013	26.98
247.08	3800	888.65	1034.97	1562.6	4.6154	1.197	0.1344	1.331	545.9	1.012	26.48
250.00	3995	883.78	1048.45	1548.3	4.6431	1.178	0.1333	1.319	541.1	1.011	25.78
250.07	4000	883.63	1048.78	1548.0	4.6438	1.177	0.1332	1.318	541.0	1.010	25.76
252.95	4200	878.73	1062.17	1533.6	4.6726	1.162	0.1322	1.309	537.6	1.010	25.08
255.00	4347	875.20	1071.76	1523.2	4.6941	1.151	0.1315	1.302	535.1	1.010	24.59
257.08	4500	871.61	1081.51	1512.6	4.7167	1.140	0.1308	1.295	532.5	1.010	24.09
260.00	4722	866.48	1095.31	1497.4	4.7500	1.125	0.1298	1.285	528.9	1.010	23.39
261.00	4800	864.68	1100.04	1492.1	4.7618	1.120	0.1295	1.281	527.6	1.011	23.15
263.51	5000	860.14	1112.00	1478.1	4.7925	1.107	0.1287	1.272	524.4	1.012	22.55
265.00	5122	857.41	1119.12	1470.7	4.8114	1.099	0.1282	1.267	522.5	1.012	22.19
267.14	5300	853.46	1129.38	1459.0	4.8396	1.089	0.1276	1.258	519.7	1.014	21.68
269.47	5500	849.11	1140.64	1446.1	4.8717	1.077	0.1268	1.249	516.7	1.015	21.13
270.00	5546	848.10	1143.10	1443.1	4.8729	1.075	0.1268	1.249	516.0	1.015	21.00
272.85	5800	842.60	1157.07	1426.9	4.9211	1.061	0.1259	1.235	512.2	1.019	20.32
275.00	5997	838.43	1167.61	1414.5	4.9543	1.051	0.1254	1.226	509.3	1.022	19.81
275.03	6000	838.43	1167.75	1414.3	4.9548	1.050	0.1252	1.226	509.2	1.022	19.80
277.15	6200	834.24	1178.22	1401.9	4.9892	1.040	0.1247	1.216	506.3	1.025	19.29

TABLE 3.9. (continued)

Temp. °C	Pressure kPa	Density kg/m^3	Enthalpy kJ/kg	Specific heat kJ/kg	Heat capacity kJ/kg·K	Dynamic viscosity 10^4(Pa s)	Kinematic viscosity 10^6(m^2/s)	Thermal diffusivity 10^7(m^2/s)	Thermal conductivity 10^3W/(m·K)	Prandtl number	Surface tension 10^3N/m
280.00	6476	828.50	1192.33	1384.9	5.0379	1.027	0.1240	1.204	502.4	1.030	18.62
281.25	6600	825.97	1198.58	1377.3	5.0603	1.021	0.1236	1.198	500.7	1.032	18.32
283.23	6800	821.90	1208.50	1365.1	5.0969	1.012	0.1231	1.189	497.9	1.036	17.85
285.00	6983	818.20	1217.43	1354.1	5.1313	1.004	0.1227	1.180	495.4	1.040	17.43
285.16	7000	817.86	1218.25	1353.1	5.1344	1.003	0.1226	1.179	495.2	1.040	17.40
287.06	7200	813.87	1227.86	1341.1	5.1728	0.995	0.1223	1.170	492.5	1.045	16.95
290.00	7520	807.56	1242.92	1322.1	5.2360	0.981	0.1215	1.155	488.2	1.052	16.26
290.72	7600	805.93	1246.64	1317.4	5.2522	0.978	0.1214	1.151	487.1	1.054	16.09
294.24	8000	798.15	1264.90	1293.9	5.3355	0.962	0.1205	1.132	482.0	1.065	15.26
295.00	8088	796.43	1268.85	1288.8	5.3543	0.959	0.1204	1.127	480.8	1.068	15.08
296.80	8300	792.33	1278.29	1276.5	5.4007	0.951	0.1200	1.117	478.1	1.074	14.67
298.46	8600	788.46	1291.44	1259.1	5.4685	0.940	0.1192	1.100	474.4	1.083	14.09
300.00	8688	784.87	1295.28	1254.0	5.4890	0.936	0.1193	1.099	473.4	1.086	13.92
300.90	8800	782.72	1300.09	1247.6	5.5151	0.932	0.1191	1.093	471.9	1.090	13.71
302.49	9000	778.94	1308.63	1236.1	5.5631	0.925	0.1188	1.083	469.5	1.097	13.34
304.83	9300	773.22	1321.29	1218.9	5.6375	0.915	0.1183	1.069	465.9	1.107	12.81
305.00	9323	772.80	1322.24	1217.6	5.6433	0.914	0.1183	1.068	465.6	1.108	12.77
306.35	9500	769.47	1329.63	1207.4	5.6889	0.908	0.1180	1.059	463.5	1.114	12.46
308.59	9800	763.77	1341.99	1190.3	5.7689	0.898	0.1176	1.044	460.0	1.126	11.94
310.00	9992	760.17	1349.82	1179.3	5.8219	0.892	0.1173	1.034	457.7	1.134	11.62
310.06	10000	759.99	1350.14	1178.9	5.8242	0.892	0.1174	1.034	457.6	1.135	11.61
312.21	10300	754.38	1362.24	1161.8	5.9103	0.882	0.1169	1.019	454.2	1.147	11.12
313.62	10500	750.58	1370.23	1150.4	5.9700	0.876	0.1167	1.008	451.9	1.158	10.81
315.00	10698	746.88	1378.08	1139.1	6.0311	0.869	0.1164	0.998	449.7	1.166	10.49

TABLE 3.9. (continued)

Temp. °C	Pressure kPa	Density kg/m^3	Enthalpy kJ/kg	Specific heat kJ/kg	Heat capacity kJ/kg·K	Dynamic viscosity 10^4(Pa s)	Kinematic viscosity $10^6(m^2/s)$	Thermal diffusivity $10^7(m^2/s)$	Thermal conductivity 10^3W/(m·K)	Prandtl number	Surface tension 10^3N/m
316.38	10900	743.05	1386.03	1127.6	6.0954	0.863	0.1161	0.988	447.5	1.175	10.19
317.06	11000	741.18	1389.95	1121.8	6.1280	0.860	0.1160	0.983	446.4	1.180	10.03
318.40	11200	737.41	1397.74	1110.4	6.1950	0.854	0.1158	0.972	444.2	1.191	9.74
320.00	11442	732.82	1407.13	1096.5	6.2793	0.847	0.1156	0.960	441.6	1.204	9.38
321.03	11600	729.87	1413.19	1087.5	6.3361	0.842	0.1154	0.951	439.9	1.213	9.15
323.58	12000	722.28	1428.48	1064.4	6.4879	0.830	0.1149	0.930	435.7	1.236	8.59
324.00	12067	721.03	1431.01	1060.6	6.5143	0.828	0.1148	0.926	435.0	1.240	8.50
324.83	12200	718.49	1436.06	1052.9	6.5682	0.824	0.1147	0.919	433.6	1.248	8.32
325.45	12300	716.59	1439.84	1047.1	6.6095	0.821	0.1146	0.913	432.5	1.255	8.19
327.29	12600	710.83	1451.14	1029.6	6.7386	0.813	0.1144	0.897	429.8	1.275	7.79
328.00	12717	708.57	1455.54	1022.8	6.7912	0.804	0.1135	0.890	427.9	1.275	7.64
328.50	12800	707.01	1458.64	1017.9	6.8291	0.807	0.1141	0.885	427.4	1.289	7.53
329.69	13000	703.14	1466.11	1006.2	6.9235	0.801	0.1139	0.874	425.4	1.303	7.28
335.43	14000	683.53	1503.19	946.6	7.4651	0.773	0.1131	0.815	415.7	1.388	6.07
337.60	14400	675.54	1517.96	922.2	7.7215	0.761	0.1127	0.790	411.9	1.427	5.61
338.00	14467	674.17	1520.41	918.1	7.7668	0.759	0.1126	0.785	411.3	1.434	5.54
339.79	14800	667.42	1532.72	897.4	8.0067	0.750	0.1124	0.764	408.3	1.471	5.18
340.00	14839	666.62	1534.14	895.0	8.0359	0.749	0.1124	0.761	407.9	1.477	5.13
340.86	15000	666.36	1540.10	884.9	8.1617	0.744	0.1117	0.747	406.5	1.495	4.96
342.94	15400	653.77	1554.91	859.5	8.5009	0.733	0.1121	0.725	402.9	1.546	4.55
344.00	15606	650.53	1562.80	846.2	8.6928	0.727	0.1118	0.709	401.1	1.577	4.34
344.99	15800	646.37	1568.78	833.5	8.8857	0.721	0.1115	0.696	399.5	1.602	4.15
345.99	16000	642.01	1577.26	820.3	9.0983	0.715	0.1114	0.681	397.8	1.636	3.95
346.99	16200	637.63	1584.71	806.9	9.3263	0.709	0.1112	0.666	396.2	1.669	3.76

TABLE 3.9. (continued)

Temp. °C	Pressure kPa	Density kg/m^3	Enthalpy kJ/kg	Specific heat kJ/kg	Heat capacity kJ/kg·K	Dynamic viscosity 10^4(Pa s)	Kinematic viscosity $10^6(m^2/s)$	Thermal diffusivity $10^7(m^2/s)$	Thermal conductivity 10^3W/(m·K)	Prandtl number	Surface tension 10^3N/m
348.00	16406	633.03	1592.53	793.0	9.5790	0.703	0.1111	0.651	394.5	1.707	3.57
348.95	16600	628.61	1599.90	779.6	9.8366	0.697	0.1109	0.636	393.0	1.744	3.39
350.00	16818	623.60	1608.23	764.4	10.1505	0.691	0.1108	0.618	391.4	1.793	3.19
350.87	17000	619.31	1615.22	751.5	10.4350	0.685	0.1106	0.604	390.1	1.831	3.03
352.75	17400	609.68	1630.80	722.3	11.1468	0.672	0.1102	0.570	387.4	1.933	2.69
354.00	17669	602.99	1641.47	702.1	11.7083	0.664	0.1101	0.546	385.8	2.016	2.47
354.60	17800	599.70	1646.71	692.1	12.0098	0.659	0.1099	0.535	385.1	2.054	2.36
355.51	18000	594.46	1654.82	676.4	12.5138	0.653	0.1098	0.516	384.1	2.128	2.21
358.00	18557	579.24	1678.06	630.7	14.2710	0.633	0.1093	0.462	382.3	2.366	1.78
358.19	18600	578.03	1679.92	627.0	14.4340	0.632	0.1093	0.458	382.2	2.387	1.75
359.07	18800	572.21	1688.61	609.5	15.2597	0.625	0.1092	0.438	382.1	2.493	1.61
359.93	19000	566.16	1697.51	591.4	16.2144	0.617	0.1090	0.416	382.3	2.620	1.47
360.00	19015	565.67	1698.20	590.0	16.2937	0.616	0.1089	0.415	382.4	2.624	1.46
361.65	19400	553.34	1716.04	553.1	18.6538	0.601	0.1086	0.372	384.3	2.919	1.20
363.33	19800	539.20	1735.89	511.0	22.1974	0.584	0.1083	0.325	389.0	3.332	0.95
364.00	19962	532.99	1744.45	492.6	24.1379	0.576	0.1081	0.305	392.1	3.544	0.85
364.16	20000	531.49	1746.48	488.2	24.6439	0.575	0.1082	0.300	392.9	3.607	0.83
365.79	20400	514.32	1769.56	437.3	32.0097	0.554	0.1077	0.246	405.7	4.378	0.60
367.39	20800	493.44	1796.65	375.5	46.7156	0.530	0.1074	0.186	429.4	5.774	0.40
368.00	20953	483.51	1809.12	347.6	57.0439	0.519	0.1073	0.161	443.5	6.665	0.33
368.18	21000	480.40	1813.05	339.2	61.2034	0.515	0.1072	0.153	448.5	7.007	0.30
369.74	21400	444.46	1857.32	237.0	The calculation in the near-critical region is uncertain.						
370.00	21467	435.33	1868.42	211.9	-	-	-	-	-	-	-
370.74	21660	358.00	1965.73	0.0	critical point						

3.4. LIQUID METALS

The history of the study of thermophysical properties of liquid metals in the Russian Federation has been over five decades long. In the early 1950s the properties of liquid metals, which were a totally new class of coolants, were unknown. The development of this type of coolants was associated with new requirements of nuclear power engineering, in particular with the development of fast sodium cooled reactors.

As compared with other coolants (gas, water), liquid metals have two major advantages, such as low pressure in the system (owing to their high boiling point) and high thermal conductivity owing to their electron conductivity. The use of liquid metal coolants made it possible to provide high rate of heat transfer in power plants as well as the temperatures of working surfaces of their constructions close to coolant temperature [7, 10].

The most significant research in this field were carried out in 1950–1970 years. The first tables on thermophysical properties of liquid metals were developed on the basis of the results of experimental investigations performed in ENIN [28] by the initiative of Academician A.I. Leipunsky, the IPPE's research supervisor. These tables were included in many well known monographs [7, 10–14].

Further development of nuclear power engineering required the study of properties of liquid metal coolants such as lead, Pb-Bi alloy, lithium, cesium, Na-K alloy, etc. In particular, lead is considered promising for applications in new generation reactors as well as for targets of accelerator-driven systems.

It has been found that a number of thermophysical properties of liquid metals have a pronounced effect on the features of both hydrodynamic and heat-mass transfer processes in power plants. Specifically, relatively low Prandtl and Peclet numbers typical of liquid metals offer no advantages in terms of decreasing temperature nonuniformities in NPP designs as compared with water. The disadvantage of many liquid metals is also their high chemical activity at interaction with oxygen, water and structural materials, which may cause heat transfer deterioration in the plant under certain conditions [11].

The basic results of long-term studies on thermophysical properties of liquid metals are presented in the reviews and monographs [7, 11, 18, 19, 26, 27, 30, 39, 40, 45, 46].

3.4.1. Basic thermophysical properties (Li, Na, K, Cs, Hg, Pb, Bi, Ga, In, alloys NaK, NaKCs, PbBi, PbLi)

Basis thermophysical properties of Li, Na, K, and Cs are shown in Table 3.10 [34], basic thermophysical properties of Hg, Pb, Ga, and In are shown in Table 3.11 [34], and thermophysical properties of NaK, NaKCs, PbBi and PbLi alloys in Table 3.12 [9].

3.4.2. Approximate correlations and comments to tables on thermophysical properties (Li, Na, K, Cs, Hg, Pb, Bi, Ga, In, alloys NaK, NaKCs, PbBi, PbLi)

In the course of deriving the tables on density, the correlation in Ref. [40] was used because we believe that it is the most exact. We have established that data presented in other Refs [11, 19, 39, 46] are related to lithium contained 0.3–0.5 wt.% of various impurities and they are taken in Ref. [39].

Other properties of alkaline metals have been detailed in the monograph [12] where more reliable sources were used in addition. The same data are available also in other recent monographs [25, 33]. Other properties were calculated by the formulas: a (m^2/s) = $\lambda/(C_p \cdot \rho)$; ν (m^2/s) = μ/ρ; Pr = ν/a.

TABLE 3.10. BASIC THERMOPHYSICAL PROPERTIES OF Li, Na, K, Cs [34]

Property		Li	Na	K	Cs
Atomic number		3	11	19	55
Atomic mass, amu		6.94	22.99	39.1	132.9
Melting point	°C	180.5	98	63.6	28.5
	K	453.7	371	336.8	301.6
Boiling point	°C	1347	883	774	678
	K	1620	1156	1047	951.6
Heat of fusion,	kJ/mol	663	113.1	61.4	15.73
	kJ/kg	4.6	2.64	2.40	2.09
Heat of vapourization	kJ/mol	19409	3873	1983	495.9
	kJ/kg	134.7	89.04	77.53	65.90
Density, kg/m^3	solid at 20°C	534	966	862	1873
	liquid at 450°C	491	844	739	1597
Heat capacity kJ/(kg·K)	solid 20°C	3.569	1.230	0.756	0.242
	liquid 450°C	4.205	1.272	0.763	0.220
Thermal conductivity W/(m·K)	solid 20°C	84.7	130	102.4	35.9
	liquid 450°C	51.3	71.2	41.9	18.5
Viscosity at 450°C, m^2/s		7.1×10^{-7}	3×10^{-7}	2.4×10^{-7}	1.28×10^{-7}
Prandtl number at 450°C		0.0287	0.0045	0.0032	0.0021
Surface tension at 450°C, mN/m		371	164	84.9	50.4
Volume change on melting, %		+3.9	+2.65	+2.5	+2.7
Critical temperature, K		3503±10	2497±18	2239±49	2035±23
Critical pressure, Mpa		38.42±0.54	25.22±0.6	15.95±0.6	11.46±0.4
Critical density, kg/m^3		110.4±0.5	212±2	192±6	425±7
Compressibility $z=P_cV_c/RT_c$		0.0832	0.132	0.175	0.212

TABLE 3.11. BASIC THERMOPHYSICAL PROPERTIES OF Hg, Pb, Bi, Ga, In [34]

Property		Hg	Pb	Bi	Ga	In
Atomic number		80	82	83	31	49
Atomic mass, amu		200.6	207.2	209.0	69.72	114.82
Melting point,	°C	–38.9	327.4	271.4	29.8	156.2
	K	234.3	600.8	544	302.9	429.32
Boiling point, °C	°C	356.7	1745	1552	2403	2080
	K	629.7	2018	1825	2676	2353
Heat of fusion,	kJ/kg	11.62	24.7	50.15	80.2	28.47
	kJ/mol	2.331	5.12	10.48	5.59	3.27
Heat of vapourization,	kJ/kg	294.9	865.8	857	3673	1972
	kJ/mol	59.15	179.4	179.1	256.1	226.4
Density, kg/m^3	solid at 20°C	14.193 (–38.9°C)	11340	9780	5907	7310
	liquid at 450°C	12510	10520	9854	5822	7010
Heat capacity, kJ/(kg·K)	solid at 20°C	27.98	0.127	0.129	0.371	0.238
	liquid at 450°C	0.137	0.147	0.150	0.380	0.252
Thermal conductivity, W/(m·K)	solid at 20°C	8.34	35	8.4	40.6	81.6
	liquid at 450°C	13	17.1	14.2	50.9	48
Viscosity at 450°C, m^2/s		0.66×10^{-7}	1.9×10^{-7}	1.3×10^{-7}	1.59×10^{-7}	-
Prandtl number at 450°C		0.0087	0.0174	0.0135	0.0069	-
Surface tension at 450°C, mN/m		359	438	370	693	540
Volume change at melting, %		+3.7	+3.6	–3.3	–3.2	+3.94
Critical temperature, K		1763±15	5000±200	5100±200	7200±200	6600±200
Critical pressure, Mpa		153.5	180±30	150	400±50	250±50
Critical density, kg/m^3		5300±100	3250±100	2660±200	1760±50	2000±100
Compressibility $z = P_cV_c/RT_c$		0.0396	0.276	0.278	0.265	0.262

TABLE 3.12. BASIC THERMOPHYSICAL PROPERTIES OF NaK, NaKCs, PbBi, PbLi ALLOYS [9]

Property		NaK	NaKCs	PbBi	PbLi
Atomic number		34	76.8	208.2	173.16
Melting point	°C	–12.6	–78	125	235
	K	260.5	195	398	508
Boiling point	°C	784	-	1638	-
	K	1057	-	1911	-
Heat of fusion	kJ/mol	-	-	38.9	29.6
	kJ/kg	-	-	8.09	5.12
Heat of vapourization	kJ/mol	-	-	862	-
	kJ/kg	-	-	179.2	-
Density, kg/m^3	solid at 20°C	-	-	10474	9495
	liquid at 450°C	759	1235	10150	9326
Heat capacity kJ/(kg·K)	solid at 20°C	-	-	0.128	~0.250
	liquid at 450°C	0.873	0.384	0.146	~0.175
Thermal conductivity W/(m·K)	solid at 20°C	-	-	10	~40
	liquid at 450°C	26	13.7	14.2	~51
Viscosity at 450°C, m^2/s		2.4×10^{-7}	1.54×10^{-7}	1.4×10^{-7}	1.3×10^{-7}
Prandtl number at 450°C		0.0063	0.0053	0.0147	0.027
Surface tension at 450°C, mN/m		110	81	393	436 (?)
Volume change on melting, %		+2.5	+2.6	~+0.5	+3.6 (?)
Weight fractions of components in alloy		22/78	4.2/22.1/73.7	44.5/55.5	99.32/0.6
Molar fractions of components in alloy		32/68	13.9/43.5/42.6	43.7/56.3	83/17

3.4.2.1. Lithium [11, 25, 33, 40]

Density

$$\rho\cdot 10^{-3}\ (kg/m^3) = 0.53799943 - 0.016043986(T \times 10^{-3}) - 0.099963362(T \times 10^{-3})^2 + 0.054609894\cdot(T \times 10^{-3})^3 - 0.015087628(T \times 10^{-3})^4 + 0.0027045593(T \times 10^{-3})^5 - 0.00031537739(T \times 10^{-3})^6. \quad (3.1)$$

Heat capacity

$$C_p\ [J/(kg\cdot K)] = (31.227 + 0.205 \times 10^6\ T^{-2} - 5.265 \times 10^{-3} T + 2.628 \times 10^{-6}\ T^2)/6.941. \quad (3.2)$$

Thermal conductivity

$$\lambda\ [W/(m\cdot K)] = 24.8 + 45.0 \times 10^{-3}\cdot T - 11.6 \times 10^{-6}\cdot T^2. \quad (3.3)$$

Dynamic viscosity

$$\ln\mu\ (Pa\cdot s) = -4.16435 - 0.63740 \ln T + 292.1/T. \quad (3.4)$$

Surface tension

$$\sigma\ (\mathrm{N/m}) = 438.98 - 18.44 \times 10^{-3}T - 132.20 \times 10^{-6}\,T^2 + 37.44 \times 10^{-9}T^3. \qquad (3.5)$$

Vapour pressure

$$\ln P_s\ (\mathrm{MPa}) = -2.0532\ln(T \times 10^{-3}) - 19.4268(T \times 10^{-3})^{-1} + 9.4993 + 0.753(T \times 10^{-3}). \qquad (3.6)$$

Electrical resistivity

$$\rho_e\ (\Omega\cdot\mathrm{m}) = [0.9249 \times 10^9\cdot T^{-1} + 2.3167 \times 10^6 - 0.7131 \times 10^3\cdot T]^{-1}. \qquad (3.7)$$

3.4.2.2. Sodium [11, 40]

Density

$$\begin{aligned}\rho\cdot 10^{-3}\ (\mathrm{kg/m^3}) = {} & 0.89660679 + 0.5161343(T \times 10^{-3}) - 1.8297218(T \times 10^{-3})^2 + \\ & + 2.2016247(T \times 10^{-3})^3 - 1.3975634(T \times 10^{-3})^4 + 0.44866894(T \times 10^{-3})^5 - \\ & - 0.057963628(T \times 10^{-3})^6 \qquad (3.8)\end{aligned}$$

Heat capacity

$$C_p\ [\mathrm{J/(kg\cdot K)}] = (38.12 - 0.069 \times 10^6\cdot T^{-2} - 19.493 \times 10^{-3}\cdot T + 10.24 \times 10^6\cdot T^2)/22.99. \qquad (3.9)$$

Thermal conductivity

$$\lambda\ [\mathrm{W/(m\cdot K)}] = 99.5 - 39.1 \times 10^{-3}T. \qquad (3.10)$$

Dynamic viscosity

$$\ln\mu\ (\mathrm{Pa\cdot s}) = -6.4406 - 0.39580\ln T + 556.8/T. \qquad (3.11)$$

Surface tension

$$\sigma\ (\mathrm{N/m}) = 247.00 - 142.3 \times 10^{-3}\cdot T + 50.33 \times 10^{-6}T^2 - 16.62 \times 10^{-9}\cdot T^3. \qquad (3.12)$$

Vapour pressure

$$\begin{aligned}\ln P_s\ (\mathrm{MPa}) = {} & -2.4946\ln(T \times 10^{-3}) - 13.2905(T \times 10^{-3})^{-1} + 7.8441 + \\ & + 1.7093(T \times 10^{-3})\, 0.1716(T \times 10^{-3})^2 - 0.0088(T \times 10^{-3})^3 - \\ & - 0.0091(T \times 10^{-3})^4 + 0.0029(T \times 10^{-3})^5 \qquad (3.13\end{aligned}$$

Electrical resistivity

$$\rho_e\ (\Omega\cdot\mathrm{m}) = [4.9053 \times 10^9\cdot T^{-1} - 2.7768 \times 10^6 + 0.4329 \times 10^3\cdot T]^{-1}. \qquad (3.14)$$

3.4.2.3. Potassium [40]

Density

$$\begin{aligned}\rho\cdot 10^{-3}\ (\mathrm{kg/m^3}) = {} & 0.90281376 - 0.16990711(T \times 10^{-3}) - 0.26864769(T \times 10^{-3})^2 - \\ & - 0.50568188(T \times 10^{-3})^3 - 0.46537912(T \times 10^{-3})^4 + \\ & + 0.20378107(T \times 10^{-3})^5 - 0.034771308(T \times 10^{-3})^6. \qquad (3.15)\end{aligned}$$

Heat capacity

$$C_p\ [\mathrm{J/(kg\cdot K)}] = (39.288 - 0.086 \times 10^6T^{-2} - 24.334 \times 10^{-3}T + 15.863 \times 10^{-6}T^2)/39.098. \qquad (3.16)$$

Thermal conductivity

λ [W/(m·K)] = 60.5 – 25.8 × 10^{-3}T. (3.17)

Dynamic viscosity
$\ln\mu$ (Pa·s) = – 6.4846 – 0.42903·lnT + 485.3/T. (3.18)

Surface tension
σ (N/m) = 130.48 – 45.72 × 10^{-3}·T – 32.65 × 10^{-6}·T^2 + 12.12 × 10^{-9}·T^3. (3.19)

Vapour pressure
$\ln P_s$(MPa) = –0.9875ln(T × 10^{-3}) – 10.8427(T × $10^{-3})^{-1}$ + 8.9156 – 1.5573(T·10^{-3}) +
+ 1.1129(T × $10^{-3})^2$ – –0.1124(T × $10^{-3})^3$ – 0.1276(T × $10^{-3})^4$ +
+ 0.0324(T × $10^{-3})^5$. (3.20)

Electrical resistivity
ρ_e (Ω·m) = [2.9394 × 10^9 × T^{-1} – 1.6125 × 10^6 + 0.1580 × 10^3T]$^{-1}$. (3.21)

3.4.2.4. Caesium [40]

Density
ρ × 10^{-3} (kg/m^3) = 1.9058924 + 0.29801989(T × 10^{-3}) – 2.8529531(T × $10^{-3})^2$ +
+ 4.6810162(T × $10^{-3})^3$ –4.0361819(T × $10^{-3})^4$ +
+ 1.736613(T × $10^{-3})^5$ – 0.29684317(T × $10^{-3})^6$. (3.22)

Heat capacity
C_p [J/(kg·K)]= (46.727 – 0.363 × 10^6 T^{-2} – 40.865 × 10^{-3}T + 24.449 × $10^{-6}T^2$)/132.9. (3.23)

Thermal conductivity
λ [W/(m·K)] = 18.9 + 4.1 × 10^{-3}T – 6.5 × $10^{-6}T^2$. (3.24)

Dynamic viscosity
$\ln\mu$ (Pa·s) = – 6.4072 – 0.40767 lnT + 432.8/T. (3.25)

Surface tension
σ (N/m) = 88.02 – 59.49 × 10^{-3} T + 13.30 × 10^{-6} T^2 – 4.04 × 10^{-9} T^3. (3.26)

Vapour pressure
$\ln P_s$ (MPa)= – 0.7063ln (T × 10^{-3}) – 9.3205(T × $10^{-3})^{-1}$ + 8.7226 –
– 2.4528(T × 10^{-3}) +1.2463(T × $10^{-3})^2$ + 0.4933(T × $10^{-3})^3$
– 0.5969(T × $10^{-3})^4$ +0.135(T × $10^{-3})^5$. (3.27)

Electrical resistivity
ρ_e (Ω·m) = [0.8185 × 10^9·T^{-1}+ 0.1684 × 10^6 – 0.2678 × 10^3·T]$^{-1}$. (3.28)

3.4.2.5. Mercury [15, 16, 27, 28, 34]

Thermophysical and transport properties of mercury are given in Refs [16 (1971), 34 (1991)].

Density [15]
$\rho\,(kg/m^3) = 13595\,(1 - 1.8144 \times 10^{-4}\,t - 7.016 \times 10^{-9}\,t^2 - 2.8625 \times 10^{-11}\,t^3 -$
$- 2.617 \times 10^{-14}\,t^4).$ (3.29)

Heat capacity
$C_p\,[J/(kg{\cdot}K)] = 0.1508 - 6.630 \times {\cdot}10^{-5}T + 6.4185 \times 10^{-8}T^2 + 0.8049/T.$ (3.30)

Thermal conductivity
$\lambda\,[W/(m{\cdot}K)] = 8.178 + 1.36 \times 10^{-2}\,t - 6.378 \times 10^{-6}t^2.$ (3.31)

Dynamic viscosity at T = (303–773) K
$\mu\,(Pa{\cdot}s) = 0.31 \times 10^{-3}\,T^{\,0.07939}\,\exp(341.13/T).$ (3.32)

Surface tension [15]
$\sigma\,(mN/m) = 497 - 0.281(T - 234).$ (3.33)

Volumetric expansion coefficient
$\overline{\beta}\cdot 10^{\,4}\,(1/K) = 1.8144 + 7.016 \times 10^{-5}\,t + 2.8625 \times 10^{-7}\,t^2 + 2.617 \times 10^{-10}\,t^3\,.$ (3.34)

Electrical resistivity at t = (–39 ÷ 1000) °C
$(\rho/\rho_0)_e{\cdot}10^8(\Omega{\cdot}m) = 1 + 0.8896 \times 10^{-3}\,t + 1.0075 \times 10^{-6}\,t^2 - 1.05 \times 10^{-10}\,t^3 +$
$+ 2.702 \times 10^{-13}\,t^4 + 1.199 \times 10^{-15}\,t^5,$ (3.35)
where $\rho_0 = 0.9407 \times 10^{-6}$ ohm·m in Ref. [8]; $\rho_0 = 0.9412 \times 10^{-6}$ ohm·m in Ref. [6a]

Vapour pressure
$\ln P_s(Pa) = 33.197 - 7765.6/T - 1.5337\,\ln T + 0.864 \times 10^{-3}\,T.$ (3.36)

Sound velocity for $t = t_{melt} - 200°C$.
$a\,(m/s) = 1460 - 7765.6/T - 0.4671\,t \pm 1$ m/s. (3.37)

3.4.2.6. Gallium [30, 34, 36]

Density at T = (303–1000) K [30 (1982)]
$\rho{\cdot}10^{-3}\,(kg/m^3) = (6.262 \pm 0.01) - (6.682 \pm 0.035) \times 10^{-4}T + (4.35 \pm 0.015) \times 10^{-8}T^2.$
(3.38)

Heat capacity at T = (303–1500) K [34(1991)]
$C_p\,[J/(kg{\cdot}K)] = 417.781 - 753.308 \times 10^{-4}T + 322.371 \times 10^{-7}T^2.$ (3.39)

Thermal conductivity at T = (303–1500) [30 (1982)]
$\lambda\,[W/(m{\cdot}K)] = 7.08 + 8.014 \times 10^{-2}T - 2.7 \times 10^{-5}T^2.$
(3.40)

Kinematic viscosity at T = (303–773) K

$\nu \cdot 10^7$ (m^2/s) =28.6 + 2.0 × 10^{-2} T + 3.27 × $10^{-6}T^2$. (3.41)

Formula (3.41) was derived by approximation the data in Ref. [158] cited in Ref. [36].

Surface tension at T = (303–773) K (in Ref. [34 (1991):

σ (N/m) =708 – 3.9 × 10^{-5}(T – 303). (3.42)

Electrical resistivity at *T* = (303–1500) K (in Ref. [30 (1982):

$\rho_e \cdot 10^8(\Omega \cdot m)$ = (19.322 ± 0.04) + (2.206 ± 0.035) × 10^{-2}T – (2.09 ± 0.012) × $10^{-6}T^2$. (3.43)

3.4.2.7. Lead [9, 21, 28, 30, 31, 34, 41]

Density

$\rho \cdot 10^{-3}$ (kg/m^3) = (11.42 ± 0.01) – (12.42 ± 0.012) × 10^{-4}T. (3.44)

Heat capacity C_p = 147.3 J/(kg·K).

Thermal conductivity in Ref. [41]:

λ [W/(m·K)] = 15.8 + 108 × 10^{-4} (T – 600.4). (3.45)

Kinematic viscosity at T = (303–773) K

$\nu \cdot 10^8$ (m^2/s) = 15.87 × 10^3/T – 2.65. (3.46)

Formula (3.46) is empirical; it was derived on the basis of experimental data obtained by N.A. Nikolsky *et al.* in Ref. [28].

Surface tension in Ref. [31]:

σ (N/m) = 446 – 0.064(T – 600). (3.47)

Electrical resistivity,

at T = (600–1200) K in Ref. [30]:

$\rho_e \cdot 10^8$ ($\Omega \cdot m$) = (65.73 ± 0.15) + (4.65 ± 0.05) × 10^{-2}T. (3.48)

at T = (1000–2400) K in Ref. [9]:

$\rho_e \cdot 10^8$ ($\Omega \cdot m$) = – 84.5 + 0.3655*T* – 2.135 × $10^{-4}T^2$ + 4.77 × $10^{-8}T^3$. (3.49)

3.4.2.8. 22Na-78K alloy [40]

Density was calculated on the basis of the additivity law by weight fractions:

$1/\rho_{NaK}$= $0.22/\rho_{Na}$·+ $0.78/\rho_K$. (3.50)

Heat capacity was defined on the basis of the additivity law by weight fractions:
C_p [J/(kg·K)]= $0.22C_p(Na) + 0.78C_p(K)$. (3.51)

Thermal conductivity
λ [W/(m·K)]= $15.0006 + 30.2877 \times 10^{-3}T - 20.8095 \times 10^{-6}\cdot T^2$. (3.52)

Kinematic viscosity
$\nu\cdot 10^8$ (m^2/s)= $200.7657 - 0.734683\cdot T + 1.12102\cdot \times 10^{-3}\cdot T^2 -$
$-0.774427 \times 10^{-6}\cdot T^3 + 0.200382 \times 10^{-9}\cdot T^4$ (3.53)

Surface tension was evaluated on the basis of the additivity law by molar fractions:
σ (N/m) = $\sigma_{Na}\cdot 0.32 + \sigma_K\cdot 0.68$. (3.54)

Vapour pressure in terms of MPa was calculated by the Raoult's law.

Electrical resistivity
$\rho_e\cdot 10^8$ (Ω·m) = $0.0570831\cdot t + 33.8419$. (3.55)

3.4.2.9. 4.2Na-22.2K-73.6Cs alloy [40]

Density was defined on the basis of the additivity law by weight fractions:
$1/\rho = 0.0416/\rho_{Na} + 0.2014/\rho_K + 0.737/\rho_{Cs}$. (3.56)

Heat capacity was calculated on the basis of the additivity law by weight fractions:
C_p [J/(kg·K)]= $(42.8 - 35.3 \times 10^{-3}\cdot T + 23.4 \times 10^{-6}\cdot T^2)/76.81$.
(3.57)

Thermal conductivity
λ [W/(m·K)] = $8.2 + 27.3 \times 10^{-3}\cdot T - 41.0 \times 10^{-6}\cdot T^2 + 16.1 \times 10^{-9}\cdot T^3$.
(3.58)

Dynamic viscosity
$\ln\mu$ (Pa·s) = $-6.954 - 0.353\ln T + 511.3/T$. (3.59)

Surface tension was estimated on the basis of the additivity law by molar fractions:
σ (N/m) = $\sigma_{Na}\cdot 0.139 + \sigma_K\cdot 0.435 + \sigma_{Cs}\cdot 0.426$. (3.60

Vapour pressure
$\ln P$ (MPa)= $0.434 \ln(T \times 10^{-3}) - 8.433(T \times 10^{-3})^{-1} + 6.208$. (3.61)

Electrical resistivity
$\rho_e\cdot 10^8$ (Ω·m) = $0.23\cdot T/\lambda$. (3.62)

3.4.2.10. 44.5Pb–55.5Bi alloy [21, 22, 28, 30, 31]

Density was evaluated on the basis of the additivity law by weight fractions:

$\rho \cdot 10^{-3}$ (kg/m^3) = (11.05 ± 0.01) – (12.49 ± 0.012) × 10^{-4}T. (3.63)

Heat capacity C_p = 146 J/(kg·K).

Thermal conductivity. Taking into account the closeness of atomic weights of alloy components, their weight and volume percentages (Pb – 0.491, Bi – 0.509), the justified assessments of alloy thermal conductivity can be made by the additivity law. The data of such calculation are in a full agreement with the experimental data in Ref. [28].

Kinematic viscosity in terms of m^2/s was evaluated by approximation of experimental data in Ref. [28]:

$\nu \cdot 10^8$ (m^2/s) = 68.9 – 0.126T + 6.95 × $10^{-5} \cdot T^2$. (3.64

Surface tension. Taking into account the closeness of the values of surface tension of pure alloy components, it can be assumed that the additivity law will be adequately true that gives the following formula:

σ (N/m) = 416 – 0.0703(T – 398). (3.65)

This result is confirmed by direct measurements in Ref. [31].

Electrical resistivity according to the data in Ref. [22]:

$\rho_e \cdot 10^8$ (Ω·m) = (83.35 ± 0.5) + (5.23 ± 0.09) × 10^{-2}T, (3.66)

and according to the additivity law ρ_e(Pb) and ρ_e(Bi) are practically consistent.

3.4.2.11. 99.32Pb–0.684Li (Li17Pb83) alloy [19, 25, 44, 47, 48]

Weight fractions of components in alloy: Li – 0.00681; Pb – 0.99319.

Density

$\rho \cdot 10^{-3}$ (kg/m^3) = 9499 – 0.850 (t – 235), (3.67)

where t is temperature, °C. The approximated formula (3.60) was derived by averaging the values of density estimated by the following three methods:

1) calculation on the basis of the additivity law by volume fractions,
$\rho \cdot 10^{-3}$ (kg/m^3) = 9482 –1.145 (t – 235). (3.68)
2) approximation of data in Ref. [41] carried out in Ref. [47],
$\rho \cdot 10^{-3}$ (kg/m^3) = 9495 – 0.695 (t – 235). (3.69)
3) from calculation performed by G.Kuhlborsch, F.Reiter (Nucl. Eng. Des./Fusion, 1984, Vol.1, No 2) that based on the experimental data obtained by H.Ruppersberg and W. Speicher (Z. Naturfor., 1976, Bd. 31a, S. 47),
$\rho \cdot 10^{-3}$ (kg/m^3) = 9519 – 0.71 (t – 235). (3.70)

Heat capacity was evaluated as the mean value of heat capacity calculated by two methods:

1) by the additivity law,
C_p [J/(kg·K)]= C_{pLi}·0.00681 + C_{pPb}·0.99319; (3.71)
2) by approximation of data in Ref. [44],
C_p [J/(kg·K)]= $190.4 - 0.925 \times 10^{-2}$ (t – 235). (3.72)

Thermal conductivity

The calculating formula was derived by approximation of the data in Ref. [44]:

λ [W/(m·K)] = $11.9 + 1.96 \times 10^{-2}$ (t 235). (3.73)

Dynamic viscosity

μ (mPa·s) = 0.1828 exp(11400/RT), (3.74)

where R is the universal gas constant = 8.314 J/(mol·K).

Formula (3.74) was derived as mean values of dynamic viscosity given in two corresponding references:

1) in Ref. [19] – μ (mPa·s) = 0.1786 exp(11160/RT). (3.75)
2) in Ref. [47] with reference to B. Schulz, KfK, Personal communication, later published in Fusion Eng. Des., 1991, Vol. 14,
at $508 < T < 623$ K

μ (mPa·s) = 0.187 exp(11640/RT). (3.76)

Surface tension was calculated by extrapolation of the data in Ref. [19]:

σ (N/m) = 0.497194 – 0.000136595 t. (3.77)

Vapour pressure was estimated by approximation of the data in Ref. [19]:

$\lg P_s$ (MPa) = 10 – 9870/T. (3.78)

Electrical resistivity in terms of Ω·m is based on the data given in Ref. [44].

