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ENGLISH TRANSLATION OF SEVEN PAPERS ON THERMOPHYSICAL PROPERTIES

by

M. A. Carlson

with

Y. S. Touloukian, Editor

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DEFENSE LOGISTICS AGENCY
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report contains the English translation of six Russian papers and one French paper on the following subjects: (1) Influence of modifiers on the properties and structures of cast iron in light of the electron theory of metals, (2) Viscosity of Freon 21, Freon 22, and Freon 23, (3) Study of the magnetic state phase diagram of the chromium sulfide telluride ($\text{CrS}_2\text{Te}_{1-x}$) quasibinary system, (4) Density of molten metals and their temperature depend- ence, (5) Low-temperature characteristics of the Wiedemann-Franz law in aging		

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20. ABSTRACT (continued)

alloys, (6) Relation of the thermophysical properties of low-alloy steels to temperature, and (7) Reflectivity and emissivity coefficients of UO_2 at high temperatures.

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PREFACE

For many years the United States has found itself in the position of an exporter of advanced technology and know-how to Western Europe, Japan, and the USSR, and held a position of prominence in a number of scientific and technical areas. However, it has become quite clear in recent years that this enviable position has been seriously challenged by many nations, and that the United States cannot disregard the rapidly developing foreign science and technology. It is further clear that this technological and scientific competence will continue to increase and that the United States should view foreign science as a new "resource" which should be tapped to help stimulate its own science and technological innovations.

In the field of thermophysical and electronic properties information there is a wealth of knowledge generated abroad that is needed in the United States. One of the vital functions of Information Analysis Centers such as TEPIAC/CINDAS is to seek out such information and to translate the results into a form readily usable by our own engineers and scientists who are not particularly renowned for their versatility and facility in foreign languages. Otherwise, much valuable knowledge may go unused by default because of our failure to absorb it properly into our technology. Based on the records maintained at TEPIAC, it is estimated that in the areas of thermophysical and electronic properties the dollar value of the output of the rest of the world is of the same order of magnitude as that of the United States. Hence, it would behoove us to diligently seek out this information on a systematic basis and thus double the financial resources allocated for this purpose by the private sector and the Federal government. The cost of securing and processing this information would be only a tiny fraction of the value received in research dollars and trained manpower.

The seven translations listed in this report were prepared at CINDAS after it was concluded that no English translations were currently available within the USA. In this effort, the editorial assistance provided by Mr. B. Bentsen is gratefully acknowledged.

Editor

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REFLECTIVITY AND EMISSIVITY COEFFICIENTS OF UO_2 AT HIGH TEMPERATURES

F. Cabannes, J. P. Stora, and J. Tsakiris

C. R. Acad. Sci. Paris, 264B(1), 45-8, 1967*

ABSTRACT

By utilizing the method of modulated incident flux, one measures the monochromatic component of reflection in the infrared and visible region. One can then deduce the emissivity and demonstrate the need for correcting the values cited in the literature.

1. The utilization of UO_2 in a reactor necessitates calculations to enable the control of the temperature of the material. To calculate the heat transfer by radiation, and make temperature measurements by optical pyrometry, one must know the emissivity of the surface of UO_2 at high temperatures.

Few values have been published; according to [1], the monochromatic emissivity in the visible decreases from 0.85 at room temperature to 0.37 at 2000 K [2]. We will show that our results do not agree with these and that the method used in [1] is very dangerous and risky and introduces important systematic errors.

2. Below a few tenths of a millimeter of thickness annealed UO_2 samples are not at all transparent in the visible and infrared [3], so one can deduce ϵ_0 from the monochromatic reflectivity ρ_0 : $\epsilon_0 = 1 - \rho_0$. Since it is easy to carefully polish the surface of annealed UO_2 , one can obtain a specular reflection that one can easily measure [4].

Using the method of modulated incident flux, [5] one can eliminate the errors that result from surface temperature measurement.

The samples were cut and formed into small rectangular rods (2.5 x 3.5 x 3.5 mm) with one face polished. They were heated by Joulian effect in an atmosphere of argon or hydrogen. A window of NaCl was placed on top of the heating chamber to permit the measurement of ρ_0 similar to the apparatus described in [5].

*Meeting of November 28, 1966.

Figure 1 gives the values of ϵ_{σ} in the spectral region 7000–17000 cm^{-1} ($14 > \lambda > 0.6 \mu\text{m}$) at 300, 1200, and 1600 K. At room temperature our results are in agreement with those of [1] but we observe at high temperatures that ρ_{σ} decreases and ϵ_{σ} increases slightly.

Figure 2 gives the variation of ρ_{σ} with T in the visible red ($\sigma = 15300 \text{ cm}^{-1}$, $\lambda = 0.65 \mu\text{m}$) and the infrared ($\sigma = 2900 \text{ cm}^{-1}$, $3.5 \mu\text{m}$). The influence of the argon atmosphere or hydrogen is not detectable. The values obtained with samples of three annealings were the same.

Figure 3, which gives the values of ρ_{σ} of one sample, shows that the surface does not follow the same course of measurement at high temperatures (the experiment points are numbered in the order in which they were obtained).

As ϵ_{σ} does not vary much with the frequency σ , one can calculate the total emissivity ϵ_T with sufficiently good precision, and finds that

ϵ_T	0.86	0.90	0.90 ₂
T(°K)	300	1200	1600

3. The disagreement between our results and those of [1] can be explained, in our opinion, by important systematic errors that were introduced in the methods of measuring ϵ_{σ} by luminescence.

In [1] in the first measurement, a sample of UO_2 was supported by a thin wire of tungsten and heated in vacuum by induction in a tube of graphite. ϵ_{σ} is deduced from the luminescence of UO_2 and tungsten. The difference between the two surface temperatures introduces an important error in the low emissivity of tungsten ϵ_{σ} . In the second measurement, a small piece of polished UO_2 , consisting of powdered UO_2 is heated in a graphite enclosure. ϵ_{σ} is deduced by the luminescence of the surface of UO_2 and the cavity.

A temperature difference of 250 K between the surface and the cavity can explain the discrepancy between the value of 0.40 cited in [1] and that of 0.94 which we found. Such a difference in temperature is not at all abnormal because the thermal conductivity of UO_2 is not very large and the surface in which one measures the luminescence radiates to a high degree.

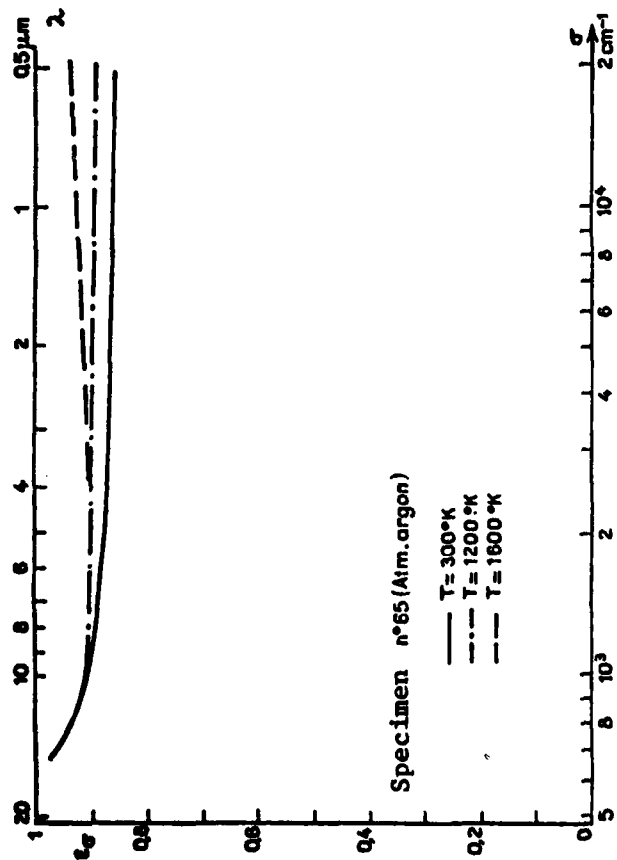


Figure 1

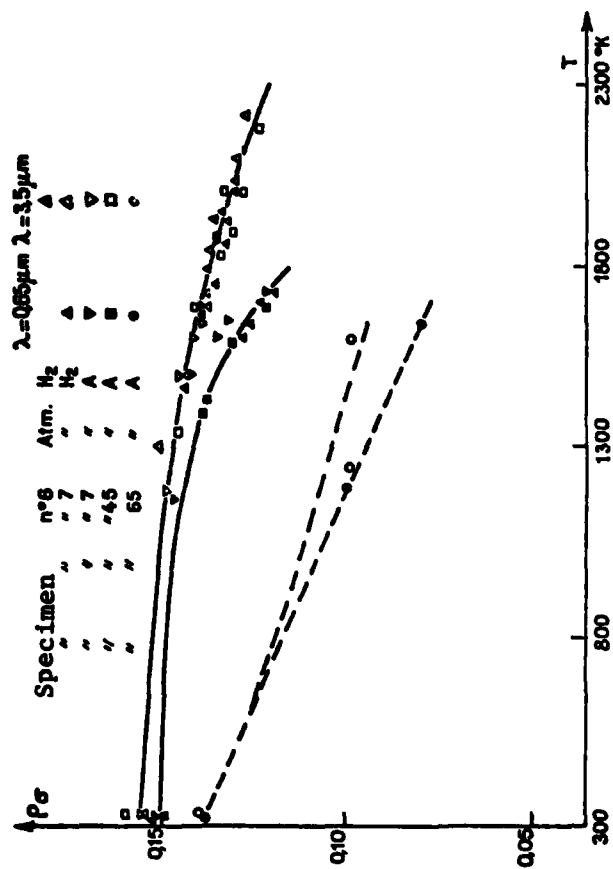


Figure 2

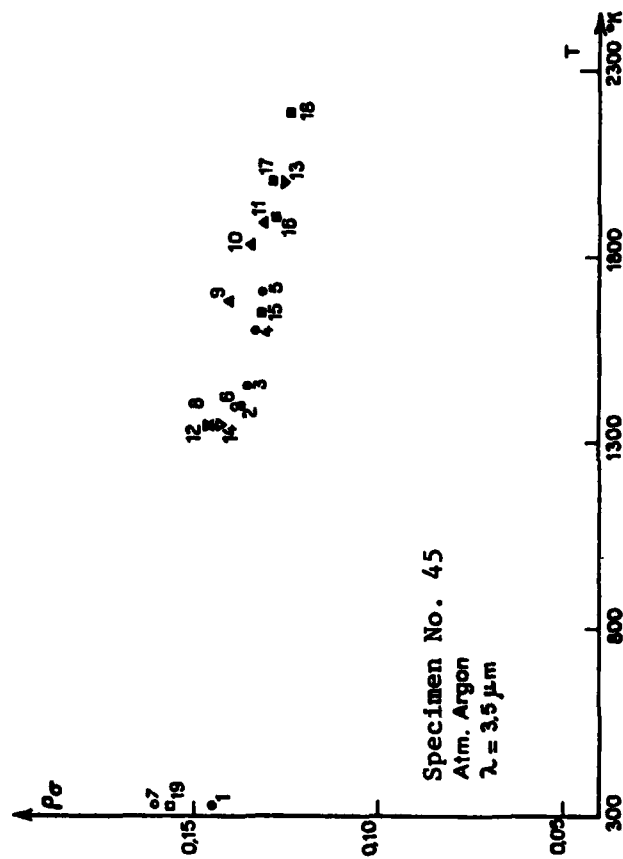


Figure 3

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4. One has carefully controlled that the diffused reflection is negligible and does not introduce into the value of ϵ_0 an error that exceeds 0.04.
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INFLUENCE OF MODIFIERS ON THE PROPERTIES AND STRUCTURE OF CAST IRON IN LIGHT OF THE ELECTRON THEORY OF METALS

V.F. Sumtsov and R.G. Nemirovskii

Liteinoe Proizvod., (1), 18-19, 1975

Nearly every known element-nodularizers of graphite in cast iron have a smaller magnitude of electronegativity in comparison with others, i.e., they can easily give up their own valence electrons which is confirmed by the small ionization potential of the nodularizing element. Therefore, it is proposed that the graphite-nodularizing elements during admission into cast iron give off the electrons into the total electron fraction of the alloy which then must increase. Some physical properties of the metals (Hall effect, thermionic emission) are explained by the presence of free electrons. Therefore, for an analysis of the influence of the elements on the electron structure of cast iron, the variation of the physical characteristics cited during admission of modifiers into cast iron: magnesium and FTsM-5 alloy, and for comparison, the alloying elements Al and Cr, were studied.

The influence on the Hall effect of the modifiers was studied in cast iron having 3.35% C; 0.54% Mn; 2.04% Si; 0.35% P and 0.087% S. Sample platelets of 2-3 mm thickness were cast into graphite molds and annealed for 10 hours at 950°C. The annealed flakes were polished to thickness t of 0.35 to 0.65 mm and cut into specimens for the investigation.

The apparatus for measuring the Hall effect (Fig. 1) permitted one to measure the emf with an accuracy up to 10^{-6} V. In it are the voltage stabilizer 1, autotransformers 2, 3, rectifiers 4, 5, ammeters 6, 7, reversing switches 8, 9, electromagnets 10, variable resistor 11, sample 12, and potentiometer 13. For stabilization of the temperature of the samples, the sample was put into a bath of flowing transformer oil. The Hall potential E_x of each sample was measured 8 times: for two values of forward and reverse current directions, and two directions of the magnetic induction. The variation of the current was in the range of 20-60 amps, and of the magnetic induction B , from 0.19 to 0.26 Teslas. The results of the eight observations were averaged in order to exclude all stray potentials in the specimen. Subsequently the value of the normal Hall coefficient was calculated. Simultaneously, the mic-

rostructure of the sample and the effect of the admission of the modifiers on it was appraised. The Hall coefficient was determined according to the relation,

$$R_0 = \frac{E_x \cdot t}{J \cdot B}$$

In this the maximum root mean square error, $S_n = 0.047$. A confidence interval was determined for the closest to each other values of R_0 with a confidence probability, $\alpha = 0.95$. It proved to be equal to $\Delta x = 0.04$. Analysis of the values of the Hall coefficient of the samples showed that the results obtained can be considered reliable with a probability of $\alpha = 0.95$.

Figure 2 shows the influence of the modifiers and alloying elements on the magnitude of the Hall coefficient in cast iron. Apparently, introduction of Mg and Ce into cast iron reduced the value of the Hall coefficient but the addition of Al or Cr, on the other hand, increased it. Inasmuch as R_0 is inversely proportional to the volume of the concentration of the current carriers, we concluded that Mg and Ce increases the electron conductivity number in cast iron but Al and Cr decreases it. Analysis of the microstructure of the samples revealed that in the initial cast iron the graphite had a flake-like form; in cast iron containing 0.01% Mg, the form of the graphite remained more compact, but with 0.03% and higher Mg, well-formed modules were produced. The very same occurred during the addition in cast iron of the alloy FTsM-5: A sample with 0.025% Ce had compact graphite, but in samples with 0.04 Ce uniformly dispersed graphite nodules were observed. In samples with Cr and Al, the graphite was either in flake-like form or of interdendritic construction. Etching of the polished sections and testing the samples for microhardness showed that the metallic base of cast iron was ferritic with $H_p = 75$ to 165 kg/mm^2 .

For investigating the thermionic emission of cast iron, cylindrical samples, 10 mm in diameter and 150 mm long, were cast in graphite molds and annealed into ferrite. Then they were treated for 2 hours at $850\text{--}900^\circ\text{C}$ in a hydrogen atmosphere. The microstructure of the cast iron was studied on the same samples after measuring the emission current. Cast iron having a composition of 2.96% C; 0.51% Mn; 2.34% Si; 0.35% P and 0.036% S was modified by magnesium and for comparison it was alloyed with Al and Cr. The apparatus for measuring the

thermionic emission of cast iron included the specimen which served as the cathode, an annular anode, guard rings and a vacuum system consisting of a vacuum hood, fore-vacuum and diffusion pumps, hoses and accessories. A vacuum of $10^{-10} \rightarrow 10^{-5}$ mm Hg was maintained in the system. The design of the system for measuring the emission current (Fig. 3) consisted of a stabilized source of DC voltage U_{st} , the sample 0 of 8 mm diameter, an annular anode A of 40 mm in diameter and 40 mm long, two guard rings, OK, of the same diameter for limiting the emission surfaces to the length of the sample, rheostats R_1 and R_2 and a tube voltmeter LB for measuring the microdrop in voltage of the emission current. The sample was heated with a water-cooled copper electrode F, which was supplied a voltage of 220 V from split transformers. The temperature of the surfaces of the sample was measured by contact Pt - PtRh thermocouples with a potentiometer. The anode voltage of 200 V was held constant in all experiments. Measuring was performed on 1-2 samples of one chemical composition, repeating the experiments 3-4 times. The effective work function ϕ of the electrons in cast iron was determined in electron-volts according to the relation

$$\phi = 1.984 \times 10^{-4} T (2.079 + 2 \log T - \log j),$$

where T is the absolute temperature of the surface of the sample in $^{\circ}\text{K}$; j is the density of the emission current in A/cm^2 . Using the average of the observed values, the graph in Figure 4 depicts the dependence of the emission current density on the temperature of the surface of the sample and on the chemical composition of the cast iron. Apparently, the introduction of Mg in the quantities used in the studies raised the thermoemission of cast iron. The addition of Al and Cr, on the other hand, somewhat decreased it.

