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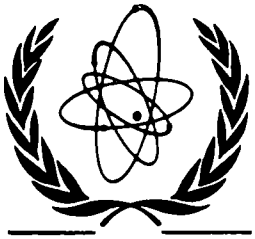

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Moscow, 1975

Key words: tokamak reactor
first wall
sputtering
impurities
materials
plasma radiation

INTRODUCTION

The first wall and the limiter are the critical points in the construction of large tokamak reactors.

We shall briefly enumerate the parameters of the T-20 device that are most important from the point of view of choosing a material for the first wall, and also the most important assumptions concerning the behaviour of the plasma in the device. These parameters and assumptions form the basis of the discussion that follows.

1. As the T-20 is a demonstration reactor intended for research on the behaviour of a deuterium-tritium plasma, it is quite unnecessary to achieve a balance between the extent of plasma losses and the plasma heating by α-particles originating from a thermonuclear reaction; in other words, supplementary methods of heating the plasma are permissible for sustaining the energy balance throughout the discharge pulse.

2. The preheating should increase in the discharge process as a result of constant penetration of impurities and of the increase in the power of radiation from the column. Since the extent of supplementary preheating is limited, the useful discharge period, i.e. the lifetime of the high-temperature (~ 10 keV) plasma, is also limited in the T-20. If the extent of heating is assumed to be equal to the extent of plasma losses (stationary in the case of hydrogen), the useful discharge period is limited by the moment when the radiation due to impurities becomes equal to the energy release with the α-particles, i.e. $30 \times 10^6 (I-\alpha_{cr}Z)^2$ W, where α_{cr} is the proportion of impurities with charge Z in relation to the electrons.

3. As regards the impurities, it is assumed that they all accumulate during the discharge process. Some conflicting views on this subject are discussed in Section II.

4. During the useful discharge period of the T-20 a plasma column with the following parameters must be produced:

(a) $R = 5$ m, $a = 2$ m, $V = 4 \times 10^8$ cm^3, $S = 4 \times 10^6$ cm^2, $I = 6$ mA,
$\beta_y = \dfrac{8\pi nK(T_e + T_i)}{H\varphi^2} = 1$, current lifetime = 20 s.
$n_e = 3.8 \times 10^{13}$ cm^{-3}, $T_i = 10$ keV (the distributions of $n_e(r)$, $T_i(r)$, and $T_e(r)$ are assumed to be parabolic);

(b) Maximum neutron load on wall 10^{13} n/cm^2 · s, maximum full power released with α-particles 30 MW;

(c) Plasma losses with heat conductivity and diffusion 50 MW (energy lifetime of plasma 2 s).

5. The following model of plasma losses is assumed:

(a) The main channel of energy losses to the limiter or wall is anomalous electron heat conductivity;

(b) Near the wall or limiter $n_e \sim 10^{13}$ cm^{-3}, $T_e \sim 100$ eV;

(c) The diffusion lifetime of the particles is 5–6 times longer than the energy lifetime, i.e. about 10 s;

(d) The maximum useful pulse length of the T-20 is 20 s.

6. Maintenance of the material and energy balance of the plasma, i.e. constancy of T and n_e over the entire useful period is assumed to be achieved by the joint action of neutral injectors at 80, 160 keV and HF-heating.

7. The operating schedule comprises:

(a) 1 s - current rise;

(b) 4 s - plasma heating and rise of n_e to a quasi-steady-state value;

(c) 20 s - plateau stage;

(d) 5 s - stopping of current.

8. The energy cycle includes heating for four seconds with fast neutrals, the power of injection being ~ 50 MW. This power is then reduced to 20 MW through the addition of 30-MW heating by α-particles. Subsequently the heating power is increased again to 50 MW to compensate for the radiation losses of the plasma.

9. The capacity of the device is 10^3 pulses in the first series of experiments and 10^5 in the second series. The rest of this paper deals only with the first series.