3.4.3. Tables of thermophysical properties

TABLE 3.13. PROPERTIES OF LITHIUM BY EQS (3.1–3.7)

Temperature		Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6(m^2/s)	Kinematic viscosity 10^8(m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure MPa	Electrical resistivity 10^8(Ω·m)
K	°C									
473	200	513	4357	43.5	19.45	110.79	5.70	404.6	1.290E-07	25.4
483	210	512	4348	43.8	19.68	108.10	5.49	403.5	2.914E-07	25.7
493	220	512	4339	44.2	19.90	105.56	5.30	402.2	6.366E-07	26.0
503	230	511	4330	44.5	20.12	103.16	5.13	401.0	1.347E-06	26.3
513	240	510	4322	44.8	20.35	100.89	4.96	399.8	2.768E-06	26.6
523	250	509	4314	45.2	20.57	98.74	4.80	398.5	5.529E-06	26.9
533	260	508	4306	45.5	20.79	96.70	4.65	397.3	1.076E-05	27.2
543	270	507	4299	45.8	21.01	94.76	4.51	396.0	2.041E-05	27.5
553	280	507	4292	46.1	21.22	92.91	4.38	394.7	3.783E-05	27.8
563	290	506	4285	46.5	21.44	91.15	4.25	393.4	6.857E-05	28.1
573	300	505	4279	46.8	21.66	89.48	4.13	392.1	1.217E-04	28.4
583	310	504	4272	47.1	21.87	87.88	4.02	390.7	2.117E-04	28.7
593	320	503	4266	47.4	22.09	86.35	3.91	389.4	3.612E-04	29.0
603	330	502	4260	47.7	22.30	84.89	3.81	388.0	6.055E-04	29.2
613	340	501	4255	48.0	22.52	83.49	3.71	386.6	9.976E-04	29.5
623	350	500	4249	48.3	22.73	82.15	3.61	385.2	1.617E-03	29.8
633	360	499	4244	48.6	22.94	80.86	3.52	383.8	2.581E-03	30.1
643	370	499	4239	48.9	23.16	79.63	3.44	382.4	4.058E-03	30.3
653	380	498	4234	49.2	23.37	78.45	3.36	381.0	6.292E-03	30.6
663	390	497	4230	49.5	23.58	77.31	3.28	379.6	9.624E-03	30.9
673	400	496	4225	49.8	23.79	76.22	3.20	378.1	1.453E-02	31.1
683	410	495	4221	50.1	24.00	75.17	3.13	376.6	2.168E-02	31.4
693	420	494	4217	50.4	24.20	74.15	3.06	375.2	3.196E-02	31.7
703	430	493	4213	50.7	24.41	73.18	3.00	373.7	4.659E-02	31.9
713	440	492	4209	51.0	24.62	72.24	2.93	372.2	6.718E-02	32.2
723	450	491	4205	51.3	24.83	71.33	2.87	370.7	9.589E-02	32.5

TABLE 3.13. (continued)

Temperature K	Temperature °C	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6(m^2/s)	Kinematic viscosity 10^8(m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure MPa	Electrical resistivity 10^8(Ω·m)
733	460	490	4201	51.6	25.03	70.46	2.81	369.2	1.355E-01	32.7
743	470	489	4198	51.8	25.24	69.61	2.76	367.7	1.897E-01	33.0
753	480	488	4195	52.1	25.44	68.80	2.70	366.1	2.632E-01	33.2
763	490	487	4191	52.4	25.64	68.01	2.65	364.6	3.619E-01	33.5
773	500	486	4188	52.7	25.85	67.25	2.60	363.0	4.935E-01	33.8
783	510	485	4185	52.9	26.05	66.51	2.55	361.5	6.676E-01	34.0
793	520	484	4183	53.2	26.25	65.79	2.51	359.9	8.961E-01	34.3
803	530	483	4180	53.5	26.45	65.10	2.46	358.3	1.194E+00	34.5
813	540	483	4177	53.7	26.65	64.43	2.42	356.7	1.579E+00	34.8
823	550	482	4175	54.0	26.85	63.78	2.38	355.1	2.074E+00	35.0
833	560	481	4172	54.2	27.05	63.15	2.33	353.5	2.707E+00	35.3
843	570	480	4170	54.5	27.25	62.54	2.30	351.9	3.509E+00	35.6
853	580	479	4168	54.7	27.44	61.95	2.26	350.3	4.522E+00	35.8
863	590	478	4166	55.0	27.64	61.37	2.22	348.7	5.792E+00	36.1
873	600	477	4164	55.2	27.84	60.81	2.18	347.0	7.375E+00	36.3
883	610	476	4162	55.5	28.03	60.27	2.15	345.4	9.340E+00	36.6
893	620	475	4161	55.7	28.22	59.74	2.12	343.8	1.176E+01	36.8
903	630	474	4159	56.0	28.42	59.23	2.08	342.1	1.474E+01	37.1
913	640	473	4157	56.2	28.61	58.73	2.05	340.4	1.838E+01	37.3
923	650	472	4156	56.5	28.80	58.25	2.02	338.8	2.280E+01	37.6
933	660	471	4155	56.7	28.99	57.77	1.99	337.1	2.816E+01	37.8
943	670	470	4154	56.9	29.18	57.32	1.96	335.4	3.462E+01	38.1
953	680	469	4152	57.2	29.37	56.87	1.94	333.8	4.237E+01	38.4
963	690	468	4151	57.4	29.56	56.43	1.91	332.1	5.163E+01	38.6
973	700	467	4151	57.6	29.74	56.01	1.88	330.4	6.266E+01	38.9
983	710	466	4150	57.8	29.93	55.59	1.86	328.7	7.575E+01	39.1
993	720	465	4149	58.1	30.11	55.19	1.83	327.0	9.121E+01	39.4
1003	730	464	4148	58.3	30.30	54.80	1.81	325.3	1.094E+02	39.6
1013	740	463	4148	58.5	30.48	54.41	1.79	323.6	1.308E+02	39.9
1023	750	462	4147	58.7	30.66	54.04	1.76	321.9	1.558E+02	40.1
1033	760	461	4147	58.9	30.84	53.68	1.74	320.1	1.849E+02	40.4
1043	770	460	4147	59.1	31.02	53.32	1.72	318.4	2.187E+02	40.7
1053	780	459	4147	59.3	31.20	52.97	1.70	316.7	2.579E+02	40.9
1063	790	458	4147	59.5	31.38	52.63	1.68	315.0	3.032E+02	41.2
1073	800	457	4147	59.7	31.55	52.30	1.66	313.2	3.553E+02	41.4
1083	810	456	4147	59.9	31.73	51.98	1.64	311.5	4.152E+02	41.7
1093	820	454	4147	60.1	31.90	51.66	1.62	309.8	4.837E+02	42.0
1103	830	453	4147	60.3	32.07	51.35	1.60	308.1	5.619E+02	42.2
1113	840	452	4148	60.5	32.25	51.05	1.58	306.3	6.511E+02	42.5
1123	850	451	4148	60.7	32.42	50.76	1.57	304.6	7.524E+02	42.7
1133	860	450	4149	60.9	32.59	50.47	1.55	302.8	8.672E+02	43.0
1143	870	449	4149	61.1	32.75	50.19	1.53	301.1	9.970E+02	43.3
1153	880	448	4150	61.3	32.92	49.91	1.52	299.4	1.143E+03	43.5
1163	890	447	4151	61.5	33.09	49.64	1.50	297.6	1.308E+03	43.8
1173	900	446	4152	61.6	33.25	49.38	1.48	295.9	1.493E+03	44.1
1183	910	445	4153	61.8	33.42	49.12	1.47	294.1	1.701E+03	44.4
1193	920	444	4154	62.0	33.58	48.86	1.46	292.4	1.933E+03	44.6
1203	930	443	4155	62.2	33.74	48.62	1.44	290.7	2.192E+03	44.9
1213	940	442	4156	62.3	33.90	48.37	1.43	288.9	2.481E+03	45.2

TABLE 3.13. (continued)

Temperature K	Temperature °C	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity $10^6(m^2/s)$	Kinematic viscosity $10^8(m^2/s)$	10^2 Prandtl number	Surface tension $10^3N/m$	Pressure MPa	Electrical resistivity $10^8(\Omega\cdot m)$
1223	950	441	4157	62.5	34.06	48.14	1.41	287.2	2.801E+03	45.4
1233	960	440	4159	62.7	34.21	47.90	1.40	285.4	3.157E+03	45.7
1243	970	439	4160	62.8	34.37	47.68	1.39	283.7	3.552E+03	46.0
1253	980	438	4162	63.0	34.52	47.45	1.37	282.0	3.988E+03	46.3
1263	990	437	4163	63.1	34.67	47.23	1.36	280.2	4.469E+03	46.6
1273	1000	436	4165	63.3	34.82	47.02	1.35	278.5	5.000E+03	46.8
1283	1010	435	4167	63.4	34.97	46.81	1.34	276.8	5.583E+03	47.1
1293	1020	434	4169	63.6	35.12	46.61	1.33	275.1	6.224E+03	47.4
1303	1030	433	4171	63.7	35.27	46.40	1.32	273.3	6.928E+03	47.7
1313	1040	432	4173	63.9	35.41	46.21	1.30	271.6	7.697E+03	48.0
1323	1050	431	4175	64.0	35.56	46.01	1.29	269.9	8.539E+03	48.3
1333	1060	430	4177	64.2	35.70	45.82	1.28	268.2	9.458E+03	48.5
1343	1070	429	4180	64.3	35.84	45.64	1.27	266.5	1.046E+04	48.8
1353	1080	428	4182	64.5	35.98	45.45	1.26	264.8	1.155E+04	49.1
1363	1090	427	4184	64.6	36.12	45.27	1.25	263.1	1.274E+04	49.4
1373	1100	426	4187	64.7	36.26	45.10	1.24	261.4	1.403E+04	49.7
1383	1110	425	4190	64.9	36.39	44.92	1.23	259.7	1.542E+04	50.0
1393	1120	424	4192	65.0	36.52	44.75	1.23	258.0	1.694E+04	50.3
1403	1130	423	4195	65.1	36.66	44.59	1.22	256.3	1.857E+04	50.6
1413	1140	422	4198	65.2	36.79	44.42	1.21	254.6	2.034E+04	50.9
1423	1150	421	4201	65.4	36.91	44.26	1.20	252.9	2.225E+04	51.2
1433	1160	420	4204	65.5	37.04	44.11	1.19	251.3	2.431E+04	51.5
1443	1170	419	4207	65.6	37.17	43.95	1.18	249.6	2.652E+04	51.9
1453	1180	418	4210	65.7	37.29	43.80	1.17	247.9	2.890E+04	52.2
1463	1190	417	4213	65.8	37.41	43.65	1.17	246.3	3.146E+04	52.5
1333	1060	430	4177	64.2	35.70	45.82	1.28	268.2	9.458E+03	48.5
1343	1070	429	4180	64.3	35.84	45.64	1.27	266.5	1.046E+04	48.8
1363	1090	427	4184	64.6	36.12	45.27	1.25	263.1	1.274E+04	49.4
1373	1100	426	4187	64.7	36.26	45.10	1.24	261.4	1.403E+04	49.7
1383	1110	425	4190	64.9	36.39	44.92	1.23	259.7	1.542E+04	50.0
1393	1120	424	4192	65.0	36.52	44.75	1.23	258.0	1.694E+04	50.3
1403	1130	423	4195	65.1	36.66	44.59	1.22	256.3	1.857E+04	50.6
1413	1140	422	4198	65.2	36.79	44.42	1.21	254.6	2.034E+04	50.9
1423	1150	421	4201	65.4	36.91	44.26	1.20	252.9	2.225E+04	51.2
1433	1160	420	4204	65.5	37.04	44.11	1.19	251.3	2.431E+04	51.5
1443	1170	419	4207	65.6	37.17	43.95	1.18	249.6	2.652E+04	51.9
1453	1180	418	4210	65.7	37.29	43.80	1.17	247.9	2.890E+04	52.2
1463	1190	417	4213	65.8	37.41	43.65	1.17	246.3	3.146E+04	52.5
1473	1200	417	4217	65.9	37.53	43.50	1.16	244.6	3.421E+04	52.8
1483	1210	416	4220	66.0	37.65	43.36	1.15	243.0	3.715E+04	53.1
1493	1220	415	4224	66.1	37.77	43.22	1.14	241.4	4.030E+04	53.4
1503	1230	414	4227	66.2	37.88	43.08	1.14	239.7	4.368E+04	53.8
1513	1240	413	4231	66.3	37.99	42.94	1.13	238.1	4.729E+04	54.1
1523	1250	412	4235	66.4	38.11	42.81	1.12	236.5	5.114E+04	54.4
1533	1260	411	4238	66.5	38.22	42.68	1.12	234.9	5.525E+04	54.7
1543	1270	410	4242	66.6	38.32	42.55	1.11	233.3	5.963E+04	55.1
1553	1280	409	4246	66.7	38.43	42.42	1.10	231.7	6.429E+04	55.4
1563	1290	408	4250	66.8	38.54	42.30	1.10	230.2	6.926E+04	55.8
1573	1300	407	4255	66.9	38.64	42.18	1.09	228.6	7.454E+04	56.1

TABLE 3.14. PROPERTIES OF SODIUM BY EQS (3.8–3.14)

Temperature		Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6(m^2/s)	Kinematic viscosity 10^8(m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure Pa	Electrical resistivity 10^8(Ω·m)
K	°C									
373	100	925	1382	84.9	66.42	73.67	1.11	200.1	1.848E-05	9.49
383	110	923	1378	84.5	66.44	70.25	1.06	198.9	4.457E-05	9.81
393	120	921	1374	84.1	66.46	67.15	1.01	197.8	1.027E-04	10.1
403	130	919	1370	83.7	66.48	64.32	0.97	196.7	2.267E-04	10.4
413	140	917	1366	83.3	66.51	61.74	0.93	195.6	4.813E-04	10.8
423	150	915	1362	83.0	66.54	59.37	0.89	194.5	9.856E-04	11.1
433	160	913	1358	82.6	66.56	57.19	0.86	193.5	1.951E-03	11.4
443	170	911	1354	82.2	66.59	55.19	0.83	192.4	3.743E-03	11.8
453	180	909	1350	81.8	66.62	53.33	0.80	191.3	6.972E-03	12.1
463	190	907	1347	81.4	66.65	51.61	0.77	190.2	1.264E-02	12.5
473	200	904	1343	81.0	66.68	50.01	0.75	189.2	2.232E-02	12.8
483	210	902	1340	80.6	66.70	48.53	0.73	188.1	3.849E-02	13.2
493	220	900	1336	80.2	66.73	47.14	0.71	187.1	6.489E-02	13.5
503	230	898	1332	79.8	66.75	45.85	0.69	186.0	1.071E-01	13.9
513	240	895	1329	79.4	66.77	44.64	0.67	185.0	1.733E-01	14.3
523	250	893	1325	79.0	66.79	43.50	0.65	184.0	2.752E-01	14.6
533	260	890	1322	78.7	66.81	42.44	0.64	182.9	4.293E-01	15.0
543	270	888	1318	78.3	66.82	41.44	0.62	181.9	6.586E-01	15.4
553	280	886	1315	77.9	66.83	40.49	0.61	180.9	9.945E-01	15.8
563	290	883	1312	77.5	66.84	39.60	0.59	179.9	1.480E+00	16.2
573	300	881	1309	77.1	66.85	38.76	0.58	178.9	2.170E+00	16.6
583	310	878	1306	76.7	66.85	37.96	0.57	177.8	3.141E+00	17.0
593	320	876	1303	76.3	66.84	37.21	0.56	176.8	4.488E+00	17.4
603	330	873	1301	75.9	66.83	36.50	0.55	175.8	6.336E+00	17.8
613	340	871	1298	75.5	66.82	35.82	0.54	174.8	8.843E+00	18.2
623	350	869	1295	75.1	66.80	35.17	0.53	173.9	1.221E+01	18.6
633	360	866	1292	74.7	66.78	34.56	0.52	172.9	1.668E+01	19.1
643	370	864	1290	74.4	66.75	33.98	0.51	172.0	2.256E+01	19.5
653	380	861	1287	74.0	66.72	33.42	0.50	170.9	3.024E+01	19.9
663	390	859	1285	73.6	66.68	32.89	0.49	169.9	4.015E+01	20.4
673	400	856	1283	73.2	66.64	32.38	0.49	167.0	5.287E+01	20.8
683	410	854	1280	72.8	66.59	31.90	0.48	168.0	6.904E+01	21.3
693	420	851	1278	72.4	66.54	31.44	0.47	167.0	8.946E+01	21.7
703	430	849	1276	72.0	66.48	30.99	0.47	166.1	1.150E+02	22.2
713	440	846	1274	71.6	66.42	30.57	0.46	165.1	1.469E+02	22.7
723	450	844	1272	71.2	66.35	30.16	0.45	164.1	1.863E+02	23.1
733	460	841	1270	70.8	66.27	29.77	0.45	163.2	2.346E+02	23.6
743	470	839	1269	70.4	66.19	29.40	0.44	162.2	2.937E+02	24.1
753	480	837	1267	70.1	66.10	29.04	0.44	161.3	3.654E+02	24.6
763	490	834	1265	69.7	66.01	28.69	0.43	160.3	4.520E+02	25.1
773	500	832	1264	69.3	65.91	28.36	0.43	159.4	5.560E+02	25.6
783	510	829	1262	68.9	65.80	28.04	0.43	158.5	6.802E+02	26.1
793	520	827	1261	68.5	65.69	27.73	0.42	157.5	8.279E+02	26.6
803	530	824	1260	68.1	65.57	27.43	0.42	156.6	1.003E+03	27.2
813	540	822	1259	67.7	65.45	27.14	0.41	155.6	1.209E+03	27.7
823	550	820	1258	67.3	65.32	26.87	0.41	154.7	1.450E+03	28.2
833	560	817	1257	66.9	65.18	26.60	0.41	153.8	1.732E+03	28.8
843	570	815	1256	66.5	65.04	26.34	0.41	152.8	2.060E+03	29.3

TABLE 3.14. (continued)

Temperature K	Temperature K	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6(m^2/s)	Kinematic viscosity 10^8(m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure Pa	Electrical resistivity 10^8(Ω·m)
853	580	812	1255	66.1	64.89	26.10	0.40	151.9	2.440E+03	29.9
863	590	810	1254	65.8	64.73	25.86	0.40	151.0	2.878E+03	30.5
873	600	808	1253	65.4	64.57	25.62	0.40	150.1	3.382E+03	31.1
883	610	805	1253	65.0	64.40	25.40	0.39	149.1	3.960E+03	31.6
893	620	803	1252	64.6	64.23	25.18	0.39	148.2	4.620E+03	32.2
903	630	801	1252	64.2	64.05	24.97	0.39	147.3	5.371E+03	32.8
913	640	798	1252	63.8	63.86	24.77	0.39	146.4	6.223E+03	33.4
923	650	796	1251	63.4	63.67	24.57	0.39	145.5	7.188E+03	34.0
933	660	793	1251	63.0	63.47	24.38	0.38	144.5	8.276E+03	34.7
943	670	791	1251	62.6	63.27	24.20	0.38	143.6	9.500E+03	35.3
953	680	789	1251	62.2	63.06	24.02	0.38	142.7	1.087E+04	35.9
963	690	786	1251	61.8	62.84	23.85	0.38	141.8	1.241E+04	36.6
973	700	784	1252	61.5	62.62	23.68	0.38	140.9	1.412E+04	37.2
983	710	782	1252	61.1	62.39	23.52	0.38	140.0	1.603E+04	37.9
993	720	779	1252	60.7	62.16	23.36	0.38	139.0	1.815E+04	38.6
1003	730	777	1253	60.3	61.92	23.21	0.37	138.1	2.050E+04	39.2
1013	740	775	1253	59.9	61.68	23.06	0.37	137.2	2.309E+04	39.9
1023	750	772	1254	59.5	61.43	22.91	0.37	136.3	2.595E+04	40.6
1033	760	770	1255	59.1	61.17	22.78	0.37	135.4	2.910E+04	41.3
1043	770	768	1256	58.7	60.91	22.64	0.37	134.5	3.256E+04	42.1
1053	780	765	1256	58.3	60.65	22.51	0.37	133.6	3.636E+04	42.8
1063	790	763	1257	57.9	60.38	22.38	0.37	132.6	4.051E+04	43.5
1073	800	761	1259	57.5	60.10	22.26	0.37	131.7	4.504E+04	44.3
1083	810	758	1260	57.1	59.82	22.14	0.37	130.8	4.998E+04	45.0
1093	820	756	1261	56.8	59.53	22.02	0.37	129.9	5.535E+04	45.8
1103	830	754	1262	56.4	59.24	21.91	0.37	129.0	6.119E+04	46.6
1113	840	751	1264	56.0	58.95	21.80	0.37	128.0	6.752E+04	47.3
1123	850	749	1265	56.0	58.65	21.69	0.37	127.1	7.437E+04	48.1
1133	860	747	1267	55.2	58.35	21.59	0.37	126.2	8.177E+04	48.9
1143	870	744	1269	54.8	58.04	21.49	0.37	125.3	8.977E+04	49.8
1153	880	742	1270	54.4	57.72	21.40	0.37	124.4	9.838E+04	50.6
1163	890	740	1272	54.0	57.41	21.30	0.37	123.4	1.076E+05	51.4
1173	900	737	1274	53.6	57.09	21.21	0.37	122.5	1.176E+05	52.3
1183	910	735	1276	53.2	56.76	21.12	0.37	121.6	1.283E+05	53.1
1193	920	733	1278	52.8	56.43	21.04	0.37	120.6	1.397E+05	54.0
1203	930	730	1281	52.5	56.10	20.95	0.37	119.7	1.520E+05	54.9
1213	940	728	1283	52.1	55.76	20.87	0.37	118.8	1.651E+05	55.8
1223	950	725	1285	51.7	55.42	20.80	0.38	117.8	1.791E+05	56.7
1233	960	723	1288	51.3	55.08	20.72	0.38	116.9	1.940E+05	57.6
1243	970	721	1290	50.9	54.73	20.65	0.38	116.0	2.099E+05	58.6
1253	980	718	1293	50.5	54.38	20.58	0.38	115.0	2.267E+05	59.5
1263	990	716	1296	50.1	54.03	20.51	0.38	114.1	2.447E+05	60.5
1273	1000	713	1299	49.7	53.67	20.45	0.38	113.1	2.637E+05	61.4
1283	1010	711	1302	49.3	53.31	20.38	0.38	112.2	2.839E+05	62.4
1293	1020	709	1305	48.9	52.94	20.32	0.38	111.2	3.053E+05	63.4
1303	1030	706	1308	48.5	52.58	20.26	0.39	110.3	3.279E+05	64.4
1313	1040	704	1311	48.2	52.21	20.21	0.39	109.3	3.518E+05	65.5

TABLE 3.14. (continued)

Temperature K	Temperature °C	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6(m^2/s)	Kinematic viscosity 10^8(m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure Pa	Electrical resistivity 10^8(Ω·m)
1323	1050	701	1314	47.8	51.84	20.15	0.39	108.3	3.771E+05	66.5
1333	1060	699	1318	47.4	51.46	20.10	0.39	107.4	4.037E+05	67.6
1343	1070	696	1321	47.0	51.08	20.05	0.39	106.4	4.318E+05	68.6
1353	1080	694	1325	46.6	50.70	20.00	0.39	105.4	4.613E+05	69.7
1363	1090	691	1328	46.2	50.32	19.95	0.40	104.5	4.924E+05	70.8
1373	1100	689	1332	45.8	49.94	19.91	0.40	103.5	5.251E+05	71.9
1383	1110	686	1336	45.4	49.55	19.87	0.40	102.5	5.594E+05	73.1
1393	1120	684	1340	45.0	49.16	19.83	0.40	101.5	5.954E+05	74.2
1403	1130	681	1344	44.6	48.77	19.79	0.41	100.5	6.332E+05	75.4
1413	1140	679	1348	44.2	48.38	19.75	0.41	99.5	6.728E+05	76.5
1423	1150	676	1352	43.9	47.98	19.71	0.41	98.5	7.142E+05	77.7
1433	1160	674	1356	43.5	47.59	19.68	0.41	97.5	7.575E+05	78.9
1443	1170	671	1361	43.1	47.19	19.65	0.42	96.5	8.028E+05	80.2
1453	1180	668	1365	42.7	46.79	19.62	0.42	95.5	8.502E+05	81.4
1463	1190	666	1370	42.3	46.39	19.59	0.42	94.5	8.995E+05	82.7
1473	1200	663	1374	41.9	45.98	19.56	0.43	93.5	9.511E+05	84.0
1483	1210	661	1379	41.5	45.58	19.54	0.43	92.4	1.005E+06	85.3
1493	1220	658	1384	41.1	45.17	19.52	0.43	91.4	1.061E+06	86.6
1503	1230	655	1389	40.7	44.76	19.49	0.44	90.4	1.119E+06	87.9
1513	1240	653	1394	40.3	44.35	19.47	0.44	89.3	1.179E+06	89.3
1523	1250	650	1399	39.9	43.94	19.46	0.44	88.3	1.242E+06	90.6
1533	1260	647	1404	39.6	43.53	19.44	0.45	87.3	1.308E+06	92.0
1543	1270	645	1409	39.2	43.12	19.42	0.45	86.2	1.376E+06	93.4
1553	1280	642	1414	38.8	42.70	19.41	0.45	85.1	1.446E+06	94.9
1563	1290	639	1420	38.4	42.29	19.40	0.46	84.1	1.519E+06	96.3
1573	1300	637	1425	38.0	41.87	19.39	0.46	83.0	1.595E+06	97.8

TABLE 3.15. PROPERTIES OF POTASSIUM BY EQUATIONS (3.15–3.21)

Temperature K	Temperature °C	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m^2/s)	Kinematic viscosity 10^8 (m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure Pa	Electrical resistivity 10^8 (Ω·m)
373	100	821	813	50.9	76.22	53.87	0.71	109.5	3.033E-03	15.8
383	110	818	811	50.6	76.27	51.63	0.68	108.9	6.263E-03	16.3
393	120	816	809	50.4	76.32	49.59	0.65	108.2	1.245E-02	16.9
403	130	814	806	50.1	76.37	47.71	0.62	107.5	2.391E-02	17.4
413	140	811	804	49.8	76.42	45.99	0.60	106.9	4.444E-02	17.9
423	150	809	802	49.6	76.45	44.40	0.58	106.2	8.015E-02	18.5
433	160	806	800	49.3	76.49	42.94	0.56	105.5	1.406E-01	19.1
443	170	804	798	49.1	76.52	41.58	0.54	104.9	2.402E-01	19.6
453	180	802	795	48.8	76.54	40.32	0.53	104.2	4.007E-01	20.2
463	190	799	793	48.6	76.56	39.14	0.51	103.5	6.534E-01	20.8
473	200	797	791	48.3	76.57	38.05	0.50	102.8	1.043E-06	21.4
483	210	795	789	48.0	76.57	37.02	0.48	102.1	1.632E+00	22.0
493	220	792	788	47.8	76.57	36.07	0.47	101.5	2.507E+00	22.6
503	230	790	786	47.5	76.56	35.17	0.46	100.8	3.783E+00	23.2
513	240	788	784	47.3	76.55	34.32	0.45	100.1	5.615E+00	23.8
523	250	785	782	47.0	76.52	33.53	0.44	99.4	8.207E+00	24.4
533	260	783	781	46.8	76.49	32.78	0.43	98.7	1.182E+01	25.1
543	270	781	779	46.5	76.45	32.08	0.42	98.0	1.679E+01	25.7
553	280	778	778	46.2	76.40	31.41	0.41	97.3	2.355E+01	26.4
563	290	776	776	46.0	76.34	30.78	0.40	96.5	3.261E+01	27.0
573	300	774	775	45.7	76.28	30.18	0.40	95.8	4.463E+01	27.7
583	310	771	773	45.5	76.21	29.62	0.39	95.1	6.042E+01	28.4
593	320	769	772	45.2	76.13	29.08	0.38	94.4	8.094E+01	29.1
603	330	767	771	44.9	76.04	28.57	0.38	93.7	1.073E+02	29.8
613	340	764	770	44.7	75.94	28.08	0.37	93.0	1.410E+02	30.5
623	350	762	769	44.4	75.83	27.62	0.36	92.2	1.836E+02	31.2
633	360	760	768	44.2	75.71	27.18	0.36	91.5	2.370E+02	31.9
643	370	757	767	43.9	75.59	26.76	0.35	90.8	3.034E+02	32.7
653	380	755	766	43.7	75.45	26.36	0.35	90.1	3.855E+02	33.4
663	390	753	766	43.4	75.31	25.98	0.34	89.3	4.861E+02	34.2
673	400	750	765	43.1	75.16	25.61	0.34	88.6	6.086E+02	34.9
683	410	748	764	42.9	75.00	25.26	0.34	87.9	7.569E+02	35.7
693	420	746	764	42.6	74.83	24.92	0.33	87.1	9.353E+02	36.5
703	430	743	763	42.4	74.65	24.60	0.33	86.4	1.148E+03	37.3
713	440	741	763	42.1	74.46	24.29	0.33	85.7	1.402E+03	38.1
723	450	739	763	41.9	74.26	24.00	0.32	84.9	1.702E+03	38.9
733	460	736	763	41.6	74.05	23.71	0.32	84.2	2.055E+03	39.8
743	470	734	762	41.3	73.84	23.44	0.32	83.5	2.468E+03	40.6
753	480	732	762	41.1	73.62	23.18	0.31	82.7	2.949E+03	41.5
763	490	730	762	40.8	73.38	22.92	0.31	82.0	3.507E+03	42.4
773	500	727	763	40.6	73.14	22.68	0.31	81.2	4.152E+03	43.2
783	510	725	763	40.3	72.89	22.45	0.31	80.5	4.893E+03	44.1
793	520	723	763	40.0	72.64	22.22	0.31	79.7	5.743E+03	45.1
803	530	720	763	39.8	72.37	22.01	0.30	79.0	6.712E+03	46.0
813	540	718	764	39.5	72.09	21.80	0.30	78.2	7.815E+03	46.9
823	550	716	764	39.3	71.81	21.60	0.30	77.5	9.064E+03	47.9
833	560	713	765	39.0	71.52	21.41	0.30	76.7	1.047E+04	48.8

TABLE 3.15 (continued)

Temperature K	Temperature °C	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m^2/s)	Kinematic viscosity 10^8 (m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure Pa	Electrical resistivity 10^8 (Ω·m)
843	570	711	765	38.8	71.22	21.22	0.30	76.0	1.206E+04	49.8
853	580	709	766	38.5	70.91	21.04	0.30	75.2	1.384E+04	50.8
863	590	706	767	38.2	70.60	20.87	0.30	74.5	1.584E+04	51.8
873	600	704	768	38.0	70.27	20.70	0.29	73.7	1.806E+04	52.8
883	610	701	769	37.7	69.94	20.54	0.29	73.0	2.053E+04	53.9
893	620	699	770	37.5	69.60	20.38	0.29	72.2	2.327E+04	54.9
903	630	697	771	37.2	69.26	20.23	0.29	71.5	2.631E+04	56.0
913	640	694	772	36.9	68.90	20.09	0.29	70.7	2.965E+04	57.1
923	650	692	773	36.7	68.54	19.95	0.29	70.0	3.334E+04	58.2
933	660	690	775	36.4	68.17	19.81	0.29	69.2	3.738E+04	59.3
943	670	687	776	36.2	67.80	19.68	0.29	68.5	4.182E+04	60.5
953	680	685	778	35.9	67.42	19.55	0.29	67.7	4.667E+04	61.6
963	690	682	779	35.7	67.03	19.43	0.29	67.0	5.196E+04	62.8
973	700	680	781	35.4	66.64	19.31	0.29	66.2	5.772E+04	64.1
983	710	678	783	35.1	66.24	19.20	0.29	65.5	6.397E+04	65.2
993	720	675	785	34.9	65.83	19.09	0.29	64.7	7.076E+04	66.5
1003	730	673	787	34.6	65.42	18.98	0.29	64.0	7.811E+04	67.7
1013	740	670	789	34.4	65.00	18.88	0.29	63.3	8.605E+04	69.0
1023	750	668	791	34.1	64.58	18.78	0.29	62.5	9.461E+04	70.3
1033	760	666	793	33.9	64.15	18.68	0.29	61.8	1.038E+05	71.6
1043	770	663	795	33.6	63.71	18.59	0.29	61.0	1.137E+05	73.0
1053	780	661	797	33.3	63.27	18.50	0.29	60.3	1.244E+05	74.3
1063	790	658	800	33.1	62.83	18.42	0.29	59.5	1.358E+05	75.7
1073	800	656	802	32.8	62.38	18.33	0.29	58.8	1.480E+05	77.1
1083	810	653	805	32.6	61.92	18.25	0.29	58.1	1.610E+05	78.6
1093	820	651	807	32.3	61.46	18.17	0.30	57.3	1.749E+05	80.0
1103	830	648	810	32.0	61.00	18.10	0.30	56.6	1.898E+05	81.5
1113	840	646	813	31.8	60.53	18.03	0.30	55.9	2.055E+05	83.0
1123	850	643	816	31.5	60.06	17.96	0.30	55.1	2.223E+05	84.6
1133	860	641	819	31.3	59.58	17.89	0.30	54.4	2.401E+05	86.1
1143	870	638	822	31.0	59.10	17.83	0.30	53.7	2.590E+05	87.7
1153	880	636	825	30.8	58.62	17.76	0.30	52.9	2.789E+05	89.4
1163	890	633	828	30.5	58.13	17.70	0.30	52.2	3.001E+05	91.0
1173	900	631	831	30.2	57.64	17.65	0.31	51.5	3.224E+05	92.7
1183	910	628	835	30.0	57.14	17.59	0.31	50.8	3.459E+05	94.4
1193	920	626	838	29.7	56.65	17.54	0.31	50.0	3.708E+05	96.2
1203	930	623	842	29.5	56.15	17.49	0.31	49.3	3.969E+05	97.9
1213	940	621	845	29.2	55.64	17.44	0.31	48.6	4.244E+05	99.8
1223	950	618	849	29.0	55.14	17.39	0.32	47.9	4.533E+05	101.6
1233	960	616	853	28.7	54.63	17.35	0.32	47.2	4.836E+05	103.5
1243	970	613	857	28.4	54.12	17.30	0.32	46.5	5.154E+05	105.4
1253	980	611	861	28.2	53.61	17.26	0.32	45.8	5.487E+05	107.4
1263	990	608	865	27.9	53.10	17.22	0.32	45.1	5.836E+05	109.4
1273	1000	605	869	27.7	52.58	17.19	0.33	44.4	6.201E+05	111.4
1283	1010	603	873	27.4	52.06	17.15	0.33	43.7	6.583E+05	113.5
1293	1020	600	877	27.1	51.54	17.12	0.33	43.0	6.981E+05	115.6
1303	1030	598	881	26.9	51.02	17.08	0.33	42.3	7.397E+05	117.7
1313	1040	595	886	26.6	50.50	17.05	0.34	41.6	7.830E+05	120.0

TABLE 3.15. (continued)

Temperature K	Temperature °C	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m^2/s)	Kinematic viscosity 10^8 (m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure Pa	Electrical resistivity 10^8 (Ω·m)
1323	1050	593	890	26.4	49.98	17.03	0.34	40.9	8.281E+05	122.2
1333	1060	590	895	26.1	49.45	17.00	0.34	40.2	8.751E+05	124.5
1343	1070	587	900	25.9	48.93	16.97	0.35	39.5	9.239E+05	126.8
1353	1080	585	904	25.6	48.40	16.95	0.35	38.8	9.747E+05	129.2
1363	1090	582	909	25.3	47.87	16.93	0.35	38.2	1.027E+06	131.7
1373	1100	579	914	25.1	47.35	16.91	0.36	37.5	1.082E+06	134.2
1383	1110	577	919	24.8	46.82	16.89	0.36	36.9	1.139E+06	136.7
1393	1120	574	924	24.6	46.29	16.87	0.36	36.2	1.198E+06	139.3
1403	1130	572	929	24.3	45.76	16.86	0.37	35.5	1.259E+06	142.0
1413	1140	569	934	24.0	45.23	16.84	0.37	34.9	1.322E+06	144.7
1423	1150	566	940	23.8	44.70	16.83	0.38	34.2	1.387E+06	147.5
1433	1160	564	945	23.5	44.17	16.82	0.38	33.6	1.454E+06	150.3
1443	1170	561	951	23.3	43.65	16.81	0.39	32.9	1.524E+06	153.3
1453	1180	558	956	23.0	43.12	16.80	0.39	32.3	1.596E+06	156.2
1463	1190	556	962	22.8	42.59	16.79	0.39	31.7	1.670E+06	159.3
1473	1200	553	967	22.5	42.06	16.79	0.40	31.0	1.747E+06	162.4
1483	1210	550	973	22.2	41.53	16.78	0.40	30.4	1.826E+06	165.6
1493	1220	547	979	22.0	41.01	16.78	0.41	29.8	1.907E+06	168.9
1503	1230	545	985	21.7	40.48	16.78	0.41	29.2	1.990E+06	172.2
1513	1240	542	991	21.5	39.96	16.78	0.42	28.5	2.076E+06	175.6
1523	1250	539	997	21.2	39.43	16.78	0.43	27.9	2.165E+06	179.2
1533	1260	537	1003	21.0	38.91	16.79	0.43	27.3	2.256E+06	182.8
1543	1270	534	1010	20.7	38.39	16.79	0.44	26.7	2.349E+06	186.5
1553	1280	531	1016	20.4	37.87	16.80	0.44	26.1	2.445E+06	190.3
1563	1290	528	1022	20.2	37.35	16.80	0.45	25.5	2.544E+06	194.1
1573	1300	526	1029	19.9	36.83	16.81	0.46	24.9	2.645E+06	198.1

TABLE 3.16. PROPERTIES OF CAESIUM BY EQUATIONS (3.22–3.28)

Temperature		Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m^2/s)	Kinematic viscosity 10^8 (m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure Pa	Electrical resistivity 10^8 (Ω·m)
K	°C									
303	30	1835	245.6	19.46	44.69	36.52	0.82	71.1	3.358E-04	35.9
313	40	1829	245.5	19.48	44.93	34.53	0.77	70.6	8.629E-04	37.0
323	50	1824	245.3	19.55	45.19	32.75	0.72	70.1	2.088E-03	38.2
333	60	1819	245.0	19.54	45.47	31.17	0.69	69.5	4.787E-03	39.4
343	70	1813	244.6	19.54	45.78	29.74	0.65	69.0	1.044E-02	40.6
353	80	1808	244.1	19.54	46.10	28.44	0.62	68.5	2.176E-02	41.8
363	90	1802	243.5	19.53	46.44	27.27	0.59	68.0	4.352E-02	43.0
373	100	1797	242.9	19.52	46.80	26.20	0.56	67.5	8.376E-02	44.2
383	110	1791	242.2	19.52	47.17	25.23	0.53	67.0	1.556E-01	45.4
393	120	1785	241.5	19.51	47.55	24.33	0.51	66.5	2.800E-01	46.6
403	130	1780	240.7	19.50	47.94	23.51	0.49	65.9	4.888E-01	47.8
413	140	1774	240.0	19.48	48.35	22.75	0.47	65.4	8.298E-01	49.0
423	150	1768	239.2	19.47	48.76	22.05	0.45	64.9	1.373E+00	50.3
433	160	1763	238.4	19.46	49.18	21.40	0.44	64.4	2.218E+00	51.5
443	170	1757	237.6	19.44	49.60	20.80	0.42	63.9	3.504E+00	52.7
453	180	1751	236.7	19.42	50.04	20.24	0.40	63.4	5.421E+00	53.9
463	190	1745	235.9	19.40	50.47	19.71	0.39	62.9	8.225E+00	55.2
473	200	1740	235.1	19.39	50.92	19.22	0.38	62.4	1.226E+01	56.4
483	210	1734	234.3	19.36	51.36	18.76	0.37	61.9	1.795E+01	57.7
493	220	1728	233.5	19.34	51.81	18.33	0.35	61.4	2.588E+01	58.9
503	230	1722	232.7	19.32	52.26	17.93	0.34	61.0	3.675E+01	60.2
513	240	1717	231.9	19.29	52.72	17.55	0.33	60.5	5.145E+01	61.5
523	250	1711	231.1	19.27	53.18	17.19	0.32	60.0	7.109E+01	62.8
533	260	1705	230.4	19.24	53.63	16.85	0.31	59.5	9.700E+01	64.1
543	270	1699	229.6	19.21	54.09	16.53	0.31	59.0	1.308E+02	65.3
553	280	1694	228.9	19.18	54.55	16.23	0.30	58.5	1.744E+02	66.7
563	290	1688	228.2	19.15	55.01	15.94	0.29	58.0	2.301E+02	68.0
573	300	1682	227.5	19.12	55.47	15.67	0.28	57.5	3.006E+02	69.3
583	310	1677	226.8	19.08	55.93	15.41	0.28	57.1	3.890E+02	70.6
593	320	1671	226.2	19.05	56.39	15.17	0.27	56.6	4.989E+02	72.0
603	330	1665	225.6	19.01	56.84	14.93	0.26	56.1	6.344E+02	73.3
613	340	1659	225.0	18.97	57.29	14.71	0.26	55.6	8.002E+02	74.7
623	350	1654	224.4	18.93	57.75	14.50	0.25	55.1	1.002E+03	76.0
633	360	1648	223.9	18.89	58.20	14.30	0.25	54.7	1.245E+03	77.4
643	370	1642	223.3	18.85	58.64	14.11	0.24	54.2	1.536E+03	78.8
653	380	1637	222.9	18.81	59.08	13.92	0.24	53.7	1.883E+03	80.2
663	390	1631	222.4	18.76	59.52	13.75	0.23	53.3	2.293E+03	81.6
673	400	1625	222.0	18.72	59.96	13.58	0.23	52.8	2.776E+03	83.0
683	410	1620	221.5	18.67	60.39	13.42	0.22	52.3	3.342E+03	84.5
693	420	1614	221.2	18.62	60.82	13.26	0.22	51.8	4.002E+03	85.9
703	430	1608	220.8	18.57	61.24	13.11	0.21	51.4	4.766E+03	87.4
713	440	1603	220.5	18.52	61.66	12.97	0.21	50.9	5.647E+03	88.9
723	450	1597	220.2	18.47	62.07	12.84	0.21	50.4	6.660E+03	90.3
733	460	1591	220.0	18.41	62.48	12.71	0.20	50.0	7.818E+03	91.9
743	470	1586	219.7	18.36	62.88	12.58	0.20	49.5	9.137E+03	93.4

