Ion–solid interaction in fusion reactors*

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(Received 27 August 1975; in final form 6 October 1975)

The impact of energetic ions and atoms from the plasma on the first wall causes serious problems in achieving and maintaining a thermonuclear plasma. Simple model calculations show that sputtering by working gas particles is the main source of impurities in the plasma. Wall erosion is estimated to be up to ~0.1 mm/yr. Recent experiments show that blistering due to ions and atoms in the mean energy range of the plasma particles (1–20 keV) does not contribute to wall erosion and may be completely avoided. The charge and energy distributions of working gas particles backscattered from the first wall is largely responsible