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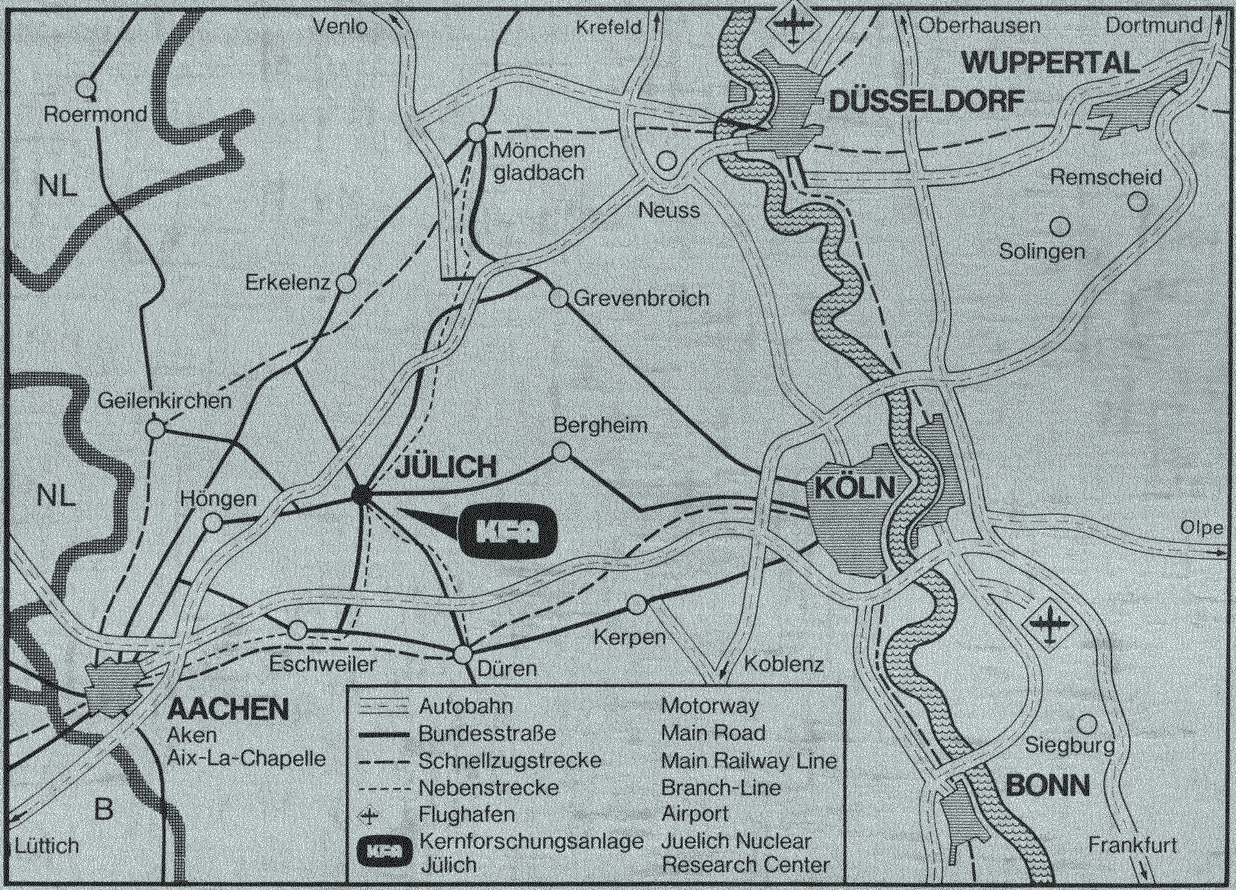

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On a Criterion for Plasma-Wall-Interaction in a Reactor

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Abstract

A criterion is formulated for the permissible degree of plasma-wall-interaction of a thermonuclear plasma. Taking the growth of α-particle concentration as a measure, the criterion is expressed in form of a simple relation between few characteristics such as "relative toxicity" and "energy related material yield". The criterion is applied to the example of sputtering by fuel particles in the presence of a cool plasma mantle showing that high-Z materials like tungsten might become advantageous if the "temperature" of the bombarding particles is in the range between 10 and 25 eV.

Introduction

In a burning thermonuclear plasma, the introduction of non-fuel constituents, so-called impurities, leads essentially to increased radiation losses, additional pressure components, and modification of the overall transport properties, at least the first two of these being generally undesirable (edge radiation cooling excepted). Whilst for impurities of high atomic number Z radiation losses are the dominant disadvantage, it appears that for impurities of very low Z the related increase of the plasma pressure represents an equal if not the dominant difficulty.

The sources of these impurities are the very fusion processes themselves generating alpha-particles (only DT-reactions are considered in the following), and the invasion of non-fuel material from outside the plasma, mainly caused by plasma-wall-interaction processes occurring at the surface of the burning chamber. The energy of the fusion-alphas (3.5 MeV) is eventually carried to the chamber wall being subject to said plasma-wall-interaction processes [1 - 3]. In the following an attempt is made to use the general relation between alpha-particle production and the generation of wall released impurities in order to formulate a criterion on the "permissible" degree of plasma-wall-interaction.

Later on this criterion will be applied to the example of sputtering in the presence of a cold plasma or cold gas mantle; there the introduction of appropriate characteristic factors is intended to separate somewhat the contributions of the different processes occurring within the chain of events.