TABLE 3.16. (continued)

Temperature		Density	Heat capacity	Thermal conductivity	Thermal diffusivity	Kinematic viscosity	10^2 Prandtl number	Surface tension	Pressure	Electrical resistivity
K	°C	kg/m^3	J/(kg·K)	W/(m·K)	10^6 (m^2/s)	10^8 (m^2/s)		10^3N/m	Pa	10^8 (Ω·m)
753	480	1580	219.6	18.30	63.28	12.46	0.20	49.0	1.063E+04	94.9
763	490	1574	219.4	18.24	63.67	12.35	0.19	48.6	1.232E+04	96.5
773	500	1569	219.3	18.19	64.06	12.23	0.19	48.1	1.423E+04	98.0
783	510	1563	219.2	18.13	64.44	12.13	0.19	47.7	1.637E+04	99.6
793	520	1557	219.1	18.06	64.81	12.03	0.19	47.2	1.876E+04	101.2
803	530	1551	219.1	18.00	65.17	11.93	0.18	46.7	2.143E+04	102.8
813	540	1546	219.1	17.94	65.53	11.83	0.18	46.3	2.439E+04	104.4
823	550	1540	219.1	17.87	65.89	11.74	0.18	45.8	2.767E+04	106.1
833	560	1534	219.2	17.81	66.23	11.65	0.18	45.4	3.131E+04	107.8
843	570	1528	219.3	17.74	66.57	11.57	0.17	44.9	3.531E+04	109.5
853	580	1523	219.4	17.67	66.90	11.49	0.17	44.4	3.971E+04	111.2
863	590	1517	219.6	17.60	67.22	11.41	0.17	44.0	4.454E+04	112.9
873	600	1511	219.8	17.53	67.54	11.34	0.17	43.5	4.982E+04	114.7
883	610	1505	220.0	17.45	67.85	11.26	0.17	43.1	5.558E+04	116.4
893	620	1499	220.3	17.38	68.15	11.19	0.16	42.6	6.186E+04	118.2
903	630	1493	220.6	17.30	68.45	11.13	0.16	42.2	6.868E+04	120.1
913	640	1488	220.9	17.23	68.73	11.06	0.16	41.7	7.608E+04	121.9
923	650	1482	221.3	17.15	69.01	11.00	0.16	41.3	8.409E+04	123.8
933	660	1476	221.7	17.07	69.28	10.94	0.16	40.8	9.273E+04	125.7
943	670	1470	222.2	16.99	69.54	10.88	0.16	40.4	1.021E+05	127.6
953	680	1464	222.6	16.90	69.80	10.83	0.16	39.9	1.121E+05	129.5
963	690	1458	223.1	16.82	70.05	10.78	0.15	39.5	1.229E+05	131.5
973	700	1452	223.7	16.74	70.29	10.73	0.15	39.0	1.344E+05	133.5
983	710	1446	224.3	16.65	70.52	10.68	0.15	38.6	1.468E+05	135.5
993	720	1440	224.9	16.56	70.75	10.63	0.15	38.1	1.600E+05	137.6
1003	730	1434	225.5	16.47	70.96	10.59	0.15	37.7	1.742E+05	139.7
1013	740	1428	226.2	16.38	71.17	10.54	0.15	37.2	1.892E+05	141.8
1023	750	1422	227.0	16.29	71.37	10.50	0.15	36.8	2.052E+05	144.0
1033	760	1415	227.7	16.20	71.57	10.46	0.15	36.3	2.222E+05	146.2
1043	770	1409	228.5	16.11	71.75	10.43	0.15	35.9	2.403E+05	148.4
1053	780	1403	229.3	16.01	71.93	10.39	0.14	35.4	2.594E+05	150.7
1063	790	1397	230.2	15.91	72.10	10.36	0.14	35.0	2.797E+05	153.0
1073	800	1391	231.1	15.82	72.27	10.32	0.14	34.5	3.011E+05	155.3
1083	810	1384	232.0	15.72	72.43	10.29	0.14	34.1	3.237E+05	157.7
1093	820	1378	233.0	15.62	72.58	10.26	0.14	33.6	3.475E+05	160.1
1103	830	1372	234.0	15.51	72.72	10.24	0.14	33.2	3.727E+05	162.6
1113	840	1365	235.1	15.41	72.86	10.21	0.14	32.7	3.991E+05	165.1
1123	850	1359	236.1	15.31	72.99	10.18	0.14	32.3	4.269E+05	167.6
1133	860	1353	237.2	15.20	73.11	10.16	0.14	31.8	4.560E+05	170.2
1143	870	1346	238.4	15.09	73.22	10.14	0.14	31.4	4.866E+05	172.9
1153	880	1340	239.6	14.99	73.33	10.12	0.14	30.9	5.186E+05	175.6
1163	890	1333	240.8	14.88	73.44	10.10	0.14	30.5	5.522E+05	178.3
1173	900	1327	242.1	14.77	73.53	10.08	0.14	30.0	5.872E+05	181.1
1183	910	1321	243.3	14.65	73.62	10.06	0.14	29.6	6.239E+05	184.0
1193	920	1314	244.7	14.54	73.71	10.05	0.14	29.1	6.621E+05	186.9
1203	930	1308	246.0	14.43	73.79	10.03	0.14	28.7	7.019E+05	189.9
1213	940	1301	247.4	14.31	73.86	10.02	0.14	28.2	7.435E+05	192.9

TABLE 3.16. (continued)

Temperature K	Temperature °C	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m^2/s)	Kinematic viscosity 10^8 (m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure Pa	Electrical resistivity 10^8 (Ω·m)
1223	950	1294	248.9	14.19	73.93	10.01	0.14	27.8	7.867E+05	196.0
1233	960	1288	250.4	14.07	73.99	10.00	0.14	27.3	8.317E+05	199.2
1243	970	1281	251.9	13.95	74.05	9.99	0.13	26.9	8.784E+05	202.4
1253	980	1275	253.4	13.83	74.10	9.98	0.13	26.4	9.270E+05	205.7
1263	990	1268	255.0	13.71	74.15	9.97	0.13	26.0	9.773E+05	209.1
1273	1000	1261	256.6	13.59	74.19	9.96	0.13	25.5	1.030E+06	212.6
1283	1010	1255	258.3	13.46	74.23	9.96	0.13	25.1	1.084E+06	216.1
1293	1020	1248	259.9	13.33	74.26	9.95	0.13	24.6	1.140E+06	219.7
1303	1030	1241	261.7	13.21	74.29	9.95	0.13	24.2	1.198E+06	223.4
1313	1040	1235	263.4	13.08	74.32	9.95	0.13	23.7	1.257E+06	227.2
1323	1050	1228	265.2	12.95	74.34	9.95	0.13	23.2	1.319E+06	231.1
1333	1060	1221	267.1	12.82	74.35	9.95	0.13	22.8	1.383E+06	235.0
1343	1070	1214	268.9	12.68	74.37	9.95	0.13	22.3	1.449E+06	239.1
1353	1080	1208	270.8	12.55	74.38	9.95	0.13	21.9	1.517E+06	243.3
1363	1090	1201	272.8	12.41	74.39	9.95	0.13	21.4	1.587E+06	247.6
1373	1100	1194	274.8	12.28	74.39	9.96	0.13	21.0	1.659E+06	252.0
1383	1110	1187	276.8	12.14	74.40	9.96	0.13	20.5	1.733E+06	256.5
1393	1120	1180	278.8	12.00	74.40	9.97	0.13	20.0	1.810E+06	261.1
1403	1130	1173	280.9	11.86	74.40	9.98	0.13	19.6	1.888E+06	265.9
1413	1140	1166	283.1	11.72	74.40	9.98	0.13	19.1	1.969E+06	270.8
1423	1150	1160	285.2	11.57	74.39	9.99	0.13	18.7	2.051E+06	275.9
1433	1160	1153	287.4	11.43	74.39	10.00	0.13	18.2	2.136E+06	281.0
1443	1170	1146	289.6	11.28	74.38	10.02	0.13	17.7	2.223E+06	286.4
1453	1180	1139	291.9	11.13	74.37	10.03	0.13	17.3	2.313E+06	291.9
1463	1190	1132	294.2	10.99	74.37	10.04	0.14	16.8	2.404E+06	297.6
1473	1200	1124	296.6	10.84	74.36	10.06	0.14	16.3	2.498E+06	303.4
1483	1210	1117	298.9	10.68	74.36	10.07	0.14	15.9	2.593E+06	309.4
1493	1220	1110	301.4	10.53	74.35	10.09	0.14	15.4	2.692E+06	315.7
1503	1230	1103	303.8	10.38	74.35	10.11	0.14	14.9	2.792E+06	322.1
1513	1240	1096	306.3	10.22	74.35	10.13	0.14	14.5	2.894E+06	328.7
1523	1250	1089	308.8	10.07	74.35	10.15	0.14	14.0	2.999E+06	335.6
1533	1260	1081	311.4	9.91	74.35	10.17	0.14	13.5	3.106E+06	342.7
1543	1270	1074	314.0	9.75	74.36	10.20	0.14	13.1	3.215E+06	350.1
1553	1280	1066	316.6	9.59	74.37	10.22	0.14	12.6	3.326E+06	357.7
1563	1290	1059	319.3	9.43	74.38	10.25	0.14	12.1	3.440E+06	365.6
1573	1300	1051	322.0	9.27	74.40	10.28	0.14	11.6	3.556E+06	373.8

TABLE 3.17. PROPERTIES OF MERCURY AT SATURATION LINE [8, 27] (FROM CORRELATIONS 3.29–3.37)

Temperature		Density	Heat capacity	Thermal conductivity	Thermal diffusivity	Kinematic viscosity	10^2 Prandtl number	Surface tension	Electrical resistivity	Heat capacity
K	°C	kg/m^3	J/(kg·K)	W/(m·K)	10^6 (m^2/s)	10^{-7}(m^2/s)		mN/m	10^8 (Ω·m)	10^{-3} J/kg
273	0	13595	140.4	8.18	4.285	1.242	2.81	486	94.120	306.8
293	20	13546	139.6	8.45	4.467	1.151	2.58	480	95.830	306.1
313	40	13497	138.9	8.71	4.648	1.078	2.32	475	97.616	305.4
333	60	13448	138.2	8.97	4.826	1.018	2.11	469	99.478	304.7
353	80	13400	137.6	9.23	5.002	0.969	1.94	464	101.41	304.0
373	100	13351	137.1	9.48	5.175	0.927	1.80	458	103.42	303.3
393	120	13303	136.7	9.72	5.346	0.892	1.67	452	105.51	302.6
413	140	13255	136.3	9.96	5.513	0.862	1.57	447	107.68	302,0
433	160	13207	136.0	10.19	5.675	0.836	1.47	441	109.92	301.3
453	180	13136	135.7	10.42	5.836	0.813	1.39	435	112.24	300.7
473	200	13112	135.5	10.64	5.990	0.793	1.32	430	114.64	300.1
523	250	12993	135.2	11.18	6.365	0.753	1.18	416	121.01	298.4
573	300	12873	135.3	11.69	6.710	0.723	1.07	402	127.96	296.8
623	350	12754	135.7	12.16	7.030	0.701	0.99	388	135.56	295.1
673	400	12633	136.4	12.60	7.310	0.683	0.92	374	143.90	293.3
723	450	12510	137.5	13.01	7.560	0.670	0.87	360	153.80	291.3
773	500	12386	138.9	13.39	7.780	0.660	0.83	345	163.50	289.1
823	550	12259	140.6	13.73	7.960	0.653	0.80	331	175.50	286.6
873	600	12130	142.7	14.04	8.110	0.647	0.78	317	188.40	283.8
923	650	11998	145.1	14.33	8.230	0.643	0.76	303	203.40	280.5
973	700	11863	147.8	14.58	8.320	0.641	0.75	289	220.80	276.8
1023	750	11725	150.7	14.79	8.370	0.640	0.74	275	240.80	272.7
1073	800	11584	154.0	14.98	8.400	0.640	0.74	261	264.00	268.0

TABLE 3.18. PROPERTIES OF GALLIUM BY EQUATIONS (3.38–3.43)

Temperature		Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m^2/s)	Kinematic viscosity 10^8 (m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Electrical resistivity 10^8 (Ω·m)
K	°C								
303	30	6084	397.9	28.9	11.93	22.84	1.91	712.6	25.81
313	40	6077	397.4	29.5	12.22	22.66	1.85	712.1	26.02
323	50	6071	396.8	30.2	12.52	22.48	1.80	711.7	26.23
333	60	6064	396.3	30.8	12.81	22.30	1.74	711.2	26.43
343	70	6058	395.7	31.4	13.09	22.12	1.69	710.7	26.64
353	80	6052	395.2	32.0	13.38	21.95	1.64	710.3	26.85
363	90	6045	394.7	32.6	13.67	21.77	1.59	709.8	27.05
373	100	6039	394.2	33.2	13.95	21.59	1.55	709.3	27.26
383	110	6032	393.7	33.8	14.24	21.42	1.50	708.9	27.46
393	120	6026	393.2	34.4	14.52	21.25	1.46	708.4	27.67
403	130	6020	392.7	35.0	14.80	21.07	1.42	707.9	27.87
413	140	6013	392.2	35.6	15.08	20.90	1.39	707.5	28.07
423	150	6007	391.7	36.2	15.36	20.73	1.35	707.0	28.28
433	160	6001	391.2	36.7	15.64	20.55	1.31	706.5	28.48
443	170	5995	390.7	37.3	15.92	20.38	1.28	706.1	28.68
453	180	5988	390.3	37.8	16.19	20.21	1.25	705.6	28.88
463	190	5982	389.8	38.4	16.47	20.04	1.22	705.1	29.09
473	200	5976	389.4	39.0	16.74	19.87	1.19	704.7	29.29
483	210	5969	388.9	39.5	17.01	19.70	1.16	704.2	29.49
493	220	5963	388.5	40.0	17.28	19.53	1.13	703.7	29.69
503	230	5957	388.1	40.6	17.55	19.37	1.10	703.3	29.89
513	240	5951	387.6	41.1	17.81	19.20	1.08	702.8	30.09
523	250	5944	387.2	41.6	18.08	19.03	1.05	702.3	30.29
533	260	5938	386.8	42.1	18.34	18.87	1.03	701.9	30.48
543	270	5932	386.4	42.6	18.60	18.70	1.01	701.4	30.68
553	280	5926	386.0	43.1	18.86	18.54	0.98	700.9	30.88
563	290	5920	385.6	43.6	19.12	18.38	0.96	700.5	31.08
573	300	5913	385.2	44.1	19.38	18.21	0.94	700.0	31.27
583	310	5907	384.8	44.6	19.63	18.05	0.92	699.5	31.47
593	320	5901	384.5	45.1	19.88	17.89	0.90	699.1	31.67
603	330	5895	384.1	45.6	20.13	17.73	0.88	698.6	31.86
613	340	5889	383.7	46.1	20.38	17.57	0.86	698.1	32.06
623	350	5883	383.4	46.5	20.63	17.41	0.84	697.7	32.25
633	360	5876	383.0	47.0	20.88	17.25	0.83	697.2	32.45
643	370	5870	382.7	47.5	21.12	17.09	0.81	696.7	32.64
653	380	5864	382.3	47.9	21.36	16.93	0.79	696.3	32.83
663	390	5858	382.0	48.3	21.60	16.78	0.78	695.8	33.03
673	400	5852	381.7	48.8	21.84	16.62	0.76	695.3	33.22
683	410	5846	381.4	49.2	22.08	16.47	0.75	694.9	33.41
693	420	5840	381.1	49.7	22.31	16.31	0.73	694.4	33.60
703	430	5834	380.8	50.1	22.54	16.16	0.72	693.9	33.80
713	440	5828	380.5	50.5	22.77	16.00	0.70	693.5	33.99
723	450	5822	380.2	50.9	23.00	15.85	0.69	693.0	34.18
733	460	5816	379.9	51.3	23.23	15.70	0.68	692.5	34.37

TABLE 3.18. (continued)

Temperature		Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m^2/s)	Kinematic viscosity 10^8 (m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Electrical resistivity 10^8 (Ω·m)
K	°C								
743	470	5810	379.6	51.7	23.45	15.55	0.66	692.1	34.56
753	480	5804	379.3	52.1	23.67	15.39	0.65	691.6	34.75
763	490	5797	379.1	52.5	23.89	15.24	0.64	691.1	34.94
773	500	5791	378.8	52.9	24.11	15.09	0.63	690.7	35.12
783	510	5785	378.6	53.3	24.33	14.94	0.61	690.2	35.31
793	520	5779	378.3	53.7	24.54	14.80	0.60	689.7	35.50
803	530	5773	378.1	54.0	24.75	14.65	0.59	689.2	35.69
813	540	5768	377.8	54.4	24.96	14.50	0.58	688.8	35.87
823	550	5762	377.6	54.8	25.16	14.35	0.57	688.3	36.06
833	560	5756	377.4	55.1	25.37	14.21	0.56	687.8	36.25
843	570	5750	377.2	55.5	25.57	14.06	0.55	687.4	36.43
853	580	5744	377.0	55.8	25.77	13.92	0.54	686.9	36.62
863	590	5738	376.8	56.1	25.96	13.78	0.53	686.4	36.80
873	600	5732	376.6	56.5	26.16	13.63	0.52	686.0	36.99
883	610	5726	376.4	56.8	26.35	13.49	0.51	685.5	37.17
893	620	5720	376.2	57.1	26.54	13.35	0.50	685.0	37.35
903	630	5714	376.0	57.4	26.73	13.21	0.49	684.6	37.54
913	640	5708	375.9	57.7	26.91	13.07	0.49	684.1	37.72
923	650	5702	375.7	58.1	27.09	12.93	0.48	683.6	37.90
933	660	5696	375.6	58.4	27.27	12.79	0.47	683.2	38.08
943	670	5691	375.4	58.6	27.45	12.65	0.46	682.7	38.26
953	680	5685	375.3	58.9	27.62	12.51	0.45	682.2	38.45
963	690	5679	375.1	59.2	27.80	12.37	0.45	681.8	38.63
973	700	5673	375.0	59.5	27.97	12.24	0.44	681.3	38.81

TABLE 3.19. PROPERTIES OF LEAD BY EQUATIONS (3.44–3.49)

Temperature		Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m^2/s)	Kinematic viscosity 10^8 (m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Electrical resistivity 10^8 (Ω·m)
K	°C								
603	330	10670	147.30	15.83	10.07	23.90	2.37	445.81	93.77
613	340	10660	147.30	15.94	10.15	23.46	2.31	445.17	94.23
623	350	10650	147.30	16.04	10.23	23.03	2.25	444.53	94.70
633	360	10630	147.30	16.15	10.31	22.60	2.19	443.89	95.16
643	370	10620	147.30	16.26	10.39	22.18	2.13	443.25	95.63
653	380	10610	147.30	16.37	10.47	21.78	2.08	442.61	96.09
663	390	10600	147.30	16.48	10.56	21.38	2.03	441.97	96.56
673	400	10580	147.30	16.58	10.64	20.99	1.97	441.33	97.02
683	410	10570	147.30	16.69	10.72	20.61	1.92	440.69	97.49
693	420	10560	147.30	16.80	10.80	20.24	1.87	440.05	97.95
703	430	10550	147.30	16.91	10.88	19.88	1.83	439.41	98.42
713	440	10530	147.30	17.02	10.97	19.53	1.78	438.77	98.88
723	450	10520	147.30	17.12	11.05	19.19	1.74	438.13	99.35
733	460	10510	147.30	17.23	11.13	18.86	1.69	437.49	99.81
743	470	10500	147.30	17.34	11.21	18.54	1.65	436.85	100.28

TABLE 3.19. (continued)

Temperature		Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m^2/s)	Kinematic viscosity 10^8 (m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Electrical resistivity 10^8 (Ω·m)
K	°C								
753	480	10480	147.30	17.45	11.30	18.22	1.61	436.21	100.74
763	490	10470	147.30	17.56	11.38	17.92	1.57	435.57	101.21
773	500	10460	147.30	17.66	11.46	17.63	1.54	434.93	101.67
783	510	10450	147.30	17.77	11.55	17.34	1.50	434.29	102.14
793	520	10440	147.30	17.88	11.63	17.06	1.47	433.65	102.60
803	530	10420	147.30	17.99	11.72	16.80	1.43	433.01	103.07
813	540	10410	147.30	18.10	11.80	16.54	1.40	432.37	103.53
823	550	10400	147.30	18.20	11.89	16.29	1.37	431.73	104.00
833	560	10390	147.30	18.31	11.97	16.05	1.34	431.09	104.46
843	570	10370	147.30	18.42	12.06	15.82	1.31	430.45	104.93
853	580	10360	147.30	18.53	12.14	15.60	1.29	429.81	105.39
863	590	10350	147.30	18.64	12.23	15.39	1.26	429.17	105.86
873	600	10340	147.30	18.74	12.31	15.19	1.23	428.53	106.32
883	610	10320	147.30	18.85	12.40	15.00	1.21	427.89	106.79
893	620	10310	147.30	18.96	12.48	14.82	1.19	427.25	107.25
903	630	10300	147.30	19.07	12.57	14.64	1.17	426.61	107.72
913	640	10290	147.30	19.18	12.66	14.48	1.14	425.97	108.18
923	650	10270	147.30	19.28	12.74	14.33	1.12	425.33	108.65
933	660	10260	147.30	19.39	12.83	14.18	1.11	424.69	109.11
943	670	10250	147.30	19.50	12.92	14.04	1.09	424.05	109.58
953	680	10240	147.30	19.61	13.00	13.92	1.07	423.41	110.04
963	690	10220	147.30	19.72	13.09	13.80	1.05	422.77	110.51
973	700	10210	147.30	19.82	13.18	13.69	1.04	422.13	110.97
983	710	10200	147.30	19.93	13.27	13.59	1.02	421.49	111.44
993	720	10190	147.30	20.04	13.36	13.51	1.01	420.85	111.90
1003	730	10170	147.30	20.15	13.44	13.43	1.00	420.21	112.37
1013	740	10160	147.30	20.26	13.53	13.35	0.99	419.57	112.83
1023	750	10150	147.30	20.36	13.62	13.29	0.98	418.93	113.30
1033	760	10140	147.30	20.47	13.71	13.24	0.97	418.29	113.76
1043	770	10120	147.30	20.58	13.80	13.20	0.96	417.65	114.23
1053	780	10110	147.30	20.69	13.89	13.17	0.95	417.01	114.69
1063	790	10100	147.30	20.80	13.98	13.14	0.94	416.37	115.16
1073	800	10090	147.30	20.90	14.07	13.13	0.93	415.73	115.62
1083	810	10070	147.30	21.01	14.16	13.12	0.93	415.09	116.09
1093	820	10060	147.30	21.12	14.25	13.13	0.92	414.45	116.55
1103	830	10050	147.30	21.23	14.34	13.14	0.92	413.81	117.02
1113	840	10040	147.30	21.34	14.43	13.16	0.91	413.17	117.48
1123	850	10030	147.30	21.44	14.52	13.20	0.91	412.53	117.95
1133	860	10010	147.30	21.55	14.61	13.24	0.91	411.89	118.41
1143	870	10000	147.30	21.66	14.70	13.29	0.90	411.25	118.88
1153	880	9990	147.30	21.77	14.80	13.35	0.90	410.61	119.34
1163	890	9980	147.30	21.88	14.89	13.42	0.90	409.97	119.81
1173	900	9960	147.30	21.98	14.98	13.50	0.90	409.33	120.27
1183	910	9950	147.30	22.09	15.07	13.59	0.90	408.69	120.74
1193	920	9940	147.30	22.20	15.16	13.68	0.90	408.05	121.20
1203	930	9930	147.30	22.31	15.26	13.79	0.90	407.41	121.67

TABLE 3.19. (continued)

Temperature		Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m^2/s)	Kinematic viscosity 10^8 (m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Electrical resistivity 10^8 (Ω·m)
K	°C								
1213	940	9910	147.30	22.42	15.35	13.91	0.91	406.77	122.13
1223	950	9900	147.30	22.52	15.44	14.03	0.91	406.13	122.60
1233	960	9890	147.30	22.63	15.54	14.17	0.91	405.49	123.06
1243	970	9880	147.30	22.74	15.63	14.31	0.92	404.85	123.53
1253	980	9860	147.30	22.85	15.73	14.46	0.92	404.21	123.99
1263	990	9850	147.30	22.96	15.82	14.63	0.92	403.57	124.46
1273	1000	9840	147.30	23.06	15.91	14.80	0.93	402.93	124.92

TABLE 3.20. PROPERTIES OF 22Na-78K WT. % ALLOY BY EQUATIONS (3.50–3.55)

Temperature		Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m^2/s)	Kinematic viscosity 10^7 (m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure Pa	Electrical resistivity 10^8 (Ω·m)
K	°C									
273	0	863	962	21.7	26.15	7.60	2.91	146.5	7.29E-08	33.8
283	10	861	960	21.9	26.50	7.33	2.76	145.7	2.83E-07	34.4
293	20	859	958	22.1	26.85	7.06	2.63	144.9	1.00E-06	35.0
303	30	857	955	22.3	27.20	6.81	2.50	144.1	3.26E-06	35.6
313	40	855	953	22.4	27.55	6.57	2.39	143.3	9.82E-06	36.1
323	50	852	950	22.6	27.93	6.34	2.27	142.5	2.76E-05	36.7
333	60	850	948	22.8	28.28	6.12	2.16	141.7	7.27E-05	37.3
343	70	848	945	22.9	28.63	5.91	2.06	140.9	1.81E-04	37.8
353	80	846	942	23.1	28.98	5.71	1.97	140.1	4.27E-04	38.4
363	90	844	940	23.3	29.32	5.51	1.88	139.3	9.61E-04	39.0
373	100	841	937	23.4	29.70	5.33	1.79	138.5	2.07E-03	39.6
383	110	839	934	23.6	30.05	5.15	1.71	137.7	4.27E-03	40.1
393	120	837	931	23.7	30.39	4.98	1.64	136.9	8.50E-03	40.7
403	130	834	929	23.8	30.76	4.82	1.57	136.1	1.63E-02	41.3
413	140	832	926	24.0	31.10	4.67	1.50	135.3	3.04E-02	41.8
423	150	830	924	24.1	31.43	4.53	1.44	134.5	5.48E-02	42.4
433	160	827	921	24.2	31.79	4.39	1.38	133.7	9.62E-02	43.0
443	170	825	918	24.3	32.11	4.26	1.33	132.9	1.65E-01	43.6
453	180	823	916	24.5	32.43	4.13	1.27	132.1	2.75E-01	44.1
463	190	820	914	24.6	32.79	4.02	1.22	131.3	4.48E-01	44.7
473	200	818	911	24.7	33.10	3.90	1.18	130.5	7.16E-01	45.3
483	210	816	909	24.8	33.41	3.80	1.14	129.7	1.12E+00	45.8
493	220	813	907	24.9	33.75	3.70	1.10	128.9	1.72E+00	46.4
503	230	811	904	25.0	34.04	3.60	1.06	128.1	2.61E+00	47.0
513	240	809	902	25.1	34.33	3.51	1.02	127.3	3.87E+00	47.5
523	250	806	900	25.2	34.66	3.43	0.99	126.4	5.67E+00	48.1
533	260	804	898	25.2	34.94	3.35	0.96	125.6	8.18E+00	48.7
543	270	802	896	25.3	35.22	3.27	0.93	124.8	1.16E+01	49.3
553	280	799	894	25.4	35.53	3.20	0.90	124.0	1.63E+01	49.8
563	290	797	893	25.5	35.79	3.13	0.87	123.2	2.26E+01	50.4
573	300	795	891	25.5	36.04	3.07	0.85	122.4	3.10E+01	51.0
583	310	792	889	25.6	36.33	3.01	0.83	121.6	4.21E+01	51.5
593	320	790	888	25.6	36.58	2.95	0.81	120.8	5.65E+01	52.1
603	330	788	886	25.7	36.81	2.90	0.79	120.0	7.50E+01	52.7
613	340	785	885	25.8	37.08	2.85	0.77	119.2	9.87E+01	53.3

TABLE 3.20. (continued)

Temperature K	Temperature °C	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m^2/s)	Kinematic viscosity 10^7 (m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure Pa	Electrical resistivity 10^8 (Ω·m)
623	350	783	883	25.8	37.30	2.80	0.75	118.4	1.29E+02	53.8
633	360	780	882	25.8	37.56	2.75	0.73	117.6	1.66E+02	54.4
643	370	778	881	25.9	37.77	2.71	0.72	116.8	2.14E+02	55.0
653	380	776	879	25.9	37.96	2.67	0.70	115.9	2.72E+02	55.5
663	390	773	878	25.9	38.20	2.64	0.69	115.1	3.43E+02	56.1
673	400	771	877	26.0	38.38	2.60	0.68	114.3	4.31E+02	56.7
683	410	769	876	26.0	38.55	2.57	0.67	113.5	5.37E+02	57.3
693	420	766	875	26.0	38.77	2.54	0.65	112.7	6.65E+02	57.8
703	430	764	875	26.0	38.92	2.51	0.64	111.9	8.18E+02	58.4
713	440	762	874	26.0	39.07	2.48	0.63	111.1	1.00E+03	59.0
723	450	759	873	26.0	39.26	2.45	0.63	110.3	1.22E+03	59.5
733	460	757	873	26.0	39.39	2.43	0.62	109.5	1.47E+03	60.1
743	470	755	872	26.0	39.50	2.41	0.61	108.7	1.77E+03	60.7
753	480	752	872	26.0	39.67	2.38	0.60	107.9	2.12E+03	61.2
763	490	750	872	26.0	39.77	2.36	0.59	107.1	2.53E+03	61.8
773	500	748	871	26.0	39.86	2.34	0.59	106.2	3.00E+03	62.4
783	510	745	871	26.0	40.00	2.32	0.58	105.4	3.54E+03	63.0
793	520	743	871	25.9	40.07	2.31	0.58	104.6	4.17E+03	63.5
803	530	741	871	25.9	40.13	2.29	0.57	103.8	4.88E+03	64.1
813	540	738	871	25.9	40.24	2.27	0.56	103.0	5.70E+03	64.7
823	550	736	871	25.8	40.28	2.25	0.56	102.2	6.63E+03	65.2
833	560	733	872	25.8	40.37	2.24	0.55	101.4	7.68E+03	65.8
843	570	731	872	25.7	40.40	2.22	0.55	100.6	8.86E+03	66.4
853	580	729	872	25.7	40.41	2.21	0.55	99.8	1.02E+04	67.0
863	590	726	873	25.6	40.47	2.19	0.54	99.0	1.17E+04	67.5
873	600	724	873	25.6	40.46	2.18	0.54	98.2	1.34E+04	68.1
883	610	722	874	25.5	40.45	2.16	0.53	97.4	1.52E+04	68.7
893	620	719	875	25.5	40.48	2.15	0.53	96.6	1.73E+04	69.2
903	630	717	875	25.4	40.44	2.13	0.53	95.8	1.96E+04	69.8
913	640	715	876	25.3	40.39	2.12	0.52	95.0	2.22E+04	70.4
923	650	712	877	25.2	40.39	2.11	0.52	94.2	2.50E+04	71.0
933	660	710	878	25.1	40.33	2.09	0.52	93.3	2.81E+04	71.5
943	670	707	879	25.1	40.30	2.08	0.52	92.5	3.15E+04	72.1
953	680	705	881	25.0	40.22	2.06	0.51	91.7	3.52E+04	72.7
963	690	703	882	24.9	40.12	2.05	0.51	90.9	3.93E+04	73.2
973	700	700	883	24.8	40.07	2.03	0.51	90.1	4.38E+04	73.8
983	710	698	885	24.7	39.95	2.02	0.51	89.3	4.86E+04	74.4
993	720	695	886	24.6	39.87	2.01	0.50	88.5	5.39E+04	74.9
1003	730	693	888	24.4	39.73	1.99	0.50	87.7	5.97E+04	75.5
1013	740	691	889	24.3	39.58	1.98	0.50	86.9	6.59E+04	76.1
1023	750	688	891	24.2	39.48	1.96	0.50	86.1	7.26E+04	76.7
1033	760	686	893	24.1	39.31	1.95	0.50	85.3	7.99E+04	77.2
1043	770	683	895	24.0	39.19	1.93	0.49	84.5	8.78E+04	77.8
1053	780	681	897	23.8	38.99	1.92	0.49	83.7	9.62E+04	78.4
1063	790	678	899	23.7	38.85	1.91	0.49	82.9	1.05E+05	78.9
1073	800	676	901	23.5	38.64	1.89	0.49	82.1	1.15E+05	79.5
1083	810	674	904	23.4	38.42	1.88	0.49	81.3	1.25E+05	80.1
1093	820	671	906	23.3	38.24	1.87	0.49	80.6	1.37E+05	80.7

TABLE 3.20. (continued)

Temperature		Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m^2/s)	Kinematic viscosity 10^7 (m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure Pa	Electrical resistivity 10^8 (Ω·m)
K	°C									
1103	830	669	908	23.1	38.00	1.85	0.49	79.8	1.49E+05	81.2
1113	840	666	911	22.9	37.81	1.84	0.49	79.0	1.61E+05	81.8
1123	850	664	913	22.8	37.54	1.83	0.49	78.2	1.75E+05	82.4
1133	860	661	916	22.6	37.33	1.82	0.49	77.4	1.89E+05	82.9
1143	870	659	919	22.4	37.05	1.81	0.49	76.6	2.05E+05	83.5
1153	880	656	922	22.3	36.82	1.80	0.49	75.8	2.21E+05	84.1
1163	890	654	925	22.1	36.52	1.79	0.49	75.0	2.38E+05	84.7
1173	900	651	928	21.9	36.26	1.78	0.49	74.2	2.57E+05	85.2
1183	910	649	931	21.7	35.94	1.77	0.49	73.4	2.76E+05	85.8
1193	920	646	934	21.5	35.67	1.76	0.49	72.6	2.97E+05	86.4
1203	930	644	937	21.3	35.33	1.76	0.50	71.9	3.18E+05	86.9
1213	940	641	940	21.1	35.04	1.76	0.50	71.1	3.41E+05	87.5
1223	950	639	944	20.9	34.69	1.75	0.51	70.3	3.65E+05	88.1
1233	960	636	947	20.7	34.37	1.75	0.51	69.5	3.91E+05	88.6
1243	970	634	951	20.5	34.00	1.75	0.52	68.7	4.18E+05	89.2
1253	980	631	955	20.3	33.67	1.76	0.52	67.9	4.46E+05	89.8
1263	990	629	958	20.1	33.28	1.76	0.53	67.2	4.75E+05	90.4
1273	1000	626	962	19.8	32.94	1.77	0.54	66.4	5.06E+05	90.9
1283	1010	623	966	19.6	32.58	1.78	0.55	65.6	5.38E+05	91.5
1293	1020	621	970	19.4	32.16	1.79	0.56	64.8	5.72E+05	92.1
1303	1030	618	974	19.1	31.79	1.80	0.57	64.0	6.08E+05	92.6
1313	1040	616	978	18.9	31.36	1.82	0.58	63.3	6.45E+05	93.2
1323	1050	613	982	18.7	30.97	1.84	0.59	62.5	6.84E+05	93.8
1333	1060	611	987	18.4	30.52	1.86	0.61	61.7	7.24E+05	94.4
1343	1070	608	991	18.1	30.11	1.89	0.63	60.9	7.66E+05	94.9
1353	1080	605	996	17.9	29.70	1.92	0.65	60.2	8.10E+05	95.5
1363	1090	603	1000	17.6	29.22	1.95	0.67	59.4	8.56E+05	96.1
1373	1100	600	1005	17.4	28.79	1.99	0.69	58.6	9.04E+05	96.6
1383	1110	598	1009	17.1	28.31	2.03	0.72	57.9	9.53E+05	97.2
1393	1120	595	1014	16.8	27.86	2.07	0.74	57.1	1.00E+06	97.8
1403	1130	592	1019	16.5	27.40	2.12	0.77	56.3	1.06E+06	98.4
1413	1140	590	1024	16.3	26.89	2.18	0.81	55.6	1.11E+06	98.9
1423	1150	587	1029	16.0	26.42	2.23	0.85	54.8	1.17E+06	99.5
1433	1160	584	1034	15.7	25.94	2.30	0.89	54.0	1.23E+06	100.1
1443	1170	582	1040	15.4	25.41	2.37	0.93	53.3	1.29E+06	100.6
1453	1180	579	1045	15.1	24.92	2.44	0.98	52.5	1.36E+06	101.2
1463	1190	576	1050	14.8	24.42	2.52	1.03	51.8	1.42E+06	101.8
1473	1200	574	1056	14.5	23.87	2.60	1.09	51.0	1.49E+06	102.3
1483	1210	571	1061	14.2	23.35	2.70	1.15	50.3	1.56E+06	102.9
1493	1220	568	1067	13.8	22.83	2.79	1.22	49.5	1.64E+06	103.5
1503	1230	565	1073	13.5	22.30	2.90	1.30	48.8	1.71E+06	104.1
1513	1240	563	1078	13.2	21.72	3.01	1.39	48.0	1.79E+06	104.6
1523	1250	560	1084	12.9	21.18	3.13	1.48	47.3	1.87E+06	105.2
1533	1260	557	1090	12.5	20.63	3.26	1.58	46.5	1.95E+06	105.8
1543	1270	555	1096	12.2	20.04	3.39	1.69	45.8	2.04E+06	106.3
1553	1280	552	1102	11.9	19.47	3.53	1.81	45.0	2.13E+06	106.9
1563	1290	549	1109	11.5	18.90	3.68	1.95	44.3	2.22E+06	107.5
1573	1300	546	1115	11.1	18.32	3.84	2.10	43.5	2.31E+06	108.0

TABLE 3.21. PROPERTIES OF 4,2Na-22,2K-73,6Cs WT. % ALLOY BY TO EQUATIONS (3.56–3.62)

