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Translation

THERMOPHYSICAL PROPERTIES OF WORKING MEDIA OF THE GAS-PHASE NUCLEAR REACTOR

By

V.K. Gryaznov, et al.

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Moscow TEPLOFIZICHESKIYE SVOYSTVA RABOCHIKH SRED GAZOFAZNOGO YADERNOGO REAKTORA in Russian 1980 (signed to press 1 Aug 80) pp 6-63

[Chapter 1 from the book "Thermophysical Properties of Working Media of the Gas-Phase Nuclear Reactor", by Viktor Konstantinovich Gryaznov, Igor'L'vovich Iosilevskiy, Yuriy Georgiyevich Krasnikov, Nina Ivanovna Kuznetsova, Vladimir Ivanovich Kucherenko, Galina Borisovna Lappo, Boris Nikolayevich Lomakin, Georgiy Alekseyevich Pavlov, Eduard Yevgen'yevichson and Vladimir Yevgen'yevich Fortov and edited by V.M. Iyevlev, Atomizdat, 1,800 copies, 304 pages]

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The present state of the theory of estimation of thermodynamic transfer and optical properties of gases at high pressures and temperatures and the state of experimental investigations in the physics of non-ideal plasma, completely or partially ionized, is analyzed. Numerical calculations are made of the thermophysical properties of plasma of working media used in gas-phase nuclear--alkali metals, uranium, hydrogen and mixtures of them--over a wide temperature and pressure range are made.

The book is survey and reference in nature and will be useful both to specialists involved directly in the gas-phase nuclear reactor and to engineers and scientific workers specializing in various fields of the physics of low-temperature plasma.

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EDITOR'S FOREWORD

Moscow TEPLOFIZICHESKIYE SVOYSTVA RABOCHIKH SRED GAZOFAZNOGO YADERNOGO REAKTORA in Russian 1980 (signed to press 1 Aug 80) pp 3-5

[Preface by Corresponding Member of USSR Academy of Sciences V. M. Iyevlev from the book "Thermophysical Properties of Working Media of the Gas-Phase Nuclear Reactor", by Viktor Konstantinovich Gryaznov, Igor' L'vovich Iosilevskiy, Yuriy Georgiyevich Krasnikov, Nina Ivanovna Kuznetsova, Vladimir Ivanovich Kucherenko, Galina Borisovna Lappo, Boris Nikolayevich Lomakin, Georgiy Alekseyevich Pavlov, Eduard Yevgen'yevich Son and Vladimir Yevgen'yevich Fortov, Atomizdat, 1,800 copies, 304 pages]

[Text] The proposed book is survey in nature on the thermophysical properties of materials and contains reference material on the thermodynamic, transport and optical properties of vapors of alkali metals, uranium, hydrogen and mixtures of them over a wide temperature and pressure range. The indicated survey and reference material were compiled with respect to interests related to investigating the possibility of development and the anticipated characteristics of a nuclear reactor of an essentially new type--the gas-phase nuclear reactor (GYaR) and also of power plants with this type of reactor. Interest in investigations of the gas-phase nuclear reactor, including study of the properties of the working media, is determined by the assumed unique properties of this reactor, useful for many applications. It can be used both in large electric power plants and high-temperature production systems and in space power plants, engines and so on. Electric power plants with GYaR have a number of advantages which include [1-4]: high efficiency, increased heat dissipation temperature, i.e., the capability of discharging heat into the air rather than into water without significant deterioration of efficiency, an increase of the nuclear fuel conversion ratio with low uranium charge in the reactor, low accumulation of nuclear materials and so on. In this regard the gas-phase nuclear reactor will possibly be the future basis for extensive development of nuclear power engineering and technology. The contents of the book are not related directly to processes in the gas-phase nuclear reactor. However, it is feasible in the preface to dwell briefly on the schematic diagram and some distinguishing features of GYaR that determine the characteristics of the approach to study of the thermophysical properties of working media.

Different schemes of GYaR are now being investigated [1-4]. According to one of the most promising of them, substantantiated by theoretical investigations and model experiments, a GYaR is a cavity-type device. The fissionable material--

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uranium in a gaseous state--is located in the center of the cavity surrounded by a reflector-moderator. The working substance heated by thermal radiation from the uranium plasma passes between the uranium and the cavity walls. Special measures are employed--profiling of the velocity field, suppression of disturbances at the inlet of working media into the cavity, stabilization by a magnetic field and so on [3]--to reduce mixing of the uranium and working substance.

The principal advantage of the GYaR is the capability of heating the working substance to very high temperatures. The restriction here is only the need to have a temperature permitted by the structural materials of the walls on the periphery of the working substance. The temperature may reach tens of thousands of degrees in some schemes far from the walls and also in the zone of the uranium plasma. Therefore, one of the central problems in development of GYaR is that of establishing the necessary temperature fields and concentration profiles in the reactor cavity. Complex problems of magnetic hydrodynamics, diffusion and radiation and convective heat transfer, solution of which is impossible without a detailed knowledge of all the transport characteristics of the plasma, arise in solution of this problem. A knowledge of the optical properties of uranium and working substances is of special importance since the main mechanism of heat transfer is radiant energy transfer.

The high temperatures of the uranium and working substance and the requirement of the criticality of the GYaR make it necessary to have a pressure at the level of hundreds of atmospheres in the reactor cavity. With these pressures and temperatures of tens of thousands of degrees, the uranium and working substances, among which alkali metals that provide high conductivity and absorption of radiation play the important role, are in a state of a so-called strongly imperfect plasma, i.e., in a state of single- or multiply ionized gas with intensive interparticle interaction that significantly affects all the thermophysical properties of the medium. The theory of this state of matter is extremely complex and now contains a number of unresolved problems, while the experimental information is very limited. Therefore, unlike problems of traditional thermophysics, not only proper sampling of all the input data but, which is no less important, critical selection of the most reliable methods now available of calculating the thermophysical properties of the working media in a strongly imperfect plasma are required to calculate the thermodynamic and transfer properties. This circumstance has been reflected in the fact that a considerable part of this book is allocated to analysis of the principal problems of the theory and current state of generation and diagnosis of a nonideal plasma.

It should be noted that experimental investigations of an imperfect plasma have not yet been conducted adequately and this is related to the complexity of generation and diagnosis of this plasma. Theoretical investigations of an imperfect plasma are also far from complete and the collective of authors hopes that the outlined results will be used in further development of investigations on the physics of a nonideal plasma.

The book is constructed in the following manner. The first three chapters are devoted to a survey of the current state of the theory and selecting the method of calculating the the modynamic, kinetic and optical properties of an imperfect General problems of the thermophysics of an imperfect plasma are considered in these

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chapters; therefore, the outlined material may also be used in other fields of physics of high-temperature gases and plasma. These fields include the thermophysics of strong shock waves, powerful MHD generators, heavy-current discharges, the hydrodynamics of scattering of dense vapors in laser thermonuclear fusion and so on. The fourth chapter is devoted to a survey of experimental methods and results obtained on the thermophysics of an imperfect plasma. Finally, chapter 5 contains specific results of calculations of the thermophysical properties of the plasma of working media: gaseous alkali metals, uranium and also mixtures of alkali metals with uranium and hydrogen.

The participation of the authors in direct writing of the material was as follows: V. K. Gryaznov--sections 1.5 and 1.6, I. L. Iosilevskiy--sections 1.1, 1.3-1.7 and 4.5, Yu. G. Krasnikov--section 1.2, N. I. Kuznetsova--sections 3.1-3.5, V. I. Kucherenko--sections 2.5 and 2.6, G. B. Lappo--sections 3.1-3.5 and 3.7, B. N. Lomakin--sections 4.1-4.7, G. A. Pavlov--sections 2.1 and 2.3-2.6, E. Ye. Son--sections 2.1-2.6, 3.6 and 4.6 and V. Ye. Fortov--sections 1.5 and 4.1-4.7. The numerical calculations were made by V. K. Gryaznov, I. L. Iosilevskiy, V. I. Kucherenko and G. B. Lappo.

Since the book is mainly survey and reference in nature, one should turn to the cited bibliography for more detailed study of the theoretical problems and experimental methods of the generation and diagnosis of an imperfect plasma. This book on the thermophysics of an imperfect plasma is appearing for the first time; therefore the authors will be grateful for responses and critical comments.

The proposed book will be useful to specialists working not only on development of the gas-phase nuclear reactor, but also in other fields of plasma physics, MHD generators, the physics of shock waves, some schemes of thermonuclear fusion and so on.

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THERMODYNAMIC PROPERTIES

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[Text] 1.1. General Characteristics of the Behavior of the Thermodynamic Functions of Working Media

Two approaches, which have become called the chemical and physical models [2],* are usually employed to calculate the thermodynamic functions of high-temperature media in the range of parameters typical for the gas-phase nuclear reactor [1].

In most cases the simpler chemical model is considered where the presence of particles of specific varieties having a continuous energy spectrum is assumed beforehand. The effect of the internal structure of the particles (bound states) on thermodynamic functions is taken into account by introducing individual statistical sums (abbreviated statsums) [5]. This is the source of known difficulties related to the conditional nature of dividing all degrees of freedom of the system into translational and internal. In the practice of calculating thermodynamic values, these difficulties are gotten around by various types of "cuts" of the statsums on the basis of one or another physical concepts.

A subsequent, but more complex approach to determination of thermodynamic functions is based on the physical model where nuclei and electrons are considered and coulomb interaction between them is taken into account on the basis of quantum-statistical theory. In this case contributions to thermodynamic functions from continuous and discontinuous spectra occur simultaneously and are finite. These problems are considered in section 1.2. When discussing the qualitative behavior

*The names methods of initial atoms and method of mixture are used for similar approaches in the theory of neutral chemically reacting gases [3, 4].

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of the thermodynamic characteristics of working substances of complex composition, it is more convenient to use the traditional chemical model.

The problem of thermodynamic calculation can be conditionally divided into two parts. First, purely thermodynamic calculation with given, for example, pressure p and temperature T of the remaining thermodynamic values such as density ρ, internal energy U, enthalpy H, entropy S and so on and also of differential characteristics--specific heats C_p and C_V, the isentropic index $\gamma_S \equiv (\partial \ln p/\partial \ln \rho)_S$ and so on. Second, calculation of some important auxiliary values such as the composition and individual contributions of different subsystems, for example, free charges, atoms, molecules and so on. A knowledge of these values is in principle not compulsory for calculation of the thermophysical properties, but the existing approximate methods of calculating these properties rely in most cases on using them.

It follows from the results of numerous approximate calculations that the general behavior of the thermodynamic characteristics for working media in the range of parameters $p = 0.1\text{-}10^2$ MPa and $T = 10^3\text{-}10^5$ K [1] is determined first by processes of ionization and recombination of atoms and ions and second by formation and dissociation of different molecules, while at low temperatures it is determined by the gas-liquid phase transition. The effect of the nonideal nature on the behavior of the total thermodynamic values of working substances is not felt as strongly as on their composition. Although all the indicated processes may actually proceed simultaneously, it is useful to judge separately the effect of each of them on the course of thermodynamic functions.

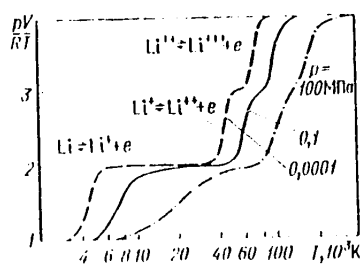

Figure 1.1. Thermodynamic Equation of State of Lithium Plasma. Results of calculation (the possibility of condensation and formation of molecules was not taken into account)

A specific band in the plane of thermodynamic parameters, for example, p, V or p, T and so on, can be set into agreement to each of these processes. The position and slope of this band are dependent on such parameters as ionization energy, energy of dissociation and so on. As an illustration, let us consider the process of ionization of lithium. Like all alkali metals, secondary ionization in lithium proceeds with a filled electron shell; therefore, the first and second ionization potentials differ significantly (see Table 1.1, section 1.6), while the primary and secondary ionization bands are clearly distinguished.

The dependence of the dimensionless value--the lithium compressability factor $Z \equiv pV/RT$ (R is the gas constant and V is the molar volume) on temperature is

*The thermodynamic calculations presented in the given book were made by using a special program described in [6].

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presented in Figure 1.1. The range of an ideal gas behavior (Z ≈ const) and the range of transition separating them corresponding to primary, secondary and tertiary ionization, can be clearly distinguished in the low-pressure range, i.e., at low densities. As pressure increases, these processes shift toward the higher temperature range and in this case both ionization bands are split and superimposed on each other so that, for example, the section corresponding to ideal singly ionized lithium essentially disappears.

The foregoing on the thermal equation of state p(V, T) is also valid with respect to the caloric equation of state U(p, T). This is illustrated in Figure 1.2 on the example of hydrogen. The value $pv \equiv p\rho^{-1}$ is used as the independent variable here, which permits clearer determination of sections of ideal gas behavior, where $U = \frac{3}{2}pV + \text{const}$. The constant constained in this relation is dependent on selection of the point of reference and is expressed by dissociation and ionization energy.

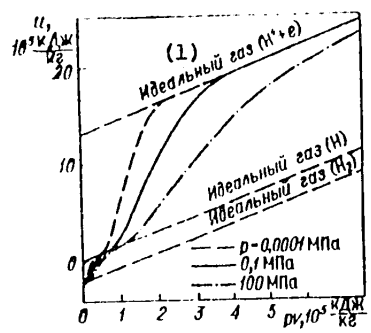

Figure 1.2. Caloric Equation of State of Hydrogen U(p, V). Results of calculation. Lines corresponding to ideal gas behavior $U = \frac{3}{2}pV + \text{const}$ are noted

Key:
1. Ideal gas

The behavior illustrated in Figures 1.1 and 1.2 on the isobars is qualitatively preserved upon intersection of the dissociation or ionization band along the isochor, isotherm, isoenthalpy or isoentropy. Specifically, such differential characteristics as, for example, specific heat, have a characteristic burst in this case (Figure 1.3). The ionization band and general course of lines T, H, U and S = const intersection this band are depicted schematically in Figure 1.4 in coordinates p, V.

The enthalpy-entropy diagram on which dissociation or ionization bands can also be distinguished is important for practical purposes (Figure 1.5).

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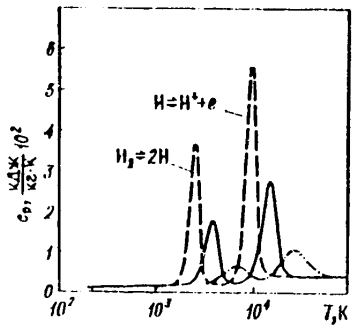

Figure 1.3. Specific Heat of Hydrogen [114]

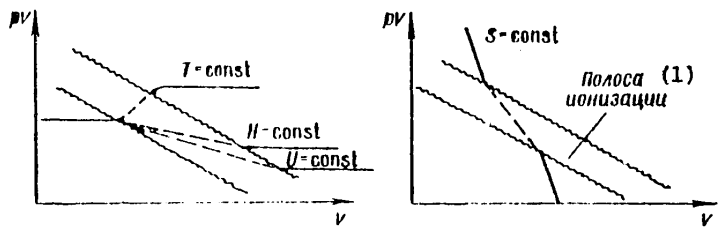

Figure 1.4. Qualitative Behavior of Lines x = const (x = T, H, U, S and so on) Upon Intersection of Isolated Ionization Band

Key:
1. Ionization band

The general course of thermodynamic functions presented above is correctly described qualitatively within the chemical model [5], based on solution of the known system of equations of chemical and ionization equilibrium using heats of dissociation, ionization and excitation energy. It is important to know with this approach how sensitive the total thermodynamic values are to selection of the method of taking the internal degrees of freedom and the effect of imperfection into account. This is shown in Figures 1.6-1.10 on the example of the thermal and caloric equations of state of cesium. It is obvious from the figures that the ambiguity related to the differences between the methods suggested in the literature [7] of taking the contribution of excited states of an atom into account is not reflected in the qualitative behavior of the curves within the ionization band (this conclusion is retained for dissociation). The effect of this intersection is felt to a greater degree with an increase of press when, as already noted, the ionization and dissociation bands are shifted to the higher temperature range.

If quantum effects are not taken into account, the interaction between charged particles can be characterized by the dimensionless parameter γ or by parameter Γ more convenient in problems of theory.

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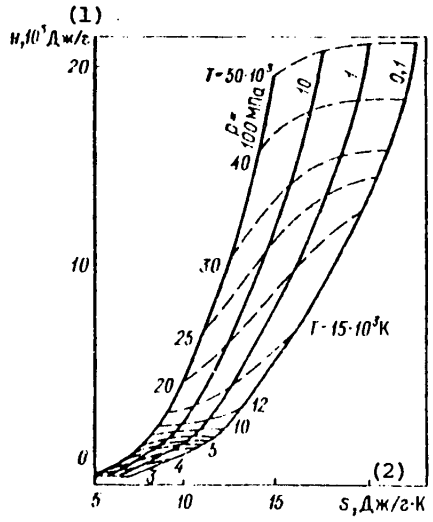

Figure 1.5. Enthalpy-Entropy Diagram for Hydrogen-Potassium Mixture (H_2 + 3 percent K): solid lines--isobars; dashed lines--isotherms

Key:
1. J/g
2. J/g·K

$$\gamma = \left(\frac{e^2}{kT}\right) n_{\text{зар}}^{1/3}; \quad \Gamma = \frac{e^2}{kTr_D}; \tag{1.1}$$
$$r_D^2 = \varkappa_D^2 = 4\pi \sum_{\text{зар}} n_i e_i^2/kT.$$

Here e is charge, k is Boltzmann's constant, r_D is the Debye radius and n_{zar} and $\sum_{zar}$ is the total concentration and sum for charged particles.

When calculating the total thermodynamic functions, the effect of coulomb interaction is doubly manifested. On the one hand, it is present in the form of direct corrections to the values of internal energy and pressure. On the other hand, it is indirectly reflected in thermodynamic properties due to a shift of ionization equilibrium because of effective variation of the ionization potential. In the range of weak imperfection $\Gamma \ll 1$, the corresponding corrections are given by the known Debye-Hueckel approximately [8]. In this case corrections to the values of energy and pressure are negative and proportional to the first power of parameter Γ, while the degree of ionization increases. According to this, the typical transition in the ionization range is smoothed over in the thermal and caloric equations of state (see Figures 1.6-1.10) and the corresponding peak is also smoothed as a function of the specific heat or compressability on temperature. Let us emphasize that the "inclusion" of charge-charge interaction monotonically increases the internal energy or enthalpy in a considerable part of the ionization band in the caloric equation of state U = U (p, V) important for some gas-dymamic problems (adiabatic flows) (see Figure 1.9).

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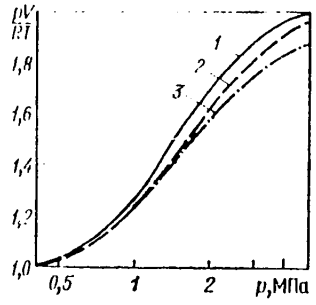

Figure 1.6. Thermal Equation of State of Cesium in Ionization Band (isocore v = 500 cm^3/g). Calculation in ideal gas approximation with regard to different number of excited states of cesium in statsum (1.71): 1--ground state; 2--
3--

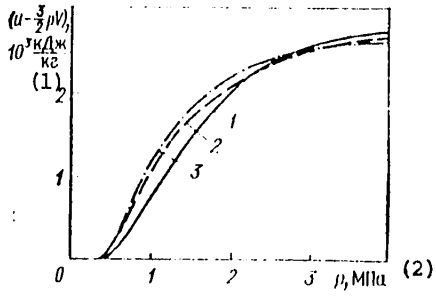

Figure 1.7. Caloric Equation of State of Cesium Plasma on Isochor v = = 500 cm^3/g. See Figure 1.6 for notations.

Key:
1. kJ/kg
2. MPa

When the ionization band intersects, for example, along the isochor (V = const), the parameter of imperfection Γ does not behave monotonically and reaches a specific maximum value [7]. This value increases with a shift to the higher density range. The effect which charge-charge interaction has on the general course of thermodynamic functions also increases in this case within the given band. The range where parameter Γ ≥ 1 can be conditionally called the range of strong imperfection. The forms and specifically the characters of correction for imperfection in this range was discussed by many authors (see, for example surveys [9-12]). It is now clear that the given problem is closely related to the role of excited states of the atom and other particles and with the sequential approach the contributions from discontinuous and continuous energy spectra of particles should be interrelated, as occurs, for example, in the physical model of a plasma where both contributions are calculated simultaneously (see section 1.2).

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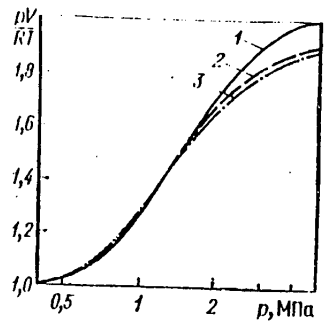

Figure 1.8. Isochor of Cesium v = 500 cm^3/g. Calculation of system of ions, electrons and atoms (in ground state) with different corrections for imperfection: 1--ideal gas; 2--ring (Debye) approximation in large canonical ensemble (1.84, 1.85); 3--correction as in single-component model [43] (see also Figures 1.16 and 1.17)

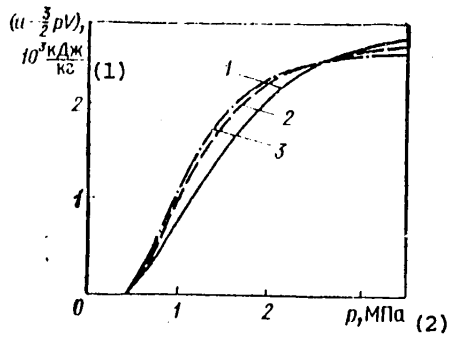

Figure 1.9. Caloric Equation of State of Cesium Plasma on Isochor v = = 500 cm^3/g. See Figure 1.8 for notations

Key:
1. kJ/kg

A large number of papers [13-16] is also devoted to the problem of the role of interaction of charged and neutral particles. The effect of this interaction is manifested differently according to existing concepts. First, bound complexes of neutral and charged particles which are regarded as a separate variety of particles, for example, H^-, H_2^+ and H_3^+, Li^-, Li^+, Li_2^+ and so on, are formed in the case of sufficiently strong attraction at close distances. The calculations show that inclusion of these particles in the calculation is weakly reflected in the total thermodynamic characteristics. Second, there is the effect of charge-neutral interaction unrelated to formation of an individual variety of particles. The following dimensionless parameter is used for the characteristic of this part of the contribution of interaction.

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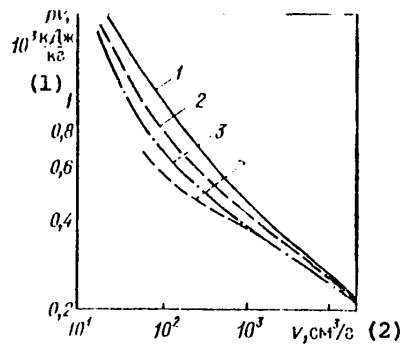

Figure 1.10. Position in p, v-Plane of Isoentropy of Cesium s = 1.9 kJ/(kg·K) When Using Different Corrections for Imperfection: 1, 2 and 3--as in figure 1.8; 4--ring (Debye) approximation in [N, V, T]-group. Summation of intra-atomic states in 1-4 to energy $E_k \leq$ $\leq I - kT$

Key:
1. kJ/kg
2. cm^3/g

$$\xi = \frac{n_0}{kT} \int \Phi(r)\, dr, \tag{1.2}$$

where n_0 is the neutral particle concentration and $\Phi(r)$ is the potential of charge-neutral interaction. The equality of this parameter to unity conditionally limits the range where charge-neutral interaction appreciably shifts the ionization equilibrium. Different estimates made for alkali metals [16] yield a typical figure on the order of approximately $-0.5 \cdot 10^{-21}$ eV·cm^3 for the value $\int \Phi(r)dr$ contained in expression (1.2). Calculations using this value show that consideration of the interaction of charged and neutral particles in the greater part of the range of interest to us weakly affects the general course of the total thermodynamic functions, leading to some smoothing of the course of these functions discussed above in the low-temperature part of the primary ionization band. The diagrams of state of hydrogen, lithium, cesium and uranium with the range of strong imperfection noted on them due to charge-charge and charge-neutral interaction are presented in Figures 1.11-1.14. The give diagrams were plotted on the basis of calculations (see Chapter 5) where the indicated interactions were already taken into account. However, in view of the approximate nature of our knowledge of the potential $\Phi(r)$ itself in [1.2) and also due to the approximate nature of the corrections that describe these interactions, the above estimate of the role of these interactions may be inaccurate.

The interaction between neutral particles can also be described within two mechanisms. Formation of a new variety of neutral particles, for example, molecules, may have a significant effect on the general course of the thermodynamic functions in the low-temperature range. This is primarily related to hydrogen (see Figures 1.2 and 1.11) and to a lesser degree to the alkali metals and is related directly to the values of the dissociation energy of H_2, Li_2, Na_2 molecules and so on (see Table 1.1).

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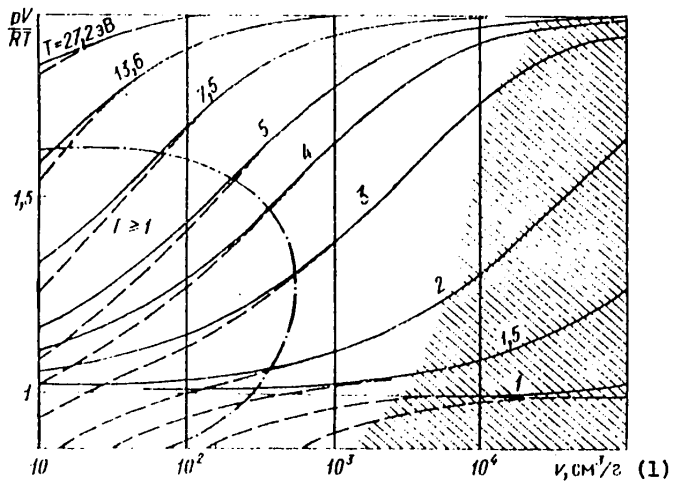

Figure 1.11. Diagram of State of Hydrogen. The range of strong imperfection is noted ($\Gamma \geq 1$). Dashed zone considered in this paper ($p \leq 50$ MPa): solid lines--isotherms in approximation of ideal gas H^+, e and H; dashed lines--additional consideration of formation of H_2, H_2^+ and H^-

Besides this effect, an interaction not leading to formation of bound states (the term "imperfection" is usually applied to this latter part) is considered separately in the chemical model. Estimates and calculations show that, being limited only by consideration of molecule formation, we introduce an error to the equation of state in the low-temperature range ($\leq$ 4,000 K) in the range of pressures of interest to us.

A qualitatively important manifestation of particle interaction, primarily of neutral particles, is the gas-liquid phase transition. According to existing estimates [17, 18] and according to experimental data, the critical parameters of alkali metals are located in the range of parameters: $T_{kr} \approx$ 2,000-3,500 K, $V_{kr} \approx$ 50-300 cm^3/mole, $p_{kr} \approx$ 10-60 MPa and $Z_{kr} \equiv p_{kr}V_{kr}/RT_{kr} \approx$ 0.1-0.2. Statistical measurements of the equation of state of cesium vapors in the sub- and near-critical range $T \leq T_{kr} \approx$ 2,050 K have now been made [19, 20]. There are no static experiments in neutral cesium vapors at supercritical temperatures, but comparison of recent experimental data at $T \leq T_{kr}$ [20] to the generalized diagram of compressability for nonmetals [21, 22] shows satisfactory agreement (Figure 1.15). If one assumes that the noted agreement is retained at $T > T_{kr}$ with accuracy sufficient for estimates in the temperature range where thermal ionization is low, one can directly compare the equation of state characterized by the diagram of compressability indicated above to the results of thermodynamic calculation that do not take into account interatomic interaction (except for formation of biatomic molecules). The boundary where the difference becomes sufficiently large can be conditionally taken as the boundary of the range of strong imperfection due to neutral-neutral interaction. This comparison was made for isotherms T = 2,000 and 3,000 K in Figure 1.15 and for isobars P = 10 and 20 MPa in Figure 1.13.

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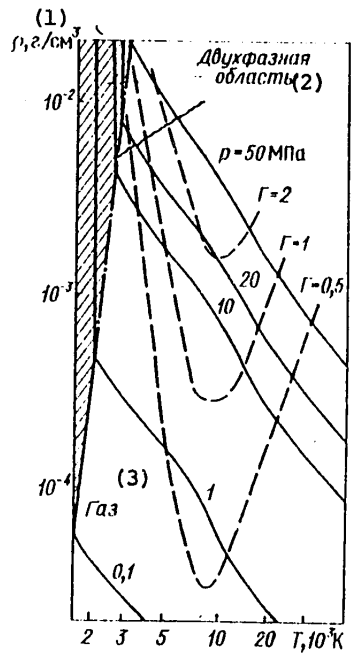

Figure 1.12. ρ-T Diagram of Lithium. Saturation boundary and range of strong charge-charge interaction (dashed line) and charge-neutral interaction (wavy line)--$\beta n_{atm}\Phi_0 = 0.5$ (1.2)) are noted

Key:
1. g/cm^3
2. Two-phase zone
3. Gas

It follows from diagrams 1.12 and 1.13 that the high-temperature part of the boundary of the two-phase zone, including the vicinity of the critical point, is in the zone where, besides neutral particle interaction, charge-neutral and charge-charge interactions are also strong. The hypothesis has frequently been advanced in the literature [9, 14] that there may be an appreciable difference of the gas-liquid phase transition in alkali metals from the phase transition in nonmetals due to this and, moreover, that there exists an independent "plasma" phase transition. The presently available experimental information does not yet indicate the presence of any qualitative anomalies in this range (see section 4.3 for more detail).

Compared to the alkali metals, uranium has a higher boiling point (approximately 4,000 K). The critical parameters of uranium, according to existing estimates, are such that ($p_{kr} \approx 600$ MPa, $T_{kr} \approx 11{,}500$ K and $\rho_{kr} \approx 5.3$ g/cm^3 [18, 23, 24]). the entire range of pressures of interest to us is subcritical. In this regard the overall pattern of thermodynamic functions in the temperature range of

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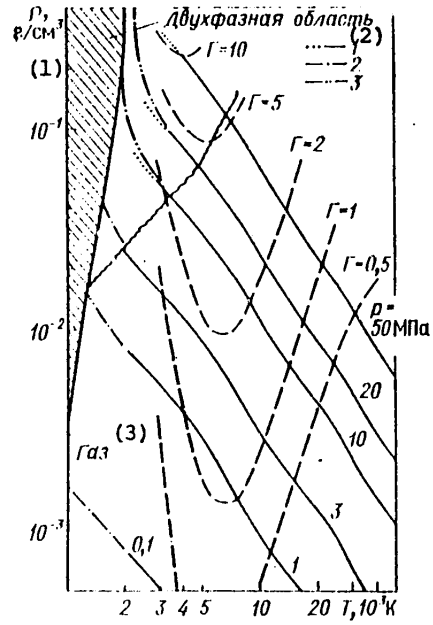

Figure 1.13. ρ-T-Diagram of Cesium. The notations are the same as in Figure 1.12: 1--calculation by method of section 1.6; 2--smooth approximation of experimental results [20]; 3--generalized equation of state for nonmetals [21, 22] ("Obert and Nelson diagram")

Key:
1. g/cm^3
2. Two-phase zone
3. Gas

$T \leq 10^4$ K is divided into two sections: a gas behavior range limited by the curve of equilibrium and a gas-liquid transition range. The condensation boundary separating them is experimentally known in a limited temperature range ($T \leq 2{,}500$ K), due to which the results of approximate extrapolation are used in practical calculations related to higher temperatures [23, 25]. The validity of this extrapolation in the case of uranium is especially needed in substantiation and experimental check since, as can be seen from Figure 1.14, the high-temperature part of the curve of equilibrium is located in the range of a strongly imperfect plasma, which according to existing concepts, may lead to violation of the known empirical rules which are the basis of the extrapolation indicated above.

1.2. Asymptotic Methods of Describing the Thermodynamics of a Weakly Imperfect Plasma

Unlike ordinary gases, the forces of interaction between particles are long-range in a plasma, due to which the effects related to interaction may be significant at

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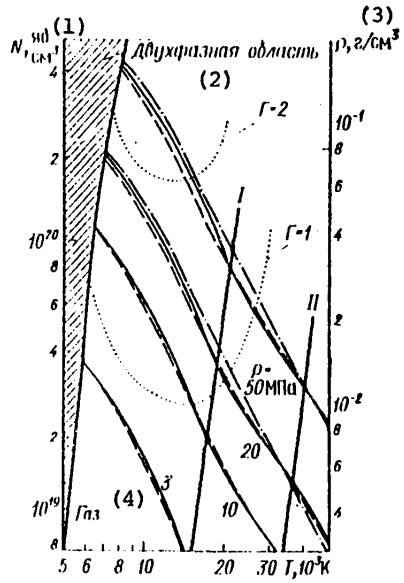

Figure 1.14. ρ-T-Diagram of Uranium. Solid lines--calculation by method of section 1.6; dashed lines--calculation using fewer known levels ([105]) and with regard to imperfection according to (1.24-1.30, 1.33); dash-dot line--calculation from [106]; the wavy lines denote passage through secondary and tertiary ionization (I--$x_{U^{++}}/x_{U^{+}} = 0.5$; II--$x_{U^{+++}}/x_{U^{++}} = 0.5$)

Key:

1. Nuclei/cm^3
2. Two-phase zone
3. g/cm^3
4. Gas

low temperatures ($T \sim 10^4$ K) even at charged particle concentrations of $n \sim 10^{18}$ cm^{-3}. Moreover, quantum-mechanics effects are manifested in an imperfect plasma: first, effects of electron generation may occur and second, when the particles interacting by coulomb's law are at short distances, their relative motion should be described quantum mechanically rather than by using laws of classical mechanics.

The degree of imperfection and quantum effects in a two-component plasma can be characterized by two independent dimensionless parameters

$$\gamma = e^2/\bar{E}n^{1/3}; \quad \Lambda_e \varkappa_D, \tag{1.3}$$

where $\bar{E}$ is some mean energy, $n^{-1/3}$ is the average distance between particles, $\Lambda_e = (2\pi\hbar^2/kTm_e)^{1/2}$ is the average de Broglie wavelength of the electron and $\varkappa_D$ is the inverse Debye radius (1.1). A set of these parameters, dependent on the particle mass and the sizes of the charges, occurs in a multicomponent plasma.

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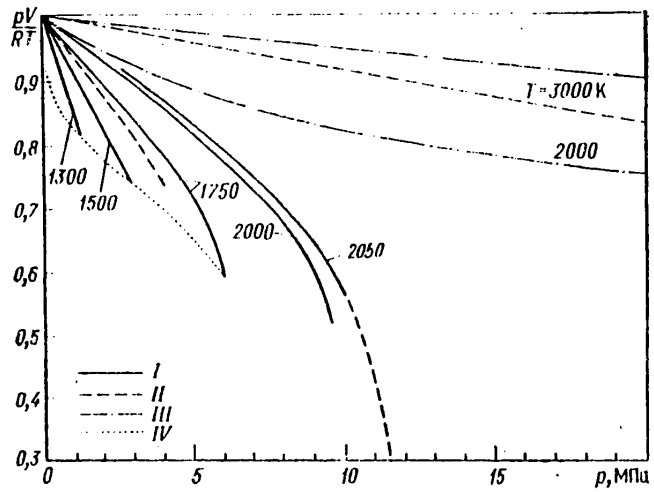

Figure 1.15. Equation of State of Cesium Vapors in Low-Temperature Range: I--smooth approximation of experimental results [20]; II--generalized equation of state for nonmetals [21, 22] ("Obert and Nelson diagram"); III--calculation by method of section 1.6; IV--Cs condensation boundary

If the temperature is high, then $\bar{E} \sim kT$ and condition $\gamma \ll 1$ can be written in the form $n^{1/3} \ll kT/e^2$. Assuming, for example, that $T \approx 10^4$ K, we find that this condition is fulfilled at concentrations less than 10^{20} cm^{-3}. At low temperatures $\bar{E} \approx p_F^2/2m_e$ ($p_F = \hbar\,(3\pi^2 n)^{1/3}$ is the Fermi pulse) and the condition $\gamma \ll 1$ reduces to the following:

$$n^{1/3} \gg 2\,(1/3\pi^2)^{2/3} m_e e^2/\hbar^2.$$

It is fulfilled at electron concentrations greater than 10^{23} cm^{-3}.

If $kT \leqslant \mathrm{Ry}$ ($\mathrm{Ry} = m_e e^4/2\hbar^2$), then conditions are initially achieved with an increase of plasma density when $\gamma \ll 1$ then $\Lambda_e \varkappa_D \approx 1$ and the electrons are then degenerate. One can consider the thermodynamics of a weakly imperfect, strongly imperfect nondegenerate and then degenerate plasma according to this sequence. The inverse pattern is observed with an increase of density at $kT \gg \mathrm{Ry}$: the plasma is initially degenerate and coulomb interaction then becomes significant. Provided that $\mathrm{Ry}/kT \gg 1$, the particle motion is quasi-classical. However, bound states may make an appreciable contribution to the thermodynamic functions. In the inverse limiting case $\mathrm{Ry}/kT \ll 1$ (the Born case), the interaction between particles is considerably quantum in nature and can be described by means of perturbation theory.

The degree of electron degeneration is described by the known parameter $n\Lambda_e^3$. If $n\Lambda_e^3 \ll 1$, then degeneration can be disregarded. We note that if parameters (1.3) are taken as independent, then Ry/kT and $n\Lambda_e^3$ will be functions of them:

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$$\mathrm{Ry}/kT = 4\pi^2\gamma^3/(\Lambda_e\varkappa_D)^2; \quad n\Lambda_e^3 = (\Lambda_e\varkappa_D)^3/(4\pi\gamma)^{3/2}. \tag{1.4}$$

Let us consider the thermodynamic properties of a plasma with charged particle concentrations up to 10^{20} cm^{-3} at comparatively low temperatures (approximately 10^4-10^5 K). Under these conditions the parameter of degeneration $n\Lambda_e^3$ will be small and the plasma can be regarded as Boltzman. Parameters (1.3) may be less or on the order of unity, however the first of them (where one should assume $\bar{E} \sim kT$) plays the main role since it achieves values of approximately 1 more quickly with an increase of charged particle density [9]. Moreover, since the first of parameters (1.4) can be greater than unity, the contribution from bound states must be taken into account. The existing results in equilibrium theory of this plasma lead to an expression for the coulomb part of the thermodynamic potential $\Delta\Omega$ in the form of an expansion by the value $\zeta = \Lambda^{-3}\exp(\mu/kT)$ [26—35]

$$-\Delta\Omega/kTV = A\zeta^{3/2} + B\zeta^2\ln\zeta + C\zeta^2 + D\zeta^{5/2}\ln\zeta + E\zeta^{5/2}, \tag{1.5}$$

where V is the volume of the system, μ is the chemical potential of the particle and A, B, C, D and E are the coefficients of expansion by value ζ dependent on temperature. The two first and the fourth terms of this expansion describe the contribution from the continuous spectrum to $\Delta\Omega$. The third and fifth terms contain the contribution from the discontinuous spectrum. Strictly speaking, this contribution was calculated for a hydrogen plasma. However, the results may also be applicable for two-component systems where hydrogen-like ions are present. Moreover, there is an approximate method [36] that permits application of formula (1.5) by using the chemical model to calculate a multicomponent plasma where nuclei or hydrogen-like ions with charges of different multiples are present and multielectron bound states may occur.

Formula (1.5) was found on the basis of the quantum-statistical approach where the method of Green functions and the diagram technique were used. There is now an extensive literature on this problem [37-39]. The quantum-statistical approach was first used in Vedenov and Larkin's investigations [26, 27] to determine the thermodynamic functions of a plasma. Let us dwell below on the main results found within the indicated formalism.

It is convenient to use the large Gibbs statistical group, where the thermodynamic potential Ω is a function of variables T, μ, and V to construct the complete thermodynamics of a system of many particles in quantum mechanics. The expression for the value of Ω, where the coulomb part $\Delta\Omega$ is contained in the form of (1.5), was found in [29, 35]. Formulas for a two-component plasma have the simplest form. Since these formulas are required for further considerations, let us write them:

$$\begin{aligned} -\Omega/kTV = p/kT = \zeta_i + \zeta_e + (\zeta_i + \zeta_e)\frac{\tilde{\Gamma}}{3}(1 + f_p) - \\ -\frac{\pi}{4}\Lambda_e\left(\frac{e^2}{kT}\right)^2\zeta_i\zeta_e - \frac{\pi}{4}\frac{1+\ln 2}{\sqrt{2}}\Lambda_e\left(\frac{e^2}{kT}\right)^2\zeta_e^2 + \\ + \frac{1}{2}\zeta_i\zeta_e\Lambda_e^3\tilde{Q}\exp(I/kT - \tilde{\Gamma}\varphi); \end{aligned} \tag{1.6}$$

$$f_p = \frac{3}{8}\tilde{\Gamma} + \frac{4}{9}\tilde{\Gamma}^2\left(2C + \ln 4\tilde{\Gamma} - \frac{35}{12}\right) - \frac{9}{44}\tilde{\Gamma}^2; \tag{1.7}$$

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$$\tilde{Q} = \sum_{(n)} g_n \exp(-\tilde{E}_n/kT)\, \omega_n^{(1)} [(I - \tilde{E}_n)/kT]; \tag{1.8}$$

$$\varphi = \frac{1}{\tilde{Q}} \sum_{(n)} g_n \exp(-\tilde{E}_n/kT)\, \omega_n^{(2)} [(I - \tilde{E}_n)/kT]; \tag{1.9}$$

$$\Gamma = e^2 (kT)^{-1} \tilde{r}_D^{-1}; \quad \tilde{r}_D^{-2} \equiv \tilde{\varkappa}_D^2 = 4\pi (kT)^{-1} (\zeta_i z_i^2 + \zeta_e) e^2. \tag{1.10}$$

The following functions are contained in expressions (1.8) and (1.9) in the sums for the discontinuous spectrum

$$\omega_n^{(1)}(x) = 1 - \exp(-x) - x \exp(-x) \quad \left(x = \frac{I - \tilde{E}_n}{kT}\right) \tag{1.11}$$

and

$$\omega_n^{(2)}(x) = \frac{2}{3}[1 - \exp(-x)] - \frac{5}{21} x F(1;\ 11/4;\ -x) - \frac{3}{7} x \exp(-x),$$

having the meaning of weight functions and which ensure the convergence of these sums. The value of g_n, which plays the role of the statistical weight of an isolated ion ($g_n = 2n^2$ for hydrogen, where n is the main quantum number), is introduced under the sign of the sum in expressions (1.8) and (1.9) to use formula (1.6) not only for a hydrogen plasma. Formula (1.6) can be used in some approximation in this form for calculation of a non-hydrogen plasma as well. In this case the experimental or approximately calculated values must be taken for the energy levels. The value $F(1;\ b;\ -z) = (b-1)\int_0^1 e^{-zx}(1-x)^{b-2}dx$ at $(b > 1)$ is a hypergeometric degenerate function, I is the ionization potential, E_n is the excitation energy of an isolated particle and C = 0.5772 is an Euler constant; the exchange corrections were taken into account in (1.6) with accuracy up to terms approximately $\Lambda_e \tilde{\varkappa}_D$ inclusively.

If the equations for charged particle concentrations are added to (1.6)

$$n_\alpha = -\frac{1}{kTV} \zeta_\alpha (\partial\Omega/\partial\zeta_\alpha)_{T,V} \quad (\alpha = i,\ e), \tag{1.12}$$

then we find the equation of state of a plasma in parametric form. The internal energy U is found from the relation

$$\frac{U}{kTV} = -\frac{1}{kTV}\left(T^2 \frac{\partial}{\partial T}\left(\frac{\Omega}{T}\right)\right)_{V,\zeta_i,\zeta_e} = \frac{3}{2}\frac{1}{kTV}\sum_{\alpha=i,e} \zeta_\alpha \left(\frac{\partial\Omega}{\partial\zeta_\alpha}\right)_{T,V}. \tag{1.13}$$

We note that the number of ions and electrons determined from relation (1.3) characterizes the total number of particles both free and bound into pairs in the considered physical model of a plasma. The chemical model is usually employed in practice where the ions and electrons are regarded as free, and, moreover, there is the concept of atoms whose number is determined as the sum of the numbers of

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bound ion-electron pairs. The question of how to go from the physical to the chemical model of a plasma is discussed in [2, 32, 34, 36].

Let us describe the expressions for charged particle densities both for the internal energy ensuing from relations (1.12) and (1.13):

$$n_i = n_e = \frac{1}{2}(\zeta_i + \zeta_e)\left[1 + \frac{\tilde{\Gamma}}{2}(1 + f_n) - \frac{1}{32}\left(1 + \frac{1 + \ln 2}{\sqrt{2}}\right)\tilde{\Gamma}\Lambda_e\tilde{\varkappa}_D\right] + \\ + \frac{1}{2}\zeta_i\zeta_e\Lambda_e^3\tilde{Q}\exp\left(I/kT - \frac{5}{4}\tilde{\Gamma}\varphi\right); \tag{1.14}$$

$$f_n = \frac{\tilde{\Gamma}}{2} + \frac{20}{27}\tilde{\Gamma}^2\left(2C + \ln 4\tilde{\Gamma} - \frac{163}{60}\right) - \frac{15}{44}\tilde{\Gamma}^2 \tag{1.15}$$

$$\frac{U}{kTV} = \frac{3}{2}(\zeta_i + \zeta_e)\left\{1 + \frac{1}{6}\tilde{\Gamma}(1 - 3f_n + 4f_p) - \frac{1}{96}\left(1 + \frac{1 + \ln 2}{\sqrt{2}}\right) \times \right. \\ \times \left(\frac{1}{2} + I/kT\right)\tilde{\Gamma}\Lambda_e\tilde{\varkappa}_D + \frac{I}{3kT}\left[1 + \frac{\tilde{\Gamma}}{2}(1 + f_n)\right]\Big\} + \\ + \frac{1}{2}\zeta_i\zeta_e\Lambda_e^3\tilde{Q}\exp(I/kT - \tilde{\Gamma}\varphi)\left[\frac{3}{2}\exp\left(-\frac{1}{4}\tilde{\Gamma}\varphi\right) + \right. \\ \left. + T\frac{d\ln\tilde{Q}}{dT} + \frac{1}{4}\tilde{\Gamma}\varphi\left(\frac{9}{2} - 4T\frac{d\ln\varphi}{dT} - I/kT\right)\right]. \tag{1.16}$$

If $\Lambda_e\tilde{\varkappa}_D < 1$, then the exchange corrections in the described relations can be omitted due to their smallness. It is also easy to note that functions (1.7) and (1.15) describe deviations of the correcting terms in expressions (1.6), (1.14) and (1.16) from their Debye values. Numerical calculations show that functions (1.7) and (1.15) are small compared to unity (approximately 0.03) at $\tilde{\Gamma} \lesssim 1$. Hence, it follows that the main correction in the positive spectrum up to values of $\tilde{\Gamma} \sim 1$ is the Debye term

$$-\frac{\Delta\Omega}{kTV} = \frac{\tilde{\varkappa}_D^3}{12\pi} = \frac{\tilde{\Gamma}}{3}\sum_{\alpha=i,e}\zeta_\alpha z_\alpha^2. \tag{1.17}$$

This circumstance permits considerable simplification of the calculations of the thermodynamic properties of an imperfect plasma, especially when we are talking about a multicomponent plasma.

1.3. The Thermodynamics of a Strongly Imperfect Plasma

As follows from the preliminary analysis made in section 1.1, an appreciable part of the range of parameters of interest to us (see Figures 1.11-1.14) falls in the range of a strongly imperfect plasma. Working out the theoretical description of this plasma is related to a number of complex and unresolved problems. Before turning to description of what we know about a strongly imperfect plasma, let us note some qualitative characteristics of the substances inherent to a specific strongly imperfect plasma of interest to us in the range of parameters important from the applied viewpoint [1].

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Let us consider the aggregate of nuclei and electrons, i.e., the physical model of a plasma, under conditions when, using the language of the chemical model, the ionization multiplicity factor is low and the free electrons are not degenerate . It is known that each charge in a plasma is on the average surrounded by a shielding cloud of charge of opposite sign. The thermodynamic properties of the plasma depend to a significant degree on the shape and parameters of this class. The concept that the mechanism of total shielding of the charge (for example, nucleus) is clearly divided into two--individual shielding at short distances by one or more "bound" electrons which shield part or all of the charge and together with the shielding nucleus form the composite ion or atom and collective shielding by all the "free" charges at long distances corresponds to the concept of a strongly imperfect plasma. It is assumed in this case that the first mechanism is realized at distances $r \gg e^2/kT$ and the shielding charge distribution corresponding to this mechanism is insensitive to variation of the thermodynamic parameters. The second mechanism, on the other hand, is accomplished simultaneously by a large number of charges at distances and is considerably dependent on the thermodynamic parameters. It is assumed that the shape of the shielding cloud within the framework of the second mechanism is essentially independent of the value of the shielded charge and the parts of potential behavior of interaction at short distances while the amplitude of the indicated cloud is directly proportional to the value of this charge. All this taken together corresponds to the so-called ring (Debye) approximation written only for a subsystem of free charges and applicable in the range $\Gamma \ll 1$.

Two typical lengths can be introduced in the general case for the quantitative characteristics of the second mechanism of shielding. The first is the so-called shielding radius r_{ekr}. There is the statement [40, 41] that the main term in the charge-charge correlation function at long distances has the form

$$q(r) \sim Ar^{-1}\exp(-r/R); \quad r \to \infty \tag{1.18}$$

and length R in the exponent of (1.18) corresponds to the concept of shielding radius. Moreover, it is known that on the average the total charge of the shielding cloud is exactly equal to the charge of the shielded particle; therefore, in some cases interaction with this cloud can be replaced by interaction with a point charge at the length which can be called the radius of interaction r_{vz}

$$\int (ze^2/r)\, q(\mathbf{r})\, d\mathbf{r} = z^2e^2/r_{вз}. \tag{1.19}$$

In a strongly imperfect plasma ($\Gamma \ll 1$), both lengths r_{ekr} and r_{vz} coincide with the Debye radius r_D of (1.1) and in this case the following condition is fulfilled

$$r_{вз} \gg r_{ср} = n_{зар}^{-1/3} \gg e^2/kT. \tag{1.20}$$

In a strongly imperfect plasma all three lengths r_D, r_{ekr} and r_{vz} differ considerably.

How does the pattern in an alkali or uranium plasma of interest to us at p ~ 10-100 MPa and T ~ 10^4 K differ qualitatively from the idealized pattern described

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above. First, at $\Gamma \geq 1$ interactions at short distances $r \sim e^2/kT$ begin to play the determining role in a formation of the second, collective part of the shielding could. It is known from study of a similar situation in simplified coulomb models [41-43] that the charge-charge correlation function is no longer described by the simplest expression of (1.18) as the imperfection increases. Additional terms of type (1.18) with parameters dependent on the behavior of interaction potential at short distances initially appeared in it and, beginning at some moment, it acquires an oscillating nature. The shielding and interaction radii (1.18, 1.19) are already otherwise dependent on the thermodynamic parameters than the Debye radius (1.1) in the range of strong imperfection ($\Gamma \geq 1$).

In a single-component model the analytical approximations developed to the present time permit one, despite the absence of a small parameter, to describe rather effectively the range not only of weak, but of strong imperfection as well. However, in the more complex case of a system with charges of different signs, for example, in the model of charged solid spheres [44, 45] when the depth of the attraction potential appreciably exceeds the value kT

$$\min \Phi_{ij}(r) \ll -kT, \tag{1.21}$$

A significant part of the charges, combining into pairs, no longer participates in collective shielding. In this situation the methods suitable for a single-component plasma become hardly effective. One of the procedures that permit one to take this fallout into account qualitatively consists in additional introduction of a new variety of composite neutral and charged particles. Mutually impermissible sections of the phase space appear for charges remaining in the discharge of free charges at short distances [46, 47]. This is necessary so as to exclude the physically identical states and can be taken into account by effective correction of the coulomb potential at short distances [46, 48]. It must be emphasized that, first, this correction depends on the selected method of separating the atoms and composite ions and thus depends on the thermodynamic parameters. Second, this correction is not paired, i.e., the interaction in a system of free charges ceases to be binary-additive. One can estimate the dimensions of the corresponding correction. Let, for example, states of the electron-ion pair with binding energy exceeding the value kT be related to the atomic charge. In this case the radius of effective correction of the coulomb potential for free ions and electrons corresponds by an order of magnetude to the dimension of the range where $\Phi_{kul}(r) \leq -kT$:

$$\Phi_{\text{опр}}(r) \neq \Phi_{\text{кул}}(r) \quad \text{at} \quad r < r^* \sim e^2/kT. \tag{1.22}$$

In a strongly imperfect plasma correction at these distances leads to the appearance of small terms compared to Debye on the order of $\Gamma r^*/r_D$ and $n_{zar}r^{*3}$, i.e., approximately Γ^2. When we then turn to the range of a strongly imperfect plasma, then as already noted, interaction at these distances becomes determinate. Therefore, the distinguishing feature of a strongly imperfect plasma is the considerable dependence of the thermodynamic properties of the subsystem of free charges on selection of the position of the boundary that separates the free and bound states. In turn, the contribution of the subsystem of atoms also reveals sensitivity to the position of this boundary in the range of a strongly imperfect plasma [6].

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Besides the difficulties which arise even in classical models at sufficiently low temperatures of (1.21), the quantum effects are significant in a real strongly imperfect plasma. The correlation between the mean potential (P) and the mean kinetic (K) energy of the system can be called one of the main manifestations of quantum effects from the viewpoint of thermodynamics. Unlike the classical system where the value of K is clearly determined by temperature, isothermal inclusion of interaction in a quantum system leads to variation of the mean kinetic energy. The known general result [49, 50] consists in the fact that the mean kinetic energy in a quantum system is not lower than its own classical range -kT/2 by a degree of freedom. Moreover, in view of the homogeneity of Coloumb potential, the values K and P, as is known [8, 21], are related to pressure and to the total internal energy by the relations:

$$U = K + \Pi, \tag{1.23}$$

$$3pV = 2K + \Pi. \tag{1.24}$$

Quantum effects are most significant upon formation of deeply bound electron states in molecules, atoms and ions. Thus an electron in the ground state of an isolated atom makes a contribution equal to the ionization potential to the mean kinetic energy according to (1.23) and (1.24), which considerably exceeds the classical value 3/2 kT in the range of a partially ionized plasma. At distances of $r \leq \Lambda_e$ the quantum effects are also felt in interaction of free charges primarily in formation of the shielding cloud. The result of this effect increases as imperfection increases when the role of interaction at short distances ($\sim e^2/kT$) becomes determinate. Let us note that the lengths Λ_e and e^2/kT are comparable to each other in a considerable part of the temperature range $T \sim 10^3$-$5 \cdot 10^4$ K of interest to us:

$$\Lambda_e \Big/ \frac{e^2}{kT} \sim 0{,}1 - 1. \tag{1.25}$$

The last distinguishing feature of a strongly imperfect plasma of specific interest to us is related to the role of neutral particles. It was assumed in the idealized pattern described at the beginning of this section, corresponding to a strongly imperfect plasma, that neutral particles are an ideal subsystem and do not participate in shielding of free charges. This hypothesis is invalid [13-16] in the range of high densities ($\rho \sim \rho_{kr}$) and low temperatures ($T \sim 10^3$-10^4 K) for atoms of alkali metals, distinguished by high polarizability α ($\alpha \sim 100$-400 atomic units). Due to interaction with the charges, the atoms acquire an induced dipole moment and at sufficiently high concentration ($n_a \sim 10^{20}$-10^{21}) their presence considerably distorts the pattern of mutual shielding of free charges. In turn, the disturbing effect of the micropoles [11] and the limitation of volume in a dense plasma permissible for realization of excited states of atoms, molecules and so on (see section 1.5) leads to distortion of the contribution of bound states to the total thermodynamic functions.

As follows from the foregoing, the complexity of the strongly imperfect plasma of interest to us is related to simultaneous superposition of several effects immediately one on the other, each of which makes description of the remaining effects difficult. Therefore, study of simplified models plays an important role in the problem of a strongly imperfect plasma. The greatest progress has been achieved

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in the simplest plasma model--a classical system of charges of one sign on a compensating background [41-43]. Satisfactory description of the equation of state is found here in the range $\Gamma \sim 1$ even within the framework of asymptotic approximations developed for the case $\Gamma \ll 1$ if those of them in which some general restrictions valid at any degrees of imperfection are fulfilled are selected for extrapolation to the range $\Gamma \sim 1$.

The following relations were used in [6] to analyze this problem:

1) the condition of a positive binary correlation function (BKF) $F_2(r)$:

$$F_2'(r) \geq 0; \tag{1.26}$$

2) the condition of exponentiality that limits the value of BKF at $r \to 0$:

$$F_2(r) \sim \exp\{-\beta\Phi(r)\}; \quad r \to 0; \tag{1.27}$$

3) the condition of local electron neutrality [51, 52]:

$$\int_0^\infty [F_2'(x) - 1]\, x^2 dx = -\Gamma \quad (x \equiv r/r_D); \tag{1.28}$$

4) the condition of shielding [51]:

$$\int_0^\infty [F_2(x) - 1]\, x^4 dx = -6\Gamma \quad (x \equiv r/r_D). \tag{1.29}$$

The simplest correction of the approximations used at $\Gamma \ll 1$ appreciably exceeds their accuracy (in the part of the equation of state) in the range $\Gamma \gtrsim 1$ with regard to (1.26)-(1.29) [6, 52] (Figure 1.16). Fulfillment of the essentially same condition comprises the basis of the so-called MSM-approximation [53]. An even more accurate description (up to $\Gamma \sim 50$) not only of the equation of state but of the BKF is found within the framework of (also asymptotic) integral approximations [54, 55]: "hyperchain" (CHNC) and BBGI equation [56]. Let us emphasize that conditions (1.28) and (1.29) in the CHNC-approximation should be fulfilled automatically,* while fulfillment of (1.28) is controlled specially in [55]. Finally, in view of the simplicity of the model, the use of the direct Monte-Carlo method, although cumbersome in the numerical sense, is acceptable for it at any values of Γ [43, 58]. Comparison of the results of the approaches enumerated above is made in Figure 1.17. Thus, the correction for imperfection, for example, in interaction energy for one particle $\Delta U/NkT$, being negative, increases monotonically in absolute value over the entire range of parameter Γ initially as $\Gamma (\Gamma \ll 1)$ and then as $\Gamma^{2/3} (\Gamma \gg 1)$ in this model in the range of a strongly imperfect plasma. The single phase transition--crystallization--occurs at $\Gamma \approx 3 \cdot 10^3$. At $\Gamma \gtrsim 1$, the typical correlation radii r_{ekr} (1.18) and r_{vz} (1.19) no longer coincide with r_D and at $\Gamma \gg 1$, r_{vz} behaves like $r_{sr} \sim n^{-1/3}$, i.e., $r_{zv} \gg r_D$. At $\Gamma \approx 5$, the BKF becomes oscillating and in this case no anomalies of any kind are observed in the equation of state.

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*Violation of condition (1.28) in [57] was apparently the reason for the invalid results in the equation of state (see [52] and Figure 1.17).

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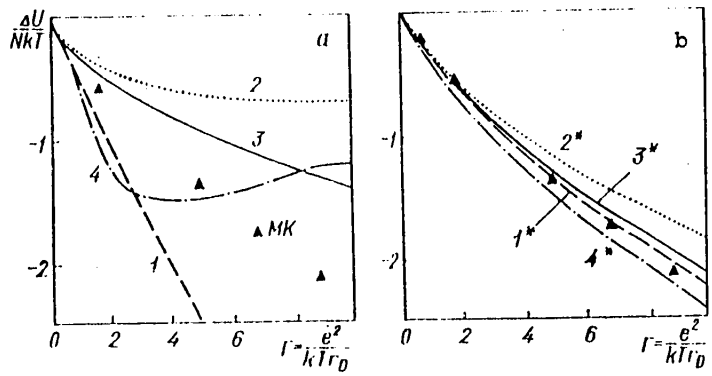

Figure 1.16. Equation of State of Single-Component Model of Plasma. Asymptotic approximations before (a) and after (b) correction to fulfill relations (1.26)-(1.29) simultaneously: 1 and 2--ring (Debye) approximation in {N, V, T}- and {μ, V, T}-groups; 3--nonlinearized Debye approximation ; 4--approximation of [41]; MK--calculation by Monte-Carlo method [43]

The classical two-component plasma with attraction of different-charge particles has been studied less. Let us note three versions of the model: with Glauberman-Yukhnovskiy potential (1.30) [59] and a system of soft (1.31) [60] and hard (1.32) charged spheres (σ is an arbitrary parameter)

$$\Phi_{\mp}(r) = \pm \frac{e^2}{\varepsilon r} + \begin{cases} \mp \frac{e^2}{r} \exp(-r/\sigma); \\ (\sigma/r)^6; \\ \infty \quad (\text{at} \quad r < \sigma). \end{cases}$$

Yet another determining parameter appears in this model, as which let us take the relation $\chi = e^2/\sigma kT$ * that characterizes the depth of attraction.* At high temperatures ($\chi \leq 1$), the model is subject to study both by asymptotic methods [61] and by means of the Monte-Carlo method [44, 45]. On the whole smooth transition from universal behavior at $\Gamma \ll 1$, when the difference (1.30) - (1.32) from the coulomb potential is reflected as a weak disturbance, to completely different behavior for different versions of the model at $\Gamma \gg 1$ when the disturbance, on the other hand, is coulomb potential is observed at these temperatures in the equation of state.

From the methodical viewpoint the indicated model is most interesting at low temperatures ($\chi \gg 1$). The range $\chi \sim 10$, $2n\sigma^3 \approx 0.1$-0.7 ($\Gamma \approx 35$-100), where the critical range of phase transition is located whose properties are determined by a

*It is more convenient in some cases to use the parameters $n\sigma^3$ or σ/r_D (σ is an arbitrary parameter).

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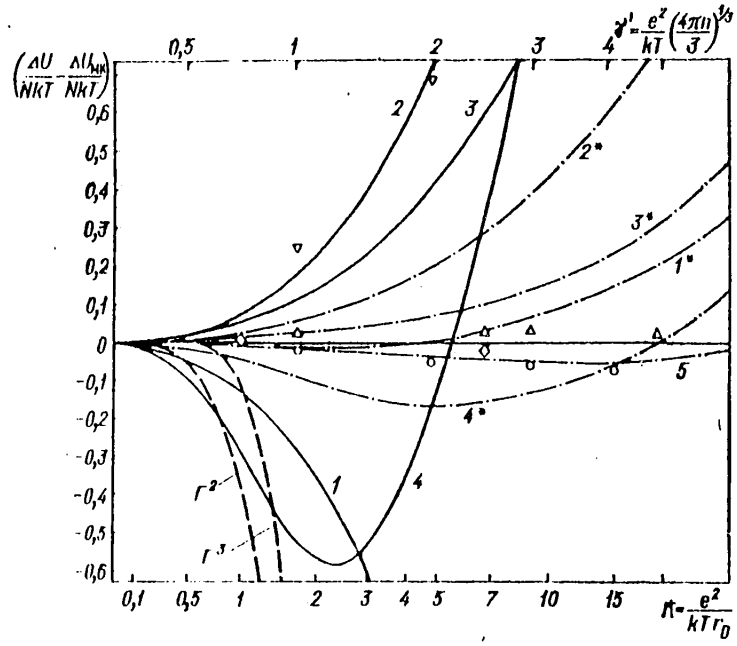

Figure 1.17. Extrapolation Properties of Different Approximations in Range of Strong Imperfection of Single-Component Plasma (the approximation of the results of [43] was used in the comparison): Γ^2 and Γ^3--asymptotic approximations with accuracy up to Γ^2 and Γ^3 in the expansion $\Delta U/Nkt$ by powers Γ and $\ln \Gamma$ ([41, 71]); 1, 2, 3 and 4--see Figure 1.16; 5--approximation with oscillating shape of $F_2(r)$ [6, 52]; O--MSM approximation [53]; ∇ and Δ--CHNC approximation of 1963 and 1973, respectively [54, 57]; $\Diamond$--solution of [55] of BBGI equation [56].

number of features rather by "packed" effects of a system of solid spheres than by the specifics of the coulomb system, was investigated in [44] by the Monte-Carlo method for model (1.32). No phase transition was found at the same parameters for version (1.31) [60]. The range $\Gamma \sim 1$ at these and lower temperatures was essentially not investigated. Reference [52] should be mentioned where an attempt was made for model (1.30) for methodical purposes to check the extent to which constructive use of conditions (1.26)-(1.28) was real to improve the extrapolation properties ($\Gamma \geq 1$) of the approximations developed for the case $\Gamma \ll 1$. The calculations can be carried out for very low temperatures ($\chi \sim 10$-40) due to selection of simple approximation as the reference point. However, these results cannot now be compared in any way due to the complexity of using the Monte-Carlo method or the apparatus of integral equations (CHNC and so on) under these conditions.

Let us turn to a real strongly imperfect plasma. One can distinguish two approaches among a large number of papers devoted to a real plasma (see surveys [9-12]).

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The first is extrapolation of asymptotic approximations similar to that described in section 1.2. In this case no composite particles of any kind are introduced a priorily into the consideration except nuclei and electrons interacting by Coloumb law. The second is the initial determination of new varieties of composite particles and effective interaction potentials between them and solution of the problem of imperfection for a system with this effective interaction.

The first approach has practical restrictions with all rigorousness. Real calculation of the terms of the initial expansion is very difficult and essentially limited by the limits of pair approximation. This means that the results of this approach are, strictly speaking, related to description of only one ionization band unique for hydrogen and of the ionization band oldest for other elements. The next step--sequential consideration of formation, for example, of a He atom or H_2 molecule has not yet been taken [62].*

Such approximations as hyperchain CHNC and others that have given a good account of themselves when describing the classical strongly imperfect plasma cannot be realized in the physical model of a real plasma due to the mentioned calculating difficulties. Extrapolation based only on several terms of expansion, as is known, is significantly ambiguous. It is known in classical theory of strongly imperfect systems [64, 65] that the extrapolation properties of asymptotic approximations are determined not so much by the abundance of older expansion terms taken into account but by how successful the mutual compensation of contributions among omitted terms is.

Let us note two papers where extrapolation to the range of a strongly imperfect plasma is assumed on the basis of approximations developed for the physical model of a plasma. Thus, relying on the approximation described in section 1.2 [35], a method of thermodynamic calculation of a strongly imperfect plasma of elements different from hydrogen was proposed in [36]. To do this, the transition is made to the chemical model of the plasma, using the statsum in the single-electron Planck-Larkin approximation (1.8) with empirical weights and energy levels for multielectron atoms and ions [66]. The composite ions figure as point charge particles z_i in subsequent relations (1.14) and (1.16).

The most significant difference of the described approximation (1.6) from others [7] is the presence of a new term, interpreted as a distortion of the contribution of the discontinuous spectrum due to interaction with free charges. Unlike the polarization charge-atom attraction, this term corresponds in sign to repulsion and is proportional in value to the concentration of atoms and composite ions multiplied by the parameter of imperfection Γ. Approximation is recommended for application in the range of sufficiently high temperatures where the contribution of molecules and also of molecular and negative ions can be disregarded.

An estimate of the range of applicability of the given approximation by comparison with the results of shock-wave experiment in cesium and noble gases (see Chapter 4)

*The complexes H_2^+, H^- and H_2 were introduced in [62, 63], but not correctly, outside any connection with the physical model of the plasma model employed.

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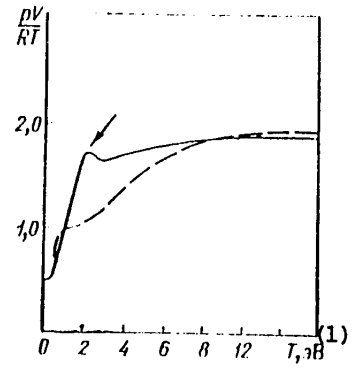

Figure 1.18. Isochor of Strongly Imperfect Hydrogen Plasma [63] v = 100 cm^3/g (Γ_{maks} ~ 1.5): solid line--result of approximation of [63]; dashed line--approximation of ideal gas (H_2, H, H^+ and e)

Key:
1. Electron volts

shows that the best agreement compared to a number of approximations proposed in the literature [7] is achieved primarily in the range of a strongly imperfect plasma with low degree of ionization due to the "repulsive" term $\phi_i n_0 \tilde{\Gamma}$ (1.6) indicated above. At $\tilde{\Gamma}$ ~ 1 and $n_e/n_0 \ll 1$, the presence of this repulsion appreciably reduces the enthalpy H as a function of pressure and volume p and V (see Figures 4.12 and 4.13), which corresponds qualitatively to the main experimentally recorded result both in cesium and in argon and xenon (Figure 4.18).

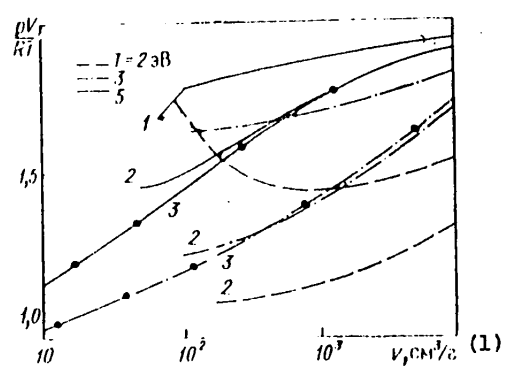

Figure 1.19. Results of Asymptotic Approximations for Strongly Imperfect Hydrogen Plasma: 1--results of [63]; 2--results of [62]; 3--calculation by method of section 1.6 (the points indicate the moment parameter Γ achieves values of 0.5, 1, 2, 3 and 5 from right to left)

Key:
1. cm^3/g

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Another approach was developed in the papers of DeWitt and Rogers [62, 63], where plasma expansion consisting of the shielded potential dependent on thermodynamic parameters* is used directly, as a result of which the group coefficients are dependent on activity. Partial summation of so-called "trees" from "ring" and "staircase" diagrams leads to an approximation which was calculated numerically due to its cumbersomeness. It must be noted that the asymptotic error of this approximation in equation of state (1.5) is approximately $\zeta^{5/2}$, whereas the terms that describe the contribution of the molecule, for example, H_2, have an order of ζ^4 and above (H_2^+ and H^- of ζ^3 and above, respectively). For the reasons discussed above, the given approximation does not logically transfer to other elements except hydrogen without losing rigorousness. Moreover, an anomaly (the arrow in Figure 1.18) appears in the range of a strongly imperfect plasma in the equation of state of [63] due to transition to a shielded potential and replacement of the coulomb spectrum in the atom by the Debye spectrum. The anomaly is smoothed somewhat, but does not disappear when the more correct form of the shielded potential is used [62]. One can assume that this anomaly does not correspond to any physical effect, but is only the result of incorrect extrapolation in the range $\tilde{\Gamma} \geq 1$. Comparison of the approximations discussed above is illustrated in Figure 1.19.

When a strongly imperfect plasma is described in the framework of the chemical model, the main difficulty is in correct determination of the effective interaction potentials between the particles as a function of the adopted method of division into subsystems. Along with pair interaction, three-, four- and older s-particle effective interactions figure in this model [48, 67, 68] but they are usually disregarded in real calculations. It is suggested in some papers [2, 48, 67, 68] that the pair pseudopotential be introduced, formally dividing it into the so-called electron-ion Slater sum [67, 68]. The method of canonical transformations is used in [34]. There are also other approximations [69]. In all cases the electron-ion pseudopotential differs from the coulomb potential by finite depth dependent on temperature and on the method of charge separation.

Since only a real plasma is replaced by a classical system of charges with sufficiently "small" ($\min\Phi^*_{ei}(r) \sim -kT$) binary-additive interaction, calculation of its thermodynamic properties presents no principal difficulties and can be carried out both by means of asymptotic approximations [54, 59, 61, 70] and by using the Monte-Carlo method [44, 45, 48, 68]. The approach suggested in [6, 52], when the approximate description of the properties of a strongly imperfect plasma relies on fulfillment of a number of general conditions presented above [(1.24), (1.26)-(1.29)], also yields satisfactory results. The results of this approximation are compared in Figure 1.20 for a two-component plasma [59] with pseudopotential differing somewhat from that suggested in [48] (Figure 1,20, b).

A practical application of the schemes proposed in [67-70] is difficult for elements except hydrogen since it requires a knowledge of the complete set of wave functions of atoms, ions and molecules. Use of hydrogen wave functions [67-69] is a source of error whose value can be established for each specific element by comparison with experiment. It is of interest to determine which pair pseudopotential

*This potential differs somewhat from the Debye potential at close distances due to quantum effects [62].

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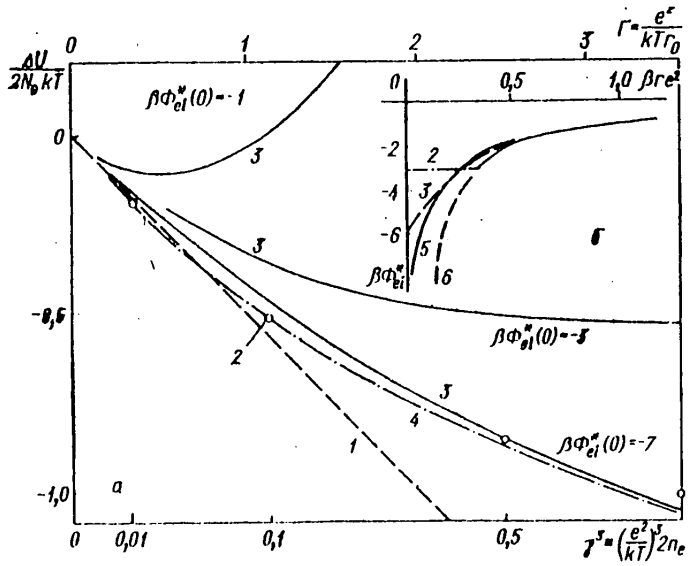

Figure 1.20. Dimensionless Energy (a) and Interaction Potential of Free Charges (b): 1--Debye approximation; 2--"configurational" energy of [48] (calculation by Monte-Carlo method for "zero" pseudopotential with $\beta\Phi^*_{ei}$ (0) = -3); 3--linearized approximation 1.24-1.30 and 1.33 [74] with different depth of pseudopotential (1.30); 4--nonlinearized approximation [52] with depth of pseudopotential (1.30) equal to $\beta\Phi^*_{ei}$ (0) = -6; 5--pseudopotential for hydrogen at T = 10^5 K [68]; 6--coulomb potential

permits one to achieve good agreement, for example, with the results of shock-wave experiment in a strongly imperfect cesium plasma [72, 73] (see Chapter 4). To answer this question, it is convenient to make use of the already mentioned approximation [74] that rather simply links the corrections for imperfection to given interaction potential. In this approximation the interaction of identically charged particles is described by coulomb potential while that of differently charged particles is described by pseudopotential (1.30) suggested in [59]. Corrections for imperfection are expressed by distribution of the shielding charge whose functional shape is selected as corresponding to ring approximation valid in the range of $\Gamma \ll 1$ [59]

$$\left.\begin{matrix} F_{ee} = F_{ii}(r) \\ F_{ei}(r) \end{matrix}\right\} = 1 \mp A\,\frac{\exp(-qr) - \exp(-pr)}{r} \quad (A = A(\Gamma);\ p = p(\Gamma);\ q = q(\Gamma)). \tag{1.33}$$

Parameters A, p and q, following the approach of [6], are determined from two shielding conditions (1.28) and (1.29) and the approximate analog of condition

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(1.27) that links the amplitude of the indicated distribution to the effective intensity of electron-ion attraction. The distinguishing feature of approximation is the use of relation (1.24) and the presence of a correction in the mean kinetic energy of the subsystem of free charges. Comparison of the results of calculation to the caloric U(p, V) and thermal p(V, T) equations of state of cesium found experimentally (see Figures 4.12-4.14) [72-73] shows [74] that the electron-ion pseudopotential should have appreciably lower effective intensity than that recommended for alkali metals in [68] to achieve the best agreement with experiments. The intensity of the indicated pseudopotential [48, 68] exceeds somewhat the value of the boundary energy with the traditional limitation of the bound and free states for energy, whereas this intensity should be equal to or even less than the latter for cesium to improve agreement with experiment. A similar conclusion is found on the basis of comparison to the experimentally measured caloric equation of state of a strongly imperfect xenon plasma [74].

In approximation (1.24)-(1.30) and (1.33) the atoms were assumed to be noninteracting; therefore, variation of the pseudopotential intensity was felt in the equation of state only in the range of developed ionization. Extrapolation of the approximation described in section 1.2 [36], on the other hand, permits one to improve agreement with experimental results in the range with low degrees of ionization. When the degree of ionization is not low, this approximation yields results that do not differ strongly both from the results of a whole series of simple approximations analyzed in [7] and from results found on the basis of the so-called "zero" approximation of the pseudopotential model [48, 68].* The given fact is possibly explained by the circumstance that expressions that rely significantly on the use of hydrogen wave functions are used both within the framework of approximation [35] and within the framework of the pseudopotential model [48, 68] for the correction for interaction in the continuous spectrum. If the conclusions made on the basis of approximation (1.24)-(1.29) and (1.33) are valid, one should conclude that the corrections indicated above depend to a much greater degree on the individuality of the chemical element than was assumed until now.

It should be said in conclusion of this section that construction of the theoretical description of the thermodynamics of a real, strongly imperfect plasma is now

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*Detailed calculations were made in this paper for methodical purposes by using the corrections recommended by the authors of [48, 68] for imperfection, corresponding to the indicated "zero approximation":

$$\frac{\Delta p}{n_p kT} = a_1\gamma^{3/2} + a_2\gamma^3 + a_3\gamma^{9/2}; \quad \frac{\Delta U}{NkT} = b_1\gamma + b_2\gamma^2 + b_3\gamma^3;$$

$$\frac{\Delta\mu_e + \Delta\mu_I}{kT} = 2\left(\sqrt{\pi}\,\gamma + c_1\gamma^3 + c_2\gamma^6 + c_3\gamma^9\right)$$

$$(a_1 = -0{,}66;\ a_2 = 0{,}59;\ a_3 = -0{,}2;\ b_1 = -0{,}89;\ b_2 = -0{,}45;$$
$$b_3 = 0{,}54;\ c_1 = 0{,}526;\ c_2 = 0{,}37;\ c_3 = -0{,}21).$$

The results of calculation were very similar to those found when using ring approximation (1.17) in combination with statistical sum (1.8) and (1.11) for atoms.

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far from complete. Definite success has been achieved in this method within the framework of the most diverse approaches, which permits, although with limited accuracy, practical calculations required in engineering applications. Intensive development of experimental (see Chapter 4) and theoretical investigations during the past decade, directed toward solution of this problem, permits one to hope for rapid progress in this direction.

1.4. The Component Composition of a Partially Ionized Imperfect Plasma

As already indicated above, the method of dividing the composite particles into an individual variety is arbitrary in the chemical model of describing the plasma. One can distinguish two approaches among the papers devoted to substantiation of the chemical model. In both cases the reference point is the system of nuclei and electrons, i.e., the physical model. Clear separation in phase space of the initial system of ranges, mutual impingement of two, three or more particles into which is determined as formation of a new variety of particle consisting of two, three and so on initial particles, comprises the basis of the first approach. This separation can be made both by the coordinate feature, i.e., by the mutual arrangement (for example, the model of a "restricted atom" [75, 76]) and by the value of the relative energy of the pair, troika and so on of particles (for example, [46, 47]) and by other features.

The next step is calculation of the free energy as a function of the scattering of nuclei and electrons through the separate regions of the phase space, that is, on the composition that is regarded as fixed. And, finally, the last step is to find an equilibrium composition corresponding to the minimum calculated free energy. Substantiation of this procedure as a whole is the variational principle of statistical mechanics [77, 39], according to which the free energy of the system $\tilde{F}_N$, considered as a functional of the test distribution function $\tilde{\rho}_N$ on the equilibrium function ρ_N is minimum with given interaction between particles:

$$\tilde{F}_N = \mathrm{Sp}\left\{\tilde{\rho}_N(\hat{H}_N + kT\ln\tilde{\rho}_N)\right\} \geqslant \mathrm{Sp}\left\{\rho(\hat{H}_N + kT\ln\rho_N)\right\} = F_N; \qquad (1.34)$$
$$\rho_N = e^{\beta\hat{H}_N}\mathrm{Sp}^{-1}\left\{\exp(-\beta\hat{H}_N)\right\}; \quad \mathrm{Sp}\left\{\tilde{\rho}_N\right\} = 1.$$

The condition of the extreme value in composition yields known conditions of chemical and ionization equilibrium, i.e., conditions of the equality of the chemical potentials of initial and final reaction products upon transition of particles between subsystems. In this case the chemical potentials are dependent on the method of separation into subsystems. In practice the benefit of the approach indicated above is dependent on the possibility of calculating the second term in the right side of (1.34), i.e., on entropy. This calculation is simplified in the approximation when the subsystems are assumed to be statistically independent. In this case entropy is additive and the interaction between subsystems is replaced by a mean interaction which can be very simple, for example, due to the electron neutrality of the atom, equal to zero. Therefore, from the viewpoint of thermodynamic calculation the states for which the hypothesis of correlation with the surrounding plasma is a good initial approximation can be divided into an individual variety. Many of the great number of criteria proposed in the literature (usually talking about separation of atoms) proceed from comparison of the total bonding energy of

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an atom with some value that characterizes the disturbing effect of the surrounding medium, for example: the mean energy of the bombarding particle approximately kT, the energy of coulomb interaction with the closest free charge approximately e^2/r_{sr} or by a reduction of the work function of the electron from an atom or ion (effective reduction of the ionization potential ΔI) and also with typical value of the breakdown microfield in the plasma [78]. We note that these values are close to each other in a strongly imperfect plasma ($\Gamma \gtrsim 1$).

The described procedure of separating the new variety corresponds to intuitive understanding of a composite particle as an aggregate of quite specific states whose population is given by the Boltzman formula, which leads to the statistical sum of traditional form

$$Q = \sum_{k=k_0}^{k^*} g_k \exp(-\beta E_k). \tag{1.35}$$

Further use of this composition in calculation of transient properties causes no confusion related to the sense contained in the concept of the atom, composite ion, molecule and so on. The disadvantage of this approach is the need to take into account that the phase volume permissible for internal and external degrees of freedom of each variety has accepted zones whose shape and value are dependent on the adopted method of separation and on the position of the corresponding boundary [46, 47]. The latter is necessary so that physically identical states do not occur upon rearrangement of atoms of different varieties. Accurate consideration of accepted zones is a complex problem when the dimensions of these zones are not small compared to the average distance between particles; therefore, one of the methods of limiting the atomic statsum used in practice [5] links the maximum main quantum number of the intra-atomic states to the mean interparticle distance.

Unlike the clear method of separation into subsystems described above, the second method is more formal. We shall outline it briefly below, following some variations of [4, 69].

The reference point is group expansion by degrees of activity or modification of it (1.5). Let us consider for simplicity a classical system of particles of one variety with brief-acting forces. Let us divide each group coefficient b_k of the initial expansion arbitrarily into parts, combinations of which we shall subsequently interpret as new effective group coefficients for a system consisting of new varieties of particles:

$$b_2 \equiv b_{|2|} + b_{|1|}; \quad b_3 \equiv b_{|3|} + b_{|12} + b_{|111} \ldots; \tag{1.36}$$

$$\begin{aligned} \beta p = \sum_k b_k \zeta^k \equiv \zeta + b_{|2|}\zeta^2 + b_{|3|}\zeta^3 + b_{|4|}\zeta^4 + \ldots \\ \ldots + b_{|1|}\zeta^2 + b_{|12}\zeta^3 + b_{|13}\zeta^4 + b_{2|2}\zeta^4 \ldots + \\ + b_{|111}\zeta^3 + b_{|112}\zeta^4 + b_{|113}\zeta^5 + b_{|12|2}\zeta^5 + \ldots, \end{aligned} \tag{1.37}$$

where $\zeta = \Lambda^{-3}\exp\beta\mu$.

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Let us formally introduce the activity ζ^* and fugitiveness f^* of new varieties

$$\left.\begin{aligned}&\zeta_1^* = \zeta_1 = f_1^*;\\&\zeta_2^* = e^{\beta\mu_2^*}/\Lambda_2^3 = e^{\beta(\mu_1+\mu_1)}/\Lambda_2^3 = \zeta_1^{*2}\,(\Lambda_2^{-3}\Lambda_1^6);\quad f_2^* \equiv b_{|2|}\zeta_1^2 =\\&= \zeta_2^*(\Lambda_2^{-3}\Lambda_1^6 b_{|2|});\quad \zeta_3^* \equiv e^{\beta\mu_3^*}/\Lambda_3^3 = e^{3\beta\mu_1}/\Lambda_3^3 = \zeta_1^{*3}\,(\Lambda_3^{-3}\Lambda_1^9);\\&f_3^* \equiv b_{|3|}\zeta_1^3 = \zeta_3^*(\Lambda_3^{-3}\Lambda_1^9 b_{|3|}).\end{aligned}\right\}\qquad(1.38)$$

One can give a form to the initial expansion (1.37) that completely imitates the expansion for a multivariety system:

$$\beta p = \sum_a f_a^* + \sum_{a,b} b_{ab}^* f_a^* f_b^* + \sum_{a,b,c} b_{abc}^* f_a^* f_b^* f_c^* + \ldots, \qquad (1.39)$$

where $b_{ab}^* = b_{ab} b_a^{-1} b_b^{-1}$, (that is $b_{|12|}^* = b_{|12|} b_1^{-1} b_{|2|}^{-1}$); $b_{abc}^* = b_{abc} b_a^{-1} b_b^{-1} b_c^{-1}$ and so on.

Determining the effective densities n_a^*, we find

$$n_a^* = \zeta_a^* \frac{\partial}{\partial \zeta_a^*}\beta p = f_a \frac{\partial}{\partial f_a}\beta p \to n = n_1^* + 2n_2^* + 3n_3^* + \ldots \qquad (1.40)$$

The ratios between n_2^*, n_3^* and so on and n_1^* have the standard form of ordinary equations of chemical equilibrium with corrections for interaction.

The method of separation (1.36) was arbitrary in the formal scheme presented above. Specifically, one can turn to clear separation into zones of two, three and so on elementary particles in the phase space, which leads to separation into parts of the statsums Z for two, three or more particles $\left(Z_N = \frac{1}{N!}\int e^{-\beta E_N} d\mathbf{p}^N d\mathbf{q}^N\right)$:

$$Z_2 \equiv Z_{|2|} + Z_{|1|1};\quad Z_3 \equiv Z_{|3|} + Z_{|1|2} + Z_{|1|1|1}, \ldots \qquad (1.41)$$

$$\left.\begin{aligned}&Vb_{|2|} = \Lambda_1^6 Z_{|2|};\quad Vb_{|1|1} = \Lambda_1^6\left(Z_{|1|1} - \frac{1}{2!}Z_1^2\right);\\&Vb_{|1|2} = \Lambda_1^9\left(Z_{|1|2} - \frac{1}{2!}Z_1 Z_{|2|}\right);\quad Vb_{|3|} = \Lambda_1^9 Z_{|3|};\\&Vb_{|1|1|1} = \Lambda_1^9\left(Z_{|1|1|1} - Z_1 Z_{|1|1} + \frac{1}{3}Z_1^3\right)\ldots\end{aligned}\right\}\qquad(1.42)$$

With this separation (1.39) is transformed into a formally accurate group expansion for a multivariety system with traditional determination of composite particles. Usually the contribution of part of the bound states of an isolated system of k particles is separated into terms $Z_{|k|}$ (k = 2, 3, 4...) that subsequently play the role of internal statsums (1.35) [5]. However, a similar but essentially different procedure is frequently used [4] when the contribution of some part of the phase space is separated into an individual term $b_{|k|}$ (1.36), but not to statsum Z_k, but directly into the group coefficient b_k or into its analog (1.5), which leads to a shift of b_k upon resummation in the initial group expansion:

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$$b_k \equiv \text{const} \int_{\Omega} W_k(q^k, p^k)\, dq^k dp^k = \text{const} \left\{ \int_{\Omega_1} W_k dq^k dp^k + \right.$$
$$\left. + \int_{\Omega - \Omega_1} W_k dq^k dp^k \right\} = b_{|k|} + \ldots \tag{1.43}$$

Different compensation terms whose number increases sharply upon transition to particles consisting of more than two elementary particles appear with this determination of the composite particles in the expression for statsum $b_{|k|}$ (1.43), besides the ordinary exponent of (1.35). These are disadvantages in calculation of such multiatomic systems as UF_6 [79] and so on. More significant is the fact that the composition obtained determination of "atoms" and "molecules" similar to (1.43) cannot be used directly in calculation of the transient properties since the values $W_k(q^k, p^k)$ contained in (1.43) no longer have the meaning of populations. The latter must be predetermined separately. Moreover, the number of properties of these "molecules" makes it inconvenient to apply this term itself to them. For example, when using the traditional determination by the internal statsum $Q(T)$ of the mean excitation energy $\varepsilon(T) = -\partial \ln Q(T)/\partial(1/T)$, the latter becomes negative at high temperatures, which differs from the ordinary intuitive concepts.

Let us turn to a plasma. In this case, as is known, partial resummation must be carried out in expansion (1.37) (section 1.2) so that the coefficients become finite in the newly found expansion. Let us emphasize that in this case there are essentially two equivalent possibilities. The first, when resummation precedes the procedure of separation of atoms, ions, molecules and so on, and the second when resummation is carried out after the new varieties have already been determined. A number of papers [26-32, 62, 63] corresponds to the first version. The pseudopotential model proposed in [48, 68], on the contrary, corresponds to the second model.* In both cases the result of the indicated resummation is a new expansion consisting of brief-acting shielded potentials. But in the first case this is a shielded coulomb potential whereas in the second case it is a shielded pseudopotential [48]. Let us recall that the difference of the latter from coulomb potential is related to a significant degree to the separation of atoms.

Instead of the second group coefficient $b_2(T)$, modified coefficients $\tilde{b}_{ee}$, $\tilde{b}_{ii}$ and $\tilde{b}_{ei}$, which are the sum of "staircase" diagrams from shielded potentials, participate in plasma decomposition, for example, for hydrogen. Unlike $b_2(T)$, coefficients $\tilde{b}_{ei}$ and so on begin with third-order rather than first-order terms with respect to e^2 and are dependent on temperature and density in a complex manner through the shielded potential. In [62, 63] these coefficients are calculated numerically, using the results of solving the Schroedinger equation with shielded potential. In this case the electron-ion coefficient breaks down into a sum by the discontinuous and continuous spectrum. The number of continuous levels is finite and depends on density. The energy of all the levels, including the round level, is also dependent on density. It is shifted upwards by the value approximately $\tilde{\varkappa} pe^2$ compared to levels in the coulomb field. Related to temperature, this value coincides with the parameter of imperfection $\tilde{\Gamma}$ (1.10). Upon extrapolation to the range of

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*The scheme of separation of atoms corresponds to (1.41) in [48] and this procedure is close to (1.43) in [68, 78].

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strong imperfection $\Gamma \gtrsim 1$, the presence of this shift leads to a sharp decrease of the contribution of the discontinuous spectrum. This is apparently explained by the anolmaly found in [63] in the behavior of the compressability factor (the arrow in Figure 1.18). In reality the Debye shift by the value $\sim \tilde{\varkappa}_D e^2$ to $b_{ei}(n, T)$ should be compensated for to a significant degree upon consideration of the remaining terms $\sim \zeta^{5/2}$ in expansion (1.5). In [62] these compensating terms are partially taken into account and as a result the anomaly was less marked (Figure 1.19). According to the statement of [80], the ground state of a hydrogen atom, due to its compactness and electron neutrality, can be shifted only by value $\sim (\tilde{\varkappa}_{Da0})^2$. This means that the contribution of the ground state in the expansion by activity should have the form $\sim \zeta_e \zeta_i \times \exp\{\beta Ry + \text{const}\ (a_0 \tilde{\varkappa}_D)^2\}$. The statsum corresponding to this requirement is suggested in [69].