In Figure 5 the influence of Mg on the current density of thermoemission of cast iron at 900° and 950°C is indicated. Apparently, the current density increases with the content of magnesium in cast iron. The effective work function ϕ (Fig. 6) was calculated from measurement data at the three sample surface temperatures of 900° , 950° and 1000°C . Apparently, the magnesium somewhat decreased ϕ while with increasing magnesium content in the cast iron within the limits investigated, its effectiveness increased. On the other hand, introduction of Al and Cr in cast iron, increased the magnitude of the work function of the electrons. Therefore, it can be surmised that in this case the introduction of magnesium in cast iron somewhat raised the concentration of free electrons,

while the introduction of aluminum and chromium decreased it. Analysis of the microstructure of cast iron showed that graphite acquired a spherical form only in the samples modified by magnesium. In the initial cast iron and in the samples modified by Al and Cr the graphite had a sheet-like or flake-like form.

Thus, one can speak of a relationship between modification and alloying processes in cast iron and its electron state, of the qualitative influence of elements on the concentration of electron conductivity in cast iron and on the form of the graphite in cast iron. In this, the introduction in cast iron of the investigated nodularizing elements raises the concentration of current carriers in it, making possible the formation of noded and compact graphite, but with a fixed concentration of current carriers, the graphite is spherical. The addition of graphitizing (Al) and carbide-forming (Cr) elements reduces the concentration of the electron conductivity which is conducive to generating flake-like graphite.

From the results obtained from these experiments the mechanism of generating compact and spherical forms of graphite in cast iron can be considered from the point of view of the electron theory of metals. During introduction into cast iron, the elements-nodularizers ionize and create local concentrations of free electrons, while the total concentration of current carriers in the alloy grows. Free electrons in fluctuation locations sharply increase the metallic bond between the layers of the graphite crystal lattice. The magnitude of this bond becomes equivalent to the covalent bond in the layer, as a consequence, the graphite grows in all directions at the same rate. Toward the nuclei of graphite being formed, a microdiffusion current of nodularizer atoms develops, which carries its own free electrons to fluctuate on locations. Due to this, the metallic bonds grow between successive neighboring layers of graphite. Globules are developed which grow further due to the inflow of atoms under conditions of elevated concentrations of free electrons.

During the introduction in cast iron of small nodularizer additions, the concentration of free electrons increases not as sharply, however, its change affects the formation and distribution of inclusions of graphite which become more noded and discrete. The effect of antinodularizers can be explained by the fact that they attach to themselves the free electrons which go into the formation of different chemical combinations of these elements. The total number of free electrons in cast iron is reduced which lead to a deterioration in

the form of the graphite.

Thus, the process of modifying cast iron is closely tied to changes in its physical characteristics upon which depend the microstructure and mechanical properties of the alloy.

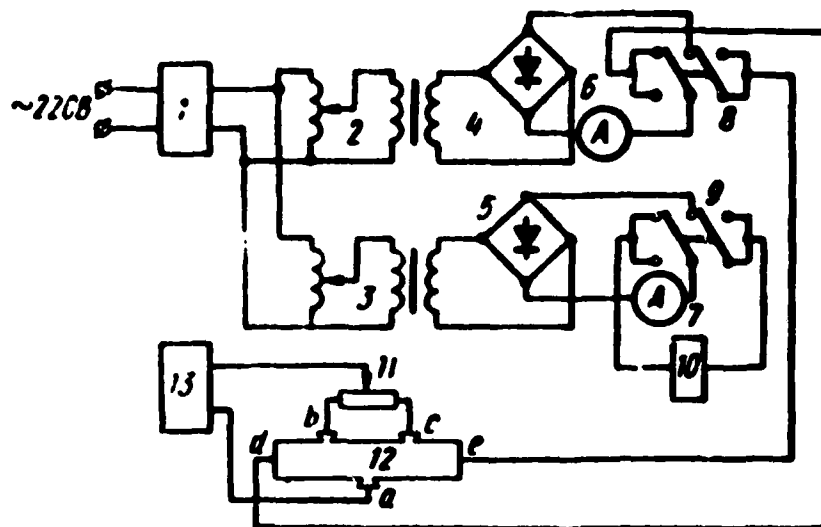


Figure 1

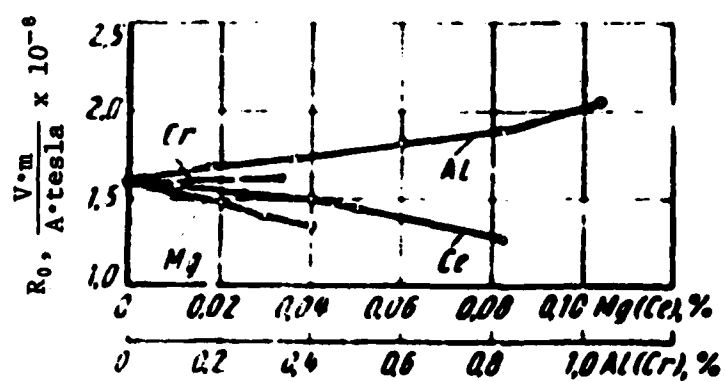


Figure 2

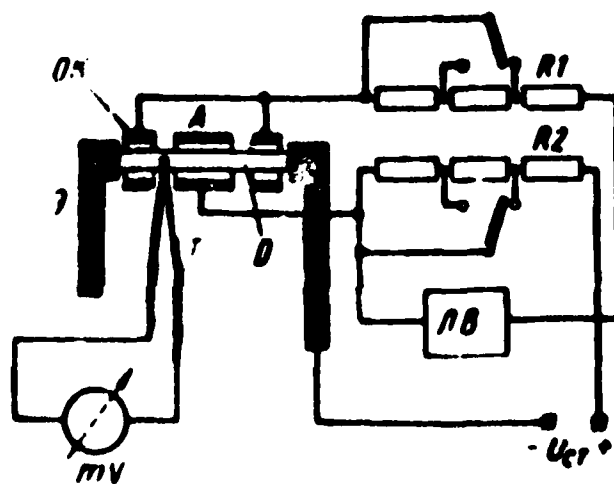


Figure 3

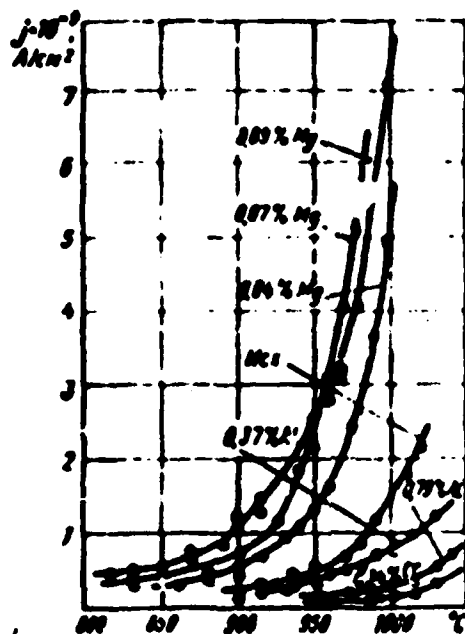


Figure 4

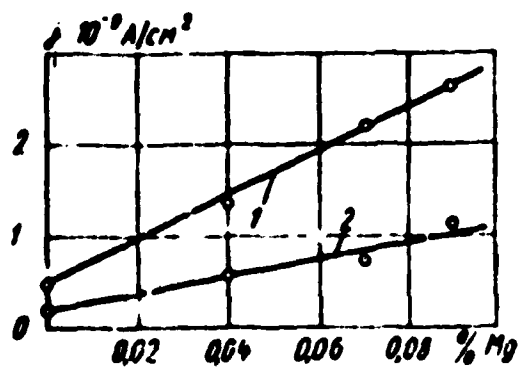


Figure 5

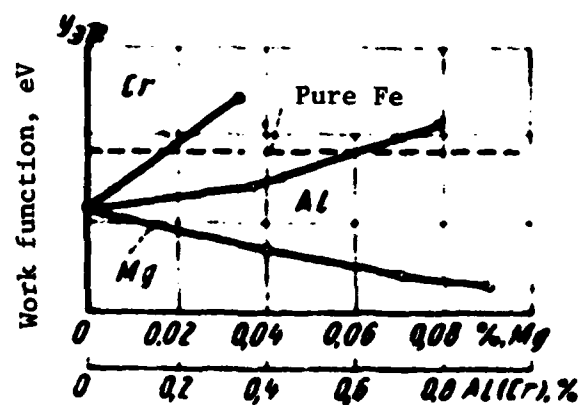


Figure 6

VISCOSITY OF FREON 21, FREON 22, AND FREON 23

V. Z. Geller

Kholod. Tekh. Tekhnol., 22, 41-5, 1976

The coefficients of dynamic viscosity η of Freon 21, Freon 22, and Freon 23 can be determined by the use of the experimental arrangement described in [2]. The results of measurements of η for Freon 22, in a wide range of parameters and conditions, have been set forth in [3].

The viscosity of Freon 21 and Freon 23 was determined from 0 to 160°C and pressures up to 60 MPa. Experiments were conducted using three viscosimeters (diameter of capillary 0.07, 0.13, and 0.20 mm) at Reynold's numbers of no more than 1000. Correspondence of values of viscosity, which were obtained using different viscosimeters, was achieved for two or three isotherms, in which the divergence of results did not exceed the error of the measurements, estimated to be $\pm 1.5\%$.

Experimental data of η for Freon 21 and 23 are presented in Tables 1 and 2. The necessary values for the calculation of the density of Freons were taken from [1,5]. Experimental data on the thermodynamic properties, as a function of temperature, were not available in the region of parameters covered; hence, the density was calculated using the generalized equation of Hirschfelder.

Experimental values of the measured viscosity of Freon were expressed as excess-viscosity vs density. The magnitudes of the viscosity at low pressure and corresponding temperatures were taken from [6].

Analysis of the results of this study shows that in the investigated region of densities for each of the Freons, the experimental data for various pressures and temperatures satisfactorily coincides with the theoretical predictions. On the basis of this dependence, the equations for the density were obtained which allowed us to compute the coefficients of dynamic viscosity of Freons over a wide range of parameters:

$$(\eta_{p,t} - \eta_t) \cdot 10^4 = \sum_{i=0}^{i=n} c_i \rho^i. \quad (1)$$

Table 3 tabulates the polynomial coefficients of density for the investigated Freons in the corresponding intervals of densities and also both the

TABLE 1. VISCOSITY OF FREON 21
 $[\eta = \text{Pa} \times 10^{-6} \text{ sec}; \text{Temperature}, ^\circ\text{C}]$

Pressure MPa	-0.18	19.92	40.06	60.10	80.07	100.04	120.43	140.44	160.73
1.07	412.3	334.7	-	-	-	-	-	-	-
1.56	-	-	272.8	227.8	191.1	-	-	-	-
2.05	-	-	-	-	-	161.8	-	-	-
3.03	-	340.4	276.3	231.8	194.9	164.1	132.5	-	-
4.01	-	-	-	-	-	-	-	108.8	-
4.99	434.2	345.2	281.0	236.6	199.9	169.7	138.7	112.9	85.5
7.45	-	355.5	287.8	-	206.1	176.2	145.4	121.2	96.0
9.90	448.9	361.2	295.4	249.4	212.1	181.7	151.6	128.0	105.0
19.70	479.5	388.1	319.2	272.4	234.5	204.3	174.2	151.8	128.5
39.31	546.8	440.3	364.0	314.5	273.7	241.9	211.4	189.0	168.0
58.92	607.3	488.5	408.4	355.2	311.4	279.4	252.8	221.1	199.0

TABLE 2. VISCOSITY OF FREON 23
 $[\eta = \text{Pa} \times 10^{-6} \text{ sec}; \text{Temperature}, ^\circ\text{C}]$

Pressure MPa	0.01	25.27	41.71	60.50	79.88	101.95	120.75	139.95	159.30
1.06	-	-	16.1	16.8	17.5	18.2	19.0	19.8	20.7
2.04	-	-	16.6	17.2	17.9	18.5	19.2	20.1	20.9
3.02	-	-	17.4	17.8	18.4	18.9	19.6	20.4	21.2
4.01	-	-	18.4	18.6	19.0	19.4	20.0	20.8	21.6
5.00	106.0	60.4	20.0	19.5	19.7	20.0	20.5	21.2	21.9
5.96	-	65.6	24.2	21.7	20.9	20.7	21.2	21.8	22.3
7.43	111.9	70.4	42.2	25.5	23.5	22.5	22.4	22.8	23.2
9.88	118.4	78.7	58.8	38.9	29.6	25.5	24.3	24.3	25.2
14.71	-	-	-	-	-	-	32.9	31.1	29.9
19.71	139.1	102.8	86.1	71.1	58.8	48.0	42.0	38.5	36.0
38.29	174.6	135.3	117.4	102.4	89.8	78.3	71.4	64.6	60.3
58.90	208.5	162.5	141.4	124.4	111.6	100.7	91.9	85.4	79.5

TABLE 3

Coefficient of Density and Value of Viscosity	Freon 21		Freon 22		Freon 23	
	$\rho=(970-1320)\text{kg/m}^3$	$\rho=(1320-1490)\text{kg/m}^3$	$\rho=(800-1390)\text{kg/m}^3$	$\rho=(20-500)\text{kg/m}^3$	$\rho=(500-1320)\text{kg/m}^3$	
C_0	$-8.8474 \cdot 10^{-2}$	3.7048	2.7685	$-7.0787 \cdot 10^2$	$-5.3349 \cdot 10^1$	
C_1	$3.0775 \cdot 10^{-1}$	-6.2876	$-1.1139 \cdot 10^1$	$2.2119 \cdot 10^{-1}$	$-1.4734 \cdot 10^{-1}$	
C_2	$4.2366 \cdot 10^{-1}$	2.7804	$1.4447 \cdot 10^1$	$-5.9365 \cdot 10^{-1}$	3.8572	
C_3	-1.6106	-	-1.3686	1.2435	-1.3575	
C_4	1.4022	-	-7.7979	7.6735	2.2806	
C_5	$-3.3894 \cdot 10^{-1}$	-	3.9500	$-1.9912 \cdot 10^{-1}$	-1.7154	
C_6	-	-	-	7.2714	4.9384	
C_7	-	-	-	$1.1275 \cdot 10^1$	-	
C_8	-	-	-	6.9539	-	
$\Delta\eta_{\text{maximum}}, \%$	5.3	3.1	3.8	4.6	6.7	
$\Delta\eta_{\text{root-mean-square}}, \%$	2.3	1.8	1.4	2.4	2.8	

maximum and root-mean square values of the divergence of the viscosity of Freon 21 and Freon 22, described as $(\eta_{p,t} - \eta_t)$, in the different intervals of density ρ , do not exceed 1%. It should be noted that in certain cases the deviation of the calculated viscosity, using eq. (1), from the experimental data, exceeds the possible error of the measurements. This, in our opinion, is related to the fact that in the region of parameters where experimental data on thermodynamic properties are lacking, the given error in the density of Freon did not affect the accuracy of the calculations of the coefficient of viscosity, yet could distort somewhat the dependence of the excess-viscosity on the density. Furthermore, analysis of the literature data has shown that for a series of liquids, the excess-viscosity dependence on density, particularly in the region of high densities, ceases to be single-valued; a separation of the indicated dependence occurs on the isotherm. Thus, the presentation of the experimental data on viscosity in $\Delta\eta$ vs ρ coordinates is recommended in this region of parameters, where reliable values of the thermodynamic properties are available which give unique values to the dependence of the excess-viscosity on the density.