Temperature		Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m^2/s)	Kinematic viscosity 10^8 (m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure Pa	Electrical resistivity 10^8 (Ω·m)
K	°C									
203	–70	1444	477	6.08	8.85	126	14.2	115.3	2.26E-10	7.68
213	–60	1441	473	6.41	9.41	110	11.7	114.7	1.62E-09	7.64
223	–50	1437	470	6.73	9.97	97.6	9.79	114.0	9.77E-09	7.62
233	–40	1434	467	7.04	10.53	87.3	8.29	113.4	5.05E-08	7.61
243	–30	1430	463	8.98	11.08	78.8	7.11	112.7	2.28E-07	7.61
253	–20	1427	460	7.64	11.63	71.6	6.16	112.1	9.14E-07	7.62
263	–10	1423	457	7.92	12.18	65.6	5.39	111.4	3.30E-06	7.63
273	0	1420	455	8.20	12.72	60.5	4.75	110.8	1.09E-05	7.66
283	10	1416	452	8.47	13.26	56.0	4.23	110.1	3.29E-05	7.69
293	20	1412	449	8.73	13.79	52.2	3.78	109.4	9.23E-05	7.72
303	30	1408	446	8.98	14.31	48.8	3.41	108.8	2.42E-04	7.76
313	40	1404	443	9.23	14.83	45.8	3.09	108.1	5.97E-04	7.80
323	50	1400	441	9.46	15.35	43.2	2.82	107.5	1.39E-03	7.85
333	60	1396	438	9.69	15.86	40.9	2.58	106.8	3.09E-03	7.90
343	70	1392	435	9.92	16.37	38.8	2.37	106.2	6.56E-03	7.96
353	80	1388	433	10.1	16.86	36.9	2.19	105.5	1.33E-02	8.01
363	90	1384	431	10.3	17.35	35.2	2.03	104.9	2.61E-02	8.08
373	100	1380	428	10.5	17.84	33.7	1.89	104.2	4.91E-02	8.14
383	110	1376	426	10.7	18.32	32.3	1.76	103.5	8.97E-02	8.21
393	120	1372	424	10.9	18.79	31.0	1.65	102.9	1.59E-01	8.28
403	130	1368	422	11.1	19.25	29.9	1.55	102.2	2.73E-01	8.36
413	140	1364	419	11.3	19.70	28.8	1.46	101.6	4.59E-01	8.43
423	150	1360	417	11.4	20.15	27.8	1.38	100.9	7.51E-01	8.51
433	160	1356	415	11.6	20.59	26.9	1.31	100.3	1.20E+00	8.60
443	170	1351	413	11.7	21.02	26.1	1.24	99.6	1.89E+00	8.68
453	180	1347	412	11.9	21.44	25.3	1.18	98.9	2.90E+00	8.77
463	190	1343	410	12.0	21.85	24.6	1.13	98.3	4.37E+00	8.86
473	200	1339	408	12.2	22.26	23.9	1.08	97.6	6.49E+00	8.95
483	210	1335	406	12.3	22.65	23.3	1.03	97.0	9.47E+00	9.05
493	220	1330	405	12.4	23.03	22.7	0.99	96.3	1.36E+01	9.15
503	230	1326	403	12.5	23.41	22.2	0.95	95.7	1.93E+01	9.25
513	240	1322	402	12.6	23.77	21.6	0.91	95.0	2.70E+01	9.35
523	250	1318	400	12.7	24.12	21.1	0.88	94.3	3.73E+01	9.46
533	260	1314	399	12.8	24.47	20.7	0.85	93.7	5.08E+01	9.57
543	270	1310	398	12.9	24.80	20.3	0.82	93.0	6.86E+01	9.68
553	280	1305	396	13.0	25.12	19.9	0.79	92.4	9.15E+01	9.80
563	290	1301	395	13.1	25.43	19.5	0.77	91.7	1.21E+02	9.91
573	300	1297	394	13.1	25.73	19.1	0.74	91.1	1.58E+02	10.03
583	310	1293	393	13.2	26.01	18.8	0.72	90.4	2.05E+02	10.16
593	320	1289	392	13.3	26.29	18.4	0.70	89.8	2.64E+02	10.28
603	330	1284	391	13.3	26.55	18.1	0.68	89.1	3.37E+02	10.41
613	340	1280	390	13.4	26.81	17.8	0.67	88.4	4.26E+02	10.54
623	350	1276	389	13.4	27.05	17.5	0.65	87.8	5.35E+02	10.68
633	360	1272	388	13.5	27.28	17.3	0.63	87.1	6.67E+02	10.81

TABLE 3.21. (continued)

Temperature K	Temperature °C	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m^2/s)	Kinematic viscosity 10^8 (m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure Pa	Electrical resistivity 10^8 (Ω·m)
643	370	1268	388	13.5	27.49	17.0	0.62	86.5	8.26E+02	10.95
653	380	1264	387	13.5	27.70	16.8	0.61	85.8	1.02E+03	11.09
663	390	1260	386	13.6	27.89	16.6	0.59	85.2	1.24E+03	11.24
673	400	1255	386	13.6	28.07	16.3	0.58	84.5	1.51E+03	11.39
683	410	1251	385	13.6	28.24	16.1	0.57	83.9	1.83E+03	11.54
693	420	1247	385	13.6	28.40	15.9	0.56	83.2	2.20E+03	11.70
703	430	1243	385	13.6	28.54	15.7	0.55	82.6	2.63E+03	11.86
713	440	1239	384	13.7	28.67	15.5	0.54	81.9	3.13E+03	12.02
723	450	1235	384	13.7	28.79	15.4	0.53	81.3	3.71E+03	12.18
733	460	1231	384	13.7	28.90	15.2	0.53	80.6	4.38E+03	12.35
743	470	1226	384	13.7	29.00	15.0	0.52	79.9	5.14E+03	12.52
753	480	1222	384	13.6	29.09	14.9	0.51	79.3	6.01E+03	12.70
763	490	1218	384	13.6	29.16	14.7	0.51	78.6	7.00E+03	12.88
773	500	1214	384	13.6	29.22	14.6	0.50	78.0	8.12E+03	13.06
783	510	1210	384	13.6	29.27	14.4	0.49	77.3	9.39E+03	13.25
793	520	1206	384	13.6	29.31	14.3	0.49	76.7	1.08E+04	13.44
803	530	1201	385	13.6	29.34	14.2	0.48	76.0	1.24E+04	13.63
813	540	1197	385	13.5	29.36	14.1	0.48	75.4	1.42E+04	13.83
823	550	1193	385	13.5	29.37	13.9	0.48	74.7	1.62E+04	14.03
833	560	1189	386	13.5	29.36	13.8	0.47	74.1	1.84E+04	14.24
843	570	1185	386	13.4	29.35	13.7	0.47	73.4	2.09E+04	14.45
853	580	1180	387	13.4	29.33	13.6	0.46	72.8	2.36E+04	14.66
863	590	1176	388	13.3	29.29	13.5	0.46	72.1	2.66E+04	14.88
873	600	1172	388	13.3	29.25	13.4	0.46	71.5	2.99E+04	15.10
883	610	1168	389	13.3	29.20	13.3	0.46	70.8	3.35E+04	15.33
893	620	1163	390	13.2	29.13	13.2	0.45	70.2	3.75E+04	15.56
903	630	1159	391	13.2	29.06	13.1	0.45	69.5	4.18E+04	15.79
913	640	1155	392	13.1	28.98	13.1	0.45	68.9	4.65E+04	16.03
923	650	1151	393	13.0	28.89	13.0	0.45	68.3	5.16E+04	16.27
933	660	1146	394	13.0	28.80	12.9	0.45	67.6	5.72E+04	16.52
943	670	1142	395	12.9	28.70	12.8	0.45	67.0	6.33E+04	16.78
953	680	1138	396	12.9	28.58	12.8	0.45	66.3	6.98E+04	17.03
963	690	1133	397	12.8	28.47	12.7	0.45	65.7	7.69E+04	17.30
973	700	1129	399	12.7	28.34	12.6	0.45	65.0	8.45E+04	17.56
983	710	1125	400	12.7	28.21	12.6	0.45	64.4	9.27E+04	17.83
993	720	1120	401	12.6	28.07	12.5	0.45	63.7	1.02E+05	18.11
1003	730	1116	403	12.5	27.92	12.4	0.45	63.1	1.11E+05	18.39
1013	740	1112	404	12.5	27.77	12.4	0.45	62.4	1.21E+05	18.68
1023	750	1107	406	12.4	27.62	12.3	0.45	61.8	1.32E+05	18.97
1033	760	1103	408	12.3	27.46	12.3	0.45	61.2	1.43E+05	19.26
1043	770	1098	409	12.3	27.29	12.2	0.45	60.5	1.56E+05	19.56
1053	780	1094	411	12.2	27.12	12.2	0.45	59.9	1.69E+05	19.87
1063	790	1089	413	12.1	26.95	12.1	0.45	59.2	1.83E+05	20.18
1073	800	1085	415	12.0	26.77	12.1	0.45	58.6	1.98E+05	20.49
1083	810	1081	417	12.0	26.59	12.0	0.45	58.0	2.14E+05	20.81
1093	820	1076	419	11.9	26.41	12.0	0.45	57.3	2.30E+05	21.13
1103	830	1071	421	11.8	26.22	12.0	0.46	56.7	2.48E+05	21.46

TABLE 3.21. (continued)

Temperature K	Temperature °C	Density kg/m³	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m²/s)	Kinematic viscosity 10^8 (m²/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure Pa	Electrical resistivity 10^8 (Ω·m)
1113	840	1067	423	11.7	26.03	11.9	0.46	56.0	2.67E+05	21.80
1123	850	1062	425	11.7	25.84	11.9	0.46	55.4	2.86E+05	22.13
1133	860	1058	428	11.6	25.65	11.8	0.46	54.8	3.07E+05	22.47
1143	870	1053	430	11.5	25.46	11.8	0.46	54.1	3.29E+05	22.82
1153	880	1049	432	11.5	25.26	11.8	0.47	53.5	3.52E+05	23.17
1163	890	1044	435	11.4	25.07	11.8	0.47	52.9	3.76E+05	23.52
1173	900	1039	437	11.3	24.87	11.7	0.47	52.2	4.02E+05	23.88
1183	910	1035	440	11.2	24.67	11.7	0.47	51.6	4.28E+05	24.24
1193	920	1030	443	11.2	24.48	11.7	0.48	50.9	4.57E+05	24.61
1203	930	1025	445	11.1	24.28	11.7	0.48	50.3	4.86E+05	24.98
1213	940	1021	448	11.0	24.08	11.6	0.48	49.7	5.17E+05	25.35
1223	950	1016	451	10.9	23.89	11.6	0.49	49.1	5.49E+05	25.72
1233	960	1011	454	10.9	23.70	11.6	0.49	48.4	5.82E+05	26.10
1243	970	1007	457	10.8	23.50	11.6	0.49	47.8	6.18E+05	26.48
1253	980	1002	460	10.7	23.31	11.6	0.50	47.2	6.54E+05	26.86
1263	990	997	463	10.7	23.13	11.5	0.50	46.5	6.92E+05	27.24
1273	1000	992	466	10.6	22.94	11.5	0.50	45.9	7.32E+05	27.62
1283	1010	988	469	10.5	22.76	11.5	0.51	45.3	7.74E+05	28.01
1293	1020	983	472	10.5	22.58	11.5	0.51	44.6	8.17E+05	28.39
1303	1030	978	476	10.4	22.40	11.5	0.51	44.0	8.61E+05	28.77
1313	1040	973	479	10.4	22.23	11.5	0.52	43.4	9.08E+05	29.16
1323	1050	969	482	10.3	22.06	11.5	0.52	42.8	9.56E+05	29.54
1333	1060	964	486	10.3	21.89	11.5	0.52	42.1	1.01E+06	29.92
1343	1070	959	490	10.2	21.73	11.5	0.53	41.5	1.06E+06	30.30
1353	1080	954	493	10.1	21.58	11.5	0.53	40.9	1.11E+06	30.68
1363	1090	949	497	10.1	21.42	11.5	0.54	40.3	1.17E+06	31.05
1373	1100	944	501	10.1	21.28	11.5	0.54	39.6	1.23E+06	31.42
1383	1110	939	504	10.0	21.13	11.5	0.54	39.0	1.29E+06	31.79
1393	1120	934	508	10.0	21.00	11.5	0.55	38.4	1.35E+06	32.15
1403	1130	930	512	9.93	20.87	11.5	0.55	37.8	1.41E+06	32.51
1413	1140	925	516	9.89	20.74	11.5	0.55	37.2	1.48E+06	32.86
1423	1150	920	520	9.86	20.62	11.5	0.56	36.5	1.54E+06	33.20
1433	1160	915	524	9.83	20.51	11.5	0.56	35.9	1.61E+06	33.53
1443	1170	910	528	9.80	20.41	11.5	0.56	35.3	1.69E+06	33.86
1453	1180	905	533	9.78	20.31	11.5	0.57	34.7	1.76E+06	34.18
1463	1190	900	537	9.76	20.22	11.5	0.57	34.1	1.84E+06	34.48
1473	1200	895	541	9.74	20.13	11.5	0.57	33.5	1.92E+06	34.78
1483	1210	889	546	9.73	20.05	11.5	0.57	32.8	2.00E+06	35.07
1493	1220	884	550	9.72	19.98	11.5	0.58	32.2	2.08E+06	35.34
1503	1230	879	555	9.71	19.92	11.5	0.58	31.6	2.17E+06	35.60
1513	1240	874	559	9.71	19.87	11.6	0.58	31.0	2.26E+06	35.85
1523	1250	869	564	9.71	19.82	11.6	0.58	30.4	2.35E+06	36.08
1533	1260	864	569	9.71	19.79	11.6	0.59	29.8	2.44E+06	36.30
1543	1270	859	573	9.72	19.76	11.6	0.59	29.2	2.54E+06	36.51
1553	1280	853	578	9.73	19.74	11.6	0.59	28.6	2.64E+06	36.70
1563	1290	848	583	9.75	19.73	11.7	0.59	27.9	2.74E+06	36.87
1573	1300	843	588	9.77	19.73	11.7	0.59	27.3	2.84E+06	37.02

TABLE 3.22. PROPERTIES OF 44.5Pb–55.5Bi WT. % ALLOY BY EQUATIONS (3.63–3.66)

Temperature K	Temperature °C	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6(m^2/s)	Kinematic viscosity 10^8(m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Electrical resistivity 10^8 (Ω·m)
403	130	10550	146	11.0	7.17	29.41	4.10	415.65	104.41
413	140	10530	146	11.1	7.24	28.72	3.97	414.95	104.93
423	150	10520	146	11.2	7.31	28.04	3.83	414.24	105.45
433	160	10510	146	11.3	7.39	27.37	3.71	413.54	105.98
443	170	10500	146	11.4	7.46	26.72	3.58	412.84	106.50
453	180	10480	146	11.5	7.53	26.08	3.46	412.13	107.02
463	190	10470	146	11.6	7.61	25.46	3.35	411.43	107.54
473	200	10460	146	11.7	7.68	24.85	3.24	410.73	108.07
483	210	10450	146	11.8	7.76	24.26	3.13	410.02	108.59
493	220	10430	146	11.9	7.83	23.67	3.02	409.32	109.11
503	230	10420	146	12.0	7.90	23.11	2.92	408.62	109.64
513	240	10410	146	12.1	7.98	22.55	2.83	407.92	110.16
523	250	10400	146	12.2	8.05	22.01	2.73	407.21	110.68
533	260	10380	146	12.3	8.13	21.49	2.64	406.51	111.21
543	270	10370	146	12.4	8.21	20.97	2.56	405.81	111.73
553	280	10360	146	12.5	8.28	20.48	2.47	405.10	112.25
563	290	10350	146	12.6	8.36	19.99	2.39	404.40	112.77
573	300	10330	146	12.7	8.43	19.52	2.32	403.70	113.30
583	310	10320	146	12.8	8.51	19.06	2.24	402.99	113.82
593	320	10310	146	12.9	8.58	18.62	2.17	402.29	114.34
603	330	10300	146	13.0	8.66	18.19	2.10	401.59	114.87
613	340	10280	146	13.1	8.74	17.78	2.03	400.89	115.39
623	350	10270	146	13.2	8.81	17.38	1.97	400.18	115.91
633	360	10260	146	13.3	8.89	16.99	1.91	399.48	116.44
643	370	10250	146	13.4	8.97	16.62	1.85	398.78	116.96
653	380	10230	146	13.5	9.05	16.26	1.80	398.07	117.48
663	390	10220	146	13.6	9.12	15.91	1.74	397.37	118.00
673	400	10210	146	13.7	9.20	15.58	1.69	396.67	118.53
683	410	10200	146	13.8	9.28	15.26	1.64	395.96	119.05
693	420	10180	146	13.9	9.36	14.96	1.60	395.26	119.57
703	430	10170	146	14.0	9.44	14.67	1.55	394.56	120.10
713	440	10160	146	14.1	9.51	14.39	1.51	393.86	120.62
723	450	10150	146	14.2	9.59	14.13	1.47	393.15	121.14
733	460	10130	146	14.3	9.67	13.88	1.44	392.45	121.67
743	470	10120	146	14.4	9.75	13.65	1.40	391.75	122.19
753	480	10110	146	14.5	9.83	13.43	1.37	391.04	122.71
763	490	10100	146	14.6	9.91	13.22	1.33	390.34	123.23
773	500	10080	146	14.7	9.99	13.03	1.30	389.64	123.76
783	510	10070	146	14.8	10.07	12.85	1.28	388.93	124.28
793	520	10060	146	14.9	10.15	12.69	1.25	388.23	124.80
803	530	10050	146	15.0	10.23	12.54	1.23	387.53	125.33
813	540	10030	146	15.1	10.31	12.40	1.20	386.83	125.85
823	550	10020	146	15.2	10.39	12.28	1.18	386.12	126.37

TABLE 3.22. (continued)

Temperature		Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6(m^2/s)	Kinematic viscosity 10^8(m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Electrical resistivity 10^8(Ω·m)
K	°C								
833	560	10010	146	15.3	10.47	12.17	1.16	385.42	126.90
843	570	10000	146	15.4	10.55	12.07	1.14	384.72	127.42
853	580	9980	146	15.5	10.63	11.99	1.13	384.01	127.94
863	590	9970	146	15.6	10.72	11.92	1.11	383.31	128.46
873	600	9960	146	15.7	10.80	11.87	1.10	382.61	128.99
883	610	9950	146	15.8	10.88	11.83	1.09	381.90	129.51
893	620	9930	146	15.9	10.96	11.80	1.08	381.20	130.03
903	630	9920	146	16.0	11.04	11.79	1.07	380.50	130.56
913	640	9910	146	16.1	11.13	11.80	1.06	379.80	131.08
923	650	9900	146	16.2	11.21	11.81	1.05	379.09	131.60
933	660	9880	146	16.3	11.29	11.84	1.05	378.39	132.13
943	670	9870	146	16.4	11.38	11.88	1.04	377.69	132.65
953	680	9860	146	16.5	11.46	11.94	1.04	376.98	133.17
963	690	9850	146	16.6	11.54	12.01	1.04	376.28	133.69
973	700	9830	146	16.7	11.63	12.10	1.04	375.58	134.22
983	710	9820	146	16.8	11.71	12.20	1.04	374.87	134.74
993	720	9810	146	16.9	11.80	12.31	1.04	374.17	135.26
1003	730	9800	146	17.0	11.88	12.44	1.05	373.47	135.79
1013	740	9780	146	17.1	11.96	12.58	1.05	372.77	136.31
1023	750	9770	146	17.2	12.05	12.74	1.06	372.06	136.83
1033	760	9760	146	17.3	12.13	12.90	1.06	371.36	137.36
1043	770	9750	146	17.4	12.22	13.09	1.07	370.66	137.88
1053	780	9730	146	17.5	12.31	13.28	1.08	369.95	138.40
1063	790	9720	146	17.6	12.39	13.49	1.09	369.25	138.92
1073	800	9710	146	17.7	12.48	13.72	1.10	368.55	139.45

TABLE 3.23. PROPERTIES OF 99.32Pb–0.68Li WT. % ALLOY BY EQUATIONS (3.67–3.78)

Temperature		Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6(m^2/s)	Kinematic viscosity 10^8(m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure Pa	Electrical resistivity 10^8(Ω·m)
K	°C									
513	240	9495	183.0	12.00	6.90	27.95	4.04	464.4	5.76E-10	124.1
523	250	9486	183.0	12.19	7.03	26.57	3.77	463.0	1.34E-09	124.6
533	260	9478	182.9	12.39	7.15	25.32	3.54	461.7	3.04E-09	125.0
543	270	9469	182.8	12.59	7.27	24.17	3.32	460.3	6.66E-09	125.4
553	280	9461	182.8	12.78	7.39	23.11	3.12	458.9	1.42E-08	125.9
563	290	9452	182.7	12.98	7.52	22.13	2.94	457.6	2.94E-08	126.3
573	300	9444	182.6	13.17	7.64	21.22	2.77	456.2	5.95E-08	126.7
583	310	9435	182.5	13.37	7.76	20.38	2.62	454.8	1.18E-07	127.1
593	320	9427	182.5	13.57	7.89	19.61	2.48	453.5	2.27E-07	127.6
603	330	9418	182.4	13.76	8.01	18.88	2.35	452.1	4.28E-07	128.0
613	340	9410	182.4	13.96	8.13	18.21	2.24	450.8	7.92E-07	128.4
623	350	9401	182.3	14.15	8.26	17.57	2.13	449.4	1.44E-06	128.8
633	360	9393	182.2	14.35	8.38	16.99	2.03	448.0	2.56E-06	129.3
643	370	9384	182.2	14.55	8.51	16.44	1.93	446.7	4.47E-06	129.7
653	380	9376	182.1	14.74	8.63	15.93	1.84	445.3	7.68E-06	130.1

TABLE 3.23. (continued)

Temperature K	Temperature °C	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6(m^2/s)	Kinematic viscosity 10^8(m^2/s)	10^2 Prandtl number	Surface tension 10^3N/m	Pressure Pa	Electrical resistivity 10^8(Ω·m)
663	390	9367	182.0	14.94	8.76	15.44	1.76	443.9	1.30E-05	130.5
673	400	9359	182.0	15.13	8.89	14.98	1.69	442.6	2.16E-05	131.0
683	410	9350	181.9	15.33	9.01	14.55	1.62	441.2	3.54E-05	131.4
693	420	9342	181.9	15.53	9.14	14.14	1.55	439.8	5.72E-05	131.8
703	430	9333	181.8	15.72	9.27	13.76	1.49	438.5	9.12E-05	132.2
713	440	9325	181.7	15.92	9.39	13.40	1.43	437.1	1.44E-04	132.7
723	450	9316	181.7	16.11	9.52	13.06	1.37	435.7	2.23E-04	133.1
733	460	9308	181.6	16.31	9.65	12.74	1.32	434.4	3.43E-04	133.5
743	470	9299	181.6	16.51	9.78	12.43	1.27	433.0	5.20E-04	134.0
753	480	9291	181.5	16.70	9.90	12.13	1.23	431.6	7.81E-04	134.4
763	490	9282	181.4	16.90	10.03	11.86	1.18	430.3	1.16E-03	134.8
773	500	9274	181.4	17.09	10.16	11.59	1.14	428.9	1.70E-03	135.2
783	510	9265	181.3	17.29	10.29	11.34	1.10	427.5	2.48E-03	135.7
793	520	9257	181.3	17.49	10.42	11.10	1.07	426.2	3.58E-03	136.1
803	530	9248	181.2	17.68	10.55	10.87	1.03	424.8	5.11E-03	136.5
813	540	9240	181.2	17.88	10.68	10.66	1.00	423.4	7.24E-03	136.9
823	550	9231	181.1	18.07	10.81	10.45	0.97	422.1	1.02E-02	137.4
833	560	9223	181.1	18.27	10.94	10.25	0.94	420.7	1.42E-02	137.8
843	570	9214	181.0	18.47	11.07	10.06	0.91	419.3	1.96E-02	138.2
853	580	9206	180.9	18.66	11.20	9.88	0.88	418.0	2.69E-02	138.6
863	590	9197	180.9	18.86	11.33	9.70	0.86	416.6	3.66E-02	139.1
873	600	9189	180.8	19.05	11.47	9.53	0.83	415.2	4.94E-02	139.5

3.4.4. Thermophysical properties of vapours of some metals (Li, Na, K, Cs) [11–13]

TABLE 3.24. PROPERTIES OF SATURATED LITHIUM VAPOUR

Temperature K	Pressure MPa	Density″ kg/m^3	Heat capacity″ J/(kg·K)	Specific heat″ 10^{-3}(kJ/kg)	Thermal conductivity″ W/(m·K)	Dynamic viscosity″ 10^7(Pa·s)	Sound velocity m/s
900	0.138E-4	0.128E-4	3.936	21.76	-	106	1270
1000	1.036E-4	0.872E-4	4.432	21.59	0.069	113	1317
1100	5.374E-4	0.413E-3	4.952	21.39	0.075	118	1364
1200	2.111E-3	0.150E-2	5.451	21.17	0.085	123	1410
1300	6.710E-3	0.444E-2	5.907	20.93	0.091	126	1456
1400	1.807E-2	0.0112	6.325	20.66	0.097	129	1501
1500	4.264E-2	0.0250	6.735	20.37	0.101	131	1543
1600	9.048E-2	0.0505	7.172	20.05	0.105	133	1582
1700	1.759E-1	0.0940	7.664	19.69	0.107	135	1617
1800	3.183E-1	0.164	8.216	19.29	0.109	137	1647
1900	5.420E-1	0.272	8.795	18.84	0.111	139	1671
2000	8.770E-1	0.431	9.329	18.32	0.112	140	1687
2100	1.359	0.660	9.730	17.76	0.115	141	1696
2200	2.027	0.981	9.924	17.15	0.117	143	1696
2300	2.929	1.421	9.881	16.50	0.120	144	1687
2400	4.114	2.012	9.619	15.85	0.122	146	1672
2500	5.639	2.790	9.191	15.19	0.125	147	1662
2600	7.508	3.754	8.674	14.58	0.127	-	1631

TABLE 3.24. (continued)

Temp. rature K	Pressure MPa	Density″ kg/m^3	Heat capacity″ J/(kg·K)	Specific heat″ 10^{-3}(kJ/kg)	Thermal conductivity″ W/(m·K)	Dynamic viscosity″ 10^7(Pa·s)	Sound velocity m/s
2700	9.744	4.911	8.140	14.00	0.131	-	1611
2800	12.41	6.299	7.624	13.45	0.135	-	1591
2900	15.55	7.935	7.149	12.92	0.137	-	1571
3000	19.19	9.829	6.722	12.42	0.142	-	1553

TABLE 3.25. PROPERTIES OF SATURATED SODIUM VAPOUR

Temp. rature K	Pressure MPa	Density″ kg/m^3	Heat capacity″ KJ/(kg·K)	Specific heat″ kJ/kg	Thermal conductivity″ 10^2W/(m·K)	Dynamic viscosity″ 10^7(Pa·s)	Sound velocity m/s
800	9.492E-4	0.339E-2	2.160	4255	3.66	-	614
900	5.135E-3	0.0166	2.399	4163	4.13	171	644
1000	1.977E-2	0.0587	2.475	4071	4.47	178	674
1100	5.939E-2	0.163	2.458	3978	4.74	184	704
1200	0.148	0.381	2.400	3885	4.86	190	731
1300	0.321	0.779	2.335	3789	4.92	197	757
1400	0.622	1.433	2.279	3688	4.97	203	781
1500	1.101	2.433	2.233	3578	5.00	210	801
1600	1.814	3.874	2.195	3459	-	219	816
1700	2.813	5.857	2.149	3349	-	227	827
1800	4.149	8.485	2.087	3190	-	234	830
1900	5.865	11.85	2.008	3043	-	-	830
2000	7.944	16.04	1.915	2890	-	-	826

TABLE 3.26. PROPERTIES OF SATURATED POTASSIUM VAPOUR

Temp. rature K	Pressure MPa	Density″ kg/m^3	Heat capacity″ KJ/(kg·K)	Specific heat″ kJ/kg	Thermal conductivity″ 10^2W/(m·K)	Dynamic viscosity″ 10^7(Pa·s)	Sound velocity m/s
800	6.407E-3	0.0395	1.155	2024	1.63	141	476
900	2.536E-2	0.142	1.193	1973	1.79	152	502
1000	7.583E-2	0.389	1.181	1920	1.97	161	525
1100	0.185	0.882	1.146	1865	2.11	169	548
1200	0.389	1.733	1.102	1810	2.22	177	570
1300	0.727	3.057	1.060	1750	2.32	185	589
1400	1.240	4.965	1.021	1685	2.41	193	604
1500	1.965	7.570	0.985	1614	2.49	202	613
1600	2.930	10.98	0.951	1535	-	-	615
1700	4.155	15.32	0.914	1449	-	-	610
1800	5.647	2.65	0.874	1356	-	-	600
1900	7.405	27.01	0.834	1256	-	-	587
2000	9.418	34.37	0.796	1150	-	-	572

TABLE 3.27. PROPERTIES OF SATURATED CAESIUM VAPOUR

Temp. rature K	Pressure MPa	Density″ kg/m^3	Heat capacity″ KJ/(kg·K)	Specific heat″ kJ/kg	Thermal conductivity″ 10^3W/(m·K)	Dynamic viscosity″ 10^7(Pa·s)	Sound velocity m/s
500	3.312E-5	1.070E-3	0.230	542	-	-	215
600	5.906E-4	1.604E-2	0.265	530	-	-	230
700	4.524E-3	0.1065	0.296	518	6.58	204	244
800	2.059E-2	0.4353	0.315	504	7.55	221	257
900	6.656E-2	1.285	0.314	490	8.40	236	270
1000	0.170	3.031	0.314	476	9.13	250	282
1100	0.365	6.101	0.315	461	9.77	264	293
1200	0.690	10.89	0.316	444	10.37	278	303
1300	1.179	17.73	0.319	425	10.96	292	311
1400	1.863	26.97	0.323	403	-	306	318
1500	2.760	38.88	0.337	377	-	321	324
1600	3.876	54.23	0.381	345	-	336	327
1700	5.213	75.00	0.453	306	-	352	321
1800	6.773	110.8	0.658	248	-	369	291
1900	8.572	173.8	-	189	-	385	-
2000	10.66	-	-	100	-	-	-

REFERENCES TO SECTION 3

1. Heat and Mass Transfer. Heat Engineering Experiment/Reference book. Edited by V.A. Grigoriev, V.M. Zorin. – M.: Energoatomizdat, 1982, P. 159 (Russian).
2. Vargaftik N.B. Reference Book on Thermophysical Properties of Gases and Liquids. – M.: Nauka, 1972, PP. 525–530. (Russian).
3. Alexandrov A.A., Grigoriev B.A. Tables of Thermophysical Properties of Water and Steam/Reference book. –M.: MEI Press, 1999 (Russian).
4. ASME Steam Tables for Industrial Use/Based on IAPWS — IF97, CRTD — Vol.58. 1999.
5. Hill P.G., MacMillan R.D., Lee V. Tables of Thermodynamic Properties of Heavy Water in SI Tables. AECL. 1981, PP. 1–13.
6. Petropoulos N.P. Heavy Water Thermophysical Properties/Nuclear Engineering Section, Nat. Tech. University of Athens.– On the web site http://arcas.nuclear.ntua.gr/codes/heavywater.html.
7. Andreev P.A., Gremilov D.I., Fedorovich E.D. Heat Exchangers of Nuclear Power Plants. – L.: Sudostroenie, 1965 (Russian).
8. Arsentiev P.P., Koledov L.A. Metallic Melts and their Properties. – M.: Metallurgiya, 1976.
9. Banchila S.N., Fillipov L.P. Study of Electrical Conductivity of Metals. – *Teplofizika Vysokikh Temperatur*, 1973, Vol. 11, No 6, PP. 1301–1304 (Russian).
10. Borishansky V.M., Kutateladze S.S., Novikov I.I., Fedynsky O.S. Liquid Metal Coolants. 3rd rev. and enl. ed. – M.: Atomizdat, 1976.
11. Bystrov P.M., Kagan D.N., Krechetova G.A. et al. Liquid Metal Coolants of Heat Pipes and Power Plants/Ed. by V.A. Kirilin. – M.: Nauka, 1988.
12. Vargaftik N.B. Reference Book on Thermophysical Properties of Gases and Liquids. – M.: Nauka, 1972 (Russian).

13. Handbook of Physical Properties of Liquids and Gases/N.B. Vargaftik, V.K. Vinogradov, V.S. Yargin, 3rd enl. and rev. ed. – N.Y.: Begell House Inc., 1996.
14. Problems of Metal Physics and Metal Science/Collection of papers. – Kiev: Acad. Sci. of Ukran. SSR. 1963 (Russian).
15. Vukalovich M.P., Ivanov A.I., Fokin L.R. et al. Thermophysical Properties of Mercury. – M.: Izdatelstvo Standartov, 1971 (Russian).
16. Kirillov P.L., Deniskina N.B. Thermophysical Properties of Liquid Metal Coolant/Review, IPPE-0291. – M.: CNIIatominform, 2000 (Russian).
17. Gogoleva V.V., Fokin L.R. Estimation of Critical Parameters of Lithium and Francium/Preprint IVTAN, No.1-061. – M.: IVTAN, 1981 (Russian).
18. Grishin V.K., Glasunov M.G., Arakelov A.G. et al. Properties of Lithium. – M.: Metallurgiya, 1963 (Russian).
19. Griaznov G.M., Evtikhin V.A., Zavialsky L.P. et al. Material Science of Liquid Metal Systems of Fusion Reactors. – M.: Energoatomizdat, 1989 (Russian).
20. Evtikhin V.A, Liublinsky I.E., Korzhavin V.M. Liquid Lithium and Vanadium Alloys in the ITER Project. – *Perspectivnye Materialy*, 1995, No.6 (Russian).
21. Kirillov P.L. Thermophysical Properties of Lead, Bismuth and Their Eutectic Alloy/Review, IPPE-0286. – Obninsk: IPPE, 1998 (Russian).
22. Krzhizhanovsky R.E., Sidorova N.P., Bogdanova I.A. Experimental Investigation of Thermal Conductivity and Electrical Resistivity of Some Binary Lead-Bismuth Alloys in Liquid State. – *Inzhenerno-Phyzicheskiy. Zhurnal*, 1975, Vol. 29, No. 2, PP. 322–325 (Russian).
23. Larikov L.N., Yurchenko Yu.F. Thermal Properties of Metals and Alloys. – Kiev: Naukova Dumka Publ., 1985 (Russian).
24. Likalter A.A. On Critical Parameters of Metals. – *Teplofizika Vysokikh Temperatur*, 1985, Vol. 23, No. 3, P. 465 (Russian).
25. Mikhailov V.N., Evtikhin V.A., Liublinsky I.E. et al. Lithium in Thermonuclear Space Power of the 21st Century. – M.: Energoatomizdat, 1999 (Russian).
26. Mozgovoy A.G., Fokin L.R., Chernov A.I. Critical Parameters of Alkaline Metals/Review. – M.:IVTAN, 1984, No. 5 (49) (Russian).
27. Nizhenko V.I., Floka L.I. Surface Tension of Liquid Metals and Alloys/Reference book. – M.: Metallurgiya, 1987 (Russian).
28. Nikolsky N.A., Kalakutskaya N.A., Pchelkin I.M. et al. Thermophysical Properties of Some Metals and Alloys in Molten State/Collection: Voprosy Teploobmena. – M.: Acad. Sci. USSR, 1959, PP. 11–45. See also– *Teploenergetika*, 1959, No.2, PP. 92–95 (Russian).
29. Ostroushko Yu.I., Buchikhin P.I., Alexeeva V.V.et al. Lithium, its Chemistry and Technology. – M.: Atomizdat, 1960 (Russian).
30. Pashaev B.P., Palchaev D.K., Paschuk E.G. et al. Density, Ultrasound Speed, Electrical and Thermal Conductivity of Fusible Metals in Liquid State/Reviews on Thermophysical Properties of Materials. – M.: IVTAN, 1982, No.3 (35) (Russian).
31. Pokrovsky N.L., Pugachevich P.P., Golubev N.A. Study of Surface Tension of Solutions of Lead-Bismuth System. – *Zhurnal Fizicheskoy Khimii*, 1969, Vol. 43, No. 8, PP. 2158–2159 (Russian).
32. Skovorodko S.N. et al. Experimental Investigation of Density of Liquid CsNaK Alloys/Collection of Abstracts: *VIII All-Union Conference on Thermophysical Properties of Materials*. – Novosibirsk: Institute of Thermophysics SB of Acad. Sci. USSR, 1988, Vol. 1, P. 199 (Russian).

33. Subbotin V.I., Arnoldov M.N., Ivanovsky M.N. et al. Lithium. – M.: IzdAT, 1999 (Russian).
34. Physical Quantities. Reference book/A.P. Babichev, N.A. Babushkin, A.M. Bratkovsky, et al.; Ed. by I.S. Grigoriev, E.Z. Meilikhov. – M.: Energoatomizdat, 1991 (Russian).
35. Fortov V.E., Dremin A.N., Leontiev A.A. Evaluation of Parameters of Critical Point. – *Teplofizika Vysokikh Temperatur*, 1975, Vol. 13, No. 5, P. 1072 (Russian).
36. Chirkin V.S. Thermophysical Properties of Materials for Nuclear Power Engineering/Reference book. – M.: Atomizdat. 1968 (Russian).
37. Shpilrain E.E., Fomin V.A., Kachalov V.V. et al. Thermophysical Properties of Alkaline-Earth Metals in Liquid Phase/Reviews on Thermophysical Properties of materials. – M.: IVTAN, 1983, No.2 (Russian).
38. Shpilrain E.E., V.A. Fomin V.A., S.N. Skovorodko S.N. et al. Study of Liquid Metal Viscosity. – M.: Nauka, 1983 (Russian).
39. Shpilrain E.E., K.A. Yakimovich K.A, Totsky E.E. Thermophysical Properties of Alkaline Metals: Handbook/Ed. by V.A. Kirilin. – M.: Izdatelstvo Standartov, 1970 (Russian).
40. Handbook of Thermodynamic and Transport Properties of Alkali Metals./Ed. R.W. Ohse. – Oxford: B. S. Publ. 1985.
41. Pottlacher G. Measurement of Thermophysical Properties of Lead by Submicrosecond Pulse-Heating Method in the Range 2000K to 5000K. – *International Journal of Thermophysics*, 1990, Vol. 11, No. 4, PP. 719–729.
42. Pottlacher G., Iager H. Determinations of Critical Point Data of Metals using Subsecond Pulse Heating Techniques: Preprint Techn. Univ. Graz. 1998.
43. Powell R.W. The Thermal and Electrical Conductivities of Molten Metals/*Proc. 8th Conf. of Thermal Conductivity*, West Lafayette, Ind. 1968. — N.Y., 1969, PP. 357–365.
44. Schulz B. Thermophysical Properties of the Li17Pb83 Alloy. — *Fusion Engineering and Design*, 1991, Vol. 14, PP. 199–206.
45. Selected Values of Thermodynamic Properties of the Elements/R. Hultgren, R.D. Decai, D.T. Hawkins et al. — Metal Park (Ohio), Amer. Soc. Metals, 1973.
46. Thermophysical Properties of Matter. The TPRC Data Series./Ed. Y.S. Touloukian, N. Y. Wash., Plenum Press, 1970.
47. Coen V. Lithium-Lead eutectic as breeding material in Fusion Reactors. — *Journal of Nuclear Materials*, 1985, Vol.133–134, No 1, PP. 46–51.
48. Holrayd R. J., Mitchell J.T. — *Nuclear Engineering and Design/Fusion*, 1984, No 1.

4. MODERATORS

4.1. BASIC PROPERTIES OF MODERATORS

Neutrons being formed at fission have the energy spectrum from 0.25 eV to 10 MeV, the most probable energy is slightly smaller than 1 MeV. The absolute majority of reactors operate on slow (thermal) neutrons with energy of 0.025 eV, because they are easily absorbed by ^{235}U, Pu^{239} nuclei and cause a larger number of fissions than high energy neutrons. Efficient moderators of neutrons are materials with light nuclei (for example, hydrogen, deuterium, beryllium, etc.) Water is a good moderator, as it contains a large amount of hydrogen. Neutron with an energy of 2 MeV undergoes on the average ξ = 19.6 collisions in water prior to being moderated to energy of 0.025 eV [1].

A moderator must have a high scattering cross section to provide a high collision number of neutrons per time unit prior to being captured, as well as a low neutron-absorption cross section that not to deteriorate a neutron balance owing to nonproductive absorption in moderator mass. The measure of this characteristic is the ratio $\xi\Sigma_s/\Sigma_a$ termed as moderating ratio. The product of the mean number of collisions prior to being attained thermal energy (ξ) by the macroscopic scattering cross section (Σ_s) is called as moderating power [2, 3]. The basic neutron-physical and thermophysical properties of moderators are presented in Tables 4.1 and 4.2, respectively.

Light water (H_2O) is characterized by the highest moderating power and the high absorption cross section. As a result in the case of moderating neutrons by light water, it is impossible to make a natural uranium fuel reactor as a critical one. For this reason, fuel enriched up to 2–4% has been used in power reactors. In reactor, water is subject to radiolysis that results in formation of gases such as hydrogen and oxygen and moreover, formation of detonating mixture is possible. Another problem consists in interaction of water with zirconium (from a fuel element cladding) accompanied by formation of ZrO_2 and H_2. The disadvantage of water is a low boiling point, thus high pressures are to be applied [2].