The approach to determining the contribution of the discontinuous spectrum differs from that described above [62, 63] (also see [69]) in the well-known paper [26] and in those succeeding it [27-35] and the final result is expressed by the undisturbed hydrogen spectrum. This is achieved due to the fact that a third-order term with respect to e^2 (or rather a term corresponding to the staircase diagram with three shielded potentials) is additionally separated from coefficient $b_{ei}(T, n)$. The main part not dependent on density, which has already been separated by sum with respect to the continuous and discontinuous spectra, is determined in that which remained. This is equivalent to the fact [31] that the part beginning with diagrams of order $(e^2)^4$ that does notyield divergences is determined even before plasma resummation in the initial coefficient $b_{ei}(T)$. The latter, being separated into the contribution of the continuous and discontinuous spectrum, leads to the known convergent expression (1.8) and (1.11). Differing somewhat from [27], the procedure of [33] leads to a more complex analytical expression [9].

Although atoms are clearly not introduced within the framework, for example, of scheme (1.36)-(1.40) directly in [26-29], this can easily be done [32, 69] and expressions (1.8), (1.11) are understood in many papers [2, 7, 32, 68, 81] as the statsum of the atom and are used not only for hydrogen in the range $\Gamma \ll 1$, but for other elements as well. Let us emphasize once again that expressions (1.8) and (1.11) were found as a result of partial compensation of the contributions of electron interactions on the one hand and ion-ion and electron-electron interactions on the other so that the terms in (1.8) and (1.11) do not have the sense of populations.

The approximation (1.6)-(1.16) described in section 1.2 [29] is a development of approach [26-32]. The same method of separating the contribution of the discontinuous spectrum is used in it, but the additional consideration of terms $\zeta^{5/2}$ led to an additional term, according to calculations of [35], containing a sum by discrete levels. Let us consider a hydrogen plasma. Following (1.38), let us introduce the atoms

$$\zeta_a \equiv \Lambda_a^{-3} \exp(\beta \mu_a) = \Lambda_a^{-3} \exp[\beta(\mu_e + \mu_i)] = \zeta_e \zeta_i \Lambda_e^3/2 \simeq \zeta_e^2 \Lambda_e^3/2. \tag{1.44}$$

Using this relation, one can replace the variable ζ_e by ζ_a in part of terms (1.6). Different methods of this replacement are possible. It is usually done only in the multiplier of the last term of (1.6). Moreover, using the simplifications in (1.6) recommended in section 1.2 for practical calculations of a weakly imperfect nondegenerate plasma, one can write the equivalent expression in the form:

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$$\beta p = 2\zeta_e(1 + \tilde{\Gamma}/3) + \zeta_a \tilde{Q} \exp(\beta \mathrm{Ry} - \varphi\tilde{\Gamma}); \tag{1.45}$$

$$n_a \equiv \zeta_a \partial\beta p/\partial\zeta_a = \zeta_a \tilde{Q} \exp(\beta \mathrm{Ry} - \varphi\tilde{\Gamma}); \quad n_{\text{вар}} = 2\zeta_e(1 + \tilde{\Gamma}/2) - n_a\varphi\tilde{\Gamma}/2; \tag{1.46}$$

$$\beta\mu_a = \ln[n_a\Lambda_a^3/\tilde{Q}] - \beta \mathrm{Ry} + \varphi\tilde{\Gamma}; \tag{1.47}$$

$$\beta\mu_e = \ln\left[\frac{n_e\Lambda_e^3}{2}\right] + \beta(\Delta\mu_e' + \Delta\mu_e'') = \ln\left[\frac{n_e\Lambda_e^3}{2}\right] - \\ - \ln\left(1 + \frac{\tilde{\Gamma}}{2}\right) + \ln\left(1 + \frac{n_a}{n_e}\frac{\varphi\tilde{\Gamma}}{4}\right); \tag{1.48}$$

$$\frac{n_e^2}{n_a} = \frac{2}{\tilde{Q}\Lambda_e^3}\exp[-\beta \mathrm{Ry} - 2\beta\Delta\mu' + \varphi\tilde{\Gamma} - 2\beta\Delta\mu_e'']. \tag{1.49}$$

Compared to the ring approximation (1.17) which yields a reduction of the ionization potential $2\Delta\mu_e'$ in the Sachs equation (1.49), approximation (1.45) leads to two additional terms of different signs. At $\tilde{\Gamma} \ll 1$, their sign is equal to

$$\varphi\tilde{\Gamma} - 2\ln\left(1 + \frac{n_a}{n_e}\frac{\varphi\tilde{\Gamma}}{4}\right) \simeq \varphi\tilde{\Gamma}\left(1 - \frac{n_a}{2n_e}\right). \tag{1.50}$$

Let us emphasize that, unlike the charge-neutral polarization attraction proportional to $n_a n_e$, the action of term $\phi\tilde{\Gamma}$ in (1.45) is proportional to $n_a n_e^{1/2}$ and is equivalent in sign to repulsion. At $(n_a/n_e) \gg 1$, this term reduces the degree of ionization and at $(n_a/n_e) \ll 1$, on the contrary, it increases it.

The corresponding expressions for pressure and energy in the chemical model have the form:

$$\beta p = (2n_e + n_a) - 2n_e\frac{\tilde{\Gamma}/6}{1 + \tilde{\Gamma}/2} + n_a\frac{\varphi\tilde{\Gamma}}{2}\left(\frac{1 + \tilde{\Gamma}/3}{1 + \tilde{\Gamma}/2}\right); \tag{1.51}$$

$$\beta U = \frac{3}{2}(2n_e + n_a) + n_a\left(\frac{\partial \ln \tilde{Q}}{\partial \ln T} - \beta \mathrm{Ry}\right) - \\ - 2n_e\frac{\tilde{\Gamma}/2}{1 + \tilde{\Gamma}/2} + n_a\varphi\tilde{\Gamma}\left(\frac{3 + \tilde{\Gamma}}{2 + \tilde{\Gamma}} - \frac{3}{2}\frac{\partial \ln \varphi}{\partial \ln T}\right). \tag{1.52}$$

Besides the ordinary coulomb correction, the repulsion term $\sim n_a n_e^{1/2}$ is also determined here.

Expressions (1.45)-(1.49) were found for hydrogen. It is suggested in [36] that an expression similar to (1.45) be used to calculate the properties of a plasma of other elements. Strictly speaking, this conversion is invalid since the structure of the terms that describe the contribution from the discontinuous spectrum of multielectron atoms and ions in plasma decomposition should differ from that found in single-electron approximation of expressions (1.8) and (1.11). A principle

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step forward in the strict approach in section 1.2 could be application of it to the systems following in complexity such as a He atom and H_2 molecule. In both cases we are talking about consideration of terms $\sim\zeta^3$ and $\sim\zeta^4$ in (1.5), i.e., about calculation of coefficients $\tilde{b}_{eei}(T, n)$ and $\tilde{b}_{eeii}(T, n)$ in plasma decomposition. The logical continuation of the approach used in [62, 63] would be direct calculation, for example, by the Hartree-Foch method (see section 1.5) of the helium or hydrogen spectrum as systems $e + e + He^{++}$ or $e + e + p + p$ that interact with each other by means of the Debye potential. The "convergent" expression for the contribution of the discontinuous helium or hydrogen spectrum can be found within the approach described in section 1.2, following for example the procedure of [31], by removing the divergent diagrams from the group coefficients $b_{eei}(T)$ and $b_{eeii}(T)$ and subsequent division of the remainder, having an order of $(e^2)^6$ in the case of $b_{eei}(T)$ and $(e^2)^8$ in the case of $b_{eeii}(T)$, by the contribution of the discontinuous and continuous spectra. As already indicated above, this problem has not yet been solved due to its complexity [62].

The essence of the approximation proposed in [36] for a nonhydrogen plasma consists in the final analysis in the fact that all the multielectron ions and atoms are described by a statsum of form (1.8) within the framework of the chemical model by analogy with (1.45) and are dependent on the charge of the nucleus z by correction ϕ_z of form (1.9) using empirical weights and energies for discontinuous levels [5, 66] and using the generalized expression (21) from [35] for multiplier $\omega_{n,z}^{(2)}$. The most significant from the viewpoint of the final results is the fact that, to avoid logical contradictions, the shift $\sim\phi_z\Gamma$ should be assigned to all the composite charges. Since the weight function $_n^{(2)}$ in (1.9) approaches a finite value for such particles as He, Li^+, Na^+ and so on at $\beta E_n \to \infty$, we are actually talking about a shift of the ground state ($\phi \approx \omega_{1,z}^{(2)}(\beta I)$). We note that the shift determined by relation (1.9) changes sign as the charge multiplicity factor increases and increases in absolute value

$$\omega_{1,z}^{(2)}(\beta I) \to -\frac{1}{4};\ \frac{1}{8};\ -\frac{3}{4};\ -\frac{19}{8};\ \ldots \text{ at } \beta I \to \infty \qquad (1.53)$$
$$z = 0;\ 1;\ 2;\ 3\ \ldots$$

Due to the presence of this shift, the results of thermodynamic calculation of an imperfect nonhydrogen plasma will differ appreciably from the results given by traditional approximations [7].

Let us note in concluding the section that, as described at the beginning of the section, an explicit method, like the formal method of the behavior of the chemical model given by relations (1.36)-(1.40) are actually equivalent to substitution of variables and do not in themselves introduce any error. The advantage of the explicit method is that, dividing the entire system into subsystems, we can rely in subsequent approximations on the variational principle of statistical mechanics. This advantage can be realized in practice, for example, when there is the possibility of avoiding the procedure of expansion by the small parameter when calculating the contribution of any of the subsystems, using, for example, the Monte-Carlo method and others [58].

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Determination of the new variety within the formal scheme (1.36)-(1.40) is more artificial in nature. The newly introduced variety of particles is not determined as a separate subsystem with clearly stipulated set of permissible states and potentials of interparticle interaction. This ambiguity makes it difficult to use some approximate apparatus besides group expansions and does not permit the use of some general relations as, for example, the Gibbs-Bogolyubov inequality [77, 39, 50] and other corollaries (1.34) to check the correctness of the results obtained for each variety separately.

The method of separation into subsystems is formally arbitrary within the schemes described above. In practice, one can make use of this arbitrariness to achieve goals related to some characteristics of approximation adopted for calculation of transient properties rather than to thermodynamic calculation. For example, separating free and bound electrons, one can strive to develop the boundary so as to leave electrons that make a contribution to the optical properties within discontinuous mechanisms in the discharge of intra-atomic particles [82]. Or, bearing in mind electrical conductivity, one can set as a goal in the first approximation to roughly separate the conducting electrons from those not participating in conductivity and so on. It is natural that in the general case different methods of division and different position of the boundary may be required to calculate the different properties. Moreover, as is emphasized, for example, in [81], separation into a total of two varieties may be too rough from the viewpoint of calculating some of the transient properties. It is suggested in [81] that one consider two additional varieties of electron-ion pairs, intermediate between the traditionally considered atoms and free charges. If the nomenclature of the varieties is then further detailed, then a logical conclusion of this procedure will be transition to a description by means of Green functions mutually coordinated from the viewpoint of thermodynamic and transient properties.

The indicated strict approach has still not been so much developed in order to be used directly in mass applied calculations carried out in practice. Therefore, considerable attention is devoted in the given paper to analysis of the characteristics of less strict approximations used in practice.

1.5. Consideration of the Effect of the Medium on the State of the Atom. Model Calculations by the Hartree-Fock and Thomas-Fermi Method

When making thermodynamic calculations of a rarefied plasma, the atoms are regarded as an ideal subsystem not interacting with the surrounding medium. With an increase of pressure, the interatomic interaction begins to be manifested upon violation of the condition

$$n_{\text{атомов}} b_0^3 \ll 1, \tag{1.54}$$

where $b_0 \sim a_0$ is the radius of the atom in the ground state. At the same time atoms in excited states play an appreciable role in a partially ionized high-pressure plasma. The effect of interparticle interaction and specifically the circumstance that the volume accessible for realization of atomic states is finite in a dense medium is reflected primarily in excited atoms [75, 83] whose size may appreciably exceed the value b_0. The conditions for application of perturbation

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theory (section 1.2) [11] when considering the effect of the medium on atoms in this plasma are violated, with regard to which model approaches must be laid out.

The system of levels of the hydrogen atom was calculated in so-called "restricted atom" approximation in [76]. A potention of the following form corresponds to this approximation

$$\Phi(r) = \begin{cases} -e^2/r & 0 < r < r_c; \\ \infty & r \geq r_c. \end{cases} \tag{1.55}$$

The results of the calculations are presented in Figure 1.21. It is obvious that compression begins to affect the energy of the ground state at radii $\leq 2a_0$. The energy of the first excited state deviates appreciably from its own undisturbed value even at $r_c \sim 10a_0$, for n = 3 (n is the main quantum number) at $20a_0$ and so on. This example illustrates the fact that the dependence of the energy of the excited state on the finiteness of the atomic volume increases sharply with an increase of the main quantum number.*

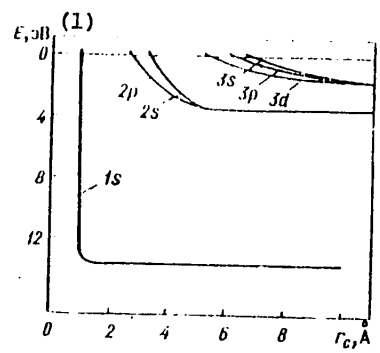

Figure 1.21. Energy Levels of Hydrogen in Limited Atom Approximation (1.55) [76]

Key:
1. Electron volt

The effect of a finite volume has an even greater influence on atoms of the alkali metals. The energy spectrum of the restricted lithium atom is presented in Figure 1.22 [85]. The ground state shifts by a value comparable to its binding energy even at $r_c \sim 10\ a_0$ while the energy of states with n = 3 at $r_c \geq 12\ a_0$ exceeds the ionization limit for an isolated atom. Similar calculations for the other

*Let us note that compression removes the degeneration in orbital moment l, which occurs in a coulomb field and levels with given values of n are lower, the higher the value of l [84].

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alkali metals show that the effect under discussion increases with an increase of atomic number (Figure 1.23). Let us emphasize that, for example, the mean interparticle distance (approximately equal to 20 Å) becomes comparable in value to the "size" (in the sense indicated above) of the excited state of the atom of the alkali metal at pressure of 10 MPa and temperature of 5,000 K.

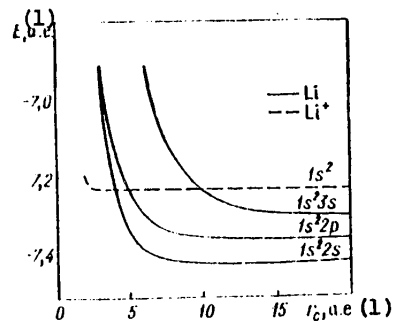

Figure 1.22. Energy Levels of Lithium in Restricted Atom Approximation: the boundary radius r_c (boundary condition 1.61)) is plotted along the x axis and the total energy of the atom is plotted along the y axis

Key:
1. Atomic units

Thus, the problem of calculating the energy spectrum of intra-atomic electrons in the effective potential field that simulates the external effect occurs in a compressed plasma. This multiparticle problem can be solved by approximate methods, the leading one among which is the Hartree-Fock method, used extensively for calculations of atomic structures [86]. A system of N electrons in the field of a nucleus with charge z, the Hamiltonian of which has the following form,* is considered in this method

$$\hat{H} = -\sum_{i=1}^{N}\left[\frac{1}{2}\Delta_i + \Phi(r_i)\right] + \sum_{j<k}^{N}\frac{1}{r_{jk}},$$

where $\Phi(r_i)$ is the effective potential, in the case of an isolated atom equal to z/r_i. The multielectron wave function is determined by the condition of the minimum functional [87]:

$$E = \int \Psi^*(q^N)\,\hat{H}\Psi(q^N)\,dq^N, \tag{1.57}$$

*Here and further in section 1.5 the atomic system of units is used in which $\hbar = 1$, $m_e = 1$ and $e = 1$.

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where q^N is the population of $\{r_1\xi_1, r_2\xi_2, \ldots, r_N\xi_N\}$ coordinates and spin variables of electrons.

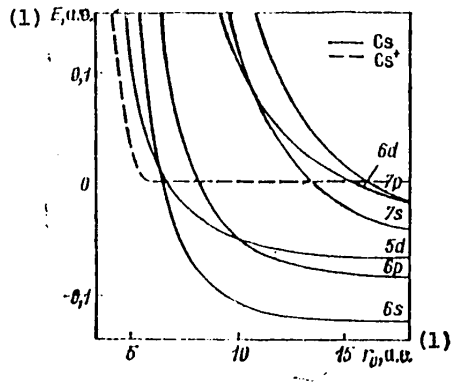

Figure 1.23. Energy Levels of Cesium in Restricted Atom Approximation: the energy of the atom counted from the ground state of a Cs^+ ion in an undisturbed state is plotted along the x axis; the calculation was made in the "frozen skeleton" approximation, i.e., without regard to the effect of the external electron on the internal electron

A determinate consisting of single-electron wave functions is selected as the approximate wave function of the atom in the Hartree-Fock method. Assuming that each electron is in a central-symmetrical field of the nucleus and of the remaining electrons and noting that the Hamiltonian (1.56) is not dependent on thin variables, one can represent a single-electron wave function in the form

$$\psi_i(q) = \frac{1}{r} f_{n_i l_i}(r)\, Y_{l_i}^{m_i}(\theta, \varphi)\, \chi_i(s) \tag{1.58}$$

(n, l, m and s are the quantum numbers in ordinary notations corresponding to this approximation). As is known [87], there are two (2l + 1) electron states corresponding to different values of m and s for given values of n and l. It is assumed that all electrons with given values of n and l have identical radial parts $f_{nl}(r)$. In the absence of spin-orbital interaction, the state of the atom is characterized by complete orbital L and spin S moments equal to zero if all the nl-shells are filled. If there are unfilled shells, the wave function of the atom is found in the form of a linear combination of determinates whose coefficients are found from the condition of equality of the complete orbital and spin moments to given values. Condition (1.57) leads to a system of nonlinear integrodifferential equations (Hartree-Fock equations) [86]:

$$\left[\frac{d^2}{dr^2} + \Phi_{n_i l_i}(r) - \frac{l_i(l_i+1)}{r^2} - \varepsilon_{n_i l_i}\right] f_{n_i l_i}(r) + \sum_{n_j \neq n_i} \varepsilon_{n_i l_i n_j l_i} f_{n_j l_i}(r) = G_{n_i l_i}(r), \tag{1.59}$$

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where $\Phi_{n_i l_i}(r)$ is the coulomb potential of electron interaction with the nucleus and with each other, $G_{n_i l_i}(r)$ is the nonlocal part of the potential or the exchange term [86] and n_i and l_i run through all values corresponding to the configuration of the atom. The eigen-values $\varepsilon_{n_i l_i}$ and the nondiagonal Lagrangian multipliers $\varepsilon_{n_i l_i n_j l_i}$ are determined from the condition of the orthonormal nature of radial functions $f_{n_i l_i}(r)$ and $f_{n_j l_i}(r)$

$$\int_0^\infty f_{n_i l_i}(r) f_{n_j l_i}(r)\, dr = \delta_{n_i n_j} \tag{1.60}$$

and the boundary conditions, one of which is the result of the finiteness of the wave function at the origin of the coordinates $f_{n_i l_i}(0) = 0$ and the second is selected as a function of the postulation of the problem. For example, the wave function of an electron in approximation of an isolated atom should decrease exponentially at long distances. In the restricted atom approximation (1.55), the second boundary condition has the form

$$f_{n_i l_i}(r)\Big|_{r=r_c} = 0. \tag{1.61}$$

Let us make use of this approximation to explain the extent to which the nonisolated nature of the atom in a dense plasma has a significant effect in the total thermodynamic characteristics. Let us consider the case of a three-component plasma consisting of atoms, single-charge ions and electrons. Let us represent the subsystem of atoms as a system of solid spheres of radius r_c. Let us disregard the electron and ion dimensions. The free energy of this model can be written in the form

$$F(\{N_i\}, V, T) = F_{\text{ид}} + \Delta F_{\text{т.с}} + \Delta F_{\text{нуп}}. \tag{1.62}$$

The first term is the free energy of an ideal plasma with the difference that the statsum of the atom is dependent on r_c according to the boundary condition (1.61). The second term describes the contribution of repulsion of solid spheres and is also dependent on r_c. In specific calculations let us make use of the approximate analytical expression from [88]

$$\Delta F_{\text{т.с}} = N_a kT\nu(3\nu - 4)(\nu - 1)^{-2}; \quad \nu = n_a(4\pi r_c^3/3). \tag{1.63}$$

For corrections to pressure and the chemical potential this yields

$$\frac{\Delta p_{\text{т.с}}}{n_a kT} = 2\nu\frac{\nu - 2}{(\nu - 1)^3}; \quad \frac{\Delta\mu_{\text{т.с}}}{kT} = \nu\frac{3\nu^3 - 9\nu + 8}{(1 - \nu)^3}. \tag{1.64}$$

Thus, the free energy in this model is dependent on r_c on the one hand, due to compression of atoms and on the other hand, due to their interaction as solid spheres. The equilibrium value of the atomic radius can be determined from the condition of the minimum free energy

$$\partial F/\partial r_c = 0. \tag{1.65}$$

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The dependence of the statsum of the atom on r_c is found from solution of the system of Hartree-Fock equations for the ground and excited states of an atom with boundary condition (1.61) at different values of r_c (see Figures 1.21-1.23).

Incomplete consideration of the interelectron correlations related to single-electron approximation leads to an error in calculation by the Hartree-Fock method. However, if a knowledge only of the energy characteristics rather than of the wave function of an atom is required, then following the method of [89], one can use the correlation corrections found for a free electron gas [90]. Disregard of the relativistic effects, which is another source of error of the Hartree-Fock method, is insignificant for light atoms and for external electrons of heavy elements whose valent shells have a simple structure.

Thermodynamic calculations made for model (1.55)-(1.65) show that effective repulsion and deformation of the discontinuous atomic spectrum in the selected potential are significantly felt both in the thermal and in the caloric equation of state of a plasma. Compared to the approximation when the atoms are regarded as an ideal subsystem, calculations using model (1.55)-(1.65) yield a lower value of density as a function of pressure and temperature and of enthalpy as a function of pressure and density (see Figures 4.17 and 4.18). The latter is significant since this is one of the main qualitative results obtained experimentally up to the present in an imperfect plasma [72, 73, 74] (see Chapter 4).

The effect of deformation of the energy levels is manifested to a significant degree in the optical properties of the plasma since photoionization of atoms by the radiation of visible light occurs from highly excited energy levels that are distorted at relatively low compression (see Chapter 4).

The external valent electrons are stripped away as the pressure in the plasma increases and the electron shells of the atoms and ions are rearranged and are broken down at extremely high pressures, leading to quasi-uniform charge distribution in the atomic cell [91]. It is possible in this case to turn from the quantum-mechanical description of bound electrons in the language of wave functions and the discontinuous energy spectrum to the quasi-classical description by distribution of the mean electron density n(r). The corresponding approximation is known [87] as the Thomas-Fermi model. Approximation of a quasi-homogeneous ideal electron gas is taken as its basis

$$n(\mathbf{r}) = \frac{\sqrt{2}}{\pi^2} T^{3/2} I_{1/2}[\lambda(\mathbf{r})]; \quad \lambda(\mathbf{r}) = p_F^2(\mathbf{r})/2T, \tag{1.66}$$

where $p_f^2(r)/2$ is the Fermi energy related to the chemical potential by the relation:

$$\mu = p_F^2(\mathbf{r})/2 + \Phi(\mathbf{r}), \tag{1.67}$$

where $\Phi(r)$ is the potential electron energy in the field of the remaining electrons and nucleus. The Poisson equation and relations (1.66)-(1.67) lead to the Thomas-Fermi equation with respect to $\lambda(r)$ in a spherical Wigner-Zeitz cell

$$\Delta\lambda(\mathbf{r}) = \frac{4\sqrt{2}}{\pi} T^{3/2} I_{1/2}[\lambda(\mathbf{r})], \tag{1.68}$$

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with boundary conditions

$$r\,[\mu - \lambda(r)]_{r\to 0} \to z; \quad \left.\frac{\partial\lambda(r)}{\partial n}\right|_{r=r_0} = 0. \tag{1.69}$$

The second condition is placed on the boundary of the cell. Solution of differential equation (1.68) with condition (1.69) permits one to determine all the thermodynamic characteristics of the model [92, 93] according to the expression for free energy

$$F = \frac{\sqrt{2}}{\pi^2} T^{3/2} \int d\mathbf{r} \left[\lambda I_{1/2}(\lambda) - \frac{2}{3} I_{3/2}(\lambda)\right] + \int \Phi(\mathbf{r})\, n(\mathbf{r})\, d\mathbf{r}.$$

Solution of the Thomas-Fermi equation is automodal with respect to the charge of the nucleus z, which permits numerical solution of the Thomas-Fermi equation once and permits one to turn to specific chemical elements by means of transformation of similitude.

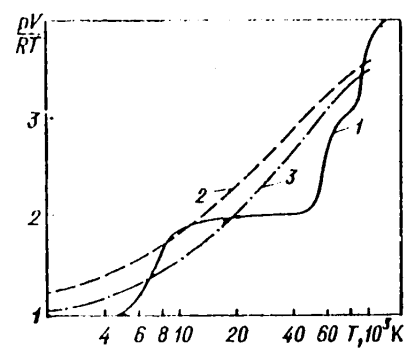

Figure 1.24. Equation of State of Lithium Plasma at p = 0.1 MPa: 1--calculation by method of section 1.6; 2--Thomas-Fermi (TF) [93]; 3--Thomas-Fermi approximation with quantum and exchange corrections (TFP) [93]

The range of applicability of this electron model is determined by incomplete consideration of the correlation of electrons and disregard of the quantum-mechanical effects [91]. Correlation corrections were caused on the one hand by exchange effects and on the other by the force correlation of electrons, which is only partially taken into account when describing the electron structure by the self-consistent field method. Quantum-mechanical effects are expressed first in the form of quantum corrections that reflect the inaccuracy of the quasi-classical description of electron motion within an atom [94] and second in the form of oscillation corrections that reproduce the irregularity of physical values determined by the discontinuous energy spectrum [95].

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When applying the Thomas-Fermi model to a plasma [92, 93, 109], one should emphasize the specific errors introduced by the cellular model itself. In this approach all correlations are automatically limited by the dimensions of the cell and cannot exceed the average distance between nuclei, which does not permit one to describe the range of a weakly imperfect Debye plasma by the given model. Moreover, the degrees of freedom and the possibilities of correlation of nuclei should be predetermined in the cellular model. The contribution of the latter is significant in the range of parameters considered in this paper.

The simplicity and universality of the Thomas-Fermi model, which makes it irreplacable in the range of extremely high temperatures and pressures, lead to restriction of its application at low pressures and temperatures where more detailed information is required about the electron structure of the chemical elements. Specifically, this is related to light atoms, in the equation of state of which the "shell" effects are especially discernible (see Figures 1.1-1.2). Consideration of the quantum and exchange (but not oscillation) corrections [93] plays no principle role in the given case since it does not change the nature of the thermodynamic functions. This is illustrated in Figure 1.24 on the example of a lithium plasma.*

1.6. Method of Calculating the Composition and Thermodynamic Functions of the Multicomponent Imperfect Plasma

A large volume of calculations of the thermophysical and specifically of the thermodynamic properties of different working substances was made for calculation-theoretical study of a wide range of problems occurring when designing a gas-phase nuclear reactor [1]. The typical results for some of them are presented in this paper. Taking the mass nature of these calculations, the variety of working substances and the determining physical processes (section 1.1) and also the need to calculate a complex of transient properties into account, thermodynamic calculation was carried out within the framework of the traditional quasi-chemical method of description (the "chemical model"). Critical discussion of this and other approaches is contained in sections 1.1-1.5.

The calculation was carried out in the temperature range $T = 4 \cdot 10^3 - 4 \cdot 10^4$ K and pressure range $p = 0.1-50$ MPa using the special program described in [6].

The following components were taken into account when calculating the equilibrium composition of working substances (instead of enumerating all the alkali metals below, one, for example, lithium, will be arbitrarily mentioned)**:

a) atoms--H, Li, U

b) binary molecules--H_2, Li_2, LiH

*The numerical results related to TF and TFP approximations presented in this book were obtained by V. K. Gryaznov and I. L. Iosilevskiy by interpolation and subsequent recalculation of the tabular data of [93].

**The main program of [6] used in making these calculations permits one to take into account up to 20 components of arbitrary complexity simultaneously consisting of not more than four chemical elements.

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c) single and multiple ions--H^+, Li^+, Li^{+2}, Li^{+3}, U^+ ... U^{+4}

d) negative ions--H^-, Li^-

e) molecular ions--H_2^+, Li_2^+

f) electrons--e.

The U_2 molecule [96] and the more complex molecules of alkali metals--Li_3, Li_4 and so on [97]--were not taken into account since the available data at present on the characteristics of these molecules are not firmly established and inclusion of them in mass practical calculations is not now justified. For the same reason complex molecular ions Li_2^-, Li_3^-, Li_4^-, ... Li_s^- were not used in the calculation. The hypothesis of abnormally high affinity of Cs_2, Cs_3, ... Cs_n molecules to the electron ($\gtrsim$ 2 eV) is advanced in [98] to explain the sharp drop of electron conductivity in cesium vapors recorded by the authors. However, an increase of conductivity, on the contrary, was recorded in other experiments in cesium vapors close to saturation (see section 4.5 for more detail). Moreover, approximate calculations of affinity to the electron of the Cs_2 molecule yielded a value of only $\approx$ 0.3 eV [99].

Each of the particles indicated above was regarded as a finite population of bound states identical to the state of an isolated particle. The population of each of these states was assumed to be proportional to the Boltzman factor and accordingly the contribution of internal degrees of freedom was described by a statsum in the traditional form

$$Q = \sum_k g_k \exp(\beta E_k)\,\omega(\beta E_k) \equiv \\ \equiv e^{\beta I} \sum_k g_k \exp(-\beta \tilde{E}_k)\,\omega(\beta E_k) = e^{\beta I}\tilde{Q}. \tag{1.71}$$

Here g_k, E_k and $\tilde{E}_k \equiv (I - E_k)$ is the weight, binding energy and excitation energy of the k-th level and $\omega(\beta E_k)$ is the cutoff factor. The ionization energy of the atoms and ions, the dissociation energy of molecules and molecular ions and the energy of affinity to the electron of negative ions were selected from [100-108]. A summary of the values used is presented in Table 1.1.

Table 1.1. Ionization Potentials of Elements and Their Ions (I), Energy of Affinity to Electron (ε) and Dissociation Energy of Molecules and Molecular Ions (D_2, D_2^+)

(1) Элемент	(2) Значение, эВ						
	I_1	I_2	I_3	I_4	ε	D_2	D_2^+
H	13,6	—	—	—	0,754	4,447	0,648
Li	5,39	75,62	122,42	—	0,59	1,026	1,26
Na	5,14	47,29	71,65	—	0,34	0,737	1,11
K	4,34	31,81	46,0	—	0,53	0,56	0,92
Cs	3,89	25,1	34,6	—	0,47	0,495	0,7
U	6,19	11,6	19,8	36,7	—	—	—
KH	·	—	—	—	—	1,85	—

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[Key continued from preceding page]:

1. Element 2. Value, eV

The statsums of binary molecules and molecular ions were calculated in the "flexible rotator-anharmonic oscillator" approximation [5]. The energy of electron, vibrational and rotational excitations was selected according to the recommendations of [5, 103]. For molecular ions the missing parameters were estimated approximately, using the known method of [5] by the dissociation energy D_2^+ and the intramolecular interatomic state r_e [104]. Up to four electron states were taken into account when calculating the statsums of molecules [103]. A summary of the spectral constants used is presented in Table 1.2 in standard notations.

The statsums of all the particles were calculated by the direct summation method. Summation of the vibrational and rotational states of molecules was limited by the condition that the sum of the vibrational G and rotational F excitation energy not exceed the dissociation energy:

$$G(v) + F(I) \leqslant D_2. \tag{1.72}$$

The sum for vibrational levels was also limited by the condition

$$G(v+1) \geqslant G(v) \tag{1.73}$$

(v and I are the vibrational and rotational quantum numbers). It was found in this case

$$I \leqslant I_{\text{макс}}(v); \quad dI_{\text{макс}}/dv < 0; \quad I_{\text{макс}}(v) \underset{v \to v_{\text{макс}}}{\to} 0. \tag{1.74}$$

When calculating the statsums of the atoms and ions of (1.71), states with the following energy were taken into account

$$\tilde{E}_k \leqslant \tilde{E}_{\text{макс}} = I - kT \tag{1.75}$$

The results obtained when using condition (1.75) are numerically similar to those found when using formula (1.11) from section 1.2.

The energy and weights figuring in (1.71) were taken as for an isolated atom and ion from [66]. In making the summation, the procedure of smoothing by selection of the specific form of the cutoff factor $\omega(\beta\tilde{E}_k)$ (1.71) was used.

$$\omega(\beta E_k) = \frac{\exp(An^*) + \exp(A)}{\exp(An^*) + \exp(An_k)}, \tag{1.76}$$

where $n^* = (I/I - \tilde{E}_{\text{макс}})^{1/2}$; $n_k = (I/I - \tilde{E}_k)^{1/2}$; $A = \text{const}$.

The given form was specifically selected so that the contribution of the ground state did not vary when making the calculations in the range where $E_{\text{maks}} < 0$. The results of smoothing are illustrated in Figure 1.25 on the example of the statsum of the cesium atom.

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Table 1.2. Spectral Data for Biatomic Molecules and Ions Used in Calculations

(1) Величина	Li_2				Na_2			
	$X^1\Sigma_g^+$	$A^1\Sigma_u^+$	$B^1\Pi_u$	$C^1\Pi_u$	$X^1\Sigma_g^+$	$A^1\Sigma_u^+$	$B^1\Pi_u$	$C^1\Pi_u$
T_e	—	14020,54	20398,41	30492	—	14659,7	20303	29372
ω_e	351,43	255,46	269,69	237,9	159,127	117,6	124,07	117,3
ωx_e	2,61	1,574	2,744	1,462	.7262	.3795	.6863	.55
ωy_e	$.295\cdot10^{-2}$	$.18\cdot10^{-2}$	—.0637	—	$-.9154\cdot10^{-3}$	$-.185\cdot10^{-3}$	$-.5441\cdot10^{-2}$	—
ωz_e	$.636\cdot10^{-3}$	$.326\cdot10^{-4}$	—	—	$.5\cdot10^{-4}$	—	$.115\cdot10^{-3}$	—
α_1	$.68\cdot10^{-2}$	$.541\cdot10^{-2}$	$.888\cdot10^{-2}$	$.964\cdot10^{-2}$	$.8564\cdot10^{-3}$	$.54\cdot10^{-3}$	$.8676\cdot10^{-3}$	$.84\cdot10^{-3}$
α_2	—	—	—	$.5\cdot10^{-4}$	$-.765\cdot10^{-5}$	—	$-.154\cdot10^{-4}$	—
β_1	—	—	—	—	$-.224\cdot10^{-8}$	—	$-.27\cdot10^{-7}$	—
β_2	—	—	—	—	$2\cdot10^{-9}$	—	$-.84\cdot10^{-10}$	—
B_e	.6726	.4975	.5577	.5076	.1548	.1107	.1258	.1282
D_e	$.987\cdot10^{-5}$	$.752\cdot10^{-5}$	$.941\cdot10^{-5}$	—	$.655\cdot10^{-6}$	$.383\cdot10^{-6}$	$.361\cdot10^{-6}$	$.612\cdot10^{-6}$

Key:
1. Value

[Table continued on following page]

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Table 1.2 [Continued from preceding page]:

Величина	K_2				KH		Cs_2	Li_2^+	Na_2^+	K_2^+	Cs_2^+
	$X^1\Sigma_g^+$	$A^1\Sigma_u^+$	$B^1\Pi_u$	$C^1\Pi_u$	$X^1\Sigma_g^+$	$A^1\Sigma^+$	$X^1\Sigma_g^+$				
T_e	—	11671.4	15370	22922	—	18684	—	—	—	—	—
ω_e	92.64	69.09	72.87	61.485	988.114	233.568	41.99	336	140	72	35
ωx_e	.354	.153	—.254	.133	16.8090	—4.88083	.08	.21	.21	.17	.05
ωy_e	—	—	$-.492\cdot10^{-6}$	$-.974\cdot10^{-4}$	.42377	—.1355	$-.164\cdot10^{-5}$	—	—	—	—
ωz_e	—	—	$-.335\cdot10^{-2}$	—	$13.75\cdot10^{-3}$	$-.153\cdot10^{-3}$	—	—	—	—	—
α_1	$.219\cdot10^{-3}$	$.150\cdot10^{-3}$	$235\cdot10^{-3}$	$.11\cdot10^{-3}$	.06461	—.0224	$.35\cdot10^{-4}$	—	—	—	—
α_2	—	—	—	$.5\cdot10^{-5}$	$-.3822\cdot10^{-2}$	$-.127\cdot10^{-2}$	—	—	—	—	—
β_1	$-.83\cdot10^{-9}$	—	$.74\cdot10^{-9}$	—	—	—	—	—	—	—	—
β_2	—	—	—	—	—	—	—	—	—	—	—
B_e	.05622	.0418	.04824	.04404	3.3996	1.3096	.0127	.62	.12	.034	.01
D_e	$.83\cdot10^{-7}$	$.61\cdot10^{-7}$	$.81\cdot10^{-7}$	—	$.152\cdot10^{-5}$	$.95\cdot10^{-4}$	$47\cdot10^{-8}$	—	—	—	—

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Only the ground state was taken into account in sum (1.71) for negative ions.

The results of calculating the statsums of different components for several temperatures are presented in Table 1.3.

Table 1.3. Statistical Sums of Atoms, Ions and Molecules

(1) Элемент	T, K				
	3000	6000	10000	20000	50000
H	2,000	2,000	2,000	2,026	2,191
Li	2,005	2,086	3,001	4,851	4,525
Na	2,002	2,053	2,903	4,552	3,916
K	2,012	2,190	3,926	5,779	4,520
Cs	2,034	2,447	5,350	7,631	5,810
Li^+	1,000	1,000	1,000	1,000	1,000
Na^+	1,000	1,000	1,000	1,000	1,017
K^+	1,000	1,000	1,000	1,001	1,657
Cs^+	1,000	1,000	1,000	1,027	5,830
Li^{++}	2,000	2,000	2,000	2,000	2,000
Na^{++}	5,040	5,351	6,644	5,813	5,925
K^{++}	4,709	5,074	5,465	5,712	6,140
Cs^{++}	4,003	4,037	4,271	4,737	5,554
K^{+++}	6,675	7,411	8,551	10,11	12,56
Cs^{+++}	5,013	5,128	5,835	7,369	9,761
U	34,4	81,0	415	1547	1623
U^+	51,4	93,3	237	643	1481
U^{++}	34,4	81,0	416	1735	4945
U^{+++}	12,3	17,5	36,7	84,1	183
U^{++++}	10,7	14,7	26,6	44,3	66,4
H_2	$0,2225 \cdot 10^2$	$0,5080 \cdot 10^2$	$0,1942 \cdot 10^3$		
Li_2	$0,1204 \cdot 10^5$	$0,2783 \cdot 10^5$	$0,7972 \cdot 10^5$		
Na_2	$0,1006 \cdot 10^6$	$0,2003 \cdot 10^6$	$0,4538 \cdot 10^6$		
K_2	$0,3628 \cdot 10^6$	$0,6469 \cdot 10^6$	$0,1375 \cdot 10^7$		
Cs_2	$0,3470 \cdot 10^7$	$0,5544 \cdot 10^7$	$0,8140 \cdot 10^7$		
KH	$0,2034 \cdot 10^4$	$0,6069 \cdot 10^4$	$0,2544 \cdot 10^5$		

Key:
1. Element

One should talk individually about the statsums of the uranium atom and ions. Due to its complexity, the structure of the levels even of an atom and the first ion of uranium U^+, despite the large volume of available information [105-108], has still not been completely studied. Information about the levels of U^{+2}, U^{+3}, ... ions is even sparser. This circumstance appreciably reduces the accuracy of thermodynamic calculations in the temperature range of interest to us. Unlike hydrogen and the alkali metals, for which a description by means of an individual system of levels is quite justified, an attempt at quasi-classical description would apparently be

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feasible when describing uranium. [91]. Of special interest in this regard is the possibility of taking into account shell effects [95], the absence of which in the known Thomas-Fermi approximation [92, 93, 109] appreciably reduces the accuracy of the approximation. Calculations by the Hartree-Fock method (section 1.5) are more accurate, but due to cumbersomeness, calculation, for example, of the entire spectrum of the uranium atom, including ~ 10^4 levels using only Hartree-Fock approximation, is unrealistic. A combination of both approximations is used in the calculation in [106].

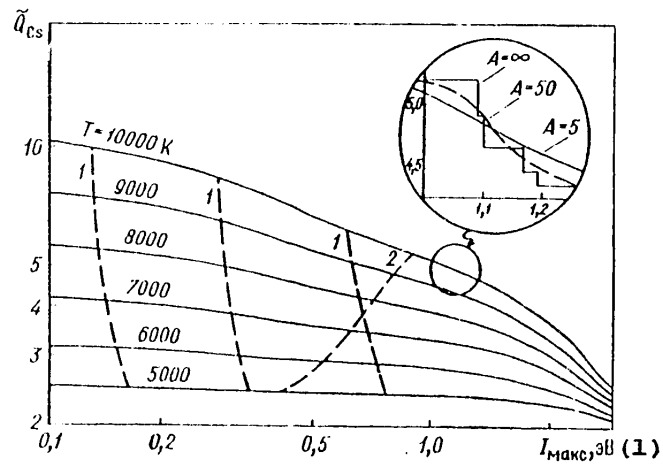

Figure 1.25. Statsum of Cesium Atom Excitation (1.71). The boundary energy $I_{maks} \equiv I - \tilde{E}_{maks}$ in multiplier $\omega(\beta E_k)$ (1.76) is plotted along the y axis: 1--restriction at average interparticle distance ($I_{maks} \approx e^2 n_\Sigma^{1/3}$) at pressure (from left to right) of 0.1, 1 and 10 MPa; 2--restriction on value of $I_{maks} = kT$ adopted in these calculations. The result of the smoothing procedure using multiplier $\omega(\beta E_k)$ (1.76) is given in the insert

Key:
1. Electron volts

The statsums of the uranium atom and ions were calculated in this paper, as for all the remaining elements, within the procedure of direct summation (1.71). The statsums of U and U^+ were calculated in this case according to the recommendations of [105] using the population of known levels, for which the summary of levels from [107] was used which includes approximately 1,000 levels for U and approximately 300 levels for U^+ found on the basis of analyzing approximately 25,000 experimentally recorded spectral lines of U and U^+. For the U^{+2} ion, assuming [105] that the absence of two 7 s electrons (compared to an atom) in the ground electron configuration does not radically alter the electron spectrum of U^{+2}, the system of levels of U was used in calculation of the statsum. The recommended levels of [105] found on the basis of concepts of electron similarity from the levels of the corresponding ions of other elements were used for U^{+3} and U^{+4} ions. The results of this calculation for some temperatures are presented in Table 1.3.

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For given temperature and pressure, the equilibrium composition was found from solution of the standard system of equations that includes the equation of state

$$p\{n_i\} \equiv p_{\text{ид}} + \Delta p = \sum_i n_i kT + \Delta p\{n_i\}, \tag{1.77}$$

the equations of chemical and ionization equilibrium (the law of effective mass and the Sachs equation) for each reaction AB ⇄ A + B

$$\frac{n_a n_b}{n_{ab}} = \frac{\tilde{Q}_a \tilde{Q}_b}{\tilde{Q}_{ab}} \frac{\Lambda_{ab}^3}{\Lambda_a^3 \Lambda_b^3} \exp\{-\beta I_{ab} + \beta\Delta\mu_{ab} - \beta\Delta\mu_a - \beta\Delta\mu_b\}, \tag{1.78}$$

and the equations of the proportion of chemical elements and equations of electron neutrality

$$\sum_i n_i \nu_i^{(\alpha)} / \sum_i n_i \nu_i^{(\beta)} = \text{const}; \tag{1.79}$$

$$\sum_i n_i z_i = 0. \tag{1.80}$$

Here $\tilde{Q}_i$, Λ_i, $\nu_i^{(\alpha)}$ and z_i are the statsum of excitation, de Broglie length, stochiometric coefficient and charge of a particle of variety i, respectively, and Δp and $\Delta\mu_i$ are corrections for imperfection to the pressure and chemical potential of a particle of variety i. The procedure of solving system (1.77)-(1.80) consisted in that an independent "basis," for example, electrons and older ions of chemical elements, was selected as a function of the pressure and temperature among all the components. The concentrations of all the components were expressed according to (1.78) by the concentrations of the basic components and the system which was nonlinear with respect to the logarithms of the basic components was solved in two iteration cycles. The corrections for imperfection were considered constant in the internal cycle and the resulting system was solved by the gradient descent method. The composition found in this manner was used in the external cycle to recalculate the corrections for imperfection, after which the composition was again found and so on until the complete convergence of the concentrations of all components. The selected procedure made it possible within the framework of a single universal program to carry out numerous variant calculations using different approximate dependence of corrections for imperfection and statsums $\tilde{Q}_i$ on the composition and thermodynamic parameters, which is required for calculation in the range of strong imperfection where there are no generally accepted forms of these functions.

Using the derived equilibrium composition, the total thermodynamic functions, primarily density, enthalpy and entropy (H = U + pV), were calculated for given values of p and T

$$\rho = \sum_i n_i m_i \tag{1.81}$$

$$h = \rho^{-1}\left\{\sum_i n_i\left(\frac{5}{2}kT + \varepsilon_i^{\text{возб}}\right) + \sum_i^{(1)} n_i I_i^{(1)} + \sum_i^{(11)} n_i\left(I_i^{(1)} + I_i^{(2)}\right) + \right.$$
$$\left. + \ldots + \sum_i^{'} n_i D_i - \sum_i^{''} n_i \varepsilon_i + \sum_i^{'''} n_i\left(I_i^{(1)} - D_i^{1}\right)\right\} + \Delta h \tag{1.82}$$

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$$Ts - h = \sum_i N_i\mu_i - \rho^{-1}\sum_i n_i\left(\frac{5}{2}kT + \varepsilon_i^{\text{возб}} - \ln\left(n_i\Lambda_i^3\tilde{Q}_i^{-1}\right) - \Delta\mu_i\right) + \Delta h$$

$$\varepsilon^{\text{возб}} = T^2 d\ln\tilde{Q}/dT \tag{1.83}$$

According to (1.82), summation is carried out in $\Sigma^{(+)}$ and $\Sigma^{(++)}$ by one-, two- and so on multiple ionized ions, in Σ' by molecules and in Σ'' and Σ''' by negative and molecular ions, due to which the zero enthalpy corresponds to an ideal gas of atoms at T = 0 K.

So-called ring (Debye) approximation in the large canonical group (1.17) [15, 110] was used in the results of calculation presented in this paper for corrections to interaction of charged particles, primarily due to the simplicity and universality of the relations given by it both in the case of single and in the case of multiple ionization

$$\beta p = \sum_i n_i - \frac{\tilde{\varkappa}_D^3}{24\pi};$$

$$\beta\Delta\mu_i = -\ln\left(1 + z_i^2\frac{\tilde{\Gamma}}{2}\right); \quad \Delta h \equiv \Delta u + \Delta pv = 4\Delta pv \tag{1.84}$$

Here $\tilde{\varkappa}_D$ is the inverse Debye radius expressed by activity and $\tilde{\Gamma} = \tilde{\varkappa}_D e^2/kT$ is the parameter of imperfection ((1.1), (1.10)). In the calculations $\tilde{\Gamma}$ was found as the positive root of the equation

$$\tilde{\Gamma}^3 = \left(\frac{e^2}{kT}\right)^3\left[4\pi\sum_i n_i z_i^2/\left(1 + z_i\frac{\tilde{\Gamma}}{2}\right)\right]. \tag{1.85}$$

The use of approximation (1.84) and (1.85) essentially does not contain the possibility of violating thermodynamic stability. The presently available information (see section 4.3) justifies the use in engineering applications of the results of calculation having no anomalies in the range of strong imperfection. Approximation (1.84) and (1.85) coincides with ordinary Debye approximation [8] in the range of weak imperfection ($\Gamma \ll 1$) and differs from it by much lower absolute value of given corrections* in the range of strong imperfection ($\Gamma \geq 1$), which on the whole corresponds to the recommendations given on the basis of approximations obtained recently both within the framework of strict asumptotic methods (section 1.2) and of different model approaches (sections 1.3, 1.5).

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*In the case of single ionization, a simple form $\Delta U/NkT = 3\Delta p/nkT = -\tilde{\Gamma}/(2+\tilde{\Gamma})$; $\Gamma^2 = \tilde{\Gamma}^2(1+\tilde{\Gamma}/2)$ can be given to approximation. Hence it is obvious that at $\tilde{\Gamma} \to \infty\ \Delta p/nkT \to \text{const} = 1/3$ (see Figure 1.16).

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The interaction of charged and neutral particles was taken into account in calculation of alkali metals. Some modification of the approximation of the second virial coefficient B(T) was used for them on the assumption that the main interaction is polarization interaction

$$\frac{\Delta\mu}{kT} = \frac{Bn_a(n_e+n_i)}{1-B(n_e+n_i)}; \quad \frac{\Delta\mu_e}{kT} = \frac{\Delta\mu_i}{kT} = \frac{Bn_a}{1-B(n_e+n_i)}; \tag{1.86}$$

$$\frac{\Delta\mu_a}{kT} = -\ln[1-B(n_e+n_i)].$$

Here n_i, n_e and n_a are the ion, electron and atom concentrations. This form corresponds to the hypothesis that each charged particle can interact with many neutral particles, but each neutral particle can interact only with some one charged particle.* The following value was used as B(T) in (1.86)

$$B(T) = \beta\Phi_0 = \beta\int\Phi(r)\,dr, \tag{1.87}$$

$\Phi(r)$ is the effective charge-neutral interaction potential. It was assumed that the bound states occurring as a result of this interaction were taken into account in the form of an individual variety of particles, for example, Li^- and Li_2^+ ions, and approximation (1.86) and (1.87) roughly describes the interaction of free charged and neutral particles. The use of the approximation presented above is explained by the fact that our knowledge of the interaction potential itself $\Phi(r)$ is insufficient to construct more complex approximations. When making specific calculations, $\Phi(r)$ was selected in the form

$$\Phi(r) = -\frac{A}{(r^2+d^2)^2}, \text{ where } A = \alpha e^2/2; \quad \Phi(0) = -\frac{A}{d^4} = -\varepsilon. \tag{1.88}$$

Here α and ε are the polarizability and electron affinity of an alkali atom. The values of polarizability [112] and the corresponding values of Φ_0 for alkali atoms of Li, Na, K and Cs are presented below.

α, a. e. (1)	166	152	296	428
Φ_0, 10^{-21}, eV·cm³ (2)	0,41	0,34	0,62	0,82

Key:
1. Atomic units
2. eV·cm³

*In the language of group expansions [111], approximation (1.86) corresponds to the sum of diagrams where each neutral particle is joined only to one charged particle and to not more than one line of interaction.

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Interaction of neutral particles was taken into account in these calculations only in the form of formation of H_2, Li_2, KH and other molecules, i.e., the interaction of "free" atoms and molecules was disregarded. Desnity effects related to the finiteness of volume permissible for realization of excited states of atoms, molecules and so on and to the dependence of this volume on thermodynamic parameters, discussed in section 1.5, were also not taken into account. Approximate consideration of these effects in the chemical model of the plasma of section 1.5 is related to complex quantum-mechanical calculation of the energy spectrum of the atom, molecule and so on in the effective potential. The cumbersomeness of this procedure did not permit its use in mass applied calculations of this paper.

Table 1.4. Condensation Temperature of Uranium, K

(1) Состав смеси	P, MPa (2)						
	0.1	0.3	1	3	10	20	50
100% U	4300	4800	5350	5950	6750	7350	8250
50% U + 50% K	4200	4550	5000	5550	6300	6800	7550
10% U + 90% K	3800	4050	4400	4800	5350	5700	6300
3% U + 97% K	3500	3750	4050	4400	4800	5150	5600

Key:
1. Composition of mixture
2. MPa

The results presented in this paper are related to the gas phase of matter. As follows from Figures 1.11-1.14, the considered range of parameters partially encompasses the condensation range for uranium alone. The parameters of the high-temperature part of the condensation boundary were determined by means of the known approximate rule of linear extrapolation in coordinates $\lg p$, $1/T$ [113] of the experimentally known low-temperature part of this function [25]. Since uranium is partially ionized at T = 5,000 K and moreover can be found in a mixture with other substances, it was assumed that the indicated rule of extrapolation is actually related to the chemical potential of atoms and in approximation of the perfection of the latter clearly links their maximum concentration to temperature $n_U^{nasyshch} = f(T)$. The condensation boundary found by the method indicated above is presented in Table 1.4 for pure uranium and for a uranium-potassium mixture. Data from [23, 25] were used in this case, which yields similar results (± 250 K at P = 50 MPa) upon extrapolation of the condensation boundary.

1.7. Discussion of the Results of Calculation. Comparison to Data of Other Calculations

Let us turn to discussion of the results presented in Chapter 5. Since the qualitatively general behavior of thermodynamic functions has already been described in section 1, let us discuss the fact of the accuracy which can be attributed to the results of calculation. It is obvious that the answer to thes quesion depends on the specific substance and the range of parameters. The calculations for hydrogen are apparently most accurate among the substances considered in the given paper. Due to the high ionization potential in the range of parameters of interest to us,

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hydrogen is everywhere weakly imperfect (see Figure 1.11). The maximum value of the parameter of imperfection $\Gamma \approx 0.6$ is achieved at p = 50 MPa and $T \approx 10\text{-}20 \cdot 10^3$ K. Inclusion of coulomb correction for imperfection in the calculation changes the values of the total thermodynamic values, for example, of density and enthalpy, by not more than 3 percent in this range. At $p \leq 5$ MPa, this difference does not exceed 1.5 percent over the entire temperature range. Since there are no experimental data for hydrogen in the parameters of interest to us, it is reasonable to take the values indicated above as the characteristic of the order of magnitude of the accuracy of thermodynamic values calculated by the method described above.

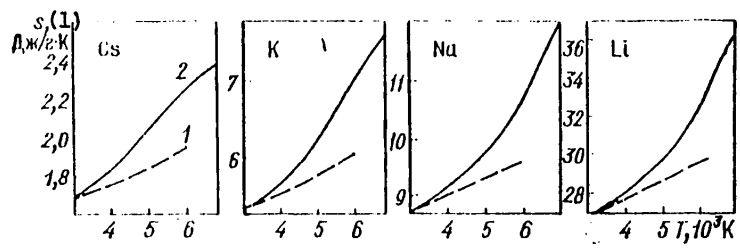

Figure 1.26. Entropy of Alkali Metal: 1--ideal gas of atoms at p = 0.1013 MPa [5]; 2--calculations of this paper for plasma at p = 0.098 MPa

Key:
1. J/g·K

There is a number of papers in the literature devoted to systematic calculation of the thermodynamic properties of hydrogen. Let us note [114], where calculations were made using ordinary Debye approximation for $p = 10^{-4}$ to 10^2 MPa and $T = 10^2$-10^5 K [8]. Similar thermodynamic calculations of hydrogen are presented in [115]. Since the results of this calculation for hydrogen and the results of [114, 115] are similar to each other, they are not presented in this book.

The results of [116] ($p \leq 1$ MPa and $T \leq 12{,}000$ K) are frequently used from thermodynamic calculations of alkali metals in engineering applicatons. Similar tables of the thermodynamic properties of alkali metals at low temperatures are contained in [3] ($p \leq 1$ MPa and $T \leq 2{,}000$ K) and [117] ($p \leq 1$ MPa and $T \leq 3{,}000$ K). The thermophysical properties of a plasma of a number of substances are calculated in [118] in the range $T \approx 10^3$-10^6 K and $V \approx 6 \cdot 10^2$ to $6 \cdot 10^6$ cm³/mole ($p \leq 10^4$ MPa). The thermodynamic properties of a plasma of alkali metals were calculated in [119] in the range T = 4,000-30,000 K and p = 1-100 MPa. Analysis of different approximations for thermodynamic description of a strongly imperfect plasma was made on the example of cesium in [7]. The effect of charge-neutral interaction on plasma composition was also analyzed on the example of cesium in [120].

The results of the calculations of this paper at low temperatures and low degree of imperfection can be compared directly to the calculated data of [5], which is the basis for most applied calculations made in an ideal gas approximation. This comparison is presented in Figure 1.26. The difference increasing with temperature corresponds to ionization of an alkali metal.

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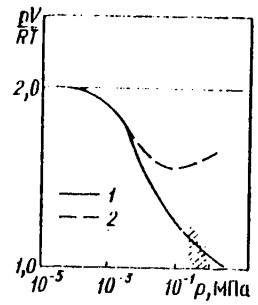

Figure 1.27. Isotherm of Cesium T = 5,000 K: 1--present calculation (section 1.6); 2--results of [116]. Experimental results of [73] are cross-hatched

Comparison of the results of this paper with those of [116, 118] for the alkali metals shows that these results are similar in the range of weak imperfection $\Gamma \ll 1$. The divergences related to different form of the corrections for imperfection become appreciable in the range $\Gamma \sim 0.1$ and ($n_{zar} r_D^3 \sim 1$). The divergences are very high in the range of strong imperfection $\Gamma > 1$ (Figures 1.27 and 1.28). This is manifested to a lesser degree for lithium and to a greater degree for cesium. For example, the degree of ionization for cesium at p = 1 MPa and T = 6,000°K and the mean molecular mass in [116] from it differ by approximately a factor of 1.5 from the value given by the present calculations. This divergence is explained by the use of the Ekker-Weizel formula [121], which strongly exaggerates the value of reduction of the ionization potential. Corrections which lead to a loss of thermodynamic stability at $\Gamma \gtrsim 1$ are actually used in both papers [116, 118]. This is expressed in a sharp increase in the degree of ionization to total ionization in [118], where the ordinary Debye-Huckel correction is used [8]. The calculations were limited by pressure p = 1 MPa in [116] in the immediate vicinity for cesium, for example, of the parameters when this jump should occur. It should be noted that the calculations are not thermodynamically self-consistent in both papers [116, 118] since the corrections for imperfection are in chemical potential and consequently in the reduction of ionization potential (1.78) and at the same time are absent in the equation of state (1.77). The isotherms $T = 5 \cdot 10^3$ and 10^4 K for cesium are presented for illustration in Figures 1.27 and 1.28 (compared to Figures 1.18 and 1.19). The calculations made in [119] is devoid of this deficiency. True, the form of corrections for imperfection in the range of weak imperfection ($\Gamma \ll 1$) used in it does not coincide with Debye approximation, but leads to violation of thermodynamic stability in the range $\Gamma \gg 1$. However, the indicated deficiency is weakly felt in the summary equation of state p(V, T) in the range of parameters of interest to us, which on the whole is close to that found in this paper. The difference does not exceed 3.5 percent at $T \leq 20{,}000$ K. However, there is an appreciable divergence in the value of enthalpy and entropy (Figure 1.29) apparently related to an error in the calculations of [119]. Moreover, only single ionization is taken into account in [119], due to which the results of this paper for T = 25,000 and 30,000 K are also inaccurate in the characteristic for cesium and potassium and to a lesser extent for sodium.

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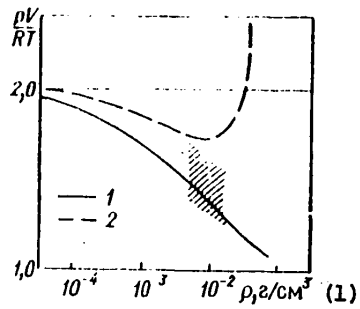

Figure 1.28. Isotherm of Cesium T = 10,000 K: 1--present calculation (section 1.6); 2--results of [118]; the experimental results of [73] are cross-hatched

Key:
1. g/cm^3

In all the papers enumerated above, as in the present paper, the chemical model or in other terminology the method of mixture [3, 4], is used in making the thermodynamic calculations. Universal calculations for all substances [92, 93, 109], conducted over a wide range of parameters using modifications of the Thomas-Fermi model, should also be noted. These calculations are less accurate than those mentioned above at the "gas" densities of interest to us ($\rho < \rho_{kr}$) since, without using the empirical information about ionization energies and spectra of particles, the typical individual features in the thermodynamic properties of different elements related to shell effects cannot be described. The indicated effects are manifested especially clearly for light elements in the range of large specific volumes. In this case the error in the caloric equation of state is usually much greater than in the thermal equation of state. This is illustrated in Figures 1.24 and 1.30 on the example of a lithium plasma. For example, the maximum difference between the results of calculation in TPF approximation [93] and in the approximation of this paper (section 1.6) for internal energy is approximately twofold and for density is approximately 25 percent* on the isobar p = 100 MPa.

It follows from the foregoing discussion that comparison of the results of different calculations to each other alone in the range of a strongly imperfect plasma can still not convincingly characterize their accuracy. More specific conclusions can be made from comparison to experimental results. This comparison is made in Chapter 4 and it follows from it that the accuracy of the present thermodynamic calculations at $\Gamma \leq 1$-2 is at least no worse than 10-15 percent in the thermal equation of state p(V, T) and 20-30 percent in the caloric equation of state H(p, V). Although experimental data on the thermodynamic properties of an imperfect plasma are available only for cesium among the alkali metals, one can assume that the accuracy of these thermodynamic calculations will be worse for cesium and better for lithium. The final conclusion can naturally be made with subsequent accumulation of experimental data.

*See the note on page 47.

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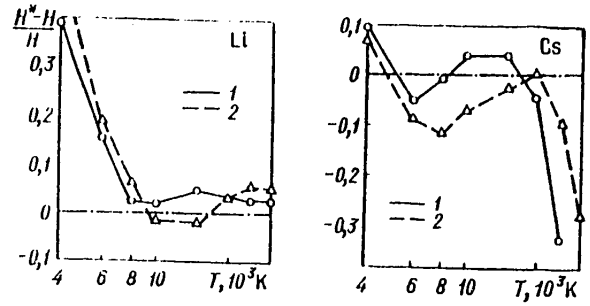

Figure 1.29. Comparison of Results of Calculating Enthalpy $[H(T) - H(0)]_{gas}$ of This Paper and That of [119] (noted by the asterisk) for a Cesium and Lithium Plasma. The value $[H(293) - H(0)]_{gas}$ of [5] is added to the enthalpy of [119]: 1--p = 1 MPa; 2--p = = 50 MPa

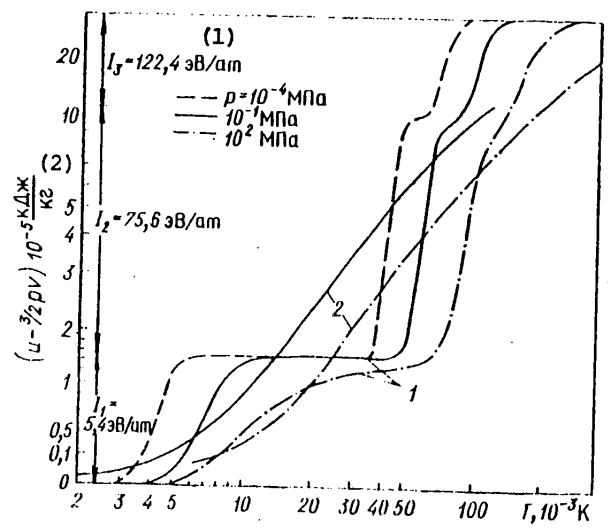

Figure 1.30. Caloric Equation of State of Lithium Plasma: 1--the present calculation (section 1.6); 2--Thomas-Fermi approximation with quantum and exchange corrections (TFP) [93]

Key:
1. eV/atom
2. kJ/kg

All the experimental data discussed in Chapter 4 are related to the total thermodynamic values and do not permit one to make direct conclusions about the composition of the plasma. It was already mentioned in section 1.1 that charge-neutral interaction, important for alkali metals, according to existing concepts, is primarily felt in variation of the composition of the plasma [13-16, 120]. Let us point out that the inclusion of a correction to charge-neutral interaction (1.86)-(1.87) in

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this paper with selected values of determining parameters (Table 1.4) is felt to a greater extent at low temperatures and high pressures (see Figures 1.12 and 1.13). Thus, the degree of ionization increases approximately sevenfold for cesium at T = 4,000 K and p = 50 MPa. The change of the degree of ionization under discussion is felt primarily in enthalpy among the total thermodynamic values. Variation of enthalpy comprises approximately 7 percent in the example given above. The experimental information now available is insufficient to characterize the accuracy of thermodynamic calculations in this range. Intensive development of pulsed methods of generation and diagnosis of an imperfect plasma (see Chapter 4) permits one to hope for rapid progress in obtaining information about the properties of a plasma in this range.

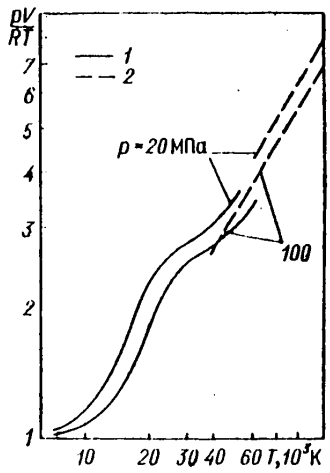

Figure 1.31. Thermal Equation of State of Uranium Plasma. Results of calculation. See Figure 1.30 for notations

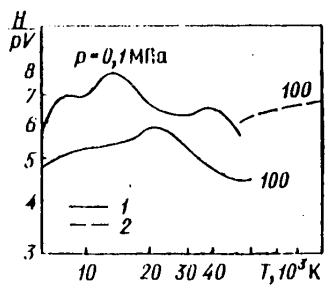

Figure 1.32. Caloric Equation of State of Uranium Plasma. See Figure 1.30 for notations

Let us now turn to the problem of the accuracy of thermodynamic calculation of uranium. As already mentioned, this accuracy depends to a significant degree on ambiguity in the spectral information required to calculate the statsums. There

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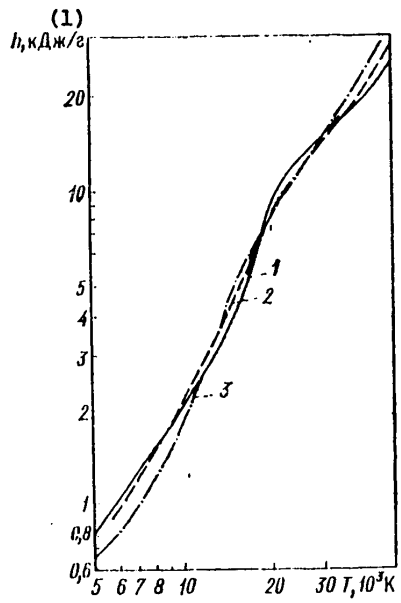

Figure 1.33. Enthalpy of Uranium at p = 50 MPa. Results of calculation. See Figure 1.14 for notations

Key:
1. kJ/g

are no experimental data in the range of interest to us; therefore, we can extract all conclusions about accuracy only from comparison of different versions of calculation. One should first mention [106] in which both the system of levels for $U-U^{+4}$ and the ionization potentials (6.22, 10.6, 18.9 and 32.1 kV) were found as a result of approximate quasi-mechanical calculation. Comparison to the results of calculation that uses the Thomas-Fermi model and its modifications is also of specific interest [92, 93, 109]. The calculations of [93] encompass only part of the range of parameters of interest to us ($T \geq 40{,}000$ K) for uranium and interpolation of the data of [93] yields results in this range similar in value to those of the present calculation (Figures 1.31 and 1.32), although they do have a different course of functions. The results of [106, 93], as indicated by comparison, agree well with each other which is apparently quite valid since the Thomas-Fermi approximation in [106] is used in implicit form when calculating the energy spectrum of uranium. Comparison of the results of [106, 93] to those of different versions of calculation by the method described above, distinguished by selection of approximation to describe plasma imperfection and to calculate the statsums of uranium and its ions (Figures 1.14 and 1.33) permits one to advance the hypothesis that the accuracy of calculating the thermodynamic properties of uranium, presented in this paper, comprises approximately 20 percent in density at $p \sim 50$ MPa and approximately 30 percent in enthalpy. This error is less at $p \sim 10$ MPa and comprises approximately 10 percent in density and approximately 20 percent in enthalpy. As in the case of alkali metals, a more definite judgment on the problem of the accuracy of

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thermodynamic calculations of uranium could be made in the presence of experimental results. The possibilities and prospects of different experimental methods are discussed in Chapter 4 in this regard.

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TRANSFER COEFFICIENTS OF AN IMPERFECT PLASMA

Moscow TEPLOFIZICHESKIYE SVOYSTVA RABOCHIKH SRED GAZOFAZNOGO YADERNOGO REAKTORA in Russian 1980 (signed to press 1 Aug 80) pp 65-118

[Chapter 2 from the book "Thermophysical Properties of Working Media of the Gas-Phase Nuclear Reactor", by Viktor Konstantinovich Gryaznov, Igor L'vovich Iosilevskiy, Yuriy Georgiyevich Krasnikov, Nina Ivanovna Kuznetsova, Vladimir Ivanovich Kucherenko, Galina Borisovna Lappo, Boris Nikolayevich Lomakin, Georgiy Alekseyevich Pavlov, Eduard Yevgen'yevich Son and Vladimir Yevgen'yevich Fortov, Atomizdat, 1,800 copies, 304 pages]

2.1. Qualitative Description of the Processes of Heat, Mass, Pulse and Charge Transfer in a Gas-Phase Nuclear Reactor

Heat, mass, pulse and charge transfer in a gas-phase nuclear reactor (GYaR), as shown by calculations, is significantly felt in functioning of the reactor [1]. The transfer processes determine the different gas-dynamic, electric and thermodynamic characteristics of the matter in the working volume of the GYaR--the mass velocity, electric current density, temperature, density, concentration of chemical elements and so on. A knowledge of the enumerated characteristics in turn permits one to estimate the degree of influence of the axial magnetic field on suppression of turbulence that develops due to tangential discontinuity of the velocities at the boundary of the uranium jet with the working substance, to calculate diffusion mixing of the central uranium jet with the working substance and to correctly consider the heat transfer processes in the GYaR.

The matter in the working volume of the gas-phase nuclear reactor is a mixture of uranium and alkali metals (or hydrogen) at temperature of 2,000-80,000 K and pressure of 10^{-1} to 10^{2} MPa. The transient region where one of the elements of the mixture (the alkali metal) is at subcritical pressure and near-critical temperature (see section 2.4), the condensation zone in which uranium and possibly other elements of the mixture exist in two phases--liquid and gaseous (phase transformations occur uniformly in a gas-phase nuclear reactor) and the most important for reactor operation--the plasma zone, must be determined in the indicated range of parameters. Since the volumetric fraction of the liquid phase in the working volume of the gas-phase nuclear reactor is negligible, the transient properties in the condensation zone should be identified with the transient properties of the gaseous phase, while the hydrodynamic processes should be considered as single-phase [1]. The transient properties of the plasma are investigated in detail in the given chapter.

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When describing a plasma on the basis of concepts of the chemical model (see Chapter 1), the following typical times are distinguished: τ_u--the time between elastic collisions of the plasma particles, τ_{kh} and τ_{nu}--the times between inelastic collisions accompanied and unaccompanied by chemical reactions and τ--the time of macroprocesses (diffusion of plasma components and so on). In approximation of $\tau \gg \tau_u$, τ_{nu} and τ_{kh}, called approximation of local thermodynamic equilibrium (LTR) below, the equilibrium particle distribution by velocity and energy, chemical equilibrium at given temperature, concentrations of chemical elements and pressure at a given point of the volume occupied by the plasma are established rather rapidly compared to the times of macroprocesses. Since the condition $\tau \gg \tau_u$, τ_{nu}, τ_{kh} is fulfilled during operation of the device, approximation of LTR is naturally used to investigate the gas-dynamic processes in a gas-phase nuclear reactor.

Let us present a hydrodynamic system of equations that describes the motion of a multielement ionized single-phase medium in the presence of electromagnetic fields and radiation fields in LTR [2-4]:

$$\partial\rho/\partial t + \nabla(\rho\mathbf{v}) = 0; \tag{2.1}$$

$$\rho(\partial c_a/\partial t + \mathbf{v}\nabla c_a) + \nabla \mathbf{i}_a = 0; \tag{2.2}$$

$$\rho(\partial\tilde{z}/\partial t + \mathbf{v}\nabla\tilde{z}) + \nabla\mathbf{j} = 0; \tag{2.3}$$

$$\rho[\partial\mathbf{v}/\partial t + (\mathbf{v}\nabla)\mathbf{v}] = -\nabla p + \nabla\Pi + (1/c)\mathbf{j}\times\mathbf{H}; \tag{2.4}$$

$$\rho[\partial h/\partial t + \mathbf{v}\nabla h] = \partial p/\partial t + \mathbf{v}\nabla p + \Pi:\nabla\mathbf{v} - \nabla(\mathbf{q} + \mathbf{q}_R) + \mathbf{j}\mathbf{E}. \tag{2.5}$$

Here equation (2.1) is the continuity equation, ρ is plasma density and v is the mean mass velocity.

Equation (2.2) is the diffusion equation of chemical elements whose number is equal to $N_a - 1$, where N_a is the number of chemical elements forming the plasma, c_a is the mass concentration of the chemical element and i_a is the mass flow of the chemical element,

$$c_a = \sum_{i=1}^{N} \frac{c_i u_{ia} m_a}{m_i}; \qquad \mathbf{i}_a = \sum_{k=1}^{N} \frac{\mathbf{i}_k u_{ak} m_a}{m_k}, \tag{2.6}$$

where u_{ak} is the number of nuclei of element a in component k, m_k and m_a are the mass of the particle of component k and element a, $c_i = n_i m_i/\rho$, where n_i is the concentration of the i-th component, N is the number of components in the plasma and i_k is the mass flow of component k (see (2.85)).

Equation (2.3) is the continuity equation for the charge, j is electric current and $\rho\tilde{z} = \rho^*$ is the volumetric density of the electric charge.

Equation (2.4) is the equation of motion of the medium, Π is the viscous stress tensor, p is pressure and $\mathbf{E}^* = \mathbf{E} + (1/c)\mathbf{v}\times\mathbf{H}$; $\mathbf{E}$, $\mathbf{H}$ are the electric and magnetic fields in the laboratory system of coordinates.

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Equation (2.5) is the equation of the energy balance, $h\{p, T, \{c_a\}, z\}$ is the specific enthalpy of the plasma, q is the convective thermal flux and q_R is the radiant energy flux.

The system of equations (2.1)-(2.5) should be supplemented by Maxwell equations that determine the fields in the plasma, the transfer equation of radiation (see chapter 3), the equation of state of the plasma and the system of equations for calculation of the thermodynamic functions of the plasma as a function of p, T, $\{c_a\}$, and $\tilde{z}$ (see Chapter 1), the expressions for i_a, q and j by gradients p, T, $\{c_a\}$ and E, H and by determination of Π. The Maxwell equations that determine the fields in the plasma of a gas-phase nuclear reactor should be used in magnetohydrodynamic approximation in which the displacement current and the force related to space charge is disregarded. In this approximation the system of Maxwell equations reduces to the equation of magnetic induction $\partial H/\partial t = -c\,\mathrm{rot}\,E$, where the electric field E is expressed from Ohm's law (2.10) in which it is assumed that $j = (c/4\pi)\mathrm{rot}\,H$. Thus, we find a closed equation for magnetic field H, after solution of which the current density and electric field are determined and equation (2.3) is superfluous in this case.

The expressions for the thermal fluxes, mass of the chemical element, pulse and charge in LTR have the form [2-4]:

$$\mathbf{q} = -(\lambda' - \lambda^T)\nabla T + \sum_{a=1}^{N_a-1} \lambda_a \nabla c_a - \lambda^E \mathbf{E}^*; \tag{2.7}$$

$$\mathbf{i}_a = \sum_{b=1}^{N_a-1} D_{ab}\nabla c_b + D_a^T \nabla T - D_a^E \mathbf{E}^*; \tag{2.8}$$

$$\Pi_{ij} = -\eta\left[(\partial v_i/\partial x_j + \partial v_j/\partial x_i) - \frac{2}{3}\delta_{ij}\partial v_k/\partial x_k\right] - \zeta\delta_{ij}\partial v_l/\partial x_l; \tag{2.9}$$

$$\mathbf{j} \approx \mathbf{j}_e = \sigma[\mathbf{E}^* - (1/e)\nabla_T \mu_e] + \alpha\nabla T. \tag{2.10}$$

The approximate equality (2.10) reflects the fact that charge transfer in a plasma under conditions realized in a gas-phase nuclear reactor occurs mainly by electrons. In expressions (2.7)-(2.10), λ' is the coefficient of transport thermal conductivity, λ^T, λ_a and λ^E are the effective coefficients of thermal conductivity, D_{ab}, D_a^T and D_a^E are the effective diffusion coefficients, η and ζ are the coefficients of shear and volumetric viscosity and σ and α are the conductivity and thermoelectromotive force of the plasma. Let us note that in the special case of the equality of mass fluxes of chemical elements and electric current to zero in the medium, the effective coefficients of thermal conductivity should be replaced by a single effective coefficient--λ_x, and the expression for q reduces to the form

$$\mathbf{q} = -(\lambda' + \lambda_x)\nabla T. \tag{2.11}$$

In this case q and λ_x are not dependent on the level of the energy reading, whereas the effective coefficients of thermal conductivity and the thermal flux in the form of (2.7) are dependent. The left side of the equation of conservation of energy in the indicated special case is also invariant with respect to the level of the energy reading since terms proportional to $(\partial h/\partial c_a)$ and $(\partial h/\partial \tilde{z})$ drop out in the left side of expression (2.5) [4, 5].

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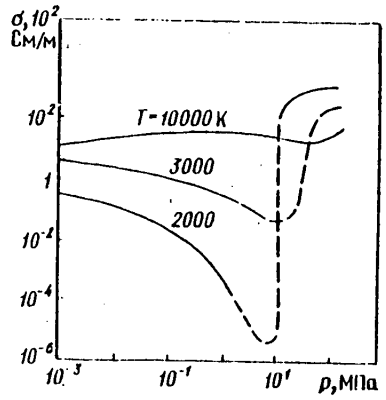

Figure 2.1. Dependence of Coefficient of Electric Conductivity of Cesium Plasma on Pressure Along Isotherms

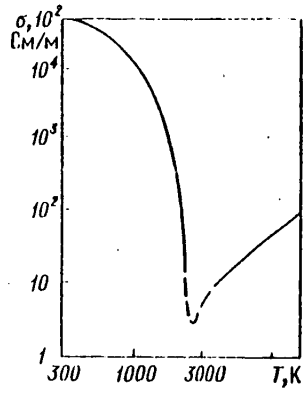

Figure 2.2. Dependence of Coefficient of Electric Conductivity of Cesium Plasma on Temperature at Pressure of p = 15 MPa

The values of the transfer coefficients (σ and α) in the range of parameters typical for a gas-phase nuclear reactor are determined mainly by the concentration of free electrons in the matter and their mobility. The functions for the transfer coefficients of a cesium and sodium plasma are presented in Figures 2.1-2.5. The low-temperature part of the curve in Figure 2.2 was measured in [7] and the high-temperature part was taken from [8]. The thermal conductivity of cesium and sodium (Figure 2.5) is also dependent mainly on the concentration and mobility of the free electrons in the high-temperature range. Transition from high values for molten metal to low values in the transition zone is common in the behavior of electric conductivity and thermal conductivity of alkali metals and subcritical isobar; the transfer coefficients increase in the high-temperature range, which is related to an increase of the degree of ionization. Variation of the thermal conductivity of metals upon transition from molten metal to a plasma is less than

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electric conductivity since heat transfer occurs in a weakly ionized plasma mainly by atoms and molecules. The effect of imperfection on the electron transfer coefficients (σ, α) is manifested by variation of both the ionization equilibrium in the plasma due to interaction and of the mobility of the free electrons.

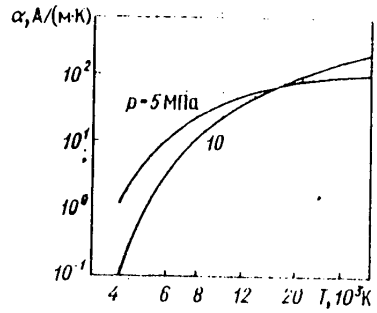

Figure 2.3. Dependence of Thermoelectromotive Force of Cesium Plasma on Temperature

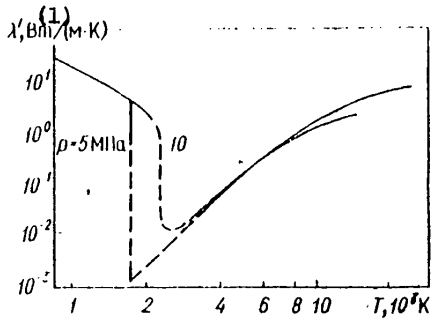

Figure 2.4. Dependence of Coefficient of Thermal Conductivity of Cesium Plasma on Temperature Along Isobars (dashed line--possible behavior of curve)

Key:
1. W/(m·K)

The effective coefficient of thermal conductivity of uranium λ_x in the plasma zone is represented in Figure 2.6 and the peaks on the curves are related to energy transfer processes due to chemical reactions of dissociation and ionization of metal vapors; the value of λ_x decreases with respect to λ' as pressure increases. A sharp decrease of the coefficient of shear viscosity of sodium (Figure 2.7) in the high-temperature range is caused by ionization of matter. The coefficient of shear viscosity and the effective coefficient of thermal conductivity (η, λ_x) are determined by the properties of the subsystem heavy particles--molecules, atoms and ions. The effect of imperfection on λ_x is manifested qualitatively in a shift to the high-temperature range and smoothing of the ionization and dissociation

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peaks; the coefficient of shear viscosity of a plasma is also smoothly dependent on temperature as interaction increases. The nature of the dependence of effective transfer coefficients on the plasma parameters is obvious from Figures 2.8-2.10. The coefficient of volumetric viscosity is not considered in detail in the given chapter since the corresponding terms, due to the short times of the relaxation processes, do not make an appreciable contribution to the equations of energy and motion under conditions of a gas-phase nuclear reactor.

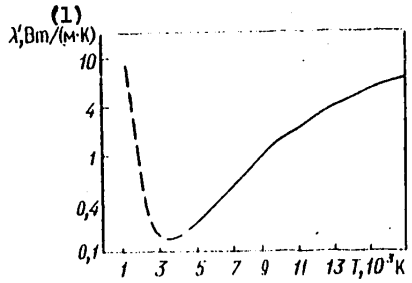

Figure 2.5. Dependence of Coefficient of Thermal Conductivity of Sodium Plasma on Temperature at p = 50 MPa (dashed line--possible behavior of curve)

Key:
1. W/(m·K)

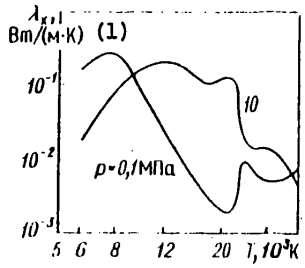

Figure 2.6. Dependence of Coefficient of Thermal Conductivity λ_x of Uranium on Temperature

Key:
1. W/(m·K)

Information about the collision characteristics of the plasma particles and its composition is required to calculate the properties of plasma transfer based on the chemical model. The first problem is discussed with respect to a plasma of alkali metals and their mixtures with uranium and hydrogen in section 2.6. The composition of the plasma is determined in section 1.5.

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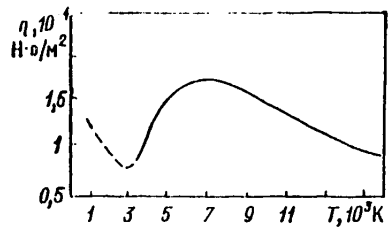

Figure 2.7. Dependence of Viscosity of Sodium on Temperature at p = 50 MPa (dashed line--possible behavior of curve)

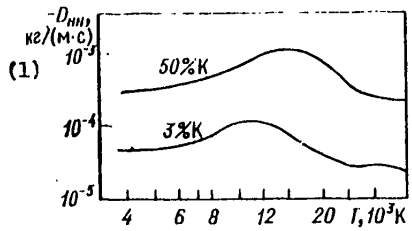

Figure 2.8. Dependence of Effective Diffusion Coefficient D_{nn} on Temperature at Pressure of 10 MPa for Mixtures with Different Potassium Content

Key:
1. kg/(m·s)

Let us estimate the electric field and space charge occurring due to the effect of thermoelectric forces during motion of an inhomogeneous ionized medium in a gas-phase nuclear reactor. The value of the ratio $\alpha/\sigma \sim 10^2$ μV/K; a field E ~ 1 V/cm occurs in the working volume of the reactor at temperature gradients of approximately 10^4 K/cm and the heat and mass transfer in a gas-phase nuclear reactor by the electric field must be taken into account because of this since the values of the corresponding terms (approximately E*) in relations (2.7) and (2.8) are on the order of terms approximately ∇T and ∇c_a. The value of the space charge found from the Poisson equation ($\rho^* \sim \nabla E$) is low compared to the mean concentration of charged particles and consequently the dependence of the thermophysical properties of the plasma in a gas-phase nuclear reactor on z can be disregarded. An axial magnetic field, whose typical value of magnetic induction is 10^2 T, does not lead to any significant anisotropy in the transfer coefficients: the parameter is $\omega\tau \sim Be/m < 1$ since the electron collision frequency is $\nu \sim 3\cdot10^{13}$-10^{14} s^{-1}.

2.2. The Kinetic Theory of a Weakly Imperfect Plasma

The working substance and the fissionable material are partially ionized at temperatures of approximately 10^3-10^5 K and pressures of 10^{-1} to 10^2 MPa under the operating conditions of a gas-phase reactor. It is complicated to describe this system

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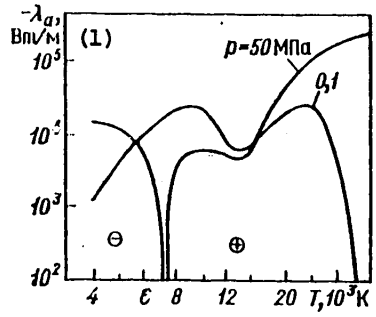

Figure 2.9. Dependence of Effective Coefficient of Thermal Conductivity λ_n of Potassium and Hydrogen Mixture (10 percent potassium) on Temperature Along Isobars

Key:
1. W/m

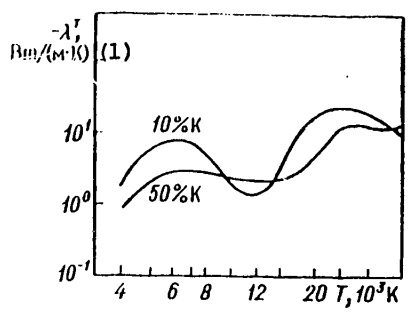

Figure 2.10. Dependence of Effective Coefficient of Thermal Conductivity of Potassium and Hydrogen Mixture on Temperature at Pressure of 50 MPa

Key:
1. W/(m·K)

kinetically. The energy thresholds of the different types of transformations (ionization, dissociation and excitation) are comparable to the thermal energy of particles; therefore, a large number of inelastic processes that affect the transfer coefficients occur in the plasma. Thus, calculation of the transfer coefficients of a real plasma may be only model in nature, based on the theory of simpler systems. One of them is a system of charged structureless particles; therefore, let us initially consider the kinetic theory and types of collision integrals of a completely ionized plasma. Let us then discuss the collision integrals in a multivariety particle system with internal structure and also the effect of excited particles and inelastic collisions on the transfer coefficients.

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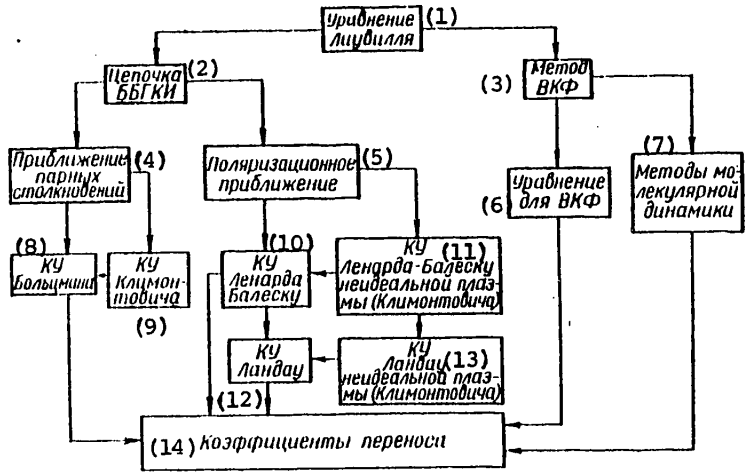

Figure 2.11. Diagram of Finding Kinetic Coefficients of Gases and Plasmas

Key:

1. Lieuville control
2. BBGKI chain
3. VKF method
4. Approximation of pair collisions
5. Polarization approximation
6. Control for VKF
7. Methods of molecular dynamics
8. Boltsman KU
9. Klimontovich KU
10. Lenard-Balescu KU
11. Lenard-Balescu KU of imperfect plasma (Klimontovich)
12. Landau KU
13. Landau KU of imperfect plasma (Klimontovich)
14. Transfer coefficients

The literature devoted to different problems of the kinetic theory of structureless particle systems with short- or long-acting potentials is rather extensive (see, for example [9-16]); therefore, let us limit ourselves here mainly to enumeration of the results. The sequential stages of calculating the kinetic coefficients in gases and a plasma are shown schematically in Figure 2.11. The initial point of kinetic theory is the Lieuville equation, which on the one hand, as a result of sequential integration by coordinates and pulses of particles, leads to the chain of BBGKI equations (Bogolyubov, Born, Green, Kirkwood and Ivon) and on the other yields formal expressions for the transfer coefficients by time correlation functions (VKF) (see section 2.3) for a similar discussion of the latter method).