I. MODEL OF PLASMA INTERACTION WITH THE WALL AND PENETRATION OF IMPURITIES

The objective is to determine the time required for penetration of the plasma by the critical quantity of material from the wall or the gases sorbed on it that will give rise to radiation losses equal to the power released

with the α-particles. It may be expected that impurities will enter the discharge by several paths, in particular as a result of:

(a) Sputtering of the wall material induced by fast ions and neutrals (sputtering coefficient $S = 10^{-1}$–10^{-3} at/ion);

(b) Oxygen and carbon desorption from electron impact ($K = 10^{-4}$–10^{-7} mol/el);

(c) Gas desorption under the action of soft X-rays and ulta-violet light;

(d) Peeling of the surface as a result of the blistering effect of helium;

(e) Sputtering due to neutron action;

(f) Vaporization of the wall by local heating.

1. If we consider only the series with 10^3 pulses (in the 10^5 pulse series questions of wall damage will be of interest in themselves), the blistering effect can apparently be ignored, as the total dose of irradiation with helium should not exceed 10^{16}–10^{17} cm^{-2} in this series, whereas peeling is observed with the blistering effect at over 5×10^{17} cm^{-2}. Moreover, neutron sputtering may be ignored if it does not display anomalous behaviour.

Finally, we have excluded local heating effects and suggested that efficient limiters should be used.

Thus, we shall be discussing effects connected only with wall sputtering induced by fast neutrals and with desorption.

2. It has been shown by direct counting that the energy spectrum of fast neutrals escaping from a plasma of the T-20 type ($n_{e\,lim} \sim 10^{13}$ cm^{-3}, $\frac{dT_i}{dr}_{lim}$ = 200 eV/cm) approximates closely to a Maxwellian distribution with T = 1 keV, and the total flux is about $\frac{N_i}{\tau_p \cdot 1.5} = 10^{21}$ s^{-1} (N_i is the total number of ions in the column, τ_p is their diffusion lifetime). Depending on the design of the chamber, they may escape in a non-uniform manner but the total number of wall atoms undergoing sputtering during time t must be $\sim \frac{N_i \bar{S}}{\tau_p} t$, where $\bar{S}$ is the value of the sputtering coefficient averaged over a Maxwellian distribution of the neutral flux. The calculation of $\bar{S}$ for deuterium and tritium is described in Annex 1.

3. Assuming that impurities spread parabolically in the column, and using the results of Gervids and Kogan (Ref. [1] of Annex 2), it is possible to evaluate, for the T-20 device, the critical quantity of impurities α_{cr} as a function of Z. In Fig. 1 $\alpha_{cr}(Z)$ is denoted by a broken line.

Next, knowing $\bar{S}(Z)$, the useful pulse length t_o can be determined, i.e. the time t at which the power of radiation is equal to the power of energy release with α-particles:

$$30 \cdot 10^6 (1 - \alpha_{cr} Z)^2 = Q_z \bar{n}_e^2 V \alpha_{cr},$$

$$\alpha_{cr} = \frac{\bar{S}}{1.5} \cdot \frac{t_o}{\tau_p},$$

Q_z is the specific power of radiation of one impurity atom.

4. The corresponding points t_o/τ_p for various materials are shown in Fig. 1. Clearly, the most promising materials are graphite, aluminium, titanium and tungsten. Molybdenum and steel, it would appear, are not very suitable for the first wall.

5. The calculation for electron desorption was performed in the same way. It was assumed that the entire heat flow (50 MW) is transmitted to the first wall (limiter) by electrons with T_e = 100 eV. From this, their flux q and the quantity of desorbed gas kq were calculated. In the interest of determinacy, oxygen was chosen as the gas. In Fig. 2 the function $t_o(Z,K)$ is plotted for the particular case in which τ_p = 10 s. It will be seen that for K = 10^{-4}–10^{-5} mol/el, t_o is reduced to 1–5 s, and the difference between materials practically disappears.

6. In the assumed model the electrons transmit their energy to the limiter or the part of the chamber that is performing the functions of a limiter. Clearly, this part of the construction calls for consideration of the possibility of a special purification by which K can be reduced to 10^{-6}, otherwise there is a danger that the useful period of the discharge will not be more than 2–3 seconds on the T-20.