The idea behind this procedure is that the burning cycle duration of a reactor will be determined by impurity production, transport, and accumulation, disregarding in our treatment other possible causes like instabilities or transformer flux-swing restrictions. When omitting at first the contribution of the wall released impurities, what remains is the temporal development of the alpha particle density as a determinant for the burning cycle duration. In case of zero unloading, the produced alphas accumulate, and the factual point of quench (of the burning cycle) will depend on whether this accumulation occurs substantially in the high-pressure plasma core or, as desired, in the plasma boundary. On the other hand, applying unloading devices [4 - 9] may result in some delay of this point of quench or, in case of sufficient outward diffusion of the alphas, even in the possibility of steady-state operation (as far as the alphas are concerned) [e.g. 8]. From this point of view, the complications connected with the introduction of a specific alpha exhaust device have to be weighed against the expected advantages of prolonged burning cycles.

Coming back now to wall-released impurities and their potential accumulation, our criterion demands that their contribution to the plasma energy balance does not essentially reduce the burning cycle duration as otherwise solely determined by the alpha particle behaviour.

From a practical point of view this means that any further method aimed to act specifically against the generation, invasion or accumulation of wall released impurities has to be applied only so far as the degrading effect of these impurities on the burning conditions becomes small compared to that of the alphas (which may be also affected by this method). Of course, the benefits from any such additional method have to be also weighed - as in the case of the above mentioned alpha exhaust - against the complications connected with its application.

For the derivation of our criterion, we define the quantity γ as a figure of merit for wall impuritiy accumulation. γ is the yield of wall material entering the thermonuclear plasma volume per energy unit which flows from the plasma to the wall; it may be called "energy related material yield".

However, unlike e.g. the coefficient of the photo-electric efficiency, γ does not describe a specific elementary process, but rather the sum of all those processes which contribute to the energy transfer from the plasma to the wall and which result in wall material release. Thus, γ may be written in the form

$$\gamma = \frac{\phi_W}{\phi_E} = \frac{\text{flux of material from the wall into the hot plasma}}{\text{flux of energy from the hot plasma to the wall}} \qquad (1)$$

Using for the further treatment within the frame of this introduction a somewhat heuristic and stepwise approach, we assume initially that the required condition be just fulfilled if for each fusion generated alpha-particle not more than one wall particle be released, that this wall particle be immediately transferred to the hot plasma core and that in the course of their further history both types of particles show equal transport behaviour. From these assumptions it follows immediately that

$$\gamma \leq \frac{1}{Q_\alpha} \qquad (2)$$

where Q_α = 3,5 MeV is the energy of the born fusion alpha. By taking Q_α instead of the total reaction energy $Q = 5\, Q_\alpha$ it is assumed that any contribution of the neutrons to γ may be neglected. Although present knowledge on neutron-sputtering [10, 11] does not contradict this assumption, it does not yet yield clear-cut proof of its justification either.

Two modifications of equ. (2) are now introduced in order to take care of the differences between the alphas and the wall particles.

The first modification concerns the fact that the various impurity species differ in their affecting the burning conditions. This property may be characterized by a factor χ called "relative toxicity" caused by a specific impurity species and normalized to that of the alphas.

Since generally more alphas than wall particles can be tolerated, χ is usually large compared to unity. The determination of χ will be discussed in the next section. Applying χ to equ. (2) yields

$$\gamma \leq \frac{1}{Q_\alpha \chi} \qquad (2a)$$

The second modification concerns the differences in origin and transport behaviour between alphas and wall particles, including mutual interactions. It is postulated that the total complex of these transport phenomena can be comparatively comprised by a single "transport-factor" K such that equ. (2a) is transformed into

$$\gamma \leq \frac{1}{Q_\alpha \chi K} \qquad (2b)$$

The actual value of K for a given situation depends on various characteristics like transport-regimes, coefficient for screening action etc. (see page 7) which may be subject of deliberate experimental influence.

Any attempts to fulfill the above criterion imply that one has to force the energy transport towards the wall and/or the wall-particle flow back into the hot plasma through such channels which keep the resulting "energy related material yield" below the limit given in equ. (2b).

Derivation of the Criterion

As a rough measure for the growth of the average α-particle density the quantity

$$\frac{d\bar{n}_\alpha}{dt} = K_\alpha \bar{R} \qquad (3)$$

is taken. The term K_α may be called α-particle transport factor, and we make the simplifying assumption that it comprises any temporal changes in α-particle density caused by the α-particle fluxes from and into the thermonuclear plasma core according to the relevant transport processes such as drift-motion, diffusion, recycling etc. $\bar{R}$ is the average thermonuclear reaction rate for $n_D = n_T = \frac{n_i}{2}$

$$\bar{R} = \frac{1}{4}\overline{n_i^2 \langle \sigma v \rangle} = \frac{\bar{P}_\alpha}{Q_\alpha} \tag{4}$$

$\bar{P}_\alpha$ = average thermonuclear power density transmitted to the born alphas. For obtaining an order of magnitude impression of the alpha-particle production the quantity R/n_i which is denoted as dc_α/dt is plotted in Fig. 1. For further treatment, equ. (3) is rewritten in the form

$$\frac{d\bar{n}_\alpha}{dt} = \frac{K_\alpha \bar{P}_\alpha}{Q_\alpha} \tag{5}$$