The chain of equations for s-partial distribution functions is

$$f_s = V^s \int f_N dx_{s+1} \cdot \cdot \cdot dx_N, \tag{2.12}$$

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where V is the volume of the system and $x_k = (r_k, p_k)$ is the coordinate of the particle in the phase space of coordinates and pulses having the form:

$$\left(L_s^{(0)} - \sum_{1<i<j<s} \theta_{ij}\right) f_s = \frac{N-s}{V} \sum_{1<i<s} \int \theta_{i,\,s+1} f_{s+1} dx_{s+1}. \tag{2.13}$$

Operators θ_{ij} and $L_s^{(0)}$ are determined by the Hamiltonian function N of particles in the following manner:

$$H = H_N^{(0)} + \Phi_N \equiv \sum_{1<i<N} \left(\frac{p_i^2}{2m} + u(r_i)\right) + \sum_{1<i<j<N} \Phi_{ij};$$
$$\theta_{ij} = \frac{\partial \Phi_{ij}}{\partial r_i} \frac{\partial}{\partial p_i} + \frac{\partial \Phi_{ij}}{\partial r_j} \frac{\partial}{\partial p_j}; \tag{2.14}$$

$$L_s^{(0)} = \frac{\partial}{\partial t} + \sum_{1<i<s} \left(\frac{\partial H_s^{(0)}}{\partial p_i} \frac{\partial}{\partial r_i} - \frac{\partial H_s^{(0)}}{\partial r_i} \frac{\partial}{\partial p_i}\right). \tag{2.15}$$

An expression in which the corollation function of three particles is equal to zero ($g_3 = 0$) is used initially to split the chain of equations (2.13);

$$f_2(1, 2) = f_1(1) f_1(2) + g_2(1, 2);$$
$$f_3(1, 2, 3) = f_1(1) f_1(2) f_1(3) + f_1(1) g_2(2, 3) + f_1(2) g_2(1, 3) + f_1(3) g_2(1, 2). \tag{2.16}$$

The numbers 1, 2 and 3 denote the variables related to the first, second and third particles. Substituting (2.15) and (2.13), we find

$$[L_{12}^{(0)} - n \int (\theta_{13} + \theta_{23}) f_3 dx_3] g(1, 2) = \theta_{12} f_2(1, 2) + n \int [\theta_{13} f(1) g(3, 2) + \theta_{23} f(2) g(1, 3)] dx_3. \tag{2.17}$$

Further, the integral terms in (2.17) can be disregarded for a gas with short-acting potentials when the gas parameter $na^3 << 1$ is small (n is particle concentration and a is the radius of the potential action), since the terms are distinct from zero only with simultaneous approach of three particles. In this case the collision integral determined by g(1, 2) has an ordinary Boltzman form and consideration of the latter term by a parameter equal to the ratio of collision time to the time of free motion of the particle yields a correction to the collision integral [13] which is significant only for thermodynamic functions rather than for transfer coefficients. Similar corrections were found in [13] for other collision integrals as well that describe a gas or a plasma.

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If the particle density increases, the collisions occurring with participation of three, four or more particles must be taken into account in the collision integral. The question of the existence of a series for the transfer coefficients similar to the virial series for thermodynamic functions arises in this regard. Tertiary collisions were considered in [17], where the first virial coefficient in expansion of transfer coefficients was found, but it was further shown [18] that a four-particle collision integral is divergent. Summation of the most divergent terms yields the following expression for the transfer coefficients [19]:

$$\lambda = \lambda_0 + n\lambda_1 + (n^2 \ln n)\lambda_2 + n^2\lambda_3 + \ldots \tag{2.18}$$

These results were not compared to experimental data.

Due to the long-acting nature of the coulomb interaction potential, the effect of density on the transfer coefficients in the presence of charged particles is more sensitive than that for neutral particles. An additional polarization approximation, according to which each particle interacts immediately with a larger number of particles of the medium, is made in this case in equation (2.17), where the condition $g_3 = 0$ was already used. Therefore, the integral terms in expression (2.17) corresponding to this interaction should be maintained and $f_2(1, 2) \simeq \simeq f(1)f(2)$. The equation for g (1, 2) can be solved formally and as a result the collision integral in a completely ionized perfect plasma can be found [13-16]:

$$\partial f_1/\partial t = -\partial J(\mathbf{p}_1)/\partial \mathbf{p}_1;$$

$$J(\mathbf{p}_1) = \pi \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \int \frac{\Phi^2(k)\,\mathbf{k}\mathbf{k}\,\delta(\mathbf{k}\mathbf{v}_1 - \omega)\,\delta(\mathbf{k}\mathbf{v}_2 - \omega)}{|\varepsilon(\mathbf{k}, \omega)|^2} \times \tag{2.19}$$

$$\times \left[f(\mathbf{v}_2) \frac{\partial f(\mathbf{v}_1)}{\partial \mathbf{v}_1} - f(\mathbf{v}_1) \frac{\partial f(\mathbf{v}_2)}{\partial \mathbf{v}_2} \right] \frac{d^3k}{(2\pi)^3}.$$

Here $\Phi(k) = 4\pi e^2 k^{-2}$ is the Fourier transform of the coulomb potential and the dielectric permeability for a multivariety system is

$$\varepsilon(k, \omega) = 1 + \sum_a \frac{4\pi e_a^2}{k^2} \int \frac{1}{\omega - \mathbf{k}\mathbf{v}_a + i\delta} \mathbf{k} \frac{\partial f}{\partial \mathbf{p}_a} d^3p_a \, (\delta \to 0). \tag{2.20}$$

There is no shielding of the particles in the plasma in the high-frequency range $\varepsilon(\omega, k) \to 1$. In this case the collision integral (2.19) has the form found by Landau [13] and differs logarithmically at short and long distances. Statistical shielding of particles on the Debye radius occurs in the range of low frequencies $\varepsilon(0, k) \to 1 + (kr_D)^{-2}$ and the collision integral is convergent at long distances. Close collisions of charged particles must be correctly taken into account to eliminate the divergence at short distances. The presence of dielectric permeability dependent on frequency in the Lenard-Balescu collision integral (2.19) reflects the fact of dynamic shielding of a moving particle in a plasma. To find the collision integral convergent at short and long distances, it was suggested in [20] that the following combination be used as the collision integral (Hubbard approximation):

$$I = I^{Б} - I^{Л} + I^{ЛБ}. \tag{2.21}$$

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The basis for this suggestion was the concept that the collision integral should be equal to the Boltzman collision integral (I^B) with correction for dynamic polarization of the medium equal to the difference of the Lenard-Balescu integrals I^{LB} and Landau integral I^L. A similar result was also found in [21]. The lack of coordination of Hubbard approximation (2.21) with the expression for the equilibrium correlation function at long distances, which can be found from the kinetic equation, was noted in [13]. On the other hand, as will be shown below, it is this analogy with the method of calculating the thermodynamic potential of the plasma [22] when finding the collision integral by the method of Green functions leads to approximation (2.21).

There is yet another correction for interaction, related to the dependence of the collision integral on the external field, in a strongly imperfect plasma [23]. If an electric field is superimposed on a plasma, the dependence of a two-particle correlation function on the field appears and this dependence further leads to the appearance of an additional term in the collision integral, proportional to the external field, and as a result the electric conductivity of the plasma varies by the value

$$\Delta\sigma = \sigma(1 - \Gamma/3), \tag{2.22}$$

where Γ is the classical parameter of interaction (1.1).

Besides different method of finding the kinetic equation for a gas or a plasma, based on the BBGKI chain, the method of Green time functions is frequently used [24] by which the collision integral can be written. The kinetic equation is quantum in this case and therefore is written for the Wigner distribution function rather than for the ordinary distribution function since the pulse and coordinate cannot be measured simultaneously. The kinetic equation for an inhomogeneous gas or plasma can be found in the following form [24]:

$$\left[\frac{\partial}{\partial t} + \frac{\mathbf{p}}{m}\frac{\partial}{\partial \mathbf{r}} - \frac{\partial\tilde{\Phi}}{\partial \mathbf{r}}\frac{\partial}{\partial \mathbf{p}} + \frac{\partial\tilde{\Phi}}{\partial t}\frac{\partial}{\partial \omega}\right] G^{<}(\mathbf{p}, \omega, \mathbf{r}, t) = \tag{2.23}$$

$$= -G^{<}(\mathbf{p}, \omega, \mathbf{r}, t)\,\Sigma^{>}(\mathbf{p}, \omega, \mathbf{r}, t) + G^{>}(\mathbf{p}, \omega, \mathbf{r}, t)\,\Sigma^{<}(\mathbf{p}, \omega, \mathbf{r}, t).$$

Here $G^<$ and $G^>$ are the lagging and leading Green functions that determine the particle density and density of the permissible states of particles with pulse p and energy ω, respectively. The natural energy operators $\Sigma^>$ and $\Sigma^<$ determine the collision frequency related to exit and arrival of particles to the considered element of the phase space. Let us note that the natural energy operator in the method of equilibrium Green temperature functions determines the contribution to thermodynamic functions from bound states. The use of staircase approximation for the proper energy operator in the expression for the thermodynamic potential leads to Debye correction in the continuous spectrum and to the Planck-Larkin statistical sum in the discontinuous spectrum. Similar approximation in $\Sigma^>$ and $\Sigma^<$ for the collision integral [22] leads to approximation (2.21).

Other approximations for the collision integral are also known in the literature [25-27] in which the contribution of close collisions is taken into account by the

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Boltzman collision integral and that of far collisions is taken into account by the Lenard-Balescu integral with exponential cutoff of the contributions of far and near collisions, respectively. It is stated that the results of calculating the transfer coefficients with this approximation are insensitive to the parameter that separates the range of near and far collisions. These approximations are based on heuristic arguments and are rather qualitative; therefore, they cannot claim to be accurate numerical results even for a weakly imperfect plasma.

An important transfer characteristic--the electric conductivity of a plasma without regard to electron-electron collisions--can be calculated to compare the different forms of collision integrals in a plasma since consideration of electron-electron collisions introduces nonlinearity into the problem of calculation and similar calculation of electric conductivity of a plasma with known collision integral is impossible. The electric conductivity of a plasma and the collision frequency of electrons and ions are equal to, respectively,

$$\sigma = \frac{n_e e^2}{m\nu}; \quad \nu = \frac{2}{3} n_i \left(\frac{8kT}{\pi m}\right)^{1/2} \pi \left(\frac{e^2}{kT}\right)^2 \ln \Lambda. \tag{2.24}$$

If the collision integral of electrons and ions is selected in Boltzman form with static Debye interaction potential, the expression for the coulomb logarithm without consideration of quantum effects will have the form [28]

$$\ln \Lambda = \ln \Gamma^{-1} - 2C + \frac{3}{2} \ln 2 - \frac{1}{2}, \tag{2.25}$$

where Γ is the interaction parameter and $C = 0.5772...$ is the Euler constant.

Born approximation was used in [29] to calculate scattering on the Debye potential with regard to exchange quantum corrections. We make the following comment for this reason. The condition of applicability of Born approximation [48] is expressed by one of two inequalities: $\Phi \ll \hbar^2/mr_0^2$ or $\Phi \ll \hbar v/r_0$. These inequalities are reduced for Debye potential to the form

$$r_D \ll a_0; \quad f \ll \Lambda_e, \tag{2.26}$$

where r_D and a_0 are the Debye and Bohr radii, $f = e^2/kT$ is the coulomb scattering amplitude and Λ_e is the thermal wavelength of an electron. The parameter in [29] is the value

$$\eta^* \equiv \frac{1}{b} = \frac{\hbar^2}{8r_D^2 mkT} \sim \left(\frac{\Lambda_e}{r_D}\right)^2 \simeq (\varkappa \Lambda_e)^2, \tag{2.27}$$

where $\varkappa = r_D^{-1}$ is the Debye wave vector. The quantum corrections are small in the range of small values of η^* ($\eta^* \ll 1$) and should not affect the classical result (2.25). The thermal wavelength of an electron is greater than the Debye radius and consequently of the interparticle distance at large values of the quantum parameter ($\eta^* \gg 1$); therefore, the conditions of the applicability of the classical Boltzman equation are violated, specifically the effects of nonpair scattering (see section 2.4), electron degeneration and so on should be taken into account. At small values of quantum parameter η^*, it is preferable to use calculations of the scattering phases on the Debye potential rather than Born approximation [31].

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Calculation of the collision frequency for the Lenard-Balescu integral (2.19)

$$\nu_{LB} = \frac{n}{12\pi^2 m^{1/2} (kT)^{3/2}} \int_0^\infty dq q^3 \exp\left(-\frac{\hbar^2 q^2}{8mkT}\right) \times$$

$$\times \int_{-\infty}^{\infty} dz \left| \frac{4\pi e^2}{q^2 \varepsilon(q, z)} \right|^2 \exp\left(-\frac{z^2}{2}\right)$$

with dielectric permeability (2.20) $\varepsilon(q, z) = 1 + \frac{\varkappa^2}{q^2}(A + iB)$,

$$A = 2 - z \exp\left(-\frac{z^2}{2}\right) \int_0^z dt \exp\left(\frac{t^2}{2}\right); \quad B(z) = \left(\frac{\pi}{2}\right)^{1/2} z \exp\left(-\frac{z^2}{2}\right)$$

leads to the following expression for the coulomb logarithm:

$$(\ln \Lambda)_{LB} = \int_0^\infty \frac{q^3 \exp(-\eta^2 q^2/4)\, dq}{(q^2+1)(q^2+2)} = \ln\frac{1}{\eta^*} - \frac{C}{2} + 0(\eta^{*2} \ln \eta^*). \tag{2.28}$$

The transfer coefficients for a plasma with Lenard-Balescu collision integral were calculated in [30, 32].

The coulomb logarithm for the Landau collision integral is found at $\varepsilon(q, \omega) = 1$:

$$(\ln \Lambda)_{\Lambda} = \int_0^\infty \frac{q^3 \exp(-\eta^2 q^2/4)}{(q^2+2)^2} = \ln\frac{1}{\eta^*} - \frac{C}{2} + \frac{1}{2}\ln 2 + 0(\varepsilon^2). \tag{2.29}$$

For approximation (2.21) we find [22]:

$$(\ln \Lambda)_{GD} = \ln \Gamma^{-1} - 2C + \frac{3}{2}\ln 2, \tag{2.30}$$

or with regard to quantum corrections [33]:

$$\left.\begin{aligned} &(\ln \Lambda)_{WD} = \ln \Gamma^{-1} - 2C + \frac{3}{2}\ln 2 - \frac{1}{2}\exp(z) E_1(z); \\ &E_1(z) = \int_z^\infty t^{-1} \exp(-t)\, dt, \quad z = \frac{1}{4}\left(\frac{f}{\Lambda_e}\right)^2 \exp(2C), \end{aligned}\right\} \tag{2.31}$$

therefore, in the high-temperature range kT >> Ry, instead of expression (2.30) we find [34]:

$$(\ln \Lambda) = \ln r_D/\Lambda_e - \frac{C}{2} + \frac{1}{2}\ln 2. \tag{2.32}$$

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Approximation with exponential cutoff [25-27] leads to the following expression:

$$(\ln \Lambda)_{KA} = \ln \Gamma^{-1} - 2C + \ln 2. \tag{2.33}$$

Let us also note the expression for the coulomb logarithm proposed by Spitzer and Haerm [35] in which the divergent integrals were cut off at short distances corresponding to charged particle scattering by angle 90° and at long distances on the Debye radius:

$$(\ln \Lambda)_{SH} = \ln (3\sqrt{2}\Gamma^{-1}). \tag{2.34}$$

Sometimes to avoid formal divergences at large values of parameter Γ, the transport scattering cross-section on a shielded potential is calculated in Born approximation, maintaining the following terms with respect to parameter Γ:

$$\ln \Lambda = \int_0^{q_{\text{макс}}} \frac{q^3 dq}{(q^2+1)^2} = \frac{1}{2}\left[\ln(1+\Lambda^2) - \frac{\Lambda^2}{1+\Lambda^2}\right]. \tag{2.35}$$

Here parameter $\Lambda = q_{\text{maks}}/\varkappa$ is determined by the maximum value of the transmitted pulse.

Both the collision integral and the results obtained by using it for transfer coefficients are valid only for a weakly imperfect plasma, i.e., at $\Gamma \ll 1$ and in this case the different values coincide for coulomb logarithms (2.25)-(2.35). The following expression has the best extrapolation properties in the range $\Gamma \simeq 1$ coinciding with the experimental results discussed in Chapter 4

$$\ln \Lambda = \frac{1}{2}\ln(1+\Lambda^2), \tag{2.36}$$

$\Lambda = 3\sqrt{2}\Gamma^{-1}$ which was also used in subsequent calculations of the transfer coefficients (see Chapter 5).

Collisions not only with structureless charged particles but with atoms, molecules and radicals as well in different energy states must be taken into account in a real partially ionized plasma, which complicates the kinetic equation and makes it difficult to analyze the effect of different factors on electron transfer coefficients. The main analytical method of solving the kinetic equation with respect to the electron distribution function is the Chapman-Enskog method [10, 36], which is based on expansion of the anisotropic part of the distribution function determined by electric and magnetic fields, temperature gradients and concentration, into a series by orthogonal polynomials. The expansion was carried out by Sonin polynomials with regard to elastic collisions alone. Solution of the kinetic equation for a completely ionized plasma with electron-ion and electron-electron collisions by the Chapman-Enskog method is difficult due to the need to retain a large number of Sonin polynomials when calculating electric conductivity and thermo-EMF. For a completely ionized plasma detailed consideration of electron-electron collisions (corresponding to an infinitely large number of Sonin polynomials in the Chapman-Enskog method) was carried out by Spitzer and Haerm [35], who proceeded from the Landau collision integral for charged particles. A second-order differential equation with respect to correction to the equilibrium distribution function was solved

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numerically and as a result corrections were found to electron transfer coefficients of a completely ionized plasma. The corresponding results are presented in section 2.6.

The electron-atom (molecule) collision integral is added in the kinetic equation for electrons in the case of a partially ionized plasma. Application of the Chapman-Enskog method with regard to electron-electron collisions also requires consideration of a large number of polynomials by which the expansion was carried out [16]. The variational method [37, 38] in which the extreme properties of transfer coefficients are used is sometimes applied with increasing dependence of the electron-atom elastic scattering dependence on the relative particle velocity for correct consideration of electron-electron collisions. Since this method is less widespread compared to the Chapman-Enskog method, let us describe it in more detail.

The kinetic equation for electrons in a steady spatially homogeneous plasma has the form

$$\psi \equiv -\frac{e\mathbf{E}}{m}\frac{\partial f}{\partial \mathbf{v}} = (K_{ea} + K_{ei} + K_{ee})\varphi, \tag{2.37}$$

where ϕ is correction to the equilibrium electron distribution function f in electric field E and K is the collision integrals.

Let us determine the scalar product $(\varphi, \psi) = \int \varphi(\mathbf{v})\psi(\mathbf{v})d^3v$. The current density is $\mathbf{j} = e\int \mathbf{v}f(v)\varphi(v)d^3v = \frac{kT}{E}(\varphi, \psi)$. Let us introduce into consideration the functional $\lambda(\chi) = (\varphi|K|\varphi) - (\chi - \varphi|K|\chi - \varphi) = 2(\chi|\psi) - (\chi|K|\chi)$, which reaches a maximum when the function $\chi(\mathbf{v})$ coincides with precise solution of the kinetic equation; at the same time it is not required to know the precise solution of $\phi(\mathbf{v})$ to calculate the functional $\lambda(\chi)$. Let us expand the χ function by the basic functions and make use of the extreme condition:

$$\chi = \sum a_i\chi_i, \quad \partial\lambda/\partial a_i = 2(\chi_i/\psi) = \sum_j a_j(\chi_i \mid K \mid \chi_j) = 0.$$

After solving the system of linear equations, electric conductivity is calculated with respect to coefficients a_i:

$$\sigma = \frac{kT}{E^2}\max\lambda(\chi) = \frac{kT}{E^2}\sum_{i,j} a_i a_j(\chi_i \mid K \mid \chi_j). \tag{2.38}$$

The electric conductivity of a partially ionized cesium plasma was calculated in this manner in [38].

Calculation of the electron transfer properties of a multicomponent medium both by the Chapman-Enskog method with a large number of expansion polynomials and by the variational method is difficult due to their cumbersomeness. Moreover, the use of these methods is frequently unjustified due to the ambiguity in the cross-sections of the elementary processes. Therefore, calculations by these methods were made

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only in the simplest models of the three-component plasma type, while the main part of the calculations was made by the Frost interpolation method (see section 2.6).

As mentioned at the beginning of this section, the transfer coefficients are affected by the presence of excited states of atoms and molecules. If excited atoms are regarded as an individual variety of particles in which electron scattering occurs, then a significant contribution to electron transfer can be determined by the large electron scattering cross-sections in excited states, despite their lesser population according to the Boltzman factor $g_i \exp(-E_i/kT)$. For example, the theoretically calculated and experimentally measured electron scattering cross-sections at energy of 4.4 eV on a sodium atom in the excited state $3^2P_3/2$ is 3.21-fold greater than the scattering cross-section in the ground state. This yields an appreciable correction to the transfer coefficients determined by electrons (see section 2.4 for more details).

Let us briefly discuss the effect of inelastic collisions on the transfer coefficients. The kinetic theory and method of calculating the transfer coefficients were initially developed by Chapman and Enskog for gas particles with central interaction potential without internal degrees of freedom. Formal methods of calculating the transfer coefficients with regard to internal degrees of freedom were developed by Van-Chang and Ulenbek and the common expressions for the diffusion coefficients, viscosity, thermodiffusion and thermal conductivity were then found in [39]. When these formulas were derived, each excited state of an atom or molecule was assumed an individual variety of particles so that Maxwell distribution was assumed to be in equilibrium by velocities and Boltsman distribution was assumed by energy states. In the Chapman-Enskog method, expansion of the correction to a distribution function must be made to a double series of orthogonal polynomials. Sonin by velocities and Waldman-Trubenbacher by quantum energy states. Inelastic collisions and the related transfer of the internal energy of particles has a more significant effect on the thermal conductivity of a gas and a considerably lesser effect on other transfer coefficients. To confirm this, Fox [40] determined the effect of inelastic collisions on the electron conductivity of an argon plasma. The corresponding correction was less than 1 percent in the temperature range of 5,000-25,000 K. Another attempt to take into account inelastic collisions is contained in [41], but the results on the effect of inelastic collisions on the viscosity of partially ionized hydrogen do not agree with the conclusions of [36] about the low effect of these processes on the diffusion and viscosity of a gas. We note that work in this direction is now difficult first due to the insufficient information about differential cross-sections of inelastic processes, the course of reactions by different channels, including resonance channels and second due to the difficulty of finding the integral of inelastic collisions with regard to dissociation, ionization and other reactions and also problems of convergence by the number of orthogonal polynomials taken into account.

2.3. The Theory of Nonequilibrium Processes in Imperfect Media

Investigation of the transfer properties of a plasma on the basis of kinetic equations is possible, as is shown in section 2.2, provided there is weak interparticle interaction. The theory of nonequilibrium processes [42-47], to outline of which the given section is devoted, permits one to formally determine the transfer

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coefficients in systems with strong interaction by time correlation functions and to find the relationships between the thermodynamic and transfer characteristics of imperfect systems. These methods and the results of calculating the expressions for transfer coefficients found theoretically [42-47] for charged and neutral imperfect media--imperfect plasma, dense gases and fluids and some model systems--are also discussed in this section.

Nonequilibrium processes in imperfect media were studied by the methods described below for time intervals not too small when information about the initial state of a system becomes insignificant and the number of parameters required to describe it is reduced. The time of particle interaction is on the order of kinetic time in imperfect systems; therefore, there is no kinetic phase of evolution in the given systems (see section 2.2). Local thermodynamic equilibrium with slowly variable thermodynamic and hydrodynamic parameters compared to microscopic times is established in the hydrodynamic phase of evolution in each small macroscopic volume, the typical dimensions of the inhomogeneities of the system are high compared to microscopic dimensions and variation of the system parameters is described by the equations of hydrodynamics.

Let us explain the concept of thermal and mechanical perturbations used in the theory of nonequilibrium processes. Those which are the result of action of external fields are called mechanical perturbations of the system and in this case the Hamiltonian of the system is the sum of the undisturbed Hamiltonian and the interaction energy of the system with the external field. Perturbations that do not permit this description are called thermal perturbations [43].

The theory of nonequilibrium processes caused by external perturbations--the theory of linear response (TLO)--was developed in [42]. However, it must be noted that fluxes [2.7)-(2.10) do not contain external fields since the electric field in (2.7) and (2.8) is generally speaking the average field in the medium. Thus, the TLO apparatus can be applied to investigate nonequilibrium processes due to thermal perturbations: average electric field, temperature gradients, mean mass velocity and mass fractions of components or chemical elements if it is based on the concept of the effects from thermal perturbations in a medium by mechanical perturbations. Existing incorrect TLO methods were developed in [44, 46], where imaginary perturbations that create weakly inhomogeneous states of a medium are conisdered; a system relaxes by equations of hydrodynamics under the effect of imaginary perturbations. The mean values of the observed properties of the relaxing system (for example, space charge density, energy and so on) are expressed according to TLO by time correlation functions and are also determined from hydrodynamic equations, i.e., by phenomenological transfer coefficients. Expressions for transfer coefficients are found by comparison of the indicated determinations of mean values of the observed values. The validity of macroscopic equations of hydrodynamics is suggested in the approach of [44, 46]. Let us make use of the methods of [44, 46] to study some transfer coefficients. Let us briefly formulate the TLO without being specific about the type of disturbances but assuming that the latter are variable, adiabatically included at $t = -\infty$ and inhomogeneous. Let us write the small correction to the Hamiltonian of the medium in the form [44, 46]:

$$H^{ext}(t) = -\sum_j \int d\mathbf{r} B_j(\mathbf{r}, t) b_j^{ext}(\mathbf{r}, t). \tag{2.39}$$

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Here $B(r, t)$ is an operator corresponding to some observed property of the medium (for example, charge density) in Heisenberg presentation [48] and $b_j^{ext}(r, t)$ is the external adiabatically superimposed perturbation. Let us write the expression for $\Delta < B_i(r, t) >$ of variation of the observed property due to the effect of the perturbation (<...> denotes averaging by the statistical operator of a disturbed system):

$$\left.\begin{aligned} &\Delta\langle B_i(\mathbf{r}, t)\rangle = \sum_j \int_{-\infty}^{\infty} dt' \int d\mathbf{r}' \chi_{B_iB_j}(\mathbf{r}-\mathbf{r}', t-t')\, b_j^{ext}(\mathbf{r}', t');\\ &\chi_{B_iB_j} = 2i\theta(t-t')\frac{1}{2\hbar}\langle[B_i(\mathbf{r}, t)\, B_j(\mathbf{r}', t')]\rangle_0 = 2i\theta(t-t')\,\chi^{\cdot}_{B_iB_j};\\ &\chi_{B_iB_j}(\mathbf{k}, z) = \int \frac{d\omega\chi^{\cdot}_{B_iB_j}(\mathbf{k}, \omega)}{\pi(\omega - z)}. \end{aligned}\right\} \tag{2.40}$$

Here $\chi_{B_iB_j}$ is a reaction function or a lagging two-time Green function, $<...>_0$ is averaging by the undisturbed statistical operator, $[B_iB_j] = B_iB_j - B_jB_i$, $\chi''_{ij}(k, \omega)$ is the Fourier transform $\chi^{\cdot}_{B_iB_j}(\mathbf{r}-\mathbf{r}', t-t')$ and z is a complex variable. The properties of $\chi^{\cdot}_{B_iB_j}$ follow from the properties of Hermitian operators $B_i(r, t)$ with respect to time inversion (the case without a magnetic field is considered) [44, 48]:

$$\left.\begin{aligned} &\chi^{\cdot}_{ij}(\mathbf{r}-\mathbf{r}', t-t') = -\chi^{\cdot}_{ji}(\mathbf{r}'-\mathbf{r}, t'-t);\\ &[\chi^{\cdot}_{ij}(\mathbf{r}-\mathbf{r}', t-t')]^* = -\chi^{\cdot}_{ij}(\mathbf{r}-\mathbf{r}', t-t');\\ &\chi^{\cdot}_{ij}(\mathbf{r}-\mathbf{r}', t-t') = \varepsilon_i\varepsilon_j\chi^{\cdot}_{ji}(\mathbf{r}'-\mathbf{r}, t-t'). \end{aligned}\right\} \tag{2.41}$$

$\varepsilon_i = \pm 1$ if the corresponding operator is even or odd with respect to time inversion. Thus, $\chi''_{ij}(r - r', t - t')$ is an imaginary function, the part $\chi''_{ij}(r - r', \omega)$ is a symmetrical function with respect to substitution of i for j and r for r" and a real and odd function with respect to ω and the antisymmetrical part of $\chi''_{ij}(r - r', \omega)$ is imaginary and even. Comparison of equalities (2.41) shows that $''_{ij}(r - r', \omega)$ is an odd function with respect to ω and a real and symmetrical function with respect to r and r', i and j with identical evenness of operators B_i and B_j with respect to time inversion and vice versa when $\varepsilon_i = -\varepsilon_j$. Let us also note that Onsager reciprocity relations for transfer coefficients (see (2.53)) follow from relations (2.41).

Following the procedure described in [44, 46], we find the phenomenological determination of conductivity which links electric current with average electric field in the medium. It is assumed in this case that the medium consists of positively and negatively charged particles and in the case of a plasma the given approach corresponds to the physical model (see section 1.1). The law of conservation of electric charge and the phenomenological Ohm's law have the form (the temperature and pressure in the medium are constant and there is no magnetic field) [46]:

$$\frac{\partial\rho^*}{\partial t} + \nabla\mathbf{j} = 0, \qquad \mathbf{j} = \sigma^L\left[\mathbf{E} - \frac{1}{e}\left(\frac{\partial\mu}{\partial\rho^*}\right)_{p,T}\nabla\rho^*\right]. \tag{2.42}$$

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where $\mu = \mu_i - \mu_e$ is the difference of the chemical potentials of ions and electrons. Having carried out the Fourier transform in (2.42) and making simple calculations, we find the phenomenological determination of local longitudinal conductivity:

$$\sigma^L = \lim_{\omega \to 0} \lim_{k \to 0} \mathrm{Re} \frac{\omega \langle \rho^* (\mathbf{k}, \omega) \rangle}{\mathbf{kE}}. \tag{2.43}$$

Expressions for dielectric permeability $\varepsilon^L(k, \omega)$ and its reciprocal value $1/\varepsilon^L(k, \omega)$ are required for the calculations [45]:

$$\begin{aligned} \frac{1}{\varepsilon^L(\mathbf{k}, \omega)} - 1 &= \frac{4\pi \langle \rho^* (\mathbf{k}, \omega) \rangle}{i\mathbf{kD}(\mathbf{k}, \omega)}, \\ \varepsilon^L(\mathbf{k}, \omega) &= 1 + \frac{i4\pi \langle \rho^* (\mathbf{k}, \omega) \rangle}{\mathbf{kE}(\mathbf{k}, \omega)}. \end{aligned} \tag{2.44}$$

In these formulas $D(k, \omega)$ and $E(k, \omega)$, the Fourier transforms of the external and average electric fields are linked to the Fourier transforms of external $\tilde{\rho}(k, \omega)$ and induced $\rho^*(k, \omega)$ charge densities:

$$i\mathbf{kD}(\mathbf{k}, \omega) = 4\pi\tilde{\rho}(\mathbf{k}, \omega); \quad i\mathbf{kE}(\mathbf{k}, \omega) = 4\pi[\rho^*(\mathbf{k}, \omega) + \tilde{\rho}(\mathbf{k}, \omega)].$$

The relations between "external" longitudinal conductivity $\hat{\sigma}^L(k, \omega)$--the response of the medium to external electric field, $\sigma^L(k, \omega)$, $1/\varepsilon^L(k, \omega)$ and $\varepsilon^L(k, \omega)$, are written in the form [45]

$$\left.\begin{aligned} [\varepsilon^L(\mathbf{k}, \omega)]^{-1} &= 1 - \frac{i4\pi\hat{\sigma}^L(\mathbf{k}, \omega)}{\omega}; \\ \varepsilon^L(\mathbf{k}, \omega) &= 1 + \frac{i4\pi\sigma^L(\mathbf{k}, \omega)}{\omega}. \end{aligned}\right\} \tag{2.45}$$

Let us find external conductivity and $1/\varepsilon^L(k, \omega)$ according to (2.39) and (2.40) and let us write H^{ext} in the form

$$H^{ext}(t) = \int d\mathbf{r} \rho^*(\mathbf{r}, t) \varphi^{vn}(\mathbf{r}, t) e^{\varepsilon t}, \tag{2.46}$$

where ε is a low positive value that ensures the adiabatic nature of including the disturbance $\phi^{vn}(r, t)$. From (2.40), (2.44) and (2.46) follows:

$$\left.\begin{aligned} \langle \rho^*(\mathbf{k}, \omega) \rangle &= \chi_{\rho\rho}(\mathbf{k}, \omega) \varphi^{vn}(\mathbf{k}, \omega) = -\chi_{\rho\rho}(\mathbf{k}, \omega) \tilde{\rho}(\mathbf{k}, \omega) \frac{4\pi e^2}{k^2}; \\ \lim \varepsilon^L(\mathbf{k}, \omega) &= |\varepsilon^L(\mathbf{k}, \omega)|^2 \chi^*_{\rho\rho}(\mathbf{k}, \omega) \frac{4\pi e^2}{k^2}. \end{aligned}\right\} \tag{2.47}$$

Thus, σ^L in (2.43) has the form ($\rho^* = e\rho$) [44]:

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$$\sigma^L = \lim_{\omega \to 0} \lim_{k \to 0} \frac{e^2\omega}{k^2} \, | e^L(\mathbf{k}, \omega) |^2 \chi''_{\rho\rho}(\mathbf{k}, \omega). \tag{2.48}$$

The given expression is the strict definition of local longitudinal conductivity of a weakly inhomogeneous medium. The density-density correlation function $\chi''_\rho\rho(k, \omega)$ in (2.48) can be replaced by correlation functions $\chi''_{EE}(k, \omega)$ (one has in mind the electric field related to $\langle\rho^*(k, \omega)\rangle$) and $\chi_{jj}(k, \omega)$, which follows from (2.42). In the case of a homogeneous medium ($k = 0$), the formula for conductivity is found in [42]:

$$\sigma_{\mu\nu}(\omega) = \lim_{\varepsilon \to 0} \int_0^\beta \int_0^\infty e^{i\omega t - \varepsilon t} \langle j_\mu j_\nu (t + ih\lambda)\rangle_0 \, d\lambda \, dt, \tag{2.49}$$

where $\beta = (kT)^{-1}$ and j is a current operator. The field related to electric current by $\sigma(\omega)$ can be high-frequency in opposition to a weakly variable and weakly inhomogeneous field contained in Ohm's law in the form of (2.42).

The thermo-EMF of the medium is determined similar to σ^L. From Ohm's law $j = \sigma^L[E - \nabla\mu/e + \alpha_1 \nabla T]$ and at $\nabla\mu = 0$ we have $E(k,\omega) = -\alpha_1 ikT(k, \omega)$, i.e., $4\pi\rho^*(k, \omega) = \alpha_1 k^2 T(k, \omega)$; $\alpha_1 = \alpha/\sigma - (k/e)(\mu/kT) + (k/e)(h/kT)$. The perturbation Hamiltonian has the form $H^{ext}(t) = -\int dr q(r, t)[\delta T(r, t)/T] e^{\varepsilon t}$ where $q(r, t) = u(r, t) - [(u + p)/n] n(r, t) + n_1[n(r, t)/n - n_1(r, t)/n]\mu$, n is total concentration, u is energy density and $n_1 + n_2 = n$, $n_1 = n_2$. Thus, for α_1 we find [46]:

$$\alpha_1 = -\frac{1}{T} \lim_{\omega \to 0} \lim_{k \to 0} \mathrm{Re}\, \chi_{\rho,q}(\mathbf{k}, \omega)/k^2. \tag{2.50}$$

Let us find the expression for the coefficient of shear viscosity, also relying on linear response theory. The equation of conservation for the tangential component of pulse density p_i in linear approximation has the form

$$\frac{\partial}{\partial t} \langle \mathbf{p}_t(\mathbf{r}, t)\rangle = \frac{\eta}{\rho} \nabla^2 \langle \mathbf{p}_t(\mathbf{r}, t)\rangle.$$

Having carried out the Fourier-Laplace transformation in this equation, we find ($z = \omega + i\varepsilon$):

$$-iz\mathbf{p}_t(\mathbf{k}, z) + \frac{\eta}{\rho} k^2 \mathbf{p}_t(\mathbf{k}, z) = \mathbf{p}_t(\mathbf{k});$$

$$\mathrm{Re}\, \frac{\mathbf{p}_t(\mathbf{k}, z)}{\mathbf{v}_t(\mathbf{k})} = \frac{\eta k^2}{\omega^2 + \left(\frac{\eta^* k^2}{\rho}\right)^2}.$$

The imaginary perturbation Hamiltonian is $H^{ext}(t) = -\Theta(t) \int dr \bar{\rho}(r, t) \mathbf{v}(\mathbf{r}) e^{\varepsilon t}$; then from (2.40) for $t > 0$ follows:

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$$\frac{p_l(\mathbf{k}, z)}{v_l(\mathbf{k})} = \int \frac{d\omega'}{\pi i} \frac{\chi'_{p_l p_l}(\mathbf{k}, \omega')}{\omega'(\omega' - z)};$$

$$\mathrm{Re}\,\frac{p_l(\mathbf{k}, z)}{V_l(\mathbf{k})} = \frac{\chi''_{p_l p_l}(\mathbf{k}, \omega)}{\omega} = \frac{\eta k^2}{\omega^2 + \left(\frac{\eta k^2}{\rho}\right)^2}.$$

Hence [44]

$$\eta = \lim_{\omega \to 0} \lim_{k \to 0} \omega \chi''_{p_l p_l}(\mathbf{k}, \omega)/k^2. \tag{2.51}$$

The other transfer coefficients are also presented in a form similar to (2.48), (2.50) and (2.51) [44, 46].

The expressions for the transfer coefficients of imperfect systems were also found by the method of the nonequilibrium statistical operator [43, 47], differing from the method of indirect linear response theory. The transfer coefficients were determined in [43] by two-time lagging Green functions; in this case the expressions for vector, tensor and scalar processes have the form $\left(\mathbf{q}' = \mathbf{q} - \sum_{k=1}^{N} h_k \mathbf{i}_k\right)$ (compare to (2.7)-(2.9)

$$\left.\begin{aligned}
\mathbf{q}' &= -L_{QQ}\frac{\nabla T}{T^2} - \sum_{i=1}^{k} L_{Qk}\nabla\frac{\mu_k}{T};\\
\mathbf{i}_k &= -L_{kQ}\frac{\nabla T}{T^2} - \sum_{j=1}^{N} L_{kj}\nabla\frac{\mu_j}{T};\\
\Pi'_{ij} &= -\eta\left(\frac{\partial v_j}{\partial x_i} + \frac{\partial v_i}{\partial x_j} - \frac{2}{3}\delta_{ij}\nabla\mathbf{v}\right);\\
\Pi &= -\zeta\nabla\mathbf{v}.
\end{aligned}\right\} \tag{2.52}$$

Here μ_k is the electrochemical potential of component k and the transfer coefficients are, respectively:

$$\left.\begin{aligned}
L_{QQ} &= -\lim_{\varepsilon \to 0} kT\int\int_{-\infty}^{0}\int_{-\infty}^{t} e^{\varepsilon t}\chi_{QQ}(\mathbf{r}-\mathbf{r}', t')\,d\mathbf{r}'\,dt\,dt';\\
L_{Qj} &= \lim_{\varepsilon \to 0} kT\int\int_{-\infty}^{0}\int_{-\infty}^{t} e^{\varepsilon t}\chi_{Qj}(\mathbf{r}-\mathbf{r}', t')\,d\mathbf{r}'\,dt\,dt';\\
L_{kj} &= -\lim_{\varepsilon \to 0} kT\int\int_{-\infty}^{0}\int_{-\infty}^{t} e^{\varepsilon t}\chi_{kj}(\mathbf{r}-\mathbf{r}', t')\,d\mathbf{r}'\,dt\,dt';\\
\eta &= -\lim_{\varepsilon \to 0}\frac{k}{2}\int\int_{-\infty}^{0}\int_{-\infty}^{t} e^{\varepsilon t}\chi_{\tau\tau}(\mathbf{r}-\mathbf{r}', t')\,d\mathbf{r}'\,dt\,dt';\\
\zeta &= -\lim_{\varepsilon \to 0} k\int\int_{-\infty}^{0}\int_{-\infty}^{t} e^{\varepsilon t}\chi_{pp}(\mathbf{r}-\mathbf{r}', t')\,d\mathbf{r}'\,dt\,dt'.
\end{aligned}\right\} \tag{2.53}$$

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Here the subscripts Q, j, τ, and p correspond to operators of thermal flux density, diffusion flux, the nondivergent part of the stress tensor and the pulse density [43]. According to the Onsager reciprocity relations, which follow from [2.41], $L_{Qi} = L_{iQ}$ and $L_{ij} = L_{ji}$. The form of the fluxes (2.52) and determinations (2.53) does not vary if i_k is replaced by mass fluxes of the chemical elements i_a and μ_k is replaced by the chemical potentials of chemical elements μ_a. Using (2.52) and (2.53), one can find the determination of effective transfer coefficients by the corresponding correlation functions. It is natural that the effective transfer coefficients can be expressed by time correlation functions also by means of indirect methods of linear response theory.

The problem of division of μ_k into "electric" and "chemical" parts was considered in [47, 49] and it was shown in this case that, following the method of the nonequilibrium statistical operator, division cannot be made in general form. A coefficient that distinguishes the electric conductivity in the form of (2.49) from the local longitudinal electric conductivity of a plasma was found in explicit form for a Debye plasma:

$$\sigma^L = \sigma(0)\left[1 - \frac{1}{4}\left(\frac{e^2}{kT}\right)4\pi r_D \sum_j n_j z_j^3\right]. \tag{2.54}$$

As can be seen from the given expression, the difference between σ^L and $\sigma(0)$ in a Debye plasma exists for an asymmetrical plasma.

Microscopic calculation of transverse coefficients of imperfect media, determined by linear response functions $\chi_{B_iB_j}$ by means of different versions of the theory of nonequilibrium processes, is a complex problem. Therefore, a significant role in the theory of imperfect systems belongs to common restrictions on the extent of the response functions which are related to analytical properties, range of variations and so on. An example of restrictions is Kramers –Kronig relations and the ensuing sum rules resulting from them. Sum rules can be used in calculating the transfer coefficients of an imperfect system.

Kramers-Kronig relations for linear response functions are the consequence of the analytical nature of response functions in the upper hemisphere of the complex variable z; the analytical nature in turn follows from the cause of the perturbation. Mechanical perturbations are cause types, but the situation is more complicated in the case of thermal perturbations (see [46, 50] for more detail). Kramers-Kronig relations are valid in the range $k \to 0$ for dielectric permeability and longitudinal conductivity (response functions to an average electric field) [46, 50]; let us also assume the same thing for response functions corresponding to other thermal perturbations. Let us formulate the Kramers-Kronig relations. If the Fourier transform of a two-time lagging Green function [translator's note: pages 86 and 87 of original text are missing].

Let us disregard the second term on the right side of the first of these equations and $|\varepsilon^L(\mathbf{k}, \omega)|^2$ in the second equation since $\operatorname{Im}\varepsilon^L(\mathbf{k}, \omega) \sim \omega^{-3}$ and $|\varepsilon^L(\mathbf{k}, \omega)|^2 \sim 1$ at $\omega \to \infty$ (see (2.59)). Consequently, the series for $\operatorname{Re}\sigma^L(\mathbf{k}, \omega)$ found from the

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corresponding Kramers-Kronig relation for $\omega \to \infty$, coincides up to terms of approximately ω^{-4} with the series for $\mathrm{Re}\,\hat{\sigma}^{l}(\mathbf{k}, \omega)$; it makes no sense to carry out more precise analysis of the series $\mathrm{Re}\,\sigma^{L}(\mathbf{k}, \omega)$ since the odd moments of the imaginary part of external conductivity are equal to zero in the absence of a magnetic field. Thus, the odd moments of the imaginary part of $\sigma^{L}(k, \omega)$ are also equal to zero. From comparison of the expansion of the first term of the second side of the first equation of (2.51) at $\omega \to \infty$ and of the Kramers-Kronig expansion for $\mathrm{Im}\,\sigma^{L}(\mathbf{k}, \omega)$. we find the sum rules for the real part of $\sigma^{L}(k, \omega)$:

$$\left.\begin{aligned} &\int_{-\infty}^{\infty} \mathrm{Re}\,\sigma^{L}(\mathbf{k}, \omega)\,d\omega = \pi \frac{e^2}{k^2} \frac{\partial \chi_{\rho\rho}}{\partial t}(\mathbf{k}, t)\,|_{t=0}; \\ &\int_{-\infty}^{\infty} \omega^2\,\mathrm{Re}\,\sigma^{l}(\mathbf{k}, \omega)\,d\omega = -\pi \frac{e^2}{k^2}\left[\frac{\partial^3 \chi_{\rho\rho}}{\partial t^3}(\mathbf{k}, t)\Big|_{t=0} + \right. \\ &\left. + \frac{4\pi e^2}{k^2}\left(\frac{\partial \chi_{\rho\rho}}{\partial t}\Big|_{t=0}\right)^2\right]. \end{aligned}\right\} \tag{2.62}$$

We can extract in similar fashion the values of the higher even moments from $\mathrm{Re}\,\sigma^{l}(\mathbf{k}, \omega)$ by frequency. It is easy to write the sum rules from (2.60) and (2.62) for the real parts of $1/\varepsilon^{L}(\mathbf{k}, \omega)$, $\chi_{\rho\rho}(\mathbf{k}, \omega)$, $\varepsilon^{L}(\mathbf{k}, \omega)$, and so on. All the even moments of the real parts of the external and longitudinal conductivity, besides the zero moment, differ from each other. Thus, analysis by using the sum rules indicates a difference in the value between $\mathrm{Re}\,\hat{\sigma}^{l}(\mathbf{k}, \omega)$ and $\mathrm{Re}\,\sigma^{L}(\mathbf{k}, \omega)$. Let us also calculate the first sum rules $\mathrm{Re}\,\hat{\sigma}^{L}(\mathbf{k}, \omega)$ and $\mathrm{Re}\,\sigma^{L}(\mathbf{k}, \omega)$ for a classical plasma so as to determine the physical meaning of relations (2.60) and (2.62). FDT in the form of (2.58) has the form $\chi''_{\rho\rho}(\mathbf{k}, \omega) = \pi\beta\omega \frac{N}{V} S(\mathbf{k}, \omega)$ in the classical range ($\hbar \to 0$). Hence, from formulas (2.45) and (2.47) also follows

$$\mathrm{Re}\,\hat{\sigma}^{l}(\mathbf{k}, \omega) = \pi \frac{e^2}{k^2} \beta\omega^2 \frac{N}{V} S(\mathbf{k}, \omega). \tag{2.63}$$

Thus, calculation of the even moments $\mathrm{Re}\,\hat{\sigma}^{l}(\mathbf{k}, \omega)$ in the classical range reduces to calculation of the moments of the dynamic structural factor. The zero frequency moment of the real parts of external and longitudinal conductivity is equal to $\pi e^2 N/2Vm$ [42, 46]. Calculation of the fourth moment $S(k, \omega)$ yields:

$$\begin{aligned} &\int_{-\infty}^{\infty} \omega^4 S(\mathbf{k}, \omega)\,d\omega = \frac{3}{2} k^4 \left(\frac{1}{\beta^2 M^2} + \frac{1}{\beta^2 m^2}\right) - \frac{2\pi e^2 k^2}{\beta m^2} \frac{N}{V} \left\{\int [g_{ee}(r) - 1] \times \right. \\ &\times \left.\left(\frac{\sin kr}{kr} + \frac{3\cos kr}{k^2 r^2} - \frac{3\sin kr}{k^3 r^3}\right) \frac{dr}{r} - \frac{1}{3}\right\} - \frac{2\pi^2 k^2 N}{\beta M^2 V} \left\{\int [g_{ii}(r) - 1] \times \right. \\ &\times \left.\left(\frac{\sin kr}{kr} + \frac{3\cos kr}{k^2 r^2} - \frac{3\sin kr}{k^3 r^3}\right) \frac{dr}{r} - \frac{1}{3}\right\} - \frac{4\pi e^2 k^2}{\beta m M} \frac{N}{V} \times \\ &\times \left\{\int [g_{ei}(r) - 1] \left(\frac{\sin kr}{kr} + \frac{3\cos kr}{k^2 r^2} - \frac{3\sin kr}{k^3 r^3}\right) \frac{dr}{r} - \frac{1}{3}\right\}. \end{aligned} \tag{2.64}$$

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Hence, it is easy to write the second moment of the real parts of external and true conductivity from equalities (2.62) and (2.63). In (2.64) $g_{ii}(r)$, $g_{ee}(r)$ and $g_{ei}(r)$ are the equilibrium binary correlation functions of ions and electrons. Relations (2.63) and (2.64) permit one to conclude that the fourth frequency moment $S(k, \omega)$ in the long-wave range $\sim k^2$ and the second moment of the real part of external conductivity remain finite at $k \to 0$. The integrals from $g(r)$ in (2.64) reduce at $r \to \infty$ and the convergence of the first and second integrals in the right side of (2.64) also occurs at $r \to 0$. The integral containing $g_{ei}(r)$ diverges at $r \to 0$. The indicated divergence should be eliminated by modifying the electron-ion interaction potential at short distances, i.e., by replacing the electron-ion classical plasma by a model system which is thermodynamically stable and for which a thermodynamic limit exists. Another condition for the modified electron-ion potential is the positive definiteness of the moments of the real parts of external and longitudinal conductivity since $S(k, \omega) > 0$ [45]. When calculating the moments of higher order from the dynamic structural factor, the exponent r in the numerator of the subintegral expression increases with $g_{ei}(r)$ and the model of solid charged spheres or a model in which $g_{ei}(r) \sim \exp(-1/r)$ will provide, for example, convergence of the corresponding integrals at $r \to 0$.

The relationships of the equilibrium correlation functions to the frequency moments of time correlation functions of imperfect media, corresponding to different thermal perturbations, can be determined by the methods described above in detail for $\sigma^L(k, \omega)$.

The integral relations between the linear response functions of the medium and the derivatives of the thermodynamic values in a form distinct from (2.60) and (2.62) permit one to find the indirect methods of linear response theory [44]. The main relation between linear response functions and the derivatives of thermodynamic values by means of which it is easy to find the specific sum rules was established in [44]:

$$\lim_{k \to 0} \chi_{B_i B_j}(\mathbf{k}, 0) = (\partial B_i / \partial b_j)_{b_l \neq b_j}. \tag{2.65}$$

Here B_i is the observed properties and b_i is the thermodynamic parameters of the medium (compare (2.40)).

Let us turn to discussion of the few results of calculating the expressions for transfer coefficients by time correlation functions. Data were found mainly by numerical methods for imperfect media. Numerical investigaton of the electric conductivity of a system which simulates a weakly ionized dense plasma with strong charge-neutral interaction was carried out in [51] by the molecular dynamics method on the basis of the classical single-electron version of formula (2.49), which, as indicated above, differs from the correct expression for local longitudinal electric conductivity (2.48) and essentially corresponds to the external electric conductivity of a plasma. Approximations similar to [51] but to calculate the electric conductivity of a completely ionized imperfect plasma was used in [52]; in this case the electron-ion interaction potential was modified at short distances (see Chapter 1). Since the correlation function of the fluxes rather than the correlation function of velocities must be calculated for completely ionized media to determine electric conductivity, the accuracy of the calculations of [52] cannot be controlled. A check of the first sum rules in [51, 52] was not made.

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The coefficients of shear and volumetric viscosity, the coefficient of self-diffusion and the correlation function of velocities were calculated by the molecular dynamics method in [53] for a single-component classical plasma, i.e., a system of charged particles on a homogeneous background of opposite sign. The same values were then estimated on the basis of Kramers-Kronig relations for linear response functions, known frequency moments of different correlators and FDT. Good agreement of the estimated and calculated values of the transfer coefficients was found [54]. The self-diffusion coefficient was investigated in [55] in a classical neutral fluid by means of known even frequency moments of the dynamic structural factor, FDT and Kramers-Kronig relations. The correlation function of velocities that determines the self-diffusion coefficient was approximated by an expression with several parameters which were found by moments $S(k, \omega)$ related to the correlation function of velocities by means of FDT; the value of the self-diffusion coefficient found in [55] is in satisfactory agreement with the results of numerical experiments for liquid argon. The coefficients of shear and volumetric viscosity were calculated in exactly the same manner in [56] for liquid argon, which are in good agreement with experimental data. Thus, the sum rules for linear response functions are used directly to estimate the transfer coefficients of imperfect media.

Let us consider the analytical methods of calculating the electric conductivity of a plasma, based on expressions of transfer coefficients by time correlation functions (compared to (2.49)).

$$\sigma_{\mu\nu}(\omega) = \frac{e^2}{m^2} \int \frac{p_\mu p'_\nu}{i\omega} \left[K^R_{pp'}(\omega) - K^R_{pp'}(0)\right] \frac{d^3p\, d^3p'}{(2\pi)^3}. \tag{2.66}$$

Here $K^R_{pp'}(\omega)$ is the Fourier transform of a lagging two-part Green function which is calculated by the causal Green function at discrete points of the imaginary axis and is continued analytically to the real axis [24].

High frequency electric conductivity of a plasma was calculated in [57] by the method of Green functions and the statistical conductivity was calculated in [58]. Let us outline the method of calculating the electric conductivity of a completely ionized plasma. Let us determine the vertex part by the relation $\mathbf{R}_p(\omega_p, \omega_n) = \int \frac{d^3p'}{(2\pi)^3} \mathbf{p}' K_{pp'}(\omega_n)$, where $\omega_p = i\pi kT(2m+1)$; $\omega_n = 2n_i\pi kT$. In staircase approximation, which must be taken into account when calculating the static electric conductivity, for the vertex the following equation is valid

$$\mathbf{R}_p(\omega_p, \omega_n) = \mathbf{p} g_p(\omega_p, \omega_n) + \int \frac{d^3p'}{(2\pi)^3} kT \sum_{\omega_{p'}} g_p(\omega_p, \omega_n) \widetilde{\Phi}_{pp'}(\omega_{p'} - \omega_p) \mathbf{R}_{p'}(\omega_{p'}, \omega_n),$$

where $g_p(\omega_p, \omega_n) = -G_p(\omega_p + \omega_n/2) G_p(\omega_p - \omega_n/2)$. This equation plays the role of the kinetic equation in the method of time correlation functions. Let us represent its solution in the form

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$$R_p(\omega_p, \omega_n) = \frac{pg_p(\omega_p, \omega_n)}{1 - L_p(\omega_p, \omega_n)},$$

where function L_p satisfies the equation

$$L_p R_p(\omega_p, \omega_n) = \int \frac{d^3p'}{(2\pi)^3} kT \sum_{\omega_{p'}} g_p(\omega_p, \omega_n) \widetilde{\Phi}_{p-p'}(\omega_p - \omega_n) \times$$
$$\times R_{p'}(\omega_p', \omega_n).$$

Using the approximation $R_p = pg_p(\omega_p, \omega_n)$ on the right side and adding with respect to ω_p', we find $L_p(\omega_p, \omega_n) = (i\nu_e^{(0)} - i\nu_e)/(\omega + i\nu_e)$, where the "transport" collision frequency is

$$\nu_e = n_i \frac{p}{m} \frac{\pi}{2} \left(\frac{e^2}{\varepsilon_p}\right)^2 \int_0^\infty dq q^3 \exp\left(-\frac{\hbar^2 q^2}{8mkT}\right) \sqrt{\frac{2}{\pi}} \int_0^\infty \frac{dx \exp(-x^2/2)}{|q^2 \varepsilon(q, x)|^2}.$$

In the spatially homogeneous case, we find for static electric conductivity:

$$\mathrm{Re}\,\sigma(0) = \frac{1}{3} \frac{e^2}{m} \int \frac{d^3p}{(2\pi\hbar)^3} \left(-\frac{\partial f_p}{\partial \varepsilon_p}\right) \frac{p^2}{\nu_e}, \quad f_p = \exp(\mu_e - \varepsilon_p)/kT.$$

Here $\varepsilon_p = p^2/2m$. Calculation of the electric conductivity of a low-temperature plasma [58] in staircase approximation, which takes into account the multiple charged particle interactions, yields a result coinciding in accuracy with the approximation of [20] and corresponding to the coulomb logarithm.

The method of Green functions was used in [59] to calculate the corrections to the electric conductivity of a Lorentz gas and the corresponding diagram technique was developed in [60].

The effects of nonpair scattering when the electron wavelength Λ_e and the scattering amplitude $\sqrt{q}$ (q is the scattering cross-section) are comparable to the distance between scatterers $N^{-1/3}$, were taken into account in [59]. Expansion of the collision frequency was found with respect to parameter $\xi = N\Lambda_e q$ as a result

$$\nu_{eff} = \nu(1 + a_1\xi + a_2\xi^2 + a_3\xi^2 \ln \xi).$$

2.4. Model Approaches to Determination of Electron Transfer Coefficients of an Imperfect Plasma

The kinetic theory of gases, valid in the limiting case of locally strong potentials at $na^3 \ll 1$ (a is the radius of potential action), and of a plasma for integrally weak potentials ($\Gamma \ll 1$) was developed in section 2.2. The state of methods of calculating transfer coefficients expressed by time correlation functions was analyzed in section 2.3. For systems with weak interparticle interaction, both approaches to determination of the transfer properties are equivalent but in individual cases,

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following the second approach, one can calculate analytically or numerically the transfer coefficients for systems with strong interaction. The latter is possible for a weakly ionized plasma, single-component plasma and dense neutral systems [51-56]. Strict methods cannot be used to calculate the transfer coefficients of a multicomponent, chemically reacting, imperfect plasma. Therefore, the electron properties of transfer of an imperfect completely, partially and weakly ionized plasma are considered in the given section on the basis of model concepts and the transfer properties determined by heavy particles are considered in the next section.

The chemical model, according to which a plasma consists of a specific number of components: free electrons, ions, atoms, molecules and so on, is usually employed to calculate the transfer properties of an imperfect plasma. Let us analyze the influence of different effects on the electron transfer coefficients of a partially ionized plasma with strong coulomb interaction--electric conductivity and thermal EMF, using Frost formulas (2.97) which should be regarded as model with respect to an imperfect plasma. The collision frequency of electrons and heavy scatterers is

$$\nu_e = v \sum_n Q_{en}^{(1)}(v)\, n_n + \sum_i \gamma_{\sigma,\alpha}^{-1}(z_i)\, n_i \frac{2\pi}{v^3} \left(\frac{z_i e^2}{m_e}\right)^2 L(\Gamma). \tag{2.67}$$

Here $L(\Gamma)$ is the coulomb logarithm that describes collective effects in a plasma and $\gamma_{\sigma,\alpha}$ are the correcting factors (section 2.6). Comparison of data on electric conductivity, calculated with respect to (2.97) and (2.67) and on the adopted version of composition (section 1.7) ($L(\Gamma) = \ln[1 + (3 \times \sqrt{2}/\Gamma)^2]$) to the experimental results of [61-63] shows an excess of theory over experiment. It is difficult to achieve agreement by varying $L(\Gamma)$ but since the given procedure has no definite physical meaning, main attention should be devoted to the contribution of non-coulomb effects (to electron scattering on excited atoms, to inelastic electron collisions, to "the finite dimensions" of ions and so on) to collision frequency. Manifestation of non-coulomb effects distinguishes electron transfer in an imperfect plasma and is unrelated directly to the long-acting nature of coulomb forces.

The partially ionized imperfect plasma has a temperature of 1-3 eV in the experiments of [61-63]. If the material of the plasma has low ionization potential (for example, an alkali metal), then a significant fraction of the neutral atoms in the plasma is excited. The result of measuring the electron scattering cross-section on a sodium atom in the first excited state (3 p) is known for electron energy of 4 eV [64]: a cross-section of e - 3 s is less than that of 3 - 3 p by a factor of 2-3. Such a considerable difference indicates the need to modify expression (2.67) for a partially ionized plasma of alkali metals:

$$\nu_e \sim v \frac{n_n}{Q_n} \sum_i g_i Q_{ei}^{(1)} \exp(-E_i/kT). \tag{2.68}$$

Here Q_n is the statsum of a neutral atom and $Q_{ei}^{(1)}$ is the transport cross-section of elastic electron scattering on an atom in the i-th excited state, the energy and statistical weight of which is E_i, g_i. The fraction of excited atoms is negligible and their effect on the length of the free path of electrons should be

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disregarded in a partially ionized plasma of inert gases at temperatures of 1-3 eV. Let us investigate in more detail the effect of electron scattering by excited atoms on the collision frequency on the example of a partially ionized cesium and lithium plasma. Elastic scattering of electrons in the 6 s, 6 p and 5 d states of the cesium atom (the energy of these states is 0, 1.4 and 1.8 eV, respectively) and scattering in 2 s and 2 p states of lithium (energy of 0 and 1.8 eV) for a lithium plasma should be taken into account in the temperature range of 1-3 eV when calculating the electron transfer properties for a partially ionized cesium plasma. The electron scattering cross sections on excited lithium and cesium atoms were calculated in Born and Glauber approximations in [65]. The basis for using the indicated approximations is good agreement of calculated and experimental data on elastic scattering of electrons with energy > 1 eV on lithium, sodium and potassium atoms in the ground state [66]. The exchange interaction of impinging and valency electrons and the orbital polarization of the latter are disregarded in Glauber approximation. Estimates show that these simplifications are valid for E > 1 eV. Assuming that the atom of an alkali metal consists of a base with charge +1e and a valency electron, let us write the electron scattering amplitude on the atom ($-F_{nlm}$) in Glauber approximation (in atomic units):

$$\left.\begin{aligned} F_{nlm} &= \frac{ik}{2\pi}\int u_{nlm}(\mathbf{r})\,\Gamma(\mathbf{b},\mathbf{r})\,u_{nlm}(\mathbf{r})\,e^{i\mathbf{q}\mathbf{b}}\,d^2b\,d\mathbf{r};\\ \Gamma(\mathbf{b},\mathbf{r}) &= 1-\exp[i\chi(\mathbf{b},\mathbf{s})];\\ \chi(\mathbf{b},\mathbf{s}) &= -\frac{1}{v}\int_{-\infty}^{\infty} V(\mathbf{b},\mathbf{r},\xi)\,d\xi;\\ V &= \frac{1}{|\mathbf{r}-\mathbf{r}'|}-\frac{1}{r'}. \end{aligned}\right| \qquad (2.69)$$

u_{nlm} is the wave function of the valency electron, v and k are the velocity and wave vector of the scattered electron, $q = 2k\sin\theta/2$, θ is the scattering angle and n, l and m are the quantum numbers. Expression (2.69) is written in a coordinate system whose origin is located in the nucleus of the atom, z k, and r, r' are the radius vectors of the atomic and scattered electrons. Let us expand them: $r = s + z$ and $r' = b + \xi$, where s and b are projections of r and r' onto the xy-plane. The wave functions of the valency electron calculated by the Hartree-Fock method (see section 1.4) were used when calculating the e cross-sections of lithium and cesium. If the square of the radial part of the wave function is represented in the form

$$R_{nl}^2 = \sum_{i=1}^{\bar{m}} a_i^{nl} r^{c_i+2l+1} e^{-b_i^{nl} r},$$

then equalities (2.69) can be simplified since for F_{n00} we have

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$$
\left.
\begin{aligned}
F_{n00} &= \frac{1}{4}\sum_{l=1}^{\tilde{m}} a_l^{n0}(-1)^{c_l+2l-1}\frac{\partial^{c_l-1}\tilde{J}_0(q,\lambda)}{\partial\lambda^{c_l-1}}\Big|_{\lambda=b_l^{n0}};\\
\tilde{J}_0(q,\lambda) &= 64\pi ik\int_0^{\pi/2} d\theta\,\frac{\cos\theta}{\sin\theta}\,\frac{\lambda(\lambda^2-2q^2\operatorname{ctg}^2\theta)}{(\lambda^2+q^2\operatorname{ctg}^2\theta)^4}\times\\
&\times\left[1-\frac{1}{2\pi}\left(\frac{1}{\cos\theta}\right)^{2in}\int_0^{2\pi} d\Phi\,(1-\sin 2\theta\cos\Phi)^{in}\right].
\end{aligned}
\right\}
\qquad (2.70)
$$

Here c_i is natural numbers, $n = 1/v$ and F_{nlm} for $l, m \neq 0$ are represented similar to (2.70) [65]. The total and transport elastic scattering cross-sections are calculated in the standard manner by the scattering amplitude [48]. The results of calculating the total Q_{nlm} and transport Q^1_{nlm} elastic scattering cross-sections of electrons by Born and Glauber methods in the energy range of 1-10 eV on cesium and lithium atoms in the ground and excited states are illustrated in Figures 2.12 and 2.13, from which it is obvious that the elastic scattering cross-sections in the ground state is one-half to one-third those in the excited states. The isotherms of electric conductivity (Figures 2.14 and 2.15) were calculated with regard to this effect [65].

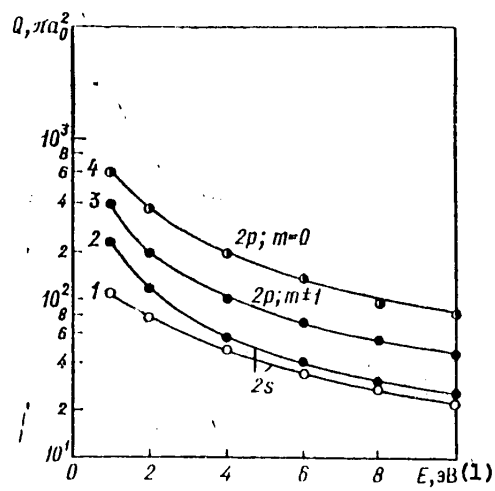

Figure 2.12. Elastic Scattering Cross-Sections of Electrons in 2 s and 2 p States of Lithium Atom: 1 and 4--Born method; 2 and 3--Glauber method

Key:
1. Electron volts

The next non-coulomb effect which influences the transfer coefficients of the plasma is the difference of the electron and ion interaction potential (v_{ei}) at

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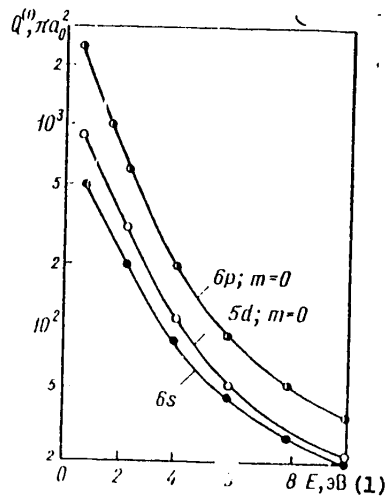

Figure 2.13. Elastic Scattering Cross-Sections of Electrons in 6s, 6p and 5d States of Cesium Atoms (the Born method)

Key:
1. Electron volts

short distances from the ion nucleus from the law $z_i e^2/r$. Thus, the typical dimensions of ion cores of heavy cesium and xenon ions comprise approximately 5 a_0, which is comparable to the shielding radius of charges in a plasma. The effect of a finite dimension of an ion on the electron collision frequency was taken into account in [67] by the quantum defect method [68], which is based on the analogy of motion of a slow free electron and a weakly bound electron in the field of an ion core. The radial part of the wave function of a free electron with pulse k and orbital moment l has asymptotic form ($r \to \infty$) upon scattering on an ion with charge z_{ie} [48]:

$$R_{kl} \sim \frac{1}{r} \sin\left[kr + \frac{z_i}{k} \ln kr - \frac{\pi l}{2} + \arg \Gamma\left(1 + l - \frac{i z_i}{k}\right) + \gamma_l\right]. \qquad (2.71)$$

where $\gamma_l = \lim_{k \to 0} \pi \Delta(n \to \infty) k^{2l+1}$.

Here the quantum defect $\Delta = n - n'$, n is the main quantum number of state, the binding energy of the electron in which is equal to $(2n'^2)^{-1}$. Correction to the transport coulomb cross-section, determined by the quantum defect method, comprises [67] approximately 25 $\mathring{A}^2$ for cesium and xenon ions at electron energies of 1.5-2 eV. Restrictions of the quantum defect method include the following: relation (2.71) is valid at $E \to 0$ and the potential v_{ei} is coulomb far from the ion nucleus. The effect of a finite dimension of a cesium ion was considered for $Q^{(1)}$ in [69] by the simplified model: Born approximation was used, the potential v_{ei} at short distances from the ion nucleus was approximated by the exponential potential and in this case $\Delta Q^{(1)} \sim 50$ $\mathring{A}^2$ was found at $e \sim 2$ eV.

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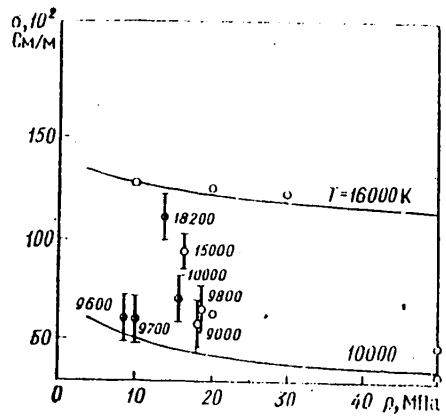

Figure 2.14. Comparison of Calculated and Measured Values of Electric Conductivity of Cesium Plasma Along Isotherms (experimental points are data of [61])

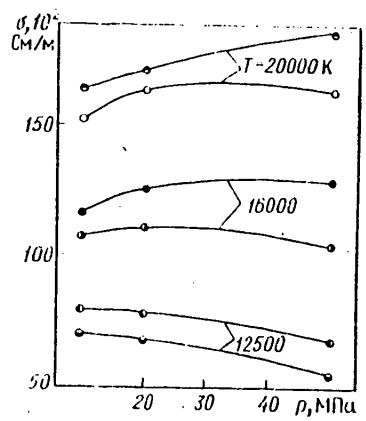

Figure 2.15. Isotherms of Electric Conductivity of Lithium Plasma Without Regard (upper curve) and With Regard to Scattering on Excited Atoms

Description of a two-particle electron scattering process on an ion, free of the deficiencies of the quantum defect and model method [69], is possible on the basis of the phase function method [70] which permits accurate calculation of the particle scattering phase during its motion in a given potential. Let us write the equation for the scattering phase $\delta_l(r)$:

$$\frac{d}{dr}\delta_l(r) = -\frac{1}{k}v_{el}(r)[\cos\delta_l(r)\,j_l(kr) - \sin\delta_l(r)\,n_l(kr)]^2; \quad \delta_l(0) = 0.$$

In this equation $j_l(x)$ and $n_l(x)$ are the known Riccati-Bessel functions [70] and the asymptotic expression for the radial part of the wave function is determined by the scattering phase

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The use of the phase function method requires that the short-range part $v_{ei}(r)$ be given accurately and the long-range part of $v_{ei}(r)$, according to model concepts, should be selected in the form of the Debye potential. Consideration of the "finite" dimension of ions leads to a reduction of the calculated values of electron transfer coefficients and is manifested more strongly, the greater the degree of ionization and imperfection of the plasma.

Let us discuss the effect of inelastic electron collisions such as excitation and ionization of atoms by an electron impact on the collision frequency of electrons with heavy scatterers. Data on the excitation and ionization cross-sections of alkali atoms by electron impact, presented in the literature, permit one to conclude that the excitation cross-sections at corresponding energies of the impinging electron are comparable in value to elastic cross-sections of electron scattering on atoms in the ground state [64]. Thus, because of the high population of excited levels of neutral atoms in a partially ionized imperfect plasma of alkali metals under conditions of [61-63], the indicated inelastic process appreciably increases the electron collision frequency and accordingly reduces the transfer coefficients. Variation of collision frequencies, based on physical concepts [71], will be described by addition of a term of the following form to ν_e

$$\nu_e \sim v \sum_a Q_{ea}(v) n_a, \tag{2.72}$$

where Q_{ea} is the excitation cross-section of a neutral of variety a (the atom in different excited states belongs to different varieties here) and n_a is the concentration of neutrals of variety a.

The next effect of significance in a fully or partially ionized perfect plasma is the correlation of particles on which electron scattering occurs. The contribution of correlation depends on the degree of orderedness of the scatterers. In the limiting case when the scatterers are fully ordered, as occurs in metal, the electron is scattered simultaneously on the entire chain of atoms; therefore (due to interference), the length of the electron path increases sharply. The high electric conductivity of metals both in the solid and molten states is naturally explained by this effect. There is partial order in a dense gas or plasma and interference effects should lead to an increase of the length of electron flight and accordingly to an increase of plasma conductivity. The effects of correlation are taken into account by the Ziman formula for the collision frequency of an electron [78] with other particles

$$\nu_e \sim v n_i \frac{1}{4k} \int_0^{2k_{max}} Q^{(1)}(k)\, a(k)\, k^3\, dk, \tag{2.73}$$

where the structural factor a(k) is determined by the equilibrium correlation function of ions $g_{ii}(r)$ [72]:

$$a(k) = 1 + 4\pi n \int \frac{\sin kr}{kr} [g_{ii}(r) - 1]\, r^2\, dr. \tag{2.74}$$

Calculation of the effect of correlation on the coulomb logarithm with nonlinear Debye correlation function [72] $g_{ii}(r) = \exp\left[-\frac{\beta e^2}{r}\exp(\varkappa r)\right]$ yields a correction to the coulomb logarithm (see Figure 2.16).

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When calculating the electron transfer coefficients of a partially ionized imperfect plasma, determination of composition [73], different from the traditional composition (section 1.7), is used. The composition of the plasma used in [73] to calculate the electric conductivity of a plasma of inert gases, is based on specific division of the energy spectrum of electrons in the plasma. The energy spectrum [73] was found on the basis of the classical expression for the density of electron states calculated in the "close neighbor" approximation, when electron interaction with its surroundings is replaced by interaction with the nearest ion, while interaction with remaining particles, as weaker interaction, is taken into account by methods of perturbation theory. The "atoms"--electron-ion states with high negative energy (kT) are determined in the electron energy spectrum, and electron scattering on them is considered as that on a single particle. The excited atoms (VA) are states with energy from -kT to e^2/r_{sr}; r_{sr} is the average distance between plasma particles, quasi-bound states (KS) are formations with energy from $-e^2/r_{sr}$ to zero and collision complexes (SK) are electron-ion pairs with positive energy. Scattering of free electrons excited atoms, quasi-bound states and collision complexes is equivalent to scattering on a coulomb center. Besides free electrons, charge transfer in a partially ionized plasma is accomplished, according to [73], by electrons bound in quasi-bound states and collision complexes by means of the collision mechanism. Collision transfer occurs due to the fact that the motion of electrons in the quasi-bound states and collision complexes, which accordingly occurs along segments of elliptical and hyperbolic orbits, is infinite since the nearest ion is replaced during electron motion. In a weakly imperfect plasma the main contribution to charge transfer is made by free electrons and in an imperfect plasma by electrons belonging to quasi-bound states and collision complexes. The disadvantages of the described approach should include some arbitrariness in selection of the mechanisms of electron scattering on excited atoms, quasi-bound states and collision complexes; therefore, agreement of the model to experimental data in electron conductivity of a weakly imperfect and partially ionized imperfect plasma of different materials [73] is conditional.

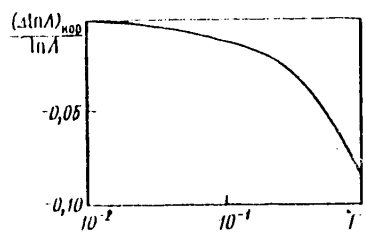

Figure 2.16. Effect of Ion Correlation on Coulomb Component of Electric Conductivity of Plasma

The concept of the composition of a partially ionized imperfect plasma, as can be clearly seen from the previous discussion, is not the only one. For electron transfer in a partially ionized plasma of inert gases in the range of parameters considered in the given section, electron scattering on excited atoms and inelastic collisions with plasma particles are insignificant and consequently in this case a model that does not use the concept of plasma composition can be formulated.

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Let us describe one of the possible single-electron models of this type, based on concepts of quasi-classical theory of a continual course [74]. Let us assume that a plasma consists of electrons and ions. According to the continual course theory (TKP), the electron moves in "authorized" paths in a random, effective potential V(r) created by fluctuations of ion density; the fluctuations of V(r) are not dependent on the presence of an electron at a given point $V(r) = \sum_{\alpha=1}^{N} v_{ei}(\mathbf{r} - \mathbf{R}_\alpha)$.

Here R_α is the radius vector of the ion and summation is carried out for all ions, and v_{ei} is the electron-ion interaction potential.

According to TKP, the authorized paths satisfy the condition V < E (E is the electron energy remaining during motion of the constant). For any energy E, the entire space is divided into authorized and forbidden, the fraction of the authorized space (we denote it by c(E)) is equal to $\int_{-\infty}^{E} F(V)\,dV$. F(V) is the potential distribution function and by definition [74]:

$$F(V) = \frac{1}{\Omega^N}\int d\mathbf{R}_1 \ldots d\mathbf{R}_N W(\mathbf{R}_1 \ldots \mathbf{R}_N)\,\delta(V - V(\mathbf{r}));$$

W is the probability of a given ion configuration in a random potential and Ω is the volume of the system. F(V) has a Gaussian form provided that in the sphere of influence of potential v_{ei} there are sufficiently many ions and W = 1:

$$F(V) = \pi^{-1/2}\sigma_v^{-1}\exp\left(-V^2/\sigma_V^2\right); \quad \sigma_V^2 = 2n_i\int v_{ei}^2(r)\,d\mathbf{r}.$$

The main contribution to F(V) is made by ion fluctuations in a sphere with effective radius r_0; therefore, the condition that the electron moves in V(r) like a classical particle is the inequality $\sigma_V \sim \frac{e^2}{r_0} \times n^{1/2} \gg \frac{\hbar^2}{m_e r_0^2}$, where $1 = n_i r_0^3$. In the left side of the inequality is the depth of the typical potential hole and in the right side is the energy of the ground state of the electron with respect to the bottom of the hole. It is qualitatively clear that there is some energy E_c, beginning with which at least one authorized path penetrates the entire system of scatterers, i.e., electrons with $E > E_c$ contribute to electric conductivity and those with $E < E_c$ are localized. Determination of E_c and $c(E_c)$ in the given random potential is one of the purposes of TKP. Another important value is the percolation probability P(E), determined as the conditional probability that the point belongs to an unrestricted path if it is in an authorized space. At $E < E_c$, P(E) = 0 and P(E) rapidly approaches unity at $E > E_c$; therefore, it is usually sufficient to assume that $P(E) = \theta(E - E_c)$. It was established in [75] that $c(E_c) = 0.17$ (i.e., $E_c = -0.68\,\sigma_V$) for F(V) in Gaussian form and is not dependent on the form of $v_{ei}(r)$ and it is necessary only that sufficiently many ions be located in the effective sphere of a two-particle potential.

Let us determine the electric conductivity of the plasma, following simple concepts:

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$$\sigma = \frac{2}{3}\frac{e}{m_e}\frac{1}{kT}\exp(\beta\mu_e)\int_{E_c}^{\infty}\tau(E)\rho(E)\exp(-E/kT)\,EdE. \qquad (2.75)$$

Here $\rho(E)$ is single-electron density of states, $\tau(E)$ is the time of the free path equal to l/v (v is electron velocity) [74]

$$\tau(E) = \frac{1}{c(E)}\int_{-\infty}^{E} dV\frac{2}{m_e}(E-V)^{-1/2}\frac{l\lambda}{l+\lambda};$$

l is the ordinary gas-kinetic length of the path--$1/n_i Q_{ei}^{(1)}(E - V)$, $Q_{ei}^{(1)}$ can be calculated by the phase function method and one can easily take into account the effect of the finite dimensions of ions, λ describes scattering from the edges of authorized paths, $\lambda \to \infty$ when $E \to \infty$. The analysis $\lambda(E)$: $\lambda \sim r_0 c(E)\,[1 - c(E)]^{-1}$ was made in [74]. Under the conditions considered in the given section, $l \sim \lambda$ at $E < 0$.

The single-electron density of states $\rho(E)$ is determined in quasi-classical approximation in the following manner [74]:

$$\rho(E) = \frac{(2m)^{3/2}}{2\pi^2\hbar^3}\frac{1}{\Omega^N}\int[E - V(r)]^{1/2}W(\mathbf{R}_1\ \ldots\ \mathbf{R}_N)\,d\mathbf{R}_1\ \ldots\ d\mathbf{R}_N.$$

The density of states was calculated provided that $W = 1$ and $n \gg \sqrt{n} \gg 1$ [75]:

$$\rho(E) = \left(\frac{2}{\pi^3}\right)^{1/2}\left(\frac{m_e}{2\pi\hbar^2}\right)^{3/2}\sigma_v^{1/2}\exp(-E/2\sigma_v^2)\,D_{-3/2}\left(\frac{\sqrt{2}E}{\sigma_v}\right),$$

where $D_{-3/2}(x)$ is the function of a parabolic cylinder. The electric conductivity of a non-Debye completely ionized plasma was calculated in [76] by a model similar to (2.75). In this case E_c in (2.75) was assumed equal to zero and the correction to the length of the free path related to reflection of electrons from the edges of authorized zones was not taken into account; nevertheless the results of [76] are in satisfactory agreement with experimental results in the range $\Gamma < 0.3$.

We note that the Poisson distribution function for $F(V)$ and the corresponding variables $\rho(E)$ and E_c should be used in some cases (when the condition $n \gg 1$ is violated) for an imperfect plasma instead of the Gaussian distribution function of potential and the density of states and the value E_c corresponding to it.

In concluding the given section, let us briefly discuss the existing concepts of electron transfer in vapors of metals at subcritical pressures and near-critical densities. The indicated range, let us call it the transition range, is characterized by qualitative variation of the electron properties of metals upon variation of density near the critical range. Experimental investigations of the transition zone were conducted on mercury [77-80] and cesium [7, 81-83]. It is shown that variation of electron properties and metal-dielectric transition occur rather smoothly in mercury while a Mott type transition probably occurs in cesium [84]. The transition zone is roughly divided by density into two zones similar in properties to a metal and to a plasma--the gaseous zone. Model determination of the

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interface of these zones in cesium vapors was conducted in [84] and in this case the experimental data of [81-83] were used. The substance is a dense plasma in the gaseous zone. The use of precise approaches to describe its properties is difficult since interaction between the plasma components is strong. Minimum values of conductivity of metal vapors on the subcritical isobar are apparently achieved in the gaseous zone. The models [85-87] are essentially oriented toward a part of the gaseous zone sufficiently remote from the critical point ($0.1\rho_{kr} < \rho < 0.4\rho_{kr}$) with low degree of ionization, where neutral interaction has the main effect on the thermodynamic properties of the plasma. Interaction of charged particles with neutral particles and between each other under these conditions without affecting the thermodynamic characteristics of the medium, significantly shifts the ionization equilibrium, i.e., it is reflected in the properties of the electron transfer in the plasma. Separation of electrons into free electrons, i.e., those participating in the transport mechanism of charge transfer and localized electrons, is carried out by different methods in the models of [85-87]. In [85] the localized electrons are described by "fluctuations"--formations occurring due to localization of electrons on fluctuations of density; localization is interpreted in the sense of (2.75) in [87]. Selection between the indicated approaches cannot be made due to the paucity of experimental data.

2.5. Effective Transfer Coefficients of a Multicomponent Imperfect Plasma

When designing devices in which the working substance is in the plasma state, one must solve the problem of heat shielding of the surfaces touching the plasma. The thermal fluxes generated by the plasma are determined by the profiles of component concentrations in the plasma space. Consequently, when investigating heat transfer of a multicomponent plasma with restricting surfaces in a gas-phase nuclear reactor, in the channels of MHD generators and behind the shock wave trailing after a spacecraft during its motion at hypersonic velocity in the atmosphere of a planet, correct consideration of multicomponent diffusion is important. In the indicated cases the plasma should be considered as a chemically equilibrium and quasi-neutral plasma, i.e., one should use LTR approximation and turn from investigation of the diffusion of components to investigation of the diffusion of chemical elements (see (2.8)). Diffusive heat transfer described by effective coefficients of thermal conductivity in (2.7) has a significant effect on the convective thermal flux and the gas-dynamic characteristics of plasma flow. The coefficients of transport thermal conductivity (λ') and shear viscosity (η) are also required to close the system of gas-dynamic equations (2.1)-(2.5).

The definition and general propertis of effective transfer coefficients are discussed in the given section. A model is suggested for calculation of effective transfer coefficients, shear viscosity coefficients and transport thermal conductivity of an imperfect plasma, by means of which the tables of values of the transfer coefficients of a plasma of alkali metals, uranium and their mixtures were calculated over a broad range of parameters (see Chapter 5).

Formal determination of effective transfer coefficients of imperfect media by phenomenological coefficients and investigation from general properties are possible by means of linear thermodynamics of irreversible processe by gradients [88]. Effective transfer coefficients can also be determined by time correlation functions on the basis of one of the versions of the theory of nonequilibrium

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processes discussed in section 2.3. Let us use the first approach as the most illustrative and one leading most rapidly to the goal. Let us formulate the expression for production of entropy ($\dot{\sigma}$) of a multicomponent imperfect plasma in LTR approximation, i.e., with respect to chemical elements [2]

$$\dot{\sigma} = -\frac{1}{T^2}\mathbf{q}\nabla T - \frac{1}{T}\sum_{a=1}^{N_a}\mathbf{i}_a\left(T\nabla\frac{\mu_a}{T} - z_a\mathbf{E}^*\right) - \frac{1}{T}\Pi_{ij}\frac{\partial v_j}{\partial x_i} \tag{2.76}$$

According to the second principle of thermodynamics $\dot{\sigma} \geq 0$. Expression (2.76) was found by the standard method [88, 2] when using the phenomenological laws of conservation in the form of (2.1)-(2.5), $\mu_a = (\partial u/\partial c_a)_{p,s,c_b\neq c_a}$ is the specific chemical potential of the element a, $u = u(p, s, \{c_a\}, z)$. For transformation of (2.76) to a more convenient form, let us substitute the Gibbs-Dyugem relation $T\nabla(\mu_a/T) = \nabla_T\mu_a - (h_a/T)\nabla T$ and the symmetrical tensor of viscous stresses in the form of (2.9) into the given expression and let us use the condition $\sum_{a=1}^{N_a} i_a = 0$, then

$$\dot{\sigma} = -\frac{1}{T^2}\mathbf{q}'\nabla T - \frac{1}{T}\sum_{a=1}^{N_a-1}\mathbf{i}_a\left[\nabla_T(\mu_a - \mu_e) - \frac{e}{m_e}\mathbf{E}^*\right] - \frac{1}{T}(\Pi\nabla\mathbf{v} + \Pi':\mathbf{T}). \tag{2.77}$$

The chemical element "electrons" whose charge per unit mass is $z_e = -e/m_e$ (the remaining values of z_a are equal to zero) is determined in (2.77);

$$\mathbf{T} = 1/2(\partial v_i/\partial x_j + \partial v_j/\partial x_i) - 1/3\delta_{ij}\nabla\mathbf{v};\quad \mathbf{q}' = \mathbf{q} - \Sigma h_a\mathbf{i}_a;$$

h_a is the specific enthalpy of the chemical element. Let us rewrite (2.77): $\sigma = \sum_i j_i X_i \geq 0$, here j_i is fluxes and X_i is thermodynamic forces. The fluxes are linear functions of thermodynamic forces: $j_i = \alpha_{ik}X_k$ and thus:

$$\dot{\sigma} = \sum_{i,k}\alpha_{ik}X_kX_i, \tag{2.78}$$

α_{ik} is the phenomenological transfer coefficients of (2.78). The fluxes and thermodynamic forces in (2.77) are linearly independent of each other and consequently σ is a positively determined quadratic form that satisfies the Silverster criterion, according to which all the major minors of the matrix compiled from phenomenological coefficients are negative. Another property of α_{ik} is the symmetrical or antisymmetrical nature with respect to subscripts i and k in an isotropic medium--Onsager reciprocity relations [89]. The symmetrical nature of α_{ik} occurs in the case if the parameters of state denoted by subscripts i and k are at the same time even or odd functions of the velocities of all particles; the antisymmetrical nature occurs when parameters j_i and X_k have different evenness [89]. The

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reciprocity relations are also valid for linearly dependent fluxes and thermodynamic forces [88].

The phenomenological transfer equations $j_i = \alpha_{ik}x_k$ generally link the fluxes and thermodynamic forces of different tensor dimensionality. However, if j_i and X_k have different tensor dimensionality, the Descartes components j_i and X_k are transformed differently during transformations of rotation and reflection of the coordinate system. It may be that the fluxes will not be dependent on all the thermodynamic forces due to the properties of symmetry of the considered system. The given statement is called the Curie principle [88]. The values of j_i and X_k of different tensor dimensionality are unrelated to each other in an isotropic medium. The result of the isotropic nature of the medium is that the values of α_{ik} are scalar; moreover, production of entropy in the form of [2.77] can be divided into three terms--scalar σ_0, vector σ_1 and tensor σ_2, each of which is negative. In an isotropic medium for mass flow of a chemical element and q', we have:

$$\begin{aligned} \mathbf{q}' &= -\alpha_{QQ}\frac{\nabla T}{T^2} - \frac{1}{T}\sum_{a=1}^{N_a-1}\alpha_{Qa}\left[\nabla T(\mu_a-\mu_e) - \frac{e}{m_e}\mathbf{E}^*\right], \\ \mathbf{i}_a &= -\alpha_{aQ}\frac{\nabla T}{T^2} - \frac{1}{T}\sum_{b=1}^{N_a-1}\alpha_{ab}\left[\nabla T(\mu_b-\mu_e) - \frac{e}{m_e}\mathbf{E}^*\right]. \end{aligned} \tag{2.79}$$

It is obvious from the Onsager reciprocity relations and the positive nature of the vector term in production of entropy that $\alpha_{aQ}=\alpha_{Qa}$, $\alpha_{ab}=\alpha_{ba}$, $\alpha_{QQ}>0$ and $\alpha_{aa} > 0$; since $\alpha_{QQ}/T^2=\lambda$ (see (2.11)), then $\lambda > 0$ and the positive definition of shear and volumetric viscosities follows from σ_0, $\sigma_2 > 0$.

Let us determine the effective diffusion coefficients and thermal conductivity of a multicomponent imperfect plasma. Provided that the pressure in the plasma is constant, let us express $\Delta_T(\mu_a - \mu_n)$ by the gradients c_a (let us disregard terms of approximately $\nabla\tilde{z}$) and, having substituted the derived expression into (2.79), we will have $\left([\partial(\mu_a-\mu_e)/\partial c_b]_{p,T,c_{b\neq a}} \equiv \mu_b^a\right)$:

$$\left.\begin{aligned} &\mathbf{i}_a = \sum_{b=1}^{N_a-1} D_{ab}\nabla c_b + D_a^T\nabla T - D_a^E\mathbf{E}^*; \\ &D_{ab} = -\frac{1}{T}\sum_{f=1}^{N_a-1}\alpha_{af}\mu_b^f; \qquad D_a^T = -\frac{\alpha_{aQ}}{T^2}, \\ &D_a^E = -\frac{e}{m_eT}\sum_{b=1}^{N_a-1}\alpha_{ab}. \end{aligned}\right\} \tag{2.80}$$

In similar fashion for thermal flux:

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$$\left.\begin{aligned}
q &= -(\lambda - \lambda_T)\nabla T + \sum_{a=1}^{N_a-1} \lambda_a \nabla c_a - \lambda_E \mathbf{E}^*,\\
\lambda_T &= \sum_{a=1}^{N_a-1} (h_a - h_e) D_a^T,\\
\lambda_a &= \sum_{b=1}^{N_a-1} \left[-\frac{\alpha_{Qb}}{T} \mu_a^b - (h_b - h_e) D_{ba} \right],\\
\lambda_E &= \frac{e}{T m_e} \sum_{a=1}^{N_a-1} [-\alpha_{Qa} + (h_a - h_e) D_a^E].
\end{aligned}\right\} \qquad (2.81)$$

Formulas (2.80) and (2.81) are convenient when investigating the properties of effective transfer coefficients.

Let us consider the consequence of the positive nature of production of entropy for a two-component mixture and let us introduce the notations $-\lambda_a' = -(1/T)\alpha_{Qa}\mu_a^a$, $\lambda_a^* = -(h_a - h_b)D_{aa}$, $\lambda_a = \lambda_a' + \lambda_a^*$, then $q' = -\lambda\nabla T + \lambda_a'\nabla c_a$ (the terms approximately E* are omitted for simplicity). After substituting q' and i_a into the expression for (2.77) and after simple transformations using the condition of stability with respect to diffusion [88]: $\mu_a^a > 0$, we find $\lambda D_{aa} > \lambda_a' D_a^T$. It obviously follows from (2.80) and (2.81) that $\lambda_a' D_a^T = -\tilde{\lambda}_T D_{aa}$; therefore,

$$(\tilde{\lambda} - \tilde{\lambda}_T) D_{aa} > \lambda_a D_a^T. \qquad (2.82)$$

One can also ascertain the property of having a fixed sign of the effective diffusion coefficient: $-D_{aa} > 0$; D_a^T has no specific value. The limiting relations $D_a^T(T, p, c_a) = 0) = D_a^T(T, p, c_a = 1) = 0$ are valid for the effective thermodiffusion coefficient; the law of the approach of D_a^T to zero at $c_a \to 0, 1$ depends on the composition of the mixture, temperature and pressure.