II. ADDITIONAL REMARKS

There were two uncertainties in connection with our model: first, as regards the behaviour of impurities and, second, as to the nature of the boundary conditions.

1. It may be found that impurities penetrate only partially into the central region of the column. This simplifies the problem. Thus, if only 10% of the impurities penetrate to the centre (case of a divertor with 90% efficiency), the behaviour of t_o will be equivalent to that shown in Fig. 2, but with the vertical scale reduced by a factor of 10. That is to say, at K = 10^{-4} the value will be 8 s for steel and 15 s for titanium. If only light impurities (O,C) are screened, the reduction in Fig. 2 will be of the order of the desorption coefficient K.

2. If the coefficient of secondary electron emission of the limiter proves to be small, a potential difference equal to 3-4 times T_e and having an ion-accelerating effect may occur near its surface. Sputtering of the limiter due to the impact of accelerated helium may in this case make a contribution comparable to that of wall sputtering induced by neutrals, i.e. it may lower t_o by a factor of 2.

3. We have not considered the desorption process due to the action of ultra-violet light and soft X-rays. In the case of a smooth wall this effect is negligible compared to electron desorption. However, in the case of a special chamber construction (honeycomb- or needle-type) with a large effective area, this effect may result in the penetration of impurities from the wall. In designing the chamber it is therefore desirable to avoid surfaces that cannot be cleaned directly by the discharge.

CONCLUSIONS

Summing up, it may be concluded that the material of the first wall of the T-20 device must satisfy at least the following requirements:

(1) It should be such that there is comparatively little sputtering due to the action of fast neutral hydrogen atoms.

In a first approximation preference should be given to materials with a minimal product $\bar{S}Z^2$. The most likely materials are graphite, C, Ti, Al or their compounds (a possible compound that has not been discussed is silicon carbide, which is used for MHD-converter electrodes).

(2) The material of the first wall must permit effective cleaning so that the electron desorption coefficient of surface impurities does not exceed 10^{-5} mol/el for an electron energy T_e = 100 eV.

It should be borne in mind that the first wall will be heated to ~ 600°C in the process of conditioning or operation. At the same time, considerable diffusion of dissolved oxygen or carbon towards the surface can be expected. In this respect it is desirable that the purest materials should be used.

Possibly preference will be given precisely to such materials (e.g. ultra-pure Nb) if the electron desorption coefficient cannot be reduced below 10^{-5} for other materials.

(3) In the first stages of research preceding the construction of the T-20, it is intended to test possible materials for the first wall in the form of screens protecting the wall of the vacuum chamber of operating tokamaks. For this purpose it is desirable to have samples of the materials in sheet form, with a thickness of about 1 mm and a total weight of 100-300 kg.

In the T-20 variant the sheets should have a thickness of 3-5 mm and a total weight of 10-30 t.

(4) In the T-20 variant the first wall must be designed to permit the use of a cooling system. This means that it should be possible to make vacuum welded joints for the coolant supply (e.g. helium).

(5) Brittle materials (graphite, carbides, tungsten) may be used for the vacuum wall lining panels. In constructing such panels the possibility of cooling them must also be taken into account.

(6) Other conditions being equal, preference should be given to the materials with the least neutron activation in fluxes of both fast (14 MeV) and thermal neutrons.