In connection with this explanation it is possible to obtain an equation for viscosity as a function of temperature and pressure covered in the experiment. A more simple form of such an equation can be obtained by the description of the lines of constant liquid viscosity in p and t coordinates. Reference [4] shows on the basis of the analysis of systems of differential hydrodynamic equations and equations of state, that these curves are straight lines for a wide range of parameters.

Taking into consideration the possibility of thermodynamic similarity of Freon 21, Freon 22, and Freon 23, in reduced coordinates $\tau = T/0.7 T_{cp}$, $\pi = P/0.7 P_{cp}$, constant viscosity lines were constructed, each of which were described by the linear equation

$$\tau = A + B\pi. \quad (2)$$

Values A_i and B_i were approximated by a polynomial to the ninth degree through the inverse ratio of the reduced viscosity $\eta^* = \eta/\eta_{0.7}$ ($\eta_{0.7}$ = the values of the viscosity at temperature $0.7 T_{cp}$ and pressure $0.7 P_{cp}$). Such a choice as a reference value is entirely justified because over the experimental range of the parameters the viscosity is determined with greater accuracy than at the critical point or along the saturation line.

As a result of the calculations, which were carried out with the help of an ETsVM computer by the method of least squares, an equation was obtained which described the viscosity of Freon 21, Freon 22, and Freon 23:

$$\tau = A(\eta^*) + B(\eta^*)\pi \quad (3)$$

where

$$A(\eta^*) = \sum_{i=0}^{i=9} a_i \eta^{*-i}; \quad B(\eta^*) = \sum_{i=0}^{i=9} b_i \eta^{*-i}$$

$a_0 = 0.4675667$	$b_0 = 0.1874835 \cdot 10^{-2}$
$a_1 = 0.9431701$	$b_1 = -0.2177574 \cdot 10^{-2}$
$a_2 = -0.6246534$	$b_2 = 0.2598676 \cdot 10^{-1}$
$a_3 = -0.5736217 \cdot 10^{-2}$	$b_3 = -0.1644747 \cdot 10^{-1}$
$a_4 = 0.4256320$	$b_4 = -0.1116226 \cdot 10^{-2}$
$a_5 = -0.2256243$	$b_5 = 0.1053093 \cdot 10^{-1}$
$a_6 = -0.3896274 \cdot 10^{-1}$	$b_6 = -0.9075259 \cdot 10^{-2}$
$a_7 = 6765168 \cdot 10^{-1}$	$b_7 = 0.3631583 \cdot 10^{-2}$
$a_8 = -0.1294374 \cdot 10^{-1}$	$b_8 = -0.6781164 \cdot 10^{-3}$
$a_9 = 0.4801993 \cdot 10^{-3}$	$b_9 = 0.5055942 \cdot 10^{-4}$

The values of $\eta_{0.7}$, which were found from the experimental data for Freon 21, Freon 22, and Freon 23 corresponded to 271.6, 253.9, and 232.6 Pa x 10^{-6} sec. The values of the critical parameters of the Freons which were necessary for the calculations were taken from [1,5].

Examination of the calculated results showed that the root mean square deviations from the experimental data of Freon 21, Freon 22, and Freon 23 were 0.42, 0.70, and 0.53%, respectively. The maximum deviations did not exceed 2.1, 3.6, and 2.7%, respectively. Since eq. (3) is based on experimental data which includes that for Freon 21 in the reduced temperature interval from 0.5 to 1.0, it can be used for the calculation of the viscosity of Freon 22 and Freon 23 in corresponding states at low temperatures. Table 4 presents calculated values of the dynamic viscosity according to eq. (3) along the saturation lines in the temperature interval -120 to +40°C. It is necessary to note that in the region of parameters where there are experimental data, the differences between the calculated and experimental values of the viscosity do not exceed 2%.

TABLE 4. VISCOSITY OF FREONS ALONG THE SATURATION LINE

[$\eta = \text{Pa} \times 10^{-6} \text{ sec}$; Temperature, $^{\circ}\text{C}$]

Refrigerant	-120	-100	-80	-60	-40	-20	0	20	40
Freon 21	-	-	-	-	-	-	418.7	330.8	269.1
Freon 22	-	-	-	460.1	338.7	260.4	207.9	168.2	134.2
Freon 23	646.4	417.0	288.0	212.3	162.9	123.7	-	-	-

The calculation of the viscosity using eq. (3) involves the execution of several iterations because it contains η in implicit form; however, with the use of an EVM computer such a procedure does not cause special difficulty.

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STUDY OF THE MAGNETIC STATE PHASE DIAGRAM OF THE CHROMIUM SULFIDE TELLURIDE ($\text{CrS}_x\text{Te}_{1-x}$) QUASIBINARY SYSTEM

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Chalcogenides of Cr having NiAs type structure possess various types of magnetic ordering (CrTe is ferromagnetic but CrSi and CrS are antiferromagnetic) and, therefore, are more convenient substances for study of magnetic interaction. Grazhdankina, N.P., noted a strong decrease of Curie temperatures and reduction of magnetic moment in solid solutions on the basis of CrTe in the system $\text{CrS}_x\text{Te}_{1-x}$ with increases in concentration of sulfur. X-ray diffraction investigation of the alloy system showed that with an increase in the content of CrS in CrTe solid solutions, a linear reduction in the stable NiAs type cells is observed down to the $\text{CrS}_{0.2}\text{Te}_{0.8}$ composition. A region of heterogeneous mixture of solid solutions of NiAs and monoclinic type structure is observed during increases in the concentration of sulfur by more than 20 at. %.

In this work are presented the results of measurement of the magnetic saturation and coefficient of linear expansion of the solid solution of the system $\text{CrS}_x\text{Te}_{1-x}$ ($x = 0 \rightarrow 0.2$) in the temperature ranges 4.2-360 K and 80-520 K, respectively.

Samples were sintered by ceramic technology from powders of the constituent components. The products obtained were ground and pressed into cylindrical shapes which were annealed at 950°C, with subsequent quenching in cold water.

Measurement of the magnetic saturation of the samples was accomplished by changing the magnetic field strength from 0 to 20 kOe. The concentration dependence of the magnetic saturation and the Curie temperatures of the investigated solid solutions are presented in Figure 1. The Curie temperatures were determined from the curves of the temperature dependence of magnetization which were obtained with a magnetic field of 8 kOe. Magnetic saturation, determined at 20 K with a magnetic field of 20 kOe, changes practically linearly from 76.2 gauss·cm³/g in CrTe up to 40.5 gauss·cm³/g with a composition of 20 atomic percent of CrS.

The Curie temperature of CrTe, according to our measurements, is 340 ± 2 K. With compositions $\text{CrS}_{.1}\text{Te}_{.9}$ and $\text{CrS}_{.2}\text{Te}_{.8}$, the Curie temperatures are 270 ± 2 K and 214 ± 2 K, respectively.

The value of the magnetic saturation and the Curie temperature of the samples of composition $\text{CrS}_{.3}\text{Te}_{.7}$ practically coincide with the values obtained for the composition $\text{CrS}_{.2}\text{Te}_{.8}$. This fact is indirect proof that in the investigated system during the quenching of the samples from 950°C the range of solid solution on the basis of CrTe extends to no more than 20 mole % CrS.

During measurements of the magnetization of CrTe in the low temperature regions it was discovered that below 120 K the magnetization in fields up to 4 kOe slowly decreases with decreasing temperature. With the increase of the strength of the applied magnetic field, the point of starting of the reduction of the magnetization moves to lower temperatures. In the range of external magnetic fields on the order of 15-20 kOe, reduction of the magnetization was not observed. Such a characteristic temperature dependence of the magnetization at low temperatures was caused by the appearance of an antiferromagnetic component of the magnetic moment. During the imposition of a strong magnetic field, the effect of reducing the magnetization is not observed since the external field counteracts the rotation and antiferromagnetic ordering of the magnetic moments.

The effect of the appearance of the antiferromagnetic component of magnetic moment, in the region of low temperatures, was observed also in samples of solid solutions of CrTe.

Investigation of the temperature dependence coefficient of linear expansion was conducted in the temperature range 80-520 K on a quartz dilatometer with a sensitivity not worse than $0.020 \mu\text{m}$, the measuring device was based on the use of an induction transducer as a differential transformer.

Measurements were accomplished on sintered cylindrical samples 10 mm in diameter and 15-20 mm long. The results are presented in Figure 2. It is apparent from the trend of the curves of the temperature dependence of the coefficient of linear expansion that there exists a well defined minimum. In the case of CrTe and samples of composition $\text{CrS}_{.1}\text{Te}_{.9}$ the coefficient of linear expansion correspond to the temperature of 336 K for CrTe, 258 K for $\text{CrS}_{.2}\text{Te}_{.8}$, and 204 K for $\text{CrS}_{.2}\text{Te}_{.8}$. These are found in good agreement with the ferromag-

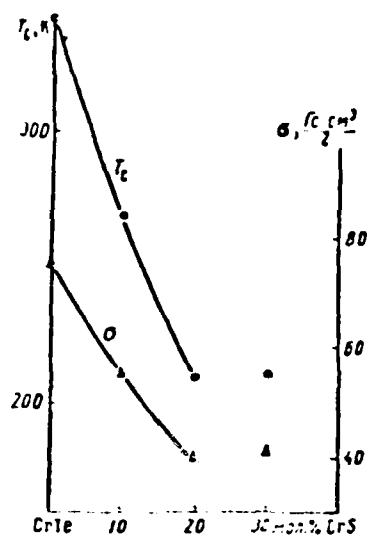


Figure 1. Concentration Dependence of the Saturation Magnetization σ and the Curie Temperatures of Solid Solutions of the quasi-binary System $\text{CrS}_x\text{Te}_{1-x}$.

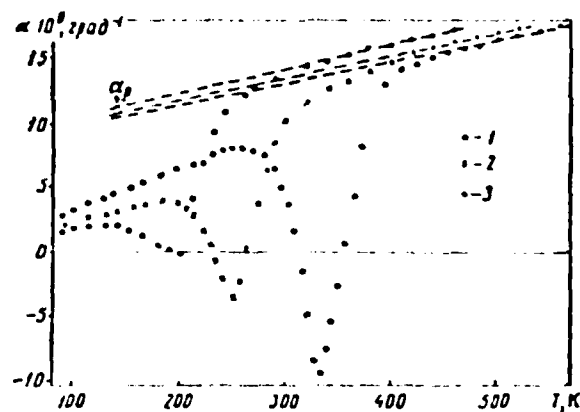


Figure 2. The Temperature Dependence of the Coefficients of Linear Expansion of Solid Solutions of the System $\text{CrS}_x\text{Te}_{1-x}$: 1) CrTe ; 2) $\text{CrS}_{.1}\text{Te}_{.9}$; 3) $\text{CrS}_{.2}\text{Te}_{.8}$.

netic paramagnetic transition temperatures of 341, 264, and 198 K, respectively, which are found from neutron-diffraction investigations of temperature dependences of the intensity of magnetic repulsions.

The highest value of the Curie temperature obtained from the magnetization curve in comparison with the values obtained in the dilometric and neutron-graphic investigations, are due to the marked influence of the magnetic field on the temperature of the magnetic transition.

By using the correlation

$$w_s(T) = 3 \int_T^{\infty} \{\alpha_p - \alpha_F(T)\} dT,$$

connecting the value of the magnitude of magnetostriction $w_s(T)$ with the paramagnetic coefficient of thermal expansion, α_p and the magnetic contribution to the coefficient of linear expansion $\alpha_F(T)$, one can evaluate the magnitude of w_s of the investigated samples. Calculations show that in the solid solutions of the system $\text{CrS}_x\text{Te}_{1-x}$ the lower Curie point has a linear dependence of the spontaneous magnitude of magnetostriction on temperature. At 80 K, $w_s = 13.5 \times 10^{-3}$ for CrTe, 9.3×10^{-3} for $\text{CrS}_{.1}\text{Te}_{.9}$, and 6.2×10^{-3} for $\text{CrS}_{.2}\text{Te}_{.8}$. The spontaneous value of the magnetostriction for CrTe conforms with the estimate presented by V. A. Gordinko et al. [3].

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DENSITY OF MOLTEN METALS AND THEIR TEMPERATURE DEPENDENCE

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NOMENCLATURE

- ρ = density
- ρ_{Rb} = density of rubidium
- ρ_{k} = density of potassium
- ρ_{Cs} = density of cesium
- ρ_{Hg} = density of mercury
- ρ_{Sb} = density of antimony
- ρ_{m} = density at the melting point
- t = temperature, °C
- t_{m} = temperature at the melting point, °C
- T = temperature in °K
- T_{m} = temperature at the melting point, °K
- α = coefficient of volumetric thermal expansion
- A = a constant (eq. 10)
- B = temperature coefficient of density (eq. 11)
- a^2 = capillary constant (eq. 18)
- σ = surface tension (eq. 18)
- g = acceleration of gravity (eq. 18)
- v_{m} = atomic volume at the melting point

DENSITY OF MOLTEN METALS AND THEIR TEMPERATURE DEPENDENCE

In many experimental methods, the density of molten metals, appears in the analytic expression for the calculation of the free surface energy of these metals. In comparing the data of various authors concerning the free surface energy, it is often necessary to adjust these data based on a density value which can be considered to be most reliable. The reliable knowledge of the density of liquid metals is also necessary in the diffraction investigations of the structure of alloys. Volume changes, which take place in molten metals with increasing temperatures, are also directly connected to their structure. Experimental data on the temperature dependence of the density of liquids at present are basic to the determination of the critical parameters (critical temperature and density), which are very essential also for liquid metals, because they enable us to estimate the properties of the little-investigated melts by knowing the properties of a limited number of well studied liquids.

In the present work an attempt is made to systematize our own and the literature data on the density of liquid metals. In the process of the determination of the most reliable data we encountered a number of difficulties. We could not use strict statistical methods for the following reasons: (1) the limited volume of data available at this time in the case of each element for valid statistical treatment; (2) in many works, the authors' indicated accuracy for the determination of the density must be considered as invalid since the results of the different investigations, taking into account their indicated errors, disagree among themselves to a much greater extent; (3) in some works the data needed for the statistical analysis are not given. In the analysis of the available data we took into account the following factors: Conditions prevailing during the experiment, purity of the investigated substances, the temperature range of the investigation, and the degree of agreement of the results of the several investigators.

We considered reference works on specific groups of metals. For recommended values (see Table 4), we selected the results of specific works due to the lack of appropriate statistical treatments. Recognizing that our recommendation was partly subjective, we considered it necessary to present (see Table 1) the data and the references of all of the works examined. This was felt to

be advisable in order to facilitate a more serious statistical analysis of additional accumulated experimental results that may be forthcoming in the future.

We will dwell briefly on the methods of determination of the density of liquid metals listed in Table 1. The method of "Hydrostatic Suspension" (Archimedes' Method) is subdivided into (1) the method of direct hydrostatic suspension, the essence of which is that a previously determined weight and volume standard is suspended in the investigated melt; (2) and the method of indirect hydrostatic suspension in which the investigated liquid metal in a crucible is suspended in a melt of known density, which is inert with respect to the metal of the standard.

The basis of the method of "dilatometry" consists of the determination of the height of the liquid metal and its change with temperature in the calibrated crucible.

In the pycnometer method the density of the liquid metal is determined by the weight of a certain volume. To this method also belongs the method of "Fixed Volume" in which, at a prescribed temperature one fixes the volume of the metal under study, and determines its weight subsequent to the experiment.

The method of "Maximum Pressure" in a gas bubble is based on the determination of the different pressures, necessary for the pressing out a bubble of gas through the capillary filled with the melt at various depths.

The "Gamma Method" is based on the study of the change of the intensity of γ -rays passing through the melt being studied.

The method of determining the density by the measurement of the size of liquid drops has a number of variations. In the "Resting Drop" method, one studies the form of the liquid drop lying on a solid flat surface. In the large drop method one investigates the form of induced symmetrical drops formed by heating the metal in small cups with specially machined edges. In the "Falling Drop" method a drop of the liquid metal is stopped on movie film as it separates from a rod and its elongation is studied. In the "Suspended Drop" method one studies a volume of metal suspended in a magnetic field. The method of determining density from the size of drops must also incorporate determining the volume of falling drops from the parameters of critically suspended drop.