In the case of a mixture consisting of three or more chemical elements, clear relations between the effect of transfer coefficients from the condition $\sigma_1 > 0$ cannot be found in general form. For example, for a three-element plasma a symmetrical positively specific matrix with the elements $A_{ij}(\lambda_a' \equiv \sum_b D_b^T \mu_a^b T)$ corresponds to the vector term of production of entropy in the form of (2.77):

$$\left.\begin{aligned}
&A_{11} = \frac{\lambda}{T^2}; \quad A_{22} = \frac{D_{aa}}{T}\mu_a^a + \frac{D_{ba}}{T}\mu_a^b; \quad A_{33} = \frac{D_{bb}}{T}\mu_b^b +\\
&+ \frac{D_{ab}}{T}\mu_b^a; \quad A_{12} = \frac{D_a^T}{T}\mu_a^a + \frac{D_b^T}{T}\mu_a^b; \quad A_{13} = \frac{D_a^T}{T}\mu_b^a + \frac{D_b^T}{T}\mu_b^b;\\
&A_{23} = \frac{1}{2}\left(\frac{D_{ab}}{T}\mu_a^a + \frac{D_{aa}}{T}\mu_b^a + \frac{D_{bb}}{T}\mu_a^b + \frac{D_{ba}}{T}\mu_b^b\right).
\end{aligned}\right\} \qquad (2.83)$$

Calculating the determinant or the major minors of matrix (2.83) and the thermodynamics derivatives μ_a^b in some approximation, one can find the relations in the form of inequalities between the effective diffusion coefficients and thermal conductivity--λ. Investigation of a matrix of type (2.83), corresponding to σ_1

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in the form of (2.76), and of the relationships between the effective diffusion and thermal conductivity coefficients is apparently infeasible since the latter are expressed by D_{ab}, D_a^T, D_a^E, H_a and μ_a^a (compared (2.81) and (2.80)).

The Onsager reciprocity relations for phenomenological transfer coefficients also place specific restrictions on the effective diffusion coefficients. The matrices of phenomenological coefficients $\alpha_{ab} - \alpha$, $\mu_b^a - \mu$ and $D_{ab} - D$ are obviously related to each other (see (2.82)): $D = -\alpha\mu$, $\alpha = -D\mu^{-1}$; since $\alpha = \tilde{\alpha}$, then

$$D\mu^{-1} = \mu^{-1}\tilde{D}. \tag{2.84}$$

Calculating the thermodynamic derivatives in the matrix μ and setting the corresponding elements of the left and right sides of (2.84) equal to each other, one can find the relations between the effective diffusion coefficients in the form of equalities.

The thermodynamics of irreversible processes, linear in gradients, does not yield a formula for calculation of transfer coefficients since it is phenomenological theory. The theory of nonequilibrium processes (section 2.3) links the transfer coefficients to the corresponding correlation functions, calculation of which is difficult for an imperfect plasma. Let us formulate the model approach to calculation of the effective transfer coefficients of a multielement imperfect plasma [90], based on the chemical model of a plasma and used in calculation of the tables of values of effective coefficients given in Chapter 5. The mass fluxes of chemical elements are determined by the mass fluxes of the plasma components (see (2.6)). Let us introduce the expressions for the mass flux of a component and also of a convective thermal flux which follow from the expression for production of entropy formulated with respect to components and the Curie principle for an isotropic plasma and which coincide with the expressions used in kinetic theory [36] in approximation of an ideal plasma (p = const):

$$\left.\begin{aligned}
\mathbf{i}_k &= \frac{n^2}{\rho} m_k \sum_{j=1}^{N} D_{kj} m_j \mathbf{d}_j - D_k^T \nabla T \\
\mathbf{q} &= -\lambda' \nabla T - \sum_{k=1}^{N} h_k \mathbf{i}_k - nkT \sum_j \frac{D_j^T}{n_j m_j} \mathbf{d}_j \\
\mathbf{d}_j &= \frac{\rho_j}{p} \nabla_{T,p} \mu_j - \frac{\rho_j}{p}\left(\frac{z_j e}{m_j}\mathbf{E}^* - \sum_{i=1}^{N} \frac{n_i z_i e}{\rho}\mathbf{E}^*\right).
\end{aligned}\right\} \tag{2.85}$$

In (2.85) $n = \Sigma n_i$, h_i is the enthalpy per unit mass of component i, D_{ij} is multicomponent diffusion coefficients (MKD), D_i^T is thermodiffusion coefficients and we subsequently disregard the last term in d_j (approximately ρ^*). The chemical potential per unit mass of plasma component, according to the chemical model, is expressed in the form $\chi\mu_i = (kT/m_i)\ln n_i + \chi_i(T) + \Delta\mu_i$ and the value $_i(T)$ is related to the statsum of component i [89] and $\Delta\mu_i$ is the contribution due to interaction which was discussed in Chapter 1. Let us omit $\Delta\mu_i$ and d_j (the opposite case is considered in [90]), then the equations of chemical equilibrium can be written in

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"ideal" form $x_i = \prod_{l=1}^{N_a+1} x_l^{u_{il}} K_i(T, p)$ and in LTR $x_i = x_i(c_1 \ldots c_{N_a-1}, p, T)$ ($\{x_i\}$ is the set of relative concentrations of basic components, u_{it} is the stochiometric coefficient, $K_i(T, p)$ is the constant of equilibrium of the i-th reaction and $x_i = n_i/n$); the first term in d_j is equal to ∇x_j. Let us express ∇x_j by ∇c_a and ∇T, using the equations of chemical equilibrium in ideal form and the function $x_t = x_t(p, T, \{c_a\})$, and then let us substitute ∇x_j into d_j, d_j into i_k and q (2.85) into (2.6) and q, after which, having grouped the terms with identical gradients, we find the effective coefficients of thermal conductivity for the convective thermal flux and diffusion for the mass flux of chemical element (2.7) and (2.8) (compare (2.81) [3, 4]:

$$
\left.
\begin{aligned}
\lambda^T &= \sum_{i,j=1}^{N} h_i \frac{n^2}{\rho} m_j D_{ij} x_j \left[\frac{1}{x_j} \left(\frac{\partial x_j}{\partial T} \right)_{p,\{x_l\}} + \right. \\
&\left. + \sum_{l=1}^{N_a+1} \frac{u_{jl}}{x_l} \left(\frac{\partial x_l}{\partial T} \right)_{p,\{c_a\}} \right] - \sum_{i=1}^{N} \left\{ \frac{h_i D_i^T}{m_i} + kT^2 \frac{D_i^T}{m_i} \times \right. \\
&\left. \times \left[\frac{1}{x_i} \left(\frac{\partial x_i}{\partial T} \right)_{p,\{x_l\}} + x_i \sum_{l=1}^{N_a+1} \frac{u_{il}}{x_l} \left(\frac{\partial x_l}{\partial T} \right)_{p,\{c_a\}} \right] \right\}; \\
\lambda_a &= \sum_{i=1}^{N} \left\{ \left[\frac{n^2}{\rho} h_i \sum_{j=1}^{N} m_j D_{ij} x_j \sum_{l=1}^{N_a+1} \frac{u_{jl}}{x_l} \left(\frac{\partial x_l}{\partial c_a} \right)_{p,T,c_b \neq c_a} \right] - \right. \\
&\left. - \frac{kT^2 D_i^T}{m_i} \sum u_{il} \left(\frac{\partial x_l}{\partial c_a} \right)_{p,T,c_b \neq c_a} \right\}; \\
\lambda^E &= \sum_{i=1}^{N} \left[\left(h_i \frac{n^2}{p\rho} \sum_{j=1}^{N} m_j D_{ij} n_j z_j e \right) - \frac{T D_i^T}{m_i} z_i e \right]; \\
D_{ab} &= \sum_{i,j=1}^{N} m_a u_{ia} \frac{n^2}{\rho} m_j D_{ij} x_j \sum_{l=1}^{N_a+1} \frac{u_{jl}}{x_l} \left(\frac{\partial x_l}{\partial c_b} \right)_{p,T,c_a \neq c_b}; \\
D_a^T &= \sum_{i,j=1}^{N} m_a u_{ia} \left\{ \frac{n^2}{\rho} m_j D_{ij} x_j \left[\frac{1}{x_j} \left(\frac{\partial x_j}{\partial T} \right)_{p,\{x_l\}} + \right. \right. \\
&\left. \left. + \sum_{l=1}^{N_a+1} \frac{u_{jl}}{x_l} \left(\frac{\partial x_l}{\partial T} \right)_{p,\{c_a\}} \right] - \frac{D_i^T}{m_i} \right\}; \\
D_a^E &= \frac{n^2}{p\rho} \sum_{i,j=1}^{N} u_{ia} m_a m_j D_{ij} n_j z_j e.
\end{aligned}
\right\} \qquad (2.86)
$$

It is obvious that the thermal flux q and the effective coefficients of thermal conductivity are dependent on the level of the energy reading since an ambiguity is contained in h_i.

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The "effective transfer coefficients" were repeatedly introduced in the literature to simplify the real multicomponent diffusion and heat transfer. Two methods of taking multicomponent diffusion into account are usually employed. In the first method the fluxes of different ocmponents are expressed by the thermodynamic forces (specifically, the concentration graidents) with proportionality coefficients--multicomponent diffusion ccefficients MKD and in the other method they are expressed by the Stefan-Maxwell method, and on the other hand the concentration gradients are expressed by the fluxes with proportionality coefficients, called resistance coefficients. Discussion of "hydrodynamic approximation" for multicomponent diffusion in the Stefan-Maxwell form is contained in monograph [119]. The Stefan-Maxwell relations have the simplest form in the case when the first approximation is used in expansion of the distribution function by Sonin polynomials--then the resistance coefficients are equal to the reciprocal binary diffusion coefficients and thermodiffusion coefficient is equal to zero. The resistance coefficients are expressed in higher approximations [120] by determinants containing Ω^*_{is} similar to MKD.

Simplification of multicomponent diffusion in mixtures was suggested in [121, 122]. The concept of the diffusion of chemical elements in an equilibrium mixture of two elements--uranium and hydrogen--was introduced in [122]. The effective diffusion coefficients in a "frozen" flow, which were calculated in the boundary layer, were introduced in [123] and approximate expressions for these coefficients were discussed in [123] as a function of the molecular mass and diffusion properties of different components. Multicomponent diffusion in the Stefan-Maxwell form in chemically equilibrium flows was considered in [124, 125] when the gradients of component concentrations are expressed by the gradients of chemical elements using laws of effective masses and the current and external potential difference were assumed equal for the plasma.

A description of multicomponent diffusion [2-4] is used in this paper when the fluxes of basic elements are expressed by the sum of fluxes of the components participating in transfer of a given element and the conditions of local thermodynamic equilibrium are fulfilled at each point that permit the gradients of component concentrations to be expressed by the gradients of the fraction of chemical elements. One must have MKD, D_i^T, h_i, equilibrium composition of a plasma and derivatives of basic components with respect to T and c_a to calculate the effective transfer coefficients with respect to (2.86). The values of T and c_a were determined numerically on a compute- and calculation of the composition and h_i is discussed in Chapter 1. Model calculation of MKD and D_i^T was carried out on the basis of a system of classical kinetic equations, the collision integrals in which consist of I_a^y--the ela-ic collision integral that describes the collision of neutrals with each other and neutrals with charges, I^{nu}--the integral of inelastic collisions and I_e^y--the integral of elastic collisions that characterizes the interaction of charged particles. The integral of charged particle collisions was selected in Boltsman form (I_e^y for a weakly imperfect plasma is considered in section 2.2) and the charge-charge interaction potential was assumed to be Debye. Theoretical substantiation of the indicated selection of the collision integral I_e^y could not be made, but comparison of electric conductivity (which can be expressed by MKD [36]) of an imperfect cesium plasma, calculated by means of the given model kinetic equation, to known experimental results shows satisfactory agreement [65]. The coincidence between the values of the shear viscosity coefficient of an imperfect single-component coulomb system calculated by the molecular dynamics

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method [53] by formula (2.51) and by the values determined from solution of the corresponding model kinetic equation, is also good. Thus, the coulomb effects not taken into account in I_e^y in Boltsman form apparently make a small numerical contribution to the kinetic coefficients of an imperfect plasma. Consequently, the use of a model system of kinetic equations to calculate the transfer coefficients of an imperfect plasma is feasible.

2.6. Method of Calculating the Transfer Coefficients of an Imperfect Plasma. Discussion of the Results of Calculation

The method of calculating the transfer coefficients of an imperfect plasma whose values are presented in the tables is outlined in the given section. The analysis made in sections 2.1-2.5 and discussion of experimental data (section 4.5) substantiate the use of the model system of kinetic equations to calculate the transfer coefficients of an imperfect plasma. The collision integral of KU, which is pointed out above, consists of three terms determined by elastic collisions of charged particles with each other, by elastic collisions of neutral and charged particles and by inelastic collisions of particles. The integral of elastic collisions of charged particles is selected in Boltsman form with Debye interaction potential between particles (see section 2.5). The integral of elastic collisions of neutral particles and neutrals with charges is also selected in Boltsman form. Processes related to chemical transformations of particles--dissociation, ionization and so on, processes of excitation, recharging, transfer of excitation and so on are generally contained in the integral of inelastic collisions. Information about inelastic collisions and collisions of excited particles with each other is very limited; there are rather reliable data on recharging of some atoms on their own ions [91] and electron scattering on excited atoms [65]. Solution of the KU system with inelastic collision integral is cumbersome and moreover the convergence of calculated values of transfer coefficients with an increase of the number of orthogonal polynomials used in their calculation has not been investigated. Thus, all inelastic processes with the exception of recharging of an atom on its own ion was disregarded due to two circumstances: the paucity of information about collisions of excited particles and inelastic collisions and the complexity of expressions for the transfer coefficients with regard to inelastic collisions--in specific calculations of the transfer properties of working substances presented in the tables (5.1-5.7); it was assumed that excited particles interact elastically with each other as do particles in the ground state. The simplifications enumerated above permit one to expand the anisotropic part of the particle distribution function by Sonin polynomials. The dependence of the transfer coefficients on the number of Sonin polynomials used in their calculation was investigated in many papers [71], where it was established that the convergence of multicomponent diffusion and thermodiffusion coefficients by which the effective transfer coefficients of plasma viscosity and also the thermal conductivity of nonionized gases are determined, is very rapid. Since ambiguity in the collision cross-sections of the plasma particles of working substances comprises no less than 50 percent, it is sufficient for practical calculations to use the expressions for multicomponent diffusion and viscosity coefficients in first order by Sonin polynomials and thermodiffusion and thermal conductivity coefficients in second order. Spitzer asymptotics [35] of shear viscosity and transport thermal conductivity coefficients in the range of complete ionization was provided by "correction" of coulomb interaction cross sections. The convergence of transfer coefficients--electric

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conductivity and thermo-EMF that determine electric current is slow for a partially ionized plasma. Therefore, the Frost interpolation method (2.97) was used to calculate conductivity and the thermo-EMF [71].

Let us write the formulas for the transfer coefficients of a plasma used in the calculations. The thermodiffusion coefficients of the components have the form [36]

$$D_k^T = -\frac{8m_k}{5T}\frac{\begin{vmatrix} L_{ij}^{00} & L_{ij}^{01} & 0 \\ L_{ij}^{10} & L_{ij}^{11} & x_i \\ x_j\delta_{jk} & 0 & 0 \end{vmatrix}}{\begin{vmatrix} L_{ij}^{00} & L_{ij}^{01} \\ L_{ij}^{10} & L_{ij}^{11} \end{vmatrix}}. \tag{2.87}$$

In (2.87) the values of L_{ij} are the quadratic matrices of N-th order with elements:

$$\left.\begin{aligned}
&L_{ii}^{00} = 0; \quad L_{ij}^{00} = 0{,}64\frac{T}{p}\left(\frac{x_i x_j}{\mathcal{D}_{ij}} + \sum_{k\neq i}\frac{x_i x_k m_j}{m_i \mathcal{D}_{ik}}\right) \quad i \neq j;\\
&L_{ii}^{01} = 1{,}6\frac{T}{p}\sum_{k\neq i}\frac{x_i x_k m_k\left(1{,}4C_{ik}^{*} - 1\right)}{(m_i + m_k)\mathcal{D}_{ik}};\\
&L_{ij}^{01} = 1{,}6\frac{T}{p}x_i x_j\frac{m_i\left(1{,}4C_{ij}^{*} - 1\right)}{(m_i + m_j)\mathcal{D}_{ij}} \quad i \neq j;\\
&L_{ij}^{10} = \frac{m_j}{m_i}L_{ij}^{01}; \quad L_{ii}^{11} = -\frac{4x_i^2}{\lambda_i} - 0{,}64\frac{T}{p}\times\\
&\times\sum_{k\neq i}\frac{x_i x_k\left(7{,}5m_i^2 + 6{,}25m_k^2 + 3m_k^2 B_{ik}^{*} + 4m_i m_k A_{ik}^{*}\right)}{(m_i + m_k)^2\mathcal{D}_{ik}};\\
&L_{ij}^{11} = 0{,}64\frac{T}{p}\frac{x_i x_j m_i m_j}{(m_i + m_j)^2\mathcal{D}_{ij}}\left[13{,}75 - 3B_{ij}^{*} - 4A_{ij}^{*}\right] \quad i \neq j.
\end{aligned}\right\} \tag{2.88}$$

Here $\mathcal{D}_{ij}$ and λ_i are the binary diffusion coefficient and thermal conductivity of a "pure gas" of particles of the i-th variety

$$\mathcal{D}_{ij} = \frac{3}{16}\frac{k^3T^3}{\mu_{ij}p\Omega_{ij}^{(1,1)}}; \quad \lambda_i = \frac{15}{4}\frac{k}{m_i}\eta_i. \tag{2.89}$$

Ther thermal conductivity of the plasma is determined by expressions (2.88) and (2.89) [36]

$$\lambda' = 4\frac{\begin{vmatrix} L_{ij}^{00} & L_{ij}^{01} & 0 \\ L_{ij}^{10} & L_{ij}^{11} & x_i \\ 0 & x_j & 0 \end{vmatrix}}{\begin{vmatrix} L_{ij}^{00} & L_{ij}^{01} \\ L_{ij}^{10} & L_{ij}^{11} \end{vmatrix}}. \tag{2.90}$$

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The interaction cross sections of charged particles were corrected in (2.90) so that the value of λ' in (2.91) coincide with the Spitzer value λ' in the complete ionization range and with the subsequent form of electron thermal flux [71]:

$$\mathbf{q}^e = -\frac{5}{2}kT\frac{\mathbf{j}_e}{e} - \lambda'\nabla T - T\alpha\left(\mathbf{E}^* - \frac{1}{e}\nabla\eta\mu_e\right).$$

The viscosity of the mixture was calculated by the formula [36]:

$$\eta = \frac{\begin{vmatrix} H_{ij} & x_i \\ x_j & 0 \end{vmatrix}}{|H_{ij}|}; \tag{2.91}$$

$$H_{ii} = \frac{x_i^2}{\eta_i} + \sum_{\substack{k=1\\k\neq i}}^{N} \frac{2x_i x_k}{(m_i + m_k)} \frac{RT}{p\mathcal{D}_{ik}}\left[1 + 0{,}6\frac{m_k}{m_i}A_{ik}^*\right];$$

$$H_{ij} = -\frac{2x_i x_j}{m_i + m_j}\frac{RT}{p\mathcal{D}_{ij}}\left[1 - 0{,}6A_{ij}^*\right] \quad i \neq j.$$

In this case

$$\eta_i = \frac{5}{8}\frac{kT}{\Omega_{ii}^{(2,2)}}. \tag{2.92}$$

The multicomponent diffusion coefficients are determined in the following manner:

$$D_{ij} = \frac{1}{m_j}\sum_{k=1}^{N} x_k m_k \frac{K^{ji} - K^{ii}}{|K_{ij}|};$$

$$K_{ii} = 0; \qquad K_{ij} = \frac{x_i}{\mathcal{D}_{ij}} + \frac{m_j}{m_i}\sum_{k\neq i}\frac{x_k}{\mathcal{D}_{ik}}, \quad i \neq j, \tag{2.93}$$

where K^{ij} and K^{ii} are the expressions:

$$K^{ji} = (-1)^{i+j}\begin{vmatrix} 0 & \dots & K_{1,i-1} & K_{1,i+1} & \dots & K_{1,N} \\ \vdots & & \vdots & \vdots & & \vdots \\ K_{j-1,1} & \dots & K_{j-1,i-1} & K_{j-1,i+1} & \dots & K_{j-1,N} \\ K_{j+1,1} & \dots & K_{j+1,i-1} & K_{j+1,i+1} & \dots & K_{j+1,N} \\ \vdots & & \vdots & \vdots & & \vdots \\ K_{N,1} & \dots & K_{N,i-1} & K_{N,i+1} & \dots & 0 \end{vmatrix}. \tag{2.94}$$

In formulas (2.88) and (2.91), A^*, B^* and C^*:

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$$A^* = \frac{\Omega^{(2,2)*}}{\Omega^{(1,1)*}}; \quad B^* = \frac{5\Omega^{(1,2)*} - 4\Omega^{(1,3)*}}{\Omega^{(1,1)*}}; \quad C^* = \frac{\Omega^{(1,2)*}}{\Omega^{(1,1)*}}. \tag{2.95}$$

Here $\Omega_{ij}^{(l,s)*}$ was determined by the interaction cross sections of the i-th and j-th particles

$$\left.\begin{aligned} \Omega_{ij}^{(l,s)*} &= \frac{\Omega_{ij}^{(l,s)}(2\pi\mu_{ij}/kT)^{1/2}}{1/2(s+1)!\left[1-\frac{1}{2}\frac{1+(-1)^l}{1+l}\right]\pi\rho^2}; \\ \Omega_{ij}^{(l,s)} &= \left(\frac{kT}{2\pi\mu_{ij}}\right)^{1/2}\int_0^\infty e^{-\gamma^2}\gamma^{2s+1}Q_{ij}^{(l)}d\gamma; \\ Q_{ij}^{(l)} &= 2\pi\int_0^\pi(1-\cos^l\theta)\,\sigma_{ij}(\theta, v)\sin\theta d\theta; \end{aligned}\right\} \tag{2.96}$$

$\sigma(\theta, v)$ is the differential scattering cross-section, v is the relative particle velocity, $\gamma = mv^2/2kT$, μ_{ij} is the reduced mass and ρ is a constant that characterizes the interaction of varieties i and j. The values of $\Omega_{ij}^{(l,s)*}$, tabulated for different interaction potentials (Table 2.1), were used in calculating the plasma transfer coefficients.

Table 2.1. Types of Potentials Used in Calculations

(1) Потенциал	(2) Форма	(3) Параметры	(4) Литература
Ленарда-Джонса (5)	$4\cdot\varepsilon\left[\left(\frac{\rho}{r}\right)^{12}-\left(\frac{\rho}{r}\right)^{6}\right]$	ρ, ε	[91]
Степенной (6)	$-\varepsilon r^{-6}+\beta r^{7/2\gamma-2}\exp(2\gamma r)$	β, ε, γ	[91]
Поляризационный (7)	$-\varepsilon(r^2+\rho^2)^{-2}$	ε, ρ	[101]
Экспоненциальный (8)	$-\varepsilon\exp(-r/\rho)$	ε, ρ	[105]
Экранированный (9)	$+\varepsilon(\rho/r)\exp(-r/\rho)$	ε, ρ	[101, 116]
Морзе (10)	$\varepsilon\{\exp[-2\beta(r-\rho)/\rho]-2\exp[-\beta(r-\rho)/\rho]\}$	ε, ρ, β	[102, 103]
	$\varepsilon\exp(-n_\varepsilon(r-r_\varepsilon)^2/2r$	ε, n_ε, r_ε	[106]

Key:
1. Potential
2. Form
3. Parameters
4. Literature
5. Lenard-Johns
6. Power
7. Polarization
8. Exponential
9. Shielded
10. Morse

The parameters of the interaction potentials of neutral atoms and molecules are presented in Table 2.2 and the interaction of neutral particles with charged

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particles was described by polarization potential with values of polarizability presented in Table 2.3. The resonance levels of electron energies of atoms and molecules required to estimate polarizability are presented in the same table:

$$\alpha = 2 \sum_k{}' \frac{(D_z^2)_{0k}}{E_k - E_0} = \sum_k{}' \frac{f_{0k}}{(E_k - E_0)^2},$$

f_{0k} is the transition oscillator force 0 → k and the oscillator force for resonance transition was assumed equal to unity in the estimates. The estimated values of polarizability are noted in Table 2.3 by the symbol *. In those cases when the interaction potentials of neutral particles are unknown, the interactions between them were assumed dispersion and the then Van der Waals constants were estimated by the London formula [91]:

$$C_{12} = \frac{3\alpha_1\alpha_2\Delta E_1\Delta E_2}{2(\Delta E_1 + \Delta E_2)}.$$

The parameters of biatomic molecules were taken from survey [98].

Recharging must be taken into account in the collision integrals for odd values of (l, s). The resonance recharging cross-sections were calculated by asymptotic theory [92]:

$$Q = \frac{\pi R_0^2}{2}; \quad \frac{1}{v}\sqrt{\frac{\pi R_0}{2\gamma}}\,\Delta(R_0) = 0{,}28,$$

and the potential of resonance exchange interaction is equal to (in atomic units)

$$\Delta = A^2 \exp\left(-\frac{1}{\gamma}\right) R^{2/\gamma - 1} \exp(-R\gamma).$$

Parameters A and γ are presented in Table 2.4.

Calculations of electric conductivity and thermo-EMF of a plasma were made by the formulas [71]:

$$\sigma = \frac{4\pi}{3}\frac{n_e e^2}{kT}\int_0^\infty \frac{v^4}{\nu_e} f_e^0\,dv;$$

$$\alpha = \frac{4\pi}{3}\frac{n_e e}{T}\int_0^\infty \frac{v^4}{\nu_e}\left(\frac{m_e v^2}{2kT} - \frac{5}{2}\right) f_e^0\,dv;$$

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Table 2.2. Parameters of Interaction Potentials of Neutral Particles

(1) Взаимодействие	(2) Потенциал	(3) $\varepsilon_{a.e}$	$\rho_{a.e}$	$\beta_{a.e}$	γ	(4) Литература
H_2—H_2	4	1.100(+2)	1.85			[107]
H_2—H	4	5.145(1)	7.372			[107]
H_2—Li_2	2	112		0		
H_2—LiH	2	79.1		0		
H_2—Li	2	77.4		0		[114]
H—H	6	1.745(—1)	1.401			
H—Li_2	2	89.8		0		
H—LiH	2	69.3		0		[106]
H—Li	4	1.786(—1)	1.197			[106, 109]
	4	1.531(—1)	1.218			
Li_2—Li_2	2	2838		0		[115]
Li_2—LiH	2	1787		0		
Li_2—Li	2	2793		0		[114]
LiH—LiH	2	1152		0		[115]
LiH—Li	2	1216		0		[115]
Li—Li	2	1400		136 630		[108, 110]
Cs—Cs	2	5200		11 536		[110]
Cs_2—Cs_2	2	451				
Cs_2—Cs	2	2500				
Li—K	4	1.286(—3)	1.021			
K_2—K_2	4	2.845	1.966			[111]
K_2—K	4	1.569	4.556			
K—U	4	89.38	1.251			
K—K	4	2778	2.21			[110, 117]
K—U	4	882	1.17			
U—U	4	2808	1.74			[117]
K—H	4	18.08	1.202			
K_2—H	4	1.82	2.52			
K—H_2	4	190	1.59			
K_2—H_2	4	3.4	2.908			
Na_2—Na_2	4	10.14	2.759			
Na_2—Na	4	5.661	3.1			
Na—Na	4	13.46	2.19			[117]

Note. In those cases when the literature is not indicated, the parameters of the potential were estimated by combination rules [113] or the constants of Van der Waals interaction were calculated by the known polarizabilities of the particles (Table 2.3) and resonance energy on the basis of the London formula [91].

Key:
1. Interaction
2. Potential
3. Atomic unit
4. Literature

$$\nu_e = \sum_a Q_{ea}^{(1)} v n_a + v \sum_i \gamma_{\sigma,\alpha}^{-1}(z_i) n_i \frac{2\pi}{v^4} \left(\frac{z_i e^2}{m_e}\right) \ln\left[1 + \left(\frac{3\sqrt{2}}{\Gamma}\right)^2\right]. \qquad (2.97)$$

The values of the correction coefficients $\gamma_{\sigma,\alpha}$ are presented in Table 2.5 [93].

Let us discuss the transport electron scattering cross-sections on neutrals used in the calculations. To describe elastic electron scattering on a hydrogen atom

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Table 2.3. Polarizability of Atoms and Molecules and Resonance Excitation Energy [68]

(1) Частица	H	Li	K	Cs	U	H_2	Li_2	K_2	LiH
$\alpha_{a.e}$ (2)	4.5	160	280	360	185*	6.52	243*	353*	133*
$\Delta E_{a.e}$	.375	.0679	.0592	.0408	.0735	.0418	.0641	.0532	.0860

*Polarizability was estimated in the approximation f = 1 for the resonance level (f is the oscillator force)

Key:
1. Particle
2. Atomic units

Table 2.4. Parameters that Determine Resonance Recharging Cross-Section [112]

Атом, ион (1)	H	Li	Na	K	Cs
γ	1,00	.629	.615	.565	.535
A	2,00	.82	.74	.52	.39

Key:
1. Atom, ion

Table 2.5. Correction Coefficients for Conductivity and Thermo-EMF

z	1	2	4	16	∞
γ_σ	.5116	.6833	.7849	.9225	1
γ_α	.2727	.4137	.5714	.8279	1

and molecule and also of all alkali metals except cesium, data systemized in [94] were used. These data can also be used for the reason that they are presented in numerical form with small division by electron energy. Elastic electron scattering on cesium atoms was studied more reliably in [95]. The electron scattering

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cross sections on molecules of alkali metals and their hydrides were calculated by polarization potentials. The electron scattering cross-section on a uranium atom was approximated by estimation [96].

Let us present the expression for coefficient λ_x [5], corresponding to q in the form of (2.85) without regard to D_i^T (see (2.11)):

$$\lambda_x = k \sum_{e=1}^{m} \frac{(\Delta H_e/RT)^2}{\sum_{i=1}^{N} (u_{ei}/x_i) \sum_{j=1}^{N} (u_{ei}x_j - u_{ej}x_i)\, \Delta_{ij}^{(1)}};$$

$$\Delta H_e = RT^2 \frac{d \ln K_e(T, P)}{dT}; \tag{2.98}$$

$$\Delta_{ij}^{(1)} = \frac{16}{5} \sqrt{\frac{2m_i m_j}{\pi kT (m_i + m_j)}}\, \pi\sigma^2 \Omega_{ij}^{(1,1)*}.$$

Here m is the number of chemical reactions in the plasma and $K_e(T, P)$ is the constant of the e-th chemical reaction whose equation is written in "ideal" form.

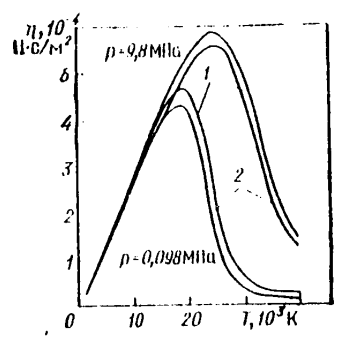

Figure 2.17. Dependence of Viscosity of Helium Plasma on Temperature: 1--results of authors; 2--data of [93]

The values of η, λ', λ_x, σ and α of a lithium, sodium, potassium, cesium and uranium plasma and K + U and K + H mixtures were calculated by the formulas presented above; the effective transfer coefficients (Tables 5.6-5.7) were also calculated for a plasma of mixtures over a wide range of temperatures, pressures and fractions of chemical elements in mixtures. Comparison of the transfer coefficients calculated by the described method to experimental data is discussed in section 4.5. Comparison to calculated data for a weakly imperfect argon plasma [91] in viscosity and total thermal conductivity ($\lambda' + \lambda_x$) shows good agreement (see Figures 2.12-2.16) the same as for multicomponent diffusion coefficients of a helium plasma [93]. The comparisons were made for the transfer coefficients of a hydrogen plasma and other substances [97] which show that the method used to calculate the transfer coefficients of an imperfect plasma (see Tables 5.1-5.5) in the range

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of weak imperfection yields calculated results that agree with known data. Slight divergences are related to different methods of calculating the composition and different types of data on elementary processes in a plasma (Figures 2.17-2.22).

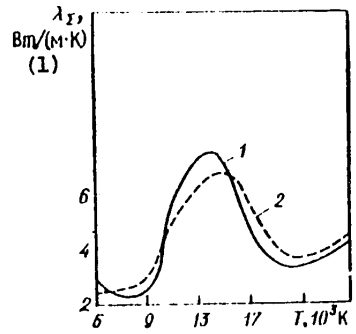

Figure 2.18. Dependence of Thermal Conductivity of Hydrogen Plasma on Temperature at p = 0.1 MPa: 1--results of authors; 2--data of [118]

Key:
1. W/(m·K)

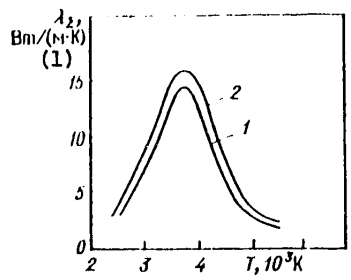

Figure 2.19. Dependence of Thermal Conductivity of Hydrogen Plasma on Temperature at p = 0.1 MPa: 1--results of authors; 2--data of [97]

Key:
1. W/(m·K)

The electric conductivity of a plasma of alkali metals was calculated in [99, 100]. Comparisons of calculations of the electric conductivity of a cesium plasma to the results of [99, 100] at pressures of 1 and 10 MPa are presented in Figure 2.23, a. In [100] the calculations were made only for pressure of 1 MPa. The differences in calculations of the given paper from [100] are related to the difference in the methods of calculating the composition of the plasma since the calculation was carried out by Ekker-Weizel theory in [100], which exaggerates the reduction of

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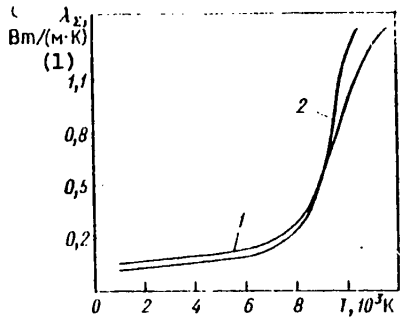

Figure 2.20. Dependence of Thermal Conductivity of Argon Plasma on Temperature at p = 1 MPa: 1--results of authors; 2--data of [91]

Key:
1. W/(m·K)

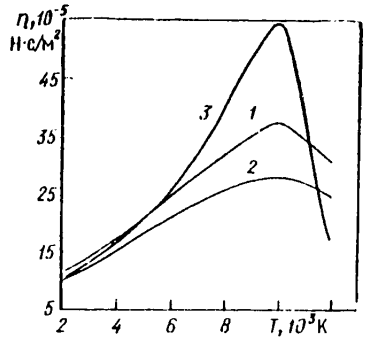

Figure 2.21. Viscosity of Argon Plasma at p = 1 MPa: 1--results of authors; 2 and 3--data of [91]

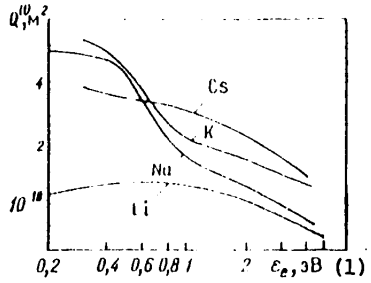

Figure 2.22. Transport Cross-Section of Electron Scattering on Atoms of Alkali Metals

Key:
1. Electron volts

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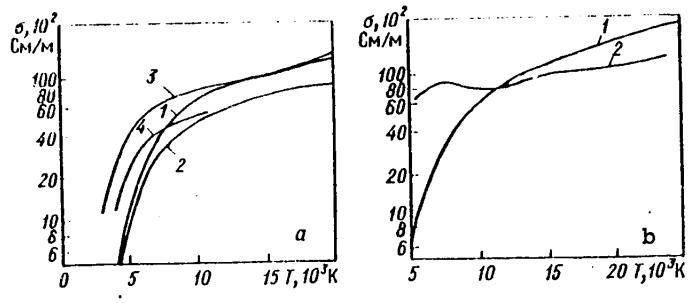

Figure 2.23. Dependence of Electric Conductivity of Cesium Plasma on Temperature at Pressure of p = 1 MPa (a) and 10 MPa (b): 1--results of authors; 2--data of [99]; 3--Spitzer coulomb component of electric conductivity of plasma; 4--data of [100]

ionization potential and accordingly electron concentration. A similar difference exists with the calculations of [99], where the composition of the plasma was calcualted by Debye theory in a canonical group and the degree of ionization was also exaggerated. This is illustrated especially clearly in Figure 2.23, b at temperatures of $(5-7)\cdot 10^3$ K, where imperfection is greatest. In the high-temperature range, the differences in the calculations with the results of [99] are related to the different asymptotics of the expressions of electric conductivity of a completely ionized plasma in the weakly imperfect range ($\Gamma \to 0$) since the calculating formulas of [99] have no Spitzer asymptotics (see section 2.2).

The results of calculation of the present paper are compared to experimental data in Chapter 4.

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OPTICAL PROPERTIES OF GASES AND PLASMA

Moscow TEPLOFIZICHESKIYE SVOYSTVA RABOCHIKH SRED GAZOFAZNOGO YADERNOGO REAKTORA in Russian 1980 (signed to press 1 Aug 80) pp 119-146

[Chapter 3 from the book "Thermophysical Properties of Working Media of the Gas-Phase Nuclear Reactor", by Viktor Konstantinovich Gryaznov, Igor' L'vovich Iosilevskiy, Yuriy Georgiyevich Krasnikov, Nina Ivanovna Kuznetsova, Vladimir Ivanovich Kucherenko, Galina Borisovna Lappo, Boris Nikolayevich Lomakin, Georgiy Alekseevich Pavlov, Eduard Yevgen'yevich Son and Vladimir Yevgen'yevich Fortov, Atomizdat, 1,800 copies, 304 pages]

[Text] 3.1. Transfer of Radiation in a Gas-Phase Nuclear Reactor. Elementary Processes of Absorption in a Plasma of Working Media

The fissionable material in a gas-phase nuclear reactor is in a plasma state at temperature several tens of thousands of degrees and pressure of several tens of MPa. The main mechanism of energy transfer from fissionable material to the working substance is radiant heat transfer. For this reason one of the most important problems occurring in solving that of the transfer of fission energy of nuclear fuel to the working gas by radiation is investigation of the properties of a uranium plasma and the gases which can be used as a working substance. A knowledge of the spectral absorption coefficients and the radiant thermal conductivity coefficients over a broad range of temperatures and pressures permits one to calculate the temperature fields of the uranium jet and working substance of a gas-phase nuclear reactor.

As pointed out in the introduction, alkali metals, their eutectic mixtures and also the mixtures with substances having ionization potentials can be considered as promising working substances for different nuclear power plants. Among the latter the most studied are the properties of hydrogen [1,4]; therefore, the properties of mixtures containing hydrogen [9] and also the optical properties of uranium and its mixtures with alkali metals [10] are investigated in the given chapter in addition to pure substances [5, 6] whose optical properties for a number of parameters were considered earlier [7-8].

The number of components that absorb radiation is high and is considerably dependent on the range of temperatures and pressures. In a uranium plasma this is neutral uranium, its ions of different multiplicity factor and an electron gas; a plasma of an alkali metal will also have a similar component composition.

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Mixtures of uranium with alkali metals contain components typical for uranium and alkali metals according to the percentage content of each substance in the mixture. A lithium-hydrogen plasma has a more diverse composition: molecules of Li_2, LiH and H_2, lithium and hydrogen atoms, positive and negative lithium and hydrogen ions and electrons. Potassium-hydrogen and sodium-hydrogen plasmas have similar composition.

Let us enumerate the elementary processes which determine the spectral absorption coefficient: 1) free-free transitions in the ion and neutral atom fields that determine the absorption of radiation in the infrared region when the plasma is ionized to a sufficient degree, 2) bound-free transitions corresponding to photoionization from the ground and excited states of atoms and ions both positive and negative and 3) bound-bound transitions which determine the striated molecular and linear spectrum of atoms and ions.

The population of named elementary absorption mechanisms on specific spectral sections for each temperature and pressure yield the total absorption coefficient of the plasma, complexly dependent on the wave number of the photon ν, cm^{-1}. The Rosseland mean and the coefficient of radiant thermal conductivity and also the mean Planck absorption coefficient--required data to calculate the degree of blackness of the plasma and of the temperature fields in a gas-phase neuclearreactor--are determined by the spectral absorption coefficient.

The radiant thermal conductivity coefficients of a plasma are determined by the known formula [11]

$$\lambda_R = \frac{16}{3}\sigma l_R T^3, \tag{3.1}$$

where σ is a Stefan-Boltzman constant and l_R is the Rosseland mean from the length of the free path of radiation $l_\nu = K_\nu^{-1}$ which is determined by averaging by the Planck function B_ν:

$$l_R = \int_0^\infty l_\nu \frac{dB_\nu}{dT} d\nu \Bigg/ \int_0^\infty \frac{dB_\nu}{dT} d\nu. \tag{3.2}$$

Table 3.1. Dependence of Spectral Range of Calculating the Radiant Thermal Conductivity Coefficient on Temperature, 10^3 cm^{-1}

$u = \frac{h\nu}{kT}$	T, 10^3 K									
	2	5	10	15	20	25	30	35	40	45
0,5	0,7	1,7	3,4	5,1	7	8,7	10,5	12	14	15,5
4	5,6	13,6	27,2	40,8	56	69,6	84	96	11,2	125
10	14	34	68	102	140	175	210	240	280	310

The spectral absorption coefficient K_ν is determined by the set of elementary absorption processes and is a complex function of frequency, temperature, pressure

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and component composition of the mixture. If one goes to the dimensionless variable u = hc /kT in the range in the numerator of (3.2), then

$$l_R = \int_0^\infty l(u)\, R(u)\, du, \tag{3.3}$$

where R(u) is the universal weight function expressed by the derivative of the Planck function in temperature. The value of R(u) has a maximum at u = 4. In practical calculations the frequency range of integration is limited. The range of values of u at which R(u) is sufficiently high and the contribution to l_R is significant can be determined by the inequality $0.5 \leq u \leq 10$; therefore, to calculate the Rosseland mean one must know the spectral absorption coefficient of radiation over a wide spectral range whose boundaries are dependent on temperature Table 3.1). The spectral range that makes a significant contribution to the coefficient of radiant thermal conductivity expands significantly as temperature increases. According to the boundaries presented in the table, the spectral absorption coefficient was calculated in the range of wave numbers from $5 \cdot 10^2$ to $3 \cdot 10^5$ cm^{-1} when calculating the radiant thermal conductivity coefficient for temperatures $\leq$ 40,000 K. The elementary mechanisms of absorption which were taken into account when calculating the spectral absorption coefficient and the radiant thermal conductivity coefficient are considered in detail in the following sections.

3.2. Deceleration Absorption on Ions and Atoms

A process inverse to bremstrahlung of electrons in fields of ions and atoms makes the main contribution to absorption with an adequate degree of ionization in the infrared region of the spectrum. According to Kramers theory [12] the deceleration absorption coefficient in an ionized gas is

$$K_\nu^{II} = \frac{4}{3}\left(\frac{2\pi}{3mkT}\right)^{1/2} \frac{Z_i^2 e^6}{\hbar c m \nu^3} n_i n_e g. \tag{3.4}$$

The Gaunt correction factor g is determined by the ratio of distances of long and short collisions and for a low-temperature plasma ($2\pi c\nu < \omega_p$, where ω_p is the plasma frequency)

$$g = \frac{\sqrt{3}}{\pi} \ln \frac{B}{\Gamma}; B = \frac{1}{\sqrt{e}}\left(\frac{2}{C}\right)^2 \approx 0{,}765, \tag{3.5}$$

where C is an Euler constant.

This expression follows from the fact that the rate of energy loss by bremstrahlung from the unit volume is proportional to the correlation function of the electric field in dipole approximation [11]

$$\left\langle \frac{dw}{dt} \right\rangle = \frac{2z^2 e^4}{3m^2 c^3 v} \langle \mathbf{E}(\mathbf{r}, t)\mathbf{E}(\mathbf{r}', t)\rangle, \tag{3.6}$$

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while the Fourier components of this correlator are determined by the longitudinal dielectric permeability $\varepsilon_L(\omega)$, where $\omega = 2\pi c\nu$ is the frequency of the electric field:

$$\langle \mathbf{E}(\mathbf{r}, \omega)\mathbf{E}^*(\mathbf{r}', \omega')\rangle = 16\pi^3 \frac{kT}{\omega} \operatorname{Im}\left[\frac{1}{\varepsilon_L(\omega)}\right] \delta(\omega - \omega')\,\delta(\mathbf{r} - \mathbf{r}'). \tag{3.7}$$

The presence of ion correlations during electron scattering on ions makes a small correction to the correlator of noninteracting ions [12] at least for a wekaly imperfect plasma. For this reason calculations of deceleration absorption were made by formula (3.4).

Ionization of the alkali metal occurs in a mixture of an alkali metal with a substance having high ionization potential and the radiation absorption on neutral atoms of the nonionized material is significant. Therefore, deceleration absorption in a field of the hydrogen atom in the infrared and visible regions of the spectrum must be taken into account in mixtures containing hydrogen. The absorption cross-section with free-free electron transitions in the field of a hydrogen atom was calculated in [13, 14] and in some later communications (see survey [15]). A cross-section [14] found by means of wave functions of the free electron in a static Hartree field of a hydrogen atom was used in the given paper. The photoabsorption cross-section with free-free transitions in the field of a hydrogen molecule was taken from [16], where it was calculated by means of asymptotic wave functions. Free-free transitions were considered for mixtures containing up to 50 percent alkali metal and for pure alkali metals and in field of neutral atoms of an alkali metal since their concentration is maintained at a sufficiently high level over a wide temperature range (except the very highest). The contribution to total absorption from this mechanism becomes comparable to other deceleration processes in the infrared and visible regions of the spectrum. Calculation of the deceleration absorption cross-sections on atoms of an alkali metal used in the given paper is presented in [17].

3.3. Photoionization of Atoms, Ions and Molecules

Photoionization of atoms is significant in the absorption spectrum for all mixtures and at all the considered temperatures. Photoionization of an alkali metal from the ground and excited states is of important significance to temperatures on the order of 15,000 K in the visible and near-ultraviolet regions of the spectrum and photoionization of hydrogen from excited states is important at higher temperatures.

The absorption coefficient determined by photoionization of atoms as a function of ν is expressed by the formula [18]

$$K_\nu^{bf} = \frac{N}{Q} \sum_{nl} a_{nl}(\nu)\, g_{nl} \exp(-E_{nl}/kT), \tag{3.8}$$

where N is the concentration of absorbing atoms, E_{nl} is the energy level with quantum numbers n and l calculated from the ground state of the atom, g_{nl} is the statistical weight of the level, Q is the statistical sum of the atom and $a_{nl}(\nu)$ is the photoionization cross-section of level E_{nl}.

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Summation in expression (3.8) is carried out at the given value of ν for all energy levels that meet the condition $I - E_{nl} < \nu$ (I is the ionization potential of the atom).

Coulomb interaction of particles leads to the occurrence of a random microfield of a plasma [19, 20] in which Stark expansion and a shift of highly excited energy levels of atoms and molecules occur. Moreover, there is a thermodynamic decrease of ionization potential in an imperfect plasma. The boundary between regions where one or another effect predominates is determined by the formula [21]

$$T = 1{,}85 n_e^{7/16}, \tag{3.9}$$

where T is temperature, K and n_e is electron concentration, m^{-3}. The different possibilities of taking the shift of the photoionization cross-section threshold in an imperfect plasma into account are discussed in section (3.6) and the shift of the photoionization cross-section threshold in the main part of calculations presented in Chapter 5 was assumed equal to the thermodynamic decrease of the ionization potential since it turned out as a result of correcting calculations that the use of different values of threshold shifts is weakly dependent on the radiant thermal conductivity of the plasma.

One must know the photoionization cross-sections of a large number of energy levels of atoms to calculate the photoionization absorption coefficient.

The photoionization cross-section for the energy level of an atom characterized by quantum numbers n and l is expressed by the formula [18, 22]

$$a_{nl}(\nu) = \frac{8\pi^3 e^2 \nu}{3c} \sum_{l'=l\pm 1} c_{l'} \left| \int_0^\infty P_{nl}(r)\, r^3 G_{kl'}(r)\, dr \right|^2, \tag{3.10}$$

where $P_{nl}(r)$ is the radial function of an electron in the bound state with quantum numbers n and l and $G_{kl'}(r)$ is the radial wave function of an electron in the free state with energy $\hbar k^2/2m$ and with orbital quantum number l.

The Schroedinger equation for a hydrogen atom has a precise solution and its radial wave functions are known [29]. Precise formulas of the photoionization cross-sections of hydrogen are presented in [11] for four levels with main quantum numbers n = 1, 2, 3 and 4. (Since the states of hydrogen are degenerate with respect to l, the given expressions are the sums of cross-sections for all values of l at given value of n). The absence of data for levels with greater value of the main quantum number should not introduce errors into the calculations since the population of these levels is very low at low temperatures and they are cut off due to reduction of ionization potential at high temperatures.

The approximate semi-empirical method of the Burgess-Seaton quantum defect [23] was used to calculate the photoionization cross-sections of the atoms and ions of alkali metals. In this method the semi-empirical Bates and Damgaard function, which is an ideal asymptotic solution of the Schroedinger equation corresponding to the experimental value for the given energy level, is used in this method as

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the radial wave function of an electron in the bound state. The radial wave function of an electron in the free state is determined by the quantum defect method and is expressed by the following asymptotic formula [23]:

$$G(k, l', z, r) \sim k^{-1/2} \sin\left[kr - \frac{1}{2} l'\pi + \frac{z}{k} \ln(2kr) + \right.$$
$$\left. + \arg\Gamma\left(l' + 1 - \frac{iz}{2}\right) + \delta_{l'}(k^2)\right]. \qquad (3.11)$$

Here the phase $\delta_{l'}(k^2) = \pi\mu_{l'}(k^2)$; $\mu_{l'}(k^2)$ is the quantum defect for l' levels extrapolated to the region of positive energies. The quantum defect equal to $\mu(E_{nl}) = n_l - n_l^*$, is determined by experimental values of the energy levels of the atom as the difference of the nominal (hydrogen) and effective main quantum numbers. The experimental values of the energy levels of alkali metals were taken from [24].

An experimental investigation of the absorption cross-sections of the atoms of alkali metals from the ground state was carried out in a number of papers [25-27]. The form of the photoionization cross-section found in these experiments for lithium is in satisfactory agreement with calculation by the quantum defect method (Figure 3.1). The characteristic feature of the behavior of the photoionization cross section of sodium, potassium and cesium is a minimum value of the cross-section near the threshold. It is interesting to note that calculation by the quantum defect method also yields a minimum beyond the threshold for alkali metals, but its position is shifted toward higher frequencies compared to experiment and iffers in absolute value. Experimentally derived photoionization cross-sections from the ground states of alkali metals, except lithium, were used in calculations of the total absorption coefficient.

The photoionization cross-sections from excited levels are easily described by Burgess-Seaton approximation. Thus, available experimental data on the photoionization cross-section from the excited level $3^2P_{1/2,\ 3/2}$ of a sodium atom [28] confirm the correctness of the selected method. In Figure 3.2 experiment is compared to calculations made by the quantum defect method [29] and in approximation of radial wave functions found by the Hartree-Fock method.

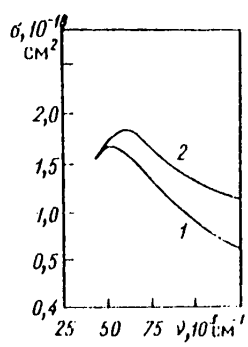

Figure 3.1. Photoionization Cross-Section of Lithium from Ground State: 1--calculation; 2--experiment

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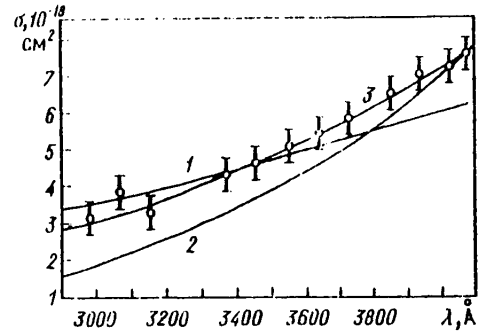

Figure 3.2. Photoionization Cross-Section from Excited Level $3^2 P_{1/2, 3/2}$ of Sodium: 1--calculation by quantum defect method; 2--calculation by Hartree-Fock method; 3--experiment

As mentioned earlier, the maximum energy to which calculations of the absorption coefficient were made corresponds to a frequency of $3 \cdot 10^5$ cm^{-1}. Since the ionization potentials of lithium and sodium ions are so high that the ionization thresholds of the ions are far beyond this boundary, photoionization of lithium and sodium ions were not considered in the present calculations. The ionization potentials of potassium and cesium ions lie within the considered range. Therefore, secondary photoionization, whose contribution is significant at high temperatures when a plasma is strongly ionized, was taken into account in calculations of the optical properties of media with participation of potassium and cesium in the far ultraviolet range.

Let us consider photoionization of uranium and its ions. Analysis of known methods of photoionization shows that their application to atomic systems containing a large number of electrons is practically impossible. The difficulties of calculation were determined by a deficiency of experimental data on the scheme of terms, the type of bond, configuration impurities and so on.

At the same time there is considerable experimental information about the energy levels and oscillator forces for the atom and first ion of uranium [30]. However, direct calculation that takes into account these data would be too cumbersome and moreover information about the spectrum of uranium is available only for part of the discontinuous spectrum. For this reason an approximate method of calculating the absoprtion coefficient was suggested that is based on general information about the spectrum of the uranium atom and ion known from [30]. The photoionization absorption coefficient is determined by formula (3.8). Following [20], let us assume that the frequency dependence of the photoionization cross-section is the same as that in the Kramers formula, i.e., for quanta with frequencies $\nu \geq E_j$ (E_j is the energy level of j calculated from the continuum), we have the following function:

$$a_j^{bf} = A\nu^{-3}. \tag{3.12}$$

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The constant A is found from the expression for the oscillator force of bound-free transitions:

$$f = \frac{mc}{\pi e^2 h} \int_{E_j}^{\infty} a_j^{bf} d\nu = \frac{mcA}{2\pi e^2 h (E_j)^2}. \tag{3.13}$$

Thus, the following formula is found for the photoionization cross-section:

$$a_j^{bf} = \frac{2\pi e^2 h f}{mc} \frac{E_j^2}{\nu^3}. \tag{3.14}$$

This expression coincides with the Kramers formula if the hydrogen-like expressions are taken for the ionization potential and oscillator force:

$$E_j = z^2 e^2/(2a_0 n^2); \quad f = 8g/(3\sqrt{3}\pi n), \tag{3.15}$$

where g is a Gaunt factor. Let us assume that the frequency dependence ν^{-3} in the photoionization cross-section is also valid in the discontinuous spectrum (Figure 3.3) and integration in formula (3.13) can then be applied to the energy of the first line of the Ridberg series Ej and one can assume the sum of oscillator forces as f = 1, according to the rule of sums. The derived formula will effectively take into account the continuous spectrum and absorption in the lines. Making an assumption about the sum of the oscillator forces, we assume that an excited electron is located in the effective field of the ion and all transitions between excited states of the atom occur without variation of the state of the ion. Consideration of transitions with excitation of the residual ion and transitions of other valency electrons may lead to some increase of the photoionization cross-section at high frequencies of absorbed quanta and is included in the ambiguity of the proposed model.

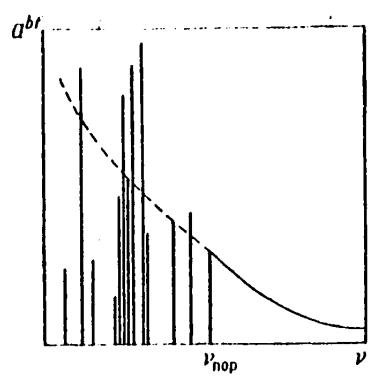

Figure 3.3. Behavior of Photoionization Cross-Section Near Threshold. The dashed line shows extrapolation of the cross-section for bound-bound transitions.

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The photoionization cross-section in this approximation is determined by the formula

$$a_j^{bf} = \frac{2\pi e^2 h}{mc} \frac{(\Delta E_j^2)}{\nu^3} (\nu > E_j). \tag{3.16}$$

Substantiation of the assumption of the continuity of the continuum transition to the discontinuous spectrum may be the following concepts. Electron motion is quasi-classical in states with large quantum numbers and motion along an elliptical orbit, corresponding to a large value of quantum number and low negative energy, is very close to motion along a hyperbolic orbit with low positive energy. Let us consider transitions from the n-th level when a photon is absorbed within semi-classical concepts. If frequency increases, the electron in the final state enters elliptical orbits that more and more approach a parabolic orbit. At $\nu = \nu_n$ it enters a parabolic orbit and at frequency ν, somewhat exceeding ν_n, it enters hyperbolic orbits close to a parabolic orbit. Since electron motion in the final state varies continuously, one should expect that the mean effective absorption cross-section of light by atoms in the n-th state will also be continuous upon transition from the discontinuous spectrum to the continuum (see Figure 3.3). For this reason semi-classical formula (3.16) will yield a good estimate for transitions from levels with low quantum numbers, including for ΔE_j, as occurs upon comparison of the semi-classical and quantum photoionization cross-sections from the ground level of a hydrogen-like atom. Therefore, the lines according to the method outlined above were also subsequently taken into account when calculating the absorption coefficient for U^{++}, U^{+++} and U^{++++}, i.e., formula (3.16) was applied to photon energy of $\Delta E_j \leq \nu \leq E_j$, which corresponds to bound-bound transitions. In the outlined method for calculating the photoionization cross-section, one must find the first line of the Ridberg series E_j for each level of j. This can be done by assuming that the effective main quantum number n_j corresponds to each level of j so that

$$E_j = \mathrm{Ry} Z^2 n_j^{-2}; \quad \Delta E_j = E_j - \mathrm{Ry}\, Z^2/(n_j + 1)^2, \tag{3.17}$$

where Z is the multiplicity factor of the atomic remainder.

The next approximation is related to a large number of levels of the uranium atom and ions; therefore, one can convert in formula (3.8) from summation by levels to integration if the number of states of the atomic levels is introduced in the form of $N(E) = c(-E)^{-\alpha}$, where the constants c and α are found from experimental data [30]. The contribution to the absorption coefficient due to photoionization, according to (3.16) is determined by the mean value

$$\langle \Delta E^2 \rangle = \frac{\int_{-E}^{-\Delta I} (\Delta E^2)\, g(E) \exp[-(I+E)/kT]\, \rho(E)\, dE}{\int_{-I}^{-\Delta I} g(E) \exp[-(I+E)/kT]\, \rho(E)\, dE}, \tag{3.18}$$

where I is ionization potential and $\Delta I = kT$ is a reduction of ionization potential. Integration in (3.18) is carried out by the range of energy levels that satisfy

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the condition $E - \Delta I \leq \nu$ at the given value of photon frequency ν. The statistical weight of level $g(E)$ varies irregularly, assuming similar values [30]; therefore, let us further assume that it is dependent on energy. Substituting the density of states $\rho(E) = dN/dE$ into (3.18) and assuming that

$$\Delta E_n = \frac{dE_n}{dn}\Delta n = 2\mathrm{Ry}^{-1/2}(-E)^{3/2}Z^{-1}, \tag{3.19}$$

we find the expression for the absorption coefficient:

$$K_\nu^{bf} = 2^6\pi^3\frac{e^2}{hc}a_0^2\left(\frac{kT}{hc\nu}\right)^3\frac{N}{z^2}\int_1^{1+h\nu/kT}\varepsilon^{2-\alpha}e^{\varepsilon}d\varepsilon\Bigg/\int_1^{I/kT}\varepsilon^{-\alpha-1}e^{\varepsilon}d\varepsilon, \tag{3.20}$$

where a_0 is the Bohr radius.

Photoionization was taken into account integrally in numerical calculations only from the upper levels, for which there are no experimental data in [30], and direct summation was carried out for the lower levels. The value of the statsum of the uranium atom is required for these levels. Convenient approximation formulas based on the data of [30] are presented in [31]:

$$\begin{gathered} Q_U = -0{,}0308T^4 + 0{,}888T^3 - 1{,}814T^2 + 5{,}544T + 13; \\ Q_{U^+} = 0{,}0024T^5 - 0{,}08751T^4 + 1{,}001T^3 - 1{,}418T^2 + 12{,}04T + 10. \end{gathered} \tag{3.21}$$

Here T is the temperature in thousands of K. The approximation is valid at $T < 15{,}000$ K.

Parameter α required for the calculations was selected as equal to

$$\alpha_U = 4;\quad \alpha_{U^+} = 5{,}4;\quad \alpha_{U^{++}} = \alpha_{U^{+++}} = \alpha_{U^{++++}} = 4.$$

Besides the photoionization processes of atoms described above, continuous absorption in the region of the near ultraviolet was observed in some experiments [25, 26, 32] in molecules which are absorbing components in the working substances under discussion. They include photoionization of the Li_2 molecule. The absorption cross-section found in [26] due to photoionization of Li_2 was used in these calculations of the total absorption coefficient at low temperatures. The photoionization cross-section of sodium was measured [25] in the range of wave numbers 38,000-62,500 cm^{-1} and it has a value of approximately 10^{-18} cm^2. The potassium molecule also has a continuous absorption spectrum in the near ultraviolet [26] and its cross-section is of the same order as that for sodium. The photoionization threshold of the LiH molecule has a value of 62,500 cm^{-1} but the cross-section of this process is unknown. The photoionization cross-section of the hydrogen molecule was measured in [32] but the corresponding range of frequencies is insignificant at low temperatures for mixtures, while photoionization of atomic hydrogen whose concentration exceeds the concentration of molecules and whose frequency interval is the same, is more significant at high temperatures.

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There are negative ions of hydrogen H^- and of the alkali metal Li^-, Na^-, K^- and Cs^- in mixtures of hydrogen with alkali metals at temperatures above 4,000 K in specific quantities (depending on the concentration of the alkali impurity) and the H^- concentration in this mixture is several orders higher than that in pure hydrogen.

The energy of electron affinity to hydrogen comprises 0.75 eV; therefore, the negative hydrogen ion may absorb photons over a wide range of the spectrum due to photodetachment of an electron. The cross-section of this process, according to calculations of different authors, is rather high (approximately 10^{-16} cm^2) and therefore the presence of even a relatively small number of H^- should make a significant contribution to the total absorption in the infrared and visible regions of the spectrum. The photodetachment cross-section of a negative hydrogen ion found in [33] was used in the present calculations. The wave function of the finite state in this calculation was taken in the form of the product of the unperturbed function of the hydrogen atom by the wave function of the electron moving in a static Hartree potential of the hydrogen atom and the Henrich function with 11 parameters determined by the Ritz variational principle was used as the wave function of the bound state. There are now many papers devoted to theoretical and experimental investigations of the photodetachment cross-section of a negative hydrogen ion. There are more accurate calculations obtained by means of Hartree-Fock wave functions with regard to exchange in the survey of these papers [34]. However, the difference between them is small compared to the accuracy of other determining processes.

The continuous absorption cross-section for the process of electron photodetachment of a negative ion of an alkali metal was calculated [17] using the wave function of the bound state, consisting of two s-electrons outside the closed shell. The free states were described in the purely polarization potential. These results were used in the calculations.

3.4. Absorption in Atomic Lines

A uranium atom with six electrons on the outer incomplete shell is characterized by a large number of tight levels (Figure 3.4). The experimentally measured 30,000 lines of the uranium atom and its first ion at low pressure in the visible and near ultraviolet regions of the spectrum are presented in [30]. The uranium lines broaden and overlap [35] as pressure increases since the absorption spectrum in the lines is actually quasi-continuous, i.e., that where individual lines do not break down; therefore, the method of calculating the spectral absorption coefficients in the lines of the uranium atom and its first ion was as follows. The mean absorption coefficient for the frequency range $\Delta\nu$, found by summation of all lines belonging to a given frequency interval, was calculated:

$$K_\nu^{bb} = \frac{\pi e^2}{mc} \frac{N}{\Delta\nu Q} \sum_k g_k f_k \exp\left(-\frac{E_k}{kT}\right), \tag{3.22}$$

where E_k is the energy level from which transition occurs, g_k is the statistical weight and f_k is the transition oscillator force. Lines with their own oscillator forces that determine the contribution of each line [36], known from experiment,

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were taken into account in the calculations. A total of 326 lines of neutral uranium and 316 lines of its first ion, for which the oscillator forces are known, was taken into account in the calculation. Ions of higher multiplicity factor play the main role in absorption in a uranium plasma at temperatures above approximately 15,000 K. Since there are no transition probabilities and other spectroscopic data for couble, triple and quadruple ionized uranium, the contribution of the lines to the absorption coefficient was taken into account integrally by the method discussed in section 3.3.

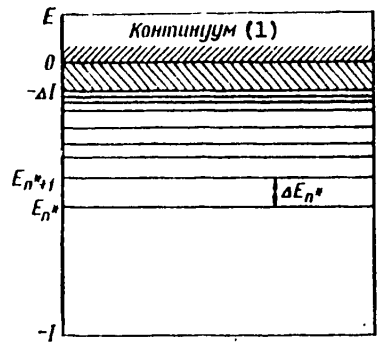

Figure 3.4. Diagram of Energy Levels of Uranium Atom: ΔE_n*--first line of Ridberg series corresponding to transitions to level E_n*; I--ionization potential; ΔI--reduction of ionization potential

Key:
1. Continuum

The absorption lines of the atoms of alkali metals are isolated from each other in the visible and near-ultraviolet regions of the spectrum. The absorption coefficient in the spectral line of the atom is determined not only by the oscillator force but also by the shape of the contour of the line which in turn is dependent on temperature, pressure and concentrations of the plasma components:

$$K_\nu^{bb} = \frac{\pi e^2}{mc^2} f N J_\nu, \tag{3.23}$$

where $J\gamma$ is the contour of the spectral line.

Spectral lines broaden at high pressures mainly due to interaction with neutral (Van der Waals and resonance) and charged (Stark) particles. Doppler and radiation broadening are insignificant. The contour J_ν can be regarded as a convolution of the controus of each mechanism in the case when many different mechanisms affect broadening of the line. Broadening of the lines of atoms of alkali metal by neutral particles of H and H_2 and also by charged particles is described by impact theory, i.e., the shape of the contour can be selected as dispersion in each individual case. Convolution of the dispersion contours is again a dispersion contour where the half-width and shift are the sum of the half-widths and shifts of individual types of interaction. The dispersion shape of the contour was taken in the

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case of resonance broadening of alkali metals for the limbs of the line but the half-width was selected in this case so that the expressions of dispersion and Gaussian contours for the limbs of the lines coincided. As a result the contour of the spectral line is described by the expression

$$J_\nu = W_\Sigma [4\pi^2 (\nu - \nu_0 - \Delta_\Sigma)^2 + (W_\Sigma/2)^2]^{-1}, \qquad (3.24)$$

where W_Σ is the total half-width and Δ_Σ is the total shift.

At low temperatures and low additions of alkali metal when the main mechanism of broadening of the spectral lines is Van der Waals interaction of atoms of the alkali metal with hydrogen atoms and molecules, the half-width of the line is determined by the velocity of relative motion of interacting particles, dependent on the temperature, concentration of the broadening particles and the interaction constant, which is dependent on the energy levels of the interacting particles and the oscillator forces of the corresponding transitions [18].

Resonance broadening, which was calculated in [37], is significant at low temperatures and large additions of alkali metal.

The charged particle concentration increases as the temperature in a plasma increases, i.e., Stark broadening due to interaction with charged particles is added to the considered broadening mechanisms. The parameters of Stark broadening used in this paper were calculated in [38]. Insufficient data were found by linear interpolation and the half-width was found by summation of the effective resonance and Startk half-widths. The total shift of the center of the lines was determined by summation of the shifts due to all mechanisms. The oscillator forces of transitions were taken from [36, 38, 39]. In the calculations presented in Chapter 5, 16 lithium and sodium lines each and 18 potassium and cesium lines each, which absorb mainly in the visible and near-ultraviolet regions of the spectrum, where taken into account. The contribution of ions of alkali metals to absorption of the lines was not considered in the calculations, which is insignificant for Li^+ and Na^+ but may be significant for K^+ and Cs^+ at high temperatures. Therefore, data on the radiant thermal conductivity coefficients for potassium and cesium in the tables of Chapter 5 are limited to 30,000 K.

Absorption in hydrogen lines of the Lyman and Balmer series was considered at temperature of 10,000 K since molecular hydrogen absorption significantly predominates over all other elementary processes at lower temperatures in the ultraviolet region of the spectrum and lines of the Balmer series lying in the visible region of the spectrum make an appreciable contribution only at temperatures above 10,000 K. Analysis of the component compositions of hydrogen mixtures with alkali metals showed that the width and shape of the hydrogen lines are determined by interaction with charged particles (Stark broadening) and all remaining types of broadening of spectral lines are insignificant at the considered temperatures. A number of papers [38, 40, 41], in which the numerical contours of the spectral lines of hydrogen of the Lyman and Balmer series at temperatures of 10,000, 20,000 and 40,000 K and at different concentrations of charged particles (10^{23}, 10^{24} and 10^{25} m^{-3}) are presented, is devoted to the theory of Stark broadening of hydrogen lines. The absorption coefficients in hydrogen lines were calculated using these results.

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Extrapolation toward higher values was made as a function of the charged particle concentration in different versions of the working substance. The limbs of the lines were calculated by formulas and tables presented in [38, 41, 42].

3.5. Molecular Absorption

Biatomic molecules have typical electron absorption spectra that are bands which consist of a number of rotational lines. This complex structure does not permit one to avoid some approximations in calculation. The integral absorption coefficient of the rotational line is described in Born-Oppenheimer approximation in the following manner [43]:

$$\int K_\nu^{bb} d\nu = \frac{8\pi^3}{3hc} \left| R_{\text{эл}}^{nm} \right|^2 q_{v'v''} \frac{N_n}{2J+1} \chi_{J'J''} \nu_{nm}. \tag{3.25}$$

In this formula the value of the electron matrix element $R_{\text{эл}}^{mn} = \int \psi_m^* r \psi_n d\tau$ is dependent only on the electron eigen-functions of the ground and excited states. The Franck-Condon factors $q_{v'v''} = \left| \int \psi_{v'} \psi_{v''} d\tau \right|^2$ are determined by the vibrational eigenfunctions related to combining electron states. Henley-London factors $\chi_{J'J''}$ determine the force of the rotational line while ν_{nm} is the position of the given rotational line characterized by the difference of electron, vibrational and rotational therms.

The spectral dependence of the absorption coefficient, corresponding to specific electron transition in biatomic molecules whose rotational lines are broadened and overlapped, is determined by the formula [49]

$$K_\nu^{bb} = \frac{8\pi^3}{3hc\Delta\nu} R_{\text{эл}}^2 \frac{N_0 g_e \exp\left(-\frac{E_e}{kT}\right)}{Q(2-\delta_{0,\Lambda})} \sum_{v'=0}^{v'_{\text{гр}}} \sum_{v''=0}^{v''_{\text{гр}}} \exp\left(-\frac{E'_v}{kT}\right) q_{v'v''} \times$$
$$\times \sum_{J=0}^{J_{\text{гр}}} \exp\left(-\frac{E_J}{kT}\right) \sum_{J''=J-1,\,J,\,J+1} \chi_{JJ''} \nu_{ev'J;\,e''v''J''}, \tag{3.26}$$

where $\delta_{0,\Lambda} = 1$ for $\Delta\Lambda = 0$ and $\delta_{0,\Lambda} = 0$ for $\Delta\Lambda \neq 0$, which yields Λ-doubling (Λ is the projection of the total orbital moment to the internuclear axis). The positions of the centers of the lines, the static sums and the energy levels are determined by spectroscopic constants [44-45]. Summation is made in expression (3.26) for all the vibrational and rotational quantum numbers up to the boundary value. The boundary value of the vibrational quantum number v_{gr} follows from determination of the dissociation energy since the vibrational levels are applicable at high temperatures up to the dissociation boundary. The last discontinuous level v_{gr} is reached at

$$G(v_{\text{гр}} + \delta) = D_0, \tag{3.27}$$

where $0 \leq \delta \leq 1$, D_0 is the dissociation energy of the molecule and G is the analytical function of the vibrational quantum number. The boundary value of the

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rotational quantum number at given vibrational number is determined by the function found in [46]: $J_v^{gr} = J_0^{gr} (1 - v/v_{gr})$. This relation permits one to determine J_v^{gr} simply and with sufficient degree of accuracy if J_0^{gr} is known, i.e., the value of J^{gr} which corresponds to v = 0 and v_{gr}. The value of J_0^{gr} was determined graphically from the value of the potential barrier for the effective potential curve plotted by the RKR method (Ridberg-Klein-Reese) for different values of J.

The Franck-Condon factors that determine the intensity distribution in the electron system of bands were found by quantum-mechanics calculations. The vibrational functions are solutions of the Schroedinger equation with corresponding interaction potential of atoms in a biatomic molecule. The Morse potential, for which the Schoredinger equation is solved analytically, is the most frequently used in these calculations. The wave functions for it are associated Laguerre polynomials by which the Franck-Condon factors are calculated. This method of calculations was used to calculate the Franck-Condon factors of three systems of lithium bands, $(X^1\Sigma_g^+ \to A^1\Sigma_u^+,\ X^1\Sigma_g^+ \to B^1\Pi_u,\ X^1\Sigma_g^+ \to C^1\Sigma_u^+)$, three systems of sodium bands $(X^1\Sigma_g^+ \to A^1\Sigma_u^+,\ X^1\Sigma_g^+ \to B^1\Pi_u,\ X^1\Sigma_g^+ \to C^1\Sigma_u^+)$ and four systems of potassium bands $(X^1\Sigma_g^+ \to A^1\Sigma_u^+,\ X^1\Sigma_g^+ \to B^1\Pi_u,\ X^1\Sigma_g^+ \to C^1\Sigma_u^+,\ X^1\Sigma_g^+ \to D^1\Pi_u)$.

The Franck-Condon factors cannot be calculated by using the Morse potentials for molecules of hydrides of alkali metals, which are one of the main absorbing components at low temperatures, since these molecules have abnormal values of spectroscopic constants in the first excited state. The RKR method, which is dependent only on the experimental values of spectroscopic constants, was used to plot the potential curves of the ground and excited states of hydride molecules. The vibrational wave functions were found from solution of the Schroedinger equation with a potential given numerically. The numerical method of Numerov was used to solve the Schoredinger equation [47]. The eigen-functions and tables of Franck-Condon factors were calculated to the boundary value of the vibrational quantum number in each electron state. The Franck-Condon factors, also calculated by using the RKR potentials, were taken from [48] for two systems of bands of the hydrogen molecule $(X^1\Sigma_g^+ \to A^1\Sigma_u^+$ и $X^1\Sigma_g^+ \to B^1\Pi_u)$.

The absolute value of the absorption coefficient is determined by the square of the matrix element of the dipole moment of transition. Quantum-mechanical calculation of this value for multielectron molecules is related to great difficulties but quantum-mechanical calculations yield satisfactory results for hydrogen and LiH, which have a small number of electrons. There is a number of values of the oscillator force both experimental and those found by quantum-mechanical calculations for systems of bands X → A and X → B of the hydrogen molecule [49-51]. A number of experimental values of oscillator forces found for the system X → A upon transition to vibrational levels v = 4, 5, 6 lies in the range from 0.51 to 0.28, according to data of different authors. There is also a difference in the experimentally determined values of oscillator forces for the system of bands X → B (v' = 0, 1, 2): from 0.7 to 0.29. Theoretical calculation of the dependence of the electron moment of transition R_e on the internuclear distance for the systems of bands under discussion was carried out in [51]. It turned out in this case that this dependence is significant for the system X → A (from 0.5 atomic unit to 1.5 atomic units). The dependence is weak for the system of bands X → B as a whole: despite the steep rise from 0.5 atomic unit to 0.9 atomic unit at R = 2 atomic units, R_e retains a value of 0.9 atomic unit everywhere. This dependence

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of the dipole moment of transition can probably explain the significant divergence of the experimental values of oscillator forces discussed above. The mean values of oscillator forces, according to [51], were used in calculating the total absorption coefficient in systems of bands X → A and X → B of the hydrogen molecule. Calculations of the oscillator forces by the Geitler-London method and the molecular orbital method [52] for the LiH molecule yielded a coincident result. The dependence of the value of R_e on the internuclear distance was investigated in these calculations. The mean value of R_e, corresponding to the oscillator force equal to 0.13, was used in our calculations.

The data available in the literature on oscillator forces for lithium and sodium molecules are presented in survey [53]. An experimental value of $f_e = 0.3$ was used in calculations for the red system X → A of the lithium molecule and the theoretical value of $f_e = 0.66$ was used for the blue-green system X → B. There is a value $f_e \approx 0.2$ estimated by the molecular orbital method for the sodium molecule [54].

The oscillator forces were estimated by a method similar to [54], which takes into account only two optical electrons outside the closed shell, for the violet system of lithium bands, two systems of sodium bands and four systems of potassium bands.

Table 3.2. Oscillator Forces of Systems of Lithium, Sodium and Potassium Molecule Bands

(1) Молекула	Система (2)			
	X→A	X→B	X→C	X→D
Li_2	0,3	0,66	0,12	—
Na_2	0,2	0,35	0,08	—
K_2	0,15	0,23	0,1	0,04

Key:
1. Molecule
2. System

The oscillator forces of systems of lithium, sodium and potassium molecule bands used in the present calculations are presented in Table 3.2. Besides the system of bands in the visible region of the spectrum described above, the lithium hydride molecule has a continuous absorption band in the near ultraviolet [55]. Two discrete bands and a continuous spectrum were observed in the system of bands corresponding to transition from the ground state $X^1\Pi_g$ of the lithium hydride molecule to the excited state $B^1{}_u$. The spectroscopic constants of the $B^1\Pi_u$-state of lithium hydride, in cm^{-1}, are presented below.

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T_e	ω_e	$\omega_e x_e$	B_e	α_e	r_e (Å)
34912	215,5	42,2	3,388	0,986	2,376

The potential curve of state plotted by these constants permits one to conclude that the observed continuous absorption spectrum corresponds to transition to the repulsion part of the curve (Figure 3.5). A very small potential hole (183 cm^{-1}) in state $^1\Pi_u$ provides the basis to disregard bound-bound transitions and to assume that the photodissociation process of the LiH molecule makes the main contribution to absorption. This elementary absorption process was calculated by the method proposed in [56]:

$$K_\nu^{bf} = \frac{8\pi^3}{3hc}\nu R_e^2(\nu)\sum_v N_v q_v(\nu), \tag{3.28}$$

where ν is the transition frequency, $R_e^2(\nu)$ is the square of the matrix element of the dipole moment of transition and $q_v(\nu)$ is the density of the Franck-Condon factors. The sum in (3.28) can be transformed to a more convenient expression if the eigen-functions of the ground state are replaced by Hermitian polynomials and if the Franck-Condon factors are replaced by values for a harmonic oscillator:

$$\sum_v N_v q_v(\nu) = \frac{1}{\sqrt{\pi}}\sqrt{\frac{1-z}{1+z}}\exp\left[-\frac{1-z}{1+z}\xi^2\right], \tag{3.29}$$

where $\xi = \sqrt{\alpha}\,(r - r_e)$; $z = \exp(-\theta/T)$; $\theta = 1{,}439\omega_e$; $\alpha = 4\pi^2\mu c\omega_e h^{-1}$; μ is the reduced mass of the molecule and r_e is the equilibrium internuclear state. Formula (3.28) then assumes the form

$$K_\nu^{bf} = \frac{8\pi^3}{3hc}\nu R_e^2(\nu)\frac{1}{\sqrt{\pi}}\sqrt{\frac{1-z}{1+z}}\exp\left[-\frac{1-z}{1+z}\xi^2\right]. \tag{3.30}$$

Normalization in calculation of this process was carried out for conditional oscillator force $f_e = 0.1$ since there are no reliable data on the probability of transition of this system.

Besides molecular absorption in electron band systems, a great deal of attention was devoted to absorption in the infrared region of the spectrum, specifically to absorption of heteronuclear molecules of hydrides of alkali metals due to vibrational-rotational transitions, although it is known that the absorption level due to this mechanism is significantly lower than that in electron band systems. This is related to the fact that photons with long wavelength lying in the infrared region of the spectrom are responsible for radiation transfer at low temperatures. The integral absorption coefficient of the spectral line corresponding to vibrational-rotational transition is determined by the expression

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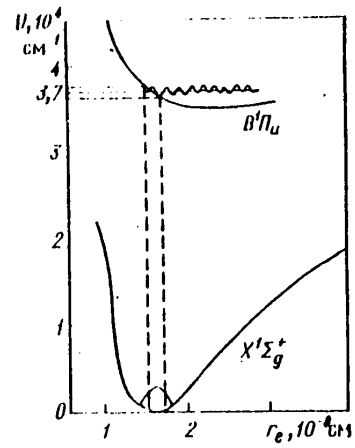

Figure 3.5. Potential Curves of Ground $X'\Sigma_g^+$-State and Excited $B^1\Pi_u$-State of Lithium Hydride Molecule

$$\int K_\nu^{bb} d\nu = \frac{8\pi^3}{3hc} (R_{v'v''})^2 \frac{N_{vj}}{2j+1} \chi_{jj'} \nu_{v'j'v''j''}, \tag{3.31}$$

where N_{vj} is the number of molecules at a given vibrational level. The value of $R_{v'v''}$ is similar to the matrix element of an electron dipole moment of transition

$$R_{v'v''} = \int \psi_{v'}^* \mu(\rho) \psi_{v''} d\rho, \tag{3.32}$$

where $\psi_{v'}^*$ and $\psi_{v''}$ are the vibrational eigen-functions related to the ground state of the molecule. The spectral absorption coefficient for vibrational-rotational bands in the range of infrared frequencies was calculated by a formula similar to (3.26), with regard to (3.31) and according to the sampling rules for vibrational-rotational transitions according to which it makes no sense to take into account overtones above $\Delta v = 3$ since their intensity is several orders less than that of the main band. The calculating steps was selected with regard to the vibrational and rotational spectroscopic constants and the absorption coefficient was normalized for experimental values of the derivative of the dipole moment [57] for the lithium hydride molecule. The same normalization was adopted for other hydrides due to the absence of reliable data.

Vibrational-rotational transitions for homonuclear molecules are forbidden in dipole approximation, but the presence of vibrational-rotational spectra of homonuclear molecules induced by high pressure was established in the experiments of [58-60] and quadradic dependence of the intensity of the bands on pressure was noted. As indicated by calculations made in [61, 62], the dipole moment of the complex consisting of two molecules interacting with each other is determined by the presence of a quadrupole moment in colliding molecules. The exchange forces that arise upon overlapping of wave functions distorted by interaction are also significant.

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The spectral absorption coefficient determined by this process was calculated by the formula

$$K_\nu = \frac{16\pi^3 N^2}{3hcQ\Delta\nu} \sum_{v_1=0}^{v_{1\text{макс}}} \sum_{v_1'=v_1\pm 1}^{v_{1\text{макс}}} R_{v_1 v_1'} \sum_{J_1, J_2} P_{v_1 J_1} P_{v_2 J_2} \sum_{J_1'=J_1-2,\, J_1,\, J_1+2} \times$$
$$\times \sum_{J_2'=J-2,\, J_2,\, J_2+2} [a(J_1)\, a(J_2)\, \delta(J_1'J_1)\, \delta(J_2'J_2)\, I_1 + L_1(J_1J_1')\, a(J_2) \times$$
$$\times \delta(J_2'J_2)\, I_2 + L(J_2, J_1')\, a(J_1')\, \delta(J_1'J_1)\, I_3 + L(J_1J_1') \times \tag{3.33}$$
$$\times L(J_2J_2')\, I_4]\, \nu_{v_1J_1v_2J_2;\, v_1'J_1'v_2'J_2'}$$

The notations a(J) and L(J, J') in formula (3.33) are the same as in [61]:

$$\nu_{v_1J_1v_2J_2;\, v_1'J_1'v_2'J_2'} = E_{v_1'J_1'} + E_{v_2'J_2'} - E_{v_1J_1} - E_{v_2J_2};$$

E_{vJ} is the vibrational-rotational energy level of v and J and $P_{v_1J_1}$ and $P_{v_2J_2}$ are the Boltzman probabilities of state of a system of two particles

$$I_i = \int_{R_{\text{мин}}}^{R_{\text{макс}}} \exp\left[-\frac{\Phi(R)}{kT}\right] D_i^2(R)\, R^2 dR, \tag{3.34}$$

where $\Phi(R)$ is the intermolecular interaction potential and the Lenard-Johns potential was used in the given calculation (see Chapter 2). The values of $D_i(R)$ are given in [61] in the form of tables; R_{v,v'_1} is the vibrational matrix element. Summation was carried out with respect to J in formula (3.33) according to the sampling rules for quasi-molecules of $(H_2)_2$, $\Delta J = 0, \pm 2$. Summation was carried out with respect to v from v = 0 to v = 14 according to the value of the maximum vibrational number for the ground state of the hydrogen molecule. Q is the statistical sum of the $(H_2)_2$ quasi-molecule. The calculations were made in the spectral range from $2 \cdot 10^3$ cm^{-1} to 10^4 cm^{-1}. The ration K_ν/N^2 for the $(H_2)_2$ quasi-molecule for different temperatures is shown in Figure 3.6.

3.6. The Effect of Imperfection on the Optical Properties of a Plasma

Absorption of radiation by an isolated atom is described by narrow lines in the discontinuous spectrum where radiation broadening is determined by the finite line in the excited state, but photoionization and by deceleration absorption in the continuous spectrum. The series of lines converges toward the photoionization threshold. The presence of the surrounding medium for an atom in a plasma leads to several effects.

First, the lines in the spectrum of atoms induced by interaction of the atom with the surrounding particles and by the Doppler effect are broadened and shifted. As already mentioned, Doppler broadening is insignificant compared to impact and Stark broadening; therefore, only these mechanisms of line broadening were taken into account in the calculations.

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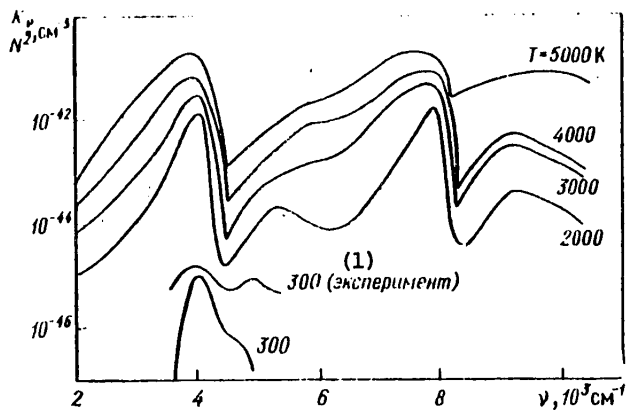

Figure 3.6. Absorption of Molecular Hydrogen Induced by Pressure in the Infrared Region of the Spectrum as a Function of Temperature

Key:
1. Experiment

Second, the presence of a plasma leads to variation of the spectrum near the photoionization threshold. Broadening of the lines lying near the continuum leads to their fusion, which can be interpreted as shifting of the photoionization threshold toward lower frequencies. The presence of coulomb interaction leads to shifting of the ionization equilibrium, as was discussed in Chapter 1. This effect can also be used in dividing the spectrum into discontinuous and continuous. But since the oscillator forces change continuously from the discontinuous spectrum to the integral due to the density of the oscillator forces in the continuum, the resulting absorption coefficient hardly changes; therefore, the boundary was shifted in the present calculations by the value of thermodynamic reduction of the ionization potential. An early survey of papers on the effects of displacement of the photoionization boundary due to the Stark and Debye mechanisms is contained in [63] and later surveys up to 1967 are contained in [38, 15]; therefore, we shall limit ourselves here to an outline of papers written on this problem after 1967.

A series of papers apparently going back to [64] is based on refinement of the Inglis-Teller theory. Let us consider for an example a hydrogen atom in an electric field uniform on atomic size with intensity F. Variation of the ionization potential of the atom in the field is

$$\Delta E(F) = 2e\sqrt{eF}\,.$$

If the distribution function of the electric field in the plasma W(F) is known, then the radiation intensity in the continuum is determined by the average value

$$I(\nu) = A\int^{\infty} \exp\left[-\frac{h\nu - E_n + \Delta E(F)}{kT}\right] W(F)\,dF.$$

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Here $A \sim g(N_i N_e/n^3 T^{3/2})$, where g is the Gaunt factor, n is the main quantum number and N_e and N_i are the electron and ion concentrations. In dimensionless form the field distribution function is

$$W(F)\,dF \equiv W(\beta)\,d\beta, \tag{3.35}$$

where $\beta = F/F_0$, $F_0 = 2{,}61\ eN^{2/3}$. For noncorrelated ions, $W(\beta)$ is the Holtsmark function [69]:

$$W(\beta) = \frac{2}{\pi\beta}\int_0^\infty x \sin x \exp\left[-\left(\frac{x}{\beta}\right)^{3/2}\right] dx. \tag{3.36}$$

The spectral density of the radiation intensity of the continuum for n = 2 was calculated in [64] with Mozer and Baranger field distribution function [65] which differs from (3.36) when the parameter of imperfection Γ increases. The appearance of the interaction parameter in (3.36) is natural since the correlation function of ion distribution contains this parameter (only this parameter in the classical range). Smoothing of the photoionization peak and its gradual fall toward the red side of the boundary was found as a result of calculations. The factor of the realizability of W_n such that the statistical weight of state decreases $g_n \to W_n g_n$ was introduced in the same paper [64] so that the population of state n becomes

$$N_n = \frac{N}{z(T)}\, w_n g_n \exp\left(-\frac{E_1 - E_n}{kT}\right). \tag{3.37}$$

The field distribution function $W(\beta, \Gamma)$ calculated by Hooper [67] was used in [66]. The Shroedinger equation with potential distorted by the external field was solved to determine the condition of decay of the bound state. In this case the decay of the bound state occurred when the minimum height of the barrier formed by the incident coulomb field of the nucleus on the one hand and by the external field on the other was compared to the energy of the bound state. The following integral was selected as the factor for realizing the bound state

$$w_n = \int_0^{F_n/F_0} W(\beta)\,d\beta. \tag{3.38}$$

This method was used to calculate the absorption coefficients of the plasma for photoionization propagated into the low-frequency range from the boundary. It was assumed in the calculations that the photoionization cross-sections are independent of the electric field disturbing the atom. Paper [68] is devoted to this same problem (although with a less clear physical meaning).