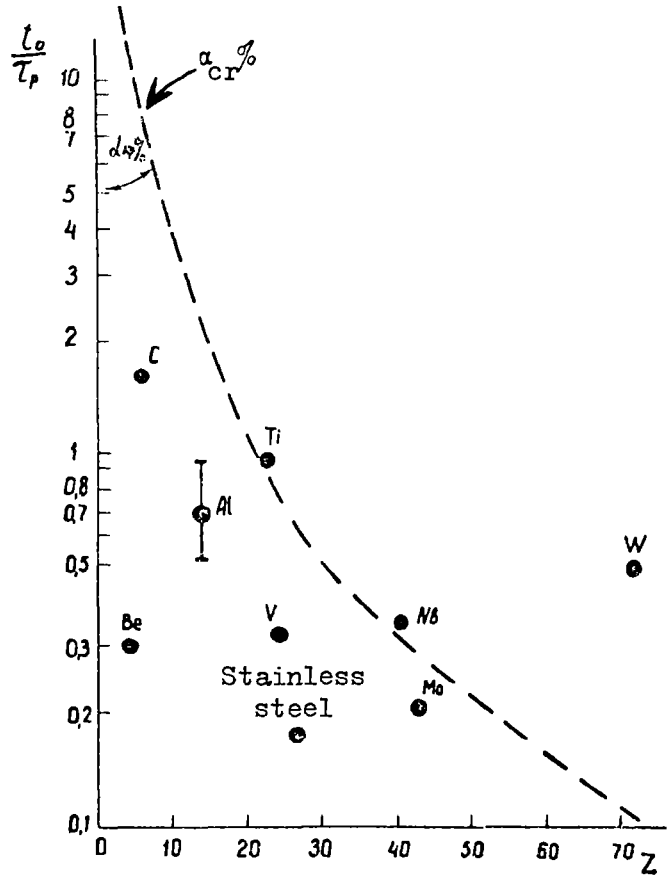
$\frac{l_0}{\tau_p}$
10
8
7
5
4
3
2
1
0,8
0,7
0,5
0,3
0,2
0,1
α_{cr}%
C
Ti
Al
W
Be
V
Nb
Mo
Stainless steel
0
10
20
30
40
50
60
70
Z

Fig. 1

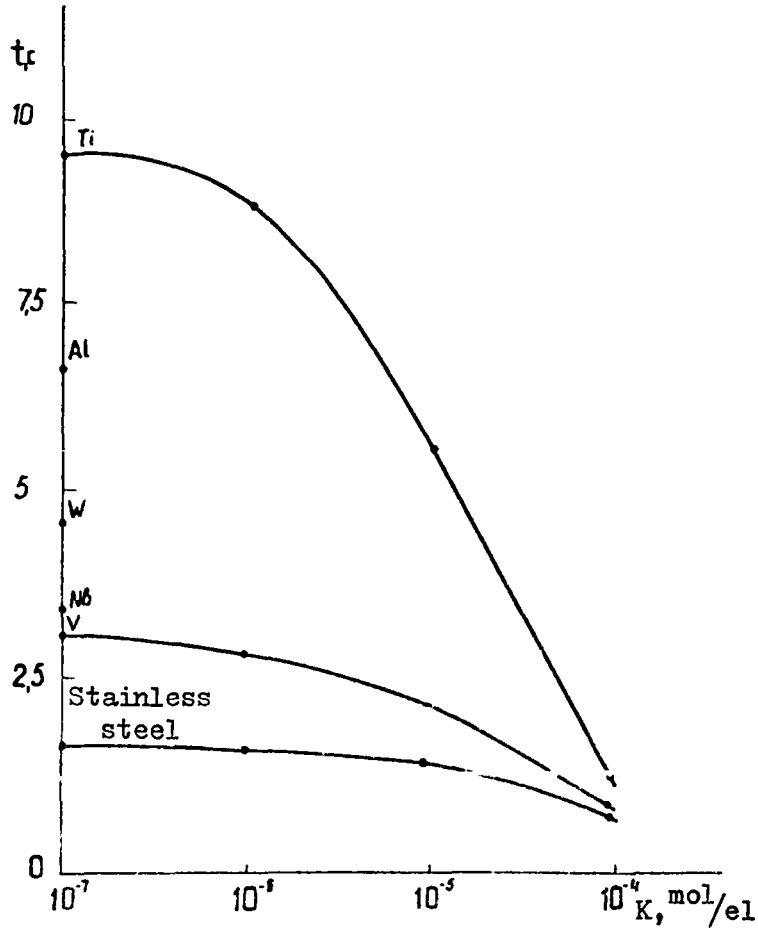
t_r
10
7,5
5
2,5
0
Ti
Al
W
Nb
V
Stainless steel
10^{-7}
10^{-6}
10^{-5}
10^{-4}
K, mol/el