Heavy water (D_2O) has the absorption cross section, which is rather lower as compared to light water, and the highest moderating ratio among all moderators. The natural uranium fuel reactor can become critical, if D_2O is used as moderator. The disadvantages of heavy water are its high cost and the need of high pressures [2].

Graphite (C) used as a moderator in power reactors (gas cooled reactors, channel reactors of high power RBMK, etc.) is an anisotropic material. It has good moderating characteristics and satisfactory mechanical properties. Reactor artificial graphite is produced from oil coke. Its production technology is rather complicated and involves the following preliminary operations: coke crushing, incineration to purify material, preparing charge from particles of different sizes, and molding (pressing). In the course of molding process, there occurs anisotropy of product properties to parallel and to perpendicular directions vs. a pressing axis. The final operations of manufacturing graphite are as follows: preliminary annealing at 1000-1300°C, long-term annealing at 450–500°C, fining and impregnation by carbon-bearing materials (pitch, alcohol etc.) to increase compression strength. Structural graphite is characterized by pronounced anisotropy of its properties. However, graphite materials (GR-220, GR-280) used in uranium-graphite reactors have rather low anisotropy. Typical density of reactor graphite is of 1600–1700 kg/m^3, which is considerably smaller, than the theoretical one (2260 kg/m^3). Such difference is caused by graphite porosity being formed during its manufacture.

TABLE 4.1. BASIC NEUTRON-PHYSICAL PROPERTIES OF MODERATORS

Property	Light water H_2O [1, 3]	Heavy water D_2O [1, 3]	Beryllium, metal Be [4, 5]	Beryllium oxide BeO [6]	Graphite C [7]	Zirconium hydride $ZrH_{1.85}$ [1, 3]
Molar mass, amu	18.01528	20.0276	9.01218	25.0116	12.0111	93.0887
Density at normal conditions, kg/m^3	1000	1100	1840	2860	1710	5620
Scattering cross section, σ_s, 10^{-24} cm^2	44	15	6.15	11.2	4.75	44
Absorption cross section, σ_a, 10^{-24} cm^2	660	2.6	7.6	9.0	3.53	799
Macroscopic scattering cross section (above-thermal), Σ_s, cm^{-1}	1.496	0.350	0.757	0.666	0.397	1.60
Macroscopic absorption cross section сечение (thermal), Σ_a, cm^{-1}	0.0197	3.88×10^{-5}	8.2×10^{-4}	4.7×10^{-4}	2.6×10^{-4}	0.0291
Mean collision number to thermalization (from 2 MeV to 0.025 eV), n	20.6	37.4	92.7	108	116	22.3
Moderating power, $\xi\Sigma_s$, cm^{-1}	1.385	0.1784	0.1561	0.1156	0.0626	1.37
Mean logarithmic energy loss per neutron collision with moderator nucleus	0.926	0.510	0.206	0.176	0.165	0.856
Moderating ratio, $\xi\Sigma_s/\Sigma_a$	70.3	2100*)	190	332	240	47
Diffusion length, cm	2.69	147	24.4	36.5	56.4	2.45
Number of atoms (H, D, Be, C respectively) in cm^3, 10^{23} cm^{-3}	0.669	0.662	1.230	0.689	0.852	0.673

*) For concentration of D_2O – 99.8% and H_2O – 0.2%.

TABLE 4.2. BASIC THERMOPHYSICAL PROPERTIES OF MODERATORS (UNDER NORMAL CONDITIONS)

Property		Light water H_2O [8]	Heavy water D_2O [8]	Beryllium, metal Be [9–11]	Beryllium oxide BeO [6, 12]	Graphite (reactor) C [7]	Zirconium hydride $ZrH_{1.85}$ [13]
Molar mass, amu		18	20.03	9.012	25.01	12	93.1
Melting point	K	273.15	276.98	2560	2823	4530	923
	°C	0	3.813	1287	2550	4260	650
Boiling point	K	373.15	374.58	2744	4393	-	-
	°C	100	101.43	2471	4120	-	-
Heat of fusion, kJ/kg		333.8	315.2	835	3416	27900	-
Heat of vapourization, kJ/kg		2256	2071	32963	19596	59450	-
Density, kg/m^3		1000	1100	1840	2860	1710	5620
Heat capacity, kJ/(kg K)		4.217	4.23	1.825	1.229	0.710	0.410
Thermal conductivity, W/(m K)		0.5609	0.5595	157	93	103/89	32–36
Thermal diffusivity, m^2/°C		0.133×10^{-6}	0.120×10^{-6}	0.354×10^{-4}	0.425×10^{-4}	0.847×10^{-4}	0.14×10^{-4}
Coefficient of volumetric thermal expansion, 1/K		4.55×10^{-4}	4.1×10^{-4}	34×10^{-6}	24×10^{-6}	$(9.6–14.7) \times 10^{-6}$	-
Electrical resistivity, Ω·m		-	-	$0.15–4 \times 10^{-8}$	10^{10}	$(1.65–2.18) \times 10^{-7}$	5.47×10^{-7}
Surface tension at T_{melt}, mN/m		74.64	74.6	1100	-	-	-
Vapour pressure at T_{melt}, Pa		610	668	4.38×10^4	475	5.15×10^4	2.7×10^4
Integral emissivity at 1000 K		-	-	0.14	0.33	0.85	-

In the course of using graphite, the main problems are in its chemical reactions with oxygen, water steam, metals that requires creation of inert atmosphere in reactor. Under radiation, internal energy is being accumulated in the crystal lattice of graphite owing to atomic displacements. At ordinary temperatures (<350°C) and fluence of 10^{19} neutr/cm^2, the value of stored energy in graphite can achieve up to 1.7 MJ/kg. In the generation of this energy (Wigner effect), graphite can be heated up to 1000°C. Therefore in the case of operating graphite in reactors at low temperatures, it is periodically exposed to slow heating (annealing). At high temperatures this problem is not significant, because accumulation and generation of internal energy occurs continuously [7, 14].

Zirconium hydride ($ZrH_{1.85}$) is hydrogen-bearing moderator that has good moderating characteristics practically similar to those of water (see Table 4.1). In the case, when zirconium hydride is mixed with uranium, these reactors are characterized by reliable safety and high stability as they have the high negative temperature coefficients of reactivity. Zirconium hydride is produced by heating metallic zirconium in hydrogen at 350°C [2].

Beryllium (Be) has the small absorption cross section, which together with a high number of atoms in 1 cm^3 and the high scattering cross section provides its application as a good moderator and reflector in reactors. However, beryllium is not widely used for power engineering due to its high cost and such its properties as brittleness, swelling and embrittlement at radiation. The advantages of beryllium are in low density, high melting point and low coefficient of thermal expansion (see Table 4.2). Under exposure to radiation, nuclear reactions with formation of helium and tritium are occurred in beryllium (see below). An essential feature of beryllium is its low value of induced activity under the action of major types of radiations. Beryllium and its compounds are toxic [2, 14].

Beryllium oxide (BeO) is used as a moderator not only in nuclear reactors, but also as a matrix of dispersion fuel elements. Beryllium oxide is the best moderator among high temperature oxides. Besides, BeO is a source of additional neutrons being formed at the reactions of types (α, n), (γ, n), (n, 2n). The radiation effect on BeO and its radiation stability have been extensively studied. Under radiation of BeO in reactor, formation of helium and tritium takes place according to the reaction (n, 2n):

$$^{9}_{4}Be + n \rightarrow {}^{8}_{4}Be + 2n; \quad {}^{8}_{4}Be + 2{}^{4}_{2}He;$$

and the reaction (α, n):

$$^{9}_{4}Be + n \rightarrow {}^{6}_{2}He + {}^{4}_{2}He; \quad {}^{6}_{2}He \rightarrow {}^{6}_{3}Li + \beta; \quad {}^{6}_{3}Li + n \rightarrow {}^{4}_{2}He + {}^{3}H.$$

Helium is formed in about ten times larger quantity than tritium. For more details on the change of BeO properties under radiation, see Refs [2, 6].

4.2. GRAPHITE (CARBON)

Carbon comes in several modifications; their properties are being different, namely: graphite, diamond, fullerene (produced artificially) and other. These modifications are different in the structure of molecules and their arrangement in the crystal lattice. The basic properties of graphite are as follows:

Atomic number of carbon	6
Atomic mass	12.011 amu
Specific volume	3.42×10^{-6} m^3/mol or 0.285×10^{-3} m^3/kg [11]
Theoretical density	$\rho = 2266$ kg/m^3 [11]

In recent years, a considerable disagreement of experimental data on graphite melting point is observed [15, 16]. This is caused by difficulties of high temperature experiment. According to early research $T_{melt} \cong 3700–4000$ K, whereas owing to the most recent data, $T_{melt} \cong 4530-080$ K. The reasons of such difference are still unknown. Thermophysical properties of graphite can greatly differ depending on its production method and owing to its anisotropic structure.

Graphite used as a moderator must not contain any impurities of elements with the high neutron absorption coefficient (boron, cadmium, etc.) or volatile matters (hydrocarbons and others). Graphite blocks of RBMK reactor with dimensions of 250 × 250 × 600 mm are manufactured from graphite type GR-280 and designated to operate under conditions of gas medium with composition: 75% He; 25% N_2; $O_2 < 0.01\%$, at temperatures 300–800°C and neutron flux ~ 3×10^{13} n/(cm^{2}s) [17].

It has been noted that pressing graphite during its production results in anisotropy of its physical properties. The basic physical characteristics of reactor graphite type GR-280 in initial state given in Table 4.3, where the numerator is the values of characteristics to parallel direction about a pressing axis, and the denominator is the values of these characteristics to perpendicular direction about a pressing axis.

TABLE 4.3. BASIC PHYSICAL CHARACTERISTICS OF REACTOR GRAPHITE TYPE GR-280 IN INITIAL STATE [7]

Property	Mean value	Max.	Min.
Density, ρ (kg/m^3)	1710	1780	1630
Linear expansion coefficient, $\alpha \times 10^6$ (1/K)	3.2/4.9	3.6/5.4	2.7/4.6
Thermal conductivity, λ [W/(m K)]	103/89	-	-
Electrical resistivity, ρ_e (μΩ·m)	10/13	14/16	8/10

The graphite crystal has a layer-like structure. In this case, atoms in each layer are located in a hexagonal lattice. Bonding between parallel layers is provided by weak Van der Waals forces. In the course of pressing, particles of coke are oriented along the pressing direction; therefore, thermal and electrical conductivity of graphite is higher in this direction as compared to transverse direction.

Graphite is commonly a porous material. The surface area of graphite with pores taken into account is estimated to be 0.47–0.87 m^2/g [18]. Reactor graphite with density of 1740 kg/m^3 has porosity in the region of 23% [19].

In the course of operating under reactor conditions, there occurs the change of graphite properties caused by displacement of carbon atoms from the lattice sites. The change of the lattice parameters under radiation depends on radiation temperature, neutron spectrum, value of integral flux and radiation rate, as well as the degree of graphitization of initial graphite. The effect of preliminary radiation was also discovered. The fluence of neutrons with energy of more 0.18 MeV and the operating conditions has the greatest effect on this process. In this case, the change of such graphite properties as density, thermal expansion coefficient, thermal conductivity, electrical resistivity as well as its mechanical properties takes place [20].

Heat of fusion of graphite is evaluated as 27900 kJ/kg in Ref. [21]. Heat of vapourization of graphite is evaluated as 59450 kJ/kg in Ref. [18].

Radiation of graphite at rather low temperatures (<300°C) results in the accumulation of displaced atoms in the interlattice area. This causes the accumulation of Wigner energy that can be generated with increasing temperature up to the level, at which the energy of thermal vibrations of atoms provides a way for them to fill again the vacant sites in the crystal lattice. Therefore, graphite is to be annealed to prevent accumulation of such energy [17].

Enthalpy and heat capacity of graphite are calculated by the following formulas of the MATPROP code [22]:

$$H(T) - H(298,15)\ (kJ/kg) = -1446.04 + 2.0231T + 3.9322 \times 10^{-5}T^2 + 4.2671 \times 10^5 T^{-1} - 6.60145 \times 10^7 T^{-2} + 3.9963 \times 10^9 T^{-3}. \quad (4.1)$$

At 298≤ T ≤ 1273 K

$$C_p\ [kJ/(kg \cdot K)] = 2.031 + 7.8645 \times 10^{-5}\ T - 4.2671 \times 10^5 T^{-2} + 1.3203 \times 10^8 T^{-3} - 1.199 \times 10^{10} T^{-4}. \quad (4.2)$$

At 1273≤ T ≤ 3273 K

$$C_p\ [kJ/(kg \cdot K)] = 1.131 + 6.62 \times 10^{-4}T - 9.969 \times 10^{-8}T^2. \quad (4.3)$$

At 3273≤ T ≤ 5000 K

$$C_p\ [kJ/(kg \cdot K)] = 6.12 \times 10^{-5}T^{1.3}. \quad (4.4)$$

These formulas are in a good agreement with the well known experimental data. The uncertainty of Eq. (4.2) is of ± 10%. The heat capacity of graphite according to Eqs (4.2.–4.4) is given in Table 4.4.

TABLE 4.4. HEAT CAPACITY OF GRAPHITE BY EQUATIONS (4.2.–4.4.)

Temperature		Heat capacity
°C	K	KJ/(kg·K)
25.15	298.15	0.711
27	300	0.715
77	350	0.848
127	400	0.982
186	459	1.108
227	500	1.220
327	600	1.404
427	700	1.542
527	800	1.648
627	900	1.730
727	1000	1.795
827	1100	1.848
927	1200	1.892
1027	1300	1.929
1127	1400	1.961
1227	1500	1.988
1327	1600	2.013
1427	1700	2.035
1527	1800	2.055
1627	1900	2.073
1727	2000	2.090
1827	2100	2.105
1927	2200	2.120
2027	2300	2.134

TABLE 4.4. (continued)

Temperature		Heat capacity
°C	K	kJ/(kg·K)
2127	2400	2.147
2227	2500	2.160
2327	2600	2.172
2427	2700	2.183
2527	2800	2.195
2627	2900	2.206
2727	3000	2.216
2827	3100	2.227
2927	3200	2.237
3027	3300	2.247
3127	3400	2.257
3227	3500	2.267

Values of enthalpy and heat capacity of graphite type UPV-1 in the range of temperature range 1200–2000 K are given in Ref. [23]. At high temperatures the data by various authors disagree greatly (± 20% and more). The uncertainties in data on heat capacity of graphite are shown in Table 4.5.

Density of reactor graphite depending on temperature is presented in Table 4.6 [17].

TABLE 4.5. UNCERTAINTIES OF DATA ON GRAPHITE HEAT CAPACITY

Temperature K	Uncertainty %
<500	on average 10
500–800	Linear from10 to 5
800–2500	5
2500–3000	Linear from 5 to 11
>3000	11

TABLE 4.6. DENSITY OF REACTOR GRAPHITE IN INITIAL STATE [17]

Temperature °C	Density kg/m^3
20	1710
100	1710
200	1710
300	1700
400	1700
500	1700
600	1700
700	1690
800	1690
900	1680
1000	1680

Thermal conductivity of reactor graphite in initial state depending on temperature based on different data is presented in Table 4.7. The table presents also the values of *coefficient of linear thermal expansion*, where the numerator is the value of coefficient to parallel direction about a pressing axis, and denominator is the value of coefficient to perpendicular direction about a pressing axis.

TABLE 4.7. THERMAL CONDUCTIVITY AND COEFFICIENT OF LINEAR THERMAL EXPANSION OF REACTOR GRAPHITE IN INITIAL STATE

Temperature °C	Thermal conductivity λ [W/(m·K)]			Linear expansion coefficient 10^6 (1/K) Ref. [17]
	Ref. [17]	Ref. [24]	Ref. [18]	
20	103/89	120/85	-	3.2/4.9
100	90/74	113/80	-	3.4/5.0
200	77/60	103/74	-	3.8/5.2
300	70/54	93/68	-	4.2/5.5
400	65/50	85/64	-	4.4/5.7
500	59/46	79/60	88	4.6/5.8
600	53/40	73/55	-	4.8/5.9
700	48/37	68/51	75	4.9/6.0
800	45/34	65/48	-	5.1/6.1
900	43/32	-	-	5.2/6.2
1000	40/30	-	59	5.3/6.3
1500	-	-	45	-
2000	-	-	40	-
2500	-	-	36	-
3000	-	-	26	-
3250	-	-	18	-
3500	-	-	6	-

Vapour pressure above solid graphite. The results of available experimental research and the recommendations given in reference books differ significantly, particularly at T > 2000 K that can be shown from the following correlations, which are true within the narrow range of temperatures:

according to data in Ref. [25] at 1850–3400 K

$$\lg P\ (\mathrm{Pa}) = 12.8313 - 36781.5/T \qquad (4.5)$$

according to data in Ref. [11] at 1700–3000 K

$$\lg P\ (\mathrm{Pa}) = 15.7488 - 40384.5/T \qquad (4.6)$$

The electrical resistivity of electrode graphite vs. temperature is presented in Table 4.8, for the transverse directions and along the axis [26].

Emissivity of graphite for $\lambda = 0.65$ μm is given in Table 4.9, where ε_λ is the spectral radiation coefficient; ε_t is the integral radiation coefficient [25, 27].

TABLE 4.8. ELECTRICAL RESISTIVITY 10^{-5} Ω m OF ELECTRODE GRAPHITE [26]

Temperature °C	Transverse direction	Along the axis
0	2.18	1.65
100	1.97	1.5
200	1.87	1.45
300	1.80	1.42
400	1.77	1.38
500	1.77	1.38
600	1.80	1.39
700	1.82	1.40
800	1.85	1.42
900	1.92	1.48
1000	1.97	1.55
1100	2.0	1.58
1200	2.03	1.60
1300	2.10	1.65
1400	2.15	1.70
1500	2.20	1.73
1600	2.25	1.77
1700	2.32	1.82
1800	2.37	1.87
1900	2.42	1.92
2000	2.50	1.95

TABLE 4.9. EMISSIVITY OF GRAPHITE [21, 23]

Temperature K	ε_T*	ε_λ**
1000	0.87	0.94
1200	0.86	0.90
1400	0.86	0.88
1600	0.86	0.86
1800	0.86	0.85
2000	0.86	0.84
2200	0.86	0.83
2400	0.86	0.81
2600	0.85	0.80
2800	0.84	0.79

*ε_T — coefficient of thermal radiation (the ratio of total body radiation to total blackbody radiation at the same temperature);

**ε_λ – spectral coefficient of thermal radiation (the ratio of body radiation at wave length λ = 0.65 μm to blackbody radiation with the same wave length and temperature).

Radiation effect on thermophysical properties of graphite at radiation temperature 500-550°C and measurement temperature 20°C was studied in Refs [17, 28]. The experimental results are presented in Table 4.10, where a and b are the directions that are parallel and perpendicular about a pressing axis, respectively.

TABLE 4.10. RADIATION EFFECT ON THERMOPHYSICAL PROPERTIES OF GRAPHITE AT 500–550°C [17, 28]

Neutron fluence $F \times 10^{-21}$ (1/cm^2) E > 0.18 MeV	ρ_{20} 10^{-6}(kg/m^3)	λ_{20} W/(m·K)		α_{20} 10^{-6} (1/K)		ρ_{e20} (Ω·m)	
		a	b	a	b	a	b
0	1710	75	55	4.4	5.7	10	13
0.5	1710.5	42	30.8	4.54	5.87	22	23.4
1	1712	31.5	23.1	4.62	5.98	29	31.2
2	1710	24.8	18.1	4.8	6.20	32	37.8
3	1692	24.0	17.6	4.94	6.44	32	37.8
4	1686	23.3	17.1	5.02	6.55	32	37.8
5	1677	23.3	17.1	5.06	6.72	32	37.8
6	1671	22.5	17.1	5.1	6.89	32	37.8
7	1664	22.5	17.1	5.15	6.95	32	37.8
8	1657	22.5	17.1	5.19	7.06	32	37.8
9	1650	22.5	17.1	5.24	7.12	32	37.8
10	1643	22.5	17.1	5.24	7.17	32	37.8
11	1638	22.5	17.1	5.28	7.24	32	37.8
12	1636	22.5	17.1	5.28	7.29	32	37.8
13	1634	22.5	17.1	5.28	7.40	32	37.8
14	1633	22.5	17.1	5.28	7.45	32	37.8
15	1638	21.0	15.4	5.28	7.52	32	37.8
16	1640	19.5	14.3	5.28	7.57	32.5	37.8
17	1648	17.3	12.6	5.28	7.63	33	39
18	1657	15.8	11.5	5.24	7.68	34	41.7
19	1671	14.2	10.5	5.24	7.74	37	45.5
20	1696	12.8	9.4	5.19	7.80	40	49.4
21	1772	11.3	8.3	5.15	7.80	46	55.9
22	1772	10.0	7.1	5.1	7.85	54	67.5
23	1840	-	-	5.06	7.91	60	78
24	-	-	-	-	-	-	-

4.3. BERYLLIUM

The basic properties of beryllium are as follows:

Atomic number	4
Atomic mass	9.012 amu
Specific volume	4.877×10^{-6} m^3/mol or 0.541×10^{-3} m^3/kg [25]
Theoretical density	1848 kg/m^3 [29]
Melting point	1287°C = 1560 ± 10 K [11]
Boiling point	2471°C = 2744 K [25]
Heat of fusion*	1442 kJ/kg [25]
Heat of vapourization	32290 kJ/kg [25]
Sound velocity	12650–13000 m/s [25, 30]

* The data are in the range 877–1625 kJ/kg

4.3.1. Properties of solid beryllium depending on temperature

Density is estimated by the formula based on the data in Ref. [11]:

$$\rho(T)\ (kg/m^3) = 1869.84 - 0.07168T - 1.6151 \times 10^{-5}T^2 \ . \qquad (4.7)$$

Heat capacity is calculated from correlation in Refs [30, 31]:

$$C_p[kJ/(kg \cdot K)] = 2.1097 + 0.985 \times 10^{-3} T - 0.381 \times 10^5 T^{-2} \ . \qquad (4.8)$$

Thermal conductivity is defined by the formula derived on the basis of the recommended data in Ref. [32]:

$$\lambda\ [W/(m \cdot K)] = 202.5 - 0.1723\ T + 5.467 \times 10^{-5}\ T^2. \qquad (4.9)$$

Thermal diffusivity in terms of m^2/s is determined as $a = \lambda / C_p \rho$.

The basic thermophysical properties of solid beryllium evaluated by Equations (4.7–4.9) are presented in Table 4.11.

TABLE 4.11. BASIC THERMOPHYSICAL PROPERTIES OF SOLID BERYLLIUM BY EQUATIONS (4.7–4.9)

Temperature		Density[1)] kg/m^3	Heat capacity[2)] J/(kg·K)	Thermal conductivity[3)] W/(m·K)	Thermal diffusivity 10^5(m^2/s)	Electrical resistivity 10^8(Ω·m) [30]
°C	K					
20	293	1847	2.398	157	3.54	4.0
100	373	1841	2.477	146	3.20	6.5
200	473	1832	2.576	133	2.82	9.0
300	573	1823	2.674	122	2.50	12.5
400	673	1814	2.773	111	2.21	15
500	773	1805	2.871	102	1.97	18
600	873	1795	2.970	94	1.76	22
700	973	1785	3.068	87	1.58	26
800	1073	1774	3.167	81	1.43	30
900	1173	1764	3.265	76	1.31	34
1000	1273	1752	3.364	72	1.22	-
1100	1373	1741	3.462	69	1.15	-
1200	1473	1729	3.561	67	1.09	-
1287	1560	1719	3.646	67	1.07	-

1) For hot-pressed beryllium.
2) Data on heat capacity given in reference books often differ because of they are not related with structure and density of beryllium.
3) Smoothed curve for specimen 2 — hot-pressed beryllium, after exposure of 1000 h at 1300 K (see Table 4.12).

Thermal conductivity of beryllium specimens depends on their density, purity, production method and processing. As it can be seen from Table 4.12, thermal conductivity can differ by 1.5–2 times [32].

In Table 4.12, the specimens are as follows:

1) Well-annealed polycrystalline beryllium of high purity,
2) Hot-pressed beryllium after exposure of 1000 hours at 1300 K,
3) Hot-pressed beryllium,
4) Cold-pressed beryllium. The similar situation is observed for electrical resistivity of beryllium specimens.

Emissivity of beryllium. The spectral radiation coefficient of beryllium ε_λ for a wave length of 0.65 μm in solid and liquid state is 0.61 [11]; for a wave length of 0.55μm, 0.61 and 0.81, respectively [30]. The integral emissivity coefficient of beryllium as a function of temperature is presented in Table 4.13 [30].

TABLE 4.12. THERMAL CONDUCTIVITY OF BERYLLIUM IN RELATION TO ITS STRUCTURE AND PRODUCTION METHOD [28]

Temperature K	Specimens	1	2	3	4
300	Thermal conductivity [W/(m·K)]	200	156	182	97
400		161	146	170	91
500		139	132	156	84
600		126	119	145	78
700		115	110	134	74
800		106	100	120	68
900		98.2	86	109	64
1000		90.8	80	96	61
1100		84.2	78	86	57
1200		78.7	75	84	55
1300		73.8	73	82	51
1400		69.4	-	-	-
1500		-	67	76	46

TABLE 4.13. INTEGRAL EMISSIVITY COEFFICIENT OF BERYLLIUM ε_t [30]

Temperature		ε_t
°C	K	
20	293	0.044
100	373	0.047
200	473	0.050
300	573	0.054
400	673	0.062
500	773	0.077
600	873	0.103
700	973	0.142
800	1073	0.198
900	1173	0.274
1000	1273	0.373
1100	1373	0.497
1200	1473	0.651
1287	1560	0.811

Coefficient of linear thermal expansion of beryllium. The values of mean linear expansion coefficient $\bar{\alpha}$ for the corresponding temperature range are shown in Table 4.14 [30]. The values of linear expansion coefficients of beryllium to the directions, which are parallel and perpendicular about a pressing axis, $\alpha_{//}$ and $\alpha_{\perp}$ respectively, are presented in Table 4.15. After annealing, the value of $\alpha_{//}$ is somewhat decreased by 5–10%, and the value of $\alpha_{\perp}$ increased by 20–30% [25, 33].

TABLE 4.14. MEAN COEFFICIENT OF LINEAR THERMAL EXPANSION OF BERYLLIUM [30]

Temperature °C	$\bar{\alpha} \times 10^6$ (1/K)
25–100	11.5
25–200	13.5
25–300	14.4
25–400	15.2
25–500	16.0
25–600	-
25–700	17.2
25–800	-
25–900	-
25–1000	18.8

TABLE 4.15. ANISOTROPY OF COEFFICIENT OF LINEAR THERMAL EXPANSION OF BERYLLIUM [30]

Temperature K	$\alpha_{//} \times 10^6$ (1/K)	$\alpha_{\perp} \times 10^6$ (1/K)
300	9.2	12.4
400	11.5	14.9
500	12.9	16.9
600	14.0	18.3
800	15.9	20.2
1000	17.6	21.4
1200	19.5	23.4

Vapour pressure above solid beryllium. The following two correlations are known:
in Refs [30, 31, 34] at $T < T_{melt}$

$$\lg P(at) = 6.186 + 1.454 \times 10^{-4} T - \frac{16734}{T}; \quad (4.10)$$

in Ref. [30] at $T_{melt} < T < 2058$ K

$$\lg \mathrm{P(mm\,Hg)} = 6.494 - \frac{11710}{\mathrm{T}}. \quad (4.11)$$

According to the data in Ref. [11] at 960 ≤ T ≤1500 K another formula follows:

$$\lg P(Pa) = 11.389 - \frac{16755}{T}, \qquad (4.12)$$

According to the data in Ref. [8] at 1000 ≤ T ≤2000 K another equation follows:

$$\lg P(Pa) = 10.990 - \frac{16252}{T}. \qquad (4.13)$$

The values of vapour pressure above solid beryllium calculated by Equations (4.10–4.13) are presented in Table 4.16. In this case, Equations (4.10, 4.11) were transferred to the SI-system [P (Pa)].

TABLE 4.16. VAPOUR PRESSURE [Pa] ABOVE SOLID BERYLLIUM

Temperature K	Eqs (4.10, 4.11)	Eq. (4.12)	Eq. (4.13)
500	6.059×10^{-23}	-	-
600	2.371×10^{-17}	-	-
700	2.364×10^{-13}	-	-
800	2.380×10^{-10}	-	-
900	5.190×10^{-8}	5.920×10^{-8}	-
1000	3.882×10^{-6}	4.305×10^{-6}	5.470×10^{-6}
1100	1.333×10^{-4}	1.40×10^{-4}	1.64×10^{-4}
1200	2.554×10^{-3}	2.67×10^{-3}	2.80×10^{-3}
1300	0.0312	0.0317	0.0308
1400	0.2681	0.2637	0.2407
1500	1.737	1.654	1.43
1600	19.911	8.263	6.8
1700	53.656	34.129	26.915
1800	129.51	120.41	91.44
1900	284.90	-	273.10
2000	579.23	-	731.14

4.3.2. Properties of liquid beryllium depending on temperature

Density of liquid beryllium at 99.8% of the theoretical density according to the data in Ref. [11] at T < 2750 K is estimated by formula:

$$\rho(T)(kg/m^3) = 1690 - 0.116(T - 1560). \qquad (4.14)$$

Heat capacity of liquid beryllium at $T > T_{melt}$ is 3.3 kJ/(kg K) in Ref. [9]

Surface tension of liquid beryllium is 1100 mN/m at 1773 K in Ref. [25] and 1145 mN/m at 1553 K in Ref. [11].

4.4. BERYLLIUM OXIDE

The basic properties of beryllium oxide are as follows:

Molecular mass	25.0116 amu
Molar volume, m^3/mol or m^3/kg	8.31×10^{-6} m^3/mol; 3.322×10^{-4} m^3/kg
Theoretical density, kg/m^3	3010 ± 0.3 kg/m^3 [25]
Melting point, °C (K)	2550°C (2823 K) [6]
Boiling point, °C (K)	4120°C (4393 K) [25]
Heat of fusion, kJ/kg	3416 kJ/kg [25]
Heat of vapourization kJ/kg	19600 kJ/kg [6]

At temperature of 2050–2150°C the polymorphic transformation of phases $\alpha \rightarrow \beta$ takes place. The heat of phase transition is 2.1 ± 0.04 kJ/kg [6].

Density of beryllium oxide is calculated by correlation [25]:

$$\rho\ (\text{kg/m}^3) = \rho_0\ (1 - \beta t), \quad (4.15)$$

where $\rho_0 = \rho(t{=}0) = 2870$ kg/m^3 , $\beta = 3\alpha$ is coefficient of volumetric thermal expansion of BeO, and α is coefficient of linear thermal expansion of BeO.

The basic thermophysical properties of beryllium oxide for a density of 2870 kg/$m^3$are presented in Table 4.17.

TABLE 4.17. BASIC THERMOPHYSICAL PROPERTIES OF BERYLLIUM OXIDE FOR A DENSITY OF 2870 kg/m^3

Temperature		Density kg/m^3	Heat capacity KJ/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^5(m^2/s)	Linear expansion coefficient 10^6(1/K)
K	°C	[Eq. (4.15)]	[Eqs (4.17, 4.18)]	[6]		[Eq. (4.16)]
100	373	3005	1.229	157	4.253	5.60
200	473	2999	1.464	79.9	1.819	6.05
300	573	2992	1.617	66.9	1.383	6.50
400	673	2985	1.731	54.1	1.047	6.95
500	773	2977	1.826	47.4	0.872	7.37
600	873	2968	1.910	40.8	0.720	7.79
700	973	2958	1.988	35.7	0.607	8.19
800	1073	2948	2.014	30.6	0.515	8.57
900	1173	2937	2.036	(27.0)	0.452	8.93
1000	1273	2926	2.057	24.0	0.399	9.27
1100	1373	2915	2.079	(21.0)	0.347	9.58
1200	1473	2903	2.101	18.8	0.308	9.87
1300	1573	2891	2.122	(16.5)	0.269	10.12
1400	1673	2879	2.144	15.5	0.251	10.35
1500	1773	2867	2.166	(14.0)	0.225	10.54
1600	1873	2855	2.187	(12.5)	0.200	10.70
1700	1973	2844	2.209	(12)	0.191	10.81
1800	2073	2833	2.231	(11.9)	0.188	10.89
1900	2173	2822	2.253	-	-	10.93
2000	2273	2813	2.274	-	-	10.92
2100	2373	-	2.296	-	-	-
2200	2473	-	2.318	-	-	-

The coefficient of linear thermal expansion of BeO is calculated as:

$$\alpha \times 10^6 \, (1/K) = 5.133 + 4.65 \times 10^{-3}t - 1.539 \times 10^{-7}t^2 - 3.621 \times 10^{-10}t^3, \quad (4.16)$$

This equation generalizes the data in Refs [6, 12]. The data are also known as the graphical curve of function $\alpha \cdot = f(t)$ published in Ref. [6] on P. 56.

The data on coefficients of linear thermal expansion for BeO differ greatly. In this case, such factor as the purity of specimen (quantity and type of impurity) as well as its production technology is of considerable importance. The Beo specimens manufactured by the same technology show a wide scattering in the linear expansion coefficient up to 20–25% (see Table 34 on P. 57 in Ref. [6]). This data scattering is caused by imperfection of applied methods and equipment [6].

The comparison of the values of linear thermal expansion coefficient for BeO is shown in Table 4.18.

Heat capacity of beryllium oxide is evaluated by correlations in Refs [6, 35]:

At $298 \leq T \leq 1200$ K

$$C_p \, [kJ/(kg \cdot K)] = 1.455 + 0.606 \times 10^{-3}T - 0.544 \times 10^5 T^{-2}. \quad (4.17)$$

At $1200 \leq T \leq 2820$ K

$$C_p \, [kJ/(kg \cdot K)] = 1.791 + 0.201 \times 10^{-3}T. \quad (4.18)$$

Beryllium oxide has the highest specific heat capacity among all refractory oxides. At temperature T > 2820 K, the value of C_p is equal to 2.678 kJ/(kg·K).

TABLE 4.18. COMPARISON OF VALUES OF LINEAR THERMAL EXPANSION COEFFICIENT [10^{-6}/K] FOR BeO

Temperature °C	Mean value acc. to [36–39]	Data acc. to [6, 12, 25]
100	6.0	5.5
200	7.2	6.0
400	9.0	7.2
600	9.8	7.7
800	10.5	8.4
1000	11	9.3
1100	-	9.6
1200	11.5	10.0
1300	-	10.15
1400	12.2	10.4
1500	-	10.5
1600	12.6	10.6
1700	-	10.8
1800	-	10.9
1900	-	10.9
2000	-	10.9
2100	-	10.9

Thermal conductivity. Beryllium oxide has extremely high thermal conductivity, which exceeds thermal conductivity of most other oxides. Thermal conductivity of beryllium oxide like other properties depends on specimen purity; thus its density, temperature, and other parameters can vary by an order (see Table 4.19) [32].

TABLE 4.19. THERMAL CONDUCTIVITY OF BERYLLIUM OXIDE IN RELATION TO DENSITY AND TEMPERATURE [32]

Temperature		Thermal conductivity W/(m·K)				
°C	K	ρ = 3010 kg/m^3	ρ = 2870 kg/m^3	ρ = 2620 kg/m^3	ρ = 2000 kg/m^3	ρ = 1890 kg/m^3
100	373	220	157	157.8	58.3	33.5
200	473	174.6	79.9	113	41.9	25.1
300	573	133.8	66.9	84.4	34.5	20.9
400	673	93	54.1	66.6	27.2	16.7
500	773	69.6	47.4	54.0	22.1	15.65
600	873	46.9	40.8	46.1	17.1	14.6
700	973	36.9	35.7	41.0	15.2	12.5
800	1073	27.01	30.6	-	13.4	10.5
900	1173	20.3	24	-	8.8	8.6
1000	1273	17.25	18.8	-	-	-
1200	1473	16.3	15.5	-	-	-
1400	1673	15.4	(12.01)	-	-	-
1800	2073	-	-	-	-	-

Under neutron radiation, the more is the specimen density, the more decreases thermal conductivity. The variations of thermal conductivity caused by radiation can be eliminated by thermal annealing at 1400°C.

Electrical resistivity of beryllium oxide like other properties depends heavily on the specimen purity and its density. The data on the BeO specimen with a density of 2250 kg/m^3 and impurity concentration of ~1.5% produced by sintering at 2100°C in the nitrogen atmosphere [in Ref. 6, P. 103] are presented in Table 4.20.

At a temperature of 100°C, the value of ρ_e for BeO is equal to ~10^{12} Ω·m. High purity specimens of BeO have more high resistivity, namely: 10^{20} Ω m at 20°C, 10^{16} Ω·m at 1000°C, 10^{12} Ω·m at 1600°C and 10^9 Ω·m at 2000°C [6].

The data on *emissivity* of beryllium oxide are shown in Table 4.21 [6]

TABLE 4.20. ELECTRICAL RESISTIVITY OF BERYLLIUM OXIDE [6]

Temperature °C	Electrical resistivity (Ω·m)
1000	8×10^{9}
1100	1.6×10^{9}
1200	8×10^{8}
1300	8×10^{7}
1400	2.5×10^{7}
1500	8×10^{6}
1600	3.5×10^{6}
1700	1.5×10^{6}
1800	6.5×10^{5}
1900	3.5×10^{5}
2000	1.6×10^{5}
2100	8×10^{4}

TABLE 4.21. EMISSIVITY OF BERYLLIUM OXIDE [6]

Temperature K	Emissivity		
	Integral ε_t	Total ε	Monochromatic ε_λ (λ = 0.665 μm)
900	0.34	-	-
1000	0.37	-	-
1100	0.40	-	-
1200	0.42	0.336–0.351	-
1300	0.44	0.361–0.382	0.057
1400	0.46	0.392–0.405	0.068
1500	0.48	0.420–0.425	0.08
1600	0.49	0.439–0.447	0.091
1700	0.50	0.453–0.474	0.102
1800	0.51	0.463–0.499	0.113
1900	-	0.470–0.513	0.124
2000	-	0.474–0.517	0.135
2100	-	0.475–0.514	0.146

Vapour pressure above solid beryllium oxide is calculated by correlation in Ref. [38]:
at $1000 \leq T \leq 2800$ K

$$\lg P(\mathrm{Pa}) = 13.13 - \frac{31030}{T} \quad (4.19)$$

According to the calculations presented in Refs [6, 38], evaporation of beryllium oxide occurs in the form of beryllium atoms.

Vapour pressure above beryllium oxide in liquid state is estimated as:
at 2850 ≤T ≤ 4120 K

$$\lg P(\mathrm{Pa}) = 17.88 - \frac{42920}{T} \quad (4.20)$$

The values of vapour pressure above BeO calculated by Equations (4.19, 4.20) are presented in Table 4.22. However, the comparison between calculations and experimental data shows a considerable disagreement.