In [69] the n_i - T-diagram was divided into three zones as a function of the relationships between the last observed quantum number n_1, the last realized quantum number due to the effect of microfields n_2' and the last realized level in the Debye field n_2''. The lines fuse in the range $n_1 < n_2', n_2''$ and for calculations the photoionization cross-section can be lengthened to the low-frequency part of the spectrum to level n_1. The density of the oscillator forces with respect to energy,

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according to a statement of the authors, has a gap caused by the nonhydrogen-like density of states and by the behavior of the square of the dipole moment of the electron in the short-range (due to interaction) electron-ion interaction potential in the range $n_2' < n_1, n_2''$ and $n_2'' < n_1, n_2'$. The photoionization threshold in this "nonrealization mode" can be easily expressed and the interval either free of spectral lines or with weak lines is adjacent to it. Comparisons by the authors of the absorption coefficients to experimental results for continuous radiation of an argon plasma permit this interpretation.

It was found in Chapter 1 that the thermodynamic weight of highly excited states is non-Boltsman and it can be represented for a hydrogen atom in the form $n^2F_n(\beta)\exp(\beta E_n)$ and the weight function $F_n(\beta)$ varies from 1 to 0 upon transition from the ground to highly excited states. We find the contribution to radiation from bound states with the same accuracy as when finding the contribution of bound states to thermodynamic functions [17].

Plasma interaction with the radiation field is described by a Hamiltonian (in the atomic system of units):

$$H^{int} = -\frac{1}{c}\int j(x)\,A(x)\,dr. \tag{3.39}$$

Here calibration with scalar potential equal to zero was adopted and the vector potential is

$$A(x) = \frac{1}{\sqrt{V}}\sum_{k,\rho} e_{\rho,k}\left(\frac{2\pi c^2\hbar}{\omega}\right)^{1/2}\left[a_{k,\rho}e^{i(kr-\omega t)} + a^{+}_{k,\rho}e^{-i(kr-\omega t)}\right]. \tag{3.40}$$

Here $a_{k,\rho}$ and $a^{+}_{k,\rho}$ are the operators of photon annihilation and production and $e_{\rho,k}$ is the photon polarization vector with frequency $\omega = 2\pi c\nu$. The operator of charged particle current in the representation of interaction with respect to an electromagnetic field and Heizenberg representation with respect to interacting particles has the form

$$j(x) = \frac{i\hbar}{2}\sum_{\lambda}\frac{e_\lambda}{m_\lambda}\left[\nabla\psi^{+}_{\lambda}(x)\,\psi_\lambda(x) - \psi^{+}_{\lambda}(x)\,\nabla\psi_\lambda(x)\right] - \sum_{\lambda}\frac{e^2_\lambda}{2m_\lambda c}A_\lambda\psi_\lambda(x)\,\psi_\lambda(x). \tag{3.41}$$

The subscript λ indicates the variety of particles with charge e_λ and mass m_λ.

The probability of radiation per unit time, averaged by the initial states i and added by finite states f is:

$$dw = \frac{2\pi}{\hbar}\sum_{i,f} e^{\beta(\Omega + \mu_\lambda N^i_\lambda - E_i)}\,|\langle i\,|\,H^{int}\,|\,f\rangle|^2\,\delta(E_i - E_f - \hbar\omega)\,\frac{V dk}{(2\pi)^3}. \tag{3.42}$$

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Substituting Hamiltonian (3.39), we find:

$$dw(q, \omega) = \frac{4\pi^2 \omega d\omega dO}{\hbar c^3} \left(\delta_{\alpha\beta} - \frac{q_\alpha q_\beta}{q^2}\right) K_{\alpha\beta}(q, \omega), \tag{3.43}$$

where O is an element of the solid angle.

$$K_{\alpha\beta}(q, \omega) = \sum_{i,f} e^{\beta(\Omega + \mu_\lambda N_\lambda^i - E^i)} \langle f \mid j_\alpha(0) \mid i \rangle \times$$
$$\times \langle i \mid j_\beta(0) \mid f \rangle \delta(k_i - k_f - q)\, \delta(\omega - \varphi_{if}).$$

Here the transition frequency of the system is $\omega_{if} = E^i + \mu_\nu N_\lambda^i - E_f - \mu_\lambda N_\lambda^f$. Let us express the correlation function of currents $K_{\alpha\beta}$ by a two-particle lagging Green function:

$$G_{\lambda\lambda'}^R(x_1 x_2;\ x_2' x_1') = \theta(t - t')\, \mathrm{Sp}\left\{e^{\beta(\Omega + \mu_\lambda N_\lambda - H)} \times \right.$$
$$\left. \times \left[\psi_\lambda^+(x_1') x_\lambda(x_1)\, \psi_\lambda^+(x_2')\, \psi_{\lambda'}(x_2')\right]\right\} \tag{3.44}$$

Coordinate x also includes the time variable and in expression (20.12) $t_2^+ = t_2' = t'$ and $t_1^+ = t_1' = t$. Let us turn to the Fourier transform with respect to coordinates and time and let us calculate the track by a complete system of eigen-functions of the Hamiltonian H. As a result we find

$$\tilde{G}_{\lambda\lambda'}^R(q_1 q_2;\ q_3, q_4, \omega) = \delta(q_1 + q_2 - q_3 - q_4)\, G_{\lambda\lambda'}^R(p, p';\ q, \omega); \tag{3.45}$$

$$G_{\lambda\lambda'}^R(p, p';\ q, \omega) = (2\pi)^3 l \sum_{i,f} e^{\beta(\Omega + \mu_\lambda N_\lambda^i - E^i)} \frac{1 - e^{\beta\hbar\omega_{if}}}{\omega_{if} + \omega + i0} \delta(q +$$
$$+ k_i - k_f) \left\langle i \left| a_{\lambda'}^+\left(p - \frac{q}{2}\right) a_\lambda\left(p + \frac{q}{2}\right) \right| f \right\rangle \left\langle f \left| a_\lambda'\left(p' + \right.\right.\right.$$
$$\left.\left.\left. + \frac{q}{2}\right) a_\lambda'\left(p' - \frac{q}{2}\right) \right| i \right\rangle. \tag{3.46}$$

Comparing (3.43) and (3.46), we find the relationship of $K_{\alpha\beta}$ and $G_{\lambda\lambda'}^R$:

$$K_{\alpha\beta}(q, \omega) = \frac{\hbar^2}{(2\pi)^{12}} R_l \sum_{\lambda,\lambda'} \frac{e_\lambda e_{\lambda'}}{m_\lambda m_{\lambda'}} \int dp\, dp'\, p_\alpha p_\beta' \frac{G_{\lambda\lambda'}^R(p, p', -q, -\omega)}{1 - e^{\beta\hbar\omega}}. \tag{3.47}$$

The lagging Green function is determined by analytical continuation of the two-particle temperature Green function to the imaginary semi-axis:

$$G_{\lambda\lambda'}^R(p, p', q, \omega) = \frac{\hbar}{i} [G_{\lambda\lambda'}(p, p', q, \omega_k)]_{i\omega_k \to \hbar\omega + i0}; \tag{3.48}$$

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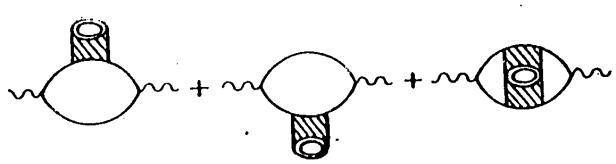
$$G_{\lambda\lambda'}(p, p', q, \omega_k) = \frac{1}{\beta^2} \sum_{\omega_1\omega_2} \exp(i\omega_1 0^+ + i\omega_2 0^+) G_{\lambda\lambda'}\Big(p + \frac{q}{2},$$

$$\omega_1, p' - \frac{q}{2}, \quad p' + \frac{q}{2}, \omega_2 + \omega_k, \quad p - \frac{q}{2}, \omega_1 - \omega_k\Big)(t \to +0).$$

Multiplying the probability of radiation dw by the photon energy, we find the spectral density of the energy emitted per unit volume of plasma [76]:

$$\frac{de_\omega}{d\omega} = \frac{4}{3\pi} \frac{e^2\omega^3 (1 - \exp \beta\hbar\omega)^{-1}}{c^3 m^2 \hbar^3} \operatorname{Im} \int \frac{dp dp'}{(2\pi\hbar)^3} pp' G^R_{pp'}(\omega). \tag{3.49}$$

The following diagrams were added in [70] to calculate the contribution of radiation occurring due to bound states:



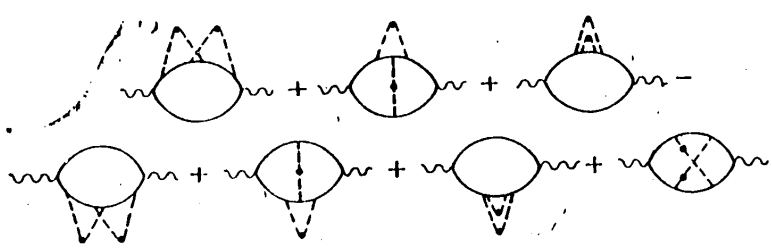
The double line here denotes the ion line while the singe line denotes the electron line. As a result of summation the expression for the radiation intensity reduces to standard form (broadening of the lines is not taken into account):

$$\frac{de_\omega}{d\omega} = \frac{4e^2\hbar n_a}{3m^3c^3 z} \sum_{n,m} \exp(-\beta E_m)\, \omega^2_{mn} \,|\, p_{nm} \,|^2 \delta(\hbar\omega + E_n - E_m). \tag{3.50}$$

Here the statistical sum of the atom is

$$Z = \sum_n n^2 e^{\beta E_n} F_n(\beta). \tag{3.51}$$

Formula (3.49) was used in [72] to take into account corrections for density to the bremstrahlung of electrons in the fields of atoms when the length of the free path of the electron is comparable to its de Broglie wave. The interaction potential of an electron and atom was regarded as short-range and only s-scattering was taken into account. As a result of summation of the diagrams



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the following expression was found:

$$de_\omega = de_\omega^{(0)} [1 + Nq\lambda_T f(\beta\omega)]. \quad (3.52)$$

The function f(x) is presented in [72]; parameter $Nq\lambda_T$ (q is the transport scattering cross section of the electron on an atom, λ_T is the thermal de Broglie wave length and N is the density of atoms) determines the unpaired nature of electron scattering on atoms. In this case an increase of the effective collision frequency with an increase of density leads to an increase of deceleration radiation intensity.

The corrections to optical properties discussed until now are related to a weakly imperfect plasma. If there is a significant increase of density, the positions of the energy levels of atoms and the matrix elements, i.e., the oscillator force in the discontinuous and continuous spectra, vary. The largest number of calculations with respect to shift of levels was made by Thomas-Fermi and Hartree-Fock methods in a model of a restricted atom [53, 73-77, 88-91]. Variation of oscillator forces related to an increase of cesium density was calculated in [73] and this variation is presented in Figure 3.7 at T = 0 and in Figure 3.8 for a photoionization cross-section with level 6s. The considerable dependence of the photoionization cross-sections and oscillator forces on density indicates the need for further detailed investigations in this field.

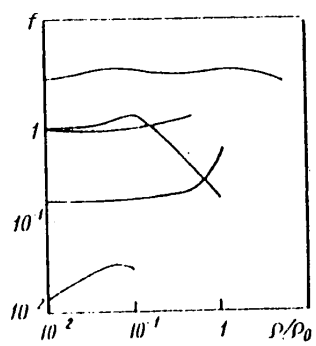

Figure 3.7. Variation of Oscillator Forces of Cesium as a Function of Density of Substance [52] (ρ_0 = 1.8785 g/cm^3)

3.7. Discussion of the Method and Results of Calculations of the Optical Characteristics of Working Media

The elementary mechanisms of absorption described in this chapter were included in the program for calculation of the spectral absorption coefficient of the working substance, which is one of the discussed mixtures for a pure substance in the plasma state. Calculations were made in the temperature range from 4,000 to 40,000 K for mixtures of different composition containing 3, 10 and 50 percent alkali metal and pressures of 0.1, 1, 10 and 100 MPa. The correction for induced emission $K_\nu = K_\nu' [1 - \exp(-hc\nu/kT)]$, which is significant at low temperatures, was introduced

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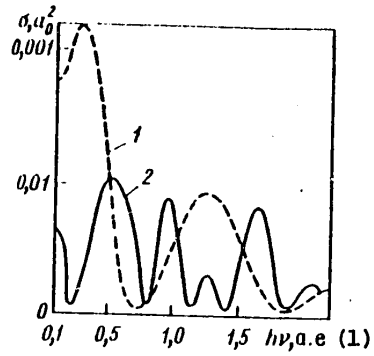

Figure 3.8. Photoionization Cross-Section of 6s-State of Cesium as a Function of Density [52] (1 - $\rho = 10^{-2}\rho_0$; 2 - $= \rho_0$)

Key:
1. Atomic unit

when calculating the total absorption coefficient. Graphs of the spectral density of absorption coefficients are presented in Chapter 5 for a number of temperatures and pressures found by summation of the contributions made by individual mechanisms in specific spectral ranges.

As indicated above, the high concentration of charged particles leads to a decrease of the ionization potentials of atoms and this limits the number of realizable levels from which photoionization occurs. Therefore, the number of levels was limited by the extent of reduction of the ionization potential and the photoionization thresholds were shifted toward a thermodynamic decrease of the ionization potential. If density increases, absorption in isolated lines of alkali metals insignificant due to their broadening because of interaction with surrounding particles. When calculating molecular absorption, averaging in the spectral range of $\Delta\nu$ in formula (3.26) implied that the absorption spectrum is quasi-continuous due to overlapping of the rotational lines occurring as a result of particle interaction in the plasma at high pressure. However, the cross-sections themselves of elementary processes and a number of other values were found in approximation of an isolated atom without regard to the effect of high pressure, which should be reflected in the accuracy of total calculations. Moreover, other assumptions were also made. Due to the absence of experimental values, estimated calculations of the oscillator forces were made for Na_2, K_2, NaH and KH molecules in the approximation when only two external electrons were taken into account. This is also true of the error in calculating the absorption coefficient. It is difficult to estimate the accuracy of these calculations: it is different in different spectral intervals and depends on temperature since different elementary processes which are known with different degree of reliability determine absorption at different temperatures in given sections of the spectrum. Moreover, some approximations in calculation of the thermodynamic effect which gives a relative value of the contribution of one or another elementary process may introduce a specific error in calculation of the total absorption coefficient. Taking this into account, the

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accuracy of these calculations can be determined by comparison with experimental results (see section 4.7).

It is difficult to give the complete characteristics of the optical properties with the large variety of mixtures and the complex dependence of the absorption coefficient on frequency, temperature and other parameters; therefore, let us note only the main characteristics. High absorption coefficients in the visible and infrared regions of the spectrum for those temperatures where the plasma is ionized to a significant degree are typical for pure alkali metals. Molecular bands and atomic lines that lead to peaks in the spectral dependence of the absorption coefficient make an important contribution to absorption in these regions of the spectrum at low temperatures. Pressure mainly affects the absolute value of the absorption coefficient, introducing its own corrections to the spectral dependence through the extent of shift of the photoionization peaks and the number of levels participating in absorption. The spectral dependence of the absorption coefficients of lithium, sodium, potassium and cesium are shown in Chapter 5 for different temperatures and pressures. The radiant thermal conductivity coefficient of alkali metals increases sharply with an increase of temperature at all pressures. This is related to the high secondary ionization potential of alkali metals and their transparency in the far ultraviolet region.

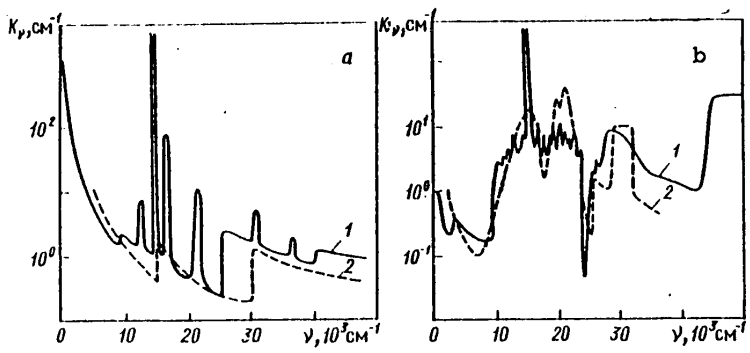

Figure 3.9. Absorption Coefficient of Lithium Plasma at Pressure of p = 1 MPa and temperature of T = 4,000 K (b) and p = 1 MPa and T = = 12,000 K (a): 1--data of authors; 2--data of [7]

The dependence of the radiant thermal conductivity coefficients for mixtures of hydrogen and alkali metals is characterized by the presence of a second minimum in the temperature range of 10,000-15,000 K, which gradually disappears as the addition of the alkali metal increases. This minimum is explained by an increase of the absorption coefficient in the ultraviolet due to hydrogen components.

The optical properties of a mixture of uranium with alkali metals, i.e., of a medium which is formed as a result of diffusion on the boundary of two zones--uranium and the alkali metal are also of interest to calculate the transfer of radiant energy. The thermophysical properties of a mixture of uranium and potassium are presented in Chapter 5. The addition of potassium to uranium does not

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significantly alter the nature of its spectrum but is felt in the absolute value and in the parts of the absorption coefficient in individual spectral regions.

Comparison of the results of calculations to other theoretical calculations is difficult since only calculations of the optical properties of alkali metals [7] where, however, the method of calculating the total absorption coefficient of a plasma is not described, are known to the authors. Nevertheless, comparison of the absorption coefficient of the lithium plasma to the results [7] presented in figure 3.9 shows agreement in characteristic value but it is obvious from the figures that the considered spectral information is abundant in the given paper.

The results of theoretical calculations are compared to experimental data in Chapter 4.

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GENERATION AND DIAGNOSIS OF AN IMPERFECT PLASMA

Moscow TEPLOFIZICHESKIYE SVOYSTVA RABOCHIKH SRED GAZOFAZNOGO YADERNOGO REAKTORA in Russian 1980 (signed to press 1 Aug 80) pp 147-189

[Chapter 4 from the book "Thermophysical Properties of Working Media of the Gas-Phase Nuclear Reactor", by Viktor Konstantinovich Gryaznov, Igor' L'vovich Iosilevskiy, Yuriy Georgiyevich Krasnikov, Nina Ivanovna Kuznetsova, Vladimir Ivanovich Kucherenko, Galina Borisovna Lappo, Boris Nikolayevich Lomakin, Georgiy Alekseyevich Pavlov, Eduard Yevgen'yevich Son and Vladimir Yevgen'yevich Fortov, Atomizdat, 1,800 copies, 304 pages]

[Text] 4.1. Characteristic Features of Experimental Investigation of an Imperfect Plasma

The ambiguity of calculations in a weakly imperfect plasma is determined mainly by inaccuracy of the input information about the ionization and dissociation potentials, electron energy levels, cross-sections of elementary processes and so on. The results of calculations in the range of this inaccuracy agree with numerous measurements of the properties of a weakly imperfect plasma [1-5]. However, a significant part of the plasma of a gas-phase nuclear reactor is found under conditions of strongly interparticle interaction where formal conditions of the applicability of perturbation theory are violated so that calculations are extrapolation in nature. The question arises of the substantiation and accuracy of this type of extrapolation that requires the use of experimental material. However, the number of experimental papers devoted to an imperfect plasma is very limited. Specifically, direct measurements of the thermophysical properties of a plasma of working substances in the range of full-scale pressures and temperatures of a gas-phase nuclear reactor cannot now be made. Therefore, to estimate the quality of the theoretical approximations used, one must resort to experiments with substances convenient for direct experimentation, bearing in mind the simulation of the properties of the plasma by the interaction parameter.

The characteristic feature of the first experiments with an imperfect plasma is the absence of a complete complex of independent measurements, which forces one to utilize theoretical concepts of unchecked accuracy when interpreting them. It is natural that this circumstance leads to known ambiguity of the results which, however, can be used for qualitative conclusions about the properties of the plasma and specifically about its phase composition. For our purposes investigations of

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a high-density plasma with appreciable coulomb interaction and developed thermal ionization will be of greatest interest. Experiments whose results were found on different installations with duplication of the means of diagnosis will mainly be used in quantitative comparison in the given chapter. These experiments can be carried out with cesium and inert gases and they are described in more detail here.

A dense plasma is a very inconvenient object for experimental investigation due to the great difficulties of generation and diagnosis of this medium. Therefore, this section of high-temperature thermophysics requires the use of nontraditional experimental methods. It is significant that there are optimum conditions corresponding to the maximum value of the interaction parameter for experiments with an imperfect plasma. The presence of this optimum is caused by two circumstances: superheating and degeneration of the electron component of the plasma. Let us consider the case when Boltsman statistics ($n_e\lambda_e^3 << 1$) is applicable. Isothermal compression of this plasma causes an increase of the coulomb interaction energy ~ $e^2n_e^{1/3}$ and accordingly an increase of the parameter of imperfection Γ. But the interparticle distance ~ $n^{1/3}$ decreases in this case and when it becomes comparable to the length of the thermal de Broglie wave of an electron $\lambda_e = (2\pi\hbar^2/m_ekT)^{1/2}$, the electron component of the plasma is degenerated. In this case the typical kinetic energy are Fermi energy $\varepsilon_F \sim \hbar^2 n_e^{2/3}/2m_e$ and the parameter of imperfection $\gamma \sim 2m_e n_e^{-1/3}\hbar^{-2}e^2$. Further compression of a degenerate plasma leads to an increase of the kinetic energy and consequently to a relative decrease of the effects of imperfection. This renormalization of interaction is manifested in an ordinary electron-ion plasma at high densities corresponding to electron concentrations of n_e ~ 10^{28} m^{-3}, unachievable for most plasma experiments.

The electron concentration with isochor heating of a gas during the initial stages of ionization increases very sharply with an increase of temperature n_e^2 ~ $T^{3/2}\exp\exp(-I/kT)$ since the parameter of imperfection Γ also increases. A further increase of temperature causes total ionization of the plasma $n_e \approx$ const and a reduction of Γ due to an increase of kinetic energy. It is natural that similar optimum conditions caused by superheating of the plasma also occur with isobaric and impact compression of the plasma. Detailed calculation of these optimums is presented in [6-8], which were the basis for development of the corresponding experimental installations.

The considerable difficulties of experimental investigation of an imperfect plasma are related to the need for high local energy concentrations in dense media [9]. To do this, the experimental installations should have high-capacity energy sources and devices for rapid feeding of this energy to the object under investigation. This object should in turn be adequate for confident diagnosis of geometric dimensions. The available possibilities are shown schematically in Table 4.1, where the typical (not necessarily maximum!) parameters of energy sources and experimental devices used in high-energy physics are presented. The extreme parameters presented in Table 4.1 do not at all correspond to the maximum effects of coulomb interaction in this case due to the restrictions considered above on degeneration and superheating of an imperfect plasma. Moreover, the given data were frequently obtained on different experimental investigations.

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Table 4.1. Energy Sources and Experimental Devices Used in High-Energy Physics

(1) Первичный источник энергии	(2) Конечная форма энерговыделения	(3) Плотность энергии, МДж/см³	(4) Температура, эВ	(5) Давление, МПа	(6) Полная энергия, МДж	(7) Длительность, с	(8) Мощность, Вт
Химические ВВ (9)		10^{-2}	0,5	$5\cdot10^{4}$	—	10^{-7}	10^{10}
	(10) Схлопывание металлических пластин	0,8	60	10^{6}	3	10^{-6}	10^{12}
	Магнитное поле 1 МЭ (11)	$4\cdot10^{-3}$	0,3	$5\cdot10^{3}$	5	10^{-6}	$5\cdot10^{12}$
	(12) Магнитное поле 25 МЭ	2,5	200	$2,5\cdot10^{6}$	1	10^{-7}	10^{13}
	Взрывные генерато (13) ры плазмы	10^{-2}	60	10^{4}	30	10^{-6}	10^{12}
Ядер- (14) ные ВВ		10^{4}	10^{7}	10^{9}	—	10^{-6}	10^{22}
	(15) Нейтронный нагрев	10	50	$2\cdot10^{6}$	10^{3}	10^{-6}	10^{15}
	(16) Ударные волны в твердом теле	5	50	$5\cdot10^{6}$	10^{4}	$3\cdot10^{-6}$	10^{15}
	(17) Ударные волны в газе	0,3	40	$2\cdot10^{4}$	10^{7}	10^{-5}	10^{18}
Сжатый газ (18)	(19) Адиабатическое сжатие	$2\cdot10^{-6}$	0,3	15	10^{3}	$6\cdot10^{-3}$	10^{5}
	(20) Ударные трубы пневматические	10^{-4}	1	25	10^{-2}	10^{-4}	$3\cdot10^{8}$
	(21) Ударные трубы на горении	10^{-5}	2	1	$2\cdot10^{-2}$	$3\cdot10^{-4}$	10^{8}
(22)	Электроразрядные ударные трубы	10^{-5}	2	0,1	10^{-2}	10^{4}	10^{8}
Конденсатор (23)		10^{-8}	—	—	40	10^{-5}	10^{12}

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Table 4.1 [Continued from preceding page]:

Первичный источник энергии	Конечная форма	Плотность энергии, МДж/см³	Температура, эВ	Давление, МПа	Полная энергия, МДж	Длительность, с	Мощность, Вт
(24) Роторная машина		10^{-3}	—	—	100	10^{-4}	10^{12}
Индукционный накопитель (25)		10^{-4}	—	—	100	10^{-4}	10^{12}
Аккумулятор (26)		$5 \cdot 10^{-4}$	—	—	1000	10^{-3}	10^{12}
	(27) Быстрый взрыв проволочек	$5 \cdot 10^{-2}$	4	10^{4}	10^{-3}	10^{-6}	10^{9}
	(28) Медленный взрыв проволочек	$2 \cdot 10^{-2}$	0,5	$5 \cdot 10^{1}$	10^{-3}	10^{-4}	10^{7}
	(29) Импульсные разряды	10^{-3}	10	10^{3}	10^{-4}	10^{-3}	10^{9}
	(30) Плазменный фокус	10^{-2}	1000	1	10^{-4}	10^{-5}	10^{10}
	(31) Дуги высокого давления	10^{-5}	2	10^{3}	10^{-4}	—	10^{4}
	(32) Печные эксперименты	10^{-6}	0,3	$5 \cdot 10^{2}$	10^{-3}	—	10^{3}
Лазер (33)		10^{-6}	—	—	$0,5 \cdot 10^{-3}$	10^{-10}	10^{13}
	Мишень (34)	10^{4}	$5 \cdot 10^{3}$	10^{7}	0,5	10^{-10}	10^{13}
(35) Электронный пучок		10^{-6}	—	—	1	10^{-8}	10^{13}
	Мишень (34)	$5 \cdot 10^{3}$	$5 \cdot 10^{3}$	10^{6}	0.1	10^{-8}	10^{13}

[Key on following page]

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Key [Continued from preceding page]:

1. Primary energy source
2. Finite form of energy release
3. Energy density, MJ/cm^3
4. Temperature, eV
5. Pressure, MPa
6. Total energy, MJ
7. Duration, seconds
8. Output, W
9. Chemical explosives
10. Collapse of metal plates
11. Magnetic field of 1 MOe
12. Magnetic field of 25 MOe
13. Explosive plasma generators
14. Nuclear explosions
15. Neutron heating
16. Shock waves in solid
17. Shock waves in gas
18. Compressed gas
19. Adiabatic compression
20. Penumatic percussion fuses
21. Combustion percussion fuses
22. Electric discharge percussion fuses
23. Capacitor
24. Rotor machines
25. Induction storage device
26. Storage battery
27. Rapid explosion of wires
28. Slow explosion of wires
29. Pulsed discharges
30. Plasma focus
31. High-pressure arcs
32. Furnace experiments
33. Laser
34. Target
35. Electron beam

Two main problems arise in experimental investigation of a dense plasma. The first is to find possible qualitatively new physical phenomena and the second is to find the quantitative characteristics of a strongly compressed plasma to compare them to theoretical models. These two problems also determine the variety of the methods used and the objects of investigation.

4.2. Electric Methods of Producing an Imperfect Plasma

If the plasma parameters are not very high, it can be produced over a prolonged period of time in stationary arcs and furnaces. The widespread method of creating a plasma is the furnace method [10, 11], where energy is delivered as a result of thermal conductivity from the solid wall confining the plasma and heated by an external electric heater. The maximum temperatures of this type of installation are limited to a value of approximately less than 3,000 K. At these temperatures even a cesium plasma (ionization potential of Cs ~ 3.89 eV) is ionized very weak-17 (~ 1 percent [12]), which makes reliable determination of the coulomb interaction effect difficult [12, 13].

The effectiveness of this method increases sharply in the molten metal range of parameters, where it is the main source of information about the thermodynamics of the liquid phase and about the curve of high-temperature boiling of mercury and alkali metals. In this case one can reach the critical point for mercury, cesium and rubidium, while the critical parameters of the remaining metals can be estimated by similar extrapolation [10, 14]. The derived data make it possible to formulate the modified principle of thermodynamic similarity for metals [15, 16] and to estimate on this basis the thermophysical properties of the remaining metals of the periodic table.

Measurements of the electric conductivity of mercury and cesium at subcritical pressures and temperatures yield valuable information about the structure and

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nature of interparticle interaction in a weakly ionized plasma [10, 11, 17]. The effects of imperfection are manifested very clearly here--a decrease of density by 20 percent leads to a decrease of the electric conductivity of mercury by a factor of 10^4 [18] and of cesium by a factor of 10^3 [19]. The presence of an exponential increase of electric conductivity during the initial stages of plasma compression [17] is explained by the polarization interaction of charges and neutrals. Electron interaction with a neutral in approximation of isotropic scattering leads to a decrease of the ionization potential by $\Delta I_{ea} = n_a h^2 \sqrt{\pi q / m^2}$, where q is the elastic scattering cross-section of slow electrons on neutrals. Ion polarization of a neutral yields the addition $\Delta I_{ia} = 4\pi n_a e^2 \alpha / r_0$, which leads to the exponential dependence of electron concentration [17]

$$n_e \sim \exp(-I + \Delta I_{ea} + \Delta I_{ia})/2kT \sim \exp kn_a \qquad (4.1)$$

with an exponent close to the value yielded by experiment. An additional mechanism that determines the electric conductivity of a weakly ionized plasma is electron localization on density fluctuations [20], which leads to the appearance of heavy cluster formations. Quantitative calculation of these phenomena under experimental conditions [18] is very difficult due to the absence of detailed data on the internal structure and interaction of these clusters. The given theoretical methods are applicable for describing the initial sections of bonding when the electrons in the system are few and the main type of interaction is charge-neutral interaction. In the general case complex self-consistent quantum-mechanical calculations are required here that specifically take into account strong coulomb interaction, zone formation and deformation of electron energy spectra. The influence of these effects specifically show measurements of optical absorption of mercury [21], where displacement of the red absorption boundary and a one-third decrease of the enrgy range between the ground 6s and first excited 6p states was recorded with subcritical compression of mercury. The aggregate of experimental data on measurement of the physical properties of low-boiling metals indicates the absence of specific phase transitions caused by bonding of the plasma [22] and by strong charge-charge [5, 23] and charge-neutral [24] interaction. The phase diagram of low-boiling metals thus has the customary appearance with a single critical point on the curve of the liquid-gas interface. The possibilities of stationary methods of furnace heating are illustrated in Figure 4.1, where the phase diagram of cesium--the most popular object to investigate an imperfect plasma--is shown. A range of parameters with strong charge-neutral interaction is realized by this method whereas higher heating of the material is required to produce appreciable effects of coulomb interaction.

For this purpose one must exclude contact of the plasma with the walls of the installation and must carry out internal heating of the medium. This method of generation is realized in electric arcs [25], for which inhomogeneous distribution of the physical parameters through the thickness is typical. This inhomogeneity is determined by competition of Joule dissipation of electric energy and dissipation of the liberated heat by diffusion and convection and with an increase of pressure it is determined by thermal conductivity and radiation [3, 26]. In high-pressure arcs, radiant energy transfer is the main mechanism and numerical solution of the radiative transfer equation is required with regard to fine details of the spectrum of resonance lines, the ionization continuum and reabsorption to calculate the

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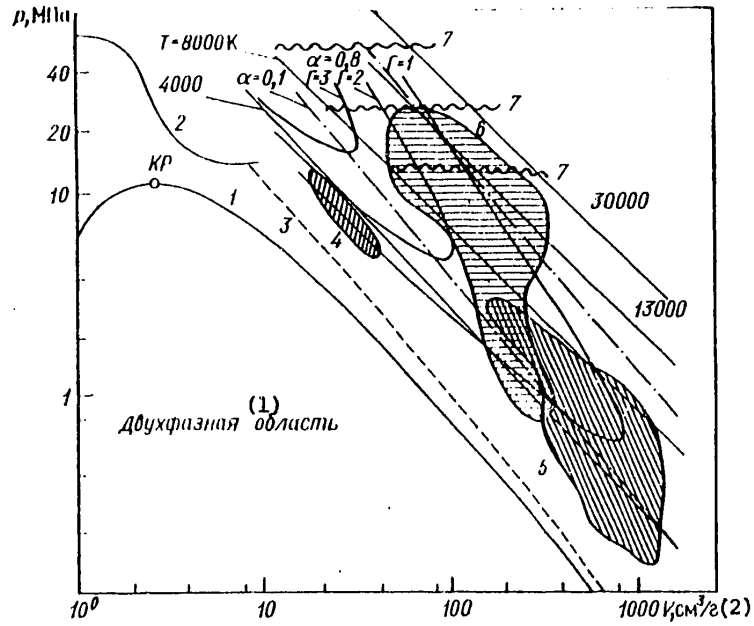

Figure 4.1. Phase Diagram of Cesium: 1--saturation curve; 2 and 3--range of statistical experiments (results of [10, 11, 19]); 4--range achieved isentropic compression [90]; 5 and 6--range achieved by incident and reflected shock waves; 7--"slow" electric explosion [83, 84] (α--degree of ionization)

Key:
1. Two-phase region
2. cm^3/g

physical conditions in the arc column [25, 27, 47, 28]. It is natural that the accuracy of these calculations inevitably decreases as plasma density increases. Moreover, the problem of stabilizing the combustion of the arc becomes acute with an increase of gas pressure ($p \geq 10$ MPa) [3, 25]. The methods used here to suppress instabilities are very diverse--these are stabilization by electrodes [25], by a gas vortex [28, 31], by fixed [29, 31] or rotating [32] walls and by sampling the gas through electrodes [30, 33, 34]. These measures permit one to achieve stable hot arcs at pressures of approximately 100 MPa although the problem of stabilization has apparently not been resolved [3] even at pressures of approximately 10 MPa for some gases (helium and hydrogen).

The main parameters measured for stationary arcs are the volt-ampere characteristics and the radiation emerging from the plasma. Using the equation of energy balance, this permits one to determine the electric and thermal conductivity of the plasma [35, 36] at low pressures (approximately 0.1 MPa) when convective and radiant transfer can be disregarded. The most complete results have now been obtained for an argon and hydrogen plasma at $T = (3\text{-}5)10^3$ K and $p \sim 0.1$ MPa. Like data on viscosity [37, 38], we use these results for comparison with the results of calculating the critical coefficients of a plasma (see Chapters 2 and 3).

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The use of electric arcs as powerful light sources determined the great interest in their optical properties. Transition from the discontinuous to the continuous spectrum as a result of broadening and fusion of spectral lines and shifting of the photoionization thresholds as plasma pressure increases [4] was recorded in early papers [39, 40]. A further increase of pressure leads to an increase of radiation intensity, which approaches the radiation of a black body [28]. Thus, the transport properties of a low-temperature plasma can be measured in high-pressure stationary arcs and the first manifestations of imperfection caused by coulomb interaction can be recorded. However, the difficulties of annealing and stabilization of stationary arcs at high pressures and also the limitation of power supply sources do not permit one to find electron concentrations in this maner greater than approximately $3 \cdot 10^{24}$ m^{-3}. Stationary methods sharply lose their effectiveness upon transition to the range of higher densities and parameters of imperfection $\Gamma > 0.25$.

Significantly higher energy concentrations can be achieved in pulse experiments (see Table 4.1). The pressures and temperatures developed in this case are comparable to or exceed the ultimate strength of the structural materials of the installations. In this case a plasma with high parameters can exist only during a short time determined by the energy capabilities of power supply sources and the cooling kinetics of the plasma volume. For a plasma with extremely high parameters (p 10^3 MPa), one can accomplish only inertial confinement during a time determined by the transit of its heated regions and by structural breakdown of experimental installations. These circumstances place increased requirements on diagnosis, which is a special complex problem in this case.

The fact is that use of traditional spectroscopic methods [41] in the physics of an imperfect plasma is difficult due to the conditionality of separating electrons into free and bound and also due to the optical opaqueness of a dense plasma. If the dimensions of the boundary region of a plasma are sufficiently high, the thermal radiation emerging from the nucleus of the plasma volume will be shielded by cold layers of plasma. In this case the recorded radiation carries information about the external boundary of the plasma and a complex system of integrodifferential equations that describe the dynamics of motion and radiation transfer in the plasma [42] must be solved to estimate the processes inside the plasma region. In order that the emerging radiation carry information about the processes inside the plasma, it is necessary that the path of the radiation inside the plasma exceed the characteristic dimension on the boundary of the plasma volume. In most cases this dimension is sufficiently large since it is determined by convective or radiant heat transfer processes, whereas the path of radiation decreases sharply with an increase of plasma density. Apparently a sufficiently sharp boundary whose role is performed by the shock wave front can be produced only with shock compression of the plasma. The thickness of this front is very small since it is determined by viscous dissipation processes and comprises several lengths of the free path of molecules [42, 43]. As already mentioned, it is difficult to establish a specific boundary between the electrons of the continuous and discontinuous spectra in a dense plasma and it is especially difficult to take into account the effect of strong interaction on the profile, position and intensity of the spectral lines and the boundaries of photorecombination and ionization continuums. Therefore, due to the difficulties of interpretation, detailed spectroscopic methods of diagnosing a dense plasma are unreliable even in those cases when optical diagnosis is still possible.

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These circumstances force one to turn to methods of diagnosis that utilize excitation of deep electron and nuclear energy levels which, due to their high binding energy, are hardly sensitive to "weak" (approximately 1 eV) external interparticle interaction. Among these methods, the method of pulse roentgenography [44-46], which makes it possible to determine the extent of absorption and consequently the density of a plasma, has been realized in practice. The characteristic feature of this method is the low inertia, absence of perturbations in the plasma and independence of external interparticle interaction.

The same independence of results from external conditions is inherent to nuclear [47] and positron [48] methods of diagnosis. In the first method it is suggested that the method of nuclear resonance of γ-fluorescence, based on recording the Doppler broadening of the nuclear γ-line excited by an external radiation source with energy of hundreds of keV, be used to measure the plasma density and temperature. The method of positron diagnosis [48] consists in recording short-wave photons occurring in the plasma upon annihilation of electron-positron pairs. The γ-radiation occurring in both methods, due to its short wave length, emerges unhindered from the plasma and is therefore accessible to recording. Unfortunately, these methods are still in the development stage due to practical difficulties. Moreover, the significant time required for recording limits the application of these methods in pulse investigations.

Thus, the possibilities of measurements in a dense plasma are very limited. Only the more general integral characteristics of plasma processes (pressure, total currents, voltages, embedded energy and so on) are accessible to recording. Obtaining detailed physical information from these data must be carried out within the framework of various types of limiting theoretical assumptions with use of calculated thermophysical data. It is natural that this leads to appreciable ambiguity [49, 71, 72] of the results obtained (see Figure 4.20, a). Independent recording of the total complex of physical parameters with possible duplication of the measurement methods must be carried out to obtain reliable data about the properties of an imperfect plasma.

The most widespread in pulse investigations of a dense low-temperature plasma are now two methods of energy accumulation--electric and dynamic methods of plasma generation. In the first of these methods, the plasma is heated as a result of Joule dissipation of energy when pulses of electric current are passed through the gases or condensed media [3]. This method of generation is the traditional one in plasma physics. The compactness of the experimental installations and the possibility of easily varying the composition and parameters of the plasma over a wide range distinguish it. At the same time these methods are essentially related to passing powerful electric currents and to formation of magnetic fields, which make diagnosis difficult and which cause inhomogeneities and development of various instabilities in a moving plasma. Dynamic methods of plasma generation are based on viscous dissipation of energy in the front of powerful ionizing shock waves or during isentropic compression. Thus, extremely high parameters of an imperfect plasma can now be achieved. It is significant that the hydrodynamics of motion can be used in this case to measure the parameters of a shock-compressed medium, which is an additional significant advantage of the given method in the absence of reliable means of diagnosing a dense plasma. However, dynamic experiments, due to the high output of the installations, require development of expensive specialized experimental benches and the use of remote high-speed methods of recording [50].

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Let us briefly consider each of these methods. Pulse discharges, compared to steady discharges, permit one to produce higher plasma parameters since they do not require stabilization and the problem of cooling the walls confining the discharge does not occur. The typical discharge times are dependent on the design features of the installations and vary over a wide range from microseconds to tens of milliseconds. The lower bound is selected from the condition of plasma thermalization and the need for diffusion of radiation and the magnetic field to the plasma channel [3]. The maximum combustion time of the discharge corresponds to the condition of the smallness of the thermal skin-layer $\delta \sim \sqrt{\lambda t}$ (λ is temperature conductivity) so as not to permit excessive heating and breakdown of the walls.

Pulsed discharges in gases are usually created by discharge of a capacitor bank across an interelectrode gap. The most complete measurements have now been carried out in xenon [51-53], where it was possible to measure pressure (with a piezosensor), temperature and concentration of electrons (interferometrically) [52, 53] in a rarefied plasma with n_e up to $3.4 \cdot 10^{24}$ m^{-3} and $\Gamma \sim 0.1$. Experiments in helium were performed with less complete diagnosis [54]. The operating modes of flash lamps, when the plasma fills a fixed volume, were investigated in detail, which permits one to estimate the number of electrons in the problem of determining the electric conductivity of the plasma. These experiments were carried out with an argon, xenon, krypton [53, 55, 56], air, nitrogen and SF_6 plasma at $p \sim 0.1$-2 MPa and $T \sim 10$-$30 \cdot 10^3$ K.

As the pressure increases, complications arise in these experiments with ignition of the discharge, for which either a low-power arc [57, 58] or electric explosion of a conductor [83] is used during the initial stages. This stimulated discharge made it possible to produce arcs in hydrogen at $p \sim 40$ MPa [59], in neon ($p \sim 50$ MPa [60], in helium ($p \sim 20$ MPa) [61] and in argon ($p \sim 160$ MPa) [60, 63]. However the high temperatures developed in this case (up to $45 \cdot 10^3$ K) lead to superheating of the plasma, as a result of which the parameters of imperfection do not exceed values of $\Gamma \sim 0.3$. Moreover, it is difficult in pulsed gas discharges to determine the dimensions of the plasma channel and accordingly to estimate the mass of the plasma. To make a more definite judgment about the amount of plasma, one must limit the discharge gap, i.e., one must carry out the discharge in a closed space. In this case the experimental cell manufactured from transparent material is filled with a gas (hydrogen [64], air [65] or xenon [66]) at initial pressure on the order of 0.1 MPa and is then heated by a current pulse to approximately 20,000 K at pressure of approximately 15 MPa; in this case $n_e \sim 10^{25}$ m^{-3} and $\Gamma \sim 0.2$. Experiments in thin capillary tubes (approximately 1 mm) had to be carried out to use optical methods of diagnosis, which has an appreciable effect on the homogeneity of the plasma. We note that the given experiments differ advantageously from most pulsed discharges by the capability of recording the equation of state of the plasma.

Methods related to heating the condensed phase of matter are used to move to the range of higher densities. These are capillary discharge with an evaporating wall (KRIS), a discharge pressed against the wall by a magnetic field (PP) and a pulsed discharge in liquids (IRZh), electric breakdown of solid dielectrics and electric explosion of metal wires. The electric power introduced into the discharge in these methods is consumed for evaporation and ionization of the condensed phase,

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which causes the plasma to move either in the axial (KRIS and PPR) or in the radial directions (IRZh and explosion of wires).

A capillary discharge with evaporating wall permits one to produce a high-density ($n_e \sim 10^{23}$-10^{26} m^{-3} and $\Gamma \sim 0.1$-0.2), high-temperature (approximately 20-50 10^3 K) and high-pressure (up to 80 MPa) plasma which is determined by the mechanical strength of the capillary tube walls. The problem of the mechanical strength of the capillary tube is eliminated to a significant degree in PPR, where the plasma flux is pressed by a magnetic field against the channel of the material being investigated. The composition of a KRIS and PPR plasma can be varied over a very wide range by varying the insulator material, as which quartz [67], lithium hydride [68, 69] and yttrium oxide [70] are used. A KRIS burns stably in capillary tubes up to 10 mm long, which permits its use as a pulsed brightness standard with T = = 39,000 K $\pm$ 10 percent. The use of a graduated capillary tube in [69] made it possible to measure the paths of optical radiation in a lithium hydride plasma; we use thses data in section 4.7.

The capillary tube was manufactured from transparent quartz filled with molten metal prior to the experiment for the possibility of recording the plasma temperature of alkali metals in experiments in isobaric heating [71, 72]. A quasi-steady state corresonding to pressure from 13 to 110 MPa and temperature of approximately (4-16)10^3 K is established in the system during the experiment (approximately $2 \cdot 10^{-2}$ second). Interpretation of the processes in this discharge is a complex task [71]. Recording the volt-ampere characteristics and surface radiation of the discharge permits one to estimate the temperature profile of the plasma and its electric conductivity by solving the Elenbaas-Heller equation [72]. However, the need for assumptions leads to the fact that the results are dependent on the method of processing [49, 71, 72].

The maximum although not always controllable plasma parameters in pulsed electric experiments can be achieved with pulse discharge in a liquid initiated by electric explosion of a wire [73-75] and by additional compressed detonation of an explosive charge [76]. Under the given conditions it is extremely difficult to make complete measurements, the results are contradictory [75, 76] and estimates of the plasma properties made on the basis of electric and optical recordings raise doubts since they clearly contradict the equations of state plotted for this region [77].

Electric detaonation of conductors by current [78-81] is used extensively in high-temperature thermophysics to determine the properties of refractory metals up to the melting point [79], to determine the characteristics of the evaporation process, estimates of the latent boiling enthalpies of metals [81] and so on. These experiments are usually carried out with low initial pressure and rapid introduction of electric energy into the metal, which leads to development of diverse instabilities of the volatile metal [81] and this limits the use of these methods in quantitative plasma investigations.

Restriction of the discharge channels by diaphragms was carried out in [46, 82] to reduce the effect of inhomogeneities. The combination of electric detonation with a cascade arc made it possible to heat a titanium plasma to T $\approx$ (17-18)10^3 K,

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$p \approx 40$ MPa and $n_e \approx 10^{26}$ m^{-3}, which corresponds to $\Gamma \approx 0.5$. We note that this is the only experiment where the measured values of electric conductivity exceeded Spitzer values.

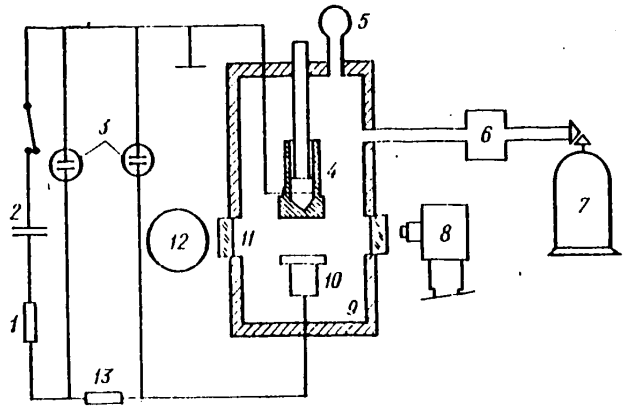

Figure 4.2. Schematic Diagram of Installation for Slow Electric Explosion of Cesium [83]: 1--ballast resistor; 2--capacitor bank; 3--oscillograph; 4--cesium ampule; 5--pressure gauge; 6--thermocompressor; 7--argon tank; 8--spectrograph; 9--high-pressure chamber; 10--anode; 11--optical windows; 12--high-speed movie cameras; 13--reference resistor

The method of slow introduction of electric power and the use of counter pressure ($p \approx 50$ MPa) of an inert gas was used in [83-85] to suppress the instabilities arising during pulsed heating. Setting up the experiment in this manner made it possible to carry out extensive investigations of the thermophysical properties of molten metals [85, 86] in the range of parameters of p up to 500 MPa and $T \approx 5{,}000$ K, approaching the high-temperature boiling curve. It is typical that no anomalies of any kind caused by metal-dielectric phase transition [22] or by plasma effects [5, 87] were found here. Attempts to expand this method to the range of a "gaseous" plasma cause the development of inhomogeneities of the plasma column, the reason for which is boiling of the fluid and development of superheating instability [88] caused by a decrease of electric conductivity with an increase of temperature.

The effects of boiling were eliminated in [83, 84] during isobaric heating of cesium in the subcritical range of pressures. A diagram of the experiment is presented in Figure 4.2. The discharge occurring between electrodes was stabilized by a gas wall of argon with constant pressure of 12.5, 25 and 50 MPa. Measurement of current and voltage jointly with optical recording of plasma expansion permits one to determine the caloric equation of state and the electric conductivity of cesium at temperatures up to 35,000 K, where $\Gamma \sim 0.7$. We note that superheated instability caused by the sharp dependence of electric conductivity on temperature was also manifested here with high energy contributions. Setting up the experiments in a similar fashion was also used in [85, 86].

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It is typical for electric methods of imperfect plasma generation that, due to the insufficient energy capacity of the power supply sources (see Table 4.1), a plasma with high parameters can be produced in small geometric dimensions. This leads to significant inhomogeneities of the plasma and greater difficulties in diagnosing it.

4.3. Dynamic Methods in the Physics of an Imperfect Plasma

Dynamic methods of investigation, based on hydrodynamic methods of heating, permit one to find extremely high energy densities, inferior in this regard only to laser and electron beam energy, but differing advantageously from the two latter by a greater volume of plasma and greater completion of means of diagnosis. Three methods of dynamic generation of a plasma--isentropic and shock compression and also isentropic expansion of matter first compressed by a shock wave--have now become most widely used.

Experiments on adiabatic compression of saturated cesium vapors were conducted from a two-stage adiabatic shock tube [89, 90] heated to produce a sufficiently high pressure of saturated cesium vapors (approximately 0.4-0.7 MPa) to 1,300 K. Cesium was compressed to pressures of approximately 5-15 MPa by measn of a relieved metal piston of special design that ensures high hermetic sealing and low friction against the wall. The absence of the two main sources of the growth of entropy--shock waves and heat transfer--was checked in a special series of control experiments. The measured pressure and volume of gas, together with the condition of isentropicity, permit one to determine the plasma energy and temperature. Higher temperatures compared to the furnace method were achieved: $T \sim (3\text{-}4)\cdot 10^3$ K (see Figure 4.1). However, even under these conditions the electron concentration did not exceed approximately 10^{24} m^3 so that the coulomb interaction effects are still manifested weakly here.

The maximum manifestation of coulomb interactions in a cesium plasma should be expected in the range of higher temperatures corresponding to the optimum with respect to superheating of the plasma. Thermodynamic calculations whose results (curves Γ = const and α = const) are presented in Figure 4.1 were made in [6] to establish the optimum. A method of shock compression based on this dissipation of the kinetic energy of the flux in the shock wave front was considered [6] to generate a plasma of optimum parameters.

Comparative analysis shows that the high homogeneity and purity of plasma exchange, the absence of electric and magnetic fields and the high reproducibility of the results make shock waves a convenient tool for investigating a strongly imperfect degenerate [9, 50] and Boltzman [91] plasma. An additional significant advantage of these methods is the possibility of using the relationship of gas-dynamic characteristics to the equation of state of the generated plasma. This relationship is expressed in general form by a complex system of nonlinear (three-dimensional in spatial coordinate) differential equations of transient gas dynamics [42], complete solution of which is found far beyond the capability of even the most modern computers. For this reason one attempts in dynamic investigations to use [42] automodel solutions of gas dynamics--solutions of the transient shock wave type and the centered Riemann rarefaction wave type that express the laws of conservation in simple algebraic or integral forms. Automodel conditions (steadiness, uniformity and so on) of the corresponding friction modes should be provided in this case to use these relations in experiment.

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The initial (noted by subscript 0) and final states are Rankin-Hugonio [92] upon propagation of a steady shock burst through matter r:

$$\left.\begin{aligned} &DV = V_0(D-u); \quad V_0(p-p_0) = Du; \\ &U - U_0 = \frac{1}{2}(p+p_0)(V_0 - V). \end{aligned}\right\} \tag{4.2}$$

Here V is specific volume, p is pressure, U is internal energy, D is the velocity of the shock wave front in the laboratory system of coordinates and u is the jump of mass velocity in the burst.

Relations (4.2) written in this form, being an expression of the general laws of conservation of mass, pulse and energy, do not contain limiting assumptions about the properties of matter being considered. The state of the medium behind the shock wave front is characterized by the values V, p, D, u and U. Measuring any two of them and assuming that the initial states U_0, V_0 and p_0 are known, one can determine by means of (4.2) all the required hydrodynamic and thermodynamic variables. Shock wave velocity D is measurement most easily and accurately by basic methods. Selecting the second measured parameter is dependent on specific experimental conditions.

Analysis of the errors of the relations contained in (4.2) shows that direct recording of density ($\rho = V^{-1}$) of a shock-compressed substance must be carried out in the case of strongly compressed plasma and gaseous media. A method of these measureme ments has now been developed, based on recording of absorption of X-radiation by a cesium [93], argon [94] and air [95] plasma. High accuracy is provided [50] by recording the mass velocity of motion with lower compressability of the system (condensed media). Thus, the parameters of state of a degenerate plasma of metals [50] and of dense Boltzman argon and xenon and plasma [96, 97] were determined. This type of recording permits one to find U = U(p, V).

In experiments to record the curves of isentropic expansion [98, 99] of a substance first compressed and heated in the shock wave front, the states in the centered discharge wave are described by Riemann integrals [42]:

$$V = V + \int_p^{p_n} (du/dp)^2\, dp; \quad U = U_n - \int_p^{p_n} p\,(du/dp)^2\, dp, \tag{4.3}$$

which are calculated along the experimentally measured isentropic curve u = u(p). The subscript "n" is related to the beginning of discharge.

Making measurements at different initial conditions and intensities of shock waves, one can determine the caloric equation of state U = U(p, V) in the range of the p-V-plane overlapped by Hugonio adiabatic curves. In experiments conducted up to the present, shock wave intensity was varied by variation of the output of the excitation sources determined by the pressure of the thrusting gas [91, 100], by the type of explosive (VV), by the throwing devices and targets [96, 98]. Moreover, different methods of varying the parameters of the initial states were used.

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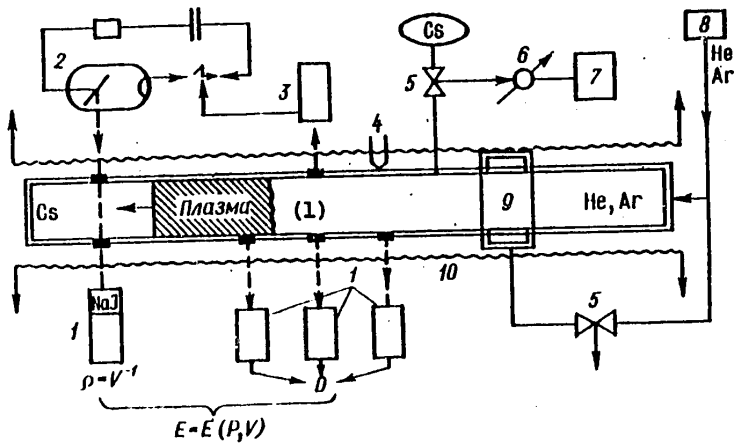

Figure 4.3. Diagram of Heated Shock Tube: 1--photomultiplier with cathode repeater; 2--X-ray tube; 3--pulse roentgenography circuit; 4--thermocouples; 5--valve; 6--vacuum meter; 7--vacuum pumps; 8--compressor; 9--membranes; 10--winding of heater

Key:
1. Plasma

A pneumatic shock tube, the diagram of which is presented in Figure 4.3, was developed [91] to create powerful shock waves in cesium vapors. The installation approximately 4 meters long was heated to approximately 1,000°K to produce high initial pressures (p ~ 0.05 MPa) of cesium vapors. The shock wave was excited in a low-pressure chamber upon expansion of helium, argon or mixtures of them first heated to approximately 50 MPa into the cesium vapor. The parameters of a shock-compressed plasma were additionally increased by using shock waves reflected from the end of the tube. According to the dynamic approach, the two mechanical parameters that characterize shock compression were measured independently in each experiment. Basic optical [91] and X-ray [101] methods were used to record the velocity of the shock wave front and to monitor the steadiness of the shock-compressed plasma flow. The density of an imperfect plasma was determined by the pulsed roentgenography method on absorption of long-wave X-radiation by the plasma. Measurement of these two parameters, according to the laws of conservation (4.2), is equivalent to recording the caloric equation of state of a shock-compressed plasma over a wide range of parameters shown in Figure 4.1. Experimental determination of the plasma temperature was made difficult under these conditions by absorption of light by the cesium molecules. Therefore, the temperature was determined on the basis of the caloric equation of state U = U(p, V) found experimentally by numerical solution of the linear inhomogeneous differential equation that expresses the first law of thermodynamics [102]:

$$[p + (\partial U/\partial V)_p]\,\partial T/\partial p - (\partial U/\partial p)_V\,\partial T/\partial V = T. \tag{4.4}$$

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This permits one to find the thermodynamically complete equation of state of an imperfect cesium plasma. The first data on shock compression of cesium were found in [91, 93] and were later confirmed by independent experiments [45, 101], where the accuracy of measurements was increased somewhat. Data now obtained in shock tubes yield consistent thermodynamically complete information [100] about the equation of state of a cesium plasma in the range of parameters: $p = 0.15-20$ MPa, $T = (2.6-20)10^3$ K, $n_e = 5\cdot10^{21}$ to $5\cdot10^{25}$ m^{-3} and $\Gamma = 0.2-2.2$ It is significant that, along with these results, the electric conductivity was measured by the method of variation of Q-factor of a vibrational circuit [103].

Interpretation of a large number of experiments with cesium indicated a significant contribution [93, 100, 104] of the discontinuous spectrum to the thermophysical characteristics of the system. This circumstance made it necessary to conduct experiments with a plasma of other chemical elements over as wide a range of parameters as possible. Inert gases were selected as the object of investigation in dynamic experiments [7, 94, 96, 97, 105] due to the fact that the absence of expenditures on dissociation and the high molecular mass make compression and heating of them in the shock wave front effective, while the absence of complex molecular and ion-molecular formations and detailed study of the elementary processes significantly facilitate interpretation of the results. Thermodynamic and hydrodynamic calculations showed [7, 8, 105] that the optimum experimental conditions correspond to shock wave intensities of approximately 9 km/s in argon and approximately 5 km/s in xenon. In this case an increase of shock wave velocity leads to superheating of the plasma, while an increase of initial gas pressure leads to degeneration of the plasma and consequently to a reduction of interaction. Realization of the optimum range of parameters requires that high-enthalpy working substances new to plasma physics be used. Condensed explosives were used as the active components in the developed explosive imperfect plasma generators [6, 7, 8] due to their significant energy capacity and speed of detonation transformation, which leads to a high level of output of the experimental installations (see Table 4.1). Moreover, the modern technology of manufacturing initial explosive charges and the level of understanding and calculation of high-speed hydrodynamic phenomena permits one to produce a homogeneous dense plasma for several microseconds in the space on the order of a centimeter, which is quite sufficient to make measurements with high accuracy (unlike, for example, phenomena from laser heating, exploding wires and capillary tube discharges).

An imperfect plasma generator, which is an explosive shock tube (Figure 4.4) with condensed explosive as the active element, was developed in [7] to realize the optimum range of parameters. Powerful ionizing shock waves were excited in this generator by expansion of the detonation products of explosives having high dynamic characteristics $p \approx 3\cdot10^4$ MPa, $T \approx 5\cdot10^3$ K, $\rho \approx 2.3\cdot10^3$ kg/m^3 and $u \approx 2.1\cdot10^3$ m/s after completion of the detonation transformation reaction. The use of a specially shaped lens and selection of the corresponding dimensions of the initial explosive charge ensured uniformity and steadiness of the parameters of the detonation front when it emerged from the explosive into the gas being investigated. The total energy release in the experiment was approximately $3\cdot10^6$ J with output of 10^{11} W, which of course led to destruction of the entire device. This circumstance forces one to conduct experiments in specially protected rooms while observing safety measures. The results of the measurements showed the high uniformity and quasi-steady nature of the plasma flow, which was accomplished by inertial delay of the

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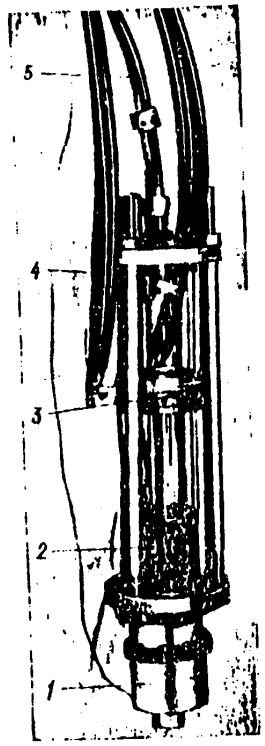

Figure 4.4. Photograph of Explosive Shock Tube: 1--detonation lens; 2--explosive charge; 3--ring insert with electric contact sensors and window for X-ray measurements; 4--mirror for optical recordings; 5--tube for delivery of gas

shock-compressed plasma by the massive walls of the shock tube channel. Good reproducibility of the shock wave parameters was achieved in experiments with the given generators.

An explosive imperfect plasma generator was equipped with a complete set of independent thermodynamic and electrophysical measurements. A diagram of these measurements is presented in Figure 4.5.

The velocity of the shock wave front was measured by basic electric contact and optical methods with an accuracy of 1-1.5 percent. The density of the shock-compressed plasma was determined by the pulsed roentgenography method by absorption of soft X-radiation by the plasma. The radiation source was a X-ray tube operating in the forced mode and the receiver was a sodium iodide scintillator and photomultiplier. The developed method ensured accuracy of recording density of approximately 92 percent, high time characteristics ($\leq 10^{-7}$ second) and the absence of perturbations in the plasma flow. The plasma temperature was measured by the

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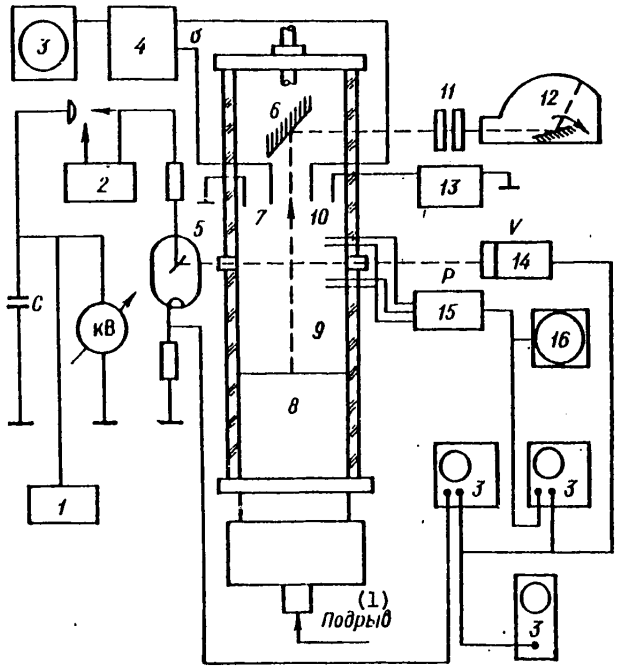

Figure 4.5. Diagram of Measurements in Explosive Imperfect Plasma Generator: 1--power supply of X-ray tube; 2--control unit; 3--oscillographs; 4--differential amplifier; 5--X-ray tube; 6--mirror; 7--potential and current probes for recording electric conductivity; 8--explosive charge; 9--generator channel; 10--probes for measuring velocity of shock wave front; 11--filter and attenuator; 12--high-speed movie camera; 13--direct current source; 14--photomultiplier with scintillator; 15--power supply of electric contacts; 16--velocity recording oscillograph

Key:
1. Blast

brightness method and will be described below. Recording the velocity of the front and measuring the density determine according to laws of conservation (4.2) the equation of state of a plasma $U = U(p, V)$, which together with the measured temperature of $T = T(p, V)$, represents thermodynamically complete information [94] about an argon plasma at $p = (1.6\text{-}5.8)10^2$ MPa, $T \simeq (15.5\text{-}23)10^3$ K, $\Gamma \approx 1.3\text{-}2.2$ and $n_e(1.5\text{-}3.5)10^{26}$ m^{-3}.

Due to the high level of electric conductivity (approximately 10^5 Cm/m), it was measured by probe methods having high spatial resolution and relatively simple realization under conditions of a single dynamic experiment. A four-point scheme [105] (see Figure 4.5) was used to eliminate the distorting effect of pre-electrode electric layers caused by flow of the strong transport current (approximately

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10^3 A) through the plasma. The dimensions of the plasma probe were measured by roentgenographic and optical methods. The linear nature of the volt-ampere characteristics shows that the developed scheme of diagnostics does not lead to violation of the isothermal nature of the plasma and eliminates the influence of pre-electrode effects--the main deficiency of probe methods in a dense plasma.

A wide range of parameters of imperfection was encompassed by the measurements (see Figure 4.19) from $\Gamma \approx 0.3$, where the difference between theories is slight and there are other data, to $\Gamma \approx 7$, where most theoretical approximations diverge. This range was investigated by using different gases--air, neon, argon and xenon in ranges partially overlapping each other and other measurements.

The parameters of an imperfect plasma close to the maximum possible for a nondegenerate plasma were achieved [96, 97] on linear explosive rectangular shock wave generators. A diagram of one of them is presented in Figure 4.6. Under these conditions the ionizing shock wave occurs upon expansion of metal and polymer targets first compressed to approximately 10^5 MPa by linear explosive throwing devices whose operating principle is based on acceleration of detonation products of metal or polymer strikers, into the gases being investigated. Special attention was devoted during development of these experimental devices to the symmetry of the generated shock waves (asynchronicity $\leq 10^{-7}$ second), reproducibility of parameters (≤ 1 percent) and also the steadiness and uniformity of the gas-dynamic flow, which was ensured by eliminating distorting rarefaction waves from the lateral and contact surfaces of the generator components. The amplitude and duration of the shock waves in a plasma were varied by using explosive systems with different dimensions and brisance and also by variation of the material and thickness of the strikers. The highest parameters were achieved in a device (see Figure 4.6) with total energy release of approximately $30 \cdot 10^6$ J and output of 10^{11} W that accelerates an aluminum striker to $5.92 \cdot 10^4$ m/s. Additional expansion of the velocity capabilities of generators was provided by using easily compressible polymer materials and also by using the effect of evaporation of metal targets in the discharge wave [98].

Joint independent recording of the two kinematic parameters--the velocity of the front and the mass velocity of motion of the plasma--was made in experiments on these generators. The measurements were made by basic electrocontact and optical methods. Open electrocontact sensors recorded the wave front with accuracy of approximately 99 percent on high-speed oscillographs. The mass velocity (error of 1.5-2 percent) was measured by closed sensors of special design that do not react to the shock wave in the plasma and that are triggered at the moment of arrival of the heavy contact surface. The system of sensors was arranged so as to take into account the possible bending of the shock wave and to monitor the parameters of the control pressure pulse. The optical method of measurements is based on recording the glow of the shock wave, variation of the intensity and cutoff of this glow upon reflection of the burst from a transparent obstacle. The plasma emission was scanned and recorded by photorecorders and electro-optical transducers.

As a result of the measurements the caloric and thermal equations of state of an imperfect argon and xenon plasma were determined over a wide range of parameters [96, 97]: $\Gamma \approx 10^{-2}$ to 5.2, $p \approx (0.3\text{-}3.4)10^2$ MPa, $T \approx (5.2\text{-}26)10^3$ K and $n_e \approx 2020$ to $3 \cdot 10^{27}$ m^{-3}. It is interesting that a plasma with density of $1.3 \cdot 10^3$ kg/m^3

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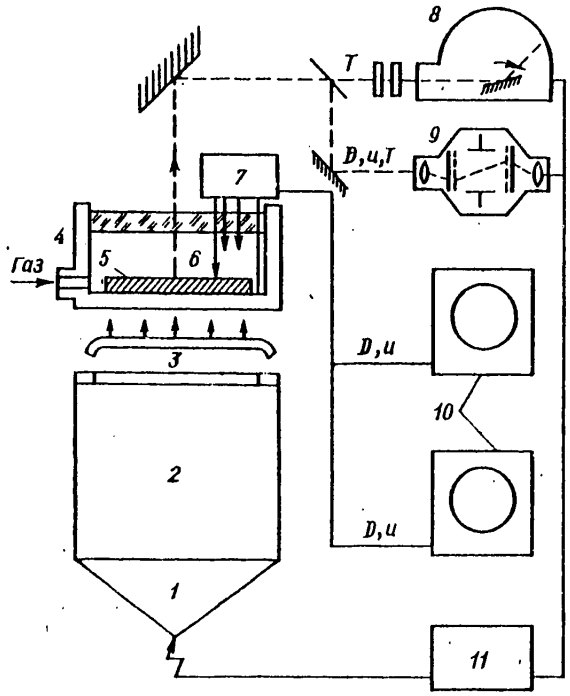

Figure 4.6. Diagram of Experiment in Explosive Rectangular Shock Wave Generator: 1--detonation lens; 2--explosive charge; 3--metal striker; 4--experimental assembly; 5--target; 6--investigated gas; 7--electric contacts and pulse shaper unit; 8--high-speed movie camera; 9--electro-optical converter; 10-oscillographs; 11--synchronization and blast unit

that exceeds the critical density ($1.15 \cdot 10^{13}$ kg/m^3) and approaches the density of the liquid phase of xenon was produced in these experiments.

The characteristic feature of experiments on dynamic regeneration of an imperfect plasma of inert gases is the possibility of making optical measurements [106]. The determining factor here is the circumstance that the thickness of the viscous shock wave is much less than the length of the path of light radiation in the plasma. Therefore, thermal radiation has the capability of emerging unhindered from the plasma psace and yields direct experimental information about the equilibrium temperature and absorption coefficients of a shock-compressed plasma.

The temperature of the shock-compressed plasma was measured by the brightness method [106]. A diagram of the experiment is presentedin Figure 4.7, where explosive rectangular shock-wave generators were used to produce the plasma. The

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dimensions of the plasma layer enclosed between the wave front and the contact surface increases in time--$\delta \sim (D - u)t$--as the shock wave moves in the gas being investigated. In this case the radiation intensity of this layer increases by the law [42]

$$J = J_0 [1 - \exp(-\delta/K_\nu)], \tag{4.5}$$

which permits one, by recording the value of this increase, to find the absorption coefficient of a plasma at selected frequency ν. As the plasma moves further, its thickness becomes greater than the typical path of radiation K_ν^{-1}. In this case the shock wave front radiates like a black body I_0 which determines the temperature of a shock-compressed plasma.

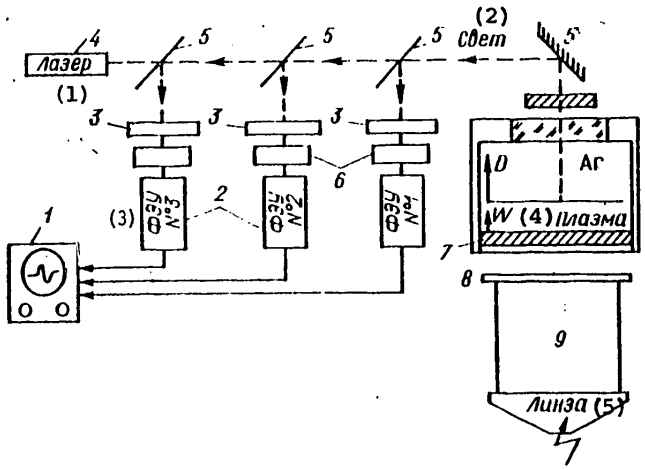

Figure 4.7. Diagram for Measuring Optical Properties of Plasma [95]: 1--oscillographs; 2--photomultipliers; 3--attenuator; 4--adjusting laser; 5--mirrors; 6--filters; 7--target; 8--striker; 9--explosive charge

Key:

1. Laser
2. Light
3. Photomultiplier
4. Plasma
5. Lens

Thus, analysis of the presently available experimental material shows that the most complete experimental information on the thermophysical properties have been obtained for a cesium plasma and a plasma of inert gases. Therefore, it is these data that can be used for quantitative comparison to the results of theoretical methods developed in Chapters 1-3.

4.4. On Condensation of an Imperfect Plasma

One of the most interesting qualitative conclusions of the theory of an imperfect plasma is prediction of the capability of stratification of a strongly compressed

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plasma to phases of different density. In this case the plasma phase transitions are predicted in different physical situations--in a strongly compressed degenerate [107] (Wigner crystal) and Boltsman plasma [5, 23], during metal-dielectric transition [22], upon metalization of vapors, upon formation of clusters [24], in media excited by optical radiation [108] and so on. The presence of this interesting physical effect would qualitatively alter the customary appearance of the phase diagram of matter [5], leading to the appearance of new phase boundaries (Figure 4.8) and states with unusual physical properties. Specifically, plasma phase transition would fundamentally alter the physical conditions in a gas-phase nuclear reactor and would require a search for new schematic versions of this device. For this reason, primarily to conduct a quantitative analysis of available experiments, one must determine the general qualitative characteristics of behavior of a strongly compressed plasma.

Speaking of plasma condensation [2, 5], it has become a custom to refer primarily to a series of papers of M. Cook et al [109], w ere in the author's opinion, abnormal effects were determined when the detonation wave emerged from a condensed explosive to the free surface of a charge. Investigating this process by means of high-speed measuring equipment, the authors observed with good reproducibility the formation of a brightly glowing plasma cluster which existed for several tens of microseconds and manifested a metallic nature of electric conductivity. The plasma cluster slightly changed its shape during flight and passed through glass tubes without visible breakdown of them, which was related in [109] to the stability (in the terminology of the authors of [112]) of the generated plasma, i.e., to the existence of binding energy and internal pressure in the system, as occurs in a quasi-crystalline model of an electron plasma [107] or in a model of a nondegenerate dense Ecker-Weizel plasma [110, 111]. In the opinion of the authors [109], the quasi-crystalline plasma phase should have density on the order of a solid, which is indicated by model concepts [2, 5].

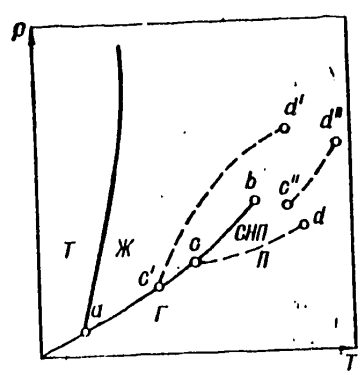

Figure 4.8. Phase Diagram With Regard to Probable Plasma Phase Transitions [5]: a, b, c and d--critical and triple points (the dashed lines denote possible variants); T, Zh, G, P and SNP--solid, liquid, gas, plasma and strongly imperfect plasma, respectively

However, close analysis of [109] showed [95] that the interpretation of the results given in them is not unique and in some cases causes serious objections and is

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inadequate for conclusions about plasma phase transition, the more so since there are no direct measurements of density--the main characteristic of the detected effect--in [109].

The pulsed roentgenography method was used [95] to record the density of a generated and detonation plasma. The results of measurements showed the absence of abnormally high density of the plasma cluster. The results of electrocontact recording of the wave and mass velocities D and u with subsequent calculation of density by laws of conservation (4.2) lead to the same conclusion. The measured density of the plasma was 8-12 times more than the density of air at atmospheric pressure, which is in good agreement with calculations of the state of an air plasma formed behind a strong shock wave front. It is significant that this calculation was made by ordinary formulas of plasma thermodynamics [5] without using any concepts of phase transitions.

The authors of [109] emphasized repeatedly that formation of a plasma cluster is unrelated to the medium surrounding the explosive but is determined by processes of chemical ionization in the detonation wave. From this viewpoint the absence of a gaseous environment is a favorable circumstance and can only intensify the effect. However, experiments conducted in [95] on expansion of detonation products to a vacuum led to the absence of a plasma cloud, which indicates the relationship of the effect to the external environment.

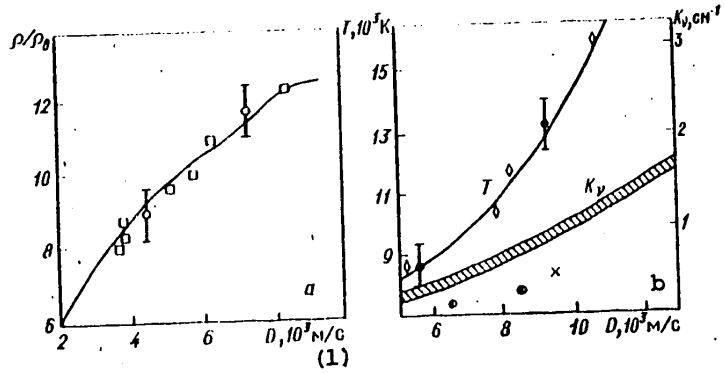

Figure 4.9. Thermodynamic (a) and Optical (b) Properties of Plasma Cluster: O and □ --X-ray and electrocontact methods, respectively, of recording equation of state; ◐, ●, ◊ and X--optical measurements

Key:
1. M/s

The values of static electric conductivity measured by probe methods (the diagram of experiment in [95] is similar to Figure 4.5) of a plasma are in good agreement with quasi-ideal gas calculations (see Figure 4.19) when using the composition of an air plasma [110]. Recording the thermal radiation emerging from the plasma makes it possible to estimate the radiation characteristics of the plasma and to find its temperature. The data (Figure 4.9, a and b) are also described well by plasma theory.

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The problem of the decay of the pressure wave on the detonation product-air boundary using semi-empirical equations of state of detonation products and the Hugonio adiabatic curves for air was solved in [95] to determine the velocity of motion of the plasma cluster. The derived value of velocity (approximately $9.2 \cdot 10^5$ km/s) is in good agreement with the measurement results and does not require the use of additional doubtful concepts on the "reactive thrust" [109] upon recombination of the metastable phase. Finally, study of the dynamics of plasma motion showed [95] that the plasma stability determined in [109] is a simple manifestation of the inertia of a massive glass shell--an effect used in an explosive shock tube [7] for inertial confinement of a plasma. This circumstance was also the main reason for the erroneous conclusions of [95] about phase transition and about the existence of "binding energy" and "internal pressure" in a dense plasma.

Thus, the experiments and analysis of available data show that the thermodynamic, optical, electric, hydrodynamic and mechanical properties of the plasma cluster are fully described on the assumption that this cluster is formed by compression of air in a strong shock wave front [95, 113], occurring upon expansion of the detonation products of a condensed explosive. The enumerated properties of a shock-compressed plasma are easily explained by existing theories of a strongly imperfect plasma and therefore the conclusions of the authors of [109] about abnormal properties of this plasma cluster, related to the quasi-crystallinity of the plasma, is erroneous.

Papers have appeared quite recently, in one of which the observation of phase transition in a high-temperature dense plasma is preliminarily reported in [114] and in the other of which it is more specifically reported [115]. It is related in [114] to abnormal expansion (an increase of thermal energy and temperature at 1-10 eV/atom) upon transit of the matter to the channel after a powerful shock wave passes through it. However, there are no direct measurements of density in these experiments and temperature was apparently recorded through the optically thick layer of an air plasma and the region of the discharged substance and the flow was distorted by the effect of discharge waves and is known to be transient.

The conclusions in [115] about plasma phase transition were made on the basis of observations of the abnormal behavior of KRIS in polyvinyl chloride and yttrium oxide. The dependence of pressure in the discharge on the length of the capillary tube, instead of a straight line (the usual path), have a form similar to the isotherm of a real gas upon intersection of a two-phase region. However, here as in [115], no direct measurements of density were made, which, together with the absence of calculated data on the rather complex thermodynamic composition, does not permit one to correctly interpret the experimental results. All this does not give one the basis to assume that the hypothesis of phase transition [114, 115] is sufficiently substantiated.

Of special interest is the search for thermodynamic anomalies in metals, where along with "plasma" phase transition, phase stratification caused by overlapping of electron wave functions and metallization of vapors, may be manifested. However, recordings of the thermodynamic and transient properties of a plasma of low-boiling metals (mercury, cesium, rubidium, potassium and sodium), made on furnace installations [10, 11], showed that the phase diagram of these metals in the vicinity of the boiling curve has ordinary appearance with a single critical point.

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Due to collectivization of external electrons, the binding energy and consequently the parameters of the critical point of most metals are sufficiently high. For example, for copper p_{kr} = 750 MPa and T_{kr} = 8,400 K and for tungsten p_{kr} = 1,600 MPa and T_{kr} = 21,000 K [16]. This circumstance leads to appreciable thermal ionization (T_{kr} becomes comparable to the ionization potential of metals) of the metal vapor on the boiling curve, which creates favorable opportunities for manifestation of coulomb interaction effects. On the other hand, the high critical parameters of the metals make it impossible to use stationary methods here and advance to the forefront pulsed and primarily dynamic methods of investigation.

Whereas recording of phase transitions is trivial under quasi-steady conditions, this problem requires special consideration in dynamic experiments. The possible hydrodynamic effects during shock and isentropic compression of a plasma with arbitrary equation of state were analyzed in [116]. The appearance of these effects would be an indication for plasma phase transitions.

According to theoretical analysis [5], plasma phase transition should have been manifested primarily in cesium due to its low ionization potential. Therefore, increased attention was devoted to cesium in the experiments [11-13, 72, 83, 84, 90, 100] and a plasma of this element has now been studied in most detail. However, numerous detailed experiments on adiabatic and shock compression of a cesium plasma did not reveal any thermodynamic or other anomalies. (The values of electric conductivity close to those typical for metals, found in [72], were subsequently reduced by one-half by the authors of [71]).

The dynamic method of isentropic discharge, based on plasma generation upon adiabatic expansion of condensed matter first compressed in a strong shock wave front, was realized in [98, 99] to study the thermodynamic properties of metals over a wide range of the phase diagram. A schematic diagram of this experiment is presented in Figure 4.10.

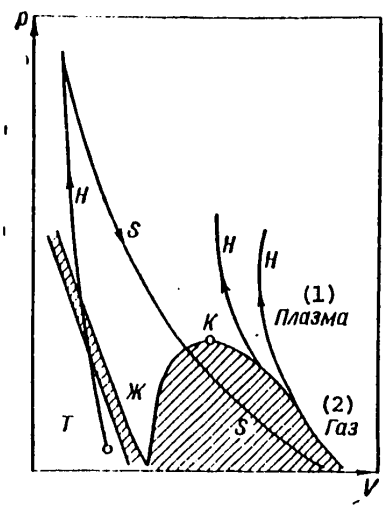

Figure 4.10. Diagram of Method of Adiabatic Expansion: H--adiabatic shock curves; S--expansion isentropic curve; K--critical point; The regions of phase mixture are cross-hatched

Key:
1. Plasma
2. Gas

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The energy release in the condensed phase, which led to melting and evaporation of the metals in the isentropic discharge wave, were calculated to select the optimum conditions of this experiment [117]. Experiments on lead, copper and antimony, conducted up to the present, made it possible to continuously follow the properties of metals in an extensive range of the phase diagram from the strongly compressed condensed state to an ideal gas, including the range of a degenerate and Boltsman plasma and subcritical and two-phase states. This experimental information was the basis for the semi-empirical equation of state [118] that described the data of dynamic experiments and having correct asymptotics to Thomas-Fermi and Debye-Huckel models at extremely high pressures and temperatures. It is significant that the equations of this structure that do not utilize concepts of plasma condensation give it good description of the experimental results on high-speed expansion of uranium [119, 120], copper [119, 121] and lead [121, 122].

The results of optical measurements of condensation upon expansion of shock-compressed metals are presented in a series of papers [122]. Although the authors of [122] were mainly interested in the kinetics of formation of the liquid phase of metals during their isentropic discharge, the data indicate the absence of phase transformations different from the liquid-phase transition.

Thus, the aggregate of data obtained up to the present indicates the continuous variation of the characteristics of metals during their expansion from the solid to the gaseous states. The experiment did not reveal appreciable breaks of the isentropic curves and any hydrodynamic anomalies which could have been interpreted as phase transitions of first kind caused by metal-dielectric transition or phase stratification of an imperfect plasma. An example of the phase diagram of copper is presented in Figure 4.11 [121], where the parameters of the critical point correspond to semi-empirical estimates [16].

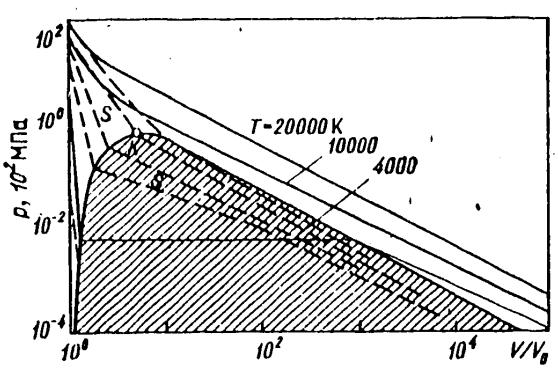

Figure 4.11. Phase Diagram of Copper [121]: K--critical point; S--isentropic expansion curves V_0 = 0.114 cm^3/g; the region of the liquid-vapor mixture is cross-hatched

Along with the method of adiabatic expansion, the method of "slow" electric explosion of conductors at high pressures is being used successfully [83, 86]. Recording of density, temperature, pressure and the energy enclosed in the metal made it possible to determine the thermophysical characteristics of metals (tantalum,

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molybdenum, niobium, lead, tungsten and uranium) over a wide range of parameters: $p \leq 5 \cdot 10^5$ MPa and $T \leq 5{,}000$ K, i.e., up to practically the curve of high-temperature boiling where further heating is accompanied by development of superheated instability. The results clearly indicate the homogeneity of molten metals and the absence of a dielectric liquid phase at high pressures [5, 22]. The numerous results of explosions of metal conductors by electric current also indicate the absence of these types of effects [46, 80, 81].

Thus, the considered experimental information rather specifically indicates the homogeneous composition of an imperfect plasma and the absence of appreciable physical anomalies in its behavior.

4.5. Comparison of Experimental and Calcualted Data on Thermodynamics

The specific methods of generation and diagnosis described in sections 4.2-4.4 permit one to investigate the thermodynamic properties of a dense plasma of different chemical elements over a wide range of pressures and temperatures.

The presently available experimental data, which can be used for quantitative comparison, are related to a cesium, argon and xenon plasma. Data for a cesium plasma encompass a wide range of the phase diagram (see Figure 4.1) and are more detailed, but simultaneous measurement of the caloric and thermal equations of state under conditions of extremely high values of the parameter of imperfection are typical for experiments with an argon and xenon plasma. Based on analysis of sections 4.2-4.4, it is this experimental information that is used for comparison with the results of different theoretical approaches described in Chapter 1.

From the viewpoint of the engineering applications considered in this paper, the main conclusions following from the results of this comparison are that the method used for practical calculations (see section 1.6) describes the experimental information with an accuracy close to experimental even for the highest of the achieved parameters of imperfections (see Figures 4.12-4.18). Since approximation of the second group coefficient and "zero" approximation of the pseudo-potential model of a plasma (section 1.3) in the considered range of parameters yield results essentially coinciding with the present method (see the inset on page 31), the conclusions are also applicable to these theories. At the same time the existing divergence from experiment goes beyond the bounds of its accuracy, with regard to which it makes sense to carry out more detailed analysis to determine the physical nature of the observed difference.

Experiments on cesium were conducted on installations of three types--a shock tube [100], an adiabatic compression tube [90] and by the method of exploding a cesium wire in an inert gas atmosphere [84]. The data are related to different regions of the phase diagram (see Figure 4.1), but partially overlap on the boundaries and agree with each other in the range of experimental accuracy. They all demonstrate one fact with different degree of clarity (directly in [84, 100] and indirectly [90]): the experimentally measured enthalpy H(p, V) in the region of incomplete, but already appreciable ionization is systematically reduced compared to the values (see Figures 4.12-4.16) predicted by traditional theories (see Chapter 1). It is typical in this case that the data of [84], insufficiently accurate to determine the noted effect in the range of single ionization, have satisfactory accuracy to

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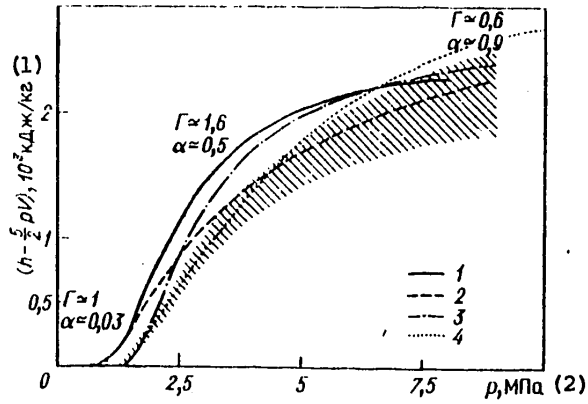

Figure 4.12. Caloric Equation of State of Cesium Plasma (V = 200 cm^3/g); the values of the parameter of imperfection Γ and the degree of ionization α are noted; the band for the smoothed experimental function H(p, V) (± 5 percent) is cross-hatched [100]: 1--ring (Debye) approximation in large canonical group (1.84, 1.85); 2--approximation (1.26-1.30, 1.33) upon selecting the extent of the electron-ion pseudo-potential and the boundaries of the intra-atomic states equal to -kT; 3--approximation found in section 1.2 (1.6-1.16); 4--approximation of ideal plasma with atoms in ground state

Key:
1. kJ/kg
2. MPa

determine it in the range of the beginning of secondary ionization. The most clearly indicated tendency is manifested upon comparison of theoretical values to results having higher accuracy in measurement of the caloric equation of state H(p, V) in a shock tube (Figures 4.12 and 4.13). What follows from this fact? As noted in [100], despite the fact that the divergence is seemingly low (approximately 20 percent), it cannot be eliminated within the considered approaches, selecting one of the traditional coulomb corrections for imperfection and using known methods of limiting the atomic statsum. At the same time the agreement of calculations on an ideal plasma approximation to statsum Q_{Cs} = 2 having no correct substantiation of any kind to experiment was unexpectedly good. Nevertheless this coincidence made it possible in the first experimental paper [91] to assume the need to reduce the corrections for interaction of free charges, which is equivalent to the appearance of additional repulsion unaccounted for by traditional approaches in a strongly compressed plasma.

The theoretical approximations considered in Chapter 1 permit one to achieve better agreement with experiment compared to traditional methods, using sequential approaches. The approximation of section 1.2 provides good agreement with experiment in the range of small degrees of ionization (see Figures 4.12 and 4.13). This was the result of considering the higher terms of the asymptotic expansion of thermodynamic potential [23] by degrees of activity. The effect is primarily related to

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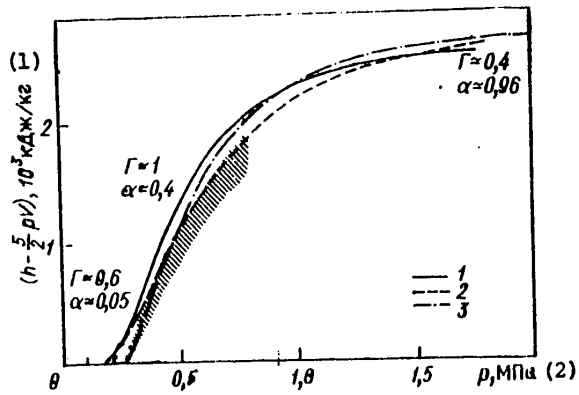

Figure 4.13. Caloric Equation of State of Cesium Plasma (V = 1,000 cm^3/s): 1--approximation of second group coefficient [26, 32]; 2 and 3--the same as in Figure 4.12

Key:
1. kJ/kg
2. MPa

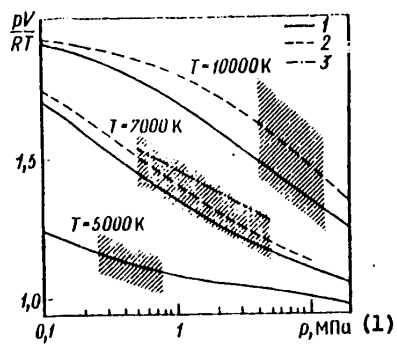

Figure 4.14. Thermal Equation of State of Cesium Plasma. The band of experimental error is cross-hatched [100]. See Figure 4.12 for notations

Key:
1. MPa

a significant (approximately $\tilde{\varkappa} e^2$) energy shift of the ground state of the atom, which differs considerably from the results of previous papers [1, 123]. Translated to the framework of the traditional "chemical" model, this approximation differs from that of the second group coefficient [124] by appearance of a new term proportional to $n_a n_e^{-1/2}$ with sign corresponding to repulsion in the Sachs equation and equation of state (1.45-1.49). Of course, interpretation of the theoretical approximation found in section 1.2 in terms of the chemical model is

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conditional due to the ambiguity of the approach itself to this model (section 1.4), but nevertheless it helps to better understand the physical meaning of the observed phenomenon.