Fig. 2

APPENDIX 1

In many cases it becomes necessary to determine the coefficient S for sputtering of a material induced by ions and at energies for which there are no experimental data. At the same time, the most advanced theory of sputtering [1] gives specific values for the sputtering coefficients but with not very great accuracy (usually to within a factor of 2-3). Dependences on ion energy and mass are described far better by that theory. We are proposing a method of determining the sputtering coefficient using the theoretical dependence on ion energy and mass and the experimental values of the sputtering coefficient for a given material obtained for any other energy or ion.

According to [1] the sputtering coefficient can be represented in the form

$$S = \Lambda E_1 \frac{Mi\,Ma}{(Mi+Ma)^2}\left(Zi^{2/3}+Za^{2/3}\right)^{-1} f(\varepsilon), \qquad (1)$$

where $\varepsilon = \frac{E}{E_1}$ and E is the ion energy,

$$E_1 = \frac{Zi\,Za\,(Zi^{2/3}+Za^{2/3})^{1/2}}{0{,}88\,a_B}\,e^2\,\frac{Mi+Ma}{Ma}. \qquad (2)$$

Figure 3 shows E_1 as a function of the atomic number of the target material, Z, for the ions H^+, D^+, T^+ and He^+. The symbol Λ represents a coefficient determined solely by the properties of the target material. The function $f(\varepsilon)$ for $\frac{Ma}{Mi} \lesssim 1$ does not depend on ion mass, but for light ions, when the ratio $\frac{Ma}{Mi}$ is high, $f(\varepsilon)$ does depend on ion mass. Weissman and Sigmund [2] have calculated the function $f(\varepsilon)$ for H^+, D^+ and He^+ ions. We have used their calculation of the $f(\varepsilon)$ functions, correcting them for $\varepsilon \lesssim 2$ so that they correspond more closely to experimental results (for this purpose we used data given in Refs [2-4]). The $f(\varepsilon)$ functions for H^+, D^+, T^+ and He^+ are shown in Fig. 4. The function $f(\varepsilon)$ for T^+ was obtained by interpolation.

Using formula (1), the $f(\varepsilon)$ functions shown in Fig. 4 and the experimental values of S_{exp} for a given material at any energy for one of the

ions H^+, D^+, T^+ and He^+ [1/], we can determine the coefficient Λ for the given material. Then, using the value of Λ obtained and the $f(\varepsilon)$ function for E_x, the value S_x can be found for any other energy for any of the ions H^+, D^+, T^+ and He^+ [1/].

The table gives the values of the coefficients for the sputtering of various substances induced by H^+, D^+, T^+ and He^+, calculated for E = 1 keV by the method proposed and using the known experimental values S_{exp}. It also gives the values of the mean sputtering coefficient $\bar{S}$ for a particle flux with a Maxwellian energy distribution at a temperature T = 1 keV. $\bar{S} = jS(T)$, where $1 \leq j \leq 15$. For $S \sim E$, $j = 1.5$; for $S \sim \sqrt{E}$, $j = 1.13$; for S = const, j = 1. We assumed that $j = 1.5$ for $\varepsilon < 0.2$ and $j = 1.2$ for $\varepsilon > 0.2$.

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1/ The use of the coefficient S for sputtering induced by heavier ions to determine Λ is possible but it apparently leads to a greater error, as the procedure involves the use of an $f(\varepsilon)$ function calculated (in Ref. [1]) in a different approximation.