TABLE 4.22. VAPOUR PRESSURE ABOVE BERYLLIUM OXIDE

Temperature		Pressure Pa
°C	K	
BeO in solid state, Eq. (4.19)		
800	1073	1.63×10^{-16}
900	1173	4.75×10^{-14}
1000	1273	5.68×10^{-12}
1100	1373	3.39×10^{-10}
1200	1473	1.16×10^{-8}
1300	1573	2.53×10^{-7}
1400	1673	3.82×10^{-6}
1500	1773	4.25×10^{-5}
1600	1873	4.252×10^{-4}
1700	1973	2.53×10^{-3}
1800	2073	1.45×10^{-2}
1900	2173	7.08×10^{-2}
2000	2273	3.01×10^{-1}
2100	2373	1.13
2200	2473	3.82
2300	2573	15.8
2500	2773	252.5
BeO in liquid state, Eq. (4.20)		
2550	2823	475
2700	2973	2780
2900	3173	226×10^{2}
3100	3373	143×10^{3}
3300	3573	737×10^{3}
3500	3773	319×10^{4}
3700	3973	119×10^{5}

REFERENCES TO SECTION 4

1. Galanin A.D. Introduction to Theory of Thermal-Neutron Reactors. – M.: Energoatomizdat, 1984, PP. 395–397 (Russian).
2. Ursu I. Fizica si Tehnologia Materialelar Nucleare, Publ. Acad. Romania, Bucuresti, 1982.
3. Handbook on Nuclear Power Technology./Translated from English. Ed. by V.A. Legasov [A Guide to Nuclear Power Technology/Ed. By F.J. Rahn et al. –New York: A Wiley-Interscience Publ., 1984]. – M.: Energoatomizdat, 1989, P. 312 (Russian).
4. White D., Berk D. Beryllium/Translated from English. – M.: IIL, 1962 (Russian).
5. Hausner H.H. Beryllium as a Moderator. – *Atomic Energy Review*, 1963, Vol. 1, No 2, PP. 99 –166
6. Beliaev R.A. Beryllium Oxide/2nd rev. and enl. ed. – M.: Atomizdat, 1980 (Russian).
7. Viatkin S.E. et al. Reactor Graphite. – M.: Atomizdat, 1967 (Russian).
8. Vargaftik N.B. Reference Book on Thermophysical Properties of Gases and Liquids. – M.: Nauka, 1972 (Russian).
9. Zinoviev V.E. Thermophysical Properties of Metals at High Temperatures/Reference edition. – M.: Metallurgiya. 1989 (Russian).
10. Azhazha V.M. et al. – *Atomnaia Energia*, 1965, Vol. 19, P. 269 (Russian).
11. Properties of Elements/Handbook in Two Volumes. Ed. by M.E. Drits, N.T. Kuznetsov – M.: Metallurgiya, 1997 (Russian).
12. Krzhizhanovsky R.E., Shtern Z.Yu. Thermophysical Properties of Non-metallic Materials (Oxides)/Reference book. – L.: Energiya, 1973 (Russian).
13. Hydride systems/Handbook.– M.: Metallurgiya, 1992 (Russian).
14. Materials for Nuclear Reactors/Translated from English. Ed. by Yu.N. Sokursky [Materials for Nuclear Engineers/Ed. By AV. McIntosh and T.J. Heal. – London: Temple Press Lim., 1960]. – M.: Gosatomizdat, 1963 (Russian).
15. Savvatimsky A.I. Melting of Graphite and Liquid Carbon. – *Uspekhi Fizicheskikh Nauk*, 2003, Vol. 173, No. 12, PP. 1371 — 1379 (Russian).
16. Basharin A.Yu. et al. Methods for Increasing Accuracy of Measurements at Experimental Determination of Graphite Melting Point. – *Teplofizika Vysokikh Temperatur*, 2004, Vol. 42, No. 1, PP. 64–71 (Russian).
17. Gabaraev B.A., Prozorov V.K., Novoselsky O.Yu. Maximum Design Temperature of Graphite Laying/Preprint NIKIET No. ET-01/53. 2001 (Russian).
18. Ubelohde A.R., Lewis F.A. Graphite and its Crystal Compounds/Translated from English. (Oxford at the Clarendon Press, 1960). – M.: Mir, 1965 (Rus).
19. Currie L.M. et al./*Proc. Int. Conf. on Peaceful Uses of Atomic Energy*. –1956, Vol. 8, P. 451.
20. Buchnev L.M. et al. Experimental Investigation of Enthalpy of Graphite Quasi-Mono Crystals. – *Teplofizika Vysokikh Temperatur*, 1987, Vol. 25, No. 6, PP. 1120–1125 (Russian).
21. Glocker G. –*Journal of Chemical Physics*, 1954, Vol. 22, P. 159, (Cit. by [18]).
22. Enthalpy and Heat Capacity of Graphite. – http://www.insc.gov/matprop/graphite/ent-hc/index.php.
23. Graphite UPV-1T. Enthalpy and Heat Capacity in the Temperature Range 1200–2000 K/GSSSD 25–90. – M.: Izdatelstvo Standartov, 1990 (Russian).
24. Trofimov A.N., Chusov I.A. et al. Experimental Investigation of Temperature Fields of RBMK Reactor Channel. – *Izvestiia Vuzov, Yadernaia Energetika*, 2000, No. 3, PP. 103–114 (Russian).

25. Physical Quantities. Reference book/A.P. Babichev, N.A. Babushkin, A.M. Bratkovsky, et al.; Ed. by I.S. Grigoriev, E.Z. Meilikhov. – M.: Energoatomizdat, 1991 (Russian).
26. High Temperature Engineering/Translated from English. – M.: IIL, 1959 (Russian).
27. Ostrovsky V.S., Virgiliev Yu.S., Kostikov V.I., Shipkov N.N. Artificial Graphite. – M.: Metallurgiya, 1986 (Russian).
28. Wockham A.J. International Database on Irradiated Nuclear Graphite Properties//*Proc. 4-th Int. Nucl. Graphite Spec. Meet*., Japan, 13–16.09, 2003.
29. Samsonov G.V. Beryllides. – Kiev. Naukova Dumka., 1966 (Russian).
30. Darwin J., Buddery J. Beryllium/Translated from English. – M.: IIL, 1962 (Russian).
31. Kubashevsky O., Evans E. Thermochemistry in Metallurgy. – M.: IIL, 1954 (Russian).
32. Thermal Conductivity of Solids/Reference Book. Ed. by A.S. Okhotin. – M.: Energoatomizdat. 1984 (Russian).
33. Novikova S.I. Thermal Expansion of Solids. – M.: Nauka, 1974 (Russian).
34. Gulbransen E.A. et al. – *Journal of Electrochem. Soc*., 1950, Vol. 97, P. 383. (Cit. by [30]).
35. Thermodynamic Properties of Individual Substances/Ed. by V.P. Glushko, L.V. Gurvich et al. 3rd rev. and enl. ed. –M.: Nauka, 1982, Vol. IV, Book 2 (Russian).
36. Beryllium Oxide. – *Journal of Nuclear Materials*, 1964, Vol. 14.
37. Beryllium Oxide/*Proc. of Intern. Conf. on Beryllium Oxide*, 21–25.10.1963, Sydney. Translated from English. –M.: Atomizdat, 1968 (Russian).
38. Kotelnikov R.B. et al. Extra Refractory Elements and Compounds. – M.: Metallurgia 1969 (Cit. by [6]) (Russian).
39. Toropov N.A., Barzakovsky V.P. HighTemperature Chemistry of Silicate and other Oxide Systems. – M.:Izdatelstvo AN SSSR, 1963 (Russian).

5. ABSORBING MATERIALS

The materials that absorb neutrons are used in reactor core in the following three cases:

1) Emergency shutdown rods, rods compensating and controlling a reactor power;
2) Burnable absorbers, which can be dispersed uniformly in fuel or placed in certain sections;
3) Additives to moderator for compensation of excess reactivity or to coolant in the emergency core cooling system (ECCS).

Each of these cases has own peculiarities and problems.

Shim rods compensate a fuel excess above its critical mass, and in the case of fuel burn-up, they are pulled out from the core up to their full removal. Control rods are located within the core and used for fine control and transition from one power level to another. Emergency shutdown rods are designed for quick cessation of fission reaction under accident conditions. At normal operation these rods are located outside of the core, and in the case of need, they are quickly pulled in it. In some cases, the functions of absorbing rods can be combined [1, 2].

The basic requirements to materials of control rods and burnable absorbers are the high neutron absorption cross section and stability at operating temperatures. Absorbing materials are to be high resistant to radiation effects and to have good corrosion resistance in coolant medium. These requirements limit the choice of these materials.

Physical and nuclear properties of chemical elements with the high neutron absorption cross section are given in Table 5.1 [2–6]. The basic thermophysical properties of absorbing materials are presented in Table 5.2.

5.1. MATERIALS OF CONTROL RODS

Materials of control rods used in water cooled reactors are boron carbide (B_4C) and silver based alloys (80% Ag, 15% In, 5% Cd). Boron carbide as powder or pellets is loaded into tubes of austenite steel, whereas alloy AgInCd – in the casing of austenite steel or nickel alloy. In fast neutron reactors with liquid metal cooling, boron carbide is used usually.

Materials of control rods (the only moving part of the reactor core) are to have high mechanical strength, resistance to shocks and vibrations, high wear strength, as well as low density to provide quick movement of these rods, low cost and good processibility [9].

5.1.1. Boron (natural)

Boron (natural) is a mixture of two isotopes 19% ^{10}B and 81% ^{11}B. Isotope ^{10}B has the absorption thermal neutron cross section of 3840×10^{-24} cm^2. Natural boron is characterized by lower absorbing ability due to dilution. Pure boron is rarely used. Boron carbide is refractory material with a melting point of 2450°C. The basic problem of using boron carbide consists in its swelling caused by helium formation under reactions [1, 9]:

$^{10}B + n \rightarrow {}^{3}H + 2\,{}^{4}He$; $^{10}B + n \rightarrow {}^{7}Li + {}^{4}He$.

After several years of operation the boron carbide rods should be replaced to prevent the cladding damage. Instead of the rods, the stainless steel plates with boron additives or cavities

filled with B_4C powder can be used. These plates are also to be replaced periodically every 4–7 years.

At absorption of neutron ^{10}B (n, α), energy of 2.78 MeV releases per one action and formation of helium gas occurs. As a result, it is necessary to cool down control rods and to provide for a cavity for helium accumulation, in order to reduce pressure in a rod cladding. Using B_4C in fast neutron reactors is of particular complexity due to higher density of neutron flux (as compared with thermal neutron reactors) and decrease of B_4C operating life. The density of power release in B_4C runs to 75 W/cm^3.

TABLE 5.1. PHYSICAL AND NUCLEAR PROPERTIES OF CHEMICAL ELEMENTS WITH THE HIGH NEUTRON ABSORPTION CROSS-SECTION [2–6]

Element	Atomic number	Atomic mass amu	Density kg/m^3	Temperature		Mean absorption cross section of all stable isotopes 10^{-24} cm^2	Isotope	Content in mixture %	Isotope absorption cross section 10^{-24} cm^2
				T_{melt} °C	T_{boil} °C				
Boron	5	10.81	2330	2075	2550	790	10	19.9	3990
Silver	47	107.87	10500	961.9	2167	63	107	51.8	37.6
							109	48.2	91
Cadmium	48	112.41	8650	320.9	766.5	2550	113	12.36	20600
Indium	49	114.52	7310	156.6	2024	194	115	95.8	202
Gadolinium	64	157.25	7895	1311	3233	48900	155	14.8	61000
							157	15.65	254000
Dysprosium	66	162.5	8550	1412	2562	948	161	19.0	585
							162	25.5	180
							163	24.9	130
							164	28.1	2700
Hafnium	72	178.4	13310	2230	3100	105	177	18.4	1500
							178	27.0	75
							179	13.8	65
							180	35.4	14
Mercury	80	200.5	13550	–39	356.7	363	199	16.9	2150
Europium	83	151.96	5240	822	1597	1850	151	47.9	9200
							155	52.1	390

TABLE 5.2. BASIC THERMOPHYSICAL PROPERTIES OF ABSORBING MATERIALS

Property	B nat.	B_4C	BN	ZrB_2	TiB_2	HfB_2	Hf	Alloy AgInCd	Eu_2O_3	Dy_2O_3	Ta
	[3, 4]	[7, 8]	[7, 8]	[7, 8]	[7, 8]	[7, 8]	[3, 4]	[1, 2]	[10]	[10]	[3, 4]
Molecular mass, amu	10.811	55.24	24.81	112.85	69.5	200.1	178.5	108.1	352	373	180.9
Melting point, °C	2075	2450	3000	3050	2920	3240	2220	800	2050	2340	2996
Density, kg/m^3	2330	2510	2250	6090	4520	11200	13090	10170	7340	8100	16650
Heat capacity, J/(kg·K)	387	960	848	230	387	396	363	230	413	290	140
Thermal conductivity, W/(m·K)	27	92	28.7	23	26	22.6	22.3	60	2.2	2.3	50
Coefficient of linear thermal expansion, $\alpha.\cdot 10^{-6}$ 1/K	5	4.5	2	5.5	7.3	5.3	5.9	22.5	10.1	8.3	6.6
Electrical resistivity, Ω·m	1.8×10^4	$(3 \div 8) \times 10^{-3}$	1.7×10^7	9.2	28.4	12	35.1×10^{-8}	-	-	-	12.4×10^{-8}

Properties are given at temperatures 20–200°C

In recent years, research were performed on using cermet B_4C + Cu as an absorbing material for fast reactors [11]. The developed technology makes it possible to obtain high density of cermet with 70% (vol.) of B_4C. In spite of the low volume concentration of cooper, the thermal conductivity of cermet at 400–700°C is much higher and is in the range of 45–50 W/(m K) instead of 18–20 W/(m K) for B_4C, which allows to provide lower temperatures of the construction design.

5.1.2. AgInCd alloy

The alloy AgInCd has compensating ability that is lower by 15% than that of B_4C. Its swelling under the action of neutron flux is not too large; therefore, it can be used in reactor for about 10 years. The disadvantage of alloy AgInCd is that coolant can be contaminated by radioactive isotope ^{110}Ag, which has the high half-life (270 days) [1, 9]. Low corrosion resistance in water and high cost of alloy are the reasons that hafnium is used as an absorbing material.

5.1.3. Hafnium

Hafnium (natural) is a mixture of six isotopes, from which ^{174}Hf has the highest thermal neutron absorption cross section. The advantage of hafnium is that in the course of its interaction with neutron, formation of helium does not occur. Moreover, its corrosion resistance in water is higher than that of zirconium cladding. Hafnium, which can be used without cladding, is characterized by necessary mechanical strength, good stability and ability to maintain high mechanical properties under radiation; it is well processed. The service life of hafnium rod can exceed 10 years [9, 12]. The comparison characteristics of control rod materials are given in Table 5.3 [2].

5.2. BURNABLE ABSORBERS

Burnable absorbers are used either as assemblies of rods in the form of solid absorbents located in certain sections of the reactor core or its uniformly mixed mixture with fuel. The materials of burnable absorbers are to have necessary concentration of absorbent, so that the rate of its burn-up corresponds to the rate of fuel burn-up. Burnable absorbers are used to compensate excess reactivity at the beginning of fuel cycle, to profile density of heat flux in the core and to provide optimum burn-up.

In pressurized water reactors, the pellets of Al_2O_3 + B_4C (3.3–7%) mixture, borosilicate glass with B_2O_3 concentration of 12.5% or solution of boron compounds (boric acid) in coolant are normally used.

Combined using boron solution in water and fuel of type as mixture of gadolinium oxide with uranium dioxide enables to reduce the initial concentration of boric acid in coolant by more than 6 times. The gadolinium isotopes ^{155}Gd, ^{157}Gd have the high thermal neutron capture cross section. Gadolinium is burnt up more fully to the end of fuel cycle that provides a better balance of neutrons and a better use of fuel. Application of pellets from a uniform mixture of UO_2 + 8%Gd_2O_3 can achieve a weak change of reactivity (or its constancy) during the core service life. The disadvantages of using this mixture are as follows:

1) Lower thermal conductivity and lower melting point as compared with UO_2;
2) Complexity of manufacturing fuel assemblies.

However, the advantages of composition UO_2 + Gd_2O_3 overweigh its disadvantages [1, 2]

TABLE 5.3. COMPARISON OF CHARACTERISTICS OF CONTROL ROD MATERIALS [2]

Material	Number of atoms in sm^3, 10^{-22}		Density kg/m^3	Compensating ability	Swelling at radiation	Processibility*	Relative cost	Corrosion resistance in water	Note
	Boron	Metal							
B_4C (73% of theoretical density)	8.0	-	1780	1	H	G	1		Reference material
Alloy AgInCd	-		10200	0.85	L	G	10–15	M	The same
Ag	-	4.8	-	-	-	-	-	-	
In	-	0.059	-	-	-	-	-	-	
Cd	-	0.023	-	-	-	-	-	-	
Hafnium	-	4.4	13100	0.85	L	G	4–8	G	One of the best materials
Boron	13.0	-	2340	1.1	H	P	3–5	P	Low operability
Europium	-	1.9	4800	0.9	-	-	30	P	No technical advantages
Eu_2O_3		2.3	6700	0.95	H	M	20–25	-	- " -
EuB_6	7.4	1.2	4500	~1.1	H	P	20–30	-	-
Eu_2O_3–70% B_4C	6.9	0.7	3600	>1	-	P	10	P	No technology
CdB_6	7.6	1.5	4700	>1	-	P	>5	P	- " -
W-70% B_4C	6.9	1.7	6800	~1	-	M	>2	P	-
Pyrohafnates $DySmHf_2O_2$	-	-	8300	0.93	-	M	>2	M	-

Processibility*: H — high; L — low; G — good; P — poor; M — medium.

REFERENCES TO SECTION 5

1. Absorbent Materials to Control Nuclear Reactors/Translated from English. Ed. by V.G. Arabey, V.V. Chekunov. – M.: Atomizdat, 1965 (Russian).
2. Handbook on Nuclear Power Technology./Translated from English. Ed. by V.A. Legasov [A Guide to Nuclear Power Technology/Ed. By F.J. Rahn et al. –New York: A Wiley-Interscience Publ., 1984]. – M.: Energoatomizdat, 1989, PP. 305–311 (Russian).
3. Properties of Elements/Handbook in Two Volumes. Ed. by M.E. Drits, N.T. Kuznetsov – M.: Metallurgia, 1997 (Russian).
4. Chirkin V.S. Thermophysical Properties of Materials for Nuclear Power Engineering/Reference book. – M.: Atomizdat. 1968 (Russian).
5. Kulikov I.S. Isotopes and Properties of Elements. – M.: Metallurgia, 1990 (Russian).
6. Vargaftik N.B. Reference Book on Thermophysical Properties of Gases and Liquids. – M.: Nauka, 1972 (Russian).
7. Samsonov G.V., Markovsky L.Ya., Zhigach A.F., Valyashko M.G. Boron, its Compounds and Alloys. – Kiev: Izdatelstvo AN USSR, 1960 (Russian).
8. Samsonov G.V. Refractory Compounds. – M.: Metallurgia, 1963 (Russian).
9. Ursu I. Fizica si Tehnologia Materialelar Nucleare, Publ. Acad. Romania, Bucuresti, 1982.
10. Krzhizhanovsky R.E., Shtern Z.Yu. Thermophysical Properties of Non-metallic Materials (Oxides)/Reference book. – L.: Energia, 1973 (Russian).
11. Maruyama T., Onose S. Thermal Conductivity of B_4C/Cu Cermet. – *Journal of Nuclear Science and Technology*, 1999, Vol. 36, No. 4, PP. 380–385.
12. Gerasimov V.V., Monakhov A.S. Materials of Nuclear Engineering.– M.: Energoatomizdat, 1982 (Russian).

6. STRUCTURAL MATERIALS

6.1. GENERAL INFORMATION

Many various materials are used in the designs of reactor core. Some core materials are likely to have the lower cross sections of thermal neutron capture; on the contrary, some others such as absorbers, shielding materials should have the considerable neutron capture cross sections.

Metals are rarely used in pure state, mainly they used as alloys (Al, Mg, Zr, Ni, Nb, Mo), steels. Depending on the structure, steels are classified as pearlitic, martensitic, ferritic and austenitic.

The name of steel and alloy types consists of the element designation followed by figures, which indicate mean percentage of alloying element. The chemical elements in steel grades are identified with letters (see Table 6.1).

The basic physical properties of some structural materials under normal conditions are presented in Table 6.2., and the physical properties of some structural materials at melting point are shown in Table 6.3.

TABLE 6.1. DESIGNATIONS OF STEELS [12]

<table>
<tr><th>Letter identifications in steel grade [cyrillic (latin)]</th><th>Alloying element in steel</th><td rowspan="21">Steels and alloys produced by special methods are additionally identified through hyphen in the end of grade by letters:
[cyrillic (latin)]
А (A) — automatic steels with letter at the beginning of grade or high quality steels with letter in the end of grade;
А–А (A-A) — specially for nuclear power engineering;
ВД (VD) — vacuum-arc refining;
ВИ (VI) — vacuum-induction melting;
ВО (VO) — vacuum-oxygen refining;
ГР (GR) — gaseous oxygen refining;
ПД (PD) — plasma insertion followed by vacuum-arc refining;
Р (R) — high speed steels with letter at the beginning of grade;
У (U)– carbon steels;
Ш (Sh) — electroslag remelting with letter at the end of grade or bearing steel with letter at the beginning of grade;
The first figures before to steel grade indicate carbon concentration in hundredth of percent, unless otherwise specified.</td></tr>
<tr><td>А (A)</td><td>Nitrogen</td></tr>
<tr><td>Б (B)</td><td>Niobium</td></tr>
<tr><td>В (V)</td><td>Tungsten</td></tr>
<tr><td>Г (G)</td><td>Manganese</td></tr>
<tr><td>Д (D)</td><td>Cooper</td></tr>
<tr><td>Е (E)</td><td>Selenium</td></tr>
<tr><td>К (K)</td><td>Cobalt</td></tr>
<tr><td>Л (L)</td><td>Molding material</td></tr>
<tr><td>М (M)</td><td>Molybdenum</td></tr>
<tr><td>Н (N)</td><td>Nickel</td></tr>
<tr><td>П (P)</td><td>Phosphorus</td></tr>
<tr><td>Р (R)</td><td>Boron</td></tr>
<tr><td>С (S)</td><td>Silicon</td></tr>
<tr><td>Т (T)</td><td>Titanium</td></tr>
<tr><td>У (U)</td><td>difference in concentration Al and other elements</td></tr>
<tr><td>Ф (F)</td><td>Vanadium</td></tr>
<tr><td>Х (Kh)</td><td>Chromium</td></tr>
<tr><td>Ц (Ts)</td><td>Zirconium</td></tr>
<tr><td>Ю (Yu)</td><td>Aluminium</td></tr>
<tr><td>‘r’</td><td>Rare-earth element</td></tr>
</table>

TABLE 6.2. BASIC PHYSICAL PROPERTIES OF SOME STRUCTURAL MATERIALS UNDER NORMAL CONDITIONS

Material, reference	Atomic mass amu	Thermal neutron capture cross section 10^{-24}cm^2 [35]	Concentration of nuclei 10^{22} cm^{-3} [35]	Melting point °C	Density kg/m^3	Heat capacity kJ/(kg·K)	Thermal conductivity W/(mK)	Linear expansion coefficient 10^{-6} 1/K	Electrical resistivity 10^{-8} Ω·m
Aluminium [14, 19]	26.98	0.215	6.23	660	2700	0.897	220	23.3	2.5–2.66
Beryllium [14, 19]	9.01	0.09	1.23	1288	1848	1.825	200	11.3	3.2–4.0
Magnesium [14, 19]	24.3	0.060	4.31	650	1740	1.040	156	24.8	3.5–4.2
Iron [14, 19]	55.85	2.43	8.49	1538	7870	0.450	74	11.8	8.6–9.7
Molybdenum [1, 14, 19, 36]	95.94	2.4	6.4	2623	10200	0.249	147	5.2	4.9
Nickel [14, 19]	58.7	4.8	9.13	1455	8900	0.440	88	13.5	6.14–6.84
Niobium [14, 19]	92.91	1.15	5.55	2477	8570	0.265	54	7.3	12.5
Chromium	52	3.07	8.31	1907	7150	0.450	95	4.9	12.9
Steel[1] (13% Cr) [3]	54.70	2.70	8.53	1480–1500	7750–7810	0.48	42	11.2	57.0
Stainless steel austenite[2] [3]	55.93	2.88	8.56	1440	7950	0.50	16	16.0	72.0
Zirconium 99.99% [14, 19]	91.22	0.185	4.29	1855	6520	0.278	24	5.7	40
Zr + 1 Nb [31, 34]	91.24	0.178	4.32	1837	6550	0.320	18	5.8	70.0
Zr + 2,5 Nb [31, 34]	91.26	0.191	4.33	1827	6570	0.315	19	5.2	72.0
Zircalloy 2 [31, 34]	91.37	0.1806	4.31	1845	6550	0.290	17	5.8	74.0
Zircalloy 4 [31, 34]	91.38	0.1812	4.34	-	6580	0.293	14.1	5.8	-

1 — Low carbon high chromium stainless steel of martensitic-ferrite class.
2 — Austenitic stainless steel type 1Kh18N10T and SS 316.

TABLE 6.3. BASIC PHYSICAL PROPERTIES OF SOME STRUCTURAL MATERIALS AT MELTING POINT [1, 6, 14, 15, 19, 36]*

Properties	Aluminium Al	Beryllium Be	Magnesium Mg	Iron Fe	Nickel Ni	Niobium Nb	Chromium Cr	Zirconium Zr 99,99% [34]	Steel[1] (C<0.2; 13% Cr) [9]	Steel[2] Kh18N10T [9]	Zr+1% Nb [34]	Zr+2.5% Nb [34]	Molybdenum Mo
Melting point, K	933	1560	923	1811	1728	2750	2180	2128	1770	1713	2110	2100	2896
Boiling point, K	2792	2744	1363	3134	3186	5017	2945	4682	3010	3090	~4600	~4600	~5080
Heat of fusion, kJ/kg	397	880	357	240	295	302	400	230**	~240**	~240**	~200**	~215**	382
Heat of vapourization, kJ/kg	10896	32963	5267	5916	6441	7426	6519	6358	–	–	–	–	6191
Density of liquid material, kg/m^3	2368	1690	1580	7034	7770	7580	6290	6000	–	6980	6020	6040	9080
Heat capacity, J/(kg·K)	1177	3330	1410	835	735	450	962	467	852	775	467	467	420
Thermal conductivity of liquid material, W/(m·K)	98	75**	84	33	69	65	46	36**	–	22**	45**	39**	70
Dynamic viscosity, 10^{-3} Pa·s	1.24 (1.95)	2.25	1.41	4.6–5.4	4.85	(5.88)	4.7–5.8	7.8 (4.31)	(4.82)**	4.45 (4.81)	(4.61)	(4.62)	(6.25)
Surface tension, mN/m [8]	915	1100	550	1830	1735	2040	1540	1455	1520	~1500	~1550	~1550	2130
Electrical resistivity of liquid material, 10^{-8} Ω·m	24.8	45	26.1	138	83	109	115	141	–	–	–	–	100
Volume expansion at melting ΔV/V, %	6.6	1.7	2.8	3.58	3.2–5.4	4.5	5.8–6.2	3.6	~4	3.9	~5.1	~6.0	~6

1 Low carbon high chromium stainless steel of martensitic-ferrite class;
2 Austenitic stainless steel of types 1Kh18N10T and SS 316;
** References only for metals;
* These data should be refined.

6.2. METALS

6.2.1. Aluminium

Aluminium is applied in research water cooled reactors at temperatures of 100–130°C. Aluminium alloys were used to manufacture claddings of uranium units (blocks) operating in reactors at temperatures up to 200°C and low pressures. At higher temperatures, intermetallics types UAl_3 and UAl_4 are formed in the course of aluminium contact with uranium, which reduce strength characteristics of metal. Aluminium alloys with nickel, iron are used for claddings and matrices of dispersion fuel elements at temperature up to 200–230°C.

Alloying aluminium by various metals permits to increase the range of operating temperatures [32]:

$$\text{up to 150–320°C} \quad \begin{cases} \text{Fe} & 0.1-1.3\% \\ \text{Ni} & 0.6-2.5\% \\ \text{Cr} & 0.09-0.6\% \end{cases}$$

$$\text{up to 100–300°C} \quad \begin{cases} \text{Si} & 0.1-1.2\% \\ \text{Mg} & 0.5-3.2\% \end{cases}$$

$$\text{up to 100–300°C} \quad \begin{cases} \text{Mn} & 0.09-1.0\% \\ \text{Cu} & 0.12-2.0\% \end{cases}$$

After thermal processing, duralumin alloys acquire high strength at normal temperatures. Composition of duralumin different grades is presented in Table 6.4.

TABLE 6.4. COMPOSITION OF DURALUMIN GRADES [3]

Grade	Element content %				
	Cu	Mg	Mn	Si	Fe
D1	3.8–4.8	0.4–0.8	0.4–0.8	≤0.7	≤0.7
D16(high strength)	3.8–4.5	1.2–1.8	0.3–0.9	≤0.5	≤0.5

These alloys cannot be used for nuclear engineering owing to the high absorption cross section of Cu (3.6×10^{-24}cm^2) and Mn (13.4×10^{-24}cm^2). Besides, the isotopes of these elements are characterized by high induced radioactivity with high half-lives for ^{64}Cu –τ (1/2) = 12.8 h and ^{56}Mn – τ (1/2) = 2.6 h [35]. Low corrosion resistance of duralumin alloys in water and steam at temperature >200°C is another obstacle to use duralumin in nuclear engineering.

Aluminium-magnesium alloys types AMg-5 and AMg-7 contained up to 7.5% Mg have good nuclear properties, lower corrosion activity in contact with water as compared with duralumin; and they have found use in some constructions [33].

6.2.2. Magnesium

Magnesium is used to manufacture fuel element claddings and matrices of dispersion fuel elements. It has the low thermal neutron absorption cross section, low density and high thermal conductivity. Fuel elements with claddings from magnesium alloys apply for

uranium-graphite and heavy water reactors, where natural uranium is used as fuel and carbon dioxide (CO_2) as coolant at temperatures of 350–450°C.

The claddings from magnesium alloys of type Magnox (Mg + 0.01 Be + 0.8% Al) are well compatible with metallic uranium at temperatures up to 500°C; they are highly resistant to oxidation. The disadvantage of these alloys is a high tendency to grain growth, loss of strength properties, oxidation in the presence of water steam. Magnesium can fire at temperatures of 470–500°C in the atmosphere of oxygen and air [32, 33].

6.2.3. Zirconium and its alloys

Zirconium is a metal with high melting point (1850°C). Its thermal neutron absorption cross section is less than $1 \times 10^{-24} cm^2$. Zirconium is well compatible with nuclear fuel and characterized by high processing properties. The zirconium thermal conductivity is close to that of stainless steel. The disadvantages of zirconium are low strength properties and low heat resistance, which can be eliminated, for example, by alloying with niobium.

Basic properties of zirconium are as follows:

Atomic number	40
Atomic mass	91.224 amu
Density at normal conditions	6511 kg/m^3 [34]
Melting point	1855°C (2128 K) [31]
Boiling point	4409°C (4680 K) [31]
Heat of fusion	153 ± 4 kJ/kg [23]
Heat of vapourization	638 kJ/kg [1]
Molar volume	0.1402×10^{-8} m^{-3} [14]
Thermal neutron capture cross section	0.18×10^{-24} cm^2 [35]

Zirconium alloys with niobium are used as claddings of fuel elements of WWER[1], RBMK[2] and transport reactors. These alloys are the basis material of assembly channel of RBMK reactor. The maximum temperature, at which zirconium alloys can be used in water cooled reactors, depends on their corrosion resistance. Alloys of type Zircalloy, in which tin is the basic alloying element that provides improvement of their mechanical properties, have a wide distribution in the USA. However in this case, the decrease of corrosion resistance in water and steam is taken place that resulted in the need for additional alloying [33].

In the Russian Federation, the alloy type Ozhenit-0.5 (0.25 Sn, 0.1 Fe, 0.1 Nb, 0.1 Ni) with low alloying was developed. This alloy is close to Zircalloy by its mechanical properties and can be used in water and steam at temperatures up to 400°C [34]. The Zr + 1% Nb alloy of type N-1 (E-110) is used for fuel element claddings, the Zr + 2.5% Nb alloy of typeN-2.5 (Э-125) is applied for tubes of assembly channels.

High corrosion resistance of niobium alloyed metals in water (350 K) and steam at temperatures of 400–550°C is caused by their ability to passivation with formation of protective films. The corrosion rate of the Zr + 2.5% Nb alloy does not exceed 0.024 g/(m^2day) in the course of 8000 h testing [16, 17]. Under irradiation, the corrosion rate increases only by 5–10% [18]. The oxidation kinetics is defined by expression:

$$\Delta m = k \tau^n, \qquad (6.1)$$

[1] WWER — water–water power reactor
[2] RMBK — graphite channel-type reactor of large power

where Δm is the weight increment of zirconium owing to formation of oxide film for time τ in hours; the values of k, n coefficients depend on the composition of alloy and temperature. Some data on oxidation kinetics of zirconium and its alloys are presented in Table 6.5.

6.2.3.1. Properties of solid zirconium depending on temperature [19–25]

Density of Zr is defined by correlation:

$$\rho(T)\ (kg/m^3) = 6550 - 0.1685\ T. \qquad (6.2)$$

Heat capacity of Zr is calculated as [20]:
for α phase of Zr at $298 \le T \le 1100$ K

$$C_p\ [J/(kg\ K)] = 238.596 + 0.181\ T - 96.1 \times 10^{-6}\ T^2 + 36.2 \times 10^{-9}\ T^3, \qquad (6.3)$$

for β phase of Zr at $1100 \le T \le 2128$ K

$$C_p\ [J/(kg\ K)] = 276.462 + 0.0141\ T - 3.08\times10^{-6}\ T^2 + 10.7\times10^{-9}\ T^3. \qquad (6.4)$$

TABLE 6.5. PARAMETERS OF OXIDATION KINETICS OF ZIRCONIUM AND ITS ALLOYS [17]

Metal	Conditions			Parameters of Eq. (6.1)	
	medium	Temperature °C	Pressure MPa	k	n
Zirconium	water	350	16.8	0.5	0.3
	steam	400	30.0	0.7	0.38
Zr-1% Nb alloy	water	350	16.8	0.2	0.5
	steam	400	30.0	0.3	0.58
	steam	450	30.0	0.35	0.71
Zr-2.5% Nb alloy	water	300	8.8	0.2	0.47
	steam	350	16.8	0.22	0.62

Thermal conductivity of Zr at $T < 2000$ K with an accuracy of ± 10% is evaluated as:

$$\lambda\ [W/(m\cdot K)] = 8.8527 + 7.0820 \times 10^{-3}\ T + 2.5329 \times 10^{-6}\ T^2 + 2.9918 \times 10^{3}\ T^{-1}. \qquad (6.5)$$

Thermal diffusivity of Zr in 10^{-6} (m^2/s) is calculated $a = \lambda / C_p \rho$.

Electrical resistivity of Zr is defined by following correlations:

at $T < 1100$ K

$$\rho_e \cdot 10^8\ (\Omega\cdot m) = -2.142 + 7.904 \times 10^{-2}\ T + 4.249 \times 10^{-4}\ T^2 - 5.71 \times 10^{-7}\ T^3 + 2.08 \times 10^{-10}\ T^4, \qquad (6.6)$$

at $1100 \le T \le 2000$ K

$$\rho_e \cdot 10^8\ (\Omega\cdot m) = 92.85 + 2.27\times10^{-2}\ T. \qquad (6.7)$$

The basic thermophysical properties of solid zirconium according to Equations (6.2–6.7) are shown in Table 6.6.

TABLE 6.6. BASIC THERMOPHYSICAL PROPERTIES OF SOLID ZIRCONIUM BY EQS (6.2–6.7)

Temperature K	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6(m^2/s)	Electrical resistivity 10^8(Ω·m)
298	6500	285	21.2	11.46	46
300	6499	285	21.2	11.42	46
400	6483	298	19.6	10.13	66
500	6466	310	19.0	9.50	85
600	6449	320	19.0	9.19	102
700	6432	331	19.3	9.09	115
800	6415	340	19.9	9.10	126
900	6398	350	20.6	9.20	133
1000	6382	360	21.5	9.35	139
1100	6365	370	22.4	9.53	143
1200	6348	307	23.5	8.30	120
1300	6331	313	24.6	8.11	122
1200	6348	307	23.5	8.30	120
1300	6331	313	24.6	8.11	122
1400	6314	320	25.9	7.90	125
1500	6297	327	27.2	7.66	127
1600	6280	335	28.5	7.40	129
1700	6264	344	30.0	7.11	131
1800	6247	354	31.5	6.80	134
1900	6230	366	33.0	6.47	136
2000	6213	378	34.6	6.12	138
2100	6196	392	36.3	5.76	141
2128	6191	396	36.7	5.66	141

6.2.3.2. Properties of liquid zirconium depending on temperature [20–24]

Density

$$\rho\ (\mathrm{kg/m^3}) = 6844.5 - 0.609898\ T + 2.05008 \times 10^{-4}\ T^2 - 4.47829 \times 10^{-8}\ T^3 + 3.26469 \times 10^{-12}\ T^4, \quad (6.8)$$

$\rho(T_{melt}) = 6107$ kg/m^3; $\rho(T_{boil}) = 5590$ kg/m^3.

Heat capacity

$$C_p\ [\mathrm{kJ/(kg \cdot K)}] = -1.48 + 1.74588 \times 10^{-3}\ T^3 - 5.26174 \times 10^{-7}\ T^2 + 5.56831 \times 10^{-11}\ T^3. \quad (6.9)$$

Electrical resistivity is calculated by the correlation,

$$\rho_e \cdot 10^8\ (\Omega \cdot \mathrm{m}) = 130 + 8 \cdot 10^{-3} T, \quad (6.10)$$

or a more exact equation,

$$\rho_e \cdot 10^8\ (\Omega \cdot \mathrm{m}) = -65.63192 + 0.10319T - 5.0937 \times 10^{-5}\ T^2 + 1.16791 \times 10^{-8}\ T^3 - 9.64305 \times 10^{-13}\ T^4. \quad (6.11)$$

Mean coefficient of volumetric expansion $\beta = 39 \times 10^{-6}$ 1/K.

Dynamic viscosity $\mu = 8 \times 10^{-3}$ Pa·s [24].

Surface tension [23]

at 2128 K (1855°C) σ = 1455 mN/m; at 2733 K (2460°C) σ = 1395 mN/m.

Thermophysical properties of liquid zirconium in the temperature range from 2128 to 4100 K calculated on the basis of Eqs (6.8–6.11) are presented in Table 6.7 [21–23].

TABLE 6.7. THERMOPHYSICAL PROPERTIES OF LIQUID ZIRCONIUM BY EQS (6.8–6.11)

Temperature K	Density kg/m^3	Heat capacity J/(kg·K)	Electrical resistivity 10^8(Ω·m)
2128	6110	700	147.3
2200	6095	645	147.9
2300	6073	510	148.6
2400	6051	445	149.3
2500	6029	462	150.1
2600	6007	477	150.8
2700	5984	490	151.5
2800	5962	502	152.3
2900	5939	512	153.1
3000	5915	522	154.0
3100	5891	531	154.9
3200	5867	539	155.8
3300	5842	548	156.8
3400	5817	558	157.8
3500	5791	568	158.9
3600	5765	580	159.9
3700	5738	593	161.0
3800	5711	608	162.0
3900	5683	625	163.0
4000	5655	644	164.0
4100	5626	667	164.9

6.2.3.3. Zirconium-niobium (1%) alloy type N-1 (E-110)

The basic component of Zr + 1% Nb alloy is zirconium with the following content of other elements (%): Nb – (0.9÷1.1), Fe – 0.015, Ni – 0.007, Al – 0.004, Ti – 0.003, C – 0.02, Si − 0.004, O – 0.05, N – 0.003, H – (0.001÷0.002).

Some thermophysical properties of this alloy are as follows:

Melting point	2130 K
Phase transition point	1140 K
Heat of fusion	150–160 kJ/kg
Heat of phase transition	42 kJ/kg
Density at 298 K	6550 kg/m^3

Density

at $300 \le T \le 1100$ K [34]
$\rho(T)$ (kg/m^3) = 6636 – 0.286 T. (6.12)

Heat capacity [26, 27]

at $300 \le T \le 1100$ K
C_p [J/(kg K)] = 238 + 0.159 T, (6.13)

at $1100 \le T \le 2000$ K
C_p [J/(kg K)] = 281 + 0.0663 T. (6.13a)

Thermal conductivity [28]

at $300 \le T \le 1100$ K
λ [W/(m·K)] = $23.5 - 0.0192\,T + 1.68 \times 10^{-5}\,T^2$, (6.14)
at $1100 \le T \le 1600$ K
λ [W/(m·K)] = 1.5 + 0.02 T. (6.14a)

Thermal diffusivity in 10^{-6} m^2/s is defined as $a = \lambda / C_p \rho$.

Linear expansion coefficient [29]

at $300 \le T \le 1100$ K
$\alpha \cdot 10^6$ (1/K) = $5.22 + 1.82 \times 10^{-3}\,T$. (6.15)

Electrical resistivity [28]

at $300 \le T \le 1100$ K
$\rho_e \cdot 10^8$ (Ω·m) = $-9.08 + 0.2535\,T - 2.0391 \times 10^{-4}\,T^2 + 9.505 \times 10^{-8}\,T^3$, (6.16)
at $1200 \le T \le 1500$ K
$\rho_e \cdot 10^8$ (Ω·m) = $94.86 + 1.411 \times 10^{-2}\,T + 2.74 \times 10^{-6}\,T^2$. (6.16a)

Spectral emissivity at temperature of 350–450 K is ε = (0.167–0.184) [34].

Thermophysical properties of Zr + 1% Nb alloy calculated by correlations (6.12–6.16a) are presented in Table 6.8.