TABLE 1. DENSITY OF LIQUID METALS

Metal	Year	References	Purity	Conditions of Experiment	t, °C	ρ_m g/cm ³	$-\frac{d\rho}{dt} \cdot 10^4$, g/cm ³ °C	Method, Accuracy
Li	1941	[114]	-	oil	181-195	0.46±0.01	-	Specific gravity flask
	1966	[20]	-	Mo, Ar (up to 65 atm)	332-1600	0.517	1.01	Specific gravity flask, 0.5%
	1967	[82]	-	Mo, 1 Kh 18 NPT	400-1125	0.503	1.021	Specific gravity flask, ±0.2%
	1970	[63]	99.85	-	242.5-917	0.504	0.95	Hydrostatic suspension, -0.3%
Na	1954-1955	[169]	-	-	up to 500	0.931	27	-
	1957	[67]	-	-	-	0.9385	2.6	-
	1963	[89]	-	Ar, steel	200-400	0.9271	2.23	Hydrostatic suspension
	1966	[20]	-	Ar, (up to 65 atm)	428-1512	0.9275	2.38	Specific gravity flask, 0.3%
K	1957	[67]	-	-	-	0.826	2.22	-
	1966	[20]	-	Ar (up to 65 atm), Mo	63.5-92	0.8274	2.38	Specific gravity flask, -0.3%
	1970	[9]	98.5	oil VM-1 (Calibrating liquid)	280-1500	0.8282	2.406	Dilatometry $\frac{d\rho}{dt} \approx 3\%$
Rb	1963	[118]	-	-	39-1100	1.5097	4.554	-
	1964	[118]	-	-	80-910	1.4740	4.10	-
	1967	[86]	97.5	glass, vacuum	45.5	1.4505	-	Specific gravity flask, 0.2%
	1967	[82]	-	1 Kh 18 NPT	50-800	1.4634	4.51	-
	1967	[11]	99.9	Ar 0.5-20 atm Kh 18 NPT	40.6-1103	1.4807	4.148	Gamma-method, up to 827° is linear, but not above
	1970	[9]	99.996	Oil VM-1 (Calibrating liquid)	39.16-92	1.4843	4.806	Dilatometry
	1970	[9]	99.996	Ar, Kh 18 N10T	39-300	1.4843	4.78±0.05	gamma-method
	1970	[9]	99.996	Ar, Kh 18 N10T	300-400	1.4843	4.28±0.05	gamma-method
	1973	[7]	99.95	Kh 18 NPT	39-1300	1.4843	*	gamma-method, 0.4%
Ca	1963	[118]	-	-	29-1100	1.8571	5.964	-
	1964	[118]	-	-	80-910	1.8747	5.97	-
	1967	[10,11]	99.9	Ar, Kh 18 NPT	33.7-852.2	1.8387	5.665	Gamma-method, 0.7%
	1967	[82]	-	Ar, Kh 18 NPT	100-750	1.8364	5.71	Specific gravity flask, 0.2%
	1970	[9]	99.99 Oxide impurity	Oil VM-1	28.5-51	1.8365	5.290	Dilatometry, $\Delta\rho/dT=1.5\%$
	1970	[9]	99.99 Oxide impurity	Ar, Kh 18 N10T	29-140	1.8365	5.42	Gamma-method
	1970	[9]	99.99 Oxide impurity	Ar, Kh 18 N10T	140-250	1.8365	5.19	Gamma-method
	1970	[63]	99.99	-	35.15-1027	1.8370 (35.15)	5.51	Differential hydrostatic suspension
	1970	[6]	99.98	Oil VM-1, glass	30-95	1.8445	6.00	Dilatometry, 0.05%
	1973	[7]	99.95	Ar, Kh 18 NPT	29-1300	1.8410	-*	Gamma-method, 0.4%
Cu	1929	[136]	-	-	1100-1200	7.98	15	Maximum pressures
	1949	[91]	Electrolyte	Ar, Al ₂ O ₃	1100-1450	8.34	12.67	resting drop
	1962	[99]	99.97	Ar, Al ₂ O ₃ , ZrO ₂ , graphite	1083-2227	7.922	8.006	Hydrostatic suspension
	1964	[143]	-	Ar, Al ₂ O ₃	1083-1500	8.03	7.88	Maximum pressures
	1964	[112]	-	Ar, Al ₂ O ₃	1460-1620	8.00	9.96	Maximum pressures
	1964	[143]	-	-	Up to 1600°	7.93	7.8	Hydrostatic suspension
	1964	[143]	-	-	Up to 1600°	8.09	7.6	-
	1964	[143]	-	-	Up to 1500	8.00	9.45	-
	1966	[1]	-	He, MgO	1083-1500	7.62	-	Specific gravity flask
	1971	[38,77,79]	V3, 99.997	He, graphite	1100-1450	8.039	9.6	Large drop, ±0.04 g/cm ³
	1972	[141]	Spectro-pure	Ar, W, Al ₂ O ₃ , ZrO ₂	1083-1650	7.938	7.26	Hydrostatic suspension
	1972	[80]	99.99	He, Al ₂ O ₃	1100-1300	7.927	7.5	Resting drop, ±1%
	1974	[85]	OVCh-11-4	He, Al ₂ O ₃	1089-1500	8.019	7.3	Gamma-method, ±0.016 g/cm ³

TABLE 1. DENSITY OF LIQUID METALS (Continued)

Metal	Year	References	Purity	Conditions of Experiment	$t, ^\circ\text{C}$	$\rho_m, \text{g/cm}^3$	$-\frac{d\rho}{dt} \cdot 10^4, \text{g/cm}^3 \cdot ^\circ\text{C}$	Method, Accuracy
Ag	1929	[136]	-	-	1100-1200	9.32	10	Maximum pressures
	1951	[116]	-	-	1000-1300	9.285	8.8	Hydrostatic suspension
	1961	[138]	-	N_2 , quartz	1050-1150	9.34	11	Maximum pressures, 0.4%
	1962	[122]	-	-	961-2177	9.346 ± 0.009	9.067	-
	1964	[143]	-	-	-	9.33	9.67	-
	1964	[143]	-	Ar, Al_2O_3	961-1400	9.33 ± 0.01	10.5	Maximum pressures
	1969	[155]	-	-	-	9.36	10.8	-
	1970	[174]	-	Ar, quartz	1030-1210	9.37	13	Maximum pressures, $\pm 0.35\%$
	1970	[42]	-	-	960-1540	9.36	6.2	Resting drop
	1971	[94]	-	-	960-1150	9.17	10.5	-
	1972	[141]	99.999	Ar, W	961-1500	9.320	9.7	Hydrostatic suspension
	1972	[80]	99.99	He, Al_2O_3	1000-1300	9.364	6	Resting drop, $\pm 1\%$
	1974	[3]	Sr999	Corundum, He	960-1530	9.35	6.1	Large drop, 0.5%
	1975	[149]	-	-	-	9.321	9.787	Hydrostatic suspension, $\pm 2.5 \times 10^{-3} \text{ g/cm}^3$
Au	1929	[136]	-	-	1100-1300	17.24	12	Maximum pressures
	1951	[116]	-	-	1100-1300	17.361	17.3	Hydrostatic suspension
	1971	[94]	-	-	t_m	17.0	11.2	-
	1975	[77]	ZL999.9	He, graphite	1075-1405	17.19	12.7	Resting drop, $\pm 0.06 \text{ g/cm}^3$
Be	1964	[120]	99.8	BeO, Ar	1283-1927	1.690	1.16	Maximum pressures
	1968	[58]	99.6	Vacuum, He	Near t_m	1.70	-	Resting drop
	1968	[58]	99.9	He	1284	1.72	-	Resting drop
Hg	1962	[153]	99.95	Ar, Steel	650-1117	1.590	2.647	Hydrostatic suspension, $\pm 0.0014 \text{ g/cm}^3$
	1968	[97]	99.5	Ar, W	959-1053	1.52; 1.47	-	Maximum pressures, 1.5%
	1972	[80]	99.99	He, Al_2O_3	700-900	1.65	2.7	Resting drop, 1%
Ca	1957	[106]	0.092N	Graphite, Vacuum	812-883	1.373	8.87	Specific gravity flask
	1968	[97]	pro. an.	Ar, Ta	1172-1382	1.3672	2.21	Maximum pressures 1.5%
	1972	[80]	99.99	He, Al_2O_3	800-1000	1.45	3.1	Large drop, 1%
Sr	1968	[97]	99.5	Ar, Ta	952-1307	2.3742	2.62	Maximum pressures 1.5%
Ba	1962	[90]	99.99	Ar, steel, W	740-930	3.3208	2.14	Hydrostatic suspension
	1968	[97]	99.5	Ar, Ta	1137-1607	3.3165	2.74	Maximum pressures, 1.5%
Zn	1921	[123]	-	H_2 , Steel	-	6.59	9.7	Different pressures in a cut U-tube 0.1%
	1949	[159]	-	Flux	420-600	6.65	11.0	Maximum pressures
	1964	[143]	-	Ar, Al_2O_3	420-700	6.577 ± 0.012	10.98-6%	Maximum pressures
	1968	[171]	99.998	Ar, graphic	420-700	6.5519	9.502	Specific gravity flask, 0.05%
	1974	[107]	99.99	Graphite, Ar	420-520	6.542	7.9	Specific gravity flask, $\pm 0.03 \text{ g/cm}^3$
	1974	[160]	99.999	Graphite, Ar	420-523	6.568	10.33	Specific gravity flask
	1975	[39]	TaVCh; 99.999	Molybdenum glass, vacuum	t_m -500	6.610	10.0	Improved areometer

TABLE 1. DENSITY OF LIQUID METALS (Continued)

Metal	Year	References	Purity	Conditions of Experiment	t, °C	ρ_m g/cm ³	$-\frac{d\rho}{dt} \cdot 10^4$, g/cm ³ °C	Method, Accuracy
Cd	1921	[123]	-	H ₂ , Glass	-	8.02	11.0	Different pressures in a cut U-tube, 0.1%
	1947	[117]	99.97	Quartz, H ₂	340-500	8.013	12.79	Maximum pressures
	1956	[165]	-	Ar, Al ₂ O ₃	385-560	8.015	11.49	Maximum pressures, 0.2%
	1968	[102]	99.999	Ar, graphite	385.4-436.7	7.9962	12.205	Specific gravity flask, 0.5%
	1972	[80]	99.99	He, Al ₂ O ₃	500-1000	8.1	6.0	Resting drop, 1%
	1974	[2]	-	Glass	321-500	7.987	12.5	Areometer, 0.1%
	1974	[156]	-	Quartz	680-1093	7.968	11.87	Dilatometry, 0.1%
	1974	[160]	99.999	Graphite, Ar	404-530	7.986	12.62	Specific gravity flask
	1975	[39]	99.999	Molybdenum glass, vacuum	t _m -500	7.996	12.2	Improved areometer, 0.1%
Hg	1964-1965	[96, 119]	-	-	-20-300	13.69098	-	
	1973	[113]	Purified	-	20	13.545842		Hydrostatic suspension $\pm 9.5 \cdot 10^{-7}$ g/cm ³
	1975	[39]	-	Molybdenum glass, vacuum	30-250	13.636	22.0	Improved areometer, 0.1%
La	1972	[80]	99.99	He, Al ₂ O ₃	850-1000	5.9	3.2	Large drop, 1%
Pr	1965	[147]	99.8	Ar, Ta	1240	6.27		Hydrostatic suspension
	1972	[80]	99.99	He, Al ₂ O ₃	950-1000	6.43	3.0	Large drop, 1%
Ce	1966	[161]	99.9	Vacuum	870-1173	6.681	2.27	Specific gravity flask ± 0.027 g/cm ³
Nd	1965	[147]	99.6	Ar, Ta	1240	6.46		Hydrostatic suspension
	1966	[161]	99.6	Vacuum	1035-1231	6.6882	5.28	Specific gravity flask ± 0.019 g/cm ³
Pu	1964	[158]	99.95	-	-	16.635	14.1	-
B	1963	[69]	99.8	BNC, Vacuum graphic	2225±50	2.08±0.03		Resting drop
Al	1953	[115]	99.996	KCl-NaCl	700-900	2.368	2.65	Hydrostatic suspension (indirect), 0.2%
	1961	[60]	99.99	Vacuum, Al ₂ O ₃	700-1300	2.38	2.5	Large drop
	1965	[100]	99.997	Ar, Alundum	677-912	2.39	3.34	Maximum pressures
	1965	[21]	99.99	Ar, graphite	991-1460	2.369	3.11	Dilatometry, 0.5%
	1968	[48]	99.996	He, Al ₂ O ₃	660-1500	2.38	-*	Large drop, 1%
	1968	[5, 50]	99.99	He, Al ₂ O ₃	900-1750	2.39	3.2	Large drop, 1%
	1971	[132]	99.998	Ar, Al ₂ O ₃	702-784	2.375	5.4	Resting drop
	1972	[22]	99.99	H ₂ BeO	1830	1.95		Large drop, 1.5%
	1972	[88]	Al-000	Vacuum, Al ₂ O ₃	660-977	2.370	2.8	Large drop, 1.5%
	1972	[74]	A 999	Al ₂ O ₃ , Helium	690-1550	2.41	3.48	Resting drop, ± 0.027 g/cm ³
	1974	[111]	-	-	700-900	2.379	2.58	Dilatometry
	1974	[111]	-	-	700-900	2.379	2.58	Dilatometry
Ga	1941	[148]	-	Glass, benzene	30-40	6.097	7	Specific gravity flask
	1965	[62, 74]	GL-00	He, Al ₂ O ₃ , graphite	30-1550	6.08	6.0	Large drop, ± 0.029 g/cm ³
	1967	[10, 11]	99.9	Ar, quartz	30-232	6.0954	7.208	Gamma method, 0.25%
	1967	[10, 11]	99.9	Ar, quartz	232-747	6.073	6.122	Gamma method, 0.25%
	1967	[10, 11]	99.9	Ar, quartz	747-1127	6.1422	5.127	Gamma method, 0.25%
	1970	[174]		Ar, quartz	900-1210	6.05	6	Maximum pressure, 0.35%
	1970	[133]	99.999	Ar, W	50-600	6.0283	-*	Specific gravity flask
	1972	[88]	Ga-000	Al ₂ O ₃	30-977	6.12	6.2	Large drop, 1.5%
	1974	[2]		Glass	300-500	6.072	6.625	Areometer, 0.1%
	1974	[8]	99.999	Ar, glass	19-56	6.04502	7.9338	Specific gravity flask, $\pm 2.4 \cdot 10^{-4}$ g/cm ³
	1975	[39]	99.999	Glass, vacuum	t _m -450	6.072	6.62	Improved areometer, 0.1%

TABLE 1. DENSITY OF LIQUID METALS (Continued)