Coefficients of sputtering of pure metals induced by H^+, D^+, T^+ and He^+ ions with energies of 1 keV

Metal	Z	Ion	S, at/ion	$\bar{S}$, at/ion	References
Be	4	H^+	$1{,}4.10^{-2}$	$1{,}6.10^{-2}$	
		D^+	$4{,}4.10^{-2}$	$5{,}2.10^{-2}$	
		T^+	$6{,}5.10^{-2}$	$7{,}8.10^{-2}$	
		He^+	27.10^{-2}	32.10^{-2}	[5]
Al	13	H^+	$(1-1{,}8).10^{-2}$	$(1{,}2-2{,}1).10^{-2}$	[6 - 7]
		D^+	$(2{,}7-5).10^{-2}$	$(3{,}2-6).10^{-2}$	
		T^+	$(4{,}4-8).10^{-2}$	$(5{,}3-10).10^{-2}$	
		He^+	$(15-27).10^{-2}$	$(18-32).10^{-2}$	
Ti	22	H^+	$3{,}5.10^{-3}$	$4{,}2.10^{-3}$	[6]
		D^+	10.10^{-3}	$1{,}2.10^{-2}$	
		T^+	$1{,}7.10^{-2}$	2.10^{-2}	
		He^+	$9{,}0.10^{-2}$	0,11	[5]
V	23	H^+	$8{,}3.10^{-3}$	10.10^{-3}	[6]
		D^+	$2{,}3.10^{-2}$	$2{,}7.10^{-2}$	
		T^+	$3{,}9.10^{-2}$	$4{,}7.10^{-2}$	
		He^+	0,10	0,13	[5]
Stainless steel	26	H^+	1.10^{-2}	$1{,}2.10^{-2}$	[8]
		D^+	$3{,}3.10^{-2}$	4.10^{-2}	
		T^+	$5{,}7.10^{-2}$	7.10^{-2}	
		He^+	0,14	0,16	[5]
Nb	41	H^+	$2{,}4.10^{-3}$	3.10^{-3}	
		D^+	$7{,}8.10^{-3}$	$9{,}3.10^{-3}$	[9]
		T^+	$1{,}5.10^{-2}$	$1{,}7.10^{-2}$	
		He^+	$4{,}4.10^{-2}$	$6{,}7.10^{-2}$	
Mo	42	H^+	$3{,}5.10^{-3}$	$4{,}2.10^{-3}$	[10]
		D^+	1.10^{-2}	$1{,}3.10^{-2}$	
		T^+	$2{,}0.10^{-2}$	3.10^{-2}	
		He^+	$4{,}5.10^{-2}$	$6{,}8.10^{-2}$	[5]
W	74	H^+	$3{,}7.10^{-4}$	$5{,}6.10^{-4}$	[6]
		D^+	$1{,}4.10^{-3}$	$2{,}0.10^{-3}$	
		T^+	$3{,}0.10^{-3}$	$4{,}5.10^{-3}$	
		He^+	$9{,}6.10^{-3}$	$1{,}4.10^{-2}$	