TABLE 6.8. THERMOPHYSICAL PROPERTIES OF Zr + 1% Nb ALLOY BY EQS (6.12-6.16a)

Temperature K	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6 (m^2/s)	Linear expansion coefficient 10^6 (1/K)	Electrical resistivity 10^8(Ω·m)
300	6550	286	19.3	10.3	5.77	51
400	6522	302	18.5	9.4	5.95	66
500	6493	318	18.1	8.8	6.13	79
600	6464	333	18.0	8.4	6.31	90
700	6436	349	18.3	8.1	6.49	101
800	6407	365	18.9	8.1	6.68	112
900	6379	381	19.8	8.2	6.86	123
1000	6350	397	21.1	8.4	7.04	136
1100	6321	413	22.7	10.1	7.22	150
1200	6293	360	25.5	11.2	-	116
1300	6264	367	27.5	12.0	-	118
1400	6236	374	29.5	12.6	-	120
1500	6207	380	31.5	13.3	-	122
1600	6178	387	33.5	14.0	-	-
2100	6035	420	35.5	14.0	-	-

6.2.3.4. Zirconium-niobium alloy type E-635

The Zr-Nb alloy type E-635 differs from the previous alloy type E-110 by addition of such alloying elements as Sn and Fe. The composition of this alloy based on zirconium is the following (%): Nb – (0.9 – 1.1), Sn – (1.0 – 1.5), Fe – (0.3 – 0.5).

The thermophysical properties of the alloy type E-635 are similar in general to the properties of the alloy type E-110. The particular correlations are presented below [37, 38].

Density at 20°C is equal to 6530 kg/m^3.

Phase transition point $\alpha \rightarrow (\alpha + \beta)$ 630–650°C;
$(\alpha + \beta) \rightarrow \beta$ 880–910°C.

Heat capacity in β phase at T > 1200 K:

$$C_p\,[J/(kg\,K)] = 221 + 0.172\,T - 5.87 \times 10^{-5}\,T^2, \quad (6.17)$$

Thermal conductivity [37].

at $400 \le T \le 1500$ K

$$\lambda\,[W/(m{\cdot}K)] = 10.583 + 348\,T^{-1} + 1.04 \times 10^{-4}\,T + 8.735 \times 10^{-6}\,T^2. \quad (6.18)$$

The data on thermal conductivity of the alloy type E-635 in unirradiated state and after exposure to radiation at the neutron flux of 2×10^{22} n/cm^2 and E > 0.1 MeV are considered in Ref. [38]. Thus the value of λ prior to radiation exposure is defined as:

$$\lambda\ [W/(m\cdot K)] = 13.1 + 1.6 \times 10^{-2}\ (T - 273), \quad (6.18a)$$

and after radiation exposure,

$$\lambda\ [W/(m\cdot K)] = 13.1 + 5.5 \times 10^{-3}\ (T - 273). \quad (6.18b)$$

Spectral emissivity at temperature of 1700–2000 K is defined by equation from data in Ref. [37]:

$$\varepsilon\ (\lambda = 0.65\ \mu m) = 1.02 - 3 \times 10^{-4}\ T \quad (6.19)$$

6.2.3.5. Zirconium-niobium (2.5%) alloy type N–2.5 (E-125) [31]

Composition of Zr + 2.5% Nb alloy with zirconium as the basis is as follows (%): Nb – 2.5, Fe – 0.015, Ni – 0.007, Al – 0.004, Ti – 0.003, C – 0.02, Si – 0.004, O – 0.05, N – 0.003, H − (0.001÷0.002). Some thermophysical properties of this alloy are as follows:

Melting point	2130 K
Phase transition point	1140 K
Heat of fusion	150–160 kJ/kg
Heat of phase transition	40 kJ/kg
Density at 298 K	6570 kg/m^3

Density

$$\rho(T)\ (kg/m^3) = 6657 - 0.2861\ T. \quad (6.20)$$

Heat capacity

at $300 \le T \le 1100$ K

$$C_p\ [J/(kg\ K)] = 221 + 0.172\ T - 5.87 \times 10^{-5}\ T^2, \quad (6.21)$$

at $1100 \le T \le 1600$ K $C_p = 380$ J/(kg K)

Thermal conductivity

at $300 \le T \le 1100$ K

$$\lambda\ [W/(m\cdot K)] = 14 + 0.0115T. \quad (6.22)$$

Thermal diffusivity in 10^{-6} m^2/s is defined as $a = \lambda / C_p \rho$.

Thermophysical properties of Zr + 2.5% Nb alloy calculated by Eqs (6.20–6.22) are shown in Table 6.9. The values of linear expansion coefficients are taken in Ref. [29].

TABLE 6.9. THERMOPHYSICAL PROPERTIES OF Zr + 2.5% Nb ALLOY BY EQS (6.20–6.22)

Temp. K	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity $10^6(m^2/s)$	Linear expansion coefficient $10^6(1/K)$ [29]
300	6571	267	17.5	9.9	4.3
400	6543	280	18.6	10.1	4.7
500	6514	292	19.8	10.4	4.8
600	6485	303	20.9	10.6	4.9
700	6457	313	22.1	10.9	5.3
800	6428	321	23.2	11.2	5.4
900	6400	328	24.4	11.6	4.0
1000	6371	334	25.5	12.0	3.0
1100	6342	339	26.7	12.4	-
1200	6314	380	-	-	-
1300	6285	380	-	-	-
1400	6256	380	-	-	-
1500	6228	380	-	-	-
1600	6199	380	-	-	-
2100	6056	-	-	-	-

6.3. STEELS

6.3.1. High temperature stainless chromium steels

The steels alloyed by chromium have found a wide use in nuclear reactor industry, because chromium has a favorable effect on corrosion resistance of steel at high temperatures.

The most important thermophysical properties of materials used for NPP units are thermal conductivity and thermal expansion coefficient. These properties govern the heat transfer processes and occurrence of thermal stresses in constructions [39–48].

Depending on the concentration of chromium and other alloying elements, the structure and thermal processing, steels are classified as pearlitic, martensitic, ferrite and austenitic. Thermophysical properties of steels of basic classes are presented in Table 6.10 [55].

The thermal conductivity of steel is reduced as the chromium content is increased. At the content of Cr < 5%, the thermal conductivity of steel decreases with increasing temperature and rises at the content of Cr >12%. The thermal conductivity of chromium steels and alloys used in heat exchangers of NPP is shown in Table 6.11 [54]. The linear expansion coefficient is reduced with increasing the chromium concentration and rises as temperature is increased.
Pearlitic steels are referred to low alloyed alloys. These steels are used to manufacture high pressure vessels and tubes for thermal power plants. In some cases, they replace more expensive chromium-nickel stainless steels. Pearlitic steels are not prone to intergranular attack (IGA) and stress-corrosion cracking. The chemical composition of some pearlitic steels is shown in Table 6.1.

TABLE 6.10. THERMOPHYSICAL PROPERTIES OF STEELS OF BASIC CLASSES

Property	Pearlitic steels			Martensitic steels		Austenitic steels		Nickel based alloy
	10	35	12Kh1MF	20Kh13	11Kh11N2V2MF	12Kh18N9T	20Kh25N20S2	KhN67MVTYu
Density, kg/m^3	7830	7810	7800	7750	7860	8000	7820	8170
Temperature$_{melt}$, °C	1530	1490–1450	1400–1450	1410–1440	1450–1500	1400–1425	1383–1410	1390
Heat capacity, J/(kg·K)								
(100°C)	451	459	471	438	475	492	492	442
(700°C)	-	-	-	966	-	945	-	615 (900°C)
Thermal conductivity, W/(m·K)	50.5	47.7	41.2	27.1	25.0	16.5	14.3	12.5
Linear expansion coefficient, 10^6 1/K								
(20–100°C)	11.6	11.09	10.8	9.6	10.75	16.6	15.0	11.7
(20–500°C)	14.6	14.02	13.2	11.3	13	17.9	18.0	13.5
ρ_e 10^8 (20°C), Ω·m	15	-	32	60	105	75	73–95	124

TABLE 6.11. THERMAL CONDUCTIVITY OF STEELS AND ALLOYS USED FOR HEAT EXCHANGERS OF NUCLEAR POWER PLANTS [54]

Temperature °C	100	200	300	400	500	600	700	800	900	1000
Alloy grade	Thermal conductivity, W/(m·K)									
1Kh2M	48.9	48.3	47.7	47.0	46.2	45.6	-	-	-	-
Kh2MFB	41.0	38.9	38.0	37.3	36.8	36.6	-	-	-	-
Kh18N9	16.3	18.0	18.8	20.1	21.5	23.8	25.6	26.8	27.4	28.1
Kh18N10T	14.4	16.2	18.7	21.2	23.0	25.0	-	-	-	-
05KhN46MVB4	-	12.3	14.7	18.4	20.5	24.7	27.2	-	-	-
03Kh21N32M3B	-	13.8	15.9	18.4	20.5	22.6	24.7	-	-	-
KhN55MVTs	11	14	16	18	20	22	25	27	29	31
0Kh18N16M3B (EI-847)	14.4	16.3	18.0	19.7	21.4	23.0	24.4	25.7	26.4	-

TABLE 6.12. CHEMICAL COMPOSITION OF SOME PEARLITIC STEELS [55]

Steel grade	Element content %							
	C	Cr	Mo	Mn	V/Nb	Ni	Si	Cu/Al
15M	0.10–0.18		0.4–0.7	-	-	-	-	-
12KhM	0.09–0.16	0.4–0.6	0.4–0.6	-	-	-	-	-
12Kh1MF	0.08–0.15	0.9–1.2	0.25–0.35	-	0.15–0.30/-			
12Kh2MFB	0.08–0.12	2.1–2.6	0.5–0.7	-	0.2–0.35/ 0.5–0.8	-	-	-
15Kh2MFA	0.13–0.18	2.5–3.0	0.6–0.8	0.3–0.6	0.25–0.35/-	≤0.4	0.17–0.37	≤0.025/-
15Kh2NMFA	0.13–0.18	1.8–2.3	0.5–0.7	0.3–0.6	0.1–0.12/-	1.0–1.5	0.17–0.37	≤0.3/-
15Kh3NMFA	0.12–0.16	2.2–2.7	0.5–0.8	0.3–0.6	0.08–0.15/-	0.8–1.3	0.17–0.37	≤0.15/-
25Kh3MFA	0.22–0.27	2.8–3.3	0.6–0.8	0.3–0.6	0.25–0.35/-	≤0.4	0.17–0.37	≤0.025/-
16GNM	0.13–0.18	-	0.4–0.55	0.8–1.1	-	1.1–1.3	-	-
10KhSND	<0.12	0.6–0.9	-	-	-	0.5–0.8	0.8–1.1	0.4–0.65/-
48TS-1	0.22–0.27	2.5–3.0	0.6–0.8	-	0.25–0.35/-	0.4–0.7	-	-
38KhMYuA	0.35–0.42	1.35–1.65	0.15–0.25	-	-	-	-	-/0.7–1.1

In nuclear power engineering, pearlitic steels are used to manufacture reactor vessels and heads, pipelines, steam generators and other units operating in contact with water, steam and liquid metals in the temperature range of 250–580°C. The low alloyed steels have the high thermal conductivity of 30–50 W/(m·K) instead of that 12–17 W/(m·K) for the high alloyed steels. They also characterized by the low linear expansion coefficient of (12–13) × $10^{-6}K^{-1}$ as compared with that (15–17) × $10^{-6}K^{-1}$ of chromium-nickel stainless steels. These thermo-physical properties are of great importance for evaluation of thermal stresses in reactor vessel [47].

6.3.1.1. Pearlitic steels

Pearlitic steels are characterized by good processing properties. Corrosion products of these steels contain no Co impurities, the presence of which deteriorates the radiation environment as a result of the formation of the isotope ^{60}Co with a half-life of 5.26 years.

The main disadvantage of pearlitic steels is their poor resistance to oxidation in air at the low chromium content (≤1%). Heat resistance of these steels increases by their alloying with molybdenum and vanadium (12KhM1F). In the course of cooling in air, pearlitic steels with the content of 2–2.5% Cr and 1% Mo gain susceptibility to formation of brittle structure that results in difficulties during manufacture operations such as deformation, welding and others. These disadvantages are eliminated by steel alloying with niobium.

Steels of type12Kh2MFB and similar ones have high plastic properties. They are well welded between each other and with other steels. These steels are designated for continuous operation (pipelines, superheaters, collectors). The specific heat capacity of pearlitic steels of two types is determined from the following correlations [50, 51]:

for steel type 15Kh2NMfA

$$C_p\ [J/(kg{\cdot}K)] = 482.2 - 0.2979T + 0.7404 \times 10^{-3}\ T^2, \quad (6.23)$$

for steel type 10GN2MFA

$$C_p\ [J/(kg{\cdot}K)] = 536.3 - 0.5290T + 0.9614 \times 10^{-3}\ T^2. \quad (6.24)$$

Thermophysical properties of some pearlitic steels are given in Table 6.13.

TABLE 6.13. THERMOPHYSICAL PROPERTIES OF SOME PEARLITIC STEELS

Temp.		Steels	15Kh2NMFA 15Kh2MFA 15Kh3NMFA 25Kh3MFA			Steel 10GN2MFA	
°C	K	Heat capacity J/(kg·K) [12]	Thermal conductivity W/(m·K) [11]	Thermal diffusivity $10^6(m^2/s)$ [11]	Linear expansion coefficient $10^6(1/K)$ [11]	Heat capacity J/(kg·K) [12]	Thermal diffusivity $10^6(m^2/s)$ [13]
20	293	458	(55)	12.4	11.2	466	14.3
100	373	474	(52)	11.4	11.9	476	13.2
200	473	507	47.3	10.1	12.5	505	11.9
300	573	555	41.9	8.85	13.15	553	10.5
400	673	617	37.6	7.57	13.5	621	9.17
500	773	694	38.2	6.28	14.0	708	7.87
600	873	786	30.7	5.05	14.4	814	6.43
700	973	893	28.0	3.80	14.8	940	4.81
800	1073	1015	25.8	4.00	15.2	1084	5.0
900	1173	1152	24.4	4.93	15.6	1248	6.1
1000	1273	1303	23.6	5.35	16.0	1431	6.73
1100	1373	1469	23.1	5.47	16.4	1633	7.5

6.3.1.2. Martensitic chromium steels

At the boron concentration of more than 2–3%, steels acquire the martensitic structure that causes problems in the course of manufacturing various components. In the case when the higher resistance to oxidation is required as compared with pearlitic steels, in particular for nuclear power engineering, martensitic chromium steels can be used to manufacture pipelines, superheaters, heat exchangers and accessories.

Steels with the Cr concentration of 14–16% are referred to the stainless class. They are used in the case when high corrosion resistance simultaneously with high oxidation resistance are desired. In nuclear power engineering, the chromium steels type Kh13 with the different content of carbon and alloying elements are used to manufacture pipelines, fastening elements and control mechanisms. The heat resistance of steels with the content of 13% Cr increases at their alloying by Mo, W and Nb. The chemical composition of the complex-alloyed stainless chromium steels is presented in Table 6.14 [47].

TABLE 6.14. CHEMICAL COMPOSITION OF COMPLEX-ALLOYED STAINLESS CHROMIUM STEELS [47]

Steel grade	Element content %						
	C	Cr	Mo	V	W	Nb	Other elements
0Kh13	≤ 0.08	11–13	–	–	–	–	–
1Kh13	0.09–0.15	12–14	–	–	–	–	–
2Kh13	0.16–0.24	12–14	–	–	–	–	–
1Kh11MF	0.12–0.19	10.0–11.5	0.6–0.8	0.25–0.40	–	–	–
1Kh12B2MF	0.10–0.17	11–13	0.6–0.9	0.15–0.30	1.7–2.2	–	–
1Kh12MVBF	~0.14	~11.6	~0.7	~0.42	~0.30	0.30	–
1Kh13M2BFR	0.12	13	1.5	0.20–0.30	-	0.4	B 0.004
1Kh12MV4B	~0.10	~12	~1	–	~4	0.8	–
2Kh11MFB	0.15–0.21	10.0–11.5	0.8–1.1	0.20–0.40	–	0.20–0.45	–
2Kh12VNMF	0.12–0.18	11.0–13.0	0.5–0.7	0.15–0.30	0.7–1.1	–	Ni0.4–0.8

With the use of chromium steels for nuclear power engineering, in particular in boiling reactors, their corrosion resistance, which depends on the Cr content, is to be taken into account. The corrosion resistance of low alloyed pearlitic steels and martensitic ones in water and steam at high temperature is distinctly lower than that of stainless steel with the high chromium content. This leads to the necessity of precautions, which have been taken to reduce depositions of corrosion products on heat-transfer surfaces and to improve the radiation environment. The corrosion rate of chromium steels in water with impurities increases at the presence of gaps, slits etc. In the case of the use of chromium-nickel steels in the circuit, the corrosion rate of chromium steels increases owing to the formation of galvanic couples.

In liquid sodium used as coolant, solubility of chromium steel components such as Fe, Cr, Nb, V and others is rather small and does not exceed thousandth percent. The oxygen impurity in sodium has a considerable effect on corrosion processes in it. Due to the effect of oxygen,

mass transfer is enhanced under non-isothermal conditions or at the presence of dissimilar materials in the circulation system. The contact of low alloyed pearlitic steels with sodium results in decarbonization of a surface layer of steels. At temperature of 600°C and the oxygen concentration of $\leq 5 \times 10^{-3}$%, steels with the Cr content of 12% are characterized by high corrosion resistance in the non-isothermal sodium flux. However owing to low heat resistance of chromium steels at temperatures above 600°C, they are not used widely.

6.3.1.3. Ferrite steels

Stainless high chromium steels of this class (15–30% Cr) have substantial oxidation resistance at high temperatures and high corrosion resistance in aggressive environments and atmosphere. They can be used for electrical resistance elements of heaters. Steels with the chromium content of 17% have low heat resistance, swell slightly under irradiation and have a tendency to grain growth and brittleness. Steels with the chromium content of 25–30% have high oxidation resistance. To reduce their tendency to grain growth, these steels are alloyed by such additives as Ti, Nb, Ta, N as well as silicon and aluminium (1–5%). These steels can be used in liquid metal circuits (Pb, PbBi). Thermophysical properties of some martensitic-ferrite chromium steels are presented in Table 6.15 [46].

TABLE 6.15. THERMOPHYSICAL PROPERTIES OF SOME MARTENSITIC-FERRITE CHROMIUM STEELS [46]

Temperature		Steels of types 08Kh13, 12Kh13 and 20Kh13				Steel type 16Kh12NMS (EP-823Sh)	
°C	K	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Linear expansion coefficient 10^6(1/K)	Electrical resistivity 10^8(Ω·m)	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6(m^2/s)
20	293	440	(22)	-	(180)	-	-
100	373	468	(23.2)	10.1	160	22.7	12.9
200	473	522	24.8	10.7	142	23.4	13.0
300	573	561	26.2	11.0	127	23.1	13.1
400	673	620	27.2	11.4	116	24.7	13.2
500	773	689	27.7	11.65	107	25.4	13.6
600	873	780	28.1	12.0	98	26.1	13.7
700	973	966	28.5	12.3	89	27.3	13.9
800	1073	-	(28.8)	(12.5)	80	-	14.1
900	1173	-	(29.2)	-	-	-	-
1000	1273	-	(29.5)	-	-	-	-

6.3.2. High temperature stainless chromium-nickel (austenitic) steels

These steels are basic structural materials for manufacturing NPP units (fuel element claddings, vessel internals, heat exchangers, pipelines, pumps and accessories). They can operate at 650–750°C, whereas the maximum operating temperature of chromium steels is 580–620°C. The composition of some stainless chromium-nickel steels is given in Table 6.16 [47]. The properties of some grades of austenitic steels are presented in Table 6.17 [49–51], Table 6.18 and Table 6.19 [46, 49, 50, 52], respectively.

Alloying chromium-nickel steels by molybdenum (content of 2–3%) increases their heat resistance and corrosion resistance in water and steam. Therefore, these steels are of great importance for nuclear power engineering. The operation experience of water cooled and liquid metal reactors indicates that at temperature <550°C the most widespread stainless austenitic steel type of 1Kh18N10T can provide safe operation of fuel element claddings. At higher operating temperatures, steels alloyed by Mo, Nb, W and other elements are to be applied. In this case, intermetallic compounds may occur in the steel structure that will serve to harden steels so called intermetallide hardening. Intermetallide hardening of chromium-nickel steels achieved by alloying with Ti (2.3%) and Al (1–3%) has found the most application. In particular, these steels have the high nickel content of 20–35%.

TABLE 6.16. COMPOSITION OF STAINLESS CHROMIUM-NICKEL STEELS [47]

Steel grade	Element concentration, %							Notes
	C	Cr	Ni	Ti	Nb	Mo	W	
0Kh18N10	≤0.08	18	10	-	-	-		Analog of steel type 304
0Kh18N10T	0.03–0.06	18	10	C 5(%)	-	-		Analog of steel 321
1Kh18N10T	≤0.12	18	10	0.5	-	-		-
0Kh18N12B	≤0.06	18	12	-	0.6	-		-
Kh18N12M2T	≤0.12	18	12	0.4	-	2.5		Analog of steel type 316 with titanium
Kh18N12M3	≤0.08	18	12	-	-	3.0		Analog of steel type 316
1Kh14N14V2M	≤0.15	14	14	-	-	0.5	2.4	-
0Kh16N15M3B	≤0.06	16	15	-	0.65	3.0	-	Analog of steel type 317 (EI-847)
0Kh16N15M3BR	≤0.06	16	15	-	0.75	2.7	-	B-0.07
4Kh14N14V2M	0.45	14	14	-	-	0.4	2.4	-
Kh15N35V3T3YuR	≤0.08	15	35	3.0	-	-	2.8	Al-1.2; B-0.005

TABLE 6.17. PROPERTIES OF AUSTENITIC STEEL TYPE 08Kh18N10T [49–51]

Temperature		Density	Heat capacity	Thermal conductivity	Thermal diffusivity	Linear expansion coefficient
°C	K	kg/m^3	J/(kg·K)	W/(m·K)	10^6(m^2/s)	10^6(1/K)
20	293	7900	478	16.6	4.4	15.8
100	373	7862	495	17.2	4.42	16.2
200	473	7821	516	18.0	4.45	16.7
300	573	7778	537	18.7	4.47	17.2
400	673	7732	558	19.4	4.50	17.7
500	773	7684	579	20.1	4.51	18.2
600	873	7634	600	20.8	4.53	18.7
700	973	7582	622	22.2	4.70	19.2
800	1073	7527	643	23.4	4.83	19.7
900	1173	7470	664	24.8	5.00	20.2
1000	1273	7411	685	26.1	5.15	20.7
1100	1373	7349	706	27.5	5.30	21.1
1200	1473	7285	727	28.9	5.45	21.6

TABLE 6.18. PROPERTIES OF AUSTENITIC STEELS OF TYPES 12KH18N9T AND 12 Kh 18N10T [46, 49, 50, 52]

Temperature		Heat capacity	Thermal conductivity	Linear expansion coefficient	Electrical resistivity
°C	K	J/(kg·K)	W/(m·K)	10^6(1/K)	10^8(Ω·m)
20	293	468	(15.1)	-	75-
100	373	486	16.3	16.1	80
200	473	510	17.6	17.0	87
300	573	531	18.9	17.4	94
400	673	553	20.5	17.8	99
500	773	574	21.8	18.2	105
600	873	594	23.5	18.6	109
700	973	614	24.7	19.1	114
800	1073	634	26.4	19.4	-
900	1173	655	28.5	-	-
1000	1273	676	(31.1)	-	-

TABLE 6.19. PROPERTIES OF AUSTENITIC STEEL 12X18H9 [46, 49, 50, 52]

Temperature		Heat capacity	Thermal conductivity	Linear Expansion coefficient	Electrical resistivity
K	°C	J/(kg·K)	W/(m·K)	10^6(1/K)	10^8(Ω·m)
20	293	512	15.9	(15.2)	71
100	373	529	16.3	16.0	74
200	473	546	18.0	17.0	82
300	573	567	18.9	17.5	89
400	673	592	20.1	17.9	95
500	773	630	21.4	18.5	100
600	873	638	23.9	18.6	105
700	973	642	25.6	18.9	109
800	1073	646	26.8	19.1	-
900	1173	651	27.4	19.3	-
1000	1273	-	28.1	19.5	-

Molybdenum and vanadium are the basic alloying elements, which add to austenitic steels to increase their high temperature resistance that is defined, primarily, by the enhancement of strength of interatomic bonds.

Under radiation of austenitic steels with neutrons at temperatures of 100–400°C, the increase of strength and yield point as well as the decrease of plasticity is taken place. Within the temperature range from 625 to 650°C, these effects do not appear that is caused by annealing radiation defects. At neutron fluence of 10^{23} n/cm^2, swelling of chromium-nickel steels is observed that is manifested as the change of component shape and sizes, structure and mechanical properties. Each atom of material undergoes up to 50 and more displacements at fluence of 2×10^{23} n/cm^2 that presents a complicated problem. The value of radiation damage depends heavily on alloying. For example, swelling of fuel element claddings from steel alloyed by molybdenum (type 0Kh18N12M2-3) is reduced by 2 times as compared with those from steel type 0Kh18N10. Adding of such elements as chromium and nickel has an opposite effect. In austenitic steels, corrosion cracking may take place, which can result in the restriction of their efficiency. Over a short time period, the metal, which is not affected by total corrosion, is attacked by through cracks, and its failure happens unexpectedly with no preliminary visible changes. The service experience of water cooled NPP shows that the most often failure units are steam generators, heat exchangers and fuel element claddings of boiling reactors. In most cases, failure is caused by combined effect of two factors such as inobservance of water regime norms, e.g. the increase of content of chlorides and oxygen in water, and action of tensile stresses.

Corrosion cracking of austenitic steels can take place in the presence of oxygen in water steam (saturated, superheated, as well as at supercritical parameters). The protection against such type of cracking is based on depressing of factors, which effect on this process (see above). Moreover, another dangerous type of corrosion is known such as intercrystalline (intergranular) corrosion (ICC). In this case, the boundaries of metal grains are subject to selective fracture in water and steam. The higher is the carbon content in steel, the more it is subject to ICC due to the formation of chromium carbides at grain boundaries. The ICC phenomenon is prevented by alloying steel with titanium and niobium. The content of titanium and niobium is to be of 5 and 8% respectively, whereas the content of carbon is of 0.01%. The steels alloyed by titanium (type of 1Kh18NH10T and others) are widely used.

6.3.2.1. Austenitic stainless steel type 316

Austenitic stainless steel type 316 is an analogue of Russian steel type Kh18N12M3. This steel is characterized by the following composition (%): C – 0.08, Cr – (16–18), Ni - (10-14), Mn – ≤2, Mo – (2–3), Si – ≤1.0, P – <0.045, S – <0.03. Basic properties of steel type 316 are as follows [43]:

Molecular mass	55.9354
Melting point	1430°C (1703 K)
Boiling point	2817°C (3090 K)
Heat of vapourization	7450 kJ/kg
Heat of fusion	270.0 kJ/kg
Volume increase at melting	3.86%
Critical constants	$P_c = 456.7$ MPa
	$T_c = 9600$ K
	$\rho_c = 1143$ kg/m^3

6.3.2.2. Properties of austenite stainless steel type 316 in solid state depending on temperature

Density

$$\rho\ (\mathrm{kg/m^3}) = 8084 - 0.4209\ T - 3.894 \times 10^{-5}\ T^2\ . \qquad (6.25)$$

Heat capacity

$$C_p\ [\mathrm{J/(kg{\cdot}K)}] = 462 + 0.134\ T. \qquad (6.26)$$

Thermal conductivity

$$\lambda\ [\mathrm{W/(m{\cdot}K)}] = 9.248 + 0.01571\ T. \qquad (6.27)$$

Linear expansion coefficient

$$\alpha\ 10^6\ (1/\mathrm{K}) = 17.89 + 2.398 \times 10^{-3}\ T + 3.269 \times 10^{-7}\ T^2. \qquad (6.28)$$

Thermal diffusivity 10^{-6} m^2/s is defined as $a = \lambda / C_p \rho$.

The properties of austenitic stainless steel type 316 in solid state calculated by correlations (6.25–6.28) are presented in Table 6.20.

TABLE 6.20. PROPERTIES OF AUSTENITIC STAINLESS STEEL TYPE 316 IN SOLID STATE BY EQS (6.25–6.28)

Temperature K	Density kg/m^3	Heat capacity J/(kg·K)	Thermal conductivity W/(m·K)	Thermal diffusivity $10^6(m^2/s)$	Linear expansion coefficient $10^6(1/K)$
300	7954	502	14.0	3.5	18.6
400	7909	516	15.5	3.8	18.9
500	7864	529	17.1	4.1	19.2
600	7817	542	18.7	4.4	19.4
700	7770	556	20.2	4.7	19.7
800	7722	569	21.8	5.0	20.0
900	7674	583	23.4	5.2	20.3
1000	7624	596	25.0	5.5	20.6
1100	7574	609	26.5	5.7	20.9
1200	7523	623	28.1	6.0	21.2
1300	7471	636	29.7	6.2	21.6
1400	7418	650	31.2	6.5	21.9
1500	7365	663	32.8	6.7	22.2
1600	7311	676	34.4	7.0	22.6
1700	7256	690	35.9	7.2	22.9

6.3.2.3. Properties of austenite stainless steel type 316 in liquid state depending on temperature

Density

$$\rho\ (kg/m^3) = 7433 + 0.0393\ T - 1.801 \times 10^{-4}\ T^2. \qquad (6.29)$$

Heat capacity C_p = 775 J/(kg· K).

Thermal conductivity [43]

$$\lambda\ [W/m \cdot K] = 12.41 + 0.003279T. \qquad (6.30)$$

Thermal diffusivity in 10^{-6} m^2/s is defined as $a = \lambda / C_p\rho$.

Linear thermal expansion coefficient

$$\alpha \cdot 10^6\ (1/K) = 18.64 + 3.917 \times 10^{-4}\ T + 2.833 \times 10^{-6}\ T^2. \qquad (6.31)$$

Dynamic viscosity

$$\lg \mu (mPa \cdot s) = \frac{2385.2}{T} - 3.5958 \qquad . \qquad (6.32)$$

Vapour pressure above liquid steel type 316 is determined as,

$$\lg P(Pa) = 11.1183 - \frac{18868}{T}, \qquad (6.33)$$

or to an accuracy of ± 30%,

$$\lg P(Pa) = 23.47496 - \frac{22027.61}{T} + 67.2678 \times 10^{-6} T - 1.4359 \ln T . \quad (6.34)$$

The properties of austenitic stainless steel type 316 in liquid state in the temperature range from 1750 to 5000 K calculated by Eqs (6.29–6.34) are shown in Table 6.21 [43, 44].

TABLE 6.21. PROPERTIES OF AUSTENITIC STAINLESS STEEL TYPE 316 IN LIQUID STATE BY EQS (6.29–6.34)

Temperature K	Density kg/m^3	Thermal conductivity W/(m·K)	Thermal diffusivity 10^6(m^2/s)	Linear Expansion coefficient 10^6(1/K)	Dynamic viscosity mPa s	Pressure Pa
1750	6950	18.1	3.4	1.86	5.9	2.2
2000	6790	19.0	3.6	1.87 × 10	4.0	4.8
2250	6610	19.8	3.9	1.97 × 10	2.9	5.4×10^2
2500	6410	20.6	4.2	5.94 × 10	2.3	3.7×10^3
2750	6180	21.4	4.5	9.52×10^2	1.9	1.8×10^4
3000	5930	22.2	4.8	1.29×10^4	1.6	6.7×10^4
3250	5660	23.1	5.3	1.2×10^5	1.4	2.1×10^5
3500	5360	23.9	5.8	8.1×10^5	1.2	5.3×10^5
3750	5050	24.7	6.3	4.2×10^6	1.1	1.2×10^6
4000	4710	25.5	7.0	1.8×10^7	1.0	2.5×10^6
4250	4350	26.3	7.8	6.5×10^7	0.92	4.8×10^6
4500	3960	27.2	8.8	2.0×10^8	0.86	8.4×10^6
4750	3560	28.0	10.1	5.6×10^8	0.81	1.4×10^7
5000	3130	28.8	11.9	1.4×10^9	0.76	2.2×10^7

6.4. NICKEL BASED ALLOYS

These alloys are promising for fuel element claddings of reactors with supercritical steam parameters at pressure of 23–25 MPa and temperature up to 600°C. They are also used for control rod channels. The main advantage of nickel based alloys is high heat resistance properties. However at radiation, their heat resistance is decreased. The operating temperature of nickel based alloys can be within the range of 800–850°C instead of that 650–750°C for austenitic steels. The properties of some nickel based alloys are given in Table 6.22 [56–58]. The basic alloying elements of such alloys are Cr, Al and Ti (see Table 6.23).

TABLE 6.22. PROPERTIES OF SOME NICKEL BASED ALLOYS [1–3]

Property	Steel grade			
	Kh18N12	Kh20N80	KhN77TYu	Kh15N60M20V5
Linear expansion coefficient, α 10^6 (1/K) in the range of 20–800°C	20	15.8	15.1	15.2
Thermal conductivity, λ, W/(m·K)				
at 100°C	16.3	11.3	10.5	9.2
at 500°C	21.0	19.3	17.6	18.0
at 700°C	26.0	25.2	24.2	-
Electrical resistivity, ρ_e,·10^6 (Ω·m)	70	126	135	140

TABLE 6.23. COMPOSITION OF NICKEL BASED ALLOYS [63, 71]

Steel type	Element content %									
	C	Ni	Cr	Ti	Al (Mn)	Fe	Mo	W	Ce	Nb	Others
Kh20N80 (nichromium)	≤0.15	77	20	-	≤ 0.2	basis	-	-	-	-	-
Kh15N60	≤0.15	58	16	-	≤ 0.2	basis	-	-	-	-	-
KhN77TYu	≤0.06	basis	21	2.5	0.75	≤ 1.0	-	-	≤0.01	-	-
KhN77TYuR	≤0.07	basis	21	2.6	0.8	≤ 1.0	-	-	≤0.01	-	Be ≤ 0.01
KhH75VMFYu	≤0.12	75	10	-	4.3	≤ 5.0	~5.7	~5.0	-	-	B – 0.01–0.02 V~0.7
KhN70VMTYu	≤0.12	basis	15	2.1	2	≤ 5.0	~5	~6	≤0.02		V~0.3
KhN80TBYu	0.08	basis	16	2.1	0.8	≤ 3.0	-	-	-	~1.25	-
KhN82TYuMB	0.10	basis	9	3	1.8	≤ 3.0	~2.3	-	-	~1.8	-
Hastalloy C	≤0.12	basis	16	-	-	6	~1.6	~4.5	-	-	-
Hastalloy X	≤0.15	45	22	-	-	20	9	0.6	-	-	-
Incoloy 800	0.04	32	20.5	-	Mn-0.75	46	-	-	-		Si-0.35 Cu-0.30
Inconel 600	0.15	basis	17	-	Mn-1.0	10	-	-	-		Si-0.5
Inconel X 750	0.08	basis	17	2.75	Al-1 Mn-1.0	9	-	-	-	1.2	Si-0.5
Inconel 718	0.10	55	21	1.15	Al-0.8 Mn-0.35	12.5	3.3	-	-	5.5	Si-0.35
Inconel 625	0.10	basis	23	0.4	Al-0.4 Mn-0.5	5	-	-	-	4.15	Si-0.5

6.5. REFRACTORY METALS

Metals with melting point ranging in 2400–3400°C and higher, e.g. V, Nb, Ta, Cr, Mo and W, are considered as refractory ones. The maximum values of operating temperatures of these metals are about 0.5 of t_{melt}, (°C). Niobium and its alloys are the most promising for the use in NPP due to beneficial combination of heat resistance, and corrosion properties, nuclear characteristics and processing properties. They can be used for manufacturing fuel element claddings, tubes, pump components and other elements of NPP circuits with liquid metal (Na, K, NaK alloys at 1000–1100°C) as well as for superheaters of water cooled NPP [72].

The composition of niobium and molybdenum alloys is presented in Table 6.24. The general physical properties of refractory materials are shown in Table 6.25 [60, 71].

6.6. SHIELDING MATERIALS

The radiation shielding is provided by surrounding the radiation source with walls or layers from radiation absorbing materials. There are three types of radiation:

1) heavy ionized particles (α particles, protons, debris);
2) β particles (positive or negative charged electron);
3) γ particles and neutrons.

The protection against the first two types of radiation produces no problems, because the free-path length of α, β particles is not too large. However, β particles in the course of absorption produce secondary (deceleration) radiation in the form of γ quanta with an energy of 0.5 MeV and X ray radiation. The shielding material is to have high moderating efficiency (i.e. involve light elements), the high neutron absorption cross section, the high scattering and absorption cross sections of γ quanta. The mixtures of substances with low atomic mass and heavy metals possess the best properties of protection against gamma- and neutron radiations. They provide efficient moderating and absorption of radiation. However, such protection is less economical and used only in research type and other reactors [63, 70].

Water, concretes and heavy elements are the widespread shielding materials.

Concrete shielding is considerably cheaper than others and presents a mixture of elements with low and mean atomic mass. It is believed that ordinary concrete (a mixture of sand, gravel, Portland cement and water) is most economical to use for shielding. To give it necessary properties, the additions are used such as barium sulphate, limonite, metal scrap, etc. In concrete, water is contained in the following three forms:

1) In bound state with other compounds,
2) As adsorbed on surfaces of cement paste;
3) As moisture in concrete pores.

The shielding characteristics of concrete are improved by adding the substances, which heavily absorb neutrons, namely: boron-bearing compounds B_4C, $2CaO\cdot3B_2O_3\cdot H_2O$, limonite $2Fe_2O_3\cdot3H_2O$ as well as high density materials. The density of normal concrete containing ~10% water is about 2450 kg/m^3, heat capacity 840 J/(kg·K), thermal conductivity ~1.2–1.5 W/(m·K), thermal diffusivity (0.5-1.5) × 10^{-6} m^2/s.

Concrete performs two functions:
1) In the view of building material,
2) As radiation shielding material.

Concrete technology is a separate engineering field. Concretes consisting of various components allow the combination of material composition with regard to specific requirements. The properties of a number of shielding concretes applied for NPP are presented in Table 6.26 [69, 70].

TABLE 6.24. COMPOSITION OF NIOBIUM AND MOLYBDENUM ALLOYS [56, 64]

Alloy type	Element content %					
	Nb	Mo	Zr	W	C	Ti or others
VN-3	basis	4.6	1.4	-	0.12	-
VN-4	basis	6.0	0.72	-	0.1	0.03 Ce
D-43	basis	-	1.7	10	0.1	-
F-48	basis	5	1.0	10	0.1	-
VM-1	-	basis	0.08–0.25	≥ 0.6	≤ 0.01	to 0.4 Ti
VM-2	-	basis	0.25–0.40	≥ 0.2	≤ 0.02	to 0.2 Ti
TZM	-	basis	0.08	-	0.02	0.5 Ti
TZC	-	basis	0.15	-	0.15	1.25 Ti

Alloys of types VN-3, VN-4, VM-1, VM-2 — for temperatures of 1250–1500°C (Russian Federation);
Alloys of types D-43, F-48, TZM, TZC — for temperatures of 1000–1300°C (USA).

TABLE 6.25. BASIC PHYSICAL PROPERTIES OF REFRACTORY METALS [60, 71]

Properties	Material					
	Vanadium V	Niobium Nb	Tantalum Ta	Chromium Cr	Molybdenum Mo	Tungsten W
Atomic number	23	41	73	24	42	74
Atomic mass, amu	50.942	92.906	180.95	51.996	95.94	183.85
Atomic volume, cm^3/mol	8.35	10.83	10.88	7.23	9.42	9.54
Concentration of nuclei, $10^{22}/cm^3$	0.722	0.555	0.552	0.833	0.641	0.632
Macroscopic capture cross section, $10^{-24} cm^2$						
for thermal neutrons	4.98	1.1	21.3	2.9	2.5	19.2
for fast neutrons (65 KeV)	0.03	0.135	0.44	0.0035	0.069	0.19
Melting point, °C	1890	2477	3017	1907	2623	3422
Density, kg/m^3	6110	8570	16400	7150	10220	19300
Heat capacity, J/(kg K)	0.422	0.265	0.140	0.450	0.250	0.132
Thermal conductivity, W/(m K)	33	54	57–63	67–94	138	170
Linear expansion coefficient, 10^{-6} 1/K	8.3	7.3	6.3	4.9–7.5	4.8–5.2	4.3–4.6
Electrical resistivity, 10^{-8} Ω·m	18.2–22	12.5–16	12.5–15	12.9–15	5–5.7	4.9–5.65

TABLE 6.26. PROPERTIES OF SHIELDING CONCRETES USED FOR NPP (WEIGHT COMPOSITION, %) [69, 70]

Concrete type	Cement grade	Aggregates		Admixes	Density kg/m^3	Relaxation distance, cm		Neutron removal cross section Σ, cm^{-1}	Maximum operating temperature °C
		Fine	Coarse			Neutrons	γ radiation		
Heavy	M-500; 7.5	Steel shot 37.5	Scrap metal 52.5	Water 2.5	6000	8.1	8.7	0.15	350
Serpentinite	M-400; 15.8	Serpentinite 29.7	Serpentinite 45.6	Water 8.9	2300	9.9	15.2	0.09	300–400
Iron-serpentinite	M-400; 11.8	Metal 50.8	Serpentinite 29.6	Water 6.6 B_4C 1.5	3550	8.4	9.3	0.108	400–450

Water has good protection properties owing to a high concentration of hydrogen nuclei. Hydrogen may be introduced in the shielding as water, paraffin wax, polyethylene, plastic materials, and metal hydrides. Concrete contains considerable amount of hydrogen in the form of bound and free water.