Since ϕ_E, the total energy flux hitting the wall and caused by the energy of the alpha-particles, as defined in equ. (1), can be described by

$$\phi_E = \bar{P}_\alpha V \tag{6}$$

where V is the volume of the hot plasma core, equ. (5) can be transformed into

$$\frac{d\bar{n}_\alpha}{dt} = \frac{K_\alpha \phi_E}{Q_\alpha V} \tag{5a}$$

In the next step we derive an equivalent equation for $d\bar{n}_W/dt$, the average density of wall material in the hot plasma core region. For this purpose we use ϕ_W, the flux of released wall material entering the hot plasma core for the first time (as defined in equ. (1)); ϕ_W is a source term equivalent to $\bar{R}V$ in the case of α-particles. Furthermore, K_W be a transport factor equivalent to K_α, comprising any further wall particle transfer to and from this region. This gives

$$\frac{d\bar{n}_W}{dt} = \frac{K_W \phi_W}{V} \tag{7}$$

Fig. 2 shows a schematic flux diagram explaining among others (see later) the quantities K_α, K_W, ϕ_E and ϕ_W.

The criterion as already presented in the introduction (equ. (2b)) is now defined as

$$\frac{d\bar{n}_\alpha}{dt} \geq \chi \frac{d\bar{n}_W}{dt} \qquad (8)$$

with χ, the "relative toxicity", comparing the degrading effects (on the burning condition) of the wall impurity density to that of the alpha density.

In order to obtain a quantitative estimate of $\chi(Z)$, with Z being the atomic number of the respective impurity species, in a first step the radiation losses are compared for the different materials and normalized to those of helium (alphas), assuming constant electron density for calculating the radiation losses. χ is related to the critical impurity concentration, which has been used e.g. to act as a figure of merit for normalizing the sputtering yields for potential wall materials [12]. Several papers dealt with a derivation of radiation losses from plasma impurities [e.g. 13 - 16], the values of χ used in table I (next section) for kT = 10 keV are based on [16] . Deriving an analytic approximation for χ from the values listed in [16] leads to equ. (9) which in its trend agrees satisfactorily with a similar formula [17] based on the interpolation of several different calculations

$$\chi \approx 5 \cdot 10^{-2} \cdot Z^{2,9} \qquad (9)$$

However, this expression is restricted to small concentrations, Z $\geq$ 6, and kT = 10 keV.

In a second step, also the reduction of the nuclear power density for constant total plasma pressure is taken into account. The resulting

$$\chi^* = \frac{\frac{4\chi - 1}{A} + Z^* + 1}{3\left(1 + \frac{1}{A}\right)} \qquad (9a)$$

is derived in the Appendix. (A = ratio of thermonuclear to bremsstrahlung power density in a pure DT-plasma, Z^* = average charge of a wall particle in the plasma.) $\chi^*(Z)$ is always smaller than $\chi(Z)$ such as to approach for high-Z values $\chi^* \approx 0.1\chi$, as is shown in Fig. 4.

Combining now equs. (5a) and (7) with condition (8), using $\gamma = \Phi_W/\Phi_E$ according to the definition given in equ. (1), and taking $K = K_W/K_\alpha$ as a general comparative transport factor supposed to normalize wall-particle transport behaviour to alpha transport behaviour, we obtain

$$\gamma \leq \frac{1}{Q_\alpha \cdot K \cdot \chi} \tag{2b}$$

as has been already formulated in the introduction. Inserting equ. (9) into equ. (2b) and taking $Q_\alpha = 0{,}56.10^{-12}$ J yields

$$\gamma \leq 3{,}6 \cdot 10^{13} \cdot K^{-1} \cdot z^{-2{,}9} \quad J^{-1} \tag{10}$$

Taking iron as an example, and deriving χ directly from the values in [16] (see table 1), equ. (10) transforms into

$$\gamma \leq 2{,}8 \cdot 10^{9} \cdot K^{-1} \quad J^{-1} \tag{11}$$

Application Example

In the following, condition (2b) will be applied to an estimate for the case of a cool plasma mantle separating the thermonuclear plasma core from the wall. Within the frame of this example we assume that sputtering by (thermal) fuel ions or atoms is the dominant impurity production process at the wall, disregarding other processes like arcing, self-sputtering, sputtering after sheath-potential acceleration etc. Thus, any contribution of Φ_E leading to an appreciable value of Φ_W be caused by the energy flux Ψ_E of the fuel ions or atoms to the wall such that

$$\Psi_E = f \cdot \Phi_E \tag{12}$$

The fraction f might, depending on the amount of radiated energy, even be small compared to one. Similarly, only a certain fraction y of the wall particle flux Ψ_W sputtered from the wall will contribute to Φ_W, the flux of wall particles entering the plasma core for the first time. Depending on the efficiency of possible shielding processes [e.g. 18, 4 - 7] in the boundary layer, also the fraction y might become small compared to unity

$$\Phi_W = y \cdot \Psi_W \tag{13}$$

Thus the factors f and y belong also to the group of characteristics mentioned in the introduction. Please note that the characterization of wall particle transport by two separate factors, i.e. K and y, although these factors are somewhat similar in nature, is justified by the assumption that the shielding coefficient (1-y) describes the trapping of those wall particles which eventually are carried back (to the wall, limiter, divertor chamber, etc.) before entering the relevant hot plasma region for the first time, whereas K characterizes the transport (normalized to the alpha-transport) from and into this region later on.