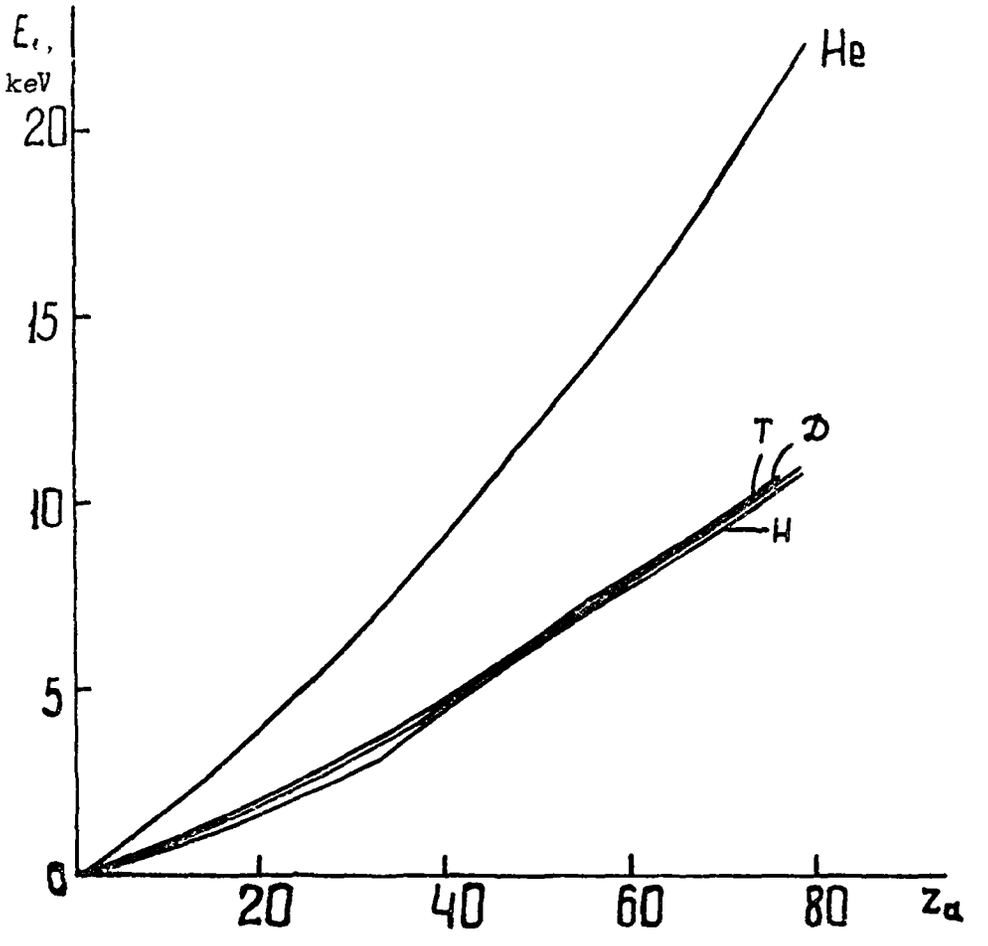
E, keV
20
15
10
5
0
20
40
60
80
Z_a
He
T
D
H

Fig. 3

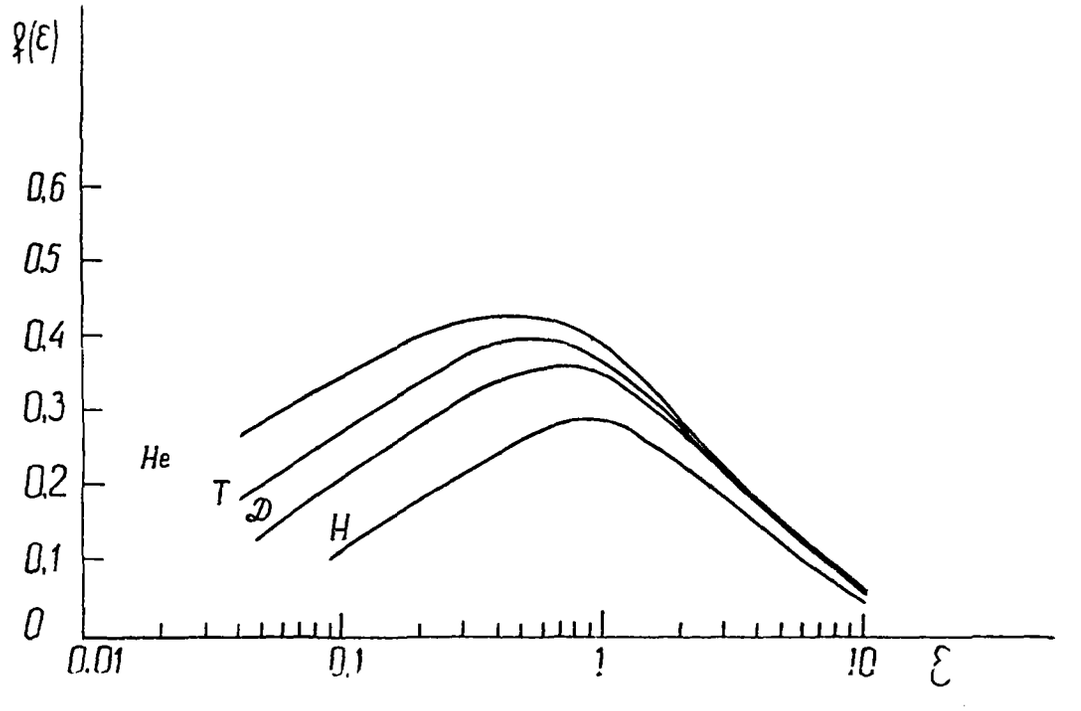
f(ε)
0.6
0.5
0.4
0.3
0.2
0.1
0
0.01
0.1
1
10
ε
He
T
D
H