Metal	Year	References	Purity	Conditions of Experiment	t, °C	ρ_m g/cm ³	$-\frac{d\rho}{dt} \cdot 10^4$, g/cm ³ °C	Method, Accuracy
In	1941	[114]	-	-	155	7.03±0.01		Dilatometry, $\alpha=0.00013$ °C ⁻¹
	1950	[173]	99.98	Paraffin in Ar, quartz	164-300	7.0324	8.13	Dilatometry, 0.2%
	1956	[165]	-	Ar, Al ₂ O ₃	231-421	7.05	8.16	Maximum pressures, 0.2%
	1962	[152]	99.977	Ar, glass, graphite, Mo	157-2013	7.023	6.798	Hydrostatic suspension, ±0.023, g/cm ³
	1968	[102]	99.999	Vacuum, graphite	161.0-264.6	7.0147	8.362	Specific gravity flask
	1970	[174]	-	Ar, quartz	595-890	6.95	5.0	Maximum pressures, 0.35%
	1970	[95]	99.999	Ar, W, graphite	160-532	7.034	7.59	Hydrostatic suspension, ±0.02 g/cm ³
	1972	[80]	99.99	He, Al ₂ O ₃	500-1000	7.12	7	Resting drop, 1%
	1972	[88]	In-000	Vacuum, Al ₂ O ₃	157-677	7.035	4.3	Large drop, 1.5%
	1974	[2]	-	Glass	156-500	6.982	7.40	Areometer, 0.1%
	1974	[156]	-	Quartz	485-835	7.027	8.29	Dilatometry, 0.1%
	1975	[39]	99.999	Glass, vacuum	t _m -500	6.982	7.40	Improved areometer, 0.1%
Ti	1956	[165, 166]	-	Ar, Al ₂ O ₃	392-651	11.29	14.94	Maximum pressures, 0.3%
	1968	[101]	99.999	Ar, graphite	314.5-508.0	11.227	14.39	Specific gravity flask, 0.05%
	1970	[174]	-	Ar, quartz	500-900	11.31	17	Maximum pressures, 0.35%
	1973	[150]	99.999	Vacuum, W	304-905	11.350	13.0	Hydrostatic suspension, ±0.003 g/cm ³
	1975	[39]	TL-11, 99.99	Molybdenum, glass vacuum	t _m -500	11.21	14.2	Improved areometer, 0.1%
	1975	[31, 38, 77]	TL-00, 99.99	Graphite	316-1010	11.28	14.3	Resting drop, ±0.04 g/cm ³
Ti	1956	[28]	98.7; 0.83% C	He, vacuum	1668±20	4.11±0.08		Specific gravity flask
	1961	[151]	Ionized	Vacuum, graphite	1700-2050	4.11	7.02	Maximum pressures
	1968	[26]	-	Vacuum	1668	4.10		Falling drop, 7%
	1969	[164]	99.8	Ar	1720-2100	4.14	2.26	Suspended drop, 1.42%
	1970	[27]	-	Vacuum	1668	4.10		Falling drop
	1973	[36]	-	Vacuum	1668	4.13		Combined, 0.4%
Zr	1961	[151]	Ionized	Vacuum, graphite	1850±20	6.09		Specific gravity flask
	1968	[26]	-	Vacuum	1850	5.70		Falling drop, 7%
	1970	[27]	-	Vacuum	1850	5.60		Falling drop, 7%
	1973	[36]	-	Vacuum, Ar	2460	5.78		Falling drop, 7%
	1973	[75]	-	Vacuum	1850	6.09		Combined, 0.8%
Hf	1973	[36]	-	Vacuum	2222	11.97		Combined, 0.9%
Si	1959	[139]	-	Quartz, air	1425	2.49±0.002		Specific gravity flask
	1960	[18]	-	H ₂ Al ₂ O ₃	1500	2.49		Hydrostatic suspension, 1-1.5%
	1963	[14]	-	He, Al ₂ O ₃	1440	2.56		Dilatometry, 2%
	1964	[143]	99.9	Ar, Al ₂ O ₃	1450-1630	2.525±0.05	3.5	Maximum pressures
	1964	[1]	-	He, MgO	1500	2.50		Specific gravity flask
	1964	[24]	99.999	He, Al ₂ O ₃	1500	2.54		Resting drop, 5%
	1965	[12]	99.999	He, Al ₂ O ₃	1410-1800	2.530	3.375	Large drop, 1%
	1967	[19]	-	Flux, Al ₂ O ₃	1455-1633	2.53	3.9	Hydrostatic suspension, 1.5%
	1970	[81]	99.99	He, Al ₂ O ₃	1412-1850	2.55	1.7	Large drop, 1%
	1971	[25]	99.999	He, BN	1410-1700	2.49	2.722	Resting drop, 1.5%
	1975	[77, 78]	KM-8	He, Al ₂ O ₃	1500-1590	2.50	3.2	Resting drop, g/cm ³

TABLE 1. DENSITY OF LIQUID METALS (Continued)

Metal	Year	References	Purity	Conditions of Experiment	t, °C	ρ_m g/cm ³	$-\frac{d\rho}{dt} \cdot 10^4$, g/cm ³ °C	Method, Accuracy
Ge	1952	[59]	99.9	Vacuum, quartz	960-1100	5.52		Dilatometry
	1964	[143]	High purity	Ar, Al ₂ O ₃	960-1630	5.490	4.86	Maximum pressures
	1967	[19]	-	Vacuum, quartz	975-1120	5.52	7.5	Specific gravity flask
	1968	[70,71]	-	Graphite, quartz	959-1827	5.598	6.250	Large drop, 0.8%
	1968	[51,53]	99.999	He	950-1600	5.60	7.34	Large drop, 1%
	1971	[79]	99.999	He, graphite	936-1400	5.655	6.0	Large drop
	1972	[80]	99.99	He, Al ₂ O ₃	950-1200	5.68	6.2	Large drop, 1%
	1972	[74]	GES	He, Al ₂ O ₃	980-1500	5.54	4.87	Resting drop, ± 0.025 g/cm ³
	1975	[149]	5M5		980-1200	5.576	3.708	Hydrostatic suspension, ± 0.02 g/cm ³
	1975	[77]	GDC-06/05	He, graphite	1030-1410	5.63	5.3	Resting drop, ± 0.02 g/cm ³
Sn	1921	[123]	-	H ₂ , glass	-	7.01	7.4	Different Pressures in a cut U-tube
	1949	[159]	-	Flux	232-600	6.98	7.61	Maximum pressures
	1962	[129]	-	-	232-2480	7.000	6.127	Hydrostatic suspension, ± 0.011 g/cm ³
	1964	[143]	-	Ar, Al ₂ O ₃	232-1600	6.978 ± 0.022		Maximum pressures
	1964	[112]	-	Ar, Al ₂ O ₃	400-1000	6.923	5.543	Maximum pressures
	1968	[172]	99.999	Vacuum, graphite	240-500	6.974	7.125	Specific gravity flask, 0.05%
	1970	[95]	99.999	Ar, W graphite	232-438	6.981	6.63	Hydrostatic suspension, 0.02% g/cm ³
	1971	[17]	-	Ar, quartz	232-1131	6.988	6.983	Dilatometry, 0.2%
	1972	[141]	99.999	Ar, W	232-1400	6.986	6.37	Hydrostatic suspension
	1972	[80]	99.99	He, Al ₂ O ₃	500-1000	6.88	5.7	Large drop, 1%
	1972	[88]	OVCh	Vacuum, Al ₂ O ₃	232-677	6.95	1.94	Large drop, 1%
	1972	[74]	OVCh-000	He, quartz graphite	880-1590	6.52	4.94	Resting drop, ± 0.063 g/cm ³
	1974	[156]	-	Quartz	629-908	6.969	7.25	Dilatometry, 0.1%
	1975	[77]	OVCh-000	He, graphite	232-1410	6.91	6.1	Resting drop, ± 0.01 g/cm ³
Pb	1921	[123]	-	H ₂ , glass	-	10.71	13.9	Different pressures in a cut U-tube, 0.1%
	1947	[117]	99.97	H ₂ quartz	340-440	10.59	14.0	Maximum pressures
	1956	[165, 166]	-	Ar, Al ₂ O ₃	437-705	10.66	13.25	Maximum pressures 0.2%
	1961	[130]	99.9	Ar, graphite	327.6-1751	10.678	13.174	Hydrostatic suspension, ± 0.0027 g/cm ³
	1962	[122]	99.9	Ar, graphite	327.6-1751	10.678	13.174	Hydrostatic suspension
	1962	[137]	-	-	327-850	10.686	11.6	Specific gravity flask
	1967	[10,11]	99.96	Ar, steel	372.7-1056	10.676	12.887	Gamma method, 0.4%
	1968	[172]	99.997	Vacuum, graphite	320-530	10.660	12.220	Specific gravity flask, 0.05%
	1969	[157]	99.999	Quartz	380-440	10.662	13.1	Specific gravity flask, ± 0.008 g/cm ³
	1969	[142]	99.999	Ar, Al ₂ O ₃ , W	330-1550	10.665	-*	Hydrostatic suspension, ± 0.003 g/cm ³
	1972	[141]	99.99	Ar, W	330-1550	10.665	-*	Hydrostatic suspension
	1972	[80]	99.99	He, Al ₂ O ₃	400-1000	10.39	9.8	Large drop, 1%
	1973	[150]	99.99	Vacuum, W	405-700	10.696	11.73	Hydrostatic suspension, ± 0.003 g/cm ³
	1975	[39]	C-000	Molybdenum glass, vacuum	t _m = 500	10.640	12.2	Improved arcometer, 0.1%
	1975	[31,38, 77]	99.999	H ₂ , graphite	337-1026	10.69	11.6	Resting drop, ± 0.04 g/cm ³
V	1961	[151]	99.5	Vacuum, BeO	1930-1940	5.734		Maximum pressures
	1968	[25]	-	Vacuum	1905	6.90		Falling drop, 7%
	1969	[164]	99.8	Ar	1920-2190	5.36	3.20	Suspended drop, 1.43%
	1970	[27]	-	Vacuum	1905	5.3		Falling drop
	1973	[30,37]	99.7 soned	Vacuum	1905	5.39		Combined, 0.46%

TABLE 1. DENSITY OF LIQUID METALS (Continued)

Metal	Year	References	Purity	Conditions of Experiment	t, °C	ρ_m g/cm ³	$-\frac{d\rho}{dt} \cdot 10^4$, g/cm ³ °C	Method, Accuracy
Nb	1968	[26]	-	Vacuum	2468	7.60		Falling drop
	1970	[27]	-	Vacuum	2468	7.6		Falling drop
	1973	[30,37]	Monocrystal- line	Vacuum	2468	7.57		Combined, 0.52%
Ta	1972	[30]	TVCh 99.94	Vacuum	t_m	14.13		Combined, 1.3%
P	1960	[131]	-	Quartz	580-680	1.16	-*	Specific gravity flask
As	1960	[131]	-	Quartz	830-850	5.06(850°C)		Specific gravity flask
Sb	1947	[117]	99.5	H ₂ , quartz	650-800	(at 650°C)		Maximum pressures
	1956	[165]	-	Ar, Al ₂ O ₃	728-917	6.50	6.30	Maximum pressures, 0.2%
	1960	[131]	-	Quartz	630-850	6.500	5.14	Specific gravity flask
	1962	[128]	99.992	Graphite	630-1637	6.483	*	Hydrostatic suspension, maximum pressures, ± 0.008 g/cm ³
	1964	[143]	99.6	Ar, Al ₂ O ₃	630-1120	6.465 $\pm$ 0.005	5.87	Maximum pressures
	1970	[174]	-	Ar, quartz	670-1010	6.48	6	Maximum pressures, 0.35%
	1970	[95]	99.999	Ar, graphite, Mo	635-745	6.538	6.73	Hydrostatic suspension, ± 0.02 g/cm ³
	1972	[103]	-	Ar, graphite	642-746	6.493	6.486	Specific gravity flask, 0.05%
Bi	1974	[156]	-	Quartz	925-1149	6.48]	6.68	Dilatometry, 0.1%
	1921	[123]	-	H ₂ , glass	-	10.07	12.5	Different pressures in a cut U-tube, 0.1%
	1958	[124]	-	Nitrogen, pyrex	311-442	10.040	12.9	Specific gravity flask, ± 0.004 g/cm ³
	1959	[154]	99.90	H ₂ , quartz	800-1000	10.17	14	Maximum pressures, 1%
	1963	[98]	99.972	Graphite	271.5-1559	10.022	11.820	Hydrostatic suspension, ± 0.013 g/cm ³
	1964	[143]	99.98	Ar, Al ₂ O ₃	320-1000	10.065 $\pm$ 0.02	12.10	Maximum pressures
	1964	[105]	99.995	H ₂ , Ar, quartz	271-750	10.057 $\pm$ 0.03	12.6 $\pm$ 0.2	Manometer + specific gravity flask, ± 0.008 g/cm ³
	1969	[157]	99.995	Quartz	320-420	10.048	12.64	Specific gravity flask, ± 0.008 g/cm ³
	1970	[125]	99.9999	Nitrogen, glass	271-720	10.05	14.1	Dilatometry, 0.7%
	1970	[95]	99.999	Ar, graphite, W	271-414	10.114	10.78	Hydrostatic suspension, ± 0.02 g/cm ³
	1971	[104]	-	Vacuum, graphite	340-430	10.028	12.367	Specific gravity flask, 0.05%
	1972	[80]	99.99	He, Al ₂ O ₃	300-1000	10.12	9.7	Large drop, 1%
	1972	[92]	-	Ar, Ta, W	271-600	10.049	12.4	Hydrostatic suspension, ± 0.002 g/cm ³
	1974	[2]	-	Glass	271-500	10.200	12	Areometer, 0.1%
	1974	[160]	99.99	Graphite	384-534	10.07	12.6	Specific gravity flask
Cr	1975	[39]	OSCh-11-4 99.999	Molybdenum glass, vacuum	t_m -500	10.020	12.0	Improved areometer, 0.1%
	1959	[32]	Electrically sublimated	H ₂ , BeO	1875-1950	6.00 $\pm$ 0.13		Resting drop
	1963	[61]	Purified twice	H ₂ , ZrO ₂	1860	6.21		Resting drop
	1968	[50,53]	99.98	He, Al ₂ O ₃	1835-1915	6.4075	3	Large drop, 1%
	1969	[164]	99.79	He, Al ₂ O ₃	1890-2230	6.28	7.23	Falling drop, 1.43-1.55%
	1971	[46]	99.98	-	1835-1915	6.16	9.1	Large drop
	1972	[22]	99.95	H ₂ , BeO	1830	6.16		Large drop

TABLE 1. DENSITY OF LIQUID METALS (Continued)

Metal	Year	References	Purity	Conditions of Experiment	t, °C	ρ_m g/cm ³	$\frac{d\rho}{dt} \cdot 10^4$, g/cm ³ °C	Method, Accuracy
Mo	1968	[26]	-	Vacuum	2615	9.0		Suspended drop, 7%
	1970	[27]	-	Vacuum	2615	9.1		Suspended drop
	1974	[29]	99.95 sintered	Vacuum	t_m	8.9		Combined, 3%
W	1968	[26]	Monocrystalline	Vacuum	t_m	16.65		Combined, 6%
	1974	[29,55]	Monocrystalline, 99.999		t_m	16.74		Combined, 0.6%
Se	1960	[131]	-	Quartz	223-301	3.981	12.5	Specific gravity flask, 0.5%
	1967	[19]	-	Vacuum, quartz	230-819	3.38	10.7	Specific gravity flask, 0.5%
	1970	[174]	-	Ar, quartz	240-600	4.00	-*	Maximum pressure, 0.5%
	1972	[141]	Ultra-pure	Argon	172-400	4.013±0.02	11.67	Hydrostatic suspension
Te	1964	[143]	High	Ar, Al ₂ O ₃	460-750	5.797	5.39	Maximum pressures
	1967	[19]	-	Vacuum, quartz	492-1000	5.83	8	Specific gravity flask, 0.5%
	1970	[174]	-	Ar, quartz	450-900	5.69	-*	Maximum pressures
	1970	[125]	99.7	Nitrogen, glass	451-720	5.86	7.3	Dilatometry, 0.7%
Mn	1963	[14]	-	He, Al ₂ O ₃	1244-1440	5.81		Specific gravity flask
	1966	[23]	99.9	He, Al ₂ O ₃	1350-1550	5.72	7	Resting drop, 2.5%
	1969	[164]	99.9	Ar	1660-1900	5.76	9.30	Suspended drop, 1.45-2.31%
	1974	[87]	99.75	Ar	1350-1550	5.58	7.0	
Re	1976	[56]	Zoned-refined (Specimen)	Vacuum	t_m	18.4		Combined, 0.6%
Fe	1929	[108]	0.04% C	Al ₂ O ₃	1545	6.97		Hydrostatic suspension
	1930	[93]	0.03% C	MgO, W	1535-1710	7.225	10	Manometer
	1949	[91]	Carbonized	Ar, Al ₂ O ₃	1510-1700	7.13	10	Lying drop
	1953	[167]	99.9	Vacuum, H ₂ , Al ₂ O ₃	1564	7.0		Specific gravity flask
	1937	[135]	99.98	Ar, H ₂ , BeO	1550	7.2		Resting drop
	1960	[144, 146]	99.95	Ar, Al ₂ O ₃	1550-1700	7.037	14.5	Maximum pressures
	1962	[127]	99.90	Ar, Al ₂ O ₃	1527-2227	7.014	8.358	Hydrostatic suspension, ±0.009 g/cm ³
	1963	[121]	-	-	1532-2827	7.015	8.83	Maximum pressures + hydrostatic suspension
	1963	[14]	-	He, Mo, Al ₂ O ₃	1600	7.11		dilatometry, 2%
	1964	[15]	99.99	-	1535-1850	7.03	*	Large drop, 0.2%
	1964	[24]	99.99	He, Al ₂ O ₃	1500	7.13		Resting drop, 5%
	1964	[112]	-	Ar, Al ₂ O ₃	1535-1635	7.075	12.34	Maximum pressures, 0.85%
	1965	[68,76]	99.99	He, Al ₂ O ₃ , BeO	1535-1880	7.00	8.62	Large drop, 0.5%
	1965	[64]	99.93	He, H ₂ , Al ₂ O ₃	1550	7.13		Large drop, 1.5%
	1966	[1]	-	He, MgO	1540	7.036	8.17	Specific gravity flask
	1967	[163]	99.9	Ar	1535-2200	7.02	8.17	Suspended drop
	1968	[45]	99.99	He, Al ₂ O ₃	1535-1900	7.06	-*	Large drop, 0.5-1%
	1968	[72]	99.9	He, Al ₂ O ₃	1535-1750	7.146	10	Large drop, 1%
	1969	[162, 164]	99.9	Ar	1800-2150	7.03	8.53	Suspended drop, 1.44%
	1969	[164]	99.9	Ar, Al ₂ O ₃	1535-2150	7.04	8.53	Maximum pressures + suspended drop
	1969	[65]	99.99	H ₂ , Al ₂ O ₃	1535-1850	7.05	7.3	Large drop, 1.8%
	1970	[44]	V-3	Ar, nitrogen	-	7.03	12	Large drop