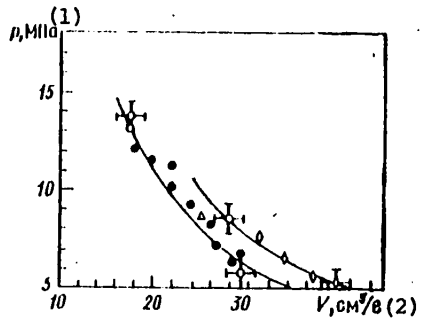

Figure 4.15. Isentropic Compression of Cesium Plasma [90]. The points are experimental data corresponding to the following initial conditions: O--t_0 = 993°C and P = 0.7 MPa; Δ--t_0 = 970°C and P = 0.5 MPa; ⊕--t_0 = 1,016°C and P = 0.59 MPa; ●--t_0 = 993°C and P = 0.6 MPa; ◊ --t_0 = 1,016°C and P = 0.425 MPa

Key:
1. MPa
2. cm^3/g

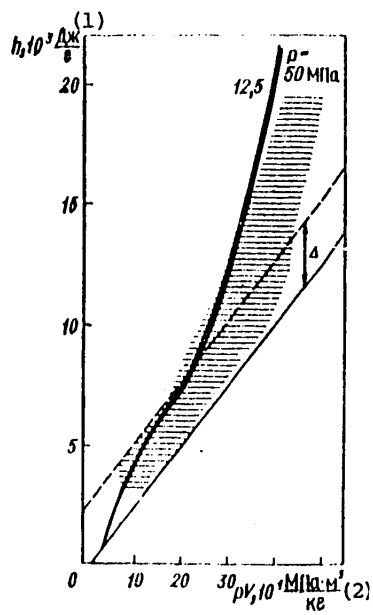

Figure 4.16. Caloric Equation of State of Dense Cesium Plasma [84]: cross-hatched field of values--experimental data; curves--calculation by the method of Chapter 1; Δ--ionization energy

Key:
1. J/g
2. $Mk \cdot m^3/kg$

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Agreement with experiment in the range of developed ionization (see Figures 4.12 and 4.13) is achieved by empirical selection of the electron-ion pseudo-potential $\Phi^*_{ei}(r)$ playing the main role in approximation (1.24)-(1.33), a decrease of the effective percentage of which is equivalent to the appearance of additional repulsion in a strongly imperfect system ($\Gamma \gtrsim 1$) (see section 1.3). Use of this approximation shows that the derived effect of free charge interaction is considerably dependent on the "individuality" of the chemical element and thus the parameters for the pseudo-potentials should be selected for a specific element. There are no experimental data that permit one to follow the variation of parameters upon transition to other alkali metals, hydrogen, uranium and so on.

Until now we have considered only the caloric equation of state H(p, V) and the thermal equation of state p(V, T) was also found on the basis of preliminary experimental information {H, p, V}. In the considered range of parameters the latter is slightly sensitive to selection of the theoretical approximation and is easily described (Figure 4.14) by most of them.

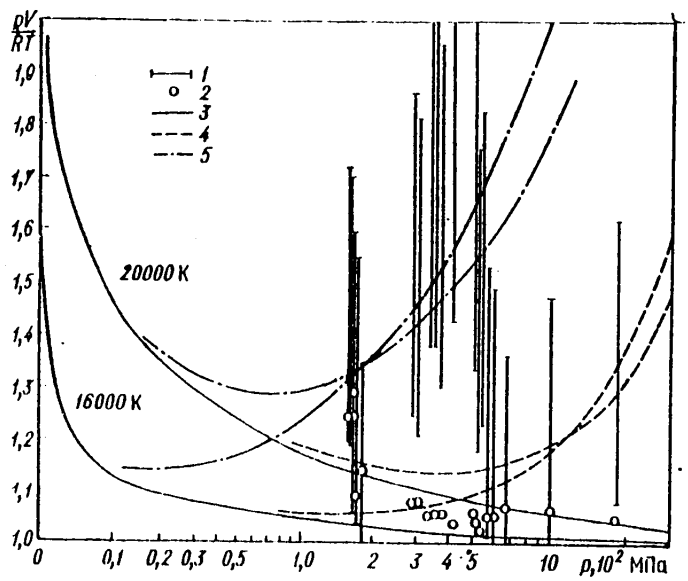

Figure 4.17. Thermal Equation of State of Argon Plasma (p = 100-2,000 MPa and T = 5,000-23,000 K): 1--experimental results of [94, 96]; 2--calculation in approixmation (1.84-1.85) for each experimental point p_{eksp} and T_{eksp}; 3, 4 and 5--calculated isotherms of 16,000 and 20,000 K in approximations: 3--(1.26)-(1.30) and (1.33); 4--with additional consideration of second and third virial coefficients of argon [151]; 5--model of restricted atom (section 1.5)

However, for the experimental results obtained by explosive methods on investigation of a superdense argon and xenon plasma (up to densities typical for the condensed phase), this behavior of the equation of state p(V, T) is not typical [94,

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96]. Traditional methods do not describe the experimental data here (Figure 4.17). At the same time the caloric information H(p, V) found by independent measurement, the same as in experiments with cesium, has a distinct tendency toward a decrease compared to the calculated information (Figure 4.18). However, the nature of this effect may be different in view of the considerably higher plasma compression.

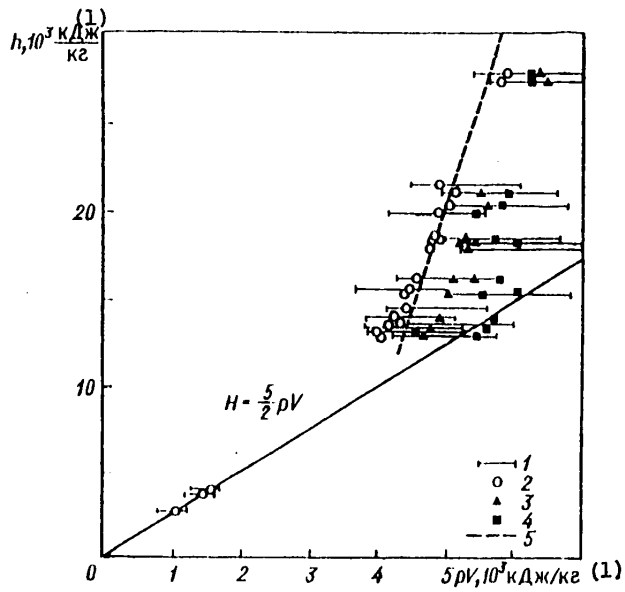

Figure 4.18. Caloric Equation of State of Argon Plasma: 1--see notations for Figure 4.17; 2, 3 and 4--calculation for each experimental point V (p_{eksp}, H_{eksp}) in approximations: 2--(1.84) and (1.85); 3--section 1.2; 4--section 1.2 in approximation of restricted atom (section 1.5); 5--calculated isotherm T = 20,000 K in approximation (1.26)-(1.30) and (1.33)

Key:
1. kJ/kg

Actually, the interparticle distances under the experimental conditions are almost an order less than in experiments with cesium. Under these conditions, along with strong coulomb interaction ($\Gamma \sim 1$-5), considerable interatomic interaction is manifested which leads to a shift and deformation of the electron energy levels of atoms and ions [125]. Calculations made using self-consistent field methods (section 1.5) demonstrate the specific role of excited states of atoms and ions in these conditions. The shift and deformation of energy levels found in approximation of the restricted atom model in a superdense plasma correspond to the appearance of additional repulsion; it is natural that the results of these calculations are considerably dependent on the specifics of electron therms of chemical elements and are more important for highly excited states.

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Analysis of the thermal equation of state (see Figure 4.17) also indicates the manifestation of repulsive mechanisms which cannot be described only by using virial coefficients corresponding to interaction of atoms in the ground state. Thus, agreement with experiment is actually achieved in all the considered theoretical approaches by introducing additional effective repulsion and reducing the contribution of bound states not described within the framework of the traditional method of calculation.

4.6. Comparison of Experimental and Calculated Data by Transfer Coefficients

Most attention was devoted to electric conductivity in experimental investigations of a low-temperature plasma due to the considerable ambiguity of theoretical predictions and the extreme importance of these characteristics for solving numerous applied problems. An additional circumstance that attracted experimenters to this problem is the relative simplicity and good perfection of measurement methods and also the possibility of making measurements under the most diverse experimental conditions. Therefore, very extensive experimental material has now been accumulated that was obtained for a plasma of different elements in a wide spectrum of installations using different recording methods. Part of this material is presented in Figure 4.19, which is schematic in nature for some experiments due to the quantum effects in a dense plasma and the difficulties of determining the coulomb contribution to the measured electric conductivity.*

In early experiments [2], the achieved parameters of imperfection did not exceed approximately 0.1. However, due to the partial ionization even in these cases, inaccurate consideration of electron-atomic scattering led to a difference of measurements from theoretical values, which was erroneously related to the manifestation of coulomb imperfection. Subsequent uniform processing of the experimental data [126] by the Frost method (2.97) with detailed analysis of the elastic electron scattering cross-sections on atoms led to the agreement of measured values to Spitzer theory [142]. This range is noted in Figure 4.19 by the cross-hatching.

The range of increased imperfections became the object of systematic investigation only very recently when dense plasma generators appeared and the physical processes occurring in them became understood. As a result of these investigations information was obtained about the electric conductivity of a plasma over a wide range of parameters from an ideally plasma state where there is good agreement of theory and experiment up to extremely high values of Γ, where most theoretical approximations lose meaning and where the experimental results are the basis for construction of physical models of electron transfer in a dense unordered medium [127-129]. It is significant that most parameters of imperfection among those achieved up to the present are close to the maximum values possible for a nondegenerate plasma.

The aggregate of experimental data now obtained (Figure 4.19) quite definitely indicates a reduction of the measured values of the electric conductivity of a

*For example, the degree of ionization does not exceed 0.1 percent at maximum pressure under the experimental conditions of [13], making the determination of $\bar{\sigma}$ impossible. In this case curve 7 in Figure 4.19 reflects the fact of the presence of measurements [13].

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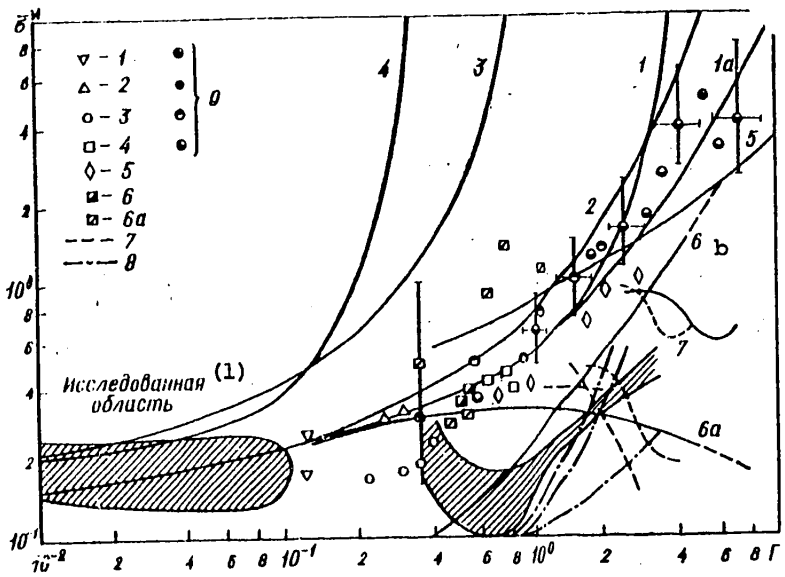

Figure 4.19. Coulomb Component of Electric Conductivity of Imperfect Plasma $\sigma^* = \sigma_{kul}/\omega_p$: calculations: 1--according to [142]; 1a--according to the method of Chapter 2; 2--according to [129]; 3--according to [143]; 4--according to [144]; 5--according to [145]; 6a and 6--according to [128]; 7--according to [127]; experiments: 1--[52, 63]; 2--[146]; 3--[65, 66]; 4--[57]; 5--[103]; 6--[63, 82]; 6a--[46]; 7--[71, 72]; 8--[83, 84]; 9--[105]; ⊕--air; ●--neon; ⊖--argon; ⊖--xenon

Key:
1. Investigated range

strongly imperfect plasma compared to the results of asymptotic theories of Chapter 2. The available qualitative divergence between different groups of experiments is related both to the actual nonconformity of primary data and to the role of quantum effects [5] and difficulties of determining the coulomb component in a weakly ionized plasma. The latter circumstance is typical for experiments with cesium [71, 83, 103], where the contribution of neutrals is especially high due to the large electron scattering cross-sections on atoms and the insufficient degree of plasma ionization.

A plasma with a high degree of ionization was produced in experiments on dynamic compression of heavy inert gases [105] since the directly measured values of electric conductivity were determined by scattering on the charged component. This circumstance considerably simplified interpretation of experiments by reducing the effect of ambiguity in the thermodynamic composition and cross-sections of elementary non-coulomb processes. It is natural in this case to use the dimensionless graph of Figure 4.19 to compare the measurements of [105] to the theory of

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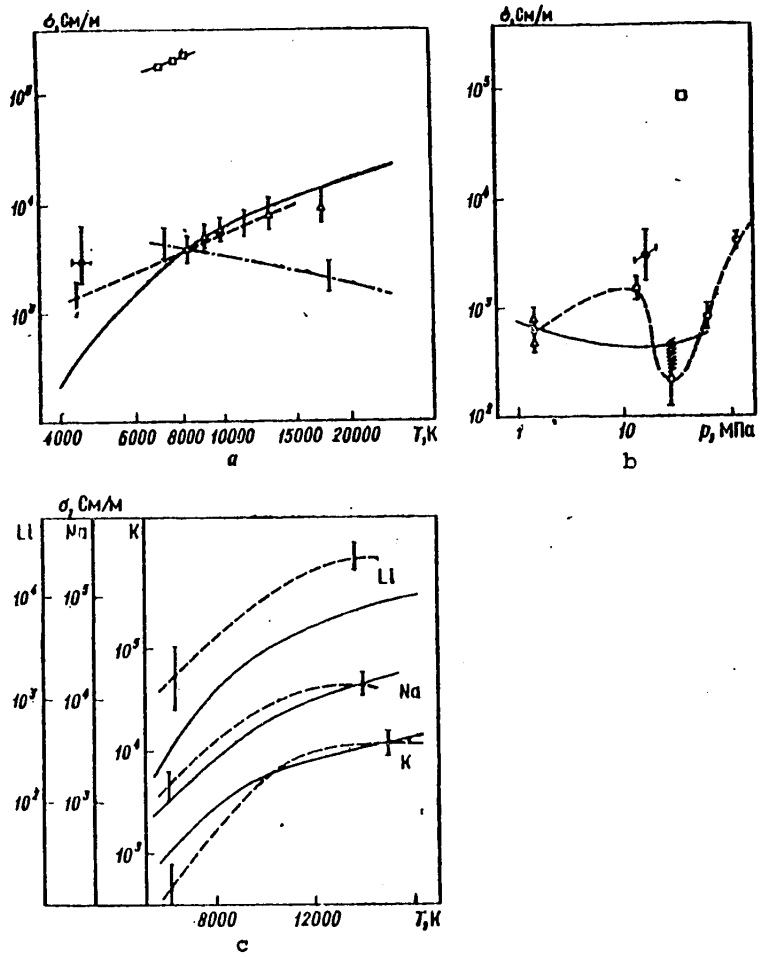

Figure 4.20. Electric Conductivity of Alkali metals: a--isobar of cesium p = (12.5 ± 0.5) MPa; b--isotherm of cesium T = 4,500 K; c--isobars of lithium, sodium and potassium p = 27.5 MPa; experimental data: dashed line--O--[12, 71]; —·— --[82]; Δ --[103]; □ --[72]; ●--[130]; ▮ --[49]; — --calculation by method in this paper

electric conductivity (Chapter 2). It is obvious that the results found in different gases (argon, xenon, neon and air) are in good agreement with each other and permit one to follow the effect of coulomb interaction on electric conductivity with continuous variation of the parameter of imperfection over a very wide range $\Gamma \approx 0.3$-7.0. The quality of theoretical description of experimental data [105] by the methods of Chapter 2 are illustrated by curve 1a in Figure 4.19. It is obvious that the theoretical approximations used in Chapter 2 describe well the weakly imperfect range and have acceptable extrapolation properties.

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At the same time direct comparison of the measurement results to calculations of the total electric conductivity is more feasible, especially in the case of the need to take into account different elementary processes of carrier scattering in a partially ionized plasma. This comparison was made for the alkali metals in Figure 4.20 a, b and c. The experiments for cesium were carried out on different installations [71, 72, 83, 103, 130] in an overlapping range of parameters. The experimental data are adequately well described (approximately 30 percent) by calculations made by the method of this paper (with the exception of data of [72]) within this range. Outside this range, in the low- and high-temperature range, the experimental data are qualitatively different in nature. The results of [103] found in a shock tube have better agreement with theoretical curve. These experimental data are also more reliable since the thermodynamic parameters of the plasma are also recorded here simultaneously with measurement of electric conductivity.

Compared to measurements of electric conductivity, the measurements of other transfer coefficients are related to extremely great complexities which determines the extremely small number of corresponding experiments in a dense plasma. Specifically, there are absolutely no reliable experimental data in the literature on the transport properties of the plasma with appreciable imperfection. Measurements of the viscosity and thermoconductivity [34, 38] of a plasma made by electric arcs are related to low pressures ($p \approx 0.1$ MPa) and do not permit one to estimate the effect of imperfection on these kinetic characteristics. Good agreement between calculation and experiment (Figures 4.21-4.23) indicates the applicability of the method of Chapter 2 to describe a quasi-ideal argon and hydrogen plasma and the reasonableness of the values of the cross-sections of elementary processes used in this calculation.

4.7. Comparison of Experimental and Calculated Data by Optical Properties

Compared to thermodynamic and transfer characteristics, the optical properties of a low-temperature plasma are characterized by extremely strong dependence on the specifics and the concrete structure of electron energy levels of the chemical elements of the plasma. Therefore, measurements made in a plasma of chemical composition close to that of a plasma of working substances must be used for quantitative comparison and experiments with other substances must be used to determine the qualitative effects of imperfection.

Conducting optical measurements in a plasma of working substances at full-scale pressure and temperature for a gas-phase nuclear reactor is related to great difficulties of preparation and diagnosis of these media. For this reason the number of reliable measurements in a plasma of alkali metals, uranium and the required mixtures is extremely limited.

A pulsed electric discharge in a graduated capillary tube was used in [69] to create a lithium hydride plasma with pressure of $p = 37$ MPa and temperature of $T = (3\text{-}4)\cdot 10^4$ K. The light absorption was recorded in the visible and near ultraviolet regions of the spectrum. The results of measuring the absorption coefficient and the optical thickness of the plasma layer with dimensions of 1 cm are presented in Figures 4.24 a and b, from which reasonable agreement of the calculated and measured values is obvious, although some excess of measurements over calculation is observed.

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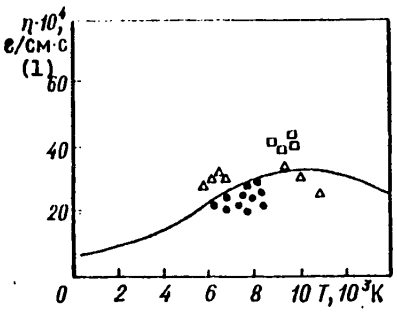

Figure 4.21. Viscosity of Argon Plasma of p = 0.1 MPa; experimental data: ●--[138]; □ and Δ--[38]; —— --calculation by the method of this paper (Chapter 2)

Key:
1. g/cm·s

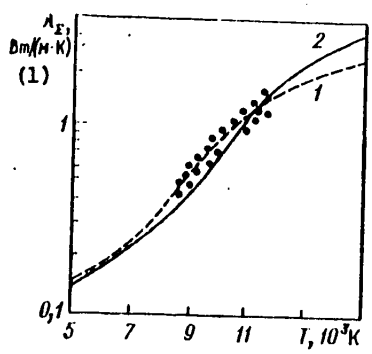

Figure 4.22. Thermal Conductivity of Argon Plasma (p = 0.1 MPa): points--experimental data of [140]; 1--calculation of [139]; 2--calculation by method of Chapter 2

Key:
1. W/(m·K)

Electric explosion of a potassium wire in a glass capillary tube and a pulsed potassium-helium arc of small geometric dimensions were used in [131] to measure the absorption coefficients of potassium. The absorption coefficients of a potassium plasma were found in these experiments for the visible region of the spectrum at temperatures of 5,000-11,000 K and pressures of 0.4-0.9 MPa, where the main elementary processes are photoionization of the atom and absorption in the spectral lines. The derived results are found in Figure 4.25, where satisfactory agreement (within the range of experimental accuracy) of the measured values and those calculated by the methods of Chapter 3 is obvious. The results of these experiments

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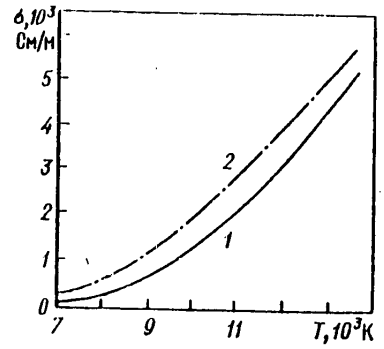

Figure 4.23. Electroconductivity of Hydrogen Plasma at p = 0.1 MPa: 1--experiment of [141]; 2--calculation of Chapter 2

are distinguished by a significant aspect: they were found by two completely independent methods with different time characteristics, which considerably increases their reliability. The observed agreement with calculation indicates that consideration of imperfection only within the component composition of a plasma (Chapter 3) is sufficient to describe the experiment in the indicated range of parameters.

Comparison of calculations of the optical properties of a uranium plasma to experiment, which are known not to have even approximately established accuracy due to the implicit insufficiency of data on the structure of electron therms and the cross-sections of elementary processes for uranium atoms and especially of uranium ions, is of special interest. Nevertheless, comparison of the experimentally determined absorption coefficient of a uranium plasma ($p \approx 5.0$ MPa and $T \approx 10^4$ K) [132] to the absorption coefficient calculated by the method described in section 3.7 indicates satisfactory agreement between them (Figure 4.26)

Speaking about measurements of other chemical elements in a plasma, one should first distinguish a large group of experiments with inert gases [133, 137]. Detailed analysis of the available material related to the weakly imperfect range shows [133] that the ratio of measured and calculated values [133] of absorption coefficients does not exceed 2 in any case.

New effects which lead to measurements of the optical spectrum can also be manifested in a plasma with an increase of plasma density, along with known broadening of the spectral lines and shift of the photoionization thresholds [4]. Thus, the possibility of nonrealization of part of the excited energy states as a result of the action of local electric micropoles is discussed in the literature [134]. In this case the photoionization threshold remains unchanged and the prethreshold region is free of spectral lines and is therefore transparent to light. The results of measuring the radiation of high-pressure mercury flash lamps were interpreted in [135] from these very positions.

At the same time the upper energy levels are distorted and deformed as a result of interparticle interaction in a strongly compressed plasma (see section 1.5 for more

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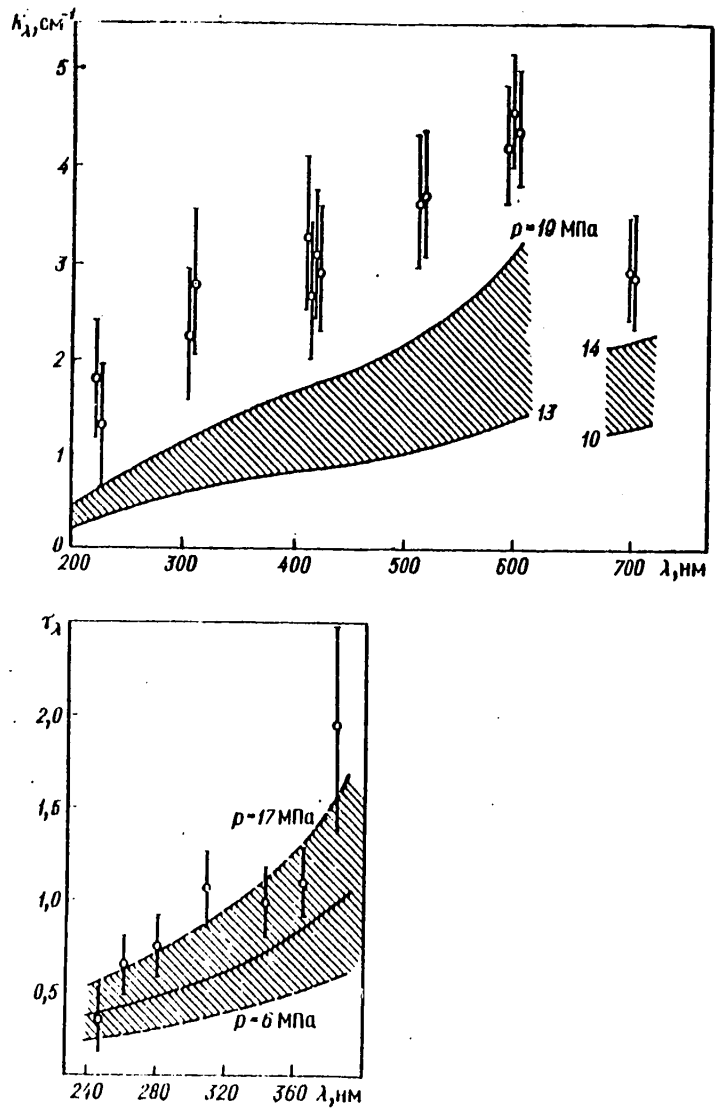

Figure 4.24. Absorption Coefficient (a) and Optical Density (b) in Continuous Spectrum of Lithium Hydride Plasma: O--experimental data of [69], p = 6-17 MPa and T = $(36 \pm 5)\cdot 10^3$ K; cross-hatched zones--data calculated by method of Chapter 3 for different pressures

detail) since part of these levels is "extruded" into the continuous spectrum. In this case the total absorption coefficient of the plasma will possibly be reduced by a value corresponding to photoionization from the disappearing energy states.

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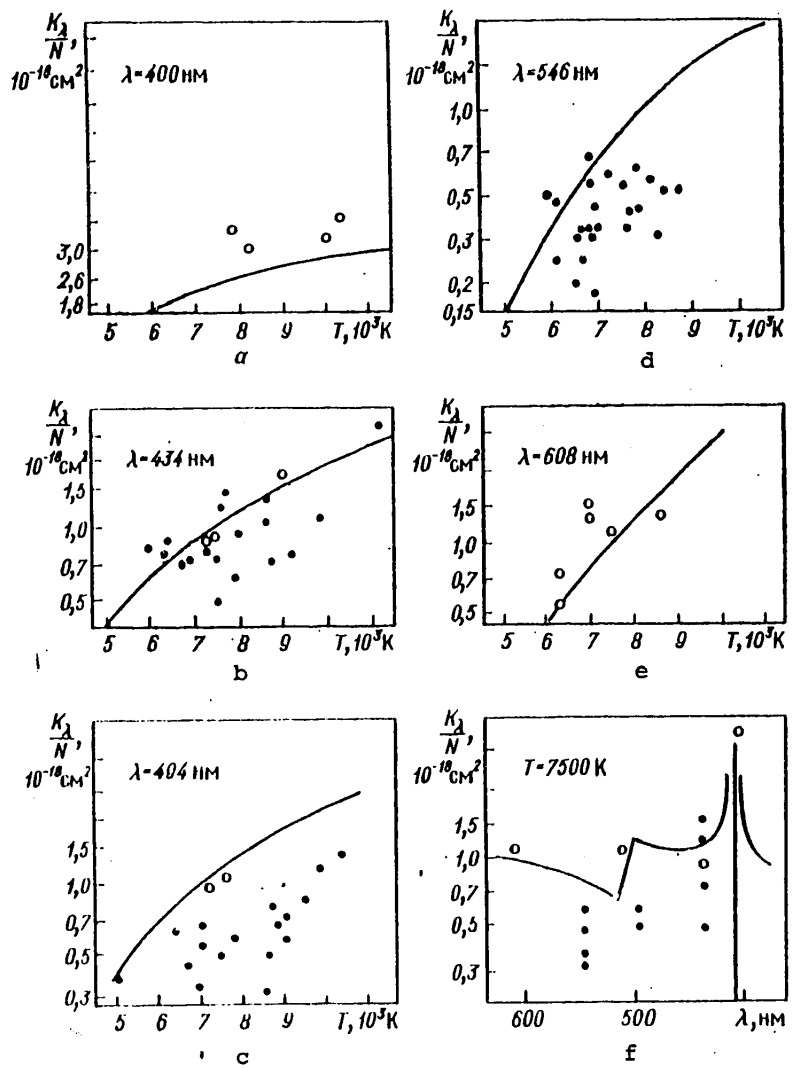

Figure 4.25. Absorption Coefficients of Potassium Plasma: O--results of measurements upon explosion of potassium wire; ●--results of measurements in potassium-helium arc; solid curves--calculation by the method of Chapter 2

It is natural that the corresponding spectral lines also disappear in this case. The given effect was obviously manifested in experiments of [130] on dynamic compression of argon (Figure 4.27). It is significant that the effect of deformation of energy levels also describes the thermodynamics of a strongly compressed plasma (see sections 1.5 and 4.5). However, we note that the opposite effect is observed

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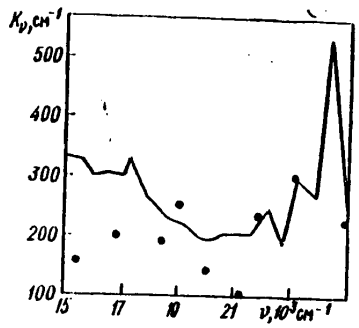

Figure 4.26. Spectral Dependence of Absorption Coefficient of Uranium Plasma: ●--experimental data from [132]; curve--calculation by method of section 3.3

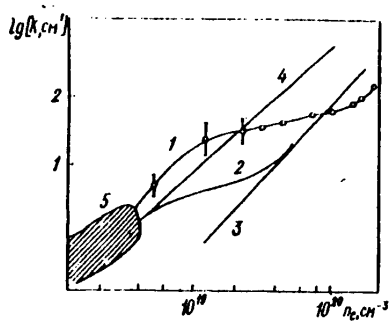

Figure 4.27. Absorption Coefficient of Argon Plasma (T = 20,000 K and λ = = 6,000 Å): 1--experimental data [136]; 2--calculation by restricted atom model (section 1.6); 3--free-free transitions; 4--free-free transitions and photoionization; 5--experimental data for weakly imperfect plasma [133, 137]

with an increase of pressure in [59], in which the optical properties of a neon plasma were investigated ($p \leq 50$ MPa and $T \approx 18{,}000$ K).

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THERMOPHYSICAL PROPERTIES OF WORKING MEDIA OF GAS-PHASE NUCLEAR REACTOR

Moscow TEPLOFIZICHESKIYE SVOYSTVA RABOCHIKH SRED GAZOFAZNOGO YADERNOGO REAKTORA in Russian 1980 (signed to press 1 Aug 80) pp 190-289

[Chapter 5 from the book "Thermophysical Properties of Working Media of the Gas-Phase Nuclear Reactor", by Viktor Konstantinovich Gryaznov, Igor' L'vovich Iosilevskiy, Yuriy Georgiyevich Krasnikov, Nina Ivanovna Kuznetsova, Vladimir Ivanovich Kucherenko, Galina Borisovna Lappo, Boris Nikolayevich Lomakin, Georgiy Alekseyevich Pavlov, Eduard Yevgen'yevich Son and Vkadimir Yevgen'yevich Fortov, Atomizdat, 1,800 copies, 304 pages]

[Text] Based on the concepts outlined in previous chapters, the thermophysical properties of different substances, which are promising working substances of a gas-phase nuclear reactor, were calculated. The calculations were carried out in the temperature range of 4,000-40,000 K and in the pressure range of 0.1-50 MPa. The composition, thermodynamic functions and transfer coefficients of a plasma of alkali metals of lithium, sodium, potassium, cesium and uranium are presented in Tables 5.1-5.5. The thermophysical properties were calculated on isotherms for pressures of 1, 3, 10, 30, 100, 300 and 500 atomspheres (0.098, 0.294, 0.98, 2.94, 9.8, 19.6 and 49 MPa). The enthalpy of an ideal gas of atoms at 0 K was taken as the beginning of reading of enthalpy. The thermophysical properties for mixtures of potassium and uranium and potassium and hydrogen are presented in Tables 5.6 and 5.7. The calculations were made in the same range of temperatures as for pure substances and at pressures of 1, 10, 100 and 500 atmospheres (0.098, 0.98, 9.8 and 49 MPa). Results corresponding to the molar content of uranium in the mixture K + U = 3, 10 and 50 percent and potassium in a mixture of K + H_2 = 3, 10 and 50 percent are presented, which is equivalent to a mass fraction of potassium of 0.843, 0.600 and 0.143 in a mixture of K + U and 0.375, 0.683 and 0.951 in a mixture of K + H_2. This selection was made to improve the possibility of interpolating the transfer properties for the case of other fractions of the considered chemical elements.

Calculations for pure uranium and for a uranium-potassium mixture were limited only by the case of the gaseous phase. The parameters of the proposed uranium condensation boundary are presented in Table 1.6 (section 1.6).

The behavior of the spectral absorption coefficient for the substances and mixtures of them considered in this paper is presented in Figures 5.1-5.14.

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Representation of numerical values determined in the following manner: the notation -.1272 + 02 denotes the number $-0.1272 \cdot 10^2$ while the notation .7243 - 03 denotes the number $0.7243 \cdot 10^{-3}$ and so on, close to the machine representation, was used in Tables 5.1-5.7 containing the results of computer calculations.

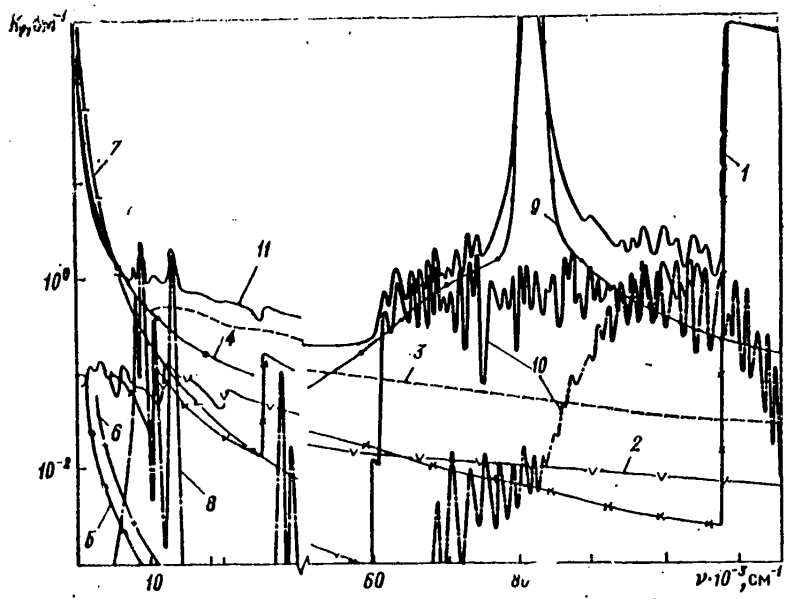

Figure 5.1. Elementary Absorption Processes of Potassium-Hydrogen Plasma (P = 20 MPa and T = 12,000 K; the potassium impurity was 3 percent by volume): 1--photoionization of hydrogen; 2--photoionization of potassium; 3--photoseparation of H^-; 4--free-free transitions in fields of hydrogen molecules; 5--free-free transitions in fields of hydrogen atoms; 6--free-free transitions in potassium fields; 7--free-free transitions in ion fields; 8--absorption in potassium lines; 9--absorption in hydrogen lines, Lyman series; 10--molecular absorption of hydrogen; 11--total absorption coefficient with correction for induced emission

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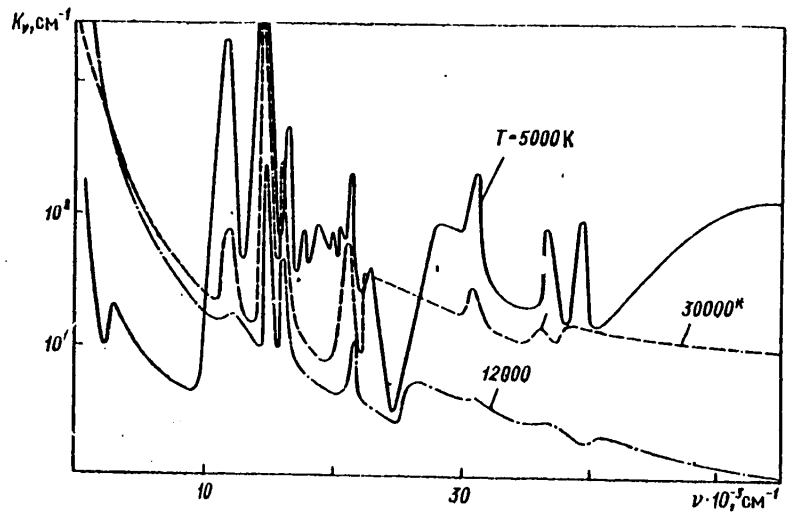

Figure 5.2. Spectral Absorption Coefficient of Lithium at 50 MPa (values corresponding to T = 30,000 K were increased by an order)

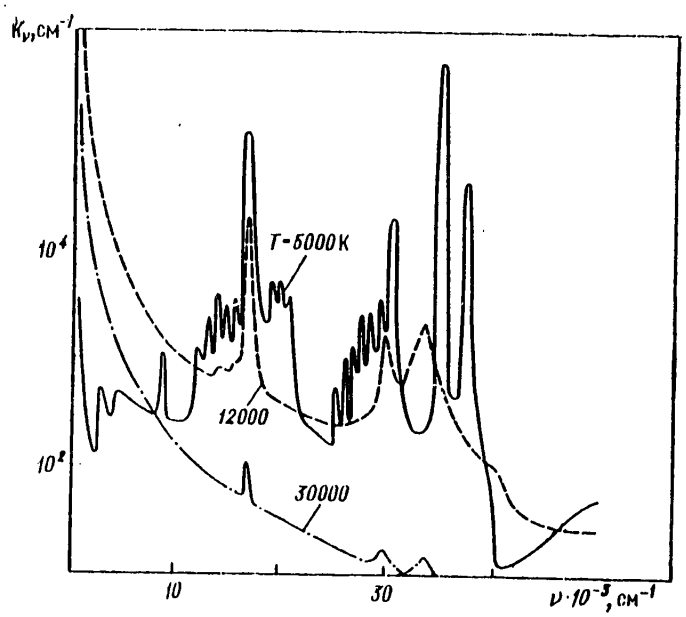

Figure 5.3. Spectral Absorption Coefficient of Sodium at 50 MPa

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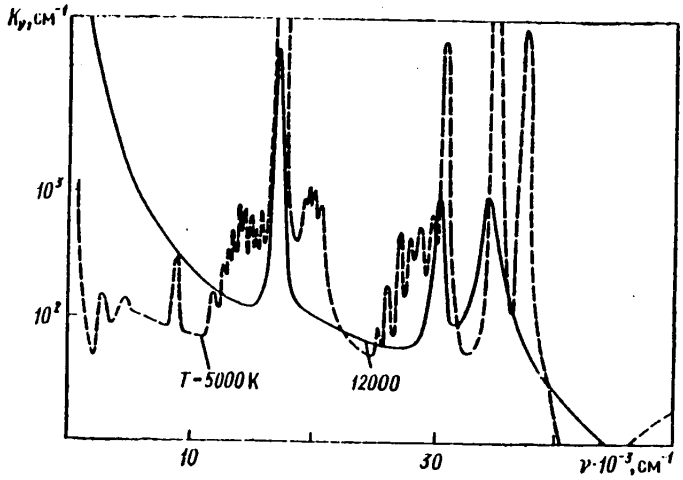

Figure 5.4. Spectral Absorption Coefficient of Sodium at 1 MPa

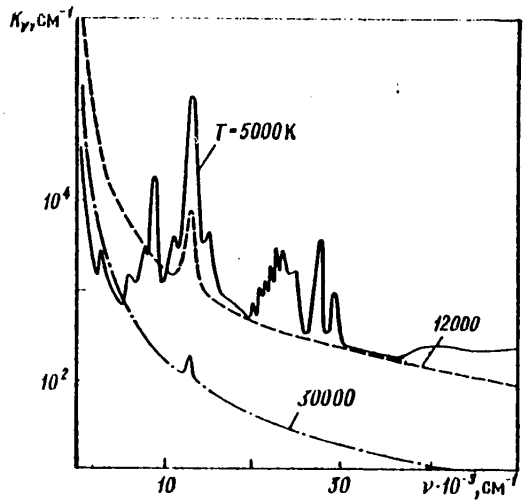

Figure 5.5. Spectral Absorption Coefficient of Potassium at 50 MPa

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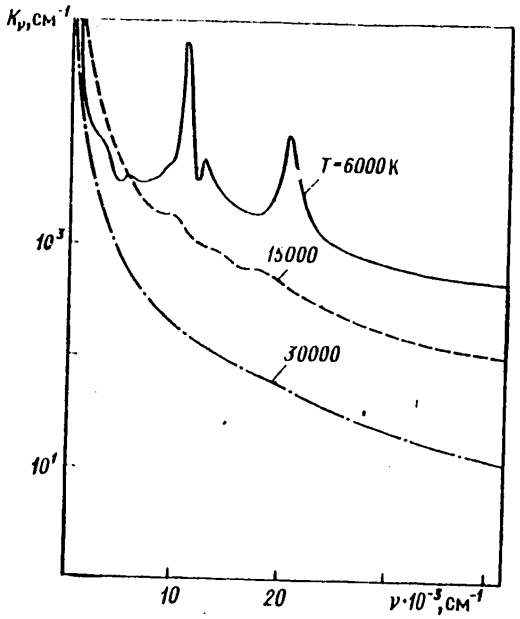

Figure 5.6. Spectral Absorption Coefficient of Cesium at 50 MPa

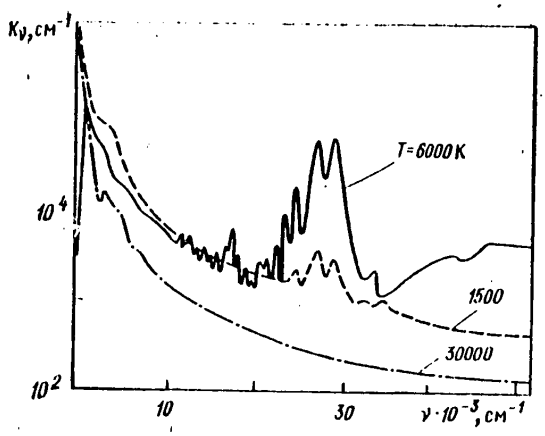

Figure 5.7. Spectral Absorption Coefficient of Uranium at 50 MPa

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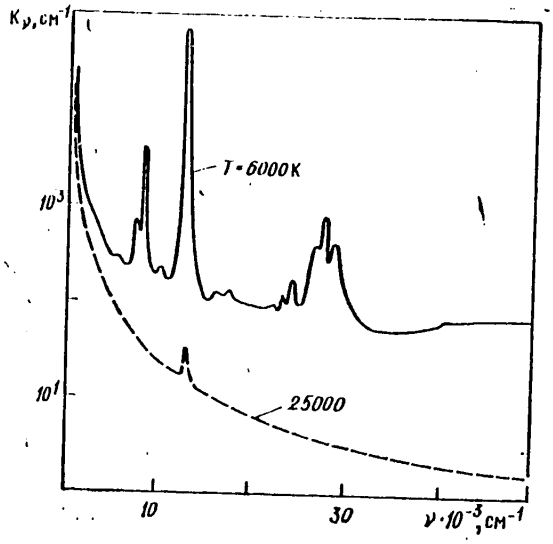

Figure 5.8. Spectral Absorption Coefficient of Uranium-Potassium Mixture (3 percent potassium by volume) at 10 MPa

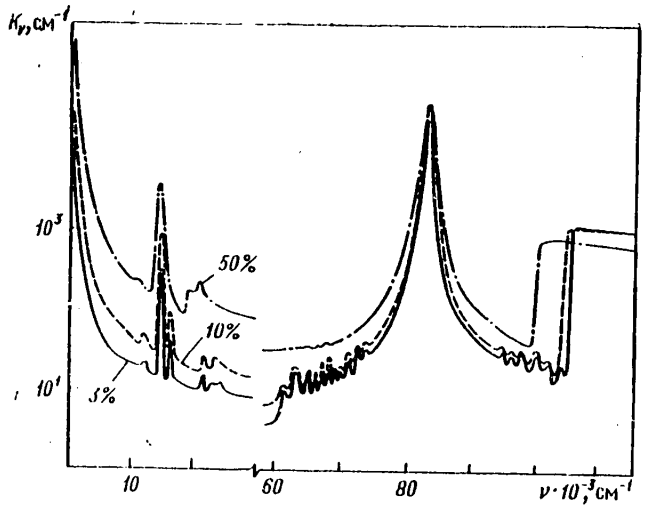

Figure 5.9. Spectral Absorption Coefficient of Hydrogen-Lithium Mixtures with Different Volumetric Content of Lithium, Pressure of 50 MPa and Temperature of 15,000 K

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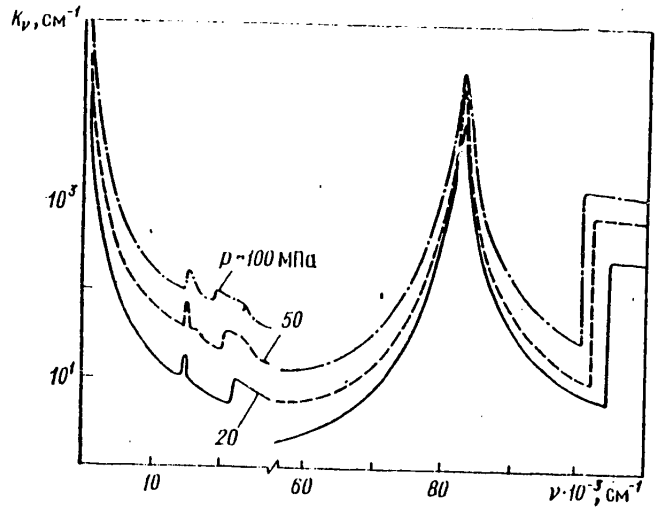

Figure 5.10. Spectral Absorption Coefficient of Hydrogen-Lithium Mixture (3 percent lithium by volume) at 20,000 K

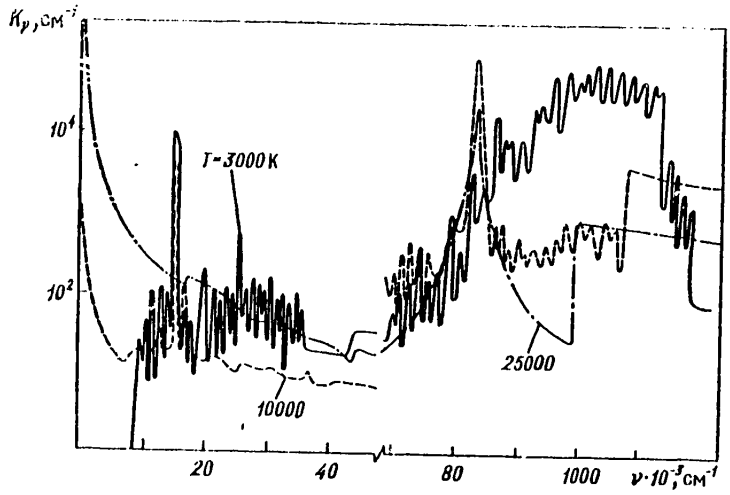

Figure 5.11. Spectral Absorption Coefficient of Hydrogen-Lithium Mixture (1 percent lithium by volume) at 100 MPa

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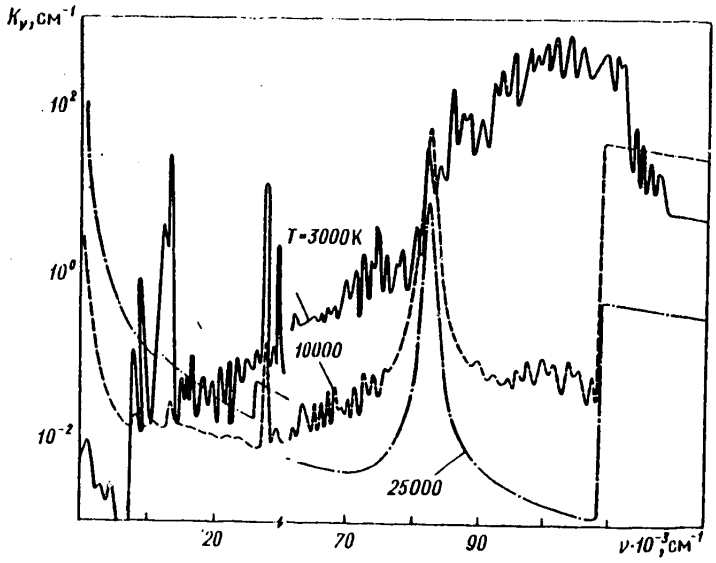

Figure 5.12. Spectral Absorption Coefficient of Hydrogen-Potassium Mixture (3 percent potassium by volume) at 1 MPa

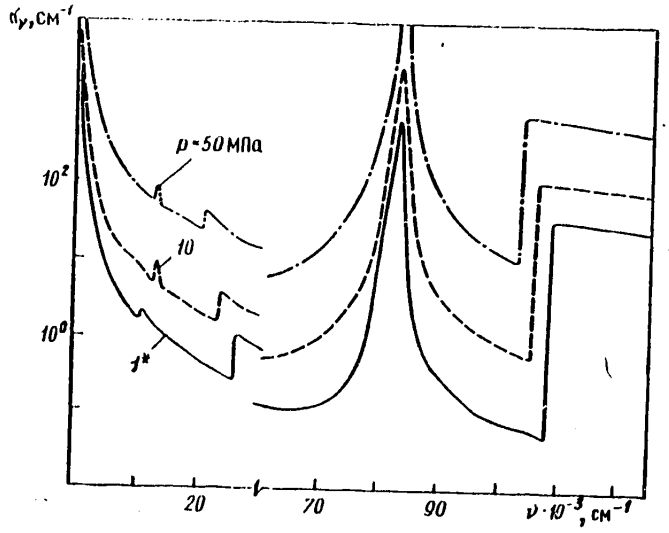

Figure 5.13. Spectral Absorption Coeffient of Hydrogen-Potassium Mixture (10 percent potassium by volume) at 20,000 K (values corresponding to p = 1 MPa are reduced by an order)

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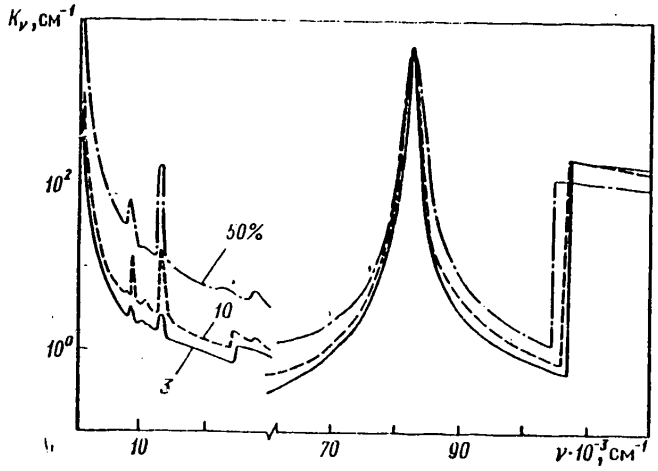

Figure 5.14. Spectral Absorption Coefficient of Hydrogen-Potassium Mixture with Different Volumetric Content of Potassium, Temperature of 15,000 K and Pressure of 10 MPa

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List of Values Presented in Tables

T, K -- temperature

p, 0.098 MPa -- pressure

n_i, 10^{26} m^{-3} -- concentration of component i

h, kJ/kg -- enthalpy (1.82)

s, kJ/(kg·K) -- entropy (1.83)

M, g/mole -- molecular mass

ρ, $kg \cdot m^{-3}$ -- density (1.81)

Γ -- Debye parameter of imperfection (1.1)

η, poise -- shear viscosity (3.91)

λ', 10^2 W/(m·K) -- coefficient of transport thermal conductivity (2.90)

λ_Σ 10^2 W/(m.K) -- coefficient of thermal conductivity $\lambda_\Sigma = \lambda' + \lambda_x$ (2.90) and (2.98)

λ_R, W/(m·K)--- coefficient of radiant thermal conductivity (3.1)

σ, 10^2 Cm/m -- electric conductivity (2.97)

α, 10^2 A/(m.K) -- thermoelectromotive force

D_{ab}, 10 kg/(m·s) -- effective diffusion coefficient (2.86)

D_E, 3 $kg^{1/2}/m^{1/2}$ -- effective electric diffusion coefficient (2.86)

D^T, 10 kg/(m·s·K) -- effective thermodiffusion coefficient (2.86)

λ_a, 10^2 W/m -- effective coefficient of thermal conductivity determined by formula (2.86)

λ^E, 10^4 $W \cdot s^2/kg \cdot m$ -- effective coefficient of thermal conductivity in formulas (2.86)

λ^T, 10^2 W/m·K -- effective coefficient of thermal conductivity (2.86)

h'_a, kJ/kg -- derivative of enthalpy by mass fraction of element A

$\beta_U = \dfrac{\Sigma n_i \nu_i^{(U)}}{\Sigma n_i \nu_i^{(U)} + \Sigma n_i \nu_i^{(K)}}$ -- molar fraction of uranium in K + U mixture

$\beta_K = \dfrac{\Sigma n_i \nu_i^{(K)}}{\Sigma n_i \nu_i^{(K)} + \frac{1}{2} \Sigma n_i \nu_i^{(U)}}$ -- molar fraction of potassium in K + H_2 mixture

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Table 5.1. Thermophysical Properties of Lithium Plasma (M = 6.94)

(1) Величина	(2) Давление, ат						
	1	3	10	30	100	200	500
				$T=4000$ K			
e^-	.1404 —03	.2500 —03	.4775 —03	.8875 —03	.1934 —02	.3413 —02	.9645 —02
Li	.1748 —01	.5271 —01	.1757	.5226	.1685 +01	.3226 +01	.7257 +01
Li^+	.1406 —03	.2510 —03	.4642 —03	.9216 —03	.2121 —02	.3892 —02	.1137 —01
Li^-	.5465 —06	.2922 —05	.1834 —04	.9724 —04	.5945 —03	.1671 —02	.6561 —02
Li_2	.9402 —05	.8553 —04	.9504 —03	.8406 —02	.8731 —01	.3198	.1613 +01
Li_2^+	.3422 —06	.1835 —05	.1162 —04	.6313 —04	.4076 —03	.1191 —02	.4836 —02
ρ	.2032 —02	.6121 —01	.2052	.6227	.2146 +01	.4462 +02	.1211 +02
h	.1303 +05	.1273 +05	.1249 +05	.1220 +05	.1156 +05	.1086 +05	.9504 +04
s	.2811 +02	.2671 +02	.2521 +02	.2383 +02	.2227 +02	.2131 +02	.2000 +02
M	.6889 +01	.6919 +01	.6959 +01	.7039 +01	.7275 +01	.7560 +01	.8194 +01
Γ	.1605	.2125	.3011	.4236	.6749	.9544	.1715 +01
η	.2870 —03	.2884 —03	.2892 —03	.2894 —03	.2890 —03	.2886 —03	.2885 —03
λ'	.1440 —02	.1382 —02	.1328 —02	.1288 —02	.1240 —02	.1201 —02	.1126 —02
λ_Σ	.1527 —02	.1438 —02	.1377 —02	.1363 —02	.1413 —02	.1479 —02	.1568 —02
σ	.1368 +01	.9209	.5758	.3677	.2279	.1797	.1467
α	.1421 —04	—.4079 —06	—.6484 —05	—.6908 —05	—.5333 —05	—.4505 —05	—3910 —05
λ_R	.1360 +05	.2660 +04	.3430 +03	.5720 +02	.8280 +01	.2860 +01	.7630

Key:
1. Value
2. Pressure, atmospheres

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Table 5.1. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T=5000$ K			
e^-	.6976 —03	.1280 —02	.2503 —02	.4727 —02	.1023 —01	.1746 —01	.4484 —01
Li	.1286 —01	.4016 —01	.1371	.4747	.1372 +01	.2695 +01	.6398 +01
Li^+	.6980 —03	.1282 —02	.2518 —02	.4805 —02	.1072 —01	.1884 —01	.5025 —01
Li^-	.9880 —06	.5644 —05	.3733 —04	.2076 —03	.1355 —02	.4002 —02	.1711 —01
Li_2	.2702 —05	.2635 —04	.3068 —03	.2806 —02	.3065 —01	.1179	.6574
Li_2^-	.6027 —06	.3447 —05	.2289 —04	.1287 —03	.8657 —03	.2631 —02	.1169—01
ρ	.1563 —01	.4781 —01	.1616	.4902	.1667 +01	.3408 +01	.8989 +01
h	.2059 +05	.1877 +05	.1760 +05	.1692 +05	.1625 +05	.1573 +05	.1470 +05
s	.2977 +02	.2804 +02	.2634 +02	.2488 +02	.2331 +02	.2240 +02	.2116 +02
M	.6602 +01	.6737 +01	.6834 +01	.6911 +01	.7044 +01	.7191 +01	.7543 +01
Γ	.2554	.3469	.4872	.6778	.1032 +01	.1402 +01	.2395 +01
η	.3228 —03	.3342 —03	.3411 —03	.3444 —03	.3457 —03	.3457 —03	.3450 —03
λ'	.2291 —02	.2218 —02	.2059 —02	.1903 —02	.1752 —02	.1679 —02	.1588 —02
λ_Σ	.2687 —02	.2461 —02	.2208 —02	.2018 —02	.1894 —02	.1882 —02	.1937 —02
σ	.5199 +01	.3836 +01	.2652 +01	.1847 +01	.1235 +01	.1001 +01	.8308
α	.1742 —03	.8825 —04	.2783 —04	—.1203 —05	—.1335 —04	—.1525 —04	—.1727 —04
λ_R	.1250 +05	.2220 +04	.2890 +03	.4620 +02	.6600 +01	.2230 +01	.5860

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Table 5.1. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				T=6000 K			
e^-	.1826 —02	.3556 —02	.7257 —02	.1403 —01	.3039 —01	.5069 —01	.1191
Li	.8343 —02	.2880 —01	.1048	.3288	.1119 +01	.2238 +01	.5489 +01
Li^+	.1826 —02	.3558 —02	.7276 —02	.1414 —01	.3113 —01	.5287 —01	.1282
Li^-	.9697 —05	.6506 —05	.4803 —04	.2856 —03	.1975 —02	.6009 —02	.2663 —01
Li_2	.6988 —06	.8322 —05	.1102 —03	.1081 —02	.1247 —01	.4951 —01	.2913
Li_2^-	.5933 —06	.3983 —05	.2946 —04	.1761 —03	.1237 —02	.3834 —02	.1753 —01
ρ	.1172 —01	.3731 —01	.1295	.3982	.1359 +01	.2768 +01	.7213 +01
h	.3625 +05	.3002 +05	.2599 +05	.2382 +05	.2232 +05	.2163 +05	.2066 +05
s	.3260 +02	.3008 +02	.2786 +02	.2613 +02	.2441 +02	.2347 +02	.2225 +02
M	.5885 +01	.6256 +01	.6527 +01	.6693 +01	.6843 +01	.6948 +01	.7157 +01
Γ	.3139	.4392	.6280	.8775	.1312 +01	.1734 +01	.2795 +01
η	.3044 —03	.3443 —03	.3716 —03	.3856 —03	.3934 —03	.3954 —03	.3955 —03
λ'	.3339 —02	.3535 —02	.3481 —02	.3206 —02	.2831 —02	.2640 —02	.2446 —02
λ_Σ	.4286 —02	.4156 —02	.3863 —02	.3461 —02	.3036 —02	.2865 —02	.2771 —02
σ	.1256 +02	.9986 +01	.7421 +01	.5507 +01	.3928 +01	.3281 +01	.2784 +01
α	.5839 —03	.3829 —03	.1993 —03	.8355 —04	.9437 —05	—.1459 —04	—.3921 —04
λ_R	.1510 +05	.4390 +04	.3720 +03	.5020 +02	.8810 +01	.3150 +01	.9410

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Table 5.1. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T=7000$ K			
e^-	.3027 —02	.6529 —02	.1432 —01	.2878 —01	.6327 —01	.1042	.2294
Li	.4357 —02	.1815 —01	.7510 —01	.2525	.9022	.1842 +01	.4649 +01
Li^+	.3027 —02	.6531 —02	.1434 —01	.2889 —01	.6406 —01	.1066	.2401
Li^-	.5306 —06	.4763 —05	.4300 —04	.2865 —03	.2144 —02	.6731 —02	.3060 —01
Li_2	.1263 —06	.2192 —05	.3742 —04	.4215 —03	.5331 —02	.2198 —01	.1353
Li_2^+	.3287 —06	.2951 —05	.2667 —04	.1781 —03	.1345 —02	.4268 —02	.1985 —01
ρ	.8508 —02	.2845 —01	.1032	.3259	.1131 +01	.2313 +01	.6024 +01
h	.6171 +05	.4852 +05	.3914 +05	.3394 +05	.3050 +05	.2916 +05	.2776 +05
s	.3651 +02	.3291 +02	.2987 +02	.2768 +02	.2567 +02	.2463 +02	.2334 +02
M	.4923 +01	.5490 +01	.5987 +01	.6311 +01	.6562 +01	.6681 +01	.6843 +01
Γ	.3209	.4718	.6985	.9920	.1481 +01	.1927 +01	.2965 +01
η	.2275 —03	.3040 —03	.3668 —03	.4036 —03	.4229 —03	.4341 —03	.4381 —03
λ'	.4321 —02	.5075 —02	.5523 —02	.5370 —02	.4825 —02	.4503 —02	.4093 —02
λ_Σ	.5591 —02	.6046 —02	.6199 —02	.5826 —02	.5186 —02	.4799 —02	.4437 —02
σ	.2299 +02	.1963 +02	.1546 +02	.1197 +02	.8938 +01	.7593 +01	.6523 +01
α	.1208 —02	.9486 —03	.6160 —03	.3507 —03	.1438 —03	.5691 —04	—.3425 —04
λ_R	.2000 +05	.3420 +04	.5000 +03	.7320 +02	.1330 +02	.4310 +01	.1470 +01

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Table 5.1. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
			T=8000 K				
e^-	.3646 —02	.6880 —02	.2150 —01	.4575 —01	.1036	.1703	.3595
Li	.1878 —02	.9887 —02	.4920 —01	.1844	.7094	.1492 +01	.3890 +01
Li^+	.3546 —02	.8881 —02	.2151 —01	.4584 —01	.1043	.1725	.3698
Li^-	.1845 —06	.2363 —05	.2836 —04	.2237 —03	.1878 —02	.6152 —02	.2893 —01
Li_2	.1029 —07	.4508 —06	.1113 —04	.1554 —03	.2270 —02	.9887 —02	.6427 —01
Li_2^-	.1160 —06	.1485 —05	.1783 —04	.1409 —03	.1188 —02	.3918 —02	.1870 —01
ρ	.6364 —02	.2163 —01	.8155 —01	.2661	.9475	.1956 +01	.5132 +01
h	.8957 +05	.7227 +05	.5687 +05	.4737 +05	.4086 +05	.3838 +05	.3597 +05
s	.4023 +02	.3608 +02	.3223 +02	.2946 +02	.2704 +02	.2585 +02	.2443 +02
M	.4181 +01	.4712 +01	.5325 +01	.5799 +01	.6187 +01	.6355 +01	.6534 +01
Γ	.2885	.4503	.7000	.1021 +01	.1540 +01	.1992 +01	.2969 +01
η	.1411 —03	.2310 —03	.3272 —03	.3945 —03	.4428 —03	.4597 —03	.4718 —03
λ'	.5251 —02	.6547 —02	.7867 —02	.8263 —02	.7978 —02	.7511 —02	.6833 —02
λ_Σ	.6245 —02	.7622 —02	.8750 —02	.8907 —02	.8423 —02	.7892 —02	.7206 —02
σ	3354 +02	.3096 +02	.2560 +02	.2032 +02	.1543 +02	.1328 +02	.1146 +02
α	.1817 —02	.1651 —02	.1252 —02	.8295 —03	.4300 —03	.2497 —03	.4521 —04
λ_R	.2680 +05	.5650 +04	.6320 +03	.1060 +03	.1860 +02	.6310 +01	.2380 +01

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Table 5.1 [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T=10\,000$ K			
e^-	.3490 —02	.9919 —02	.2894 —01	.7091 —01	.1770	.2972	.6095
Li	.3285 —03	.2378 —02	.1714 —01	.8474 —01	.4032	.9249	.2630 +01
Li^+	.3491 —02	.9919 —02	.2894 —01	.7093 —01	.1774	.2984	.6159
Li^-	.1567 —07	.3222 —06	.6762 —05	.8130 —04	.9423 —03	.3503 —03	.1840 —01
Li_2	.2655 —09	.1390 —07	.7198 —06	.1745 —04	.3874 —03	.1993 —02	.1521 —01
Li_2^+	.1013 —07	.2083 —06	.4371 —05	.5258 —04	.6103 —03	.2274 —02	.1202 —01
ρ	.4400 —02	.1417 —01	.5311 —01	.1796	.6722	.1423 +01	.3822 +01
h	.1243 +06	.1133 +06	.9601 +05	.7989 +05	.6606 +05	.6025 +05	.5452 +05
s	.4416 +02	.4069 +02	.3660 +02	.3307 +02	.2983 +02	.2827 +02	.2648 +02
M	.3626 +01	.3842 +01	.4264 +01	.4772 +01	.5332 +01	.5610 +01	.5904 +01
Γ	.2022	.3407	.5812	.9085	.1433 +01	.1864 +01	.2705 +01
η	.5743 —04	.1112 —03	.2097 —03	.3179 —03	.4246 —03	.4713 —03	.5133 —03
λ'	.7368 —02	.9376 —02	.1245 —01	.1509 —01	.1680 —01	.1691 —01	.1610 —01
λ_Σ	.7616 —02	.9856 —02	.1314 —01	.1579 —01	.1777 —01	.1739 —01	.1652 —01
σ	.4985 +02	.5356 +02	.5184 +02	.4503 +02	.3533 +02	.3104 +02	.2653 +02
α	.2670 —02	.2903 —02	.2814 —02	.2321 —02	.1537 —02	.1088 —02	.5447 —03
λ_R	.1130 +06	.2210 +05	.1620 +04	.2540 +03	.4500 +02	.1840 +02	.6080 +01

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Table 5.1. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T=12\,000$ K			
e^-	.2985 —02	.8866 —02	.2833 —01	.7735 —01	.2150	.3760	.7802
Li	.7941 —04	.6430 —03	.5686 —02	.3535 —01	.2116	.5396	.1710
Li^+	.2985 —02	.8866 —02	.2833 —01	.7736 —01	.2151	.3765	.7834
Li^-	.1877 —08	.4513 —07	.1273 —05	.2150 —04	.3514 —03	.1529 —02	.9348 —02
Li_2	.9387 —11	.6149 —09	.4794 —07	.1839 —05	.6447 —04	.4090 —03	.3871 —02
Li_2^-	.1242 —08	.2987 —07	.8424 —06	.1423 —04	.2327 —03	.1013 —02	.6212 —02
ρ	.3530 —02	.1095 —01	.3919 —01	.1299	.4926	.1060 +01	.2907 +01
h	.1420 +06	.1367 +06	.1256 +06	.1105 +06	.9279 +05	.8383 +05	.7421 +05
s	.4579 +02	.4284 +02	.3930 +02	.3586 +02	.3225 +02	.3040 +02	.2825 +02
M	.3516 +01	.3592 +01	.3787 +01	.4117 +01	.4621 +01	.4933 +01	.5317 +01
Γ	.1423	.2452	.4378	.7223	.1201 +01	.1591 +01	.2289 +01
η	.4247 —04	.7176 —04	.1381 —03	.2403 —03	.3765 —03	.4521 —03	.5322 —03
λ'	.9923 —02	.1246 —01	.1660 —01	.2180 —01	.2657 —01	.2856 —01	.2924 —01
λ_Σ	.9983 —02	.1261 —01	.1691 —01	.2225 —01	.2759 —01	.2901 —01	.2963 —01
σ	.6133 +02	.6956 +02	.7534 +02	.7306 +02	.6249 +02	.5507 +02	.4652 +02
α	.3262 —02	.3722 —02	.4068 —02	.3907 —02	.3023 —02	.2394 —02	.1493—02
λ_R	.6240 +06	.1120 +06	.6790 +04	.1010 +04	.1590 +03	.6170 +02	.1940 +02

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Table 5.1. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T=15\,000$ K			
e^-	.2394 —02	.7200 —02	.2395 —01	.7023 —01	.2176	.4045	.8881
Li	.1613 —04	.1377 —03	.1368 —02	.1016 —01	.7816 —01	.2305	.8665
Li^+	.2394 —02	.7201 —02	.2395 —01	.7023 —01	.2176	.4046	.8890
Li^-	.1633 —09	.4190 —08	.1384 —06	.3004 —05	.7077 —04	.3817 —03	.3003 —02
Li_2	.2235 —12	.1627 —10	.1604 —08	.8795 —07	.5105 —05	.4339 —04	.5786 —03
Li_2^+	.1111 —09	.2850 —08	.9411 —07	.2043 —05	.4813 —04	.2597 —03	.2045 —02
ρ	.2777 —02	.8454 —02	.2917 —01	.9262 —01	.3409	.7328	.2032 +01
h	.1622 +06	.1597 +06	.1540 +06	.1444 +06	.1285 +06	.1178 +06	.1040 +06
s	.4729 +02	.4455 +02	.4142 +02	.3830 +02	.3489 +02	.3289 +02	.3042 +02
M	.3482 +01	.3503 +01	.3567 +01	.3705 +01	.4000 +01	.4244 +01	.4620 +01
Γ	.9121 —01	.1567	.2883	.4931	.8661	.1181 +01	.1746 +01
η	.4810 —04	.6661 —04	.1082 —03	.1816 —03	.3185 —03	.4140 —03	.5419 —03
λ'	.1478 —01	.1801 —01	.2338 —01	.3035 —01	.4098 —01	.4627 —01	.5181 —01
λ_Σ	.1479 —01	.1805 —01	.2349 —01	.3057 —01	.4134 —01	.4669 —01	.5228 —01
σ	.7701 +02	.8831 +02	.1013 +03	.1087 +03	.1022 +03	.9566 —02	.8174 +02
α	.4085 —02	.4693 —02	.5408 —02	.5807 —02	.5397 —02	.4681 —02	.3411 —02
λ_R	.7360 +07	.1460 +07	.5850 +05	.9130 +04	.1110 +04	.3920 +03	.1030 +03

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Table 5.1. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
			$T=20\,000$ K				
e^-	.1790 —02	.5392 —02	.1808 —01	.5447 —01	.1802	.3538	.8414
Li	.2472 —05	.2167 —04	.2284 —03	.1881 —02	.1751 —01	.5971 —01	.2775
Li^+	.1790 —02	.5391 —02	.1809 —01	.5447 —01	.1802	.3539	.8416
Li^-	.9392 —11	.2481 —09	.8762 —08	.2170 —06	.6638 —05	.4405 —04	.4737 —03
Li_2	.3138 —14	.2411 —12	.2674 —10	.1808 —08	.1548 —06	.1771 —05	.3658 —04
Li_2^-	.6587 —11	.1740 —09	.6146 —08	.1522 —06	.4656 —05	.3090 —04	.3323 —03
ρ	.2064 —02	.6236 —02	.2110 —01	.6491 —01	.2277	.4765	.1291 +01
h	.1931 +06	.1918 +06	.1888 +06	.1838 +06	.1737 +06	.1651 +06	.1508 +06
s	.4907 +02	.4640 +02	.4343 +02	.4066 +02	.3748 +02	.3559 +02	.3306 +02
M	.3473 +01	.3477 +01	.3492 +01	.3529 +01	.3631 +01	.3741 +01	.3964 +01
Γ	.5123 —01	.8843 —01	.1628	.2824	.5129	.7186	.1106 +01
η	.7416 —04	.9223 —04	.1227 —03	.1739 —03	.2764 —03	.3734 —03	.5282 —03
λ'	.2511 —01	.3011 —01	.3730 —01	.4745 —01	.6379 —01	.7779 —01	.9449 —01
λ_Σ	.2512 —01	.3012 —01	.3732 —01	.4750 —01	.6321 —01	.7796 —01	.9474 —01
σ	.1037 +03	.1180 +03	.1373 +03	.1566 +03	.1713 +03	.1716 +03	.1599 +03
α	.5495 —02	.6255 —02	.7288 —02	.8332 —02	.9071 —02	.8916 —02	.7771 —02
λ_R	.2850 +09	.4890 +08	.1190 +07	.1530 +06	.1800 +05	.5460 +04	.1300 +04

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Table 5.1. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T=25\,000$ K			
e^-	.1428 —02	.4298 —02	.1440 —01	.4352 —01	.1460	.2918	.7201
Li	.6371 —06	.5640 —05	.6069 —04	.5182 —03	.5189 —02	.1888 —01	.9639 —01
Li^+	.1428 —02	.4298 —02	.1441 —01	.4352 —01	.1460	.2918	.7202
Li^-	.1243 —11	.3311 —10	.1194 —08	.3076 —07	.1029 —05	.7442 —05	.9404 —04
Li_2	.1613 —15	.1264 —13	.1462 —11	.1064 —09	.1059 —07	.1386 —06	.3645 —05
Li_2^+	.6896 —12	.2370 —10	.8542 —09	.2201 —07	.7364 —06	.5326 —05	.6731 —04
Li^{++}	.2311 —12	.2413 —12	.2610 —12	.2922 —12	.3506 —12	.4012 —12	.4940 —12
ρ	.1646 —02	.4958 —02	.1666 —01	.5073 —01	.1741	.3579	.9432
h	.2235 +06	.2225 +06	.2205 +06	.2170 +06	.2101 +06	.2037 +06	.1920 +06
s	.5043 +02	.4777 +02	.4484 +02	.4214 +02	.3910 +02	.3731 +02	.3488 +02
M	.3471 +01	.3473 +01	.3478 +01	.3491 +01	.3531 +01	.3579 +01	.3693 +01
Γ	.3266 —01	.5660 —01	.1033	.1807	.3307	.4674	.7332
η	.1118 —03	.1346 —03	.1680 —03	.2197 —03	.3131 —03	.3981 —03	.5582 —03
λ'	.3866 —01	.4562 —01	.5503 —01	.6818 —01	.8876 —01	.1057	.1360
λ_Σ	.3866 —01	.4563 —01	.5504 —01	.6820 —01	.8881 —01	.1058	.1362
σ	.1317 +03	.1483 +03	.1710 +03	.1958 +03	.2220 +03	.2310 +03	.2288 +03
α	.6981 —02	.7859 —02	.9069 —02	.1039 —01	.1177 —01	.1214 —01	.1156 —01
λ_R	—	—	.1180 +08	.1460 +07	.1570 +06	.4510 +05	.9360 +04

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Table 5.1. [Contined]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				T=30 000 K			
e^-	.1188 —02	.3574 —02	.1197 —01	.3611 —01	.1214	.2439	.6104
Li	.2222 —06	.1980 —05	.2153 —04	.1870 —03	.1939 —02	.7279 —02	.4028 —01
Li^+	.1188 —02	.3574 —02	.1197 —01	.3611 —01	.1214	.2439	.6103
Li^-	.2635 —12	.7050 —11	.2566 —09	.6720 —08	.2636 —06	.1755 —05	.2402 —04
Li_2	.1693 —16	.1341 —14	.1584 —12	.1193 —10	.1276 —08	.1784 —07	.5342 —06
Li_2^-	.1912 —12	.5117 —11	.1862 —09	.4878 —08	.1696 —06	.1274 —05	.1744 —04
Li^{++}	.1036 —09	.1068 —09	.1131 —09	.1232 —09	.1423 —09	.1592 —09	.1909 —09
ρ	.1369 —02	.4119 —02	.1381 —01	.4181 —01	.1420	.2893	.7489
h	.2537 +06	.2529 +06	.2513 +06	.2486 +06	.2434 +06	.2383 +06	.2290 +06
s	.5153 +02	.4888 +02	.4597 +02	.4329 +02	.4031 +02	.3858 +02	.3621 +02
M	.3471 +01	.3471 +01	.3473 +01	.3479 +01	.3498 +01	.3521 +01	.3681 +01
Γ	.2272 —01	.3941 —01	.7210 —01	.1252	.2295	.3253	.5141
η	.1599 —03	.1871 —03	.2322 —03	.2850 —03	.3883 —03	.4749 —03	.6417 —03
λ'	.5579 —01	.6443 —01	.7803 —01	.9271 —01	.1189	.1385	.1735
λ_{Σ}	.5579 —01	.6443 —01	.7803 —01	.9272 —01	.1189 —01	.1386	.1735
σ	.1611 +03	.1799 +03	.2055 +03	.2339 +03	.2668 +03	.2811 +03	.2860 +03
α	.8540 —02	.9537 —02	.1089 —01	.1241 —01	.1415 —01	.1485 —01	.1472 —01
λ_R	—	—	.6720 +08	.6790 +07	.8960 +06	.2510 +06	.4790 +05

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Table 5.1. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				T=40 000 K			
e^-	.8899 —03	.2674 —02	.8937 —02	.2692 —01	.9037 —01	.1817	.4574
Li	.4617 —07	.4130 —06	.4534 —05	.4002 —04	.4282 —03	.1655 —02	.9682 —02
Li^+	.8895 —03	.2673 —02	.8936 —02	.2692 —01	.9036 —01	.1817	.4574
Li^-	.2641 —13	.7097 —12	.2604 —10	.6920 —09	.2482 —07	.1924 —06	.2816 —05
Li_2	.6153 —18	.4921 —16	.5927 —14	.4613 —12	.5266 —10	.7831 —09	.2646 —07
Li_2^+	.1954 —13	.5250 —12	.1925 —10	.5117 —09	.1835 —07	.1422 —06	.2082 —05
Li^{++}	.2346 —06	.2389 —06	.2472 —06	.2605 —06	.2860 —06	.3090 —06	.3532 —06
Li^{+++}	.1984 —16	.6898 —17	.2237 —17	.8363 —18	.3048 —18	—	—
ρ	.1025 —02	.3080 —02	.1030 —01	.3106 —01	.1046	.2111	.5381
h	.3142 +06	.3134 +06	.3122 +06	.3102 +06	.3065 +06	.3030 +06	.2961 +06
s	.5327 +02	.5062 +02	.4772 +02	.4506 +02	.4213 +02	.4042 +02	.3814 +02
M	.3470 +01	.3470 +01	.3471 +01	.3473 +01	.3478 +01	.3486 +01	.3507 +01
Γ	.1277 —01	.2211 —01	.4047 —01	.7024 —01	.1287	.1824	.2893
η	.2845 —03	.3260 —03	.3867 —03	.4706 —03	.5881 —03	.6957 —03	.8871 —03
λ'	.1002	.1138	.1332	.1588	.1923	.2209	.2684
λ_Σ	.1002	.1138	.1332	.1588	.1923	.2210	.2684
σ	.2236 +03	.2467 +03	.2760 +03	.3128 +03	.3556 +03	.3760 +03	.3941 +03
α	.1185 —01	.1307 —01	.1474 —01	.1658 —01	.1886 —01	.2003 —01	.2066 —01
λ_R	—	—	.9090 +09	.1240 +09	.1220 +08	.3270 +07	.5910 +06

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Table 5.2. Thermophysical Properties of Sodium Plasma (M = 22.99)

(1) Величина	(2) Давление, ат						
	1	3	10	30	100	200	500
				$T = 4000$ K			
e^-	.2057 —03	.3697 —03	.7165 —03	.1371 —02	.3173 —02	.5836 —02	.1705 —01
Na	.1736 —01	.5252 —01	.1757	.5255	.1720 +01	.3351 +01	.7821 +01
Na^+	.2054 —03	.3678 —03	.7045 —03	.1309 —02	.2817 —02	.4894 —02	.1351 —01
Na^-	.3884 —06	.2105 —05	.1348 —04	.7456 —04	.5022 —03	.1534 —02	.6759 —02
Na_2	.5155 —05	.4720 —04	.5283 —03	.4724 —02	.5056 —01	.1917	.1041 +01
Na_2^-	.7463 —06	.4030 —05	.2552 —04	.1370 —03	.8583 —03	.2477 —02	.1031 —01
ρ	.6706 —01	.2022	.6774	.2048 +01	.6967 +01	.1429 +02	.3794 +02
h	.3973 +04	.3852 +04	.3769 +04	.3703 +04	.3598 +04	.3469 +04	.3206 +04
s	.9146 +01	.8715 +01	.8257 +01	.7844 +01	.7387 +01	.7116 +01	.6744 +01
M	.2273 +02	.2286 +02	.2297 +02	.2314 +02	.2361 +02	.2421 +02	.2566 +02
Γ	.1940	.2609	.3652	.5144	.8195	.1160 +01	.2077 +01
η	.1299 —02	.1325 —02	.1338 —02	.1333 —02	.1296 —02	.1246 —02	.1134 —02
λ'	.1972 —02	.1931 —02	.1878 —02	.1828 —02	.1748 —02	.1669 —02	.1500 —02
λ_{Σ}	.2022 —02	.1963 —02	.1904 —02	.1864 —02	.1833 —02	.1812 —02	.1760 —02
σ	.1987 +01	.1456 +01	.1040 +01	.7600	.5441	.4632	.4107
α	.7424 —04	.3242 —04	.4161 —05	—.8752 —05	—.1322 —04	—.1344 —04	—.1406 —04
λ_R	.1720 +05	.2650 +04	.4560 +03	.7280 +02	.9430 +01	.2850 +01	.5460

Key:
1. Value
2. Pressure, atmospheres

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Table 5.2. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T=5000$ K			
e^-	.9413 —03	.1750 —02	.3471 —02	.6671 —02	.1491 —01	.2604 —01	.6744 —01
Na	.1240 —01	.3929 —01	.1354	.4124	.1376 +01	.2726 +01	.6594 +01
Na^+	.9408 —03	.1746 —02	.3449 —02	.6547 —02	.1412 —01	.2380 —01	.5847 —01
Na^-	.7322 —06	.4303 —05	.2920 —04	.1671 —03	.1155 —02	.3591 —02	.1660 —01
Na_2	.1562 —05	.1568 —04	.1862 —03	.1725 —02	.1916 —01	.7491 —01	.4335
Na_2^+	.1300 —05	.7632 —05	.5154 —04	.2915 —03	.1943 —02	.5831 —02	.2557 —01
ρ	.5093 —01	.1568	.5319	.1615 +01	.5471 +01	.1112 +02	.2895 +02
h	.6558 +04	.5843 +04	.5388 +04	.5139 +04	.4947 +04	.4833 +04	.4629 +04
s	.9714 +01	.9153 +01	.8615 +01	.8162 +01	.7688 +01	.7418 +01	.7060 +01
M	.2148 +02	.2206 +02	.2247 +02	.2274 +02	.2309 +02	.2343 +02	.2424 +02
Γ	.2964	.4051	.5716	.7997	.1225 +01	.1664 +01	.2790 +01
η	.1213 —02	.1350 —02	.1447 —02	.1494 —02	.1503 —02	.1482 —02	.1406 —02
λ'	.2642 —02	.2725 —02	.2663 —02	.2534 —02	.2371 —02	.2274 —02	.2117 —02
λ_Σ	.2854 —02	.2857 —02	.2745 —02	.2597 —02	.2450 —02	.2387 —02	.2321 —02
σ	.8061 +01	.6193 +01	.4623 +01	.3673 +01	.3031 +01	.2803 +01	.2704 +01
α	.4754 —03	.3217 —03	.1863 —03	.9014 —04	.1764 —04	—.9727 —05	—.3643 —04
λ_R	.8660 +04	.1930 +04	.2650 +03	.4780 +02	.9770 +01	.3290 +01	.6910

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Table 5.2. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				T=6000 K			
e^-	.2270 —02	.4540 —02	.9466 —02	.1862 —01	.4125 —01	.6972 —01	.1637
Na	.7599 —02	.2699 —01	.1009	.3213	.1106 +01	.2226 +01	.5521 +01
Na^+	.2270 —02	.4537 —02	.9439 —02	.1846 —01	.4012 —01	.6634 —01	.1496
Na^-	.6868 —06	.4931 —05	.3823 —04	.2356 —03	.1704 —02	.5372 —02	.2511 —01
Na_2	.3759 —06	.4856 —05	.6781 —04	.6853 —03	.8081 —02	.3248 —01	.1954
Na_2^-	.1175 —05	.8431 —05	.6523 —04	.3997 —03	.2836 —02	.8749 —02	.3926 —01
ρ	.3733 —01	.1204	.4224	.1306 +01	.4465 +01	.9083 +01	.2352 +02
h	.1201 +05	.9718 +04	.8211 +04	.7402 +04	.6869 +04	.6654 +04	.6408 +04
s	.1070 +02	.9[illegible] +01	.9125 +01	.8571 +01	.8036 +01	.7749 +01	.7383 +01
M	.1866 +02	.2011 +02	.2120 +02	.2187 +02	.2241 +02	.2272 +02	.2326 +02
Γ	.3499	.4959	.7160	.1009 +01	.1523 +01	.2015 +01	.3183 +01
η	.8269 —03	.1094 —02	.1333 —02	.1485 —02	.1580 —02	.1596 —02	.1563 —02
λ'	.3315 —02	.3764 —02	.4010 —02	.3880 —02	.3585 —02	.3395 —02	.3161 —02
λ_Σ	.3770 —02	.4073 —02	.4205 —02	.4013 —02	.3697 —02	.3501 —02	.3351 —02
σ	.1914 +02	.1662 +02	.1348 +02	.1111 +02	.9842 +01	.1010 +02	.7247 +02
α	.1050 —02	.8826 —03	.6353 —03	.4028 —03	.1787 —03	.6631 —04	—.8036 —04
λ_R	.7900 +04	.2210 +04	.3210 +03	.6640 +02	.1560 +02	.6150 +01	.1890 +01

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Table 5.2. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T=7000$ K			
e^-	.3453 —02	.7762 —02	.1761 —01	.3622 —01	.8135 —01	.1847	.2966
Na	.3557 —02	.1590 —01	.6924 —01	.2399	.8747	.1801 +01	.4589 +01
Na^+	.3453 —02	.7759 —02	.1758 —01	.3606 —01	.8013 —01	.1309	.2801
Na^-	.3370 —06	.3382 —05	.3328 —04	.2344 —03	.1845 —02	.5945 —02	.2825 —01
Na_2	.5801 —07	.1158 —05	.2192 —04	.2619 —03	.3450 —02	.1446 —01	.9077 —01
Na_2^+	.5656 —06	.5675 —05	.5579 —04	.3917 —03	.3047 —02	.9700 —02	.4478 —01
ρ	.2675 —01	.9034 —01	.3321	.1059 +01	.3700 +01	.7578 +01	.1972 +02
h	.2028 +05	.1593 +05	.1266 +05	.1079 +05	.9555 +04	.9090 +04	.8641 +04
s	.1197 +02	.1081 +02	.9806 +01	.9091 +01	.8448 +01	.8122 +01	.7726 +01
M	.1540 +02	.1732 +02	.1914 +02	.2038 +02	.2134 +02	.2178 +02	.2230 +02
Γ	.3427	.5142	.7737	.1114 +01	.1682 +01	.2171 +01	.3316 +01
η	.4423 —03	.7214 —03	.1047 —02	.1307 —02	.1513 —02	.1584 —02	.1611 —02
λ'	.4111 —02	.5020 —02	.5864 —02	.6047 —02	.5773 —02	.5474 —02	.5069 —02
λ_Σ	.4633 —02	.5470 —02	.6185 —02	.6271 —02	.5936 —02	.5631 —02	.5260 —02
σ	.3030 +02	.2902 +02	.2506 +02	.2031 +02	.1532+02	.1272 +02	.1064 +02
α	.1673 —02	.1633 —02	.1410 —02	.1098 —02	.7483 —03	.5818 —03	.4320 —03
λ_R	.1600 +05	.3800 +04	.5750 +03	.1140 +03	.2780 +02	.1170 +02	.3680 +01

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Table 5.2. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T=8000$ K			
e^-	.3888 —02	.9874 —02	.2494 —01	.5476 —01	.1272	.2102	.4440
Na	.1421 —02	.8059 —02	.4303 —01	.1689	.6713	.1430 +01	.3774 +01
Na^+	.3888 —02	.9873 —02	.2493 —01	.5464 —01	.1262	.2068	.4283
Na^-	.1072 —06	.1542 —05	.2074 —01	.1770 —03	.1584 —02	.5340 —02	.2614 —01
Na_2	.6531 —08	.2098 —06	.5964 —05	.9129 —04	.1423 —02	.6360 —02	.4243 —01
Na_2^+	.1780 —06	.2561 —05	.3442 —04	.2934 —03	.2610 —02	.8726 —02	.4188 —01
ρ	.2026 —01	.6846 —01	.2597	.8565	.3080 +01	.6382 +01	.1678 +02
h	.2820 +05	.2328 +05	.1841 +05	.1521 +05	.1296 +05	.1209 +05	.1126 +05
s	.1303 +02	.1179 +02	.1057 +02	.9679 +01	.8900 +01	.8520 +01	.8074 +01
M	.1327 +02	.1483 +02	.1683 +02	.1851 +02	.1995 +02	.2059 +02	.2125 +02
Γ	.2979	.4747	.7534	.1119 +01	.1713 +01	.2202 +01	.3268 +01
η	.2248 —03	.4322 —03	.7459 —03	.1056 —02	.1354 —02	.1483 —02	.1581 —02
λ'	.5062 —02	.6397 —02	.8046 —02	.8889 —02	.9049 —02	.8750 —02	.8153 —02
λ_Σ	.5404 —02	.6818 —02	.8424 —02	.9179 —02	.9259 —02	.8936 —02	.8347 —02
σ	.3971 +02	.4213 +02	.4104 +02	.3692 +02	.3064 +02	.2604 +02	.2210 +02
α	.2141 —02	.2304 —02	.2248 —02	.1946 —02	.1444 —02	.1137 —02	.8394 —03
λ_R	.3060 +05	.7610 +04	.1020 +04	.2260 +03	.4910 +02	.2060 +02	.6680 +01