Fig. 4

APPENDIX 2

Model: The calculations were based on a model of coronal equilibrium for constant and uniform n_e, n_z and T_e (n_e and n_z are the densities of electrons and impurities)[1]. The coronal model itself, as will be seen by comparison (see for example Ref. [2]) with the results of calculations for a more general collisional-radiation model, can be applied satisfactorily in the case of low values of n_e, high T_e and large Z specific for a thermonuclear reactor plasma, but its stationary limit ($t \to \infty$) is attained by satisfying the Lawson condition $n_e \tau \geq 10^{14}$ cm^{-3}·sec. As is well known, for calculation of the radiation losses in the coronal model it is sufficient to know the cross-section of ionization, photorecombination, electron impact excitation and bremsstrahlung.

Cross-sections: At the temperatures in question the nuclei of even the heaviest impurities can contain only a number of electrons $N \leq 10$; thus $Z \geq N$, and interaction with the nucleus is decisive for each of these electrons. Therefore the cross-sections mentioned above can be determined with sufficient accuracy using comparatively simple and universal expressions based on various hydrogen-like approximations. In this process the interaction between electrons is calculated by introducing real ionization or excitation energies into the hydrogen-like analytical structures. It is also clear that it becomes very much easier to take screening in bremsstrahlung into account because $Z \gg N$.

In practice, the ionization cross-sections were calculated by analogy with Lotz's method [3], the rates of photorecombination were selected in Kramers' approximation, due account being taken of the number of free places in the surface shell and of capture at excited levels [4]; the rates of transition excitations with $\Delta n \neq 0$ were taken from Ref. [5] with an additional correction for asymptotic behaviour at Born temperatures; the expressions of Ref. [6] were used for transitions where $\Delta n = 0$. The energies of ionization and excitation were calculated by isoelectron extrapolation similar to that in Ref. [7] from the data of Ref. [8], but with fuller account being taken of relativistic effects than in Ref. [7]. The oscillator strengths were calculated from the tables of Beits and Damgaard [9] with some checking from more accurate data [10].

Radiation losses: Figure 5 shows the results of calculations of the power of radiation losses from bremsstrahlung, recombination and line radiation related to one particle and one electron. The non-monotonic character of

the curves is associated with the passage of helium- and neon-like shells. The slight dependence of the total losses Q_z on T_e can be explained by the influence of components increasing and diminishing with T_e. As regards the line radiation Q_z^{lin} it should be pointed out that the dominant role, mentioned by Hinnov [6], of the transitions with $\Delta n = 0$, and thus the virtual non-dependence of Q_z^{lin} on Z and T_e, no longer occur at the high T_e values under discussion, even for W.

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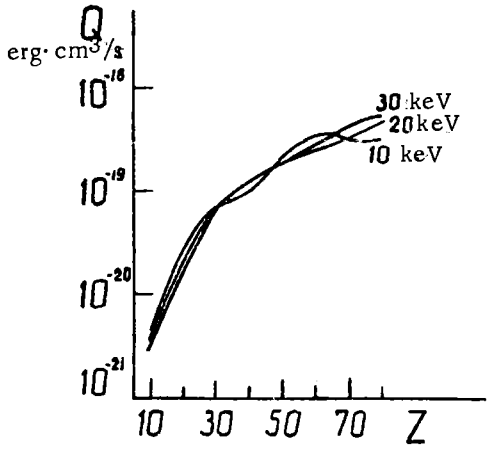

Fig. 5