TABLE 1. DENSITY OF LIQUID METALS (Continued)

Metal	Year	References	Purity	Conditions of Experiment	t, °C	ρ_m g/cm ³	$\frac{d\rho}{dt}$ · 10 ⁴ , g/cm ³ · °C	Method, Accuracy
Fe	1971	[43]	V-3	Vacuum, H ₂ , BeO, H ₂ + Nitrogen	1535-1950	7.05	8	Large drop, 1%
	1972	[57]	A-2, 99.999	He, Al ₂ O ₃	1535-1800	7.07	8.30	Large drop, 1%
	1972	[140]	99.96	Ar, ZrO ₂	1535-1700	7.024	6.2	Hydrostatic suspension, ±0.03 g/cm ³
	1972	[35,74]	A-2, V-3	He, blackening ZrO ₂	1540-1750	7.05	7.2	Resting drop, ±0.018 g/cm ³
	1973	[41]	99.94	He	1600	7.0		Resting drop
	1973	[41]	99.94	He	1535-1650	7.05	6.96	Gamma method, 0.3%
	1974	[85]	V-3	He, Al ₂ O ₃	1539-1750	7.078	6.5	Gamma method, ±0.014 g/cm ³
Co	1957	[135]	99.99	Ar, Al ₂ O ₃ , ArO ₂ , ThO ₂	1550	7.8	-	Resting drop
	1960	[144, 146]	99.99	Ar, Al ₂ O ₃	1500-1700	7.67	11.97	Maximum pressures
	1963	[61]	Cathode	Vacuum, Al ₂ O ₃	1600	7.84		Resting drop
	1963	[126]	99.9	Ar, ZrO ₂ , ThO ₂	1495-2127	7.989	10.857	Maximum pressures, ±0.02 g/cm ³
	1964	[15]	99.89	-	1492-1650	7.76	*	Large drop, 0.2%
	1964	[112]	-	Ar, Al ₂ O ₃	1500-1580	7.761	16.52	Maximum pressures, 0.85%
	1965	[68,76]	99.2	He, BeO, Al ₂ O ₃	1492-1880	7.71	10.2	Large drop, 0.5%
	1966	[23]	99.99	He, Al ₂ O ₃	1550	7.62		Resting drop, 2.5%
	1967	[163]	99.53	Ar	1492-2200	7.76	9.88	Suspended drop
	1968	[72]	99.99	He, Al ₂ O ₃	1500-1750	8.005	10.0	Large drop, 1%
	1969	[162]	99.9e	Ar	1780-2200	7.77	10.17	Suspended drop, 1.44%
	1969	[164]	99.53	Ar, Al ₂ O ₃	1492-2200	7.74	9.50	Maximum pressures + suspended drop
	1969	[4,49]	99.98	Ar	1500-1750	8.06	12.5	Large drop, 1%
	1970	[81]	99.99	He, Al ₂ O ₃	1492-1850	7.87	8.1	Large drop, 1%
	1972	[140]	99.95	Ar, Al ₂ O ₃ , ZrO ₂	1492-1750	7.75	7.1	Hydrostatic suspension, ±0.06 g/cm ³
Ni	1930	[93]	0.2% C	MgO, CO, W	1500	7.764		Manometer
	1960	[144, 146]	99.85	Ar, Al ₂ O ₃	1471-1671	7.77	10.81	Maximum pressures
	1963	[126]	99.8	Ar, ZrO ₂ , ThO ₂	1455-2127	7.905	11.589	Hydrostatic suspension, ±0.020 g/cm ³
	1963	[34,61]	Electrolytic 99.99	He, Al ₂ O ₃	1500-1790	7.78	6.0	Resting drop
	1964	[15]	99.7	-	1453-1850	7.83	-*	Large drop, 2%
	1965	[68,76]	99.99	He, BeO, Al ₂ O ₃	1453-1880	7.83	10.4	Large drop, 5%
	1966	[1]	-	He, MgO	1500	7.67		Specific gravity flask
	1966	[23]	99.98	He, Al ₂ O ₃	1500	7.70		Resting drop, 2.5%
	1967	[163]	99.95	Ar	1453-2200	7.91	10.00	Suspended drop
	1968	[72]	99.99	He, Al ₂ O ₃	1455-1750	7.908	13	Large drop, 1%
	1969	[162, 164]	99.95	Ar	1890-2150	7.95	10.80	Suspended drop, 1.44%
	1969	[164]	99.95	Ar, Al ₂ O ₃	1453-2150	7.89	9.91	Maximum pressure + suspended drop
	1969	[65]	99.99	He, Al ₂ O ₃	1453-1850	7.81	8.7	Large drop, 1.8%
	1969	[4,52]	99.9	Ar	1453-1750	7.93	12.5	Adp/dT-8%
	1972	[140]	99.85	Ar, ZrO ₂	1453-1700	7.79	6.8	Hydrostatic suspension, ±0.03 g/cm ³
Pd	1961	[144, 45]	99.95	Ar, Al ₂ O ₃	1560-1805	10.49	11.94	Maximum pressures
	1968	[72]	99.99	He, Al ₂ O ₃	1560-1750	10.398	11.59	Large drop, 1%
	1974	[54]	Pd; 99.9	Vacuum	t _m	10.52		Combined, 0.83%
Ir	1974	[54]	99.9	Vacuum	t _m	19.39	-	Combined, 0.71%

TABLE 1. DENSITY OF LIQUID METALS (Continued)

Metal	Year	References	Purity	Conditions of Experiment	t, °C	ρ_m g/cm ³	$-\frac{d\rho}{dt} \cdot 10^4$, g/cm ³ °C	Method, Accuracy
Pt	1959	[33]	99.8	Vacuum, BeO	1769	19.7±0.25		Resting drop
	1961	[144, 145]	-	Ar, Al ₂ O ₃	1780-1870	18.91	26.9	Maximum pressures
	1961	[134]	99.999	Ar, Al ₂ O ₃	1800	18.82±0.02		Resting drop
	1974	[54]	P1; 99.93	Vacuum	t_m	18.81		Combined, 0.74%

*Temperature dependence of the density is not straight-forward.

It may be of interest to note that the method of determining the density according to the dimensions of the liquid drop has been used to produce 40% of the data; the method of "Maximum Pressure" in a gas bubble, 20%; the method of the "Specific Gravity Flask", 17%; and the "Hydrostatic Suspension" method, 15%.

In Table 1 we include only those works in which the temperature dependence of the density in the investigated temperature range is given by the linear dependence

$$\rho = \rho_m - \frac{d\rho}{dt} (t - t_m) \quad (1)$$

Table 1 is arranged according to the grouping of the periodic order proposed by D.J. Mendeleev for convenience in systematizing of the metals.

We could not include in the table the temperature dependence of the density of lithium, sodium, and potassium obtained in ref. [170] by the method of maximum pressure in the gaseous bubble because the experimental data were presented only in graphical form from which it was very difficult to read the numerical data with an adequate degree of accuracy.

Also not included in Table 1 is the value of the density of liquid rubidium in the range 870-1720°C and liquid cesium in the temperature range 600-1770°C presented in ref. [109]. The author of ref. [118] extrapolated the values of the density for rubidium, obtained in the ref. [109] by means of the equation.

$$\rho_{Rb} = 1.568 - 4.769 \times 10^{-4} t \quad (2)$$

For the case of some metals, the temperature dependence of density is very complex; therefore, they are not presented in the table.

On the basis of the analysis of the literature data through 1967, the authors proposed in the temperature range from the melting point to 1400°C the following interpolation equation for the density of liquid potassium

$$\rho_K = 0.843 - 2.3 \times 10^{-4} t - 8 \times 10^{-9} t^2 \quad (3)$$

However, for liquid cesium, for temperatures up to 1300°C, the equation is

$$\rho_{Cs} = 1.857 - 5.08 \times 10^{-4} t - 0.087 \times 10^{-6} t^2 \quad (4)$$

Presented in ref. [6] are the tabulated values of the density of liquid rubidium up to 1400°C. The data for rubidium, in the temperature range from 270° up to 1336°C, can be approximated by the following equation with a root mean square deviation of $\pm 0.28\%$.

$$\rho_{\text{Rb}} = 1.361 - 0.041 \left(\frac{t-300}{100} \right) - 2.6 \times 10^{-4} \left(\frac{t-300}{100} \right)^2 - 21.1 \times 10^{-4} \left(\frac{t-300}{100} \right)^3$$

The density of liquid cesium can be described over the full temperature range by a single equation

$$\rho_{\text{Cs}} = 1.747 - 0.056 \left(\frac{t-200}{100} \right) - 6.2 \times 10^{-4} \left(\frac{t-200}{100} \right)^2 \quad (6)$$

Information about the early investigations of the density of liquid copper is compiled in ref. [143].

Supplementary information can be obtained from ref. [153] for magnesium. According to [153], works up to 1941 encompass a narrow temperature range of investigation of the density of liquid magnesium. The observed values of the density of liquid magnesium at the melting point conform well among themselves and with the data of [153]. While the values of the temperature coefficient ρ varies from -0.8×10^{-4} to $-18.1 \times 10^{-4} \text{ g cm}^{-3} \text{ C}^{-1} \cdot \text{degree}$.

It must be noted that in ref. [153], to which we give preference, that during the investigation, the magnesium was floated in a steel cup; and at the time of the experiment, up to 0.5% of the steel went into the melt. Although the authors introduced an appropriate correction for the presence of iron in magnesium for specific values of density, the value of the temperature coefficient of the density of magnesium is impossible to compute with certainty.

As noted from Table 1, an indirect dependence of density on temperature is found. The data are presented by the equation for the temperature dependence of the thermal coefficient of volumetric expansion of liquid mercury

$$\alpha \times 10^8 = 18144.01 + 0.7016 t + 28.625 \times 10^{-4} t^2 + 2.216 \times 10^{-6} t^3 \quad (7a)$$

However, for temperatures up to 300°C the data of refs. [96, 119] can be represented with a precision of $\pm .01\%$ by the following equation:

$$\rho_{\text{Hg}} = 13.69035 - 2.41 \times 10^{-3} (t-234.3) \quad (7b)$$

Ref. [110] reports data on the density of mercury, with a purity of 99.99%, in the temperature range of 20-1450°C and pressures of 1-1500 atm. The results are tabulated in the ref. [110].

Reference [16] reports values of the atomic volumes of liquid uranium and of plutonium at the melting point (13.30 and 14.52 cm³ g·atom⁻¹, respectively) from which it follows that the density of liquid uranium at the melting point equals 17.90 g cm⁻³ and for plutonium it is 16.80 g cm⁻³.

Reference [168] indicates that in a series of works the temperature dependence of liquid uranium and plutonium was investigated. Unfortunately, however, we were not able to locate the original references.

Reference [148] reports on the indirect dependence on temperature of the density of liquid aluminum. In the temperature range of 660-1500°C the temperature coefficient of ρ changes from -2.6×10^{-4} to -4.0×10^{-4} gm cm⁻³ C⁻¹.

For liquid gallium, refs. [10, 11] also report an indirect linear dependence of density on temperature. While for aluminum the value of the temperature coefficient of the density increases with increasing temperature; for gallium the temperature coefficient of density decreases from -7.208×10^{-4} at low temperatures to -5.127×10^{-4} gm cm⁻³ C⁻¹ in the temperature range of 800-1120°C.

Reference [142] reports an indirect dependence of ρ on temperature for liquid lead. In the temperature range 330-1550°C the data are represented by the equation:

$$\rho_{Pb} = 10.665 - 12.64 \times 10^{-4} (t - t_m) + 10.08 \times 10^{-8} (t - t_m)^2 \quad (8)$$

For liquid antimony, ref. [128] reports a complex dependence ρ on temperature over the range of 630-1637°C. The data are approximated by the equation

$$\rho_{Sh} = 6.596 + 2.022 \times 10^{-4} t - 3.629 \times 10^{-7} t^2 \quad (9)$$

Scrutinizing the data quoted in Table 1, one observes that in the majority of cases the density of liquid metals has been determined near the melting points. However, at the present time there is no experimental data for many of the rare earths. Some metals belonging to the actinides are not thoroughly investigated. Ruthenium, osmium, and other elements not available in sufficient quantities for experimentation purposes are not investigated at all.

We used the periodic dependence of the atomic volumes of the molten metals at their melting points vs. their atomic numbers to estimate the density of a series of liquid elements (see Figure 1). The investigation of the structure of liquid metals gives a basis to conclude that the type of packing of the atoms of the metals is maintained during melting. By taking into account the agreement of the variation of the atomic volume of the metals with the atomic number in the solid and liquid states, we estimated the density of lanthanum, ruthenium, and osmium (Table 2) at the melting point.

The temperature coefficients of the densities of liquid metals are not well studied. Even for such elements as copper, silver, cadmium, aluminum, and tin, the temperature coefficients of the densities according to the data of the different investigators differ from each other by more than two fold. Therefore, theoretical investigations of the temperature dependence of the density of liquid metals as well as the establishment of empirical and semi-empirical relations which enable the estimation of the temperature coefficient of the density of molten metals assumes special significance. In this connection, the work of ref. [168] is of particular importance. Here the author gives an equation for the estimation of the temperature coefficients of liquid metals not as yet studied. Assuming that the density of the liquid metals in a narrow temperature range can be described by an equation of the form,

$$\rho = A + BT \quad (10)$$

where T is the temperature in $^{\circ}\text{K}$, a is a constant, and B is the temperature coefficient of density; on the basis of the experimental data on the temperature dependence of the density of 34 elements the author derives the values of A on ρ at the melting point. Data with a reasonable scatter fall on a straight line whereby it appears that

$$A = \frac{27}{25} \rho_m \quad (11)$$

Taking into account that

$$\rho_m = A + BT_m \quad (12)$$

one can derive the expression

$$B = \left(-\frac{2}{25} \right) \left(\frac{\rho_m}{T_m} \right) \quad (13)$$

TABLE 2

ESTIMATES OF THE DENSITY ρ_m AND ITS TEMPERATURE COEFFICIENT
FOR SOME LIQUID METALS

METAL	ρ_m , g/cm ³	- $B \cdot 10^4$ g/cm ³ °K	
		According to Equation 13	According to Equation 16
Samarium	7.18	4.27	3.11
Europium	5.08	3.69	2.94
Gadolinium	7.52	3.80	2.82
Terbium	7.83	3.85	2.60
Dysprosium	8.11	3.86	2.99
Holmium	8.34	3.85	3.01
Erbium	8.58	3.88	3.12
Thulium	8.83	3.89	3.27
Ytterbium	6.70	4.89	3.92
Lutetium	9.31	3.86	3.05
Ruthenium	10.06	2.98	7.85
Osmium	19.50	4.46	8.91

and

$$\rho = \rho_m \left[\frac{27}{25} - \frac{2}{25} \left(\frac{T}{T_m} \right) \right] \quad (14)$$

For estimates of the temperature dependence of the density, one can also use the following considerations. As already noted [13], metals with bcc, fcc and hcp structures conserve their own packing in the first coordinate range, during melting and near the melting point. In such cases it can be assumed that the density of the super-cooled liquid without defect, at 0°K, approaches the density of a solid at the same temperature. Then in eq. (10)

$$A = \rho_0 \quad (15)$$

and

$$B = \frac{\rho_m - \rho_0}{T_m} \quad (16)$$

For verification of the validity of our proposed method of estimating the temperature coefficient of the density of liquid metals, as well as eq. (13), we selected metals for which the temperature coefficients of the densities is considered to be sufficiently accurate. Table 3 lists the results obtained. On the average, the values calculated according to eq. (16) are one-third closer to the experimental data than the values obtained from eq. (13). If one were to sum up the absolute values of ΔB and take the average, then the results obtained from eq. (16) would exhibit a 24% scatter.