Combining now equs. (12) and (13) with equs. (1) and (2b) yields

$$\frac{\Psi_W}{\Psi_E} = \frac{\Phi_W}{f \cdot y \cdot \Phi_E} \leq \frac{1}{f \cdot y \cdot \chi \cdot K Q_\alpha} \qquad (14)$$

As an intermediate step, we express Ψ_E by

$$\Psi_E = \nu \cdot E \qquad (15)$$

where ν is the rate of fuel particles hitting the wall and E is their energy, assuming here a monoenergetic distribution (later in this paper, a Maxwell-distribution will be analyzed). The resulting value of Ψ_W then follows to be

$$\Psi_W = \nu \cdot S(E) \qquad (16)$$

with S(E) being the sputtering yield. Inserting equs. (15) and (16) in equ. (14) yields

$$S(E) \leq \frac{1}{f \cdot y \cdot \chi \cdot K \cdot Q_\alpha} \cdot E \qquad (17)$$

Inserting figures into equ. (17) shows that generally this condition is only fulfilled, either if f and/or y are very small indeed, or if S(E) does only marginally exceed the extremely low sputtering yield expected to exist in the neighbourhood of the so-called "threshold energy" E_o. This fact permits a linearized Ansatz for S(E) around E_o with a $1/\cos\vartheta$-dependence (ϑ = angle of incidence) such that

$$S(E,\vartheta) = \begin{cases} \frac{a}{\cos\vartheta}(E-E_o) & \text{for } E \geq E_o \\ 0 & \text{for } E < E_o \end{cases} \quad (18)$$

In reality, however, the impinging ions or neutrals are not monoenergetic but they assume a complex velocity distribution [19, 20] which may be characterized by a tail of higher energetic particles exceeding E_o. Accordingly, it is supposed that the fuel particles hitting the wall have assumed a semi-isotropic Maxwell-distribution of mean energy kT_b, T_b being determined by the temperature and density field of the boundary region that contributes to wall bombardment (charge-exchange). The assumed thermal distribution characterized by T_b does not deviate too much from the energy distributions as discussed in the literature [19, 20].

The corresponding fluxes Ψ_E and Ψ_W are then obtained to be

$$\Psi_E = A\frac{4\pi}{m^2}n_i\left(\frac{m}{2\pi kT_b}\right)^{3/2}\int_0^\infty\int_0^{\frac{\pi}{2}} E^2 \cdot e^{-\frac{E}{kT_b}} \sin\vartheta\cos\vartheta\, d\vartheta\, dE$$

$$= A\frac{n_i\bar{v}}{4}\, 2kT_b \quad (19)$$

$$\Psi_W = A\frac{4\pi}{m^2}n_i\left(\frac{m}{2\pi kT_b}\right)^{3/2}\int_{E_o}^\infty\int_0^{\frac{\pi}{2}} E\, e^{-\frac{E}{kT_b}} \cdot S(E,\vartheta)\sin\vartheta\cos\vartheta\, d\vartheta\, dE$$

$$= A\,2a\,\frac{n_i\bar{v}}{4}\, e^{-\frac{E_o}{kT_b}}\,(2kT_b + E_o) \quad (20)$$

(A = surface of the wall). Dividing eq. (20) by eq. (19)

$$\frac{\Psi_W}{\Psi_E} = a\, e^{-\frac{E_o}{kT_b}}\left(2 + \frac{E_o}{kT_b}\right) \quad (21)$$

and inserting into equ. (14) yields

$$K f y \leq \frac{e^{\frac{E_0}{kT_b}}}{\chi \cdot Q_\alpha \cdot a \left(2 + \frac{E_0}{kT_b} \right)} = g(T_b)$$

This condition is the equivalent to eq. (2b) for the specific case of wall particle release through sputtering only, caused by the bombardment with ions or neutrals of (semi-isotropic Maxwellian distribution) thermal energy kT_b.

In the following we attempt to discuss this condition for some specific materials by inserting values for χ, a and E_o. Sputtering yields at relatively low energies are still poorly known, thus we confine our consideration to iron, molybdenum and tungsten since for these materials it appears feasible to extract estimates on a and E_o from published data [21, 22, 23].

The corresponding values chosen are listed in table 1 together with the respective χ-values derived directly from [16], assuming bombardment with deuterium ions.

As a tendency, E_o increases with Z, whereas the slope a of the sputtering curve decreases, both trends being in favour of high Z materials. The remaining question is, whether these trends will be overcompensated by the increase of χ.

Fig. 3 gives a comparison of the materials of table 1 by plotting $g(T_b)$ versus kT_b, the thermal energy of the impinging deuterium particles. Under the assumptions made kT_b must be at least one order of magnitude smaller than E_o in order to achieve plausible values of K.y.f (e.g. $\approx 10^{-2}$).

For this value of K.y.f the maximum tolerable temperatur kT_b is around 30 eV in the case of tungsten as wall material. For stainless steel, on the other hand, the corresponding tolerable temperature is nearly one order of magnitude smaller. At a given temperature of say 20 eV, the corresponding K.f.y-values differ between tungsten and iron for many orders of magnitude.

Discussion of the Example

When considering the results as shown in fig. 3 there is an evident trend - for a given K.y.f. product - towards larger tolerable temperatures of the impinging particles in cases of very high Z materials, in particular of tungsten, approaching some tens of eV as the maximum tolerable temperature. The latter does not appear unrealistic as an aim to be achieved by the cold plasma mantle approach [24], whereas the values (only some eV) required for iron might represent a rather hard condition to be experimentally fulfilled. Please note that the value of the K.y.f product to be obtained in a specific case may also depend on the atomic number of the impurity species.