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Table 5.2. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				T=10000 K			
e^-	.3535 —02	.1022 —01	.3077 —01	.7804 —01	.2014	.3417	.7054
Na	.2428 —03	.1814 —02	.1382 —01	.7229 —01	.3622	.8494	.2468 +01
Na^+	.3535 —02	.1022 —01	.3077 —01	.7800 —01	.2009	.3399	.6955
Na^-	.9080 —08	.1961 —06	.4487 —05	.5917 —04	.7495 —03	.2898 —02	.1595 —01
Na_2	.1019 —09	.5687 —08	.3289 —06	.8933 —05	.2200 —03	.1185 —02	.9481 —02
Na_2^+	.1494 —07	.3227 —06	.7382 —05	.9733 —04	.1230 —02	.4743 —02	.2588 —01
ρ	.1442 —01	.4593 —01	.1702	.5745	.2163 +01	.4594 +01	.1240 +02
h	.3714 +05	.3448 +05	.2991 +05	.2523 +05	.2092 +05	.1903 +05	.1712 +05
s	.1404 +02	.1305 +02	.1186 +02	.1079 +02	.9780 +01	.9287 +01	.8719 +01
M	.1188 +02	.1243 +02	.1361 +02	.1515 +02	.1700 +02	.1798 +02	.1906 +02
Γ	.2035	.3458	.5991	.9558	.1537 +01	.1996 +01	.2900 +01
η	.8899 —04	.1747 —03	.3616 —03	.6267 —03	.9819 —03	.1183 —02	.1401 —02
λ'	.7274 —02	.9261 —02	.1247 —01	.1545 —01	.1810 —01	.1873 —01	.1835 —01
λ_Σ	.7351 —02	.9421 —02	.1272 —01	.1574 —01	.1834 —01	.1895 —01	.1855 —01
σ	.5228 +02	.6068 +02	.6858 +02	.7022 +02	.6510 +02	.5966 +02	.5183 +02
α	.2783 —02	.3256 —02	.3742 —02	.3874 —02	.3507 —02	.3080 —02	.2441 —02
λ_R	.4110 +06	.6220 +05	.6890 +04	.1330 +04	.2110 +03	.8220 +02	.2510 +02

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Table 5.2. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				T=12000 K			
e^-	.2994 —02	.8944 —02	.2898 —01	.8083 —01	.2320	.4115	.8691
Na	.6050 —04	.4949 —03	.4488 —02	.2898 —01	.1823	.4776	.1561 +01
Na^-	.2994 —02	.8945 —02	.2898 —01	.8082 —01	.2318	.4107	.8641
Na^{++}	.6333 —17	.7279 —17	.8974 —17	.1132 —16	.1508 —16	.1780 —16	.2243 —16
Na^-	.1166 —08	.2848 —07	.8354 —06	.1500 —04	.2667 —03	.1214 —02	.7877 —02
Na_2	.3809 —11	.2547 —09	.2089 —07	.8655 —06	.3360 —04	.2254 —03	.2273 —02
Na_2^-	.1913 —08	.4674 —07	.1371 —05	.2459 —04	.4374 —03	.1989 —02	.1285 —01
ρ	.1166 —01	.3602 —01	.1277	.4192	.1685 +01	.3411 +01	.9397 +01
h	.4202 +05	.4070 +05	.3791 +05	.3394 +05	.2887 +05	.2618 +05	.2316 +05
s	.1449 +02	.1362 +02	.1259 +02	.1158 +02	.1050 +01	.9930 +01	.9260 +01
M	.1161 +02	.1181 +02	.1232 +02	.1325 +02	.1476 +02	.1577 +02	.1707 +02
Γ	.1425	.2462	.4428	.7360	.1254 +01	.1664 +01	.2435 +01
η	.7174 —04	.1175 —03	.2264 —03	.4171 —03	.7331 —03	.9512 —03	.1234 —02
λ'	.9848 —02	.1236 —01	.1651 —01	.2199 —01	.2766 —01	.3048 —01	.3218 —01
λ_Σ	.9868 —02	.1241 —01	.1662 —01	.2217 —01	.2789 —01	.3068 —01	.3236 —01
σ	.6237 +02	.7319 +02	.8699 +02	.9741 +02	.1002 +03	.9626 +02	.8648 +02
α	.3310 —02	.3898 —02	.4678 —02	.5362 —02	.5434 —02	.5255 —02	.4491 —02
λ_R	.4220 +07	.6510 +06	.4730 +05	.6350 +04	.9030 +03	.3100 +03	.8480 +02

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Table 5.2. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
			$T=15000$ K				
e^-	.2395 —02	.7220 —02	.2409 —01	.7127 —01	.2247	.4234	.9454
Na	.1273 —04	.1090 —03	.1090 —02	.8230 —02	.6519 —01	.1966	.7616
Na^+	.2395 —02	.7220 —02	.2409 —01	.7127 —01	.2247	.4232	.9438
Na^{++}	.7751 —13	.8586 —13	.1015 —12	.1248 —12	.1643 —12	.1957 —12	.2475 —12
Na^-	.1110 —09	.2860 —08	.9545 —07	.2125 —05	.5256 —04	.2947 —03	.2451 —02
Na_2	.9769 —13	.7151 —11	.7150 —09	.4052 —07	.2503 —05	.2229 —04	.3179 —03
Na_2^+	.1821 —09	.4694 —08	.1567 —06	.3487 —05	.8628 —04	.4834 —03	.4015 —02
ρ	.9191 —02	.2797 —01	.9609 —01	.3034	.1107 +01	.2370 +01	.6550 +01
h	.4795 +05	.4727 +05	.4580 +05	.4331 +05	.3905 +05	.3606 +05	.3206 +05
s	.1493 +02	.1411 +02	.1318 +02	.1228 +02	.1125 +02	.1065 +02	.9907 +01
M	.1153 +02	.1158 +02	.1175 +02	.1212 +02	.1296 +02	.1368 +02	.1485 +02
Γ	.9124 —01	.1584	.2891	.4962	.8788	.1208 +01	.1801 +01
η	.8570 —04	.1168 —03	.1860 —03	.3115 —03	.5682 —03	.7726 —03	.1092 —02
λ'	.1469 —01	.1789 —01	.2324 —01	.3026 —01	.4143 —01	.4753 —01	.5475 —01
λ_Σ	.1469 —01	.1790 —01	.2327 —01	.3033 —01	.4156 —01	.4768 —01	.5494 —01
σ	.7745 +02	.8992 +02	.1075 +03	.1262 +03	.1434 +03	.1480 +03	.1395 +03
α	.4106 —02	.4773 —02	.5726 —02	.6776 —02	.7795 —02	.8044 —02	.7383 —02
λ_R	.5290 +08	.7180 +07	.5080 +06	.5210 +05	.6450 +04	.1860 +04	.4300 +03

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Table 5.2. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				T=20000 K			
e^-	.1790 —02	.5394 —02	.1811 —01	.5466 —01	.1818	.3593	.8644
Na	.2002 —05	.4756 —04	.1853 —03	.1533 —02	.1441 —01	.4961 —01	.2349
Na^+	.1790 —02	.5393 —02	.1811 —01	.5465 —01	.1818	.3593	.7642
Na^{++}	.1057 —06	.1127 —08	.1261 —08	.1470 —08	.1852 —08	.2172 —08	.2739 —08
Na^-	.7019 —11	.1855 —09	.6572 —08	.1637 —06	.5093 —05	.3440 —04	.3831 —03
Na_2	.1481 —14	.1139 —12	.1268 —10	.8640 —09	.7557 —07	.8839 —06	.1907 —04
Na_2^-	.1155 —10	.3052 —09	.1081 —07	.2693 —06	.8379 —05	.5659 —04	.6300 —03
ρ	.6837 —02	.2065 —01	.6980 —01	.2144	.7489	.1561 +01	.4200 +01
h	.5725 +05	.5686 +05	.5604 +05	.5465 +05	.5194 +05	.4961 +05	.4569 +05
s	.1546 +02	.1466 +02	.1377 +02	.1293 +02	.1199 +02	.1143 +02	.1067 +02
M	.1150 +02	.1151 +02	.1155 +02	.1165 +02	.1193 +02	.1224 +02	.1288 +02
Γ	.5123 —01	.8893 —01	.1629	.2828	.5150	.7242	.1121 +01
η	.1340 —04	.1661 —03	.2195 —03	.3083 —03	.4866 —03	.6601 —03	.9536 —03
λ'	.2497 —01	.2994 —01	.3708 —01	.4720 —01	.6375 —01	.7819 —01	.9647 —01
λ_Σ	.2498 —01	.2994 —01	.3709 —01	.4722 —01	.6378 —01	.7824 —01	.9655 —01
σ	.1038 +03	.1185 +03	.1397 +03	.1651 +03	.1989 +03	.2187 +03	.2293 +03
α	.5504 —02	.6284 —02	.7411 —02	.8772 —02	.1061 —01	.1168 —01	.1265 —01
λ_R	.1120 +10	.1670 +09	.9840 +07	.8260 +06	.9240 +05	.2280 +05	.4380 +04

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Table 5.2. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				T=25000 K			
e^-	.1428 —02	.4299 —02	.1441—01	.4357 —01	.1465	.2936	.7290
Na	.5198 —06	.4605 —05	.4957 —04	.4236 —03	.4258 —02	.1556 —01	.8178 —01
Na^+	.1428 —02	.4299 —02	.1441 —01	.4357 —01	.1465	.2936	.7290
Na^{++}	.3476 —06	.3630 —06	.3928 —06	.4398 —06	.5278 —06	.6045 —06	.7457 —06
Na^-	.9843 —12	.2624 —10	.9471 —09	.2444 —07	.8232 —06	.5998 —05	.7720 —04
Na_2	.7958 —16	.6245 —14	.7233 —12	.5273 —10	.5293 —08	.7000 —07	.1884 —05
Na_2^-	.1623 —11	.4327 —10	.1562 —08	.4031 —07	.1358 —05	.9895 —05	.1273 —03
ρ	.5451 —02	.1642 —01	.5520 —01	.1679	.5752	.1180 +01	.3095 +01
h	.6647 +05	.6614 +05	.6553 +05	.6454 +05	.6261 +05	.6086 +05	.5765 +05
s	.1588 +02	.1507 +02	.1419 +02	.1337 +02	.1246 +02	.1193 +02	.1120 +02
M	.1150 +02	.1150 +02	.1151 +02	.1155 +02	.1166 +02	.1179 +02	.1211 +02
Γ	.3275 —01	.5661 —01	.1040	.1808	.3312	.4688	.7378
η	.2022 —03	.2433 —03	.3033 —03	.3955 —03	.5633 —03	.7201 —03	.1035 —02
λ'	.3840 —01	.4535 —01	.5471 —01	.6780 —01	.8838 —01	.1055	.1368
λ_Σ	.3842 —01	.4536 —01	.5472 —01	.6781 —01	.8840 —01	.1056	.1369
σ	.1317 +03	.1486 +03	.1724 +03	.2008 +03	.2406 +03	.2665 +03	.2988 +03
α	.6986 —02	.7876 —02	.9138 —02	.1065 —01	.1279 —01	.1417 —01	.1582 —01
λ_R	—	—	.8560 +08	.6410 +07	.7050 +06	.1770 +06	.2860 +05

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Table 5.2. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				T=30 000 K			
e^-	.1197 —02	.3583 —02	.1198 —01	.3614 —01	.1216	.2446	.6141
Na	.1787 —06	.1605 —05	.1752 —04	.1524 —03	.1583 —02	.5957 —02	.3310 —01
Na^+	.1163 —02	.3548 —02	.1194 —01	.3610 —01	.1216	.2445	.6141
Na^{++}	.1699 —04	.1786 —04	.1903 —04	.2078 —04	.2402 —04	.2688 —04	.3228 —04
Na^-	.2154 —12	.5791 —11	.2112 —09	.5539 —08	.1932 —06	.1457 —05	.2013 —04
Na_2	—	.6751 —15	.8029 —13	.6068 —11	.6520 —09	.9174 —08	.2779 —06
Na_2^+	.3459 —12	.9480 —11	.3480 —09	.9146 —08	.3193 —06	.2409 —05	.3328 —04
ρ	.4503 —02	.1361 —01	.4570 —01	.1384	.4700	.9561	.2470 +01
h	.7878 +05	.7642 +05	.7518 +05	.7417 +05	.7255 +05	.7114 +05	.6849 +05
s	.1632 +02	.1545 +02	.1454 +02	.1372 +02	.1282 +02	.1230 +02	.1159 +02
M	.1141 +02	.1147 +02	.1149 +02	.1151 +02	.1157 +02	.1163 +02	.1180 +02
Γ	.2297 —01	.3945 —01	.7219 —01	.1253	.2297	.3257	.5157
η	.2696 —03	.3310 —03	.4171 —03	.5140 —03	.7003 —03	.8575 —03	.1169 —02
λ'	.5211 —01	.6339 —01	.7823 —01	.9352 —01	.1201	.1403	.1763
λ_Σ	.5266 —01	.6377 —01	.7835 —01	.9359 —01	.1202	.1403	.1764
σ	.1545 +03	.1775 +03	.2059 +03	.2387 +03	.2811 +03	.3099 +03	.3467 +03
α	.8502 —02	.9539 —02	.1096 —01	.1267 —01	.1493 —01	.1636 —01	.1837 —01
λ_R	—	—	.6610 +09	.5810 +08	.5660 +07	.1360 +07	.2000 +06

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Table 5.2. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T=40\,000$ K			
e^-	.1123 —02	.3178 —02	.9839 —02	.2817 —01	.9198 —01	.1836	.4606
Na	.1059 —07	.1769 —06	.2851 —05	.2939 —04	.3357 —03	.1319 —02	.7802 —02
Na^+	.2003 —03	.1194 —02	.6328 —02	.2340 —01	.8609 —01	.1771	.4530
Na^{++}	.4614 —03	.9918 —03	.1755 —02	.2383 —02	.2940 —02	.3268 —02	.3806 —02
Na^-	.8137 —14	.3846 —12	.1919 —10	.5663 —09	.2109 —07	.1651 —06	.2436 —05
Na_2	—	—	.1875 —14	.1990 —12	.2590 —10	.3981 —09	.1379 —07
Na_2^-	.2401 —14	.2392 —12	.2044 —10	.7787 —09	.3268 —07	.2635 —06	.3966 —05
ρ	.2525 —02	.8342 —02	.3086 —01	.9851 —01	.3410	.6932	.1773 +01
h	.2572 +06	.1998 +06	.1440 +06	.1143 +06	.9937 +05	.9491 +05	.9069 +05
s	.2127 +02	.1882 +02	.1642 +02	.1483 +02	.1358 +02	.1297 +02	.1223 +02
M	.8524 +01	.9370 +01	.1037 +02	.1099 +02	.1133 +02	.1143 +02	.1155 +02
Γ	.1704 —01	.2755 —01	.4584 —01	.7481 —01	.1318	.1850	.2915
η	.6860 —04	.1432 —03	.3227 —03	.5932 —03	.9392 —03	.1173 —02	.1546 —02
λ'	.4943 —01	.6144 —01	.8321 —01	.1186	.1709	.2084	.2661
λ_s	.5289 —01	.6880 —01	.9296 —01	.1267	.1758	.2119	.2683
σ	.1437 +03	.1667 +03	.2077 +03	.2638 +03	.3416 +03	.3923 +03	.4699 +03
α	.1107 —01	.1239 —01	.1428 —01	.1649 —01	.1957 —01	2179 —01	.2548 —01
λ_R	—	—	—	—	.6920 +08	.1620 +08	.2350 +07

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Table 5.3. Thermophysical Properties of Potassium Plasma (M = 39.1)

(1) Величина	(2) Давление, ат						
	1	3	10	30	100	200	500
				T=4000 K			
e^-	.6714 —03	.1246 —02	.2525 —02	.5186 —02	.1430 —01	.3212 —01	.1530
K	.1648 —01	.5090 —01	.1725	.5197	.1711 +01	.3354 +01	.8075 +01
K^+	.6701 —03	.1238 —02	.2473 —02	.4910 —02	.1264 —01	.2731 —01	.1293
K^-	.2034 —05	.1159 —04	.7783 —04	.4517 —03	.3301 —02	.1078 —01	.5409 —01
K_2	.3976 —05	.3793 —04	.4353 —03	.3942 —02	.4249 —01	.1614	.8657
K_2^+	.3452 —05	.1958 —04	.1296 —03	.7272 —03	.4961 —02	.1559 —01	.7775 —01
ρ	.1114	.3392	.1144 +01	.3468 +01	.1183 +02	.2431 +02	.6584 +02
h	.2750 +04	.2558 +04	.2434 +04	.2362 +04	.2291 +04	.2237 +04	.2145 +04
s	.5667 +01	.5379 +01	.5088 +01	.4836 +01	.4565 +01	.4410 +01	.4207 +01
M	.3764 +02	.3823 +02	.3867 +02	.3906 +02	.3982 +02	.4067 +02	.4240 +02
Γ	.3498	.4792	.6879	.1008 +01	.1789 +01	.2788 +01	.6121 +01
η	.1157 —02	.1234 —02	.1283 —02	.1296 —02	.1269 —02	.1220 —02	.1097 —02
λ'	.1416 —02	.1382 —02	.1305 —02	.1227 —02	.1146 —02	.1091 —02	.9951 —03
λ_Σ	.1499 —02	.1434 —02	.1341 —02	.1263 —02	.1206 —02	.1184 —02	.1158 —02
σ	.3927 +01	.2792 +01	.1865 +01	.1303 +01	.9620	.8856	.9891
α	.1809 —03	.1104 —03	.5884 —04	.3285 —04	.1997 —04	.1700 —04	.1659 —04
λ_R	.2740 +04	.6000 +03	.1100 +03	.1960 +02	.2500 +01	.7370	.1300

Key:
1. Value
2. Pressure, atmospheres

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Table 5.3. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				T=5000 K			
e^-	.2196 —02	.4345 —02	.9139 —02	.1871 —01	.4753 —01	9490 —01	.3325
K	.1006 —01	.3458 —01	.1255	.3927	.1334 +01	.2668 +01	.6679 +01
K^+	.2194 —02	.4333 —02	.9052 —02	.1819 —01	.4407 —01	.8462 —01	.2860
K^-	.2017 —05	.1366 —04	.1028 —03	.6317 —03	.4732 —02	.1550 —01	.7695 —01
K_2	.8563 —06	.1021 —04	.1342 —03	.1307 —02	.1485 —01	.5792 —01	.3223
K_2^-	.3761 —05	.2542 —04	.1899 —03	.1146 —02	.8187 —02	.2578 —01	.1235
ρ	.7963 —01	.2531	.8781	.2703 +01	.9275 +01	.1905 +02	.5149 +02
h	.5316 +04	.4456 +04	.3898 +04	.3602 +04	.3410 +04	.3336 +04	.3257 +04
s	.6231 +01	.5797 +01	.5411 +01	.5110 +01	.4813 +01	.4653 +01	.4455 +01
M	.3318 +02	.3521 +02	.3671 +02	.3763 +02	.3844 +02	.3895 +02	.3967 +02
Γ	.4515	.6378	.9266	.1336 +01	.2206 +01	.3202 +01	.6165 +01
η	.8243 —03	.1040 —02	.1221 —02	.1324 —02	.1364 —02	.1342 —02	.1237 —02
λ'	.2175 —02	.2364 —02	.2331 —02	.2172 —02	.1967 —02	.1871 —02	.1799 —02
λ_Σ	.2423 —02	.2528 —02	.2436 —02	.2249 —02	.2045 —02	.1968 —02	.1952 —02
σ	.1218 +02	.9723 +01	.7167 +01	.5313 +01	.4000 +01	.3644 +01	.3778 +01
α	.6590 —03	.4994 —03	.3276 —03	.2062 —03	.1253 —03	.1010 —03	.8874 —04
λ_R	.1990 +04	.4750 +03	.1010 +03	.2250 +02	.3770 +01	.1360 +01	.3150 +00

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Table 5.3. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				T=6000 K			
e^-	.3789 —02	.8419 —02	.1915 —01	.4034 —01	.9883 —01	.1829	.5217
K	.4692 —02	.1998 —01	.8408 —01	.2856	.1024 +01	.2105 +01	.5427 +01
K^+	.3788 —02	.8411 —02	.1907 —01	.3979 —01	.9465 —01	.1700	.4645
K^-	.9144 —06	.8625 —05	.8173 —04	.5681 —03	.4526 —02	.1491 —01	.7273 —01
K_2	.1159 —06	.2092 —05	.3693 —04	.4220 —03	.5311 —02	.2151 —01	.1242
K_2^+	.1834 —05	.1728 —04	.1632 —03	.1124 —02	.8695 —02	.2781 —01	.1299
ρ	.5507 —01	.1845	.6725	.2136 +01	.7490 +01	.1550 +02	.4200 +02
h	.9641 +04	7709 +04	.6296 +04	.5501 +04	.4963 +04	.4794 +04	.4609 +04
s	.7016 +01	.6386 +01	.5845 +01	.5453 +01	.5098 +01	.4917 +01	.4700 +01
M	.2703 +02	.3018 +02	.3306 +02	.3498 +02	.3642 +02	.3703 +02	.3755 +02
Γ	.4516	.6745	.1016 +01	.1478 +01	.2361 +01	.3264 +01	.5658 +01
η	.4233 —03	.6682 —03	.9430 —03	.1154 —02	.1299 —02	.1325 —02	.1268 —02
λ'	.3118 —02	.3759 —02	.4098 —02	.4104 —02	.3800 —02	.3615 —02	.3540 —02
λ_Σ	.3451 —02	.4036 —02	.4294 —02	.4244 —02	.3912 —02	.3730 —02	.3688 —02
σ	.2383 +02	.2186 +02	.1833 +02	.1480 +02	.1163 +02	.1051 +02	.1036 +02
α	.1282 —02	.1140 —02	.8696 —03	.6027 —03	.3723 —03	.2860 —03	.2235 —03
λ_R	.2760 +04	.6160 +03	.1280 +03	.3230 +02	.7100 +01	.3050 +01	.9850

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Table 5.3. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				T=7000 K			
e^-	.4400 —02	.1112 —01	.2816 —01	.6275 —01	.1542	.2740	.6828
K	.1791 —02	.9801 —02	.5079 —01	.1958	.7694	.1635 +01	.4349 +01
K^+	.4400 —02	.1112 —01	.2811 —01	.6234 —01	.1506	.2623	.6299
K^-	.2462 —06	.3396 —05	.4423 —04	.3717 —03	.3339 —02	.1131 —01	.5521 —01
K_2	.1063 —07	.3174 —06	.8465 —05	.1240 —03	.1847 —02	.7967 —02	.4893 —01
K_2^+	.5224 —06	.7205 —05	.9370 —04	.7838 —03	.6901 —02	.2298 —01	.1081
ρ	.4019 —01	.1359	.5137	.1689 +01	.6105 +01	.1279 +02	.3471 +02
h	.1398 +05	.1163 +05	.9383 +04	.7930 +04	.6906 +04	.6511 +04	.6123 +04
s	.7687 +01	.6989 +01	.6319 +01	.5826 +01	.5392 +01	.5180 +01	.4932 +01
M	.2286 +02	.2554 +02	.2887 +02	.3159 +02	.3387 +02	.3481 +02	.3560 +02
Γ	.3869	.6151	.9770	.1458 +01	.2314 +01	.3113 +01	.4971 +01
η	.2011 —03	.3788 —03	.6424 —03	.9019 —03	.1137 —02	.1221 —02	.1239 —02
λ'	.4132 —02	.5292 —02	.6356 —02	.7011 —02	.6965 —02	.6727 —02	.6590 —02
λ_Σ	.4354 —02	.5564 —02	.6600 —02	.7203 —02	.7110 —02	.6862 —02	.6736 —02
σ	.3383 +02	.3438 +02	.3167 +02	.2729 +02	.2228 +02	.2011 +02	.1903 +02
α	.1825 —02	.1855 —02	.1641 —02	.1274 —02	.8441 —03	.6451 —03	.4686 —03
λ_R	.5850 +04	.1000 +04	.2200 +03	.5700 +02	.1360 +02	.5650 +01	.1920 +01

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Table 5.3. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T=8000$ K			
e^-	.4281 —02	.1183 —01	.3317 —01	.7927 —01	.2007	.3514	.8138
K	.6801 —03	.4480 —02	.2852 —01	.1275	.5610	.1248 +01	.3471 +01
K^+	.4282 —02	.1183 —01	.3315 —01	.7903 —01	.1982	.3427	.7719
K^-	.5855 —07	.1063 —05	.1889 —04	.1983 —03	.2083 —02	.7471 —02	.3787 —01
K_2	.9964 —09	.4312 —07	.1734 —05	.3411 —04	.6328 —03	.2979 —02	.1996 —01
K_2^+	.1299 —06	.2361 —05	.4187 —04	.4389 —03	.4567 —02	.1618 —01	.7975 —01
ρ	.3220 —01	.1059	.4009	.1348 +01	.5008 +01	.1062 +02	.2908 +02
k	.1695 +05	.1504 +05	.1256 +05	.1057 +05	.8994 +04	.8344 +04	.7685 +04
s	.8084 +01	.7445 +01	.6742 +01	.6176 +01	.5668 +01	.5422 +01	.5137 +01
M	.2099 +02	.2267 +02	.2545 +02	.2835 +02	.3120 +02	.3250 +02	.3373 +02
Γ	.3127	.5194	.8681	.1340 +01	.2151 +01	.2860 +01	.4383 +01
η	.1127 —03	.2231 —03	.4293 —03	.6788 —03	.9595 —03	.1088 —02	.1181 —02
λ'	.5120 —02	.6670 —02	.8782 —02	.1043 —01	.1133 —01	.1126 —01	.1110 —01
λ_Σ	.5222 —02	.6844 —02	.9006 —02	.1064 —01	.1150 —01	.1141 —01	.1124 —01
σ	.4124 +02	.4512 +02	.4543 +02	.4166 +02	.3531 +02	.3192 +02	.2928 +02
α	.2208 —02	.2440 —02	.2430 —02	.2096 —02	.1512 —02	.1182 —02	.8484 —03
λ_R	.2060 +05	.3250 +04	.5230 +03	.1080 +03	.2330 +02	.9980 +01	.3230 +01

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Table 5.3. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T=10\,000$ K			
e^-	.3592 —02	.1063 —01	.3361 —01	.9055 —01	.2506	.4442	.9782
K	.1341 —03	.1047 —02	.8702 —02	.5054 —01	.2830	.7015	.2177 +01
K^+	.3592 —02	.1063 —01	.3360 —01	.9050 —01	.2497	.4405	.9572
K^-	.4694 —08	.1084 —06	.2836 —05	.4390 —04	.6548 —03	.2726 —02	.1589 —01
K_2	.1883 —10	.1145 —08	.7862 —07	.2609 —05	.7829 —04	.4565 —03	.3832 —02
K_2^+	.1114 —07	.2571 —06	.6730 —05	.1041 —03	.1548 —02	.6414 —02	.3689 —01
K^{++}	.3406 —13	.4048 —13	.5159 —13	.6643 —13	.8877 —13	.1055 —12	.1348 —12
ρ	.2418 —01	.7579 —01	.2747	.9170	.3482 +01	.7518 +01	.2097 +02
h	.2039 +05	.1945 +05	.1766 +05	.1550 +05	.1317 +05	.1203 +05	.1077 +05
s	.8472 +01	.7940 +01	.7311 +01	.6723 +01	6128 +01	.5826 +01	.5474 +01
M	.1991 +02	.2047 +02	.2180 +02	.2384 +02	.2671 +02	.2838 +02	.3031 +02
Γ	.2051	.3527	.6261	.1026 +01	.1701 +01	.2270 +01	.3400 +01
η	.7341 —04	.1235 —03	.2382 —03	.4175 —03	.6959 —03	.8675 —03	.1062 —02
λ'	.7384 —02	.9479 —02	.1312 —01	.1697 —01	.2151 —01	.2316 —01	.2400 —01
λ_Σ	.7405 —02	.9529 —02	.1322 —01	.1712 —01	.2170 —01	.2330 —01	.2413 —01
σ	.5246 +02	.6086 +02	.6860 +02	.7025 +02	.6458 +02	.5909 +02	.5195 +02
α	.2790 —02	.3255 —02	.3699 —02	.3750 —02	.3188 —02	.2647 —02	.1914 —02
λ_R	.1710 +06	.2710 +05	.2960 +04	.5000 +03	.9170 +02	.3640 +02	.1130 +02

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Table 5.3. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T=12\,000$ K			
e^-	.3006 —02	.9035 —02	.2979 —01	.8572 —01	.2574	.4728	.1044 +01
K	.3859 —04	.3196 —03	.2994 —02	.2044 —01	.1397	.3854	.1346 +01
K^+	.3006 —02	.9036 —02	.2979 —01	.8570 —01	.2571	.4704	.1035 +01
K^-	.6545 —09	.1628 —07	.5016 —06	.9775 —05	.1954 —03	.9506 —03	.6564 —02
K_2	.9241 —12	.6330 —10	.5527 —08	.2541 —06	.1141 —04	.8267 —04	.8895 —03
K_2^+	.1627 —08	.4049 —07	.1244 —05	.2430 —04	.4852 —03	.2356 —02	.1617 —01
K^{++}	.1957 —10	.2252 —10	.2788 —10	.3555 —10	.4784 —10	.5722 —10	.7313 —10
ρ	.1976 —01	.6071 —01	.2128	.6892	.2583 +01	.5592 +01	.1572 +02
h	.2287 +05	.2232 +05	.2717 +05	.1944 +05	.1701 +05	.1556 +05	.1379 +05
s	.8698 +01	.8202 +01	.7631 +01	.7080 +01	.6472 +01	.6141 +01	.5741 +01
M	.1968 +02	.1989 +02	.2049 +02	.2164 +02	.2376 +02	.2531 +02	.2746 +02
Γ	.1428	.2475	.4489	.7602	.1313 +01	.1780 +01	.2664 +01
η	.7563 —04	.1332 —03	.1684 —03	.2803 —03	.4844 —03	.6482 —03	.8836 —03
λ'	.1000 —01	.1258 —01	.1708 —01	.2376 —01	.3334 —01	.4020 —01	.4787 —01
λ_Σ	.1001 —01	.1260 —01	.1711 —01	.2382 —01	.3344 —01	.4034 —01	.4806 —01
σ	.6237 +02	.7296 +02	.8689 +02	.9488 +02	.9521 +02	.9024 +02	.8043 +02
α	.3309 —02	.3881 —02	.4994 —02	.5087 —02	.4948 —02	.4441 —02	.3468 —02
λ_R	.9950 +06	.1360 +06	.1460 +05	.2300 +04	.3450 +03	.1270 +03	.3680 +02

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Table 5.3. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T=15\,000$ K			
e^-	.2398 —02	.7236 —02	.2425 —01	.7243 —01	.2332	.4471	.1027 +01
K	.9219 —05	.7911 —04	.7988 —03	.6143 —02	.5073 —01	.1584	.6488
K^+	.2398 —02	.7235 —02	.2425 —01	.7243 —01	.2332	.4467	.1024 +01
K^-	.6946 —10	.1798 —08	.6073 —07	.1388 —05	.3629 —04	.2118 —03	.1854 —02
K_2	.3179 —13	.2339 —11	.2377 —09	.1393 —07	.9215 —06	.8631 —05	.1306 —03
K_2^-	.1812 —09	.4691 —08	.1585 —06	.3623 —05	.9467 —04	.5524 —03	.4824 —02
K^{++}	.1205 —07	.1335 —07	.1579 —07	.1947 —07	.2582 —07	.3089 —07	.3939 —07
ρ	.1562 —01	.4747 —01	.1625	.5100	.1844 +01	.3936 +01	.1093 +02
h	.2626 +05	.2592 +05	.2521 +05	.2404 +05	.2200 +05	.2050 +05	.1834 +05
s	.8949 +01	.8470 +01	.7931 +01	.7420 +01	.6838 +01	.6500 +01	.6067 +01
M	.1959 +02	.1966 +02	.1987 +02	.2035 +02	.2148 +02	.2252 +02	.2433 +02
Γ	.9128 —01	.1585	.2901	.5008	.8966	.1241 +01	.1876 +01
η	.1050 —03	.1338 —03	.1889 —03	.2779 —03	.4584 —03	.6140 —03	.8906 —03
λ'	.1491 —01	.1819 —01	.2376 —01	.3156 —01	.4553 —01	.5621 —01	.7401 —01
λ_z	.1491 —01	.1819 —01	.2377 —01	.3158 —01	.4557 —01	.5627 —01	.7411 —01
σ	.7745 +02	.8979 +02	.1065 +03	.1227 +03	.1338 +03	.1333 +03	.1248 +03
α	.4106 —02	.4764 —02	.5666 —02	.6545 —02	.7056 —02	.6826 —02	.5859 —02
λ_R	.7500 +07	.1100 +07	.1290 +06	.1810 +05	.2330 +04	.7000 +03	.1860 +03

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Table 5.3. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				T=20 000 K			
e^-	.1794 —02	.5401 —02	.1813 —01	.5482 —01	.1833	.3643	.8868
K	.1592 —05	.1402 —04	.1484 —03	.1232 —02	.1174 —01	.4105 —01	.2007
K^+	.1778 —02	.5384 —02	.1811 —01	.5479 —01	.1833	.3643	.8863
K^{++}	.8198 —05	.8792 —05	.9858 —05	.1150 —04	.1451 —04	.1705 —04	.2157 —04
K^{+++}	.3228 —11	.1244 —11	.4706 —12	.2107 —12	.9669 —13	.6485 —13	.4036 —13
K^-	.4921 —11	.1304 —09	.4628 —08	.1159 —06	.3659 —05	.2507 —04	.2863 —03
K_2	.6342 —15	.4913 —13	.5493 —11	.3770 —09	.3359 —07	.4003 —06	.8910 —04
K_2^+	.1337 —10	.3564 —09	.1268 —07	.3178 —06	.1003 —04	.6874 —04	.7849 —02
ρ	.1160 —01	.3509 —01	.1186	.3637	.1266 +01	.2632 +01	.7067 +01
h	.3212 +05	.3164 +05	.3110 +05	.3033 +05	.2892 +05	.2772 +05	.2565 +05
s	.9285 +01	.8798 +01	.8269 +01	.7781 +01	.7233 +01	.6909 +01	.6476 +01
M	.1951 +02	.1956 +02	.1962 +02	.1977 +02	.2016 +02	.2060 +02	.2156 +02
Γ	.5141 +01	.8905 +01	.1630	.2833	.5174	.7992	.1135 +01
η	.1712 —03	.2114 —03	.2724 —03	.3666 —03	.5433 —03	.7142 —03	.1006 —02
λ'	.2503 —01	.3028 —01	.3765 —01	.4816 —01	.6609 —01	.8261 —01	.1076
λ_Σ	.2509 —01	.3031 —01	.3767 —01	.4817 —01	.6611 —01	.8263 —01	.1077
σ	.1036 +03	.1164 +03	.1392 +03	.1627 +03	.1898 +03	.2015 +03	.2060 +03
α	.5515 —02	.6286 —02	.7385 —02	.8642 —02	.1007 —01	.1060 —01	.1042 —01
λ_R	.1300 +09	.1630 +08	.1880 +07	.2240 +06	.2720 +05	.8130 +04	.1820 +04

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Table 5.3. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				T=25 000 K			
e^-	.1576 —02	.4503 —02	.1467 —01	.4391 —01	.1472	.2954	.7365
K	.3328 —06	.3464 —05	.3992 —04	.3492 —03	.3560 —02	.1313 —01	.7042 —01
K^+	.9992 —03	.3720 —02	.1372 —01	.4280 —01	.1459	.2938	.7347
K^{++}	.2883 —03	.3914 —03	.4779 —03	.5570 —03	.6791 —03	.7811 —03	.9673 —03
K^{+++}	.3798 —07	.1903 —07	.7811 —08	.3429 —08	.1478 —08	.9499 —09	.5568 —09
K^-	.6268 —12	.1864 —10	.6996 —09	.1828 —07	.6211 —06	.4556 —05	.5935 —04
ρ	.8358 —02	.2670 —01	.9240 —01	.2836	.9742	.1997 +01	.5232 +01
h	.5773 +05	.4578 +05	.3983 +05	.3739 +05	.3559 +05	.3448 +05	.3263 +05
s	.1039 +02	.9410 +01	.8651 +01	.8093 +01	.7528 +01	.7208 +01	.6781 +01
M	.1758 +02	.1867 +02	.1925 +02	.1950 +02	.1974 +02	.1995 +02	.2043 +02
Γ	.3741 —01	.6061 —01	.1066	.1827	.3329	.4709	.7420
η	.1534 —03	.2509 —03	.3624 —03	.4882 —03	.6861 —03	.8609 —03	.1215 —02
λ'	.2647 —01	.3706 —01	.5109 —01	.6685 —01	.8958 —01	.1082	.1446
λ_Σ	.2861 —01	.3847 —01	.5183 —01	.6725 —01	.8980 —01	.1084	.1447
σ	.1037 +03	.1307 +03	.1642 +03	.1987 +03	.2469 +03	.2827 +03	.3422 +03
α	.6786 —02	.7785 —02	.9132 —02	.1074 —01	.1320 —01	.1508 —01	.1826 —01
λ_R	.1410 +10	.1450 +09	.2300 +08	.2070 +07	.2010 +06	.6180 +05	.1170 +05

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Table 5.3. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				T=30 000 K			
e^-	.1543 —02	.4449 —02	.1386 —01	.3924 —01	.1263	.2505	.6240
K	.2568 —07	.4962 —06	.9398 —05	.1060 —03	.1218 —02	.4866 —02	.2796 —01
K^+	.1550 —03	.1059 —02	.6643 —02	.2771 —01	.1100	.2313	.6000
K^{++}	.6876 —03	.1689 —02	.3607 —02	.5764 —02	.8158 —02	.9639 —02	.1202 —01
K^{+++}	.4352 —05	.3891 —05	.2867 —05	.1774 —05	.8956 —06	.5892 —06	.3428 —06
K^-	.3656 —13	.2036 —11	.1201 —09	.3832 —08	.1446 —06	.1112 —05	.1562 —04
ρ	.5497 —02	.1786 —01	.6660 —01	.2179	.7747	.1595 +01	.4153 +01
h	.1203 +06	.1007 +06	.7566 +05	.5848 +05	.4809 +05	.4466 +05	.4134 +05
s	.1268 +02	.1139 +02	.9934 +01	.8846 +01	.7976 +01	.7573 +01	.7095 +01
M	.1386 +02	.1494 +02	.1663 +02	.1803 +02	.1900 +02	.1936 +02	.1980 +02
Γ	.3122 —01	.5168 —01	.8712 —01	.1398	.2415	.3359	.5246
η	.4950 —04	.1029 —03	.2408 —03	.4578 —03	.7751 —03	.1007 —02	.1404 —02
λ'	.2831 —01	.3500 —01	.4860 —01	.6952 —01	.1041	.1309	.1748
λ_Σ	.2955 —01	.3778 —01	.5285 —01	.7352 —01	.1069	.1330	.1763
σ	.1039 +03	.1215 +03	.1525 +03	.1963 +03	.2610 +03	.3054 +03	.3733 +03
α	.8031 —02	.9098 —02	.1065 —01	.1252 —01	.1521 —01	.1719 —01	.2044 —01
λ_R	—	—	.2200 +09	.1880 +08	.1320 +07	.3020 +06	.5140 +05

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Table 5.3. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				T=40 000 K			
e^-	.1279 —02	.3731 —02	.1216 —01	.3587 —01	.1161	.2261	.5408
K	.7579 —10	.2967 —08	.1237 —06	.3034 —05	.7964 —04	.4543 —03	.3838 —02
K^+	.1643 —05	.2232 —04	.2922 —03	.2516 —02	.2165 —01	.6645 —01	.2535
K^{++}	.2516 —03	.1200 —02	.5039 —02	.1566 —01	.4620 —01	.7882 —01	.1428
K^{+++}	.2581 —03	.4361 —03	.5951 —03	.6771 —03	.6916 —03	.6555 —03	.5583 —03
K^-	.6093 —16	.6956 —14	.9446 —12	.6836 —10	.5798 —08	.6420 —07	.1286 —05
ρ	.3319 —02	.1077 —01	.3846 —01	.1224	.4453	.9499	.2600 +01
h	.2213 +06	.1872 +06	.1612 +06	.1439 +06	.1226 +06	.1084 +06	.9016 +05
s	.1551 +02	.1388 +02	.1243 +02	.1132 +02	.1009 +02	.9369 +02	.8461 +01
M	.1117 +02	.1203 +02	.1281 +02	.1347 +02	.1452 +02	.1537 +02	.1664 +02
Γ	.2055 —01	.3363 —01	.5897 —01	.9904 —01	.1735	.2369	.3537
η	.4609 —04	.5817 —04	.8611 —04	.1460 —03	.3236 —03	.5345 —03	.1060 —02
λ'	.4743 —01	.5589 —01	.6740 —01	.8396 —01	.1128	.1383	.1936
λ_Σ	.4751 —01	.5604 —01	.6790 —01	.8555 —01	.1175	.1458	.2046
σ	.1391 +03	.1553 +03	.1781 +03	.2064 +03	.2525 +03	.2911 +03	.3631 +03
α	.1098 —01	.1224 —01	.1398 —01	.1607 —01	.1920 —01	.2158 —01	.2558 —01
λ_R	—	—	—	.5310 +09	.3200 +08	.5160 +07	.6420 +06

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Table 5.4. Thermophysical Properties of Cesium Plasma (M = 132.9)

(1) Величина	(2) Давление, ат						
	1	3	10	30	100	200	500
				$T = 4000$ K			
e^-	.1268 —02	.2418 —02	.5021 —02	.1060 —01	.3085 —01	.7521 —01	.4392
Cs	.1537 —01	.4880 —01	.1682	.5113	.1694 +01	.3345 +01	.8726 +01
Cs^+	.1268 —02	.2417 —02	.5018 —02	.1058 —01	.3072 —01	.7479 —01	.4369
Cs^-	.2866 —05	.1721 —04	.1197 —03	.7065 —03	.5139 —02	.1681 —01	.8656 —01
Cs_2	.3799 —05	.3824 —04	.4535 —03	.4166 —02	.4491 —01	.1683	.8414
Cs_2^+	.2957 —05	.1775 —04	.1234 —03	.7275 —03	.5279 —02	.1724 —01	.8884 —01
ρ	.3674	.1133 +01	.3850 +01	.1174 +02	.4038 +02	.8400 +02	.2451 +03
h	.9660 +03	.8697 +03	.8078 +03	.7732 +03	.7440 +03	.7263 +03	.7013 +03
s	.1829 +01	.1732 +01	.1639 +01	.1561 +01	.1480 +01	.1434 +01	.1377 +01
M	.1236 +03	.1271 +03	.1296 +03	.1315 +03	.1343 +03	.1359 +03	.1391 +03
Γ	.4793	.6660	.9648	.1437 +01	.2552 +01	.4063 +01	.9823 +01
η	.7283 —03	.7655 —03	.7899 —03	.8063 —03	.8306 —03	.8562 —03	.9119 —03
λ'	.9028 —03	.8401 —03	.7051 —03	.5884 —03	.5108 —03	.5067 —03	.6203 —03
λ_Σ	.1133 —02	.9841 —03	.7931 —03	.6501 —03	.5685 —03	.5787 —03	.7280 —03
σ	.6396 +01	.4949 +01	.3610 +01	.2718 +01	.2197 +01	.2206 +01	.3069 +01
α	.2878 —03	.1859 —03	.9903 —04	.4841 —04	.1934 —04	.1029 —04	—.2016 —05
λ_R	.7160 +03	.1580 +03	.2980 +02	.6100 +01	.1500 +01	.5950	.5820 —01

Key:
1. Value
2. Pressure, atmospheres

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Table 5.4. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T = 5000$ K			
e^-	.3242 —02	.6762 —02	.1483 —01	.3142 —01	.8238 —01	.1725	.6513
Cs	.8151 —02	.3028 —01	.1159	.3737	.1298 +01	.2637 +01	.7039 +01
Cs^+	.3242 —02	.6760 —02	.1481 —01	.3130 —01	.8198 —01	.1696	.6382
Cs^-	.1876 —05	.1446 —03	.1191 —03	.7707 —03	.5863 —02	.1911 —01	.9208 —01
Cs_2	.5387 —06	.7416 —05	.1080 —03	.1109 —02	.1290 —01	.5000 —01	.2616
Cs_2^+	.2188 —05	.1685 —04	.1387 —03	.8952 —03	.6764 —02	.2192 —01	.1052
ρ	.2515	.8186	.2898 +01	.9040 +01	.3145 +02	.6552 +02	.1876 +03
h	.1936 +04	.1599 +04	.1371 +04	.1248 +04	.1168 +04	.1137 +04	.1096 +04
s	.2043 +01	.1893 +01	.1764 +01	.1666 +01	.1573 +01	.1525 +01	.1465 +01
M	.1035 +03	.1125 +03	.1196 +03	.1240 +03	.1273 +03	.1285 +03	.1286 +03
Γ	.5479	.7945	.1178 +01	.1735 +01	.2870 +01	.4204 +01	.8307 +01
η	.6229 —03	.7517 —03	.8463 —03	.8995 —03	.9355 —03	.9519 —03	.9721 —03
λ'	.1983 —02	.2134 —02	.2089 —02	.1887 —02	.1648 —02	.1603 —02	.1839 —02
λ_Σ	.2500 —02	.2521 —02	.2326 —02	.2045 —02	.1762 —02	.1713 —02	.1970 —02
σ	.1633 +02	.1424 +02	.1155 +02	.9352 +01	.7488 +01	.7249 +01	.8635 +01
α	.8435 —03	.6811 —03	.4668 —03	.2864 —03	.1538 —03	.1049 —03	.5865 —04
λ_R	.4910 +03	.1040 +03	.2010 +02	.4810 +01	.1160 +01	.5380	.1420

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Table 5.4. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T = 6000$ K			
e^-	.4540 —02	.1078 —01	.2597 —01	.5690 —01	.1448	.2750	.8197
Cs	.3311 —02	.1577 —01	.7246 —01	.2597	.9732	.2041 +01	.5556 +01
Cs^+	.4539 —02	.1078 —01	.2596 —01	.5675 —01	.1436	.2712	.8025
Cs^-	.5728 —06	.6454 —05	.7049 —04	.5328 —03	.4449 —02	.1471 —01	.6972 —01
Cs_2	.4526 —07	.1022 —05	.2139 —04	.2697 —03	.3592 —02	.1465 —01	.8155 —01
Cs_2^+	.7292 —06	.8215 —05	.8967 —04	.6765 —03	.5618 —02	.1847 —01	.8289 —01
ρ	.1732	.5862	.2177 +01	.7035 +01	.2514 +02	.5278 +02	.1492 +03
h	.3193 +04	.2621 +04	.2157 +04	.1880 +04	.1693 +04	.1621 +04	.1537 +04
s	.2272 +01	.2079 +01	.1906 +01	.1781 +01	.1669 +01	.1613 +01	.1545 +01
M	.8422 +02	.9456 +02	.1053 +03	.1131 +03	.1188 +03	.1207 +03	.1212 +03
Γ	.4943	.7628	.1182 +01	.1755 +01	.2834 +01	.3942 +01	.6910 +01
η	.4042 —03	.6045 —03	.7943 —03	.9195 —03	.1003 —02	.1030 —02	.1048 —02
λ'	.3065 —02	.3768 —02	.4172 —02	.4218 —02	.3918 —02	.3787 —02	.4054 —02
λ_Σ	.3565 —02	.4243 —02	.4532 —02	.4473 —02	.4091 —02	.3934 —02	.4192 —02
σ	.2695 +02	.2618 +02	.2335 +02	.2008 +02	.1618 +02	.1526 +02	.1640 +02
α	.1433 —02	.1350 —02	.1095 —02	.7815 —03	.4676 —03	.3353 —03	.2146 —03
λ_R	.1180 +04	.2850 +03	.4260 +02	.1070 +02	.2660 +01	.1250 +01	.5000

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Table 5.4. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T = 7000$ K			
e^-	.4702 —02	.1249 —01	.3342 —01	.7770 —01	.1983	.3599	.9254
Cs	.1230 —02	.7342 —02	.4170 —01	.1717	.7120	.1555 +01	.4331 +01
Cs^+	.4702 —02	.1249 —01	.3341 —01	.7760 —01	.1973	.3567	.9103
Cs^{++}	.1709 —15	.2116 —15	.2727 —15	.3475 —15	.4658 —15	.5635 —15	.7630 —15
Cs^-	.1283 —06	.2028 —05	.3053 —04	.2840 —03	.2721 —02	.9384 —02	.4511 —01
Cs_2	.3303 —08	.1172 —06	.3739 —05	.6196 —04	.1001 —02	.4409 —02	.2674 —01
Cs_2^+	.1744 —06	.2756 —05	.4147 —04	.3855 —04	.3680 —02	.1264 —01	.6030 —01
ρ	.1309	.4376	.1660 +01	.5526 +01	.2033 +02	.4313 +02	.1205 +03
h	.4187 +04	.3625 +04	.3012 +04	.2578 +04	.2252 +04	.2120 +04	.1979 +04
s	.2425 +01	.2233 +01	.2037 +01	.1887 +01	.1754 +01	.1689 +01	.1612 +01
M	.7415 +02	.8157 +02	.9206 +02	.1016 +03	.1098 +03	.1131 +03	.1152 +03
Γ	.4000	.6516	.1064 +01	.1619 +01	.2613 +01	.3539 +01	.5670 +01
η	.2446 —03	.4337 —03	.6769 —03	.8778 —03	.1033 —02	.1088 —02	.1128 —02
λ'	.4111 —02	.5316 —02	.6473 —02	.7219 —02	.7261 —02	.7096 —02	.7285 —02
λ_Σ	.4389 —02	.5692 —02	.6844 —02	.7517 —02	.7471 —02	.7267 —02	.7423 —02
σ	.3530 +02	.3718 +02	.3574 +02	.3191 +02	.2714 +02	.2524 +02	.2532 +02
α	.1885 —02	.1970 —02	.1798 —02	.1423 —02	.9347 —03	.6870 —03	.4385 —03
λ_R	.4000 +04	.8230 +03	.1270 +03	.2750 +02	.6620 +01	.2890 +01	.1140 +01

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Table 5.4. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T = 8000$ K			
e^-	.4382 —02	.1242 —01	.3625 —01	.8991 —01	.2359	.4211	.1003 +01
Cs	.4915 —03	.3393 —02	.2313 —01	.1099 —01	.5121	.1173 +01	.3406 +01
Cs^+	.4382 —02	.1242 —01	.3624 —01	.8986 —01	.2353	.4186	.9910
Cs^{++}	.3517 —13	.4325 —13	.5618 —13	.7240 —13	.9738 —13	.1170 —12	.1544 —12
Cs^-	.3000 —07	.5858 —06	.1156 —04	.1334 —03	.1508 —02	.5531 —02	.2801 —01
Cs_2	.2980 —09	.1415 —07	.6502 —06	.1436 —04	.2911 —03	.1410 —02	.9480 —02
Cs_2^+	.4286 —07	.8371 —06	.1652 —04	.1905 —03	.2149 —02	.7860 —02	.3957 —01
ρ	.1075	.3490	.1311 +01	.4421 +01	.1663 +02	.3564 +02	.9977 +02
h	.4841 +04	.4413 +04	.3801 +04	.3263 +04	.2805 +04	.2607 +04	.2394 +04
s	.2513 +01	.2338 +01	.2142 +01	.1978 +01	.1827 +01	.1753 +01	.1666 +01
M	.7000 +02	.7444 +02	.8256 +02	.9181 +02	.1016 +03	.1059 +03	.1098 +03
Γ	.3164	.5324	.9073	.1426 +01	.2326 +01	.3117 +01	.4808 +01
η	.1700 —03	.3165 —03	.5602 —03	.8096 —03	.1039 —02	.1131 —02	.1207 —02
λ'	.5090 —02	.6639 —02	.8725 —02	.1040 —01	.1130 —01	.1127 —01	.1135 —01
λ_Σ	.5231 —02	.6889 —02	.9053 —02	.1072 —01	.1154 —01	.1146 —01	.1150 —01
σ	.4175 +02	.4659 +02	.4846 +02	.4638 +02	.3946 +02	.3650 +02	.3499 +02
α	.2224 —02	.2482 —02	.2512 —02	.2191 —02	.1514 —02	.1143 —02	.7386 —03
λ_R	.1570 +05	.2610 +04	.3500 +03	.7700 +02	.1660 +02	.7210 +01	.2450 +01

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Table 5.4. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
			$T = 10\,000$ K				
e^-	.3604 —02	.1073 —01	.3436 —01	.9429 —01	.2672	.4803	.1081 +01
Cs	.1095 —03	.8642 —03	.7356 —02	.4416 —01	.2580	.6555	.2110 +01
Cs^+	.3604 —02	.1073 —01	.3435 —01	.9428 —01	.2669	.4794	.1076 +01
Cs^{++}	.6417 —10	.7636 —10	.9767 —10	.1266 —09	.1709 —09	.2048 —09	.2660 —09
Cs^-	.2632 —08	.6175 —07	.1675 —05	.2720 —04	.4283 —03	.1824 —02	.1076 —01
Cs_2	.5948 —11	.3694 —09	.2654 —07	.9354 —06	.3001 —04	.1800 —03	.1533 —02
Cs_2^+	.4046 —08	.9488 —07	.2574 —05	.4180 —04	.6577 —03	.2798 —02	.1644 —01
ρ	.8193 —01	.2557	.9203	.3057 +01	.1162 +02	.2521 +02	.7131 +02
h	.5711 +04	.5480 +04	.5041 +04	.4492 +04	.3868 +04	.3548 +04	.3192 +04
s	.2610 +01	.2456 +01	.2280 +01	.2114 +01	.1943 +01	.1855 +01	.1751 +01
M	.6745 +02	.6903 +02	.7289 +02	.7910 +02	.8826 +02	.9374 +02	.1000 +03
Γ	.2055	.3543	.6330	.1047 +01	.1755 +01	.2356 +01	.3560 +01
η	.1332 —03	.2199 —03	.4068 —03	.6665 —03	.1004 —02	.1177 —02	.1345 —02
λ'	.7303 —02	.9415 —02	.1294 —02	.1648 —01	.2032 —01	.2152 —01	.2203 —01
λ_Σ	.7391 —02	.9502 —02	.1311 —01	.1671 —01	.2056 —01	.2172 —01	.2218 —01
σ	.5230 +02	.6077 +02	.6871 +02	.7134 +02	.6553 +02	.6108 +02	.5611 +02
α	.2778 —02	.3237 —02	.3650 —02	.3650 —02	.2928 —02	.2352 —02	.1594 —02
λ_R	.1560 +06	.2730 +05	.2830 +04	.5230 +03	.9070 +02	.3640 +02	.1110 +02

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Table 5.4. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T = 12\,000$ K			
e^-	.3008 —02	.9055 —02	.2997 —01	.8681 —01	.2638	.4878	.1096 +01
Cs	.3416 —04	.2837 —03	.2679 —02	.1853 —01	.1298	.3643	.1308 +01
Cs^+	.3008 —02	.9055 —02	.2997 —01	.8681 —01	.2638	.4874	.1093 +01
Cs^{++}	.1018 —07	.1171 —07	.1452 —07	.1854 —07	.2507 —07	.3009 —07	.3882 —07
Cs^-	.4015 —09	.1003 —07	.3123 —06	.6198 —05	.1274 —03	.6291 —03	.4387 —02
Cs_2	.3040 —12	.2094 —10	.1654 —08	.8721 —07	.4056 —05	.2992 —04	.3257 —03
Cs_2^+	.6484 —09	.1621 —07	.5044 —06	.1001 —04	.2057 —03	.1015 —02	.7068 —02
ρ	.6710 —01	.2060	.7201	.2325 +01	.8693 +01	.1885 +02	.5339+02
h	.6416 +04	.6268 +4	.5965 +04	.5513 +04	.4864 +04	.4467 +04	.3967 +04
s	.2675 +01	.2530 +01	.2364 +01	.2206 +01	.2032 +01	.1936 +01	.1820 +01
M	.6683 +02	.6748 +02	.6930 +02	.7288 +02	.7964 +02	.8467 +02	.9168 +02
Γ	.1428	.2478	.4502	.7651	.1329 +01	.1809 +01	.2724 +01
η	.1474 —03	.2146 —03	.3615 —03	.6059 —03	.9782 —03	.1212 —02	.1473 —02
λ'	.9966 —02	.1250 —01	.1674 —01	.2249 —01	.2879 —01	.3198 —01	.3396 —01
λ_Σ	.9982 —02	.1254 —01	.1684 —01	.2266 —01	.2901 —01	.3220 —01	.3415 —01
σ	.6212 +02	.7232 +02	.8391 +02	.9081 +02	.8776 +02	.8255 +02	.7433 +02
α	.3296 —02	.3844 —02	.4468 —02	.4769 —02	.4245 —02	.3587 —02	.2543 —02
λ_R	.1000 +07	.1650 +06	.1620 +05	.2730 +04	.4110 +03	.1510 +03	.4180 +02

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Table 5.4. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T = 15\,000$ K			
e^-	.2399 —02	.7240 —02	.2427 —01	.7260 —01	.2345	.4508	.1042 +01
Cs	.8731 —05	.7502 —04	.7588 —03	.5856 —02	.4882 —01	.1537	.6396
Cs^+	.2395 —02	.7235 —02	.2427 —01	.7258 —01	.2345	.4507	.1041 +01
Cs^{++}	.1737 —05	.1927 —05	.2281 —05	.2815 —05	.3735 —05	.4474 —05	.5724 —05
Cs^-	.4683 —10	.1213 —08	.4106 —07	.9418 —06	.2480 —04	.1454 —03	.1275 —02
Cs_2	.1058 —13	.7799 —12	.7977 —10	.4677 —08	.3124 —06	.2941 —05	.4460 —04
Cs_2^+	.7932 —10	.2067 —08	.6965 —07	.1600 —05	.4208 —04	.2466 —03	.2161 —02
ρ	.5307 —01	.1613	.5522	.1730 +01	.6253 +01	.1335 +02	.3720 +02
h	.7433 +04	.7327 +04	.7124 +04	.6799 +04	.6234 +04	.5816 +04	.5205 +04
s	.2750 +01	.2608 +01	.2450 +01	.2301 +01	.2132 +01	.2034 +01	.1908 +01
M	.6655 +02	.6679 +02	.6747 +02	.6903 +02	.7274 +02	.7618 +02	.8221 +02
Γ	.9133 —01	.1586	.2902	.5014	.8990	.1246 +01	.1888 +01
η	.1970 —03	.2558 —03	.3738 —03	.5687 —03	.9445 —03	.1224 —002	.1627 —02
λ'	.1486 —01	.1811 —01	.2354 —01	.3078 —01	.4247 —01	.4926 —01	.5755 —01
λ_Σ	.1487 —01	.1813 —01	.2359 —01	.3087 —01	.4263 —01	.4946 —01	.5777 —01
σ	.7727 +02	.8936 +02	.1053 +03	.1196 +03	.1273 +03	.1193 +03	.1123 +03
α	.4099 —02	.4742 —02	.5599 —02	.6350 —02	.5559 —02	.6117 —02	.4870 —02
λ_R	.7660 +07	.1350 +07	.1240 +06	.1940 +05	.2900 +04	.9150 +03	.2320 +03

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Table 5.4. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T = 20\,000$ K			
e^-	.1917 —02	.5561 —02	.1833 —01	.5508 —01	.1837	.3649	.8883
Cs	.1348 —05	.1309 —04	.1442 —03	.1214 —02	.1167 —01	.4099 —01	.2025
Cs^+	.1425 —02	.4936 —02	.1758 —01	.5418 —01	.1825	.3636	.8865
Cs^{++}	.2458 —03	.3122 —03	.3764 —03	.4497 —03	.5725 —03	.6742 —03	.8546 —03
Cs^{+++}	.6000 —07	.2830 —07	.1169 —07	.5387 —07	.2500 —08	.1680 —08	.1049 —08
Cs^-	.3256 —11	.9175 —10	.3327 —08	.8391 —07	.2653 —05	.1819 —04	.2073 —03
Cs_2	.1436 —15	.1355 —13	.1640 —11	.1156 —09	.1040 —07	.1242 —06	.2760 —05
Cs_2^+	.4220 —11	.1420 —09	.5561 —08	.1439 —06	.4596 —05	.3159 —04	.3606 —03
ρ	.3689 —01	.1161	.3993	.1232 +01	.4297 +01	.8941 +01	.2406 +02
h	.1237 +05	.1045 +05	.9510 +04	.9028 +04	.8512 +04	.8131 +04	.7496 +04
s	.3020 +01	.2782 +01	.2585 +01	.2428 +01	.2261 +01	.2164 +01	.2036 +01
M	.6193 +02	.6462 +02	.6603 +02	.6691 +02	.6840 +02	.6994 +02	.7326 +02
Γ	.5631 —01	.9278 —01	.1656	.2852	.5187	.7304	.1136 +01
η	.2598 —03	.3653 —03	.5037 —03	.7026 —03	.1069 —02	.1406 —02	.1914 —02
λ'	.2063 —01	.2766 —01	.3639 —01	.4718 —01	.6371 —01	.7738 —01	.9302 —01
λ_Σ	.2100 —01	.2787 —01	.3651 —01	.4727 —01	.6384 —01	.7755 —01	.9324 —01
σ	.9179 +02	.1120 +03	.1351 +03	.1565 +03	.1740 +03	.1764 +03	.1684 +03
α	.5432 —02	.6234 —02	.7296 —02	.8369 —02	.9176 —02	.9062 —02	.7930 —02
λ_R	.3450 +08	.8470 +07	.9430 +06	.1750 +06	.2690 +05	.9130 +04	.2110 +04

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Table 5.4. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T = 25.000$ K			
e^-	.1859 —02	.5354 —02	.1671 —01	.4743 —01	.1528	.3026	.7485
Cs	.7064 —07	.1341 —05	.2470 —04	.2718 —03	.3098 —02	.1179 —01	.6491 —01
Cs^+	.1947 —03	.1318 —02	.8131 —02	.3357 —01	.1326	.2782	.7172
Cs^{++}	.8083 —03	.1996 —02	.4273 —02	.6916 —02	.1009 —01	.1220 —01	.1566 —01
Cs^{+++}	.1604 —04	.1463 —04	.1101 —04	.7022 —05	.3735 —05	.2545 —05	.1556 —05
Cs^-	.1183 —04	.6406 —04	.3670 —09	.1144 —07	.4736 —06	.3113 —05	.4113 —04
ρ	.2248 —01	.7346 —01	.2744	.8994	.3216 +01	.6666 +01	.1760 +02
h	.2926 +05	.2454 +05	.1891 +05	.1511 +05	.1273 +05	.1185 +05	.1090 +05
s	.3775 +01	.3402 +01	.2995 +01	.2693 +01	.2445 +01	.2327 +01	.2184 +01
M	.4706 +02	.5097 +02	.5672 +02	.6144 +02	.6490 +02	.6641 +02	.6857 +02
Γ	.4495 —01	.7416 —01	.1256	.2019	.3493	.4853	.7558
η	.9191 —04	.2036 —03	.4403 —03	.7620 —03	.1215 —02	.1561 —02	.2227 —02
λ'	.2043 —01	.2678 —01	.3866 —01	.5659 —01	.8347 —01	.1027	.1377
λ_Σ	.2105 —01	.2786 —01	.3984 —01	.5751 —01	.8409 —01	.1032	.1381
σ	.8651 +02	.1049 +03	.1363 +03	.1754 +03	.2220 +03	.2448 +03	.2632 +03
α	.6592 —02	.7578 —02	.8963 —02	.1054 —01	.1244 —01	.1335 —01	.1377 —01
λ_R	.5630 +08	.1590 +08	.1580 +07	.3780 +06	.7540 +05	.2950 +05	.7690 +04

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Table 5.4. [Continued]

Величина	Давление, ат						
	1	3	10	30	100	200	500
				$T = 30\,000$ K			
e^-	.1664 —02	.4864 —02	.1577 —01	.4546 —01	.1429	.2762	.6672
Cs	.2030 —08	.6207 —07	.2009 —05	.3685 —04	.6452 —03	.2913 —02	.1893 —01
Cs^+	.1505 —04	.1608 —03	.1667 —02	.1117 —01	.6785 —01	.1693	.5093
Cs^{++}	.5027 —03	.1911 —02	.6545 —02	.1665 —01	.3710 —01	.5316 —01	.7868 —01
Cs^{+++}	.2146 —03	.2938 —03	.3374 —03	.3289 —03	.2681 —03	.2180 —03	.1540 —03
ρ	.1616 —01	.5219 —01	.1887	.6218	.2335 +01	.4976 +01	.1339 +02
h	.4356 +05	.3744 +05	.3222 +05	.2726 +05	.2189 +05	.1940 +05	.1692 +05
s	.4292 +01	.3874 +01	.3482 +01	.3135 +01	.2777 +01	.2600 +01	.2401 +01
M	.4061 +02	.4349 +02	.4673 +02	.5087 +02	.5657 +02	.5974 +02	.6332 +02
Γ	.3480 —01	.5743 —01	.1006	.1642	.2799	.3780	.5683
η	.3704 —04	.9465 —04	.2089 —03	.4722 —03	.1055 —02	.1551 —02	.2385 —02
λ'	.2560 —01	.3199 —01	.4241 —01	.5768 —01	.8803 —01	.1150	.1623
λ_Σ	.2591 —01	.3241 —01	.4332 —01	.5927 —01	.8997 —01	.1168	.1638
σ	.9084 +02	.1100 +03	.1361 +03	.1705 +03	.2283 +03	.2730 +03	.3411 +03
α	.7450 —02	.8751 —02	.1043 —01	.1235 —01	.1512 —01	.1708 —01	.1995 —01
λ_R	.7930 +08	.2520 +08	.2700 +07	.5810 +06	.1200 +06	.5950 +05	.1550 +05

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Table 5.4. [Continued]

Величина	Давление, ат.						
	1	3	10	30	100	200	500
				$T = 40\,000$ K			
e^-	.1340 —02	.4020 —02	.1329 —01	.3907 —01	.1258	.2452	.5887
Cs	.1106 —11	.7852 —10	.7045 —08	.3214 —06	.1396 —04	.9957 —04	.1072 —02
Cs^+	.5246 —07	.1260 —05	.3507 —04	.5642 —03	.8096 —02	.3109 —01	.1511
Cs^{++}	.1862 —04	.1532 —03	.1353 —03	.7907 —02	.3922 —01	.8377 —01	.1936
Cs^{+++}	.4344 —03	.1238 —02	.3516 —02	.7536 —02	.1308 —01	.1552 —01	.1682 —01
ρ	.9995 —02	.3071 —01	.1082	.3537	.1333 +01	.2878 +01	.7998 +01
h	.7023 +05	.6779 +05	.6196 +05	.5346 +05	.4341 +05	.3837 +05	.3275 +05
s	.5086 +01	.4759 +01	.4331 +01	.3880 +01	.3393 +01	.3144 +01	.2855 +01
M	.3358 +02	.3418 +02	.3583 +02	.3868 +02	.4312 +02	.4616 +02	.5066 +02
Γ	.2202 —01	.3789 —01	.6741 —01	.1121	.1933	.2620	.3900
η	.5384 —04	.7761 —04	.1317 —03	.2294 —03	.4960 —03	.8360 —03	.1725 —02
λ'	.3956 —01	.4693 —01	.6000 —01	.7756 —01	.1090	.1351	.1886
λ_Σ	.3962 —01	.4713 —01	.6068 —01	.7852 —01	.1105	.1370	.1913
σ	.1048 +03	.1186 +03	.1415 +03	.1739 +03	.2282 +03	.2710 +03	.3469 +03
α	.9116 —02	.1029 —01	.1210 —01	.1452 —01	.1825 —01	.2096 —01	.2531 —01
λ_R	.2070 +09	.4810 +08	.5180 +07	.1170 +07	.2660 +06	.1200 +06	.4070 +05

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Table 5.5. Thermophysical Properties of Uranium Plasma (M = 235)

(1) Параметр	(2) Давление, ат						
	1	3	10	30	100	200	500
			$T = 6000$ K				
e^-	.1280 —02	.2414 —02	.4784 —02	.8929 —02			
U	.9371 —02	.3091 —01	.1094	.3387			
U^+	.1280 —02	.2415 —02	.4784 —02	.8930 —02			
U^{++}	.6241 —08	.6967 —08	.8004 —08	.9252 —08			
ρ	.4156	.1301 +01	.4456 +01	.1357 +02			
h	.1353 +04	.1218 +04	.1132 +04	.1087 +04			
s	.1334 +01	.1270 +01	.1211 +01	.1163 +01			
M	.2098 +03	.2191 +03	.2256 +03	.2291 +03			
Γ	.2630	.3620	.5094	.6955			
η	.3395 —02	.3591 —02	.3716 —02	.3780 —02			
λ'	.2401 —02	.2505 —02	.2444 —02	.2233 —02			
λ_Σ	.4125 —02	.3580 —02	.3073 —02	.2617 —02			
σ	.2578 +02	.2812 +02	.3045 +02	.3203 +02			
α	.1375 —02	.1508 —02	.1646 —02	.1746 —02			
λ_R	.1070 +03	.3340 +02	.9600 +01	.3100 +01			

Key:
1. Value
2. Pressure, atmospheres

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Table 5.5. [Continued]

Параметр	Давление, ат						
	1	3	10	30	100	200	500
			$T = 7000$ K				
e^-	.2413 —02	.4943 —02	.1038 —01	.2009 —01	.4129 —01		
U	.5511 —02	.2108 —01	.8216 —01	.2677	.9410		
U^+	.2412 —02	.4942 —02	.1038 —01	.2009 —01	.4129 —01		
U^{++}	.2341 —06	.2670 —06	.3184 —06	.3686 —06	.4481 —06		
ρ	.3092	.1015 +01	.3611 +01	.1123 +02	.3833 +02		
h	.2076 +04	.1747 +04	.1527 +04	.1407 +04	.1330 +04		
s	.1445 +01	.1351 +01	.1271 +01	.1212 +01	.1157 +01		
M	.1801 +03	.1975 +03	.2113 +03	.2197 +03	.2255 +03		
Γ	.2865	.4110	.5954	.8275	.1185 +01		
η	.3032 —02	.3533 —02	.3880 —02	.4068 —02	.4185 —02		
λ'	.3649 —02	.4129 —02	.4486 —02	.4504 —02	.4049 —02		
λ_{Σ}	.6755 —02	.6312 —02	.5854 —02	.5369 —02	.4566 —02		
σ	.3438 +02	.3893 +02	.4447 +02	.5002 +02	.5635 —+02		
α	.1828 —02	.2075 —02	.2384 —02	.2702 —02	.3070 —02		
λ_R	.2100 +03	.5560 +02	.1600 +02	.4820 +01	.1470 +01		

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Table 5.5. [Continued]

Параметр	Давление, ат						
	1	3	10	30	100	200	500
				$T = 8000$ K			
e^-	.3245 —02	.7453 —02	.1708 —01	.3480 —01	.7428 —01	.1146	
U	.2637 —02	.1252 —01	.5710 —01	.2031	.7563	.1576 +01	
U^+	.3238 —02	.7445 —02	.1706 —01	.3478 —01	.7427 —01	.1146	
U^{++}	.3585 —05	.4170 —05	.5000 —05	.5978 —05	.7373 —05	.8371 —05	
U^{+++}	.2027 —14	.1170 —14	.7073 —15	.4747 —15	.3197 —15	.2580 —15	
ρ	.2294	.7794	.2894 +01	.9284 +01	.3241 +02	.6597 +02	
h	.2987 +04	.2460 +04	.2046 +04	.1808 +04	.1645 +04	.1585 +04	
s	.1567 +01	.1446 +01	.1340 +01	.1265 +01	.1199 +01	.1165 +01	
M	.1514 +03	.1711 +03	.1910 +03	.2050 +03	.2157 +03	.2201 +03	
Γ	.2723	.4132	.6251	.8913	.1300 +01	.1613 +01	
η	.2236 —02	.3087 —02	.3773 —02	.4181 —02	.4452 —02	.4549 —02	
λ'	.4880 —02	.5877 —02	.6929 —02	.7516 —02	.7452 —02	.7096 —02	
λ_Σ	.8261 —02	.8939 —02	.9145 —02	.9014 —02	.8382 —02	.7797 —02	
σ	.4170 +02	.4862 +02	.5762 +02	.6770 +02	.8152 +02	.9118 +02	
α	.2216 —02	.2586 —02	.3075 —02	.3633 —02	.4415 —02	.4963 —02	
λ_R	.4840 +03	.1170 +03	.2800 +02	.8280 +01	.2300 +01	.1120 +01	

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Table 5.5. [Continued]

Параметр	Давление, ат						
	1	3	10	30	100	200	500
				$T = 10\,000$ K			
e^-	.3513 —02	.9608 —02	.2675 —01	.6273 —01	.1490	.2403	.4462
U	.4438 —03	.3151 —02	.2134 —01	.9913	.4569	.1003 +01	.2793 +01
U^+	.3207 —02	.9233 —02	.2628 —01	.6214 —01	.1483	.2394	.4451
U^{++}	.1529 —03	.1880 —03	.2367 —03	.2940 —03	.3748 —03	.4319 —03	.5223 —03
U^{+++}	.2519 —10	.1306 —10	.7013 —11	.4351 —11	.2780 —11	.2200 —11	.1646 —11
ρ	.1484	.4906	.1868 +01	.6304 +01	.2324 +02	.4850 +02	.1264 +03
h	.4632 +04	.4049 +04	.3375 +04	.2845 +04	.2431 +04	.2265 +04	.2105 +04
s	.1751 +01	.1623 +01	.1488 +01	.1381 +01	.1286 +01	.1241 +01	.1189 +01
M	.1222 +03	.1332 +03	.1507 +03	.1693 +03	.1880 +03	.1969 +03	.2065 +03
Γ	.2072	.3382	.5623	.8586	.1320 +01	.1672 +01	.2272 +01
η	.7957 —03	.1626 —02	.2794 —02	.3776 —02	.4571 —02	.4897 —02	.5197 —02
λ'	.6756 —02	.8908 —02	.1181 —01	.1461 —01	.1686 —01	.1762 —01	.1750 —01
λ_Σ	.7823 —02	.1094 —01	.1450 —01	.1762 —01	.1873 —01	.1911 —01	.1857 —01
σ	.5026 +02	.6194 +01	.7787 +02	.9696 +02	.1266 +03	.1509 +03	.1981 +03
α	.2806 —02	.3368 —02	.4182 —02	.5197 —02	.6814 —02	.8860 —02	.1081 —01
λ_R	.3560 +04	.7240 +03	.1380 +03	.3400 +02	.8290 +01	.3830 +01	.1420 +01

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Table 5.5. [Continued]

Параметр	Давление, ат						
	1	3	10	30	100	200	500
				$T = 12\,000$ K			
e^-	.3534 —02	.9815 —02	.2949 —01	.7706 —01	.2050	.3486	.6840
U	.5889 —04	.6281 —03	.6247 —02	.3947 —01	.2310	.5792	.1798 +01
U^+	.1534 —02	.6397 —02	.2426 —01	.6990 —01	.1953	.3371	.6696
U^{++}	.1000 —02	.1709 —02	.2612 —02	.3577 —02	.4666 —02	.5757 —02	.7148 —02
U^{+++}	.7877 —08	.5494 —08	.3296 —08	.2047 —08	.1267 —08	.9853 —09	.7236 —09
ρ	.1012	.3408	.1292 +01	.4407 +01	.1683 +02	.3598 +02	.9658 +02
h	.7464 +04	.6115 +04	.4994 +04	.4161 +04	.3436 +04	.3117 +04	.2797 +04
s	.2006 +01	.1810 +01	.1635 +01	.1500 +01	.1377 +01	.1318 +01	.1251 +01
M	.9945 +02	.1107 +03	.1243 +03	.1397 +03	.1593 +03	.1705 +03	.1841 +03
Γ	.1751	.2789	.4645	.7391	.1191 +01	.1545 +01	.2162 +01
η	.2130 —03	.5979 —03	.1504 —02	.2730 —02	.4091 —02	.4759 —02	.5447 —02
λ'	.6625 —02	.9779 —02	.1472 —01	.2078 —01	.2722 —01	.3081 —01	.3397 —01
λ_Σ	.6984 —02	.1044 —01	.1607 —01	.2287 —01	.2961 —01	.3296 —01	.3567 —01
σ	.4742 +02	.6242 +02	.8501 +02	.1125 +03	.1555 +03	.1917 +03	.2660 +03
α	.3276 —02	.3959 —02	.4980 —02	.6309 —02	.8525 —02	.1046 —01	.1452 —01
λ_R	.1750 +05	.3500 +04	.6230 +03	.1700 +03	.3000 +02	.1380 +02	.4890 +01

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Table 5.5. [Continued]

Параметр	Давление, ат						
	1	3	10	30	100	200	500
				$T = 15\,000$ K			
e^-	.3213 —02	.9560 —02	.3071 —01	.8579 —01	.2506	.4509	.9480
U	.1335 —05	.2711 —04	.5651 —03	.6521 —02	.6474 —01	.2052	.8080
U^+	.1496 —03	.1095 —02	.7973 —02	.3824 —01	.1618	.3332	.7827
U^{++}	.1531 —02	.4231 —02	.1137 —01	.2378 —01	.4439 —01	.5936 —01	.8261 —01
U^{+++}	.6638 —06	.6957 —06	.6605 —06	.5991 —06	.4638 —06	.3871 —06	.2999 —06
U^{++++}	.4311 —14	.1687 —14	.5832 —15	.2087 —15	.6443 —16	.3287 —16	.1385 —16
ρ	.6565 —01	.2089	.7768	.2675 +01	.1057 +02	.2329 +02	.6530 +02
h	.1158 +05	.1072 +05	.9170 +04	.7459 +04	.5779 +04	.5010 +04	.4229 +04
s	.2318 +01	.2154 +01	.1943 +01	.1742 +01	.1549 +01	.1457 +01	.1356 +01
M	.8075 +02	.8437 +02	.9242 +02	.1044 +03	.1221 +03	.1339 +03	.1500 +03
Γ	.1283	.2185	.3805	.6165	.1010 +01	.1328 +01	.1883 +01
η	.6266 —04	.1293 —03	.3749 —03	.1028 —02	.2490 —02	.3584 —02	.5021 —02
λ'	.8014 —02	.1074 —01	.1607 —01	.2401 —01	.3799 —01	.4817 —01	.6208 —01
λ_Σ	.8121 —02	.1118 —01	.1771 —01	.2508 —01	.3976 —01	.5025 —01	.6492 —01
σ	.5092 +02	.6190 +02	.8120 +02	.1106 +03	.1641 +03	.2114 +03	.3088 +03
α	.3967 —02	.4731 —02	.5939 —02	.7591 —02	.1042 —01	.1289 —01	.1808 —01
λ_R	.3930 +05	.1140 +05	.2700 +04	.6110 +03	.1320 +03	.6950 +02	.2020 +02

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Table 5.5. [Continued]

Параметр	Давление, ат						
	1	3	10	30	100	200	500
				$T = 20\,000$ K			
e^-	.2430 —02	.7345 —02	.2483 —01	.7540 —01	.2510	.4945	.1169 +01
U	.8131 —08	.2031 —06	.6324 —05	.1300 —03	.2927 —02	.1534 —01	.1121
U^+	.5634 —05	.4872 —04	.4866 —03	.3691 —02	.2995 —01	.9160 —01	.3513
U^{++}	.1159 —02	.3587 —02	.1210 —01	.3578 —01	.1104	.2014	.4088
U^{+++}	.3617 —04	.4069 —04	.4659 —04	.5286 —04	.5930 —04	.6199 —04	.6271 —04
U^{++++}	.5171 —09	.2106 —09	.8038 —10	.3397 —10	.1329 —10	.7771 —11	.3805 —11
ρ	.4681 —01	.1435	.4933	.1547 +01	.5594 +01	.1203 +02	.3404 +02
h	.1385 +05	.1351 +05	.1311 +05	.1252 +05	.1138 +05	.1037 +05	.8787 +05
s	.2449 +01	.2318 +01	.2177 +01	.2040 +01	.1873 +01	.1764 +01	.1614 +01
M	.7768 +02	.7839 +02	.7928 +02	.8099 +02	.8543 +02	.9026 +02	.1004 +03
Γ	.7359 —01	.1272	.2327	.4024	.7221	.1008 +01	.1516 +01
η	.7049 —04	.1028 —03	.1713 —03	.3120 —03	.7357 —03	.1290 —02	.2648 —02
λ'	.1279 —01	.1602 —01	.2163 —01	.3064 —01	.4736 —01	.6353 —01	.9559 —01
λ_Σ	.1281 —01	.1604 —01	.2172 —01	.3099 —01	.4879 —01	.6635 —01	.1007
σ	.6515 +02	.7655 +02	.9351 +02	.1170 +03	.1611 +03	.2035 +03	.2984 +03
α	.5171 —02	.6043 —02	.7341 —02	.9103 —02	.1226 —01	.1517 —01	.2139 —01
λ_R	.5790 +05	.1850 +05	.5270 +04	.1670 +04	.4460 +03	.2020 +03	.6870 +02

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Table 5.5. [Continued]

Параметр	Давление, ат						
	1	3	10	30	100	200	500
				$T = 25\,000$ K			
e^-	.2018 —02	.5957 —02	.1985 —01	.6029 —01	.2052	.4150	.1046 +01
U	.1718 —09	.5479 —08	.2005 —06	.4743 —05	.1339 —03	.8524 —03	.8867 —02
U^+	.4393 —06	.4891 —05	.5676 —04	.4798 —03	.4575 —02	.1606 —01	.7958 —01
U^{++}	.5988 —03	.2385 —02	.9139 —02	.2901 —01	.9922 —01	.1983	.4819
U^{+++}	.2728 —03	.3940 —03	.5051 —03	.6022 —03	.7216 —03	.7981 —03	.9034 —03
U^{++++}	.4262 —06	.2238 —06	.9533 —07	.4187 —07	.1696 —07	.1013 —07	.5168 —08
ρ	.3405 —01	.1086	.3786	.1174 +01	.4084 +01	.8428 +01	.2229 +02
h	.1811 +05	.1629 +05	.1522 +05	.1464 +05	.1404 +05	.1360 +05	.1279 +05
s	.2636 +01	.2441 +01	.2271 +01	.2135 +01	.1993 +01	.1910 +01	.1795 +01
M	.7093 +02	.7484 +02	.7714 +02	.7824 +02	.7938 +02	.8044 +02	.8300 +02
Γ	.5079 —01	.8451 —01	.1512	.2610	.4776	.6755	.1061 +01
η	.6709 —04	.1124 —03	.1901 —03	.3019 —03	.5577 —03	.8404 —03	.1563 —02
λ'	.1770 —01	.2255 —01	.2981 —01	.3987 —01	.5820 —01	.7555 —01	.1120
λ_Σ	.1779 —01	.2263 —01	.2988 —01	.3995 —01	.5844 —01	.7606 —01	.1135
σ	.7172 +02	.8779 +02	.1090 +03	.1338 +03	.1739 +03	.2092 +03	.2836 +03
α	.5980 —02	.7142 —02	.8706 —02	.1058 —01	.1364 —01	.1630 —01	.2180 —01
λ_R	.2240 +06	.5770 +05	.1520 +05	.4770 +04	.1350 +04	.6450 +03	.2370 +03

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Table 5.5. [Continued]

Параметр	Давление, ат						
	1	3	10	30	100	200	500
				$T = 30\,000$ K			
e^-	.1768 —02	.5201 —02	.1695 —01	.5051 —01	.1701	.3443	.8766
U	.4364 —11	.2241 —09	.1182 —07	.3394 —06	.1106 —04	.7636 —04	.9038 —03
U^+	.3093 —07	.5524 —06	.9296 —05	.9512 —04	.1023 —02	.3804 —02	.2054 —01
U^{++}	.1580 —03	.1000 —02	.5544 —02	.2106 —01	.7913 —01	.1641	.4208
U^{+++}	.4610 —03	.1048 —02	.1941 —02	.2759 —02	.3595 —02	.4088 —02	.4790 —02
U^{++++}	.1733 —04	.1421 —04	.8789 —05	.4627 —05	.2036 —05	.1241 —05	.6433 —06
ρ	.2483 —01	.8049 —01	.2928	.9333	.3269 +01	.6714 +01	.1744 +02
h	.2466 +05	.2172 +05	.1882 +05	.1711 +05	.1602 +05	.1555 +05	.1496 +05
s	.2875 +01	.2638 +01	.2401 +01	.2225 +01	.2065 +01	.1981 +01	.1873 +01
M	.6219 +02	.6673 +02	.7209 +02	.7552 +02	.7754 +02	.7831 +02	.7937 +02
Γ	.3850 —01	.6397 —01	.1109	.1860	.3351	.4736	.7498
η	.5404 —04	.9258 —04	.1782 —03	.3149 —03	.5662 —03	.8142 —03	.1375 —02
λ'	.2316 —01	.2905 —01	.3835 —01	.5121 —01	.7321 —01	.9070 —01	.1286
λ_Σ	.2322 —01	.2918 —01	.3854 —01	.5138 —01	.7338 —01	.9093 —01	.1291
σ	.7815 +02	.9236 +02	.1158 +03	.1456 +03	.1893 +03	.2234 +03	.2882 +03
α	.6753 —02	.7673 —02	.9636 —02	.1183 —01	.1509 —01	.1767 —01	.2260 —01
λ_R	.1300 +07	.2300 +06	.4400 +05	.1220 +05	.3330 +04	.1600 +04	.6060 +03

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Table 5.5. [Continued]

Параметр	Давление, ат						
	1	3	10	30	100	200	500
				$T = 40\,000$ K			
e^-	.1415 —02	.4190 —02	.1369 —01	.4022 —01	.1312	.2607	.6534
U	.3191 —14	.4332 —12	.6060 —10	.3604 —08	.2042 —06	.1750 —05	.2577 —04
U^+	.1067 —09	.4962 —08	.2179 —06	.4580 —05	.8492 —04	.3868 —03	.2511 —02
U^{++}	.3315 —05	.5352 —04	.7543 —03	.5769 —02	.3658 —01	.9166 —01	.2734
U^{+++}	.1156 —03	.6547 —03	.3002 —02	.8461 —02	.1849 —01	.2527 —01	.3432 —01
U^{++++}	.2652 —03	.5296 —03	.7940 —03	.8237 —03	.6131 —03	.4519 —03	.2714 —03
ρ	.1499 —01	.4830 —01	.1776	.5876	.2176 +01	.4584 +01	.1212 +02
h	.4290 +05	.3757 +05	.3137 +05	.2653 +05	.2238 +05	.2066 +05	.1906 +05
s	.3394 +01	.3087 +01	.2757 +01	.2491 +01	.2245 +01	.2126 +01	.1991 +01
M	.5020 +02	.5359 +02	.5862 +02	.6402 +02	.7011 +02	.7299 +02	.7571 +02
Γ	.2480 —01	.4146 —01	.7186 —01	.1181	.2035	.2801	.4330
η	.6030 —04	.8925 —04	.1462 —03	.2479 —03	.4944 —03	.7511 —03	.1306 —02
λ'	.3818 —01	.4592 —01	.5853 —01	.7502 —01	.1052	.1294	.1740
λ_Σ	.3825 —01	.4598 —01	.5862 —01	.7523 —01	.1057	.1300	.1746
σ	.9971 +02	.1148 +03	.1348 +03	.1602 +03	.2033 +03	.2392 +03	.3042 +03
α	.8860 —02	.1007 —01	.1173 —01	.1381 —01	.1720 —01	.1995 —01	.2485 —01
λ_R	.7140 +08	.5970 +07	.5390 +06	.8500 +05	.1610 +05	.7100 +04	.2630 +04

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Table 5.6. Thermophysical Properties of Potassium-Uranium Mixtures

(1) Параметр	(2) Давление, ат			
	1	10	100	500
	$T=4000$ K; $\beta_U=3\%$			
M	.4332 +02			
ρ	.1282			
h	.2419 +04			
s	.4988 +01			
h_c'	—.2151 +04			
Γ	.3486			
η	.1290 —02			
λ'	.1404 —02			
λ_Σ	.1484 —02			
σ	.4050 +01			
α	.1975 —03			
D_{UU}	—.1449 —02			
D_U^T	.5395 —08			
D_U^E	—.7951 —03			
λ_U	.3398 +01			
λ^T	—.3584 —02			
λ_E	.1725 +04			
λ_R	.3650 +03			
	$T=5000$ K; $\beta_U=3\%$			
M	.3826 +02	.4226 +02	.4422 +02	
ρ	.9184 —01	.1011 +01	.1066 +02	
h	.4634 +04	.3422 +04	.3005+04	
s	.5476 +01	.4768 +01	.4249 +01	
h_c'	—.4457 +01	—.3120 +04	—.2648 +04	
Γ	.4507	.9232	.2174 +01	
η	.1007 —02	.1394 —02	.1545 —02	
λ'	.2180 —02	.2341 —02	.1984 —02	
λ_Σ	.2410 —02	.2438 —02	.2054 —02	
σ	.1265 +02	.7494 +01	.4108 +01	
α	.7264 —03	.3840 —03	.1590 —03	
D_{UU}	—.1467 —02	—.1651 —03	—.1729—02	
D_U^T	.3242 —07	.1121 —07	—.6266 —09	
D_U^E	.2685 —02	.1494 —02	.1053 —02	
λ_U	.7585 +01	.5936 +01	.5078 +01	
λ^T	—.7345 —02	—.6643 —02	—.4171 —02	
λ_E	.5016 +04	.4233 +04	.2727 +04	
λ_R	.7310 +03	.5270 +02	.3120 +01	

Key:
1. Parameter
2. Pressure, atmospheres

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Table 5.6. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	T=6000 K; β_U=3%			
M	.3128 +02	.3812 +02	.4195 +02	.4324 +02
ρ	.6370 —01	.7754	.8612 +01	.4794 +02
h	.8344 +04	.5492 +04	.4370 +04	.4063 +04
s	.6149 +01	.5143 +01	.4497 +01	.4151 +01
h'_c	—.8431 +04	—.5297 +04	—.4057 +04	—.3732 +04
Γ	.4503	.1014 +01	.2332 +01	.5523 +01
η	.6348 —03	.1171 —02	.1537 —02	.1550 —02
λ'	.3115 —02	.4078 —02	.3806 —02	.3589 —02
λ_Σ	.3412 —02	.4250 —02	.3903 —02	.3722 —02
σ	.2466 +02	.1905 +02	.1171 +02	.1007 +02
α	.1388 —02	.1070 —02	.5381 —03	.3806 —03
D_{UU}	—.1325 —02	—.1680 —02	—.1860 —02	—.1899 —02
D_U^T	.4494 —07	.2721 —07	.1096 —07	.7134 —08
D_U^E	.3498 —02	.2461 —02	.2309 —02	.2315 —02
λ_U	.1324 +02	.1099 +02	.9171 +01	.8529 +01
λ^T	—.7649 —02	—.1111 —01	—.9147 —02	—7694 —02
λ^E	.8904 +04	.9742 +04	.7771 +04	.7024 +04
λ_R	.1520 +04	.8230 +02	.5060 +01	.6410
	T=7000K; β_U=3%			
M	.2649 +02	.3335 +02	.3905 +02	.4103 +02
ρ	.4655 —01	.5933	.7025 +01	.3980 +02
h	.1210 +05	.8152 +04	.6036 +04	.5363 +04
s	.6729 +01	.5551 +01	.4751 +01	.4352 +01
h'_c	—.1224 +05	—.8103 +04	—.5817 +04	—.5152 +04
Γ	.3846	.9748	.2291 +01	.4928 +01
η	.3991 —03	.9051 —03	.1434 —02	.1579 —02
λ'	.4115 —02	.6275 —02	.6826 —02	.6472 —02
λ_Σ	.4320 —02	.6484 —02	.6946 —02	.6509 —02
σ	.3466 +02	.3383 +02	.2391 +02	.2018 +02
α	.1897 —02	.1945 —02	.1183 —02	.7488 —03
D_{UU}	—.1104 —02	—.1611 —02	—.1929 —02	—.2016 —02
D_U^T	.5386 —07	.3725 —07	.2008 —07	.1328 —07
D_U^E	.3725 —02	.2622 —02	.3592 —02	.3790 —02
λ_U	.1647 +02	.1684 +02	.1481 +02	.1372 +02
λ^T	—.5425 —02	—.1268 —01	—.1423 —01	—.1216 —01
λ^E	.1280 +05	.1639 +05	.1572 +05	.1432 +05
λ^R	.3330 +04	.1670 +03	.8980 +01	.1270 +01