It must be noted that eq. (16) does not apply to elements with loose packing in the solid state.

In the calculation of ρ , data were used on the temperature coefficient of expansion of the elements which were presented in refs. [66, 73, 84] and also in [83].

It is interesting to note that the results obtained using eq. (13) in general are lower than the experimental data; at the same time, the values predicted by eq. (16) tend to be higher than the experimental data.

If the metals in the iron group are excluded, for which both eqs. (13) and (16) are unsuitable, then the results obtained from eq. (13) can be considered to yield the lower limit of the expected coefficient of density for liquid metals

TABLE 3

VERIFICATION OF EQUATIONS (13) and (16)

Metal	Experimental Value $-B \cdot 10^4 \text{ g/cm}^3 \text{ } ^\circ\text{K}$	According to Equation (13)		According to Equation (16)	
		$-B \cdot 10^4$ $\text{g/cm}^3 \text{ } ^\circ\text{K}$	$\Delta B\%$	$-B \cdot 10^4$ $\text{g/cm}^3 \text{ } ^\circ\text{K}$	$\Delta B\%$
Li	1.021	0.89	13	1.00	2
Na	2.38	2.00	16	2.80	18
K	2.406	1.96	19	2.84	18
Rb	4.806	3.81	21	5.02	5
Cs	6.00	4.89	18	6.83	14
Cu	8.006	4.72	41	8.10	1
Ag	9.7	6.04	38	11.06	14
Au	17.3	10.39	40	16.24	6
Mg	2.647	1.38	48	2.04	23
Zn	9.502	7.56	20	11.57	22
Cd	12.205	10.77	12	15.71	29
Al	3.11	2.28	27	4.18	35
Sn	6.37	11.06	73	9.50	49
Pb	11.73	14.24	21	15.05	28
Fe	7.3	3.11	57	4.91	33
Co	9.88	3.51	65	5.94	40
Ni	11.589	3.66	68	6.77	42
Pd	11.94	4.60	61	11.19	6

and those obtained from eq. (16) can be considered to represent the upper limit.

To estimate the coefficient of density of uninvestigated metals we used both equations (see Table 2).

Those data which at the present time can be recommended for use are reported in Table 4. In this table are included the calculated values of the atomic volume at the melting points and the volume coefficient of thermal expansion of liquid metals at the melting point, combined with the temperature coefficient of molten metals reported by ref. [47]

$$\alpha = - \frac{1}{\rho_m} \frac{d\rho}{dT} . \quad (17)$$

Values of the temperature coefficient of the density of unknown molten metals have been calculated using eq. (16).

In closing, one arrives at the following conclusions.

For most of the metals, the density of the liquid at the melting point have been experimentally defined. Development of methods which avoid physical contact in the determination of the density allows one to hope that in the near future new information about the density of refractory and chemically active metals will become available. Current knowledge on such metals is fragmentary.

The knowledge of the temperature dependence of the density of liquid metals is most inadequate. In the majority of cases the available data are mutually inconsistent and, hence, unreliable; therefore, systematic new investigations are necessary. One must note that the opportunities provided by the traditional methods of determining the temperature dependences of the density of liquid metals have not been fully utilized. The accuracy of such methods as the hydrostatic suspension, pycnometry, maximum pressures in a gas bubble, and drops, inherently can yield the temperature coefficient of density with much greater reproducibility than that found in past works.

Since the reliability of the data on the temperature coefficients of the density of metals is low, it is necessary to present the value of the capillary constant as a source of information in terms of the surface properties of liquid metals and their temperature dependences.

TABLE 4. RECOMMENDED VALUES OF THE DENSITY OF LIQUID METALS AND THEIR TEMPERATURE COEFFICIENT

Metal	ρ_m g/cm ³	$-\frac{d\rho}{dt} \cdot 10^4$ g/cm ³ degree	METHOD	Reference	v_m cm ³ /gm-at	$\alpha = \frac{1}{\rho_m} \frac{1}{dt} \cdot 10^4$
Li	0.503	1.021	Specific gravity flask	[82,9]	13.80	2.03
Na	0.9275	2.38	Specific gravity flask	[20]	24.79	2.57
K	0.8282	2.406	Dilatometry	[9]	47.21	2.90
Rb	1.4843	4.806	Dilatometry	[9]	57.58	3.24
Cs	1.8445	6.00	Dilatometry	[6]	72.06	3.25
Cu	7.992	8.006	Hydrostatic suspension	[99]	7.95	1.00
Ag	9.320	9.7	Hydrostatic suspension	[141]	11.57	1.04
Au	17.361	17.3	Hydrostatic suspension	[116]	11.34	1.00
Be	1.69	1.16	Maximum pressures	[120]	5.33	0.69
Mg	1.590	2.647	Hydrostatic suspension	[153]	15.29	1.66
Ca	1.3672	2.21	Maximum pressures	[97]	29.32	1.62
Sr	2.3742	2.62	Maximum pressures	[97]	36.90	1.10
Ba	3.3165	2.74	Maximum pressures	[97]	41.41	0.83
Zn	6.5519	9.502	Specific gravity flask	[171]	9.98	1.45
Cd	7.9962	12.205	Specific gravity flask	[102]	14.06	1.53
Hg	13.69098	24.1		[96,119]	14.65	1.76
		Not linear				
La	5.9	3.2	Large drop	[80]	23.54	0.54
Ce	6.6871	2.27	Specific gravity flask	[161]	20.95	0.34
Pr	6.43	3.0	Large drop	[80]	21.91	0.47
Nd	6.6882	5.28	Specific gravity flask	[161]	21.57	0.79
B	2.08		Resting drop	[69]	5.20	
Al	2.369	3.11	Dilatometry	[21]	11.39	1.31
Ga	6.08	6.0	Large drop	[62]	11.47	0.99
In	7.023	6.798	Hydrostatic suspension	[152]	16.35	0.97
Tl	11.350	13.0	Hydrostatic suspension	[150]	18.01	1.14
Ti	4.14	2.26	Suspended drop	[164]	11.57	0.55
Zr	6.09	2.26	Suspended drop	[75]	14.98	
Hf	11.97		Suspended drop	[36]	14.91	
Si	2.53	3.375	Large drop	[12]	11.10	1.33
Ge	5.598	6.25	Large drop	[70]	12.97	1.12
Sn	6.986	6.37	Hydrostatic suspension	[141]	16.99	0.91
Pb	10.696	11.73	Hydrostatic suspension	[150]	19.37	1.10
V	5.36	3.2	Suspended drop	[164]	9.50	0.60
Nb	7.57		Falling drop	[37]	12.27	
Ta	14.13		Combined	[30]	12.81	
P	1.16	0.96	Specific gravity flask	[131]	26.70	0.83
As	5.06		Specific gravity flask	[131]	14.81	
Sb	6.493	6.486	Specific gravity flask	[103]	18.75	1.00
Bi	10.022	11.82	Hydrostatic suspension	[98]	20.85	1.18
Cr	6.28	7.23	Suspended drop	[164]	8.28	1.15
Mo	9.1		Falling drop	[27]	10.54	
W	16.74		Combined	[55]	10.98	
Sc	4.013	11.67	Hydrostatic suspension	[141]	19.68	2.91
Te	5.83	8.0	Specific gravity flask	[19]	21.89	1.37
I	4.010	70	U-tube edges	[40]	31.65	
Mn	5.76	9.30	Suspended drop	[164]	9.54	1.61
Re	18.4		Combined	[56]	10.12	
Fe	7.05	7.03	Large drop	[65]	7.92	1.04
Co	7.76	9.88	Suspended drop	[163]	7.59	1.27
Ni	7.905	11.589	Hydrostatic suspension	[126]	7.43	1.47
Pd	10.49	11.94	Hydrostatic suspension	[144]	10.14	1.14
Pt	18.91	26.9	Hydrostatic suspension	[145]	10.32	1.42

$$a^2 = \frac{\sigma}{\rho g} \quad (18)$$

Based on the availability of reliable information in the future, it will be easy to obtain from the capillary constant the value of the free surface energy.

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LOW-TEMPERATURE CHARACTERISTICS OF THE WIEDEMANN-FRANZ LAW IN AGING ALLOYS

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NOMENCLATURE

- L = Lorenz number
- L_I = Lorenz number for state I
- L_{II} = Lorenz number for state II
- k = thermal conductivity
- k_I = thermal conductivity for state I
- k_{II} = thermal conductivity for state II
- k_c = electronic thermal conductivity
- k_p = phonon thermal conductivity
- W_e = total electronic thermal resistivity
- W_i = intrinsic electronic thermal resistivity
- W_o = lattice defect electronic thermal resistivity
- T = temperature
- B = parameter in eq. (2)
- ρ_0 = residual electrical resistivity
- ρ_I = electrical resistivity for state I
- ρ_{II} = electrical resistivity for state II
- σ = electrical conductivity
- σ_I = electrical conductivity for state I
- σ_{II} = electrical conductivity for state II
- θ = Debye
- β_1 = parameter in eq. (3)
- β_2 = parameter in eq. (3)

LOW-TEMPERATURE CHARACTERISTICS OF THE WIEDEMANN-FRANZ LAW IN AGING ALLOYS

The physical properties of high strength structural steels of type Fe + 26.6 Ni + 1.8 Al + 2 Ti + 0.4 Nb + 0.03 C, wt. %, can vary widely above room temperature [1,2]. At low temperatures, the investigation of these alloys is of interest with respect to studying their promise as cryogenic materials.

An investigation of the thermal and electrical conductivity of the alloy N 27 YU 2 T 2 B in the range of 4.2 to 200 K, in two structural states, is presented in this work. According to magnetic measurements data, state I is approximately 84% martensite (α phase bcc lattice), obtained from a homogeneous austenite (quenched in water from 1000°C) cooled down to 77°K, and 16% remaining austenite. The size of the martensite crystals and portions of the residual austenite (crystals) equal approximately 1 μ m. The hardness of the investigated structure is approximately 250 kg/mm²; the coercive force, 20 θ , $\rho_{I_{4.2K}}$, 4.18×10^{-5} ohm·cm.

State II appears to be a highly dispersed austenite-magnetite structure, providing high strength and ductility. This state is achieved by a) uniform tempering of austenite at 650°C for 6 hours during which the austenite decomposes and the particle ∂^1 -phase (Ni₃Ti, fcc) forms with the characteristic size of 100 Å, depleting the solid solutions of Ni and Ti; b) the cooling down to 77 K during which the martensite structure forms; c) tempering at 550°C for one hour which is accompanied by an inverse transformation simultaneous with the formation in α -phase of particles of size of approximately 50-100 Å of η -phase (Ni₃Ti hcp) [2] and also particles of phase-hardened austenite with high dislocation density, $\nu \approx 500$ Å. As a result of the highly dispersed structure, the alloy is composed from the $\alpha + \gamma + \eta + \gamma' + \gamma_{ph}$ phase. In accord with the data of the magnetometer measurements, the α phase consists of approximately 62%, the γ_{ph} -phase of 22%, and the γ -phase of 16%. The hardness of the alloy in state II equals approximately 600 kg/mm², the coercive force, 140 σ ; $\rho_{II_{4.2K}}$, 3.8×10^{-5} ohm·cm.

The value of $L = k_e/T$ for the structural states I and II of the alloy was determined by measuring the thermal conductivity k and the electrical conductivity σ from 4.2-100 K. The value of k_e was determined by the relation [3]

$$k = k_e + k_\rho \quad (1)$$

where

$$\frac{1}{k_e} = W_e = \frac{\rho_0}{LT} + BT^2.$$

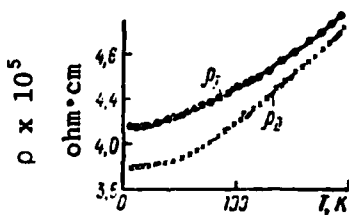
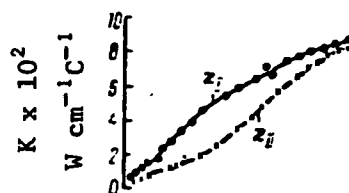
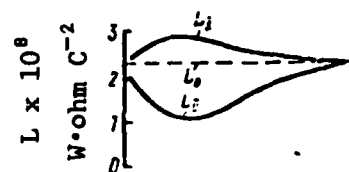
Here $W_1 = BT^2$ and $W_0 = \rho_0/LT$ determine the thermal resistivity due to the scattering of electrons by phonons and the scattering of electrons by crystal lattice defects and impurities, k_e and k_ρ correspond to electron and phonon thermal conductivity; ρ_0 , the residual resistivity (in this case $\rho_{4.2K}$); L , the Lorentz number; B , a constant characterizing the electron-phonon interaction for the given material.

For numerical estimates of W_1 and W_0 , one can make use of the value of L_0 for iron which is approximately 2.3×10^{-8} watts·ohm/deg² [3]. The magnitude of B is determined by the measured data of the thermal conductivity of very pure iron ($B \approx 10^{-4}$ cm/deg·watt [3]). However, one must note that for very pure materials, B can vary by 30-40% [4]. When $T = 100$ K, $W_1/W_0 \approx 10^{-2}$ (for "impure" materials). This ratio decreases with decreasing temperature in proportion to T^3 , i.e., phonon scattering can be neglected in the investigated temperature range and it can be assumed that $1/k_e = W_e = W_0$. In this case most of the heat flow is due to the phonons. For example when $T = 100$ K, $K_f \approx 0.06$ watts/cm degree and $k_e \approx 0.04$ watts/cm degree. When $W_0 \gg W_1$ and $k_e \sim k_\rho$ in accord with ref. [3], the k_e can be separated from k with sufficient reliability.

The obtained temperature dependence of L for the investigated alloys is shown in the diagram. The parameters k_e and σ were measured at different temperatures on identical samples. In order to calculate $L(T)$ by the smoothed function method, $k_e(T)$ and $\sigma(T)$ were taken from values at fixed temperatures over small intervals. From 4.2 K to 50 K we see that with increasing temperatures L not only can decrease, but also can increase, passing through a maximum.

The possibility of the appearance of a maximum in the relation $L(T)$ for the alloy in state I at low temperatures is in accord with the theoretical presentation in refs. [5,6]. The maximum is due to the inelastic scattering of impurity electrons caused by quasi-local oscillations and interferences by scattered electrons on the lattice phonon spectra and on impurity ions. Taking into account these facts in ref. [5] for $L(T)$ one can get the expression

$$L(T) = L_0 \left[1 + \beta_1 \left(\frac{T}{\theta} \right)^2 + \beta_2 \left(\frac{T}{\theta} \right)^3 \right].$$



Temperature Dependence of Electrical Resistivity ρ , Thermal Conductivity K , and Lorenz Number L of a Maraging Alloy.

Here β_1 and β_2 depend on the concentration of impurities, the difference in mass of the impurities and the base ions and also on the change in the amplitude of the electron scattering, which results from the introduction of the impurities. This change can have both negative and positive values.

The depletion of the solid solution of Ni and Ti due to the separating of the η and γ^1 phases [2] and the absence of a maximum of $L(T)$ are the basis for proposing that the softened phonon spectra of Fe in the given alloy can be caused by the introduction of Ni and Ti (not excluding the influence also of Nb, however, its explanation requires further investigation). Apparently, the possibility of plotting $L(T)$ for complex alloys at low temperatures must employ reliable characteristic states with small additions (approximately $10^{-1}\%$) of impurities, creating the quasi-local oscillations in the lattice, which have not been possible to represent by other methods.

Depletion of the material based on Fe and state II confirms that in the investigated interval $\sigma_I < \sigma_{II}$ and $k_I > k_{II}$. The inequality $\sigma_I < \sigma_{II}$ is caused by the fact that the separation in state II of the η and γ^1 phases reduces the Coulomb scattering of electrons and σ_{II} accordingly increases.

On the other hand, at liquid helium temperatures the wavelength λ_ρ of phonons approximates the size of the η and γ^1 phases ($\sim 50-100 \text{ \AA}$) and phonon scattering becomes significant. Because $k_\rho > k_e$ this effect is more significant than the increase in k_e due to the reduction of electron scattering.

Thus, as a result of structural properties, k_{II} relative to k_I somewhat decreases, but σ increases. This is the principal observation since it attests to the possibility of changing the thermal and electro-physical properties of the alloy with the aid of specific structural states.