In this context the question arises whether the trend to be observed in fig. 3 will continue when going from iron to materials of still lower Z-values. No statements can be made from our treatment because of lack of experimental data; a crude extrapolation from measured sputtering data to estimate the value of E_o and of a in the case of carbon suggests conditions lying in the range of those found for iron.

The relatively encouraging results in favour of tungsten, however, has to be considered with some caution because of various reasons. Firstly, the example considered assumed sputtering as the prevailing wall impurity release mechanism, disregarding processes like arcing, embrittlement, neutron sputtering, blistering, etc. Secondly, only sputtering by thermalized fuel particles (charge exchange neutrals) is taken into account, disregarding α-particle sputtering, impurity self-sputtering and acceleration by sheath-potentials. Eventually, the values taken for the slopes a and the threshold energies E_o were partly obtained from extrapolating measured data rather than from direct experimental evidence.

Despite these restrictions however, it appears to us that the results do shed some doubt on a generalized applicability of the "low Z wall philosophy" and that the use of materials with high sputtering threshold energy like tungsten in combination with the cold-mantle approach could be a possible alternative worthwhile experimental investigation. A qualitatively similar conclusion has recently been drawn by [25].

Appendix

In the following a derivation of the toxicity χ^* will be given, taking into account the thermonuclear power reduction due to the invasion of impurites into the plasma (wall particles with density n_W). The total pressure of the plasma

$$p = (n_e + n_i + n_\alpha + n_W)\,kT = 2n_o kT \qquad (1)$$

is assumed to be constant, n_o being the initial density of the clean DT-plasma. Depending on the plasma temperature a wall particle with atomic number Z will be charged to Z^* on the average. Therefore the neutrality of the plasma demands

$$n_e = n_i + 2n_\alpha + Z^* n_W \qquad (2)$$

The radiation power density is given by

$$P_{rad} = n_e\,(n_i L_i + n_\alpha L_\alpha + n_W L_W) \qquad (3)$$

with L_i, L_α, L_W being the cooling rates of plasma-, α- and wall particles, respectively. Its initial value is by a factor 1/A (depending on the plasma temperature) smaller than the corresponding thermonuclear power density

$$P_{th}\,(t=0) = \frac{n_o^2}{4} < \sigma v > Q_\alpha = A n_o^2 L_i \qquad (4)$$

with $\chi = L_W/L_\alpha$ (as used in the text) and $L_\alpha/L_i = 4$ (kT = 10 keV) an expression for the toxicity χ^* of the impurity particles can be derived.

It is given by the critical density n_W, at which the increase of radiation power density and the decrease of thermonuclear power density

$$\Delta P_{rad} - \Delta P_{th} = n_e(n_i L_i + n_\alpha L_\alpha + n_W L_W) - n_o^2 L_i - (n_i^2 - n_o^2)\frac{<\sigma v>}{4} Q_\alpha \qquad (5)$$

additionally caused by the impurity ions is as high as that of the α-particles only. Inserting equs. (1) and (2) into (5) yields

$$\frac{1}{\chi^*} = \frac{n_W}{n_\alpha} = C\left(\sqrt{1+\frac{D}{C^2}}-1\right) \tag{6}$$

$$C = \frac{\frac{1}{A}\left[4\chi-1+\frac{n_\alpha}{n_o}\left(2\chi-\frac{3}{2}+Z^*\right)\right]+\left(1-\frac{3}{2}\frac{n_\alpha}{n_o}\right)\left(Z^*+1\right)}{2\frac{n_\alpha}{n_o}\left(\frac{1}{A}\left(4\chi-\frac{Z^*+1}{2}\right)\left(\frac{Z^*-1}{2}\right)-\left(\frac{Z^*+1}{2}\right)^2\right)}$$

$$D = \frac{\frac{1}{A}\left(3+\frac{5}{4}\frac{n_\alpha}{n_o}\right)+3-\frac{9}{4}\frac{n_\alpha}{n_o}}{\left[\frac{1}{A}\left(4\chi-\frac{Z^*+1}{2}\right)\frac{Z^*-1}{2}-\left(\frac{Z^*+1}{2}\right)^2\right]\frac{n_\alpha}{n_o}}$$

At low concentration $n_\alpha/n_o \ll 1$ equ. (6) reduces to

$$\chi^* = \frac{\frac{4\chi-1}{A}+Z^*+1}{3\left(1+\frac{1}{A}\right)} \tag{7}$$

Inserting values ($A \approx 9{,}6$ and Z^* at $kT = 10$ keV) χ^* (Z) as represented in fig. 4 is obtained. A comparison between χ^* and χ shows that under the assumptions made the value of χ^* becomes up to one order of magnitude smaller than the value of χ when approaching the high-Z regime. This result enhances the obtained trend in favour of high-Z materials as stated in the discussion of the considered example.