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Table 5.6. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T=8000$ K; $\beta_U=3\%$			
M	.2428 +02	.2944 +02	.3601 +02	.3891 +02
ρ	.3724 −01	.4637	.5768 +01	.3330 +02
h	.1474 +05	.1090 +05	.7845 +04	.6733 +04
s	.7083 +01	5916 +01	.4991 +01	.4532 +01
h_c'	−.1429 +05	−.1092 +05	−.7845 +04	−.6775 +04
Γ	.3116	.8665	.2132 +01	.4319 +01
η	.2613 −03	.7038 −03	.1311 −02	.1588 −02
λ'	.5110 −02	.8597 −02	.1075 −01	.1043 −01
λ_Σ	.5220 −02	.8790 −02	.1088 −01	.1058 −01
σ	.4191 +02	.4875 +02	.3879 +02	.3170 +02
α	.2256 −02	.2779 −02	.2141 −02	.1420 −02
D_{UU}	−.7832 −03	−.1478 −02	−.1947 −02	−.2110 −02
D_U^T	.5875 −07	.4420 −07	.2660 −07	.1787 −07
D_U^E	−.7043 −03	.2278 −02	.4284 −02	.4690 −02
λ_U	.1432 +02	.2153 +02	.2137 +02	.2023 +02
λ^T	−.3583 −02	−.1152 −01	−.1747 −01	−.1594 −01
λ^E	.1665 +05	.2340 +05	.2553 +05	.2382 +05
λ_R	.1010 +05	.3450 +03	.1740 +02	.2560 +01
	$T=10\,000$ K; $\beta_U=3\%$			
M	.2291 +02	.2518 +02	.3084 +02	3498 +02
ρ	.2784 −01	.3171	.4022 +01	.2407 +02
h	.1791 +05	.1541 +05	.1148 +05	.9425 +04
s	.7439 +01	.6420 +01	.5391 +01	.4826 +01
h_s'	−.1586 +05	−.1472 +05	−.1158 +05	−.9829 +04
Γ	.2051	.6242	.1707 +01	.3367 +01
η	.1263 −03	.4407 −03	.1556 −02	.1077 −02
λ	.7366 −02	.1291 −01	.2149 −01	.1999 −01
λ_Σ	.7410 −02	.1303 −01	.2159 −01	.2012 −01
σ	.5267 +02	.7265 +02	.6284 +02	.7527 +02
α	.2807 −02	.3993 −02	.3410 −02	.4399 −02
D_{UU}	−.2874 −03	−.1024 −02	−.2198 −02	−.1840 −02
D_U^T	.2155 −07	.4381 −07	.1549 −07	.2730 −07
D_U^E	−.1781 −02	.5359 −03	.5496 −02	.4546 −02
λ_U	.5688 +01	.2125 +02	.3405 +02	.3234 +02
λ^T	−.1400 −02	−.7271 −02	−.2154 −01	−.1894 −01
λ^E	.2543 +05	.3773 +05	.4883 +05	.4840 +05
λ_R	.7910 +05	.2000 +04	.7050 +02	.9090 +01

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Table 5.6. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 12\,000$ K; $\beta_U = 3\%$			
M	.2249 +02	.2357 +02	.2741 +02	.3167 +02
ρ	.2260 −01	.2449	.2982 +01	.1806 +02
h	.2048 +05	.1863 +05	.1486 +05	.1208 +05
s	.7672 +01	.6713 +01	.5694 +01	.5060 +01
h_c'	−.1515 +05	−.1637 +05	−.1439 +05	−.1245 +05
Γ	.1441	.4493	.1316 +01	.2648 +01
η	.9268 −04	.3000 −03	.9038 −03	.1510 −02
λ′	.9819 −02	.1689 −01	.2956 −01	.3565 −01
λ_Σ	.9849 −02	.1697 −01	.2972 −01	.3576 −01
σ	.6190 +02	.8912 +02	.1106 +03	.9916 +02
α	.3332 −02	.4814 −02	.6354 −02	.5726 −02
D_{UU}	−.1205 −03	−.5914 −03	−.1596 −02	−.2166 −02
D_U^T	.7075 −08	.2822 −07	.3109 −07	.1972 −07
D_U^E	−.1558 −02	−.9457 −03	.2748 −02	.4475 −02
λ_U	−.3461 +01	.1193 +02	.3558 +02	.4471 +02
λ^T	−.1082 −02	−.4497 −02	−.1719 −01	−.2536 −01
λ^E	.3539 +05	.5261 +05	.7407 +05	.8014 +05
λ_R	.3950 +06	.1040 +05	.2780 +03	.2980 +02
	$T = 15\,000$ K; $\beta_U = 3\%$			
M	.2222 +02	.2264 +02	.2466 +02	.2799 +02
ρ	.1774 −01	.1855	.2118 +01	.1259 +02
h	.2396 +05	.2273 +05	.1950 +05	.1612 +05
s	.7933 +01	.7016 +01	.6034 +01	.5350 +01
h_c'	−.1453 +05	−.1568 +05	−.1654 +05	−.1534 +05
Γ	.9316 −01	.2942	.9003	.1891 +01
η	.1053 −03	.2243 −03	.7073 −03	.1409 −02
λ′	.1411 −01	.2295 −01	.4257 −01	.5878 −01
λ_Σ	.1412 −01	.2305 −01	.4271 −01	.5895 −01
σ	.7508 +02	.1064 +03	.1513 +03	.1593 +03
α	.4101 −02	.5781 −02	.8355 −02	.8970 −02
D_{UU}	−.6684 −04	−.2327 −03	−.1069 −02	−.1943 −02
D_U^T	−.6404 −09	.7626 −08	.2894 −07	.2522 −07
D_U^E	−.8767 −03	−.6304 −03	.1192 −03	.6528 −03
λ_U	−.2168 +02	−.1922 02	.1294 +02	.4293 +02
λ^T	−.3121 −03	−.2719 −02	−.1379 −01	−.2744 −01
λ^E	.5300 +05	.7766 05	.1160 +06	.1366 +06
λ_R	.8820 +06	.5320 +05	.1670 +04	.1460 +03

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Table 5.6. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 20\,000$ K; $\beta_U = 3\%$			
M	.2211 +02	.2225 +02	.2289 +02	.2456 +02
ρ	.1315 —01	.1346	.1440 +01	.8062 +01
h	.2925 +05	.2827 +05	.2621 +05	.2311 +05
s	.8236 +01	.7337 +01	.6418 +01	.5742 +01
h_c'	—.1825 +05	—.1824 +05	—.1788 +05	—.1791 +05
Γ	.5259 —01	.1667	.5277	.1153 +01
η	.1666 —03	.2736 —03	.6034 —03	.1238 —02
λ'	.2376 —01	.3574 —01	.6316 —01	.9848 —01
λ_Σ	.2377 —01	.3575 —01	.6327 —01	.9875 —01
σ	.9979 +02	.1355 +03	.1983 +03	.2492 +03
α	.5474 —02	.7413 —02	.1087 —01	.1366 —01
D_{UU}	—.9016 —04	—.1766 —03	—.5201 —03	—.1316 —02
D_U^T	—.1793 —08	—.1871 —08	.4094 —08	.1952 —07
D_U^E	.2617 —02	.1296 —02	.2044 —02	—.3914 —03
λ_U	—.5600 +02	—.7441 +02	—.9501 +02	—.7539 +02
λ^T	—.4768 —03	—.6836 —03	—.6145 —02	—.2098 —01
λ^E	.9156 +05	.1297 +06	.1956 +06	.2538 +06
λ_R	.1330 +07	.1210 +06	.8320 +04	.8110 +03
	$T = 25\,000$ K; $\beta_U = 3\%$			
M	.1993 +02	.2182 +02	.2237 +02	.2317 +02
ρ	.9480 —02	.1048	.1106 +01	.5946 +01
h	.5146 +05	.3595 +05	.3222 +05	.2956 +05
s	.9191 +01	.7673 +01	.6683 +01	.6025 +01
h_c'	—.2473 +05	—.2391 +05	—.2318 +05	—.2194 +05
Γ	.3810 —01	.1089	.3403	.7587
η	.2238 —03	.3762 —03	.7109 —03	.1320 —02
λ'	.3294 —01	.5185 —01	.8634 —01	.1361
λ_Σ	.3330 —01	.5193 —01	.8639 —01	.1363
σ	.1181 +03	.1649 +03	.2360 +03	.3055 +03
α	.6853 —02	.9106 —02	.1294 —01	.1671 —01
D_{UU}	—.1002 —03	—.2198 —03	—.5137 —03	—.1080 —02
D_U^T	—.2905 —08	—.2829 —08	—.2493 —08	—.2423 —08
D_U^E	.3066 —02	.1361 —02	.3476 —02	.2715 —02
λ_U	—.1256 +03	—.1523 +03	—.2084 +03	—2665 +03
λ^T	—.1381 —01	—.3481 —02	—.4185 —02	—.1645 —01
λ^E	.1339 +06	.1952 +06	.2893 +06	.3898 +06
λ_R	.5470 +07	.3500 +06	.2790 +05	.3830 +04

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Table 5.6. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 30\,000$ K; $\beta_U = 3\%$			
M	.1578 +02	.1891 +02	.2155 +02	.2244 +02
ρ	.6261 −02	.7579 −01	.8801	.4718 +01
h	.1052 +06	.6668 +05	.4303 +05	.3721 +05
s	.1116 +02	.8773 +01	.7071 +01	.6299 +01
h_c'	−.6108 +05	−.3549 +05	−.3167 +05	−.3009 +05
Γ	.3154 −01	.8820 −01	.2461	.5362
η	.1576 −03	.4478 −03	.8696 −03	.1492 −02
λ'	.3320 −01	6424 −01	.1123	.1713
λ_Σ	.3507 −01	.6510 −01	.1126	.1715
σ	.1462 +03	.1814 +03	.2708 +03	.3520 +03
α	.8085 −02	.1076 −01	.1503 −01	.1032 −01
D_{UU}	−.6755 −04	−.2216 −03	−.5677 −03	−.1116 −02
D_U^T	−.5258 −08	−.5128 −08	−.4387 −08	−.2870 −08
D_U^E	.2260 −02	.4469 −02	.4701 −02	.5779 −02
λ_U	−.1110 +03	−.2654 +03	−.3636 +03	−.4655 +03
λ^T	−.4068 −01	−.3234 −01	−.1115 −01	−.1516 −01
λ^E	.1575 +06	.2606 +06	.3980 +06	.5323 +06
λ_R	.3570 +08	.1610 +07	.7360 +05	.1130 +05
	$T = 40\,000$ K; $\beta_U = 3\%$			
M	.1272 +02	.1460 +02	.1658 +02	.1896 +02
ρ	.4380 −02	.4385 −01	.5088	.2967 +01
h	.1933 +06	.1408 +06	.1069 +06	.7897 +05
s	.1363 +02	.1094 +02	.8885 +01	.7468 +01
h_c'	−.1142 +06	−.9482 +05	−.6107 +05	−.5182 +05
Γ	.2073 −01	.5953 −01	.1746	.3569
η	.6345 −04	.2380 −03	.9690 −03	.1880 −02
λ'	.4752 −01	.7269 −01	.1441	.2436
λ_Σ	.4789 −01	.7501 −01	.1468	.2465
σ	.1380 +03	.1862 +03	.2998 +03	.4339 +03
α	.1089 −01	.1395 −01	.1924 −01	.2524 −01
D_{UU}	−.5681 −04	−.1424 −03	−.5262 −03	−.1240 −02
D_U^T	−.8087 −09	−.4981 −08	−.1007 −07	−.8619 −08
D_U^E	.7943 −03	.2556 −02	.7833 −02	.1149 −01
λ_U	−.1195 +03	−.2296 +03	−.6915 +03	−.1057 +04
λ^T	−.6891 −02	−.4760 −01	−.9213 −01	−.6186 −01
λ^E	.2423 +06	.3549 +06	.5995 +06	.8665 +06
λ_R		.1480 +08	.4300 +06	.6030 +05

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Table 5.6. [Continued]

Параметр	Давление, ат			
	1	1	10	500
	$T = 4000$ K; $\beta_U = 10\%$ $T = 5000$ K			
M	.5662 +02	.5025 +02	.5529 +02	
ρ	.1675	.1205	.1321 +01	
h	.1904 +04	.3573 +04	.2684 +04	
s	.3922 +01	.4289 +01	.3756 +01	
h_c'	—.2153 +04	—.4460 +04	—.3149 +04	
Γ	.3418	.4420	.9033	
η	.1549 —02	.1346 —02	.1708 —02	
λ'	.1344 —02	.2143 —02	.2280 —02	
λ_Σ	.1426 —02	.2379 —02	.2381 —02	
σ	.4118 +01	.1272 +02	.7590 +01	
α	.2000 —03	.7243 —03	.3850 —03	
D_{UU}	—.1892 —02	—.1916 —02	—.2153 —03	
D_U^T	.1356 —07	.7868 —07	.2731 —07	
D_U^E	.2625 —02	.5064 —02	.4402 —02	
λ_U	.4583 +01	.1044 +02	.8148 +01	
λ^T	—.3616 —02	—.7547 —02	—.6712 —02	
λ_E	.1720 +04	.4978 +04	.4220 +04	
λ_R	.1320 +03	.3500 +03	.2700 +02	

Параметр	Давление, ат			
	1	10	100	500
	$T = 6000$ K; $\beta_U = 10\%$			
M	.4142 +02	.5007 +02	.5489 +02	
ρ	.8422 —01	.1017 +01	.1123 +02	
h	.6329 +04	.4246 +04	.3420 +04	
s	.4789 +01	.4039 +01	.3650 +01	
h_c'	—.8438 +04	—.6297 +04	—.4051 +04	
Γ	.4424	.9933	.2267 +01	
η	.1025 —02	.1556 —02	.1904 —02	
λ'	.3090 —02	.4021 —02	.3727 —02	
λ_Σ	.3395 —02	.4201 —02	.3826 —02	
σ	.2452 +02	.1912 +02	.1178 +02	
α	.1317 —02	.1058 —02	.5281 —03	
D_{UU}	—.1727 —02	—.2190 —02	—.2426 —02	
D_U^T	.1098 —06	.6622 —07	.2646 —07	
D_U^E	.6654 —02	.7198 —02	.6461 —02	
λ_U	.1835 +02	.1540 +02	.1277 +02	
λ^T	—.8269 —02	—.1133 —01	—.9223 —02	
λ^E	.8829 +04	.9880 +04	.7714 +04	
λ_R	.8240 +03	.5270 +02	.3700 +01	

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Table 5.6. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 7000$ K; $\beta_U = 10\%$			
M	.3520 +02	.4402 +02	.5124 +02	.5379 +02
ρ	.6177 —04	.7811	.9175 +01	.5133 +02
h	.9169 +04	.6242 +04	.4684 +04	.4190 +04
s	.5228 +01	.4345 +01	.3743 +01	.3439 +01
h_c'	—.1223 +05	—.8106 +04	—.5810 +04	—.5133 +04
Γ	.3793	.9573	.2236 +01	.4727 +01
η	.7742 —03	.1340 —02	.1861 —02	.2012 —02
λ'	.4092 —02	.6217 —02	.6733 —02	.6311 —02
λ_Σ	.4317 —02	.6444 —02	.6862 —02	.6434 —02
σ	.3431 +02	.3363 +02	.2392 +02	.1998 +02
α	.1874 —02	.1912 —02	.1157 —02	.7109 —03
D_{UU}	—.1410 —02	—.2093 —02	—.2512 —02	—.2630 —02
D_U^T	.1327 —06	.9102 —07	.4885 —07	.3176 —07
D_U^E	.6402 —02	.8423 —02	.1007 —01	.9898 —02
λ_U	.2259 +02	.2386 +02	.2110 +02	.1947 +02
λ^T	—.6729 —02	—.1024 —01	—.1447 —01	—.1223 —01
λ^E	.1269 +05	.1630 +05	.1562 +05	.1402 +05
λ_R	.1680 +04	.9010 +02	.6150 +01	.8970
	$T = 8000$ K; $\beta_U = 10\%$			
M	.3210 +02	.3897 +02	.4737 +02	.5109 +02
ρ	.4920 —01	.6122	.7550 +01	.4309 +02
h	.1132 +05	.8326 +04	.6058 +04	.5239 +04
s	.5515 +01	.4622 +01	.3925 +01	.3577 +01
h_c'	—.1427 +05	—.1093 +05	—.7840 +04	—.6758 +04
Γ	.3091	.8537	.2089 +01	.4179 +01
η	.5408 —03	.1150 —02	.1786 —02	.2068 —02
λ'	.5091 —02	.8527 —02	.1063 —01	.1023 —01
λ_Σ	.5248 —02	.8754 —02	.1078 —01	.1035 —01
σ	.4157 +02	.4829 +02	.3867 +02	.3114 +02
α	.2236 —02	.2735 —02	.2097 —02	.1374 —02
D_{UU}	—.9605 —03	—.1898 —02	—.2529 —02	—.2748 —02
D_U^T	.1394 —06	.1081 —06	.6494 —07	.4334 —07
D_U^E	.4073 —02	.8068 —02	.1259 —01	.1279 —01
λ_U	.1919 +02	.3045 +02	.3085 +02	.2925 +02
λ^T	—.5389 —02	—.1258 —01	—.1798 —01	—.1620 —01
λ_E	.1658 +05	.2327 +05	.2540 +05	.2352 +05
λ_R	.4300 +04	.2010 +03	.1160 +02	.1770 +01

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Table 5.6. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 10\,000$ K; $\beta_U = 10\%$			
M	.2995 +02	.3318 +02	.4065 +02	.4600 +02
ρ	.3638 −01	.4175	.5281 +01	.3130 +02
h	.1408 +05	.1192 +05	.8855 +04	.7318 +04
s	.5825 +01	.5023 +01	.4233 +01	.3804 +01
h_c'	−.1585 +05	−.1471 +05	−.1158 +05	−.9821 +04
Γ	.2053	.6200	.1684 +01	.3296 +01
η	.2141 −03	.7757 −03	.1589 −02	.2103 −02
λ'	.7310 −02	.1284 −01	.1982 −01	.2127 −01
λ_Σ	.7416 −02	.1305 −01	.2062 −01	.2141 −01
σ	.5232 +02	.7199 +02	.7451 +02	.6219 +02
α	.2798 −02	.3952 −02	.4301 −02	.3285 −02
D_{UU}	−.3455 −03	−.1267 −02	−.2359 −02	−.2845 −02
D_U^T	.4848 −07	.1034 −06	.6571 −07	.3696 −07
D_U^E	.2652 −02	.3962 −02	.1239 −01	.1568 −01
λ_U	.7334 +01	.2935 +02	.4699 +02	.5023 +02
λ^T	−.2448 −02	−.9202 −02	−.2030 −01	.2257 −01
λ^E	.2535 +05	.3758 +05	.4822 +05	.4865 +05
λ_R	.3190 +05	.1040 +04	.4660 +02	.6300 +01
	$T = 12\,000$ K; $\beta_U = 10\%$			
M	.2894 +02	.3078 +02	.3604 +02	.4162 +02
ρ	.2911 −01	.3198	.3912 +01	.2355 +02
h	.1676 +05	.1469 +05	.1155 +05	.9398 +04
s	.6067 +01	.5274 +01	.4474 +01	.3988 +01
h_c'	−.1517 +05	−.1636 +05	−.1439 +05	−.1245 +05
Γ	.1472	.4504	.1310 +01	.2614 +01
η	.1117 −03	.4725 −03	.1366 −02	.2082 −02
λ'	.9309 −02	.1673 −01	.2944 −01	.3550 −01
λ_Σ	.9386 −02	.1691 −01	2971 −01	.3562 −01
σ	.5983 +02	.8834 +02	.1096 +03	.9834 +02
α	.3321 −02	.4799 −02	.6259 −02	.5580 −02
D_{UU}	−.1486 03	−.7250 −03	−.2014 −02	−.2788 −02
D_U^T	.1475 07	.6352 −07	.7303 −07	.4670 −07
D^E	.4089 −02	.6940 −03	.8327 −02	.1369 −01
λ_U	−.6062 +01	.1548 +02	.5097 +02	.6606 +02
λ^T	.2515 −02	−.6641 −02	−.1955 −01	−.2731 −01
λ^E	.3455 +05	.5238 +05	.7401 +05	.8022 +05
λ_R	.1450 +06	.4930 +04	.1810 +03	.2210 +02

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Table 5.6. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 15\,000$ K; $\beta_U = 10\%$			
M	.2809 +02	.2892 +02	.3203 +02	.3658 +02
ρ	.2246 —01	.2375	.2753 +01	.1641 +02
h	.2041 +05	.1887 +05	.1555 +05	.1269 +05
s	.6341 +01	.5583 +01	.4768 +01	.4225 +01
h_c'	—.1452 +05	—.1571 +05	—.1655 +05	—.1534 +05
Γ	.2391 +05	.3035	.9090	.1890 +01
η	.9713 —04	.2469 —03	.9610 —03	.1914 —02
λ'	.1266 —01	.2163 —01	.4204 —01	.5893 —01
λ_Σ	.1268 —01	.2191 —01	.4235 —01	.5932 —01
σ	.7031 +02	.1020 +03	.1498 +03	.1590 +03
α	.4075 —02	.5786 —02	.8367 —02	.8912 —02
D_{UU}	—.9126 —04	—.2975 —03	—.1334 —02	—.2472 —02
D_U^T	—.1585 —08	.1540 —07	.6355 —07	.5741 —07
D_U^E	.4884 —02	.3066 —02	.4966 —02	.5058 —02
λ_U	—.3195 +02	—.3047 +02	.1411 +02	.6018 +02
λ^T	—.6449 —03	—.4973 —02	—.1854 —01	—.3196 —01
λ^E	.5024 +05	.7568 +05	.1157 +06	.1376 +06
λ_R	.2850 +06	.2020 +05	.9040 +03	.1020 +03
	$T = 20\,000$ K; $\beta_U = 10\%$			
M	.2786 +02	.2808 +02	.2901 +02	.3137 +02
ρ	.1660 —01	.1704	.1833 +01	.1033 +02
h	.2482 +05	.2391 +05	.2198 +05	.1907 +05
s	.6594 +01	.5876 +01	.5136 +01	.4583 +01
h_c'	—.1825 +05	—.1819 +05	—.1786 +05	—.1795 +05
Γ	.9512 —01	.1744	.5503	.1192 +01
η	.1480 —03	.2556 —03	.6207 —03	.1423 —02
λ'	.2109 —01	.3250 —01	.5976 —01	.9698 —01
λ_Σ	.2110 —01	.3252 —01	.6004 —01	.9779 —01
σ	.9261 +02	.1271 +03	.1903 +03	.2470 +03
α	.5424 —02	.7392 —02	.1097 —01	.1397 —01
D_{UU}	—.1259 —03	—.2460 —03	—.7002 —03	—.1711 —02
D_U^T	—.3901 —08	—.4243 —08	—.7564 —08	.4002 —07
D_U^E	.7605 —02	.5806 —02	.8600 —02	.2080 —02
λ_U	—.8098 +02	—.1102 +03	—.1465 +03	—.1256 +03
λ^T	—.8361 —03	—.1005 —02	—.8656 —02	—.2898 —01
λ^E	.8616 05	.1241 06	.1916 06	.2542 +06
λ_R	.4120 +06	.3820 +05	.3100 +04	.4220 +03

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Table 5.6. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	T=25 000 K; β_U=10%			
M	.2517 +02	.2752 +02	.2823 +02	.2926 +02
ρ	.1198 −01	.1325	.1402 +01	.7546 +01
h	.4171 +05	.2995 +05	.2697 +05	.2474 +05
s	.7321 +01	.6141 +01	.5358 +01	.4833 +01
h_c'	−.2479 +05	−.2389 +05	−.2309 +05	−.2186 +05
Γ	.3959 −01	.1140	.3565	.7950
η	.1897 −03	.3403 −03	.6851 −03	.1332 −02
λ'	.2882 −01	.4641 −01	.8017 −01	.1296 −00
λ_Σ	.2911 −01	.4650 −01	.8025 −01	.1298 00
σ	.4067 +03	.1530 +03	.2232 +03	.2968 +03
α	.6684 −02	.9033 −02	.1300 −01	.1707 −01
D_{UU}	−.1435 −03	−.3081 −03	−.7165 −03	−.1478 −02
D_U^T	−.6074 −08	−.6294 −08	−.5906 −08	.3850 −08
D_U^E	.6135 −02	.6664 −02	.1040 −01	.1243 −01
λ_U	−.1719 +03	−.2203 +03	−.3130 +03	−.4087 +03
λ^T	−.1273 −01	−.4190 −02	−.4730 −02	−.1849 −01
λ^E	.1231 +06	.1845 +06	2804 +06	.3830 +06
λ_R	.1680 +07	.1020 +06	.9410 +05	.1520 +06
	T=30 000 K; β_U=10%			
M	.2011 +02	.2405 +02	.2725 +02	.2831 +02
ρ	.7986 −02	.9650 −01	.1116 +01	.5981 +01
h	.8193 +05	.5272 +05	.3517 +05	.3075 +05
s	.8794 +01	.6956 +01	.5652 +01	.5049 +01
h_c'	−.6078 +05	−.3546 +05	−.3169 +05	−.2995 +05
Γ	.3226 −01	.9061 −01	.2562	.5614
η	.1401 −03	.3917 −03	.8113 −03	.1467 −02
λ'	.3137 −01	.5757 −01	.1023	.1613
λ_Σ	.3278 −01	.5826 −01	.1025	.1618
σ	.1082 +03	.1662 +03	.2534 +03	.3367 +03
α	.7874 −02	.1055 −01	.1499 −01	.1959 −01
D_{UU}	−.1001 −03	−.3177 −03	−.7968 −03	−.1560 −02
D_U^T	−.1086 −07	−.1081 −07	−.9919 −08	−.7158 −08
D_U^E	.3912 −02	.9924 −02	.1409 −01	.1886 −01
λ_U	−.1642 +03	−.3723 +03	−5321 +03	−.7048 +03
λ^T	−.3317 −01	−.2853 −01	−.1158 −01	−.1548 −01
λ^E	.1495 +06	.2428 +06	.3796 +06	.5202 +06
λ_R	.1090 +06	.3430 +06	.2370 +05	.4030 +04

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Table 5.6. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T=40\,000$ K; $\beta_U=10\%$			
M	.1622 +02	.1864 +02	.2128 +02	.2422 +02
ρ	.4823 −02	.5603 −01	.6536	.3797 +01
h	.1497 +06	.1092 +06	.8241 +05	.6154 +05
s	.1070 +02	.8603 +01	.6993 +01	.5911 +01
h_c'	−.1143 +06	−.9461 +05	−.6086 +05	−.5170 +05
Γ	.2114 −01	.6078 −01	.1774	.3644
η	.6766 −04	.2294 −03	.8851 −03	.1778 −02
λ'	.4618 −01	.7043 −01	.1351	.2269
λ_Σ	.4651 −01	.7230 −01	.1373	.2283
σ	.1322 +03	.1777 +03	.2790 +03	.4049 +03
α	.1061 −01	.1362 −01	.1885 −01	.2509 −01
D_{UU}	−.7753 −04	−.2034 −03	−.7626 −03	−.1769 −02
D_U^T	−.1828 −08	−.1078 −07	−.2141 −07	−.1921 −07
D_U^E	.1731 −02	.5310 −02	.1677 −01	.2492 −01
λ_U	−.1845 +03	−.3527 +03	−.1007 +04	−.1549 +04
λ^T	−.7537 −02	−.4067 −01	−.7881 −01	−.5872 −01
λ^E	.2341 +06	.3428 +06	.5708 +06	.8319 +06
λ_R	—	.4500 +07	.1340 +06	.2280 +05

Параметр	Давление, ат			
	1	10	1	10
	$T=5000$ K; $\beta_U=50\%$		$T=6000$ K	
M	.1224 +03	.1312 +03	.1062 +03	.1220 +03
ρ	.2919	.3120 +01	.2135	.2449 +01
h	.1566 +04	.1293 +04	.2532 +04	.1893 +04
s	.2014 +01	.1810 +01	.2189 +01	.1919 +01
h_c'	−.4565 +04	−.3147 +04	−.8537 +04	−.5354 +04
Γ	.3792	.7624	.3851	.8477
η	.2596 −02	.2804 −02	.2548 −02	.2966 −02
λ'	.1919 −02	.1954 −02	.2903 −02	.3662 −02
λ_Σ	.2199 −02	.2082 −02	.3277 −02	.3913 −02
σ	.1298 +02	8270 +01	.2326 +02	.1938 +02
α	.6926 −03	.3822 −03	.1235 −02	.9519 −03
D_{UU}	−.4410 −02	−.4990 −02	−.3767 −02	−.4989 −02
D_U^T	.1112 −06	3967 −07	.1657 −06	.9641 −07
D_U^E	.8826 −02	.8613 −02	.9660 −02	.1339 −01
λ_U	.3681 +02	.2854 +02	.6519 +02	.6034 +02
λ^T	.7565 −02	−.6674 −02	−.9456 −02	−.1162 −01
λ^E	.4707 +04	.4061 +04	.8347 +04	.9265 +04
λ_R	.8660 +02	.7900 +01	.2240 +03	.1830 +02

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Table 5.6. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	T=7000 K; β_U=50%			
M	.9160 +02	.1105 +03	.1240 +03	
ρ	.1592	.1928 +01	.2164 +02	
h	.3697 +04	.2648 +04	.2137 +04	
s	.2368 +01	.2035 +01	.1805 +01	
h_c'	—.1202 +05	—.8148 +04	—.5801 +04	
Γ	.3437	.8329	.1879 +01	
η	.2239 —02	.2986 —02	.3394 —02	
λ'	.3921 —02	.5766 —02	.6068 —02	
λ_Σ	.4364 02	.6147 —02	.6278 —02	
σ	.3194 +02	.3184 +02	.2400 +02	
α	.1711 —02	.1660 —02	.9567 —03	
D_{UU}	—.2523 —02	—.4535 —02	—.5720 —02	
D_U^T	.1974 —06	.1362 —06	.7156 —07	
D_U^E	.7148 —02	.1491 —01	.1718 —01	
λ_U	.7146 +02	.9582 +02	.8848 +02	
λ^T	—.1063 —01	—.1482 —01	—.1506 —01	
λ^E	.1214 +05	.1563 +05	.1480 +05	
λ_R	.3980 +03	.2870 +02	.2710 +01	
	T=8000 K; β_U=50%			
M	.8075 +02	.9920 +02	.1164 +03	.1239 +03
ρ	.1231	.1533 +01	.1804 +02	.9749 +02
h	.4921 +04	.3509 +04	.2697 +04	.2422 +04
s	.2532 +01	.2150 +01	.1879 +01	.1740 +01
h_c'	—.1401 +05	—.1084 +05	—.7818 +05	—.6679 +05
Γ	.2935	.7651	.1806 +01	.3362 +01
η	.1617 —02	.2852 —02	.3527 —02	.3768 —02
λ'	.5003 —02	.8013 —02	.9740 —02	.8940 —02
λ_Σ	.5600 —02	.8554 —02	.1007 —01	.9135 —02
σ	.3978 +02	.4496 +02	.3769 +02	.2992 +02
α	.2182 —02	.2425 —02	.1779 —02	.1015 —02
D_{UU}	—.1395 —02	—.3711 —02	—.5584 —02	—.6264 —02
D_U^T	.1602 —06	.1577 —06	.9750 —07	.6275 —07
D_U^E	.4409 —02	.1217 —01	.1950 —01	.1999 —01
λ_U	.5289 +02	.1156 +03	.1343 +03	.1261 +03
λ^T	—.1016 —01	—.1659 —01	—.2007 —01	—.1733 —01
λ^E	.1625 +05	.2247 +05	.2435 +05	.2152 +05
λ_R	.9910 +03	.5620 +02	.4750 +01	.7610

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Table 5.6. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T=10\,000$ K; $\beta_U=50\%$			
M	.7053 +02	.8203 +02	.1009 +03	.1127 +03
ρ	.8568 —01	.1025 +01	.1281 +02	.7248 +02
h	.6876 +04	.5336 +04	.3940 +04	.3351 +04
s	.2751 +01	.2357 +01	.2017 +01	.1842 +01
h_c'	—.1582 +05	—.1455 +05	—.1148 +05	—.9733 +04
Γ	.2060	.5946	.1539 +01	.2874 +01
η	.5561 —03	.2052 —02	.3510 —02	.4104 —02
λ'	.7052 —02	.1241 —01	.1880 —01	.1987 —01
λ_E	.7637 —02	.1330 —01	.1950 —01	.2030 —01
σ	.5075 +02	.6802 +02	.6972 +02	.5900 +02
α	.2768 —02	.3704 —02	.3675 —02	.2528 —02
D_{UU}	—.5193 —03	—.2040 —02	—.4751 —02	—.6173 —02
D_U^T	.4803 —07	.1258 —06	.1209 —06	.9021 —07
D_Y^E	.2416 —02	.4868 —02	.1613 —01	.2141 —01
λ_U	.1679 +02	.9351 +02	.1969 +03	.2275 +03
λ^T	—.5511 —02	—.1599 —01	—.2737 —01	—.2858 —01
λ^E	.2490 +05	.3689 +05	.4761 +05	.4763 +05
λ_R	.7210+04	.2740 +03	.1570 +02	.2590 +01
	$T=12\,000$ K; $\beta_U=50\%$			
M	.6280 +02	.7217 +02	.8792 +02	.1013 +03
ρ	.6351 —01	.7500	.9424 +01	.5516 +02
h	.9731 +04	.7294 +04	.5344 +04	.4367 +04
s	.3008 +01	.2531 +01	.2143 +01	.1933 +01
h_c'	—.1552 +05	—.1632 +05	—.1430 +05	—.1237 +05
Γ	.1616	.4571	.1258 +01	.2417 +01
η	.1636 —03	.1101 —02	.3083 —02	.4207 —02
λ'	.7551 —02	.1569 —01	.2835 —01	.3471 —01
λ_Σ	.7798 —02	.1643 —01	.2946 —01	.3548 —01
σ	.5210 +02	.8347 +02	.1037 +03	.9458 +02
α	.3281 —02	.4691 —02	.5697 —02	.4742 —02
D_{UU}	—.2783 —03	—.1172 —02	—.3754 —02	—.5769 —02
D_U^T	.1483 —07	.6551 —07	.1093 —06	.9776 —07
D_U^E	.2865 —02	.3683 —02	.1100 —01	.1550 —01
λ_U	—.2673 +02	.3445 +02	.1869 +03	.2872 +03
λ^T	—.7075 —02	—.1439 —01	—.3081 —01	—.3911 —01
λ^E	.3105 +05	.5097 +05	.7371 +05	.8176 +05
λ_R	.3280 +05	.1220 +04	.5750 +02	.8640 +01

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Table 5.6. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T=15\,000$ K; $\beta_U=50\%$			
M	.5579 +02	.6053 +02	.7307 +02	.8624 +02
ρ	.4500 —01	.5030	.6298 +01	.3809 +02
h	.1371 +05	.1155 +05	.8133 +04	.6246 +04
s	.3309 +01	.2845 +01	.2348 +01	.2070 +01
h_c'	—.1458 +05	—.1612 +05	—.1665 +05	—.1526 +05
Γ	.1147	.3453	.9552	.1888 +01
η	.6118 —04	.3034 —03	.1885 —02	.3822 —02
λ'	.9323 —02	.1785 —01	.3975 —01	.6005 —01
λ_Σ	.9400 —02	.1890 —01	.4086 —01	.6164 —01
σ	.5705 +02	.8806 +02	.1434 +03	.1572 +03
α	.4004 —02	.5827 —02	.8459 —02	.8621 —02
D_{UU}	—.2307 —03	—.6511 —03	—.2564 —02	—.5022 —02
D_U^T	—.1766 —08	.9181 —08	.5133 —07	.5251 —07
D_U^E	.3526 —02	.2162 —02	.3048 —02	.3446 —02
λ_U	—.9296 +02	—.1095 +03	.3638 +01	.1984 +03
λ^T	—.1579 —02	—.1203 —01	—.3808 —01	—.5644 —01
λ^E	.4252 +05	.6915 +05	.6916 +05	.1442 +06
λ_R	.6730 +05	.4840 +04	.2520 +03	.3670 +02
	$T=20\,000$ K; $\beta_U=50\%$			
M	.5447 +02	.5527 +02	.5831 +02	.6565 +02
ρ	.3264 —01	.3398	.3756 +01	.2192 +02
h	.1647 +05	.1569 +05	.1395 +05	.1135 +05
s	.3468 +01	.3090 +01	.2684 +01	.2358 +01
h_c'	—.1830 +05	—.1800 +05	—.1797 +05	—.1850 +05
Γ	.6562 —01	.2072	.6474	.1363 +01
η	.7659 —04	.1601 —03	.5943 —03	.2018 —02
λ'	.1502 —01	.2468 —01	.5068 —01	.9427 —01
λ_Σ	.1504 —01	.2474 —01	.5164 —01	.9754 —01
σ	.7349 +02	.1037 +03	.1675 +03	.2438 +03
α	.5261 —02	.7335 —02	.1148 —01	.1554 —01
D_{UU}	—.3258 —03	—.6534 —03	—.1769 —02	—.3969 —02
D_U^T	—.3136 —08	—.3954 —08	.1974 —08	.2240 —07
D_U^E	.4178 —02	.4608 —02	.7541 —02	.2535 —03
λ_U	—.2198 +03	—.3230 +03	—.4847 +03	—.5308 +03
λ^T	—.1508 —02	—.1856 —02	—.1646 —01	—.5940 —01
λ^E	.7081 +05	.1071 +06	.1780 +06	.2614 +06
λ_R	.9710 +05	.8920 +04	.7680 +03	.1200 +03

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Table 5.6. [Continued on following page]

Параметр	Давление, ат			
	1	10	100	500
	T=25 000 K; β_U=50%			
M	.4954 +02	.5399 +02	.5547 +02	.5773 +02
ρ	.2369 −01	.2625	.2806 +01	.1523 +02
h	.2361 +05	.1871 +05	.1712 +05	.1565 +05
s	.3778 +01	.3223 +01	.2826 +01	.2550 +01
h_c'	−.2528 +05	−.2388 +05	−.2269 +05	−.2168 +05
Γ	.4590 −01	.1350	.4249	.9476
η	.9454 −04	.1929 −03	.4784 −03	.1209 −02
λ'	.2048 −01	.3420 −01	.6449 −01	.1148
λ_Σ	.2061 −01	.3427 −01	.6467 −01	.1158
σ	.8112 +02	.1219 +03	.1878 +03	.2752 +03
α	.6200 −02	.8799 −02	.1326 −01	.1891 −01
D_{UU}	−.3732 −03	−.8137 −03	−.1926 −02	−.3907 −02
D_U^T	−.4493 −08	−.5502 −08	−.6313 −08	−.1495 −08
D_U^E	.3900 −02	.5553 −02	.1005 −01	.8812 −02
λ_U	−.4000 +03	−.6026 +03	−.9508 +03	−.1368 +04
λ^T	−.0910 −02	−.5335 −02	−.5989 −02	−.2507 −01
λ^E	.9759 +05	.1549 +06	.2512 +06	.3674 +06
λ_R	.3850 +06	.2570 +05	.2275 +04	.3980 +03
	T=30 000 K; β_U=50%			
M	.4152 +02	.4893 +02	.5392 +02	.5558 +02
ρ	.1654 −01	.1975	.2242 +01	.1199 +02
h	.3824 +05	.2674 +05	.2051 +05	.1867 +05
s	.4313 +01	.3511 +01	.2948 +01	.2660 +01
h_c'	−.5867 +05	−.3543 +05	−.3126 +05	−.2938 +05
Γ	.3558 −01	.1016	.3002	.6682
η	.8306 −04	.2216 −03	.5256 −03	.1110 −02
λ'	.2574 −01	.4335 −01	.8093 −01	.1366
λ_Σ	.2616 −01	.4367 −01	.8113 −01	.1368
σ	.8765 +02	.1298 +03	.2076 +03	.2979 +03
α	.7142 −02	.9914 −02	.1495 −01	.2097 −01
D_{UU}	−.2941 −03	−.8665 −03	−.2195 −02	−.4268 −02
D_U^T	−.7328 −08	−.8118 −08	−.9041 −08	−.8730 −08
D_γ^E	.2923 −02	.5837 −02	.1169 −01	.1577 −01
λ_U	−.4701 +03	−.9381 +03	−.1540 +04	−.2208 +04
λ^T	−.1257 −01	−.4020 −01	−.1182 −01	−.1550 −01
λ^E	.1253 +06	.2001 +06	.3346 +06	.4821 +06
λ_R	.2360 +07	.7700 +05	.5620 +04	.1010 +04

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Table 5.6. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 40\,000$ K; $\beta_U = 50\%$			
M	.3351 +02	.3879 +02	.4536 +02	.5038 +02
ρ	.9988 —02	.1170	.1401 +01	.7980 +01
h	.6821 +05	.4991 +05	.3661 +05	.2902 +05
s	.5161 +01	.4180 +01	.3404 +01	.2950 +01
h_c'	—.1146 +06	—.9317 +05	—.5981 +05	—.5128 +05
Γ	.2482 +05	.6664 —01	.1908	.4004
η	.6929 —04	.1838 —03	.5964 —03	.1250 —02
λ'	.4127 —01	.6285 —01	.1135	.1886
λ_Σ	.4144 —01	.6352 —01	.1145	.1896
σ	.1117 +03	.1496 +03	.2251 +03	.3316 +03
α	.9551 —02	.1244 —01	.1771 —01	.2472 —01
D_{UU}	—.2009 —03	—.5931 —03	—.2199 —02	—.4944 —02
D_U^T	—.1736 —08	—.8710 —08	—.1647 —07	—.1761 —07
D_U^E	.1417 —02	.4159 —02	.1183 —01	.2156 —01
λ_U	—.6228 +03	—.1167 +04	—.2815 +04	—.4413 +04
λ^T	—.9079 —02	—.1864 —01	—.4433 —01	—.4837 —01
λ^E	.2053 +06	.3027 +06	.4974 +06	.7419 +06
λ_R	.1270 +09	.9780 +06	.2940 +05	.5200 +04

Table 5.7. Thermophysical Properties of Potassium-Hydrogen Mixture

(1) Параметр	(2) Давление, ат			
	1	10	100	500
	$T = 4000$ K; $\beta_K = 3\%$			
M	.1938 +01	.2521 +01	.2905 +01	.3031 +01
ρ	.5713 —02	.7432 —01	.8564	.4468 +01
h	.1468 +03	—.5488 +05	—.7887 +05	—.8523 +05
s	.9557 +02	.7317 +02	.6016 +02	.5407 +02
h_c'	—.5093 +04	—.9389 +05	—.1331 +06	—.1436 +06
Γ	.1171	.2379	.4692	.7623
η	.4288 —03	.5918 —03	.6563 —03	.6694 —03
λ'	.8462 —02	.8912 —02	.8602 —02	.8342 —02
λ_Σ	.1187	.9837 —01	.4423 —01	.2509 —01
σ	.3949 +01	.2447 +01	.1213 +01	.6746
α	.1868 —03	.7812 —04	.1538 —04	.7672 —06
D_{KK}	—.3570 —03	—.4338 —03	—.4989 —03	—.5207 —03
D_K^T	.9657 —07	.7862 —07	.1907 —07	.4915 —08
D_K^E	.6874 —02	.4165 —02	.1968 —02	.1179 —02
λ^T	—.1126	—.9923 —01	—.4175 —01	—.1998 —01
λ_K	.7556 +01	.4490 +02	.6826 +02	.7567 +02
λ^E	.1114 +04	.3238 +03	.5356 +02	—.5449 +01
λ_R	.2640 +06	.5410 +04	.1980 +03	.1870 +02

Key:
1. Parameter
2. Pressure, atmospheres

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Table 5.7. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 5000$ K; $\beta_K = 3\%$			
M	.1606 +01	.1839 +01	.2409 +01	.2753 +01
ρ	.3790 −02	.4339 −01	.5682	.3247 +01
h	.6259 +05	.2615 +05	−.3312 +05	−.5670 +05
s	.1099 +03	.9225 +02	.7029 +02	.6038 +02
h_c'	.8502 +05	.3454 +05	−.6047 +05	−.9915 +05
Γ	.1200	.2804	.6071	.1025 +01
η	.3585 −03	.4886 −03	.7003 −03	.7761 −03
λ'	.1020 −01	.1069 −01	.1133 −01	.1107 −01
λ_Σ	.2642 −01	.9115 −01	.9916 −01	.6205 −01
σ	.7921 +01	.6099 +01	.3671 +01	.2277 +01
α	.4204 −03	.2340 −03	.1133 −03	.4049 −04
D_{KK}	−.5235 −03	−.4266 −03	−.4967 −03	−.5609 −03
D_K^T	.6643 −07	.7804 −07	.8129 −07	.4490 −07
D_K^E	.1374 −01	.1128 −01	.7082 −02	.4824 −02
λ^T	−.1553 −01	−.8119 −01	−.9494 −01	−.5776 −01
λ_K	−.3061 +02	−.3436 +01	.3792 +02	.6073 +02
λ^E	.3800 +04	.2735 +04	.1011 +04	.3556 +03
λ_R	.3550 +06	.4380 +04	.1600 +03	.1820 +02
	$T = 6000$ K; $\beta_K = 3\%$			
M	.1572 +01	.1626 +01	.1933 +01	.2349 +01
ρ	.3095 −02	.3198 −01	.3801	.2310 +01
h	.8234 +05	.7234 +05	.2732 +05	−.1476 +05
s	.1135 +03	.9979 +02	.8129 +02	.6799 +02
h_c'	.1081 +06	.1006 +06	.3676 +05	−.3169 +05
Γ	.9509 −01	.2611	.6305	.1177 +01
η	.3951 −03	.4474 −03	.6377 −03	.8156 −03
λ'	.1238 −01	.1270 −01	.1339 −01	.1387 −01
λ_Σ	.1474 −01	.3309 −01	.9458 −01	.9663 −01
σ	.1024 +02	.1003 +02	.7190 +01	.4890 +01
α	.5441 −03	.5013 −03	.2835 −03	.1319 −03
D_{KK}	−.7730 −03	−.5821 −03	−.5049 −03	−.5649 −03
D_K^T	.5736 −07	.5878 −07	.7792 −07	.8318 −07
D_K^E	.1800 −01	.1887 −01	.1433 −01	.1080 −01
λ^T	−.2072 −01	−.2065 −01	−.8245 −01	−.8771 −01
λ_K	−.5662 +02	−.3266 +02	.3329 +02	.3148 +02
λ^E	.5983 +04	.6308 +04	.3994 +04	.1982 +04
λ_R	.1100 +07	.9230 +04	.2640 +03	.3190 +02

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Table 5.7. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 7000$ K; $\beta_K = 3\%$			
M	.1566 +01	.1582 +01	.1706 +01	.2001 +01
ρ	.2639 −02	.2668 −01	.2877	.1687 +01
h	.9668 +06	.9354 +05	.7224 +05	.3241 +05
s	.1157 +03	.1031 +03	.8826 +02	.7527 +02
h_c'	.1275 +06	.1268 +06	.1029 +06	.4357 +05
Γ	.7161 −01	.2148	.5679	.1063 +01
η	.4555 −03	.4810 −03	.5970 −03	.7926 −03
λ'	.1462 −01	.1505 −01	.1552 −01	.1616 −01
λ_Σ	.1520 −01	.2051 −01	.5457 −01	.9430 −01
σ	.1145 +02	.1249 +02	.1064 +02	.7690 +01
α	.6061 −03	.6374 −03	.4735 −03	.2695 −03
D_{KK}	−.9366 −03	−.7927 −03	−.6011 −03	−.5894 −03
D_K^T	.5421 −07	.5490 −07	.5789 −07	.7975 −07
D_K	.2072 −01	.2425 −01	.2180 −01	.1744 −01
λ^T	−.4777 −03	−.5666 −02	−.3994 −01	−.7935 −01
λ_K	−.7711 +02	−.5305 +02	−.2394 +02	.2128 +01
λ^E	.8018 +04	.9468 +04	.8220 +04	.5198 +04
λ_R	.1910 +08	.2810 +05	.5650 +03	.5360 +02
	$T = 8000$ K; $\beta_K = 3\%$			
M	.1564 +01	.1571 +01	.1624 +01	.1792 +01
ρ	.2306 −02	.2317 −01	.2397	.1323 +01
h	.1106 +06	.1090 +06	.9914 +05	.7227 +05
s	.1176 +03	.1051 +03	.9188 +02	.8061 +02
h_c'	.1489 +06	.1476 +06	.1396 +06	.1048 +06
Γ	.5571 −01	.1709	.4875	.9497
η	.5266 −03	.5383 −03	.6106 −03	.7655 −03
λ'	.1692 −01	.1743 −01	.1795 −01	.1837 −01
λ_Σ	.1726 −01	.1931 −01	.3416 −01	.6941 −01
σ	.1276 +02	.1426 +02	.1389 +02	.1097 +02
α	.6547 −03	.7043 −03	.6166 −03	.4065 −03
D_{KK}	−.1030 −02	−.9645 −03	−.7534 −03	−.6600 −03
D_K^T	.6261 −07	.5325 −07	.5117 −07	.6262 −07
D_K^E	.2199 −01	.2727 −01	.2787 −01	.2369 −01
λ^T	.2947 −03	−.1996 −02	−.1744 −01	−.5174 −01
λ_K	−.9333 +02	−7062 +02	−.3890 +02	−.1947 +02
λ^E	.9962 +04	.1216 +05	.1241 +05	.9473 +04
λ_R	.1570 +09	.8740 +05	.1300 +04	.9560 +02

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Table 5.7. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 10\,000$ K; $\beta_K = 3\%$			
M	.1540 +01	.1561 +01	.1579 +01	.1635 +01
ρ	.1817 −02	.1842 −01	.1865	.9655
h	.1522 +06	.1394 +06	.1341 +06	.1235 06
s	.1221 +03	.1085 +03	.9579 +02	.8638 +02
h_c'	.2310 +06	.1994 +06	.1877 +06	.1768 +06
Γ	.5026 −01	.1216	.3458	.7143
η	.6536 −03	.6746 −03	.7183 −03	.8112 −03
λ′	.2227 −01	.2265 −01	.2326 −01	.2357 −01
λ_Σ	.2849 −01	.2334 −01	.2738 −01	.4067 −01
σ	.2051 +02	.1779 +02	.1753 +02	.1583 +02
α	.1089 −02	.8848 −03	.7953 −03	.6358 −03
D_{KK}	−.5162 −03	−.9930 −03	−.1037 −02	−.8919 −03
D_K^T	.1493 −06	.8830 −07	.5407 −07	.4997 −07
D_K^E	.1191 −01	.2671 −01	.3489 −01	.3400 −01
λ^T	−.6814 −02	−.3154 −02	−.5865 −02	−.1932 −01
λ_K	−.5207 +02	−.8473 +02	−.5660 +02	−.3588 +02
λ^E	.1468 +05	.1762 +05	.2000 +05	.1871 +05
λ_R	.4020 +08	.4050 +06	.6400 +04	.3530 +03
	$T = 12\,000$ K; $\beta_K = 3\%$			
M	.1428 +01	.1524 +01	.1561 +01	.1590 +01
ρ	.1406 −02	.1500 −01	.1536	.7826
h	.2588 +06	.1903 +06	.1684 +06	.1596 +06
s	.1317 +03	.1131 +03	.9890 +02	.8967 +02
h_c'	.4034 +06	.2928 +06	.2510 +06	.2392 +06
Γ	.6360 −01	.1282	.2879	.5581
η	.7410 −03	.8070 −03	.8606 −03	.9308 −03
λ′	.2821 −01	.2978 −01	.2977 −01	.2971 −01
λ_Σ	.6105 −01	.4021 −01	.3389 −01	.3745 −01
σ	.3873 +02	.3152 +02	.2423 +02	.2068 +02
α	.2094 −02	.1651 −02	.1161 −02	.8585 −03
D_{KK}	−.1901 −03	−.5565 −03	−.1011 −02	−.1066 −02
D_K^T	.1262 −06	.1269 −06	.8416 −07	.5840 −07
D_K^E	.3536 −02	.1368 −01	.3165 −01	.3799 −01
λ^T	−.4965 −01	−.2904 −01	.1689 −01	−.1605 −01
λ_K	−.3129 +02	−.6699 +02	−.8164 +02	−.5144 +02
λ^E	.2586 +05	.2781 05	.2923 +05	.2838 +05
λ_R	.1320 +08	.4710 +06	.1490 +05	.9810 +03

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Table 5.7. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 15\,000$ K; $\beta_K = 3\%$			
M	.1083 +01	.1351 +01	.1493 +01	.1543 +01
ρ	.8579 −03	.1070 −01	.1180	.6091
h	.6621 +06	.3658 +06	.2541 +06	.2231 +06
s	.1613 +03	.1260 +03	.1052 +03	.9436 +02
h_c'	.1035 +07	.5723 +06	.3963 +06	.3470 +06
Γ	.7260 −01	.1572	.3184	.5353
η	.6202 −03	.9130 −03	.1059 −02	.1135 −02
λ′	.3095 −01	.4190 −01	.4562 −01	.4449 −01
λ_Σ	.1160	.8752 −01	.6209 −01	.5190 −01
σ	.6833 +02	.6790 +02	.5441 +02	.4181 +02
α	.3651 −02	.3653 −02	.2787 −02	.1913 −02
D_{KK}	−.7243 −04	−.2499 −03	.6928 −03	−.1017 −02
D_K^T	.5485 −07	.9218 −07	.1006 −06	.8014 −07
D_K^E	.8040 −03	.3655 −02	.1640 −01	.2862 −01
λ^T	−.9383 −01	−.9394 −01	−.7553 −01	−.5606 −01
λ_K	−.5181 +02	−.8105 +02	−.1303 +03	−.1379 +03
λ^E	.4999 +05	.5443 +05	.6085 +05	.5620 +05
λ_R	.1210 +08	.3880 +06	.1710 +05	.1760 +04
	$T = 20\,000$ K; $\beta_K = 3\%$			
M	.8190	.9507	.1222 +01	1378 +01
ρ	.4867 −03	.5705 −02	.7365 −01	.4140
h	.1270 +07	.9739 +06	.5738 +06	.4196 +06
s	.1972 +03	.1606 +03	.1232 +03	.1055 +03
h_c'	1995 +07	.1529 +07	.9064 +06	.6673 +06
Γ	.5043 −01	.1459	.3501	.5965
η	.1392 −03	.5827 −03	.1160 −02	.1429 −02
λ′	.2820 −01	.5070 −01	.7866 −01	.8961 −01
λ_Σ	.4459 −01	.1116	.1327	.1210
σ	.1029 +03	.1282 +03	.1358 +03	.1206 +03
α	.5458 −02	.6828 −02	.7209 −02	.6109 −02
D_{KK}	−.5722 −04	−.1264 −03	−.4056 −03	−.8146 −03
D_K^T	.5077 −08	.2454 −07	.5647 −07	.6974 −07
D_K^E	−.4097 −04	.3678 −03	.3571 −02	.1132 −01
λ^T	−.1723 −01	−.9106 −01	−.1715	−.1872
λ_K	−.1109 +03	−.1707 +03	−.2773 +03	−.3579 +03
λ^E	.9358 +05	.1265 +06	.1594 +06	.1691 +06
λ_R	.1110 +09	.1000 +07	.2050 +05	.2010 +04

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Table 5.7. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 30\,000$ K; $\beta_K = 3\%$			
M	.7899	.7990	.8490	.9622
ρ	.3116 —03	.3176 —02	.3439 —01	.1981
h	.1627 +07	.1582 +07	.1418 +07	.1146 +07
s	.2119 +03	.1865 +03	.1580 +03	.1346 +03
h_c'	.2423 +07	.2425 +07	.2222 +07	.1829 +07
Γ	.2289 —01	.7213 —01	.2222	.4604
η	.7209 —04	.1551 —03	.5215 —03	.1171 —02
λ'	.5529 —01	.7966 —01	.1278	.1877
λ_Σ	.5581 —01	.8308 —01	.1475	.2247
σ	.1586 +03	.2045 +03	.2726 +03	.3149 +03
α	.8526 —02	.1091 —01	.1449 —01	.1665 —01
D_{KK}	—.4678 —04	—.1275 —03	—.3098 —03	—.6160 —03
D_K^T	.3903 —09	—.3066 —09	.6645 —08	.1789 —07
D_K^E	—.1214 —02	—.9092 —03	—.2214 —03	.1015 —02
λ^T	—.4081 —02	—.1600 —01	—.6560 —01	—.1874
λ_K	—.6514 +02	—.2797 +03	—.6597 +03	—.1040 +04
λ^E	.2059 +06	.2859 +06	.4031 +06	.5074 +06
λ_R	—	.3940 +08	.2570 +06	.8670 +04
	$T = 40\,000$ K; $\beta_K = 3\%$			
M	.7850	.7888	.7989	.8294
ρ	.2319 —03	.2341 —02	.2402 —01	.1270
h	.1929 +07	.1894 +07	.1832 +07	.1705 +07
s	.2206 +03	.1954 +03	.1700 +03	.1508 +03
h_c'	.2735 +07	.2784 +07	.2753 +07	.2623 +07
Γ	.1305 —01	.4099 —01	.1292	.2850
η	.1096 —03	.1651 —03	.3270 —03	.6963 —03
λ'	.9618 —01	.1312	.1937	.2780
λ_Σ	.9635 —01	.1317	.1971	.3075
σ	.2149 +03	.2727 +03	.3625 +03	.4530 +03
α	.1474 —01	.1473 —01	.1946 —01	.2420 —01
D_{KK}	—.4476 —04	—.9463 —04	—.2370 —03	—.5436 —03
D_K^T	.1202 —08	.1429 —08	.2742 —09	.8415 —09
D_K^E	—.2179 —02	—.2530 —02	—.2857 —02	—.2160 —02
λ^T	—.4797 —02	—.5822 —02	—.2583 —01	—.8444 —01
λ_K	.8450 +02	—.6853 +02	—.4626 +03	—.1263 +04
λ^E	.3618 +06	.4872 +06	.6822 +06	.8932 +06
λ_R	—	.4090 +09	.3070 +07	.9190 +05

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Table 5.7. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 4000$ K; $\beta_K = 10\%$			
M	.3610 +01	.4650 +01	.5345 +01	.5593 +01
ρ	.1065 −01	.1371	.1576 +01	.8247 +01
h	.2489 +04	−.2601 +05	−.3859 +05	−.4192 +05
s	.5187 +02	.4008 +02	.3313 +02	.2986 +02
h_c'	−.3811 +04	−.9366 +05	−.1330 +06	−.1435 +06
Γ	.1651	.3343	.6701	.1178 +01
η	.5315 −03	.7229 −03	.8099 −03	.8305 −03
λ′	.7601 −02	.7635 −02	.7205 −02	.6969 −02
λ_Σ	.9950 −01	.8140 −01	.3641 −01	.2069 −01
σ	.4935 +01	.2805 +01	.1302 +01	.7613
α	.2465 −03	.1025 −03	.2525 −04	.8012 −05
D_{KK}	−.6533 −03	−.8088 −03	−.9215 −03	−.9565 −03
D_K^T	.1328 −06	.1072 −06	.2284 −07	−.1002 −07
D_K^E	.4463 −02	.2921 −02	.1477 −02	.9991 −03
λ^T	−.9603 −01	−.8853 −01	−.3810 −01	−.1843 −01
λ_K	.1330 +02	.8445 +02	.1265 +03	.1393 +03
λ^E	.1518 +04	.7263 +03	.2671 +03	.1215 +03
λ_R	.6990 +05	.1560 +04	.5630 +02	.5240 +01
	$T = 5\,000$ K; $\beta_K = 10\%$			
M	.2994 +01	.3430 +01	.4456 +01	.5092 +01
ρ	.7070 −02	.8100 −01	.1052 +01	.6012 +01
h	.3611 +05	.1636 +05	−.1435 +05	−.2676 +05
s	.5955 +02	.4954 +02	.3849 +02	.3321 +02
h_c'	.9084 +05	.3744 +05	−.5937 +05	−.9914 +05
Γ	.1872	.4074	.8725	.1533 +01
η	.4193 −03	.5915 −03	.8334 −03	.9287 −03
λ′	.9674 −02	.9862 −02	.9864 −02	.9369 −02
λ_Σ	.2312 −01	.7610 −01	.8121 −01	.5053 −01
σ	.1126 +02	.8209 +01	.4589 +01	.2834 +01
α	.6123 −03	.4082 −03	.1650 −03	.6889 −04
D_{KK}	.8687 −03	−.7707 −03	−.9274 −03	−.1041 −02
D_K^T	.9657 −07	.1051 −06	.1093 −06	.5856 −07
D_K^E	.8990 −02	.7873 −02	.5330 −02	.3964 −02
λ^T	−.4236 −01	−.6799 −01	−.8249 −01	−.5131 −01
λ_K	−.5777 +02	−.9064 +01	.7122 +02	.1136 +03
λ^E	.4442 +04	.3685 +04	.1852 +04	.9553 +03
λ_R	.6610 +05	.1440 +04	.5370 +02	.2840 +01

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Table 5.7. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 6000$ K; $\beta_K = 10\%$			
M	.2896 +01	.3030 +01	.3598 +01	.4359 +01
ρ	.5703 −02	.5971 −01	.7089	.4295 +01
h	.4877 +05	.4145 +05	.1743 +05	−.4517 +05
s	.6187 +02	.5417 +02	.4428 +02	.3725 +02
h_c'	.1128 +06	.1062 +06	.3967 +05	−.3004 +05
Γ	.1646	.4092	.9211	.1658 +01
η	.4091 −03	.5172 −03	.7482 −03	.9432 −03
λ'	.1212 −01	.1238 −01	.1253 −01	.1233 −01
λ_Σ	.1412 −01	.2901 −01	.7828 −01	.7862 −01
σ	.1635 +02	.1650 +02	.1060 +02	.7163 +01
α	.8876 −03	.8098 −03	.4478 −03	.2116 −03
D_{KK}	−.1378 −02	−.9933 −03	−.9255 −03	−.1054 −02
D_K^T	.1060 −06	.8317 −07	.1049 −06	.1107 −06
D_K^E	.1273 −01	.1358 −01	.1096 −01	.8869 −02
λ^T	−.6417 −03	−.1787 −01	−.6884 −01	−.7463 −01
λ_K	−.1139 +03	−.6545 +02	−.2668 +01	.5911 +02
λ^E	.7251 +04	.8131 +04	.5906 +04	.3535 +04
λ_R	.1400 +06	.2490 +04	.9400 +02	.1260 +02
	$T = 7000$ K; $\beta_K = 10\%$			
M	.2872 +01	.2926 +01	.3180 +01	.3723 +01
ρ	.4847 −02	.4946 −01	.5379	.3150 +01
h	.5744 +05	.5419 +05	.4144 +05	.2046 +05
s	.6322 +02	.5615 +02	.4800 +02	.4110 +02
h_c'	.1296 +06	.1326 +06	.1077 +06	.4667 +05
Γ	.1286	.3618	.8771	.1605 +01
η	.4507 −03	.5169 −03	.6904 −03	.9039 −03
λ'	.1453 −01	.1521 −01	.1547 −01	.1533 −01
λ_Σ	.1502 −01	.1966 −01	.4685 −01	.7761 −01
σ	.1940 +02	.2151 +02	.1738 +02	.1326 +02
α	.1055 −02	.1152 −02	.8280 −03	.4650 −03
D_{KK}	−.1816 −02	−.1400 −02	−.1066 −02	−.1085 −02
D_K^T	.1002 −06	.9197 −07	.7769 −07	.1060 −06
D_K^E	.1533 −01	.1685 −01	.1733 −01	.1457 −01
λ^T	.7764 −04	−.5193 −02	−.3458 −01	−.6580 −01
λ_K	−.1706 +03	−.1100 +03	−.5413 +02	.1772 +01
λ^E	.9950 +04	.1268 +05	.1186 +05	.8312 +04
λ_R	.5180 +06	.6010 +04	.2200 +03	.1860 +02

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Table 5.7. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 8000$ K; $\beta_K = 10\%$			
M	.2866 +01	.2890 +01	.3017 +01	.3338 +01
ρ	.4230 −02	.4275 −01	.4470	.2474 +01
h	.6515 +05	.6347 +05	.5644 +05	.4170 +05
s	.6424 +02	.5739 +02	.5002 +02	.4394 +02
h_c'	.1482 +06	.1510 +06	.1453 +06	.1092 +06
Γ	.1001	.2999	.7886	.4472 +01
η	.5099 −03	.5524 −03	.6865 −03	.8706 −03
λ'	.1694 −01	.1801 −01	.1880 −01	.1852 −01
λ_Σ	.1713 −01	.1953 −01	.3171 −01	.5894 −01
σ	.2182 +02	.2594 +02	.2467 +02	.1904 +02
α	.1174 −02	.1377 −02	.1203 −02	.7716 −03
D_{KK}	−.2136 −02	−.1826 −02	−.1328 −02	−.1192 −02
D_K^T	.9932 −07	.9394 −07	.7294 −07	.8263 −07
D_K^E	.1711 −01	.2234 −01	.2346 −01	.2036 −01
λ^T	.2245 −03	−.1845 −02	−.1722 −01	−.4385 −01
λ_K	−.2235 +03	−.1568 +03	−.7990 +02	−.4003 +02
λ^E	.1267 +05	.1691 +05	.1854 +05	.1482 +05
λ_R	.1860 +07	.1790 +05	.3800 +03	.3260 +02
	$T = 10\,000$; $\beta_K = 10\%$			
M	.2841 +01	.2867 +01	.2913 +01	.3034 +01
ρ	.3354 −02	.3390 −01	.3455	.1802 +01
h	.8401 +05	.7976 +05	.7641 +05	.6967 +05
s	.6632 +02	.5920 +02	.5226 +02	.4709 +02
h_c'	.2130 +06	.1917 +06	.1907 +06	.1819 +06
Γ	.6903 −01	.2031	.5694	.1162 +01
η	.6409 −03	.6715 −03	.7638 −03	.9053 −03
λ'	.2212 −01	.2368 −01	.2571 −01	.2594 −01
λ_Σ	.2406 −01	.2433 −01	.2885 −01	.3923 −01
σ	.2716 +02	.3139 +02	.3473 +02	.3108 +02
α	.1468 −02	.1676 −02	.1767 −02	.1411 −02
D_{KK}	−.1933 −02	−.2109 −02	−.1993 −02	−.1619 −02
D_K^T	.1829 −06	.1074 −06	.8232 −07	.6860 −07
D_K^E	.1645 −01	.2668 −01	.3316 −01	.3159 −01
λ^T	−.7053 −02	−.9696 −04	−.6626 −02	−.1982 −01
λ_K	−.2265 +03	−.2334 +03	−.1178 +03	−6705 +02
λ^E	.1894 +05	.2543 +05	.3190 +05	.3014 +05
λ_R	.1080 +08	.1180 +06	.1730 +04	.1120 +03

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Table 5.7. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 12\,000$ K; $\beta_K = 10\%$			
M	.2657 +01	.2819 +01	.2876 +01	.2940 +01
ρ	.2618 −02	.2778 −01	.2842	.1455 +01
h	.1364 +06	.1030 +06	.9400 +05	.8927 +05
s	.7102 +02	.6130 +02	.5386 +02	.4888 +02
h_c'	.3961 +06	.2769 +06	.2401 +06	.2380 +06
Γ	.6881 −01	.1615	.4430	.9027
η	.7361 −03	.8053 −03	.8903 −03	.1016 −02
λ′	.2747 −01	.2998 −01	.3267 −01	.3410 −01
λ_Σ	.4546 −01	.3470 −01	.3483 −01	.3972 −01
σ	.4097 +02	.3991 +02	.4208 +02	.4091 +02
α	.2215 −02	.2134 −02	.2150 −02	.1926 −02
D_{KK}	−.6448 −03	−.1837 −02	−.2449 −02	−.2133 −02
D_K^T	.2240 −06	.1865 −06	.1043 −06	.7776 −07
D_K^E	.6307 −02	.2109 −01	.3737 −01	.4053 −01
λ^T	−.1160 −01	−.3781 −01	−.6824 −02	−1393 −01
λ_K	−.8450 +02	−.1921 +03	−.1473 +03	−.5090 +02
λ^E	.2802 +05	.3504 +05	.4501 +05	.4764 +05
λ_R	.1320 +08	.3150 +06	.5890 +04	.3400 +03
	$T = 15\,000$ K; $\beta_K = 10\%$			
M	.2034 +01	.2521 +01	.2771 +01	.2859 +01
ρ	.1611 −02	.1997 −01	.2196	.1134 +01
h	.3461 +06	.1925 +06	.1355 +06	.1207 +06
s	.8639 +02	.6784 +02	.5690 +02	.5120 +02
h_c'	.1034 +07	.5681 +06	.3860 +06	.3347 +06
Γ	.7341 −01	.1647	.3673	.6883
η	.6183 −03	.9262 −03	.1102 −02	.1229 −02
λ′	.3006 −01	.4101 −01	.4657 −01	.4862 −01
λ_Σ	.9611 −01	.7404 −01	.5739 −01	.5302 −01
σ	.6876 +02	.7056 +02	.6411 +02	.5859 +02
α	.3672 −02	.3798 −02	.3342 −02	.2832 −02
D_{KK}	.1754 −03	−.6496 −03	−.1815 −02	−.2409 −02
D_K	.9883 −07	.1657 −06	.1646 −06	.1153 −06
D_K^E	.1126 −02	.6629 −02	.2558 −01	.4167 −01
λ^T	.5159 −01	−.5402 −01	−.4367 −01	−.3495 −01
λ_K	.9577 +02	−.1404 +03	−.1884 +03	−.8642 +02
λ^E	.5077 −05	.6162 −05	.7327 −05	.7902 +05
λ_R	.1250 +08	.3750 +06	.1290 +05	.1090 +04

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Table 5.7. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 20\,000$ K; $\beta_K = 10\%$			
M	.1552 +01	.1792 +01	.2288 +01	.2571 +01
ρ	.9221 −03	.1076 −01	.1380	.7746
h	.6599 +06	.5082 +06	.3014 +06	.2214 +06
s	.1050 +03	.8585 +02	.6625 +02	.5688 +02
h_c'	.1996 +07	.1520 +07	.9046 +06	.6639 +06
Γ	.5047 −01	.1465	.3581	.6284
η	.1566 −03	.6034 −03	.1229 −02	.1574 −02
λ'	.2797 −01	.4983 −01	.7771 −01	.9037 −01
λ_Σ	.4382 −01	.1059	.1257	.1174
σ	.1029 +03	.1286 +03	.1388 +03	.1279 +03
α	.5460 −02	.6849 −02	.7371 −02	.6507 −02
D_{KK}	−.1111 −03	−.2582 −03	−.8662 −03	−.1758 −02
D_K^T	.9127 −08	−.4411 −07	−.1011 −06	.1218 −06
D_K^E	.2441 −04	.3196 −03	.6563 −02	.1977 −01
λ^T	−.1084 −01	−.6357 −01	−.1328	−.1504
λ_K	−.2096 +03	−.3119 +03	−.4555 +03	−.4950 +03
λ^E	.9372 +05	.1274 +06	.1646 +06	.1833 +06
λ_R	.1130 +09	.1030 +07	.2070 +05	.1870 +04
	$T = 30\,000$ K; $\beta_K = 10\%$			
M	.1475 +01	.1504 +01	.1605 +01	.1813 +01
ρ	.5820 −03	.5983 −02	.650 −01	.3736
h	.8860 +06	.8410 +06	.7429 +06	.6005 +06
s	.1142 +03	.9986 +02	.8442 +02	.7207 +02
h_c'	.2424 +07	.2426 +07	.2222 +07	.1828 +07
Γ	.2341 −01	.7292 −01	.2230	.4631
η	.7832 −04	.1939 −03	.6174 −03	.1347 −02
λ'	.5167 −01	.7716 −01	.1264	.1860
λ_Σ	.5246 −01	.8111 −01	.1460	.2221
σ	.1529 +03	.2011 +03	.2718 +03	.3149 +03
α	.8488 −02	.1089 −01	.1450 −01	.1666 −01
D_{KK}	−.8818 −04	−.2338 −03	−.5907 −03	−.1191 −02
D_K^T	.1118 −08	.4820 −09	.1231 −07	.3210 −07
D_K^E	−.1801 −02	−.1494 −02	−.1490 −03	.2117 −02
λ^T	−.6861 −02	−.2286 −01	−.5946 −01	−.1659
λ_K	−.5263 +02	−.4619 +03	−.1207 +04	−.1866 +04
λ^E	.1973 +06	.2805 +06	.4026 +06	.5103 +06
λ_R	—	.4070 +08	.2570 +06	.8650 +04

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Table 5.7. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 40000$ K; $\beta_K = 10\%$			
M	.1447 +01	.1466 +01	.1494 +01	.1491 +01
ρ	.4276 −03	.4354 −02	.4497 −01	.2390
h	.1092 +07	.1042 +07	.9914 +06	.9101 +06
s	.1200 +03	.1057 +03	.9162 +02	.8104 +02
h_c'	.2739 +07	.2785 +07	.2753 +07	.2623 +07
Γ	.1367 −01	.4209 −01	.1319	.2887
η	.1038 −03	.1705 −03	.3770 −03	.8537 −03
λ'	.8502 −01	.1212	.1844	.2710
λ_Σ	.8549 −01	.1219 −01	.1886	.2994
σ	.1979 +03	.2596 +03	.3518 +03	.4466 +03
α	.1150 −01	.1462 −01	.1943 −01	.2424 −01
D_{KK}	−.9076 −04	−.1845 −03	−.4445 −03	−.1016 −02
D_K^T	.2320 −08	.2850 −08	.1844 −08	.3471 −08
D_K^E	−.3241 −02	−.3906 −02	−.4624 −02	−.3555 −02
λ^T	−.1092 −01	−.1117 −01	−.3561 −01	−.9626 −01
λ_K	.3863 +03	.1227 +03	−.5774 +03	−.2089 +04
λ^E	.3326 +06	.4635 +06	.6624 +06	.8812 +06
λ_R	—	.4340 +09	.3190 +07	.8300 +05
	$T = 4000$ K; $\beta_K = 50\%$			
M	.1485 +02	.1770 +02	.1989 +02	.2118 +02
ρ	.4385 −01	.5224	.5875 +01	.3137 +02
h	.3673 +04	−.1233 +04	−.3698 +04	−4403 +04
s	.1333 +02	.1093 +02	.9296 +01	.8470 +01
h_c'	.5498 +11	−.8901 +12	−.1314 +13	−.1425 +13
Γ	.2676	.5325	.1200 +01	.2804 +01
η	.2985 −03	.1093 −02	.1178 −02	.1171 −02
λ'	.3911 −02	.3455 −02	.3074 −02	.2958 −02
λ_Σ	.3470 −01	.3110 −01	.1453 −01	.8440 −02
σ	.4726 +01	.2293 +01	.1054 +01	.8138
α	.2325 −03	.8101 −04	.2286 −04	.1084 −04
D_{KK}	−.2678 −02	−.3135 −02	−.3410 −02	−.3478 −02
D_K^T	.4212 −07	.3089 −07	.1704 −08	.7428 −08
D_K^E	.7816 −03	.4948 −03	.2715 −03	.2592 −03
λ^T	−.3465 −01	−.3420 −01	−.1521 −01	−.7787 −02
λ_K	.4486 +02	.3244 +03	.4679 +03	.5068 +03
λ^E	.1811 +04	.1053 +04	.4965 +03	.3693 +03
λ_R	.9130 +04	.2200 +03	.7450 +01	.6530 +00

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Table 5.7. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 5000$ K; $\beta_K = 50\%$			
M	.1269 +02	.1430 +02	.1731 +02	.1953 +02
ρ	.3016 —01	.3391	.4109 +01	.2334 +02
h	.1088 +05	.6725 +04	.1436 +04	—.9488 +03
s	.1496 +02	.1271 +02	.1043 +02	.9234 +01
h_c'	.1079 +06	.4876 +05	—5277 +05	—.9539 +05
Γ	.3332	.6834	.1518 +01	.3195 +01
η	.6566 —03	.9629 —03	.1109 —02	.1251 —02
λ'	.5744 —02	.5539 —02	.4728 —02	.4275 —02
λ_Σ	.9629 —02	.2599 —01	.2978 —01	.1949 —01
σ	.1311 +02	.8387 +01	.4325 +01	.3168 +01
α	.7171 —03	.4132 —03	.1529 —03	.8222 —04
D_{KK}	—.3200 —02	—.3145 —02	—.3641 —02	—.3930 —02
D_K^T	.4469 —07	.3392 —07	.3200 —07	.1760 —07
D_K^E	.1626 —02	.1493 —02	.1044 —02	.9827 —03
λ^T	—.7172 —02	—.2571 —01	—.3163 —01	—.2079 —01
λ_K	—.2287 +03	—.5297 +02	.2730 +03	.4294 +03
λ^E	.4891 +04	.4418 +04	.2651 +04	.1941 +04
λ_R	.6390 +04	.2660 +03	.1020 +02	.1040 +01
	$T = 6000$ K; $\beta_K = 50\%$			
M	.1148 +02	.1278 +02	.1478 +02	.1722 +02
ρ	.2289 —01	.2547	.2943 +01	.1727 +02
h	.1691 +05	.1253 +05	.7789 +04	.3864 +04
s	.1606 +02	.1377 +02	.1169 +02	.1011 +02
h_c'	.1382 +06	.1236 +06	.5221 +05	—.2092 +05
Γ	.3264	.7347	.1629 +01	.3218 +01
η	.4580 —03	.7826 —03	.1102 —02	.1238 —02
λ'	.7965 —02	.8143 —02	.7425 —02	.6563 —02
λ_Σ	.8701 —02	.1270 —01	.2732 —01	.2869 —01
σ	.2282 +02	.1946 +02	.1246 +02	.9508 +01
α	.1234 —02	.9896 —03	.4688 —03	.1868 —03
D_{KK}	—.4580 —02	—.3740 —02	—.3764 —02	—.4165 —02
D_K^T	.7544—07	.3734 —07	.3336 —07	.1510 —07
D_K^E	.2467 —02	.2720 —02	.2299 —02	.2176 —02
λ^T	—.1976 —02	—.1195 —01	—.2737 —01	—.2952 —01
λ_K	—.3913 +03	—.2607 +03	—.2758 +02	.2324 +03
λ^E	.8391 +04	.9750 +04	.7661 +04	.5730 +04
λ_R	.9260 +04	.3800 +03	.2020 +02	.2830 +01

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Table 5.7. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 7000$ K; $\beta_K = 50\%$			
M	.1077 +02	.1187 +02	.1333 +02	.1519 +02
ρ	.1845 −01	.2043	.2295 +01	.1317 +02
h	.2174 +05	.1736 +05	.1302 +05	.9098 +04
s	.1680 +02	.1451 +02	.1240 +02	.1090 +02
h_c'	.1475 +06	.1566 +06	.1243 +06	.6102 +05
Γ	.2749	.6989	.1604 +01	.3042 +01
η	.3917 −03	.6410 −03	.9967 −03	.1187 −02
λ'	.1039 −01	.1116 −01	.1101 −01	.9890 −02
λ_Σ	.1063 −01	.1242 −01	.1944 −01	.2833 −01
σ	.3015 +02	.3103 +02	.2278 +02	.1657 +02
α	.1626 −02	.1657 −02	.1010 −02	.5382 −03
D_{KK}	−.6294 −02	−.4857 −02	−.4222 −02	−.4396 −02
D_K^T	.9241 −07	.5442 −07	.3016 −07	.3458 −07
D_K^E	.3151 −02	.3946 −02	.3798 −02	.3641 −02
λ^T	−.3735 −03	.8268 −02	−.1955 −01	−.2774 −01
λ_K	−.5959 +03	−.3788 +03	−.2105 +03	−.1093 +02
λ^E	.1193 +05	.1591 +05	.1534 +05	.1231 +02
λ_R	.2780 +05	.7150 +03	.3670 +02	.4800 +01
	$T = 8000$ K; $\beta_K = 50\%$			
M	.1048 +02	.1123 +02	.1250 +02	.1386 +02
ρ	.1570 −01	.1700	.1898 +01	.1058 +01
h	.2504 +05	.2159 +05	.1717 +05	.1370 +05
s	.1725 +02	.1508 +02	.1295 +02	.1153 +02
h_c'	.1572 +06	.1747 +06	.1657 +06	.1265 +06
Γ	.2203	.6165	.1497 +01	.2794 +01
η	.3985 −03	.5680 −03	.9172 −03	.1148 −02
λ'	.1268 −01	.1426 −01	.1519 −01	.1412 −01
λ_Σ	.1277 −01	.1475 −01	.1843 −01	.2487 −01
σ	.3550 +02	.4201 +02	.3623 +02	.2904 +02
α	.1905 −02	.2263 −02	.1718 −02	.9426 −03
D_{KK}	−.7847 −02	−.6280 −02	−.5008 −02	−.4805 −02
D_K^T	.1046 −06	.6807 −07	.3483 −07	.2969 −07
D_K^E	.3661 −02	.4972 −02	.5366 −02	.5151 −02
λ^T	−.9148 −01	−.5557 −02	−.1671 −01	−.2353 −01
λ_K	−.8182 +03	−.5103 +03	−.2792 +03	−.1307 +03
λ^E	.1546 +05	.2200 +05	.2462 +05	.2140 +05
R	.9050 +05	.1730 +04	.6300 +02	.8420 +01

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Table 5.7. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 10\,000$ K; $\beta_K = 50\%$			
M	.1032 +02	.1061 +02	.1151 +02	.1247 +02
ρ	.1230 —01	.1284	.1410 +01	.7694 +01
h	.3000 +05	.2807 +05	.2404 +05	.2077 +05
s	.1780 +02	.1580 +02	.1372 +02	.1232 +02
h_c'	.1942 +06	.2018 +06	.2142 +06	.2032 +06
Γ	.1443	.4391	.1190 +01	.2272 +01
η	.4754 —03	.5647 —03	.8433 —03	.1122 —02
λ'	.1711 —01	.2029 —01	.2437 —01	.2497 —02
λ_Σ	.1723 —01	.2044 —01	.2514 —01	.2809 —01
σ	.4401 +02	.5782 +02	.6144 +02	.5307 +02
α	.2361 —02	.3124 —02	.3179 —02	.2221 —02
D_{KK}	—.1012 —01	—.9227 —02	—.7206 —02	—.6230 —02
D_K^T	.1213 —06	.9007 —07	.5006 —07	.3155 —07
D_K^E	.4509 —02	.6624 —02	.8299 —02	.8356 —02
λ^T	—.4325 —03	—.2373 —03	—.1376 —01	—.2178 —01
λ_K	—.1243 +04	—.8212 +03	—.2723 +03	—.7988 +02
λ^E	.2328 +05	.3411 +05	.4535 +05	.4560 +05
λ_R	.9010 +06	.1190 +05	.2540 +03	.2590 +02
	$T = 12\,000$ K; $\beta_K = 50\%$			
M	.1009 +02	.1039 +02	.1096 +02	.1174 +02
ρ	000 —01	.1042	.1120 +01	.6065 +01
h	[illegible] +05	.3342 +05	.2990 +05	.2664 +05
s	.1845 +02	.1629 +02	.1425 +02	.1284 +02
h_c'	.3180 +06	.2460 +06	.2526 +06	.2585 +06
Γ	.1034	.3153	.9187	.1810 +01
η	.5583 —03	.6396 —03	.8622 —03	.1146 —02
λ'	.2142 —01	.2622 —01	.3380 —01	.3758 —01
λ_Σ	.2332 —01	.2666 —01	.3401 —01	.3890 —01
σ	.5271 +02	.6926 +02	.8324 +02	.7794 +02
α	.2825 —02	.3730 —02	.4408 —02	.3572 —02
D_{KK}	—.9402 —02	—.1140 —01	—.1085 —01	—.8141 —02
D_K^T	.1606 —06	.1127 —06	.6656 —07	.4106 —07
D_K^E	.4411 —02	.7839 —02	.1094 —01	.1161 —01
λ^T	—.5901 —02	—.9994 —03	—.1078 —01	—.2181 —01
λ_K	—.1250 +04	—.1072 +04	—.1680 +03	.2955 +03
λ^E	.3263 +05	.4733 +05	.6781 +05	.7488 +05
λ_R	.3400 +07	.6310 +05	.9020 +03	.6740 +02

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Table 5.7. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 15\,000$ K; $\beta_K = 50\%$			
M	.8515 +01	.9850 +01	.1049 +02	.1106 +02
ρ	.6757 −02	.7881 −01	.8543	.4570 +01
h	.7288 +05	.4712 +05	.3869 +05	.3479 +05
s	.2105 +02	.1729 +02	.1489 +02	.1044 +02
h_c'	.1009 +07	.4933 +06	.3407 +06	.3283 +06
Γ	.7933 −01	.2171	.6328	.1306 +01
η	.4933 −03	.7529 −03	.9885 −03	.1275 −02
λ'	.2436 −01	.3510 −01	.4786 −01	.5706 −01
λ_Σ	.4264 −01	.4183 −01	.4983 −01	.5801 −01
σ	.7679 +02	.8746 +02	.1085 +03	.1113 +03
α	.3825 −02	.4692 −02	.5774 −02	.5516 −02
D_{KK}	−.2430 −02	−.8621 −02	−.1246 −01	−.1131 −01
D_K^T	.1175 −06	.1532 −06	.1004 −06	.6107 −07
D_K^E	.1364 −02	.5902 −02	.1290 −01	.1548 −01
λ^T	−.5448 −01	−.5284 −02	−.1183 −01	−.2314 −01
λ_K	−.4809 +03	−.7502 +03	−.1670 +03	.1216 +04
λ^E	.5258 +05	.7164 +05	.1044 +06	.1234 +06
λ_R	.1330 +08	.3250 +[illegible]	.4340 +04	.2690 +03
	$T = 20\,000$ K; $\beta_K = 50\%$			
M	.6993 +01	7769 +01	.9300 +01	.1016 +02
ρ	.4156 −02	.4672 −01	.5677	.3143 +01
h	.1292 +06	.1038 +06	.6751 +05	.5343 +05
s	.2438 +02	.2052 +02	.1651 +02	.1449 +02
h_c'	.1996 +07	.1517 +07	.8533 +06	.6022 +06
Γ	.5075 −01	.1517	.4162	.8413
η	.1977 −03	.5619 −03	.1142 −02	.1567 −02
λ'	.2659 −01	.4457 −01	.7228 −01	.9487 −01
λ_Σ	.3815 −01	.7420 −01	.9294 −01	.1054
σ	.1030 +03	.1319 +03	.1593 +03	.1710 +03
α	.5471 −02	.7018 −02	.8473 −02	.8780 −02
D_{KK}	−.6098 −03	−.1967 −02	−.7427 −02	−.1257 −01
D_K^T	.1101 −07	.5379 −07	.1094 −06	.1014 −06
D_K^E	.8050 −04	.1013 −02	.6917 −02	.1554 −01
λ^T	−.3850 −02	−.2575 −01	−.5405 −01	−.5745 −01
λ_K	−.9239 +03	−.1095 +04	−.[illegible]930 +03	.2467 +04
λ^E	.9390 +05	.1297 +06	.1814 +06	.2276 +06
λ_R	.1220 +09	.1860 +07	.2060 +05	.1170 +04

[Continued on following page]

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Table 5.7. [Continued]

Параметр	Давление, ат			
	1	10	100	500
	$T = 30\,000$ K; $\beta_K = 50\%$			
M	.6013 +01	.6493 +01	.7100 +01	.7845 +01
ρ	.2378 —02	.2588 —01	.2882	.1625 +01
h	.2402 +06	.1954 +06	.1556 +06	.1269 +06
s	.2874 +02	.2419 +02	.2010 +02	.1742 +02
h_c'	.2439 +07	.2437 +07	.2220 +07	.1815 +07
Γ	.2655 —01	.7810 —01	.2290	.4830
η	.7275 —04	.2767 —03	.8538 —03	.1672 —02
λ'	.3782 —01	.6437 —01	.1181	.1768
λ_Σ	.3925 —01	.6967 —01	.1349	.2051
σ	.1269 +03	.1820 +03	.2667 +03	.3148 +03
α	.8278 —02	.1080 —01	.1455 —01	.1673 —01
D_{KK}	—.4204 —03	—.1026 —02	—.2930 —02	—.6346 —02
D_K^T	.1608 —08	.3194 —08	.1586 —07	.3787 —07
D_K	—.1299 —02	—.1370 —02	—.9842 —04	.2505 —02
λ^T	—.6385 —01	—.4290 —01	—.5138 —01	—.1096
λ_K	—.1023 +04	—.7243 +03	—.4274 +04	—.5177 +04
λ^E	.1674 +06	.2578 +06	.3982 +06	.5172 +06
λ_R	—	.5130 +08	.3130 +06	.9630 +04
	$T = 40\,000$ K; $\beta_K = 50\%$			
M	.5451 +01	.5819 +01	.6166 +01	.6656 +01
ρ	.1615 —02	.1734 —01	.1868	.1027 +01
h	.3604 +06	.2995 +06	.2588 +06	.2181 +06
s	.3212 +02	.2723 +02	.2306 +02	.2002 +02
h_c'	.9797 +07	.2804 +07	.2761 +07	.2625 +07
Γ	.1691 —01	.4917 —01	.1485	.3130
η	.6619 —04	.1344 —03	.4296 —03	.1204 —02
λ'	.5492 —01	.8601 —01	.1449	.2354
λ_Σ	.5581 —01	.8725 —01	.1514	.2566
σ	.1440 +03	.2075 +03	.3011 +03	.4110 +03
α	.1049 —01	.1409 —01	.1927 —01	.2451 —01
D_{KK}	—.4761 —03	—.9346 —03	—.2134 —02	—.4760 —02
D_K^T	.1928 —08	.2809 —08	.4489 —08	.9250 —08
D_K^E	—.1694 —02	—.2538 —02	—.3490 —02	—.3093 —02
λ^T	.2584 —01	—.2587 —01	.6174 —01	—.1296
λ_K	.4372 +04	.4669 +04	.3073 +04	—.2821 +04
λ^E	.2507 +06	.3832 +06	.5914 +06	.8372 +06
λ_R	—	.6040 +09	.4640 +07	.1010 +06

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Notations in Bibliography

ZhETF	--Journal of Experimental and Theoretical Physics
ZhPMTF	--Journal of Applied Mechanics and Engineering Physics
ZhPS	--Journal of Applied Spectroscopy
ZhFKh	--Journal of Physical Chemistry
ZhTF	--Journal of Engineering Physics
DAN SSSR	--Reports of the USSR Academy of Sciences
TVT	--Thermophysics of High Temperatures
UFN	--Advances of the Physical Sciences
TMF	--Theoretical and Mathematical Physics
Trudy MAI	--Proceedings of the Moscow Aviation Institute
Trudy FIAN	--Proceedings of the Physics Institute, USSR Academy of Sciences
Preprint IPM	--Preprint of Institute of Applied Mathematics
KhFTI	--Khar'kov Physicotechnical Institute
MZhG	--Mechanics of Fluids and Gases
JQSRT	--Journal of Quantum Spectroscopy and Radiative Transfer
Phys. Rev.	--The Physical Review
Rev. Mod. Phys.	--Reviews of Modern Physics

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