We conclude that due to their own thermophysical properties, the aging alloys investigated can successfully compete with the best classical cryomaterials.

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RELATION OF THE THERMOPHYSICAL PROPERTIES OF
LOW-ALLOY STEELS TO TEMPERATURE

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Low alloy steels are used extensively in many different fields of industry, particularly power engineering. In order to determine the temperature distribution and heat flow in elements of power equipment, one must consider the temperature dependence of the thermophysical coefficients of the applicable materials.

Because of the complex mathematical description of most real problems, their solution is often worked out with the help of a computer. The current practice of presenting the raw reference data in numerical tables in carrying out calculations on a computer is not the best. A more convenient presentation of the data is in analytical form. By processing the tabular data given in ref. [1], formulas were derived which characterize the temperature dependence of the thermophysical parameters of the more useful low alloy steels. For completeness, Table 1 includes the chemical composition of the steels, the critical phase transition points, and the heat treatment regimes.

The behavior of the investigated functions is such that it cannot be described by a single equation for the entire temperature range from 0°C up to 1100-1300°C. Therefore, this interval was broken into 2-3 segments, each with its own formula. The expressions obtained for the coefficients of thermal conductivity (Table 2), specific heat (Table 3), density (Table 4), and thermal diffusivity (Table 5) can be used for solving appropriate problems on a computer.

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TABLE 1. CHEMICAL COMPOSITION (wt. %) OF LOW ALLOY STEELS AND CRITICAL TRANSITION POINT, °C [1]

Alloy Designations	C	Mn	Si	Cr	Mo	Ni	V	W	Cu	Thermal Preparation	AC ₁	AC ₃	AR ₁	AR ₃
15 Khm	≤0.16	0.4-0.7	0.17-0.37	0.8-1.1	0.4-0.55	≤0.3	-	-	-	-	770	850-870	-	-
15 KhF	0.15	0.57	0.56	1.06	-	-	0.30	-	-	-	800	880	775	825
15 Kh	0.315	0.69	0.20	1.09	-	0.073	-	-	0.040	annealed, 860°C	763	-	-	-
30KhN3	0.33	0.53	0.17	0.60	0.07	3.38	-	-	0.053	annealed 860°C, then heated up to 640 C & cooled in furnace	725	-	-	-
20KhN4F	0.19	0.30	0.34	1.06	-	4.35	-	-	0.12	-	-	-	-	-
30G2	0.23	1.51	0.12	0.06	0.085	0.04	-	-	0.125	annealed, 860°C	730	-	-	-
13M	0.10-0.18	0.4-0.7	0.17-0.37	≤0.3	0.4-0.55	≤0.3	-	-	-	-	730	830	610	830
12 Khh	0.15	0.54	0.28	0.32	0.50	-	-	-	-	-	755	860	760	830
20 KhM	0.15-0.25	0.4-0.7	0.15-0.30	0.8-1.1	0.15-0.25	≤0.3	-	-	-	-	-	-	-	-
12 KhMF	≤0.12	0.4-0.6	0.2-0.4	0.9-1.2	0.25-0.35	-	0.15-0.3	-	-	-	-	-	-	-
10Kh2FM	0.06	0.32	0.22	1.55	0.18	-	0.35	-	-	heated 740 C cooled in furnace	820	900	750	860
10Kh2MB (E1454)	≤0.4	0.4-0.7	0.4-0.7	2.1-2.6	0.8-1.0	-	-	-	Nb 1.3	-	-	-	-	-
25Kh2MF (E110)	0.22-0.30	0.4-0.7	0.17-0.37	1.6-1.8	0.25-0.35	≤0.3	0.2-0.3	-	-	-	-	-	-	-
40Kh3M	0.4	0.6	0.3	2.0	0.5	-	-	0.2	-	-	-	-	-	-
20Kh3FVM	0.23	-	-	2.7	0.5	0.3	-	0.75	0.5	-	-	-	-	-
15Kh5MA	≤0.15	0.4-0.7	1.5-2.0	5-6.5	0.5	≤0.5	-	-	-	-	850	890	-	-
50 S2G	0.485	0.90	1.98	0.04	-	0.156	-	-	0.86	annealed, 830°C	779	-	-	-

TABLE 2. RELATIONS OF THE TEMPERATURE DEPENDENCE OF THERMAL CONDUCTIVITY OF LOW ALLOY STEELS

[t, in °C and λ_t in watts/meter °C]

Alloy Designations	Equation	Applicable Temp. Range	$\Delta_{\max}^*$	$t\Delta_{\max}^*$	Remarks
15 M	$\lambda_t = 47.5 - 2.23 \cdot 10^{-2} t + 0.0344 \cdot 10^{-4} t^2$	$100 \leq t \leq 900$	-3.9	400	-
20 M	$\lambda_t = 46.6 - 1.80 \cdot 10^{-2} t - 0.0156 \cdot 10^{-4} t^2$	$100 \leq t \leq 900$	-2.5	600	-
12 MKh	$\lambda_t = 43.1 - 1.10 \cdot 10^{-2} t - 0.0406 \cdot 10^{-4} t^2$	$20 \leq t \leq 900$	-2.0	300	$\lambda_{200} = 38.4$
15 KhM	$\lambda_t = 45.2 - 1.85 \cdot 10^{-2} t - 0.0031 \cdot 10^{-4} t^2$	$100 \leq t \leq 900$	-3.9	400	$\lambda_{200} = 37.2$
20 KhM	$\lambda_t = 45.2 - 1.85 \cdot 10^{-2} t - 0.0031 \cdot 10^{-4} t^2$	$100 \leq t \leq 900$	-3.9	400	$\lambda_{200} = 37.2$
12 KhMF	$\lambda_t = 45.2 - 1.85 \cdot 10^{-2} t - 0.0031 \cdot 10^{-4} t^2$	$100 \leq t \leq 900$	-3.9	400	$\lambda_{200} = 37.2$
15 KhF	$\lambda_t = 45.0 + 0.40 \cdot 10^{-2} t - 0.3670 \cdot 10^{-4} t^2$	$100 \leq t \leq 700$	1.5	600	-
30 Kh	$\lambda_t = 48.9 - 2.35 \cdot 10^{-2} t - 0.0630 \cdot 10^{-4} t^2$	$20 \leq t \leq 800$	-2.4	300	-
30 Kh	$\lambda_t = 20.8 + 0.48 \cdot 10^{-2} t + 0.0222 \cdot 10^{-4} t^2$	$800 \leq t \leq 1100$	1.0	900	-
10 Kh2MF (EI 531)	$\lambda_t = 37.0 + 1.75 \cdot 10^{-2} t - 0.4130 \cdot 10^{-4} t^2$	$100 \leq t \leq 700$	2.7	200	$\lambda_{200} = 27.3$
10 Kh2MB (EI 454)	$\lambda_t = 35.0 + 1.75 \cdot 10^{-2} t - 0.3860 \cdot 10^{-4} t^2$	$100 \leq t \leq 700$	-2.8	700	$\lambda_{200} = 27.3$
25 Kh2MF (EI 10)	$\lambda_t = 41.1 + 1.20 \cdot 10^{-2} t - 0.4 \cdot 10^{-4} t^2$	$100 \leq t \leq 400$	1.2	200	-
12 Kh2N (EI)	$\lambda_t = 63.7 - 7.65 \cdot 10^{-2} t + 0.4 \cdot 10^{-4} t^2$	$500 \leq t \leq 900$	-1.2	600	$\lambda_{200-200} = 33$
25 N3	$\lambda_t = 36.3 - 7.65 \cdot 10^{-2} t + 0.4 \cdot 10^{-4} t^2$	$20 \leq t \leq 800$	2.9	500	-
25 N3	$\lambda_t = -3.3 + 5.10 \cdot 10^{-2} t - 0.2 \cdot 10^{-4} t^2$	$800 < t \leq 1100$	-1.6	800	-
30 KhN3	$\lambda_t = 34.4 + 1.95 \cdot 10^{-2} t - 0.3740 \cdot 10^{-4} t^2$	$20 \leq t \leq 800$	-2.4	600	-
30 KhN3	$\lambda_t = 36.5 - 2.90 \cdot 10^{-2} t + 0.2 \cdot 10^{-4} t^2$	$800 < t \leq 1100$	1.0	900	-
35 KhN3	$\lambda_t = 33.3 + 2.92 \cdot 10^{-2} t - 0.5390 \cdot 10^{-4} t^2$	$100 \leq t \leq 700$	-2.0	500	$\lambda_{200} = 27.9$
20 KhN4F (E 14)	$\lambda_t = 38.1 - 0.265 \cdot 10^{-2} t - 0.131 \cdot 10^{-4} t^2$	$20 \leq t \leq 800$	3.5	700	$\lambda_{200} = 27.1$
40 Kh3M	$\lambda_t = 37.4 - 0.0284 \cdot 10^{-2} t - 0.1610 \cdot 10^{-4} t^2$	$100 \leq t \leq 700$	-2.5	300	-
20 Kh3FVM	$\lambda_t = 30.4 + 2.10 \cdot 10^{-2} t - 0.3330 \cdot 10^{-4} t^2$	$100 \leq t \leq 700$	1.3	600	-
12 Kh58MA	$\lambda_t = 25.9 + 3.82 \cdot 10^{-2} t - 0.5570 \cdot 10^{-4} t^2$	$100 \leq t \leq 600$	3.7	200	-
12 Kh58MA	$\lambda_t = 54.3 - 6.60 \cdot 10^{-2} t - 0.4 \cdot 10^{-4} t^2$	$600 \leq t \leq 900$	1.6	800	-
30 G2	$\lambda_t = 45.8 - 0.835 \cdot 10^{-2} t - 0.147 \cdot 10^{-4} t^2$	$200 \leq t \leq 800$	4.1	700	-
30 G2	$\lambda_t = 144.1 - 24.3 \cdot 10^{-2} t + 1.250 \cdot 10^{-4} t^2$	$800 < t \leq 1100$	3.9	900	-
50 S2G	$\lambda_t = 26.1 + 2.85 \cdot 10^{-2} t - 0.41 \cdot 10^{-4} t^2$	$20 \leq t \leq 500$	-3.2	500	-
50 S2G	$\lambda_t = 61.0 - 8.22 \cdot 10^{-2} t + 0.48 \cdot 10^{-4} t^2$	$500 < t \leq 1100$	-4.0	600	-
30 KhGS (EI 179)	$\lambda_t = 44.4 - 1.96 \cdot 10^{-2} t + 0.061 \cdot 10^{-4} t^2$	$200 \leq t \leq 800$	1.8	300	$\lambda_{100} = 37.2$

* $\Delta_{\max}$ and $t\Delta_{\max}$ correspond to the maximum errors in the equations when compared with the original tabulated data and their corresponding temperatures.

TABLE 3. TEMPERATURE DEPENDENCE OF SPECIFIC HEAT OF LOW ALLOY STEELS

[t in °C; C_p in K Joule/Kgm · deg]

Alloy Designation	Applicable Temperature Range and Equation					
	$50 \leq t \leq 650$	$650 < t < 700$	$700 < t < 750$	$750 \leq t \leq 1300$		
30 Kh	$C_t = 0.486 + 0.0012 \cdot 10^{-3} t + 0.00849 \cdot 10^{-4} t^2$	1.050	1.662	$C_t = 0.876 - 0.0476 \cdot 10^{-3} t + 0.00232 \cdot 10^{-4} t^2$		
30 N3	$C_t = 0.484 - 0.0008 \cdot 10^{-3} t + 0.00809 \cdot 10^{-4} t^2$	1.637	0.955	$C_t = 0.302 + 0.0569 \cdot 10^{-3} t - 0.00224 \cdot 10^{-4} t^2$		
30 KhN3	$C_t = 0.497 - 0.00032 \cdot 10^{-3} t + 0.00913 \cdot 10^{-4} t^2$	1.306	1.176	$C_t = 0.374 + 0.172 \cdot 10^{-3} t - 0.0071 \cdot 10^{-4} t^2$		
30 G2	$C_t = 0.473 + 0.0052 \cdot 10^{-3} t + 0.00712 \cdot 10^{-4} t^2$		1.449	$C_t = -0.208 + 0.133 \cdot 10^{-3} t - 0.00519 \cdot 10^{-4} t^2$		
50 S2G	$C_t = 0.495 + 0.002 \cdot 10^{-3} t + 0.0072 \cdot 10^{-4} t^2$			$C_t = 0.508 + 0.011 \cdot 10^{-3} t + 0.000222 \cdot 10^{-4} t^2$		

NOTE: D_{max} for the given equation does not exceed 3%.

TABLE 4. TEMPERATURE DEPENDENCE OF THE DENSITY OF
LOW ALLOYS STEELS

[Temperature t , °C; Density ρ_t in g/cm³]

Alloy Designation	Mathematical Formulas	Applicable Temp. Range
15 M	$\rho_t = 7.85 - 0.0442 \cdot 10^{-2} t + 0.000834 \cdot 10^{-4} t^2$	$0 \leq t \leq 600$
12 MKh	$\rho_t = 7.819 - 0.0303 \cdot 10^{-2} t - 0.000667 \cdot 10^{-4} t^2$	$0 \leq t \leq 700$
15 KhM	$\rho_t = 7.85 - 0.0454 \cdot 10^{-2} t + 0.00122 \cdot 10^{-4} t^2$	$0 \leq t \leq 600$
15 KhF	$\rho_t = 7.763 - 0.0005 \cdot 10^{-2} t - 0.00395 \cdot 10^{-4} t^2$	$0 \leq t \leq 700$
30 Kh	$\rho_t = 7.847 - 0.0342 \cdot 10^{-2} t + 0.0002 \cdot 10^{-4} t^2$	$0 \leq t \leq 1000$
30 N3	$\rho_t = 7.859 - 0.0323 \cdot 10^{-2} t + 0.0001 \cdot 10^{-4} t^2$	$0 \leq t \leq 1000$
30 KhN3	$\rho_t = 7.851 - 0.0303 \cdot 10^{-2} t - 0.00026 \cdot 10^{-4} t^2$	$0 \leq t \leq 1000$
30 G2	$\rho_t = 7.854 - 0.0354 \cdot 10^{-2} t + 0.00032 \cdot 10^{-4} t^2$	$0 \leq t \leq 1000$
50 S2G	$\rho_t = 7.729 - 0.03 \cdot 10^{-2} t - 0.00038 \cdot 10^{-4} t^2$	$0 \leq t \leq 1000$

NOTE: $\Delta_{\max}$ for the given formulas do not exceed 1%.

TABLE 5. TEMPERATURE DEPENDENCE OF THE THERMAL DIFFUSIVITY OF LOW ALLOY STEELS
 [Temperature t , °C; Thermal Diffusivity α_t meters/Hr]

Alloy Designation	Applicable Temperature Range and Equation		
	$50 \leq t \leq 700$	$700 < t < 750$	$750 \leq t \leq 1100$
30 Kh	$\alpha_t = 0.047 - 0.0035 \cdot 10^{-3} t - 0.000187 \cdot 10^{-4} t^2$	0.0090	$\alpha_t = -0.0976 + 0.0242 \cdot 10^{-2} t - 0.00123 \cdot 10^{-4} t^2$
30 N3	$\alpha_t = 0.0361 - 0.00006 \cdot 10^{-2} t - 0.00046 \cdot 10^{-4} t^2$	$650 < t < 700$ 0.0090	$\alpha_t = 0.0447 + 0.01258 \cdot 10^{-2} t - 0.000589 \cdot 10^{-4} t^2$
30 KhN3	$\alpha_t = 0.0334 - 0.00015 \cdot 10^{-2} t - 0.000354 \cdot 10^{-4} t^2$	$650 < t < 700$ 0.0112	$\alpha_t = 0.037 - 0.00363 \cdot 10^{-2} t + 0.0002 \cdot 10^{-4} t^2$
30 G2	$\alpha_t = 0.0464 - 0.0026 \cdot 10^{-2} t - 0.00026 \cdot 10^{-4} t^2$	$700 < t < 750$ 0.0097	$\alpha_t = -0.0741 + 0.019 \cdot 10^{-2} t - 0.000933 \cdot 10^{-4} t^2$
50 SG	$\alpha_t = 0.0283 + 0.000533 \cdot 10^{-2} t - 0.000278 \cdot 10^{-4} t^2$	$750 < t < 800$ 0.0090	$\alpha_t = 0.0077 + 0.00204 \cdot 10^{-2} t - 0.00008 \cdot 10^{-4} t^2$

NOTE: $\Delta_{\max}$ for the given formulas does not exceed 4% .