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	E_o/eV	a/(eV)$^{-1}$	X
SS	33	$1{,}5\cdot10^{-5}$	$6{,}8\cdot10^{2}$
Mo	120	10^{-5}	$1{,}4\cdot10^{3}$
W	217	10^{-6}	$1{,}5\cdot10^{4}$

Table I
Values of the sputtering threshold energy E_o, the slope a of the sputtering yields near E_o, and the relative toxicity χ for the materials compared in the text

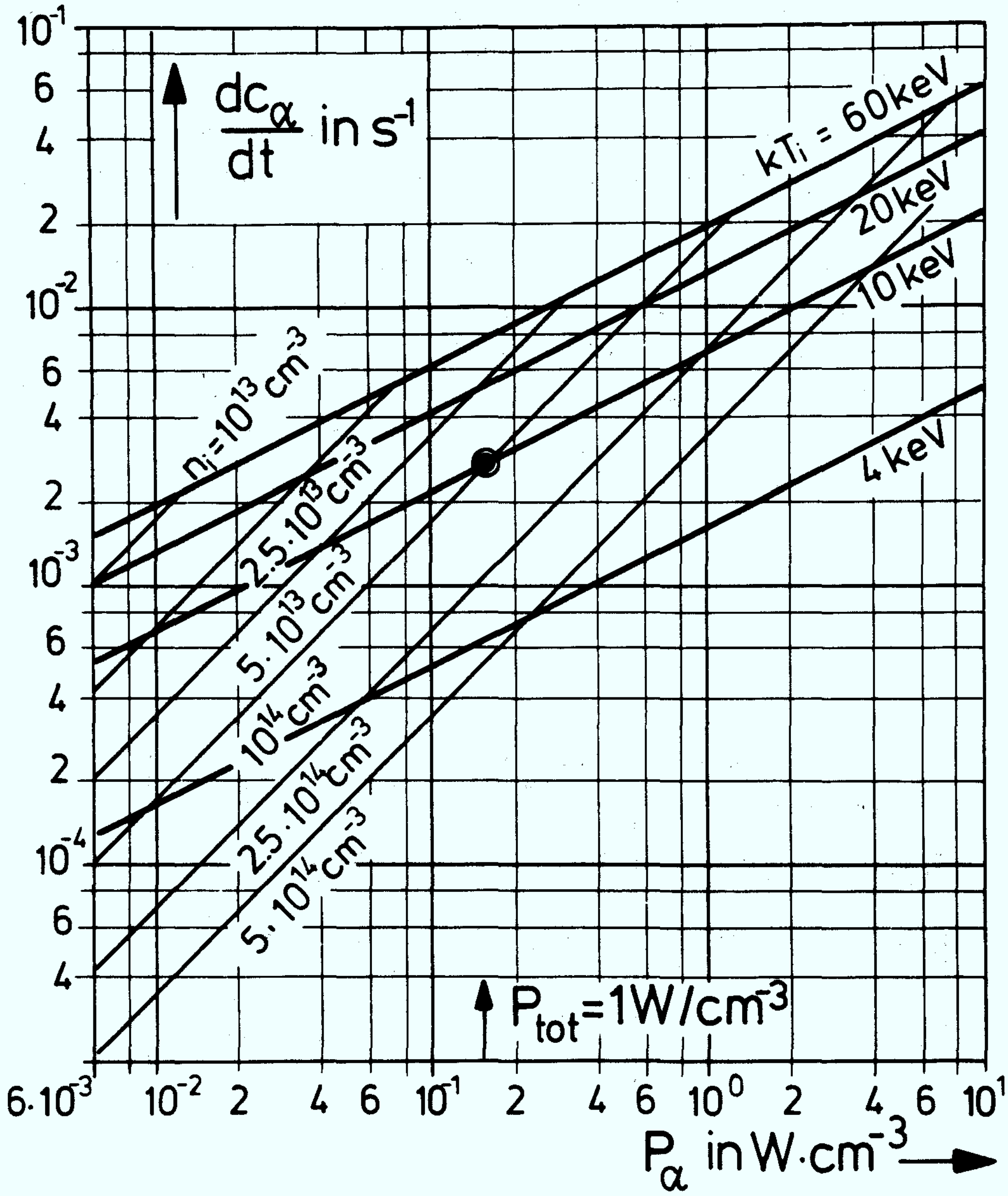
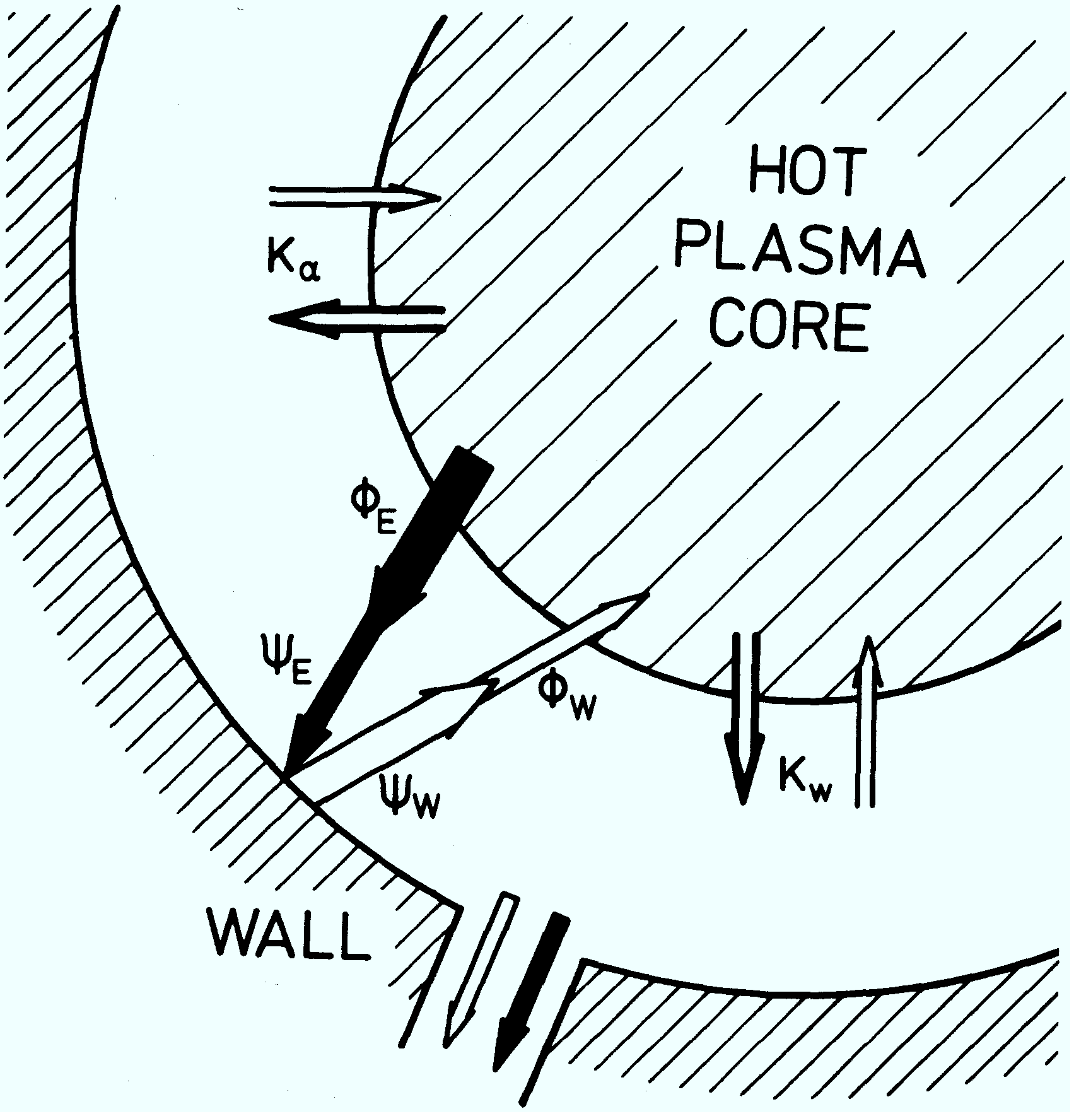