Polyethylene is a good material for protection against neutrons. It is odor free, not toxic, does not interact with acids, alkalis, oils and most spirits. However, it has low radiation resistance and is fire dangerous. At temperatures of 104–116°C, polyethylene softens, thus it is used at temperatures below 100°C.

For protection against neutrons, boron-bearing materials are used such as boron carbides, boron-bearing steels, Boral (a mixture of 10–50% boron carbide and aluminium powder coated with aluminium plates and hot rolled).

In a number of reactors lithium hydride, boron carbide or mixtures of boron carbide with aluminium are used as neutron shielding materials. Lithium hydride is not stable at high temperatures, at ~700°C it melts and dissociates into hydrogen and lithium [64].

To attenuate γ-radiation, a layer from materials such as lead, molybdenum, tungsten, uranium and others is added to neutron shielding.

REFERENCES TO SECTION 6

1. Zinoviev V.E. Thermophysical Properties of Metals at High Temperatures/Reference edition. – M.: Metallurgiya. 1989 (Russian).
2. Transport Properties of Metallic and Slag Melts/Handbook. Ed. by Acad. N.A. Vatolin. – M.: Metallurgia, 1995 (Russian).
3. Heat Power Engineering and Heat Engineering. General Problems/Reference book Ed. by A.V. Klimenko, V.M. Zorin. 3rd rev. and enl. ed. –. M.: MEI Press. 2001, Book 1 (Russian).
4. Walter A. and Reynolds A. Fast Breeder Reactors/Translated from English. – M.: Energoatomizdat. 1986 (Russian).
5. Morita K., Fisher E.A., Thurnay K. Thermodynamic Properties and EOS for Fast Reactor Safety Analysis. Pt. II. Properties of Fast Reactor Materials. – *Nuclear Engineering and Design*, 1998, Vol. 183. PP. 193–211.

6. Ubbelohde A.R. Molten State of Matter/Ed. by Yu.N. Taran. Translated from English (New York: Wiley, 1978). – M.: Metallurgiya, 1982 (Russian).
7. Fortov V.E., Dremin A.N., Leontiev A.A. The Estimation of Parameters of Critical Point. — *Teplofizika Vysokikh Temperatur*, 1975, Vol. 13, No. 5. PP. 1072–1080 (Russian).
8. Nizhenko V.I., Floka L.I. Surface Tension of Liquid Metals and Alloys/Handbook. — M.: Metallurgiya, 1981 (Russian).
9. Arsentiev P.P., Koledov L.A. Metallic Melts and their Properties. — M.: Metallurgiya, 1976 (Russian).
10. Thermal Conductivity of Solids/Reference book. Ed. by A.S. Okhotin. – M.: Energoatomizdat. 1984 (Russian)
11. Smithells C.J. Metal Reference Book/Ed. by S.G. Glazunov. Translated from English (5th ed. London: Publ. Butterworth and Co. Ltd., 1976). – M.: Metallurgiya. 1980 (Russian).
12. System of Steel Designation in Russia and Other Countries of CIS. — http://www.metaldata.info (Russian).
13. Rumiantsev V.N., Popov V.V., Troianov V.M., Efanov A.D. The Determination of Thermophysical and Physical parameters/In collection: Problems of Core Confinement in Reactor Vessel. — Obninsk: SSC RF-IPPE, 1994, PP. 74–75 (Russian).
14. Properties of Metals. –http://www.efunda.com/materials/
15. Larikov L.N., Yurchenko Yu.F. Thermal Properties of Metals and Alloys. — Kiev: Naukova Dumka, 1985 (Russian).
16. Dollezhal N.A., Emelianov I.Ya. Channel Nuclear Power Reactor. – M.: Atomizdat, 1980 (Russian)
17. Samoilov A.G. Fuel Elements of Nuclear Reactors. – M.: Energoatomizdat, 1985 (Russian).
18. Gromova A.I., Gerasimov V.V., Kabankova N.A., Shutko I.G., Volkhonsky E.V. Corrosion and Electrochemical Behavior of Zirconium Alloy with 2.5% Nb in Water and Steam at High Temperature. — *Atomnaia Energiya*, 1970, Vol. 29, No. 5, PP. 364–365 (Russian).
19. Properties of Metals. The Online Materials Database. – http://www.matweb.com/
20. Enthalpy and Heat Capacity of Solid Zirconium. Preliminary Recommendation. – http://www.insc.anl.gov/matprop/zirconium/
21. Korobenko V.N., Savvatimsky A.I. Temperature Dependence of Density and Electrical Resistance of Liquid Zirconium up to 4100 K. – *Teplofizika Vysokikh Temperatur*, 2001, Vol. 39, No. 4, PP. 566–572 (Russian).
22. Korobenko V.N., Savvatimsky A.I. Specific Heat Capacity of Liquid Zirconium up to 4100 K. – *Teplofizika Vysokikh Temperatur*, 2001, Vol. 39, No. 5, PP. 712–719 (Russian).
23. Korobenko V.N., Savvatimsky A.I. Properties of Liquid Zirconium up to 4100 K. – *Zhurnal Fizicheskoy Khimii*, 2003, Vol. 77, No. 10, PP. 1742–1747 (Russian).
24. Postovalov V.G., Romanov E.P., Kondratiev V.P., Kononenko V.I. Theory of Transfer in Liquid Metals. Calculation of Dynamic Viscosity. — *Teplofizika Vysokikh Temperatur*, 2003, Vol. 41, No. 6, PP. 860–869 (Russian).
25. Peletsky V.E., Grischuk A.P., Musaeva Z.A. Experimental Investigation of Transport Properties of Zirconium. – *Teplofizika Vysokikh Temperatur*, 1992, Vol. 30, No. 6, PP. 1090–1093 (Russian).
26. Liusternik V.U., Peletsky V.E., Petrova I.I. — *High Temperature–High Pressure*, 1993, Vol. 25, PP. 539–543.

27. Liusternik V.U., Peletsky V.E., Petrova I.I. Experimental Investigation of Calorimetric Properties of Reactor Materials Based on Zirconium Alloy E-110. – *Teplofizika Vysokikh Temperatur*, 1993, Vol. 31, No. 4, PP. 560–564 (Russian).
28. Korostin O.S., Nikulina A.V., Peletsky V.E., Petrova I.I., Popov N.N., Samsonov V.N. Experimental Investigations of the Properties of Zr-1% Nb Alloy. – *Teplofizika Vysokikh Temperatur*, 1998, Vol. 36, No. 2, PP. 223–226 (Russian).
29. Prasolov P.E., Shestak V.E., Platonov P.A., Chugunov O.K., Viktorov V.K. Anisotropy of Deformation Constants and Thermal Expansion Coefficients of Zr-1% Nb and Zr–2.5% Nb Alloys. – *Atomnaia Energiya*, 1990, Vol. 68, No. 2, PP. 98–101 (Russian).
30. Petrova I.I., Peletsky V.E. Spectral (λ=0.65 mm) Radiation of Zr-1% Nb Alloy at Solidus Temperature. – *Teplofizika Vysokikh Temperatur*, 1995, Vol. 33, No. 5, PP. 710–714 (Russian).
31. Thermophysical Properties of Materials for Water Cooled Reactors/IAEA-TECDOC-949. – Vienna: IAEA, 1997.
32. Ursu I. Fizica si Tehnologia Materialelar Nucleare, Publ. Acad. Romania, Bucuresti, 1982.
33. Structural Materials of Nuclear Reactors/Ed. by N.M. Beskorovainy. Two Parts. – M.: Atomizdat, 1977 (Russian).
34. Zaimovsky A.E., Nikulina A.V., Reshentnikov N.G. Zirconium Alloys in Nuclear Power Engineering. – M.: Energoatomizdat, 1994 (Russian).
35. Handbook on Nuclear Power Technology./Translated from English. Ed. by V.A. Legasov [A Guide to Nuclear Power Technology/Ed. By F.J. Rahn et al. –New York: A Wiley-Interscience Publ., 1984]. – M.: Energoatomizdat, 1989 (Russian).
36. Emsley J. The Elements, 2-ed., Publ. Clarendon Press, Oxford, 1991.
37. Peletsky V.E., Petrova I.I., . Samsonov B.N, Nikulina A.V. Experimental Investigation of Thermophysical Properties of Alloy E6-35 at High Temperatures/*Proc. of Inter. Conf.: Thermophysical Aspects of WWER Safety*. Ed. by A.D. Efanov. – Obninsk.: SSC RF-IPPE. 1994, Vol. 2, PP. 162–170 (Russian).
38. Kobylyansky G.P., Novoselov A.E. Radiation Stability of Zirconium and Zirconium-Based Alloys (Reference Information on Radiation Matter Science)./Ed. by V.A. Tsykanov. – Dimitrovgrad.: SSC RF — NIIAR. 1996, 176 PP (Russian).
39. Mechanic Engineering. Encyclopedia in 40 volumes. Vol. 1–2. – M.: Mashinostroenie, 1999 (Russian).
40. Structural Materials/Handbook. Ed. by B.N. Arzamasov, V.O. Brostrem, N.A. Bushe et al. – M.: Mashinostroenie, 1990 (Russian).
41. Grades of Steels and Alloys/V.G. Sorokin, A.V. Volosnikova, S.A. Vyatkin et al. Ed. by V.G. Sorokin. – M.: Mashinostroenie, 1990 (Russian).
42. Ostrovsky O.I., Grigoryan V.A., Vishkarev A.F. Properties of Molten Metals. – M.: Metallurgiya, 1988 (Russian).
43. Walter A. and Reynolds A. Fast Breeder Reactors/Translated from English. – M.: Energoatomizdat. 1986 (Russian).
44. Morita K., Fisher E.A., Thurnay K. Thermodynamic Properties and EOS for Fast Reactor Safety Analysis. Pt. II. Properties of Fast Reactor Materials. – *Nuclear Engineering and Design*, 1998, Vol. 183. PP. 193–211.
45. Samoilov A.G. Fuel Elements of Nuclear Reactors. – M.: Energoatomizdat, 1985 (Russian).
46. Ulianin E.A. Corrosion Steels and Alloys. Handbook. – M.: Metallurgiya, 1980 (Russian).

47. Structural Materials of Nuclear Reactors/Ed. by N.M. Beskorovainy. Two Parts. – M.: Atomizdat, 1977 (Russian).
48. Transport Properties of Metallic and Slag Melts. Handbook/Ed. by Acad. N.A. Vatolin. – M.: Metallurgiya, 1995 (Russian).
49. Rumiantsev V.N., Popov V.V., Troianov V.M., Efanov A.D. The Determination of Thermophysical and Physical parameters/In collection: Problems of Core Confinement in Reactor Vessel. — Obninsk: SSC RF-IPPE, 1994, PP. 74–75 (Russian).
50. Roschupkin V.V., Fordeeva L.K. Specific Enthalpy and Heat Capacity of Steels of Types 22K, 08Kh18N10T, 15Kh2NMFA, 10GN2MFA. – *Teplofizika Vysokikh Temperatur*, 1988, Vol. 26, No. 5, PP. 1016–1020 (Russian).
51. Roschupkin V.V., Chernov A.I., Pokrasin M.A., Kurichenko A.A., Ivliev A.D., Shitova A.S. Experimental Investigation of Heat Capacity and Enthalpy of Steels of Austenitic Class Type 12Kh18N9T and 12Kh18N10T in the Temperature Range of 300–1678 K. – *Teplofizika Vysokikh Temperatur*, 2001, Vol. 39, No. 3, PP. 450–459 (Russian).
52. Chekhovsky V.Ya., Tarasov V.D., Arseev I.V. Experimental Iinvestigation of thermal Diffusivity of Structural Steels in the Temperature Range of 700–1450 K.– *Teplofizika Vysokikh Temperatur*, 1988, Vol. 26, No. 2, PP. 396–397 (Russian).
53. The Same. – *Teplofizika Vysokikh Temperatur*, 1988, Vol. 26, No. 5, PP. 1016–1020 (Russian).
54. Design of Heat Exchangers for NPP/F.M. Mitenkov et al. – M.: Energoatomizdat, 1988 (Russian).
55. Thermal and Nuclear Power Plants/Handbook ed. by A.V. Klimenko and V.M. Zorin. – M.: MEI Press, 2003. Vol. 3 (Russian).
56. Structural Materials of Nuclear Reactors/Ed. by N.M. Beskorovainy. Two Parts. – M.: Atomizdat, 1977 (Russian).
57. Samoylov A.G., Kashtanov A.I., Volkov V.S. Dispersion Fuel Elements. In 2 volumes. Vol. 1. Materials and Technology. – M.: Energoizdat, 1982 (Russian).
58. Encyclopedia of Modern Technology. Structural Materials/Ed. by A.T. Tumanov. — M.: Sovetskaya. Entsiklopedia, 1964. Vol. 2 (Russian).
59. Mechanic Engineering. Encyclopedia in 40 volumes. Vol. 1–2. – M.: Mashinostroenie, 1999 (Russian).
60. Zinoviev V.E. Thermophysical Properties of Metals at High Temperatures/Reference edition. – M.: Metallurgiya. 1989 (Russian).
61. Ershov G.S., Cherniakov V.A. Structure and Properties of Liquid and Solid Metals. – M.: Metallurgiya, 1978 (Russian).
62. High-Temperature Inorganic Compounds/Collected book. Ed. by G.V. Samsonov. – Kiev: Naukova Dumka, 1965 (Russian).
63. Handbook on Nuclear Power Technology./Translated from English. Ed. by V.A. Legasov [A Guide to Nuclear Power Technology/Ed. By F.J. Rahn et al. –New York: A Wiley-Interscience Publ., 1984]. – M.: Energoatomizdat, 1989 (Russian).
64. Fundamentals of Theory, Design and Operation of Space NPP/A.A. Kulandin, S.V. Timashov, V.D. Atamanov et al. – L.: Energoatomizdat. 1987 (Russian).
65. Walter A. and Reynolds A. Fast Breeder Reactors/Translated from English. – M.: Energoatomizdat. 1986 (Russian).
66. Radiation protection at NPP/Ed. by A.P. Suvorov, S.G. Tsypin. – M.: Atomizdat. 1978 (Russian).
67. Biological Protection of Nuclear Reactors/Translated from English. – M.: Atomizdat. 1965 (Russian).

68. Komarovsky A.N. Construction of Nuclear Installations. – M.: Atomizdat. 1965 (Russian).
69. Broder D.L., Zaitsev L.N., Komochkov M.M. Concretes for Protection of Nuclear Reactors. – M.: Atomizdat. 1966 (Russian).
70. Eger T. Concretes for Radiation Safety Engineering/Translated from German. – M.: Gosatomizdat, 1960 (Russian).
71. Thermal and Nuclear Power Plants/Handbook ed. by A.V. Klimenko and V.M. Zorin. – M.: MEI Press, 2003. Vol. 3 (Russian).
72. Materials Science of Liquid Metal Systems of Fusion-Type Eeactors/G.M. Graiznov et al. – M.: Energoatomizdat, 1989 (Russian).

Appendix 1

CONVERSION FACTORS OF SOME UNITS

Length	1 inch (in) = 0.0254 m 1 foot (ft) = 0.3048 m 1 yard (yd) = 0.9144 m 1 mile, statute = 1.609 km 1 mile, nautical = 1.852 km
Square	1 $in^2 = 6.4516 \times 10^{-4}\ m^2$ 1 $ft^2 = 9.2903 \times 10^{-2}\ m^2$
Volume	1 barrel = 0.159 m^3 1 gallon (UK) = $4.546 \times 10^{-3}\ m^3$ 1 gallon (US) = $3.785 \times 10^{-3}\ m^3$ 1 $in^3 = 1.6387 \times 10^{-5}\ m^3$ 1 $ft^3 = 2.832 \times 10^{-2}\ m^3$
Time	1 year = 3.1557×10^7 s 1 days = 86,400 s
Temperature	Rankine degree 1°Ra = 0.556 K Fahrenheit degree 1°F = 1.25 K Centigrade degree 1°C = 1 K
Velocity	1 mile/hour= 1.609 km/hr
Mass	1 atomic mass units = 1.66056×10^{-27} kg 1 pound (lb) = 0.4536 kg
Density	1 $g/ft^3 = 3.53 \times 10^{-2}\ kg/m^3$ 1 $lb/ft^3 = 16.02\ kg/m^3$
Force	1 dyne= 10^{-5} N 1 kg-force (kgf) = 9.80665 N 1 lb-force (lbf) = 4.448 N
Pressure	1 at = 9.80665 10^4 Pa ≈0.1 MPa 1 bar = 10^5 Pa 1 kgf/m^2 = 9.80665 Pa 1 mm H_20 = 9.80665 Pa 1 mm Hg = 133.3 Pa
Work, Energy	1 Whr = 3600 J 1 kWh = 3.6 10^6 J 1 hp-hr = 2.648 10^6 J 1 lb × ft = 1.3558 J 1 erg = 10^{-7} J 1 kgf × m = 9.80665 J 1 kcal = 4186.8 J 1 Btu = 1.05506 кJ
Power	1 cal/s = 4.1868 W 1 kgf × m/s = 9.80665 W 1 hp = 734.499 W 1 kcal/hr = 1.163 W 1 kW = 860 kcal/hr
Density of heat flux	1 kcal/(m^2hr) = 1.1628 W/m^2 1 Btu/(hrft^2) = 3.1534 W/m^2
Thermal conductivity	1 kcal/(hr × m × K) = 1.163 W/(m × K) 1 Btu/(s × ft × F) = 6.23×10^3 W/(m × K)
Dynamic viscosity	1 poise (P) = 0.1 Pa × s 1 kgf × s/m^2 = 9.8067 Pa × s
Kinematic viscosity	1 Stokes (St) = $10^{-4} \times m^2/s$

Appendix 2
GENERAL PLANT DATA OF WWER TYPE REACTORS
(Based on IAEA-TECDOC-861, Review of Design Approaches of Advanced Pressurized LWRs, IAEA, Vienna: 1996)

TECHNICAL DATA	Units	WWER-440 Russian Federation	WWER-1000 (V-392) Gidropress Russian Federation	VPBR-600 OKBM Russian Federation	EPR France, Germany	KNGR Korea, Rep. of	ABB CENP (System 80+) USA
Power plant output, gross	MW(e)	408	1000	630	1750	1300	1350
Reactor thermal output	MW	1375	3000	1800	4900	4000	3914
Power plant efficiency, net	%	29.7	30.7	35	35.7	32.5	34.5
Reactor Coolant System							
Number of coolant loops		6	4	4	4	2	2
Primary circuit volume, including pressurizer	m^3	-	-	-	380+75	448.40	454.7
Steam flow rate	kg/s	8290	18040	10140	22240	20891	20800
Reactor operating pressure	MPa	12.5	15.7	15.70	15.50	15.50	15.5
Coolant temperature at inlet/outlet to pressure vessel	^0C	269/300	293.9/323.3	294.8/325	292.5/330	291.1/323.9	291/323.9
Maximum coolant velocity in subassembly	m/c	4.6	6.5	-	-	-	-
Reactor Core							
Active core height	m	2.5	3.53	3.53	4.2	3.81	3.81
Equivalent core diameter	m	2.88	3.16	3.04	3.80	3.65	3.658
Heat transfer surface in the core	m^2	3150	4957	4465	7975.0	6359.0	6590.0
Average linear heat rate	kW/m	-	16.67	10.8	17.86	18.14	18.1
Average fuel power density	kW/kg U	-	45.81	32.9	-	-	34
Average core power density (volumetric)	kW/l	84	107.5	69.4	103.0	98.4	95.5
Heat flux F_q	kW/m^2	-	605.2	403.10	598.00	2.35	602.00
Fuel Pin Assembly							
Number of fuel assemblies		349	163	151	241	241	241
Weight and type of loaded fuel	t	42 UO_2	80 sintered UO_2	- sintered UO_2	124 sintered UO_2	- sintered UO_2	sintered UO_2 or PuO_2
Enrichment (range) of first core	wt. %	-	1.6/3/4.4	1.0/3.6/4.0/4.4	<=5.0	1.8/2.9/3.7	1.9/2.8/3.3

TECHNICAL DATA	**Units**	**WWER-440 Russian Federation**	**WWER-1000 (V-392) Gidropress Russian Federation**	**VPBR-600 OKBM Russian Federation**	**EPR France, Germany**	**KNGR Korea, Rep. of**	ABB CENP (System 80+) ***USA***
Enrichment of reloaded fuel at equilibrium core	wt.%	3.3	4.4	4.0/4.4		4.7	
Operating cycle length	months		12	18–24	18	18	18–24
Average discharge burnup of fuel	MW day/t	28600	43000	52000	65000	60000	31700
Type of fuel assembly		hexagonal, with cover	hexagonal, without cover	triangular	square 17x17	square 16x16	square 16x16
Fuel assembly total length	mm		4670	4800	4800.0	4127.5	4350
Overall weight of fuel assembly	kg	-	-	-		662.7	662.7
Active length of fuel pins	mm	-	3530	3530	4200	3810	3810
Number of fuel pins in assembly		126	311	287	264	236	236
Number of guide tubes for control rods		-	18/1	18	25	12 or 4 per assembly	5
Number of control rods			121	139	89	93	93
Number of spacers					9	11	11
Cladding tube material		Zr+1%Nb	Zr alloy	Zr-4	Zr-4	Zr-4	Zr-4
Cladding tube wall thickness	mm	0.60	0.61	0.65	0.625	0.635	0.635
Outer diameter of fuel pin	mm	9.1	9.1	9.1	9.5	9.7	9.7
Number of absorber rods		-	18	18	24	4 or 12	4 or 12
Reactor Pressure Vessel							
Inner diameter	mm	3560	4070	5440	4870	4630	4630
Wall thickness	mm	140	190	265	250+7.5	230	229
Total height	mm		19100	23960	13105	15280	15280
Vessel weight	t	500	850	-	-	-	-
Design pressure/temperature	MPa/^{0}C	-	17.65/350	18/350	17.6/351	17.2/343.3	17.2/343.3
Material of cylindrical shell		-	15Kh2 NMFA	15X2MPA steel	16MND5/20Mn MoNi55	low carbon steel SA 508 class 2 and 3	low carbon steel SA-509
Transport weight (lower part)	t	-	417	880	405	-	508
Transport weight (RPV head)	t	-	-	-	115.5	-	81.2

TECHNICAL DATA	Units	WWER-440 Russian Federation	WWER-1000 (V-392) Gidropress Russian Federation	VPBR-600 OKBM Russian Federation	EPR France, Germany	KNGR Korea, Rep. of	ABB CENP (System 80+) *USA*
Steam Generator							
Type		Horizontal U-tube	Horizontal U-tube	Once-through, vertical	U-tube heat exchanger	Vertical U-tube	Vertical U-tube with integral moisture separator and economizer
Number		-	4	1 in 12 sections	4	2	2
Heat transfer surface	m^2	2510	5130	13930	8171	-	14460
Number of heat exchanger tubes	-	-	9157	66400	5980	12580	12580
Tube dimensions (outer diameter/thickness)	mm	-	16/1.5	13.1/1.5	19/	19.05/1.07	/1.07
Steam flow rate at nominal conditions	kg/s	829	1633	950	2276	1079	2200
Steam temperature/pressure	^{0}C/MPa	-	/6.27	305/6.38	289/7.36	285/6.9	285/6.9
Feedwater temperature/pressure	^{0}C/MPa	-	220/	230/	230/7.36	232.2/	232/7.2
Maximum outer diameter	mm	-	4300	-	-	6172	5890
Total height	mm	-	9500	3800	-	22987	23000
Tube material	-	-	0Kh18N10T	titanium alloy	Incoloy 800 or Inconel 690	Inconel 690	SB 163 NiCr Fe alloy
Primary Containment							
Type and material	-	-	Dry, double containment: steel/reinforced concrete	Dry, single	Prestressed concrete	Prestressed reinforced concrete	Dry, double containment: steel sphere and containment of reinforced concrete
Overall form (spherical/cylindrical)	-	-	Cylindrical	Cylindrical (reinforced concrete)	Cylindrical	Cylindrical	Cylindrical

TECHNICAL DATA	Units	**WWER-440 Russian Federation**	**WWER-1000 (V-392) Gidropress Russian Federation**	**VPBR-600 OKBM Russian Federation**	**EPR France, Germany**	**KNGR Korea, Rep. of**	ABB CENP (System 80+) ***USA***
Dimensions (diameter/height)	m	-	53/61.6	40/36.51	1/	45.7/70	61
Free volume	m^3	-	7500	60000	80000	91180	96300
Design pressure/temperature (severe accident situations)	kPa/^{0}C		500/	200/	4	480/	365/143.3
Design leakage rate	vol.%/day	-	0.3	0.3	<1		<0.5
Turbine Plant							
Number of turbines per reactor		2	1	1	1	1	1
Type of turbines		-	-	condense K-600-5.9/500		in line 6 flow tandem	tandem-combined
Number of turbine sections per unit (e.g. HP/LP/LP): HP — high pressure, LP — low pressure		-	-	1 HP/2LP	1 HP/3LP	1 HP/3LP	1 HP/3LP
Turbine speed	rpm	-	-	3000	1500	1800	1800
HP section inlet pressure/temperature	MPa/^{0}C	4.41	6.0	-	-	6.9/285	7.2/287.8

Appendix 3
GENERAL PLANT DATA OF FAST REACTORS COOLED BY LIQUID METAL
(Sodium for all reactors except for BREST-OD-300 cooled by lead)

TECHNICAL DATA	Units	Experimental Reactors			Demonstration Reactors				Commercial Size Reactors			
		BR-10	BOR-60	CEFR	BN-350	BN-600	Monju	BREST	BN-800	BN-1600	SPX-1	EFR
General Data												
Thermal power	MW/th	8	50	65.5	750	1470	714	700	2100	4200	2990,0	3600
Electric power	MW(e)	8	12	23.4	130	600	280	300	800	1600	1242	1580
Type of primary circuit		loop	loop	pool	loop	pool	loop	pool	pool	pool	pool	pool
Coolant temperature in primary circuit at inlet to intermediate heat exchanger	°C	470	545	514	430	550	529	540	544	550	542	545
Coolant temperature in secondary circuit at inlet to steam generator	°C	380	480	495	415	520	505	420	505	515	521	525
Steam conditions (temperature/pressure)	°C/MPa	-	430/8	480/10	410/4.5	500/13.2	483/12.5	520/25.5	490/13.7	495/13.7	487/17.7	490/18.5
Core												
Equivalent diameter of outer core zone	mm	206	460	605,8	1580	2050	1800	2232	2560	4450	3700	4051
Height of fissile zone	mm	400	450	500	1000	1030	930	1100	880	780	1000	1000
Fuel		UN	PuO_2-UO_2	PuO_2-UO_2	UO_2	UO_2	PuO_2-UO_2	UN-PuN	PuO_2-UO_2			
Inner/outer core enrichment	%	90/	45–75/	49/	$17UO_2/16UO_2$	$17UO_2/16UO_2$	16/21	-	19.5/24.7	18.2/21.1	16/19.7	18.3/26.9
Fissile material content of a core U235/Pu239/	kg	113	95/53	97.6/93.2	1220/75	2020/110	13.5/870	-	30/1870	80/5400	142/4054	81
Total plutonium	kg	-	58	121.6	77	112	1400	2080	2710	7900	5780	8808
Core volume fractions averaged over whole core fuel sodium steel		0.445 0.287 0.218	0.48 0.29 0.23	0.381 0.397 0.207	0.380 0.33 0.22	0.375 0.34 0.215	0.335 0.400 0.245	-	0.340 0.390 0.220	0.415 0.306 0.229	0.37 0.34 0.24	0.361 0.329 0.235

TECHNICAL DATA	Units	Experimental Reactors			Demonstration Reactors				Commercial Size Reactors			
		BR-10	BOR-60	CEFR	BN-350	BN-600	Monju	BREST	BN-800	BN-1600	SPX-1	EFR
Power density (maximum/averaged over core)	kW/l fuel	2182/1588	1940/ 1615	1867/ 1132	1195/1155	1587/ 940	-	-	1796/ 1152	1130/ 670	1250/ 785	1100/ 670
Burnup	MW day/t max/ average	62300/ 45500	260000	62300/45500	97000/5800 0	97000/60000	-	up to 12%/6,6–8,8%	-	-	80000/50000	-
Neutron flux maximum average	$x10^{15}$ $n/cm^2.s$	0.86 0.63	3.5 2.5	2.97 1.76	5.4 3.5	6.5 4.3	6.0 3.6	-	8.8 5.6	5.5 -	6.1 3.6	5.3 3.5
Fuel Pin Assembly												
Number of subassemblies in inner/outer core		86–90/ 0	96–100/ 0	82/ 0	61/ 113	136/ 139	108/ 90	137/ -	211/ 198	258/ 216	193/ 171	207/ 72
Number of fuel pins per subassembly		7	37	61	127	127	217	160	127	331	271	331
Outer diameter/ thickness of fuel pin	mm	8.4/ 0.4	4.42/ 0.305	6.00/ 0.40	6.9/ 0.4	6.9/ 0.4	6.5/ 0.47	9.6 -	6.6/ 0.4	8.8/ 0.55	8.5/ 0.56	8.2/ 0.52
Overall length of fuel pin	mm	615	1100	1622	2445	2445	2800	-	2410	2500	2700	2645
Cladding material (steel)		Cr16Ni15 Mo3Nb	Cr16Ni15Mo3 Nb	316 Ti (20% CW)	Cr16Ni15M o2MnTiSi (CW)	Cr16Ni15Mo2 Mn TiSi (CW)	Steel Type 316	Stainless steel	Cr16Ni15Mo2Mn TiSi (CW)		Cr17Ni13Mo2 5Mn1.5TiSi	AIM1 or PE 16
Maximum linear power of fuel pins in core	kW/m	44	44	43	40	47	36	-	48	48,7	48	52
Maximum cladding surface temperature of core fuel pin	°C	565	710	620	600	695	675	-	693	675	620	635
Pressure of fission product gas in fuel pin at operating temperature and maximum burnup	MPa	5.0	4.0	3.46	4.4	5.0	6.9	-	5.0	-	4.0	6.2
Number of safety/control rods		2/ 2(Ni)	3/ 2	2/ 2	3/ 2	6/ 2	6/ 3	up to 40	12/ 2	12/ 2	24/ 21	- 5+12

TECHNICAL DATA	Units	Experimental Reactors			Demonstration Reactors				Commercial Size Reactors			
		BR-10	BOR-60	CEFR	BN-350	BN-600	Monju	BREST	BN-800	BN-1600	SPX-1	EFR
Heat Transport System												
Number of coolant loops primary secondary	pc.	2 2	2 2	2 2	6 6	3 3	3 3	4 -	3 3	3 6	4 4	3 6
Sodium inventory primary secondary	t	1.7 5	16 25	260 48,2	470 450	770 830	760 760	$740 m^3$ Pb	820 1025	2600 2700	3200 1500	2200 1300
Coolant flow rate (total) primary secondary	kg/s	48 50	270 220	396 274	3950 4400	6600 6090	4250 3090	$3.8 m^3/c$ -	8600 8400	19500 17800	15700 13100	19300 15300
Maximum coolant velocity in core	m/s	4.0	8.0	5.0	7.4	8.0	6.9	1.7	7.3	5.7	7.7	7.8
Coolant temperature in primary circuit hot leg cold leg	^0C	470 350	545 330	514 360	430 280	535 365	529 397	540 -	547 354	550 397	545 395	545 395
oolant temperature in primary circuit hot leg cold leg	^0C	380 270	480 210	495 310	415 260	510 315	505 325	-	505 309	515 345	525 345	525 345
Steam temperature at steam generator inlet/outlet	^0C	-	430 200	480 190	410 158	505 240	487 240	520 340	490 217	495 240	490 237	490 240
No. of steam generators per secondary circuit evaporators superheaters reheaters	pc.	-	1 1 0	1 1 0	2 2 0	8 8 8	1 1 0	-	10 10 0	2 - 0	1 - 0	1 - 0
Sodium temperature in steam generator at inlet/outlet to evaporator superheaters reheaters	^0C	-	- 300/450 -	-/463 310/495 463/-	391/260 417/319	449/328 518/449 518/449	469/325 505/469	-	451/309 505/451	-/345 515/-	345/ -/525	345/ -/525
Pressure of steam at the outlet of superheater	MPa	-	8.8	10.0	4.9	13.7	12.5	-	13.7	13.7	18.4	18.5

TECHNICAL DATA	Units	Experimental Reactors			Demonstration Reactors				Commercial Size Reactors			
		BR-10	BOR-60	CEFR	BN-350	BN-600	Monju	BREST	BN-800	BN-1600	SPX-1	EFR
Tube material: evaporator	-		2.25Cr1 Mo	9 Cr1 Mo	2.25Cr1 Mo	2.25Cr1 Mo	2.25Cr-1 Mo	9Cr1Mo (evap. and superh. in one unit)	10Cr2 Mo VNB	2.25Cr1 Mo	Ni33Cr21 TiAlMn	9 Cr1 Mo VNB
superheater			2.25Cr1 Mo and SS	9 Cr1 Mo	2.25Cr1 Mo	Cr18Ni19	austenitic steel		10Cr2 Mo VNB	2.25Cr1 Mo	-	9 Cr1 Mo VNB
Reactor Vessel												
Inside diameter	mm	338	1400	8800	6000	12860	7100	-	12900	17000	21000	17200
Wall thickness	mm	7	20	50	50	30	50	-	30	25	60	35
Total height	mm	4500	6200	8340	11900	12600	17800	-	14000	14000	17300	15900
Containment Building												
Material		-	rectangular (concrete)	cylindrical with dome (concrete & steel)	rectangular (concrete)	rectangular (concrete)	cylindrical with dome (carbon steel)	-	rectangular (concrete)	cylindrical building (concrete)	cylindrical with dome (concrete)	cylindrical (reinforced concrete)
Gross volume	m^3	-	-	17000	-	-	130000	-	-	-	6500	136000
Maximum design pressure	MPa	-	-	0.1	-	-	0.03	-	-	-	0.3	0.05

Bibliography

IAEA-TECDOC-1531, Fast reactor Database, IAEA, Vienna, 2006.

White Paper of Nuclear Power/Edited by Prof. E.O. Adamov. MINATOM of Russian Federation – M.: NIKIET Press, 2001.

Adamov E.O. et al. Conceptual Design of BREST-300 Lead cooled Fast Reactor.–Proc. of ARS'94 Topical Meeting, 17–21 April 1994, Pittsburg, USA. ANS, 1994, vol. 1 pp. 509–515.

Appendix 4

GENERAL PLANT DATA OF RBMK* TYPE REACTORS

TECHNICAL DATA	Units	RBMK-1000	RBMK-1500
Electric power	MW	2x500	2x750
Thermal power	MW	3200	4800
Overall Efficiency	-	31.3	31.3
Reactor Coolant System			
Coolant flow rate through reactor	m^3/s	10.4	8.9
Core inlet/outlet coolant temperature	^0C	270/284	270/284
Average steam quality at outlet of evaporation channels	%	14.5	30
Steam output of reactor	kg/s	1560	2450
Steam pressure in separators	MPa	6.9	6.9
Steam pressure/temperature ahead of turbine	$MPa/^0C$	6.4/280	6.4/280
Reactor Core			
Core height (length)	m	7.0	7.0
Equivalent core diameter	m	11.8	11.8
Core volume	m^3	760	760
Heat transfer surface	m^2	9070	8850
Average linear power	kW/kg U	17.8	25.4
Average power density (volumetric)	kW/l	4.2	6.3
Average heat flux from a fuel surface unit	kW/m^2	350	540
Maximum power of fuel (evaporation) channel	kW	3000	4500
Coefficient of radial power generation non-uniformity	-	1.2-1.33	1.4
Coefficient of axial power generation non-uniformity	-	1.25–1.35	1.4
Fuel Assembly			
Mass and type of fuel	t	192 U metal	189 U metal
Initial enrichment	wt. %	1.8	1.8
Operating cycle duration	day	1080	690
Average burnup	MW/day t	18500	21000
Number of fuel (evaporation) channels		1693	1661
Number of fuel assemblies in a fuel channel	-	2	2
Number of fuel pins in a fuel assembly	-	18	18
Outer diameter of fuel pin	mm	13.6	13.6
Thickness of fuel pin cladding	mm	0.9	0. 9
Material of fuel pin cladding	-	Zirconium alloy	Zirconium alloy
Number of control rods	-	179	235
Number of evaporation circulating loops		2	2
Outside diameter/thickness of header wall	mm	1025/62.5	1025/62.5
Number of main centrifugal pumps		8	8
Number of separating drums		4	4
Steam output of separating drum	t/h	1450	2200
Permissible steam humidity at the outlet of separating drum	%	< 0.1	< 0.1
Dimensions (diameter/length) of separating drum	m	2.3/30.7	2.6/34
Weight of separating drum (in dry state)	t	216.5	292
Pressure in ECCS	MPa	10	10

Bibliography:
Dollezhal N.A., Emelianov I.Ya. The Pressure Tube Nuclear Reactor. – M.: Atomizdat, 1980.
Margulova T.Kh. Nuclear Power Plants/3rd rev. and enl. ed. – M.: Vysshaia Shkola, 1978.
The power of GE technology at work. Fuel. Services. New Plants. – Nuclear Engineering International, 2002, vol. 47, No. 578, p. 24–26, 28, 29.

* RBMK — High Energy Channel Reactor, Russian Federation.

SYMBOLS

Speed of light in vacuum	$c = 2.998 \times 10^{8}$ m/s
Gravity constant	$G = 6.672 \times 10^{-11}$ N·m^2/kg^2
Plank constant	$H = 6.626 \times 10^{-34}$ J·s $h/2\pi = 1.055 \cdot 10^{-34}$ J·s
Avogadro constant	$N_A = 6.022 \times 10^{23}$ mol^{-1}
Faraday constant	F = 96485 C/mol
Universal gas constant	R = 8.314 J/(mol· K)·
Boltzmann constant	$k = R/N_A$=1.3807 × 10^{-23} J/K
Stefan-Boltzmann constant	$\sigma_o = 5.670 \times 10^{-8}$ W/(m^2· K^4)
First constant of radiation	$C_1 = 2hc^2 = 3.742 \times 10^{-16}$ W·m^2
Second constant of radiation	C_2 = hc/k = 0.01439 m· K
Wien constant	$C_3 = \lambda_{max} \cdot T = 2.8978 \times 10^{-3}$ m· K
Solar constant	S = 1325 W/m^2
Acceleration of gravity (standard)	g_o = 9.8066 m/s^2
Proton mass	$m_p = 1.503302 \times 10^{-10}$ J = 1.672623 × 10^{-27} kg
Neutron mass	$m_n = 1.505374 \cdot 10^{-10}$ J = 1.674928 × 10^{-27} kg
Electron mass	$m_e = 8.187241 \times 10^{-14}$ J = 9.109 × 10^{-31} kg
Electron charge	1.602 × 10^{-19} C
Ratio m_p/m_e	1836.153
Electron-volt	1eV = 1.602 × 10^{-19} J

SOME USEFUL DATA

Molecular mass of air	M = 28.96 amu
Molecular mass of water	M = 18.015 amu
Sound velocity in air	A = 343 m/s at 20^{o}C; 0.1 MPa
Atomic mass unit	1 amu = 1.660 × 10^{-27} kg
Mole volume of ideal gas	22.414 dm^3/mol

CONTRIBUTORS TO DRAFTING AND REVIEW

Bobkov, V.P.	Institute for Physics and Power Engineering (IPPE), Russian Federation
Fokin, L.R.	United Institute of High Temperatures of Russian Academy of Sciences (IVTAN), Russian Federation
Petrov, E.E.	Institute for Physics and Power Engineering (IPPE), Russian Federation
Popov, V.V.	Institute for Physics and Power Engineering (IPPE), Russian Federation
Rumiantsev, V.N.	Institute for Physics and Power Engineering (IPPE), Russian Federation
Savvatimsky, A.I.	United Institute of High Temperatures of Russian Academy of Sciences (IVTAN), Russian Federation

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA
ISBN 978–92–0–106508–7