Fig. 1

Temporal change of the α-particle concentration, dc_α/dt, $\bar{K}_\alpha = 1$ vs P_α , the thermonuclear α-particle power density



<u>Fig. 2</u>

Schematic diagram explaining the transport factors K_α and K_W, the energy fluxes Φ_E and Ψ_E, and the wall particle fluxes Φ_W and Ψ_W.

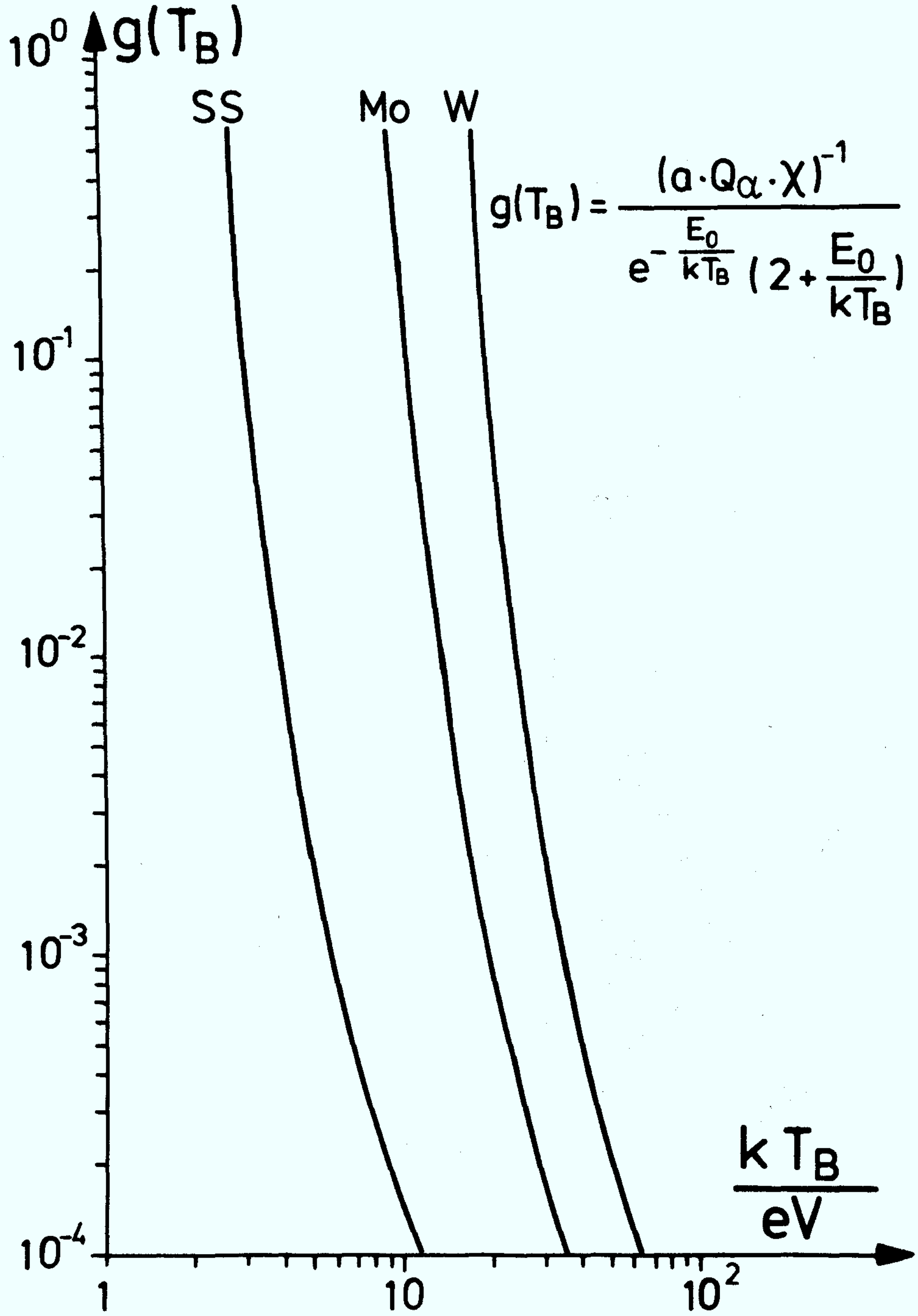


Fig. 3

Plot of the maximum tolerable value of the k.y.f product, named $g(T_B)$, vs an assumed kinetic temperature kT_B of the fuel particles hitting the wall

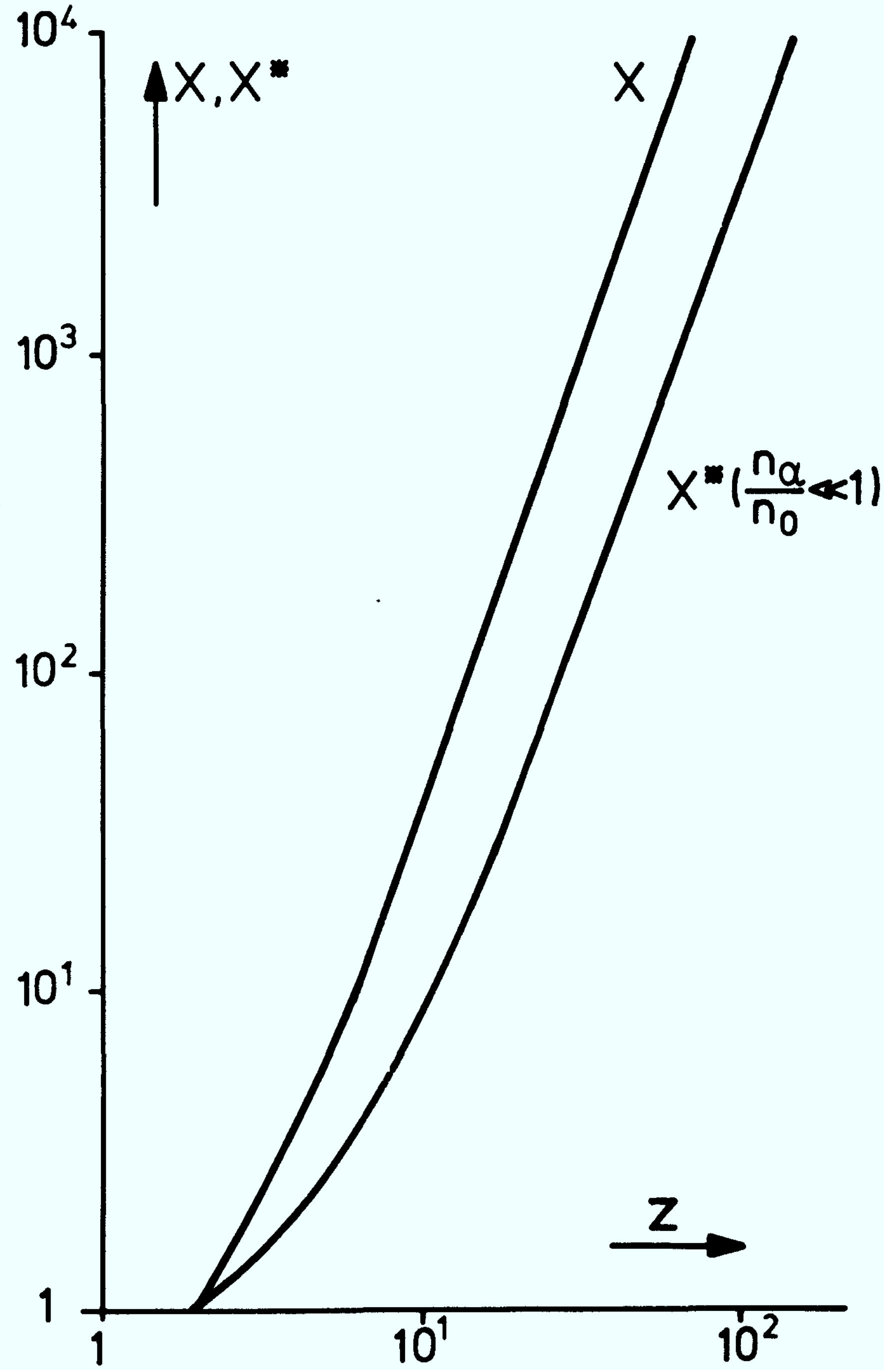


Fig. 4

Plot of the relative toxicity vs the atomic number Z of impurity species. Accounting only for radiation losses, the relative toxicity is expressed as χ, whereas including also the corresponding rarefaction of the fuel (constant total plasma pressure), the toxicity is called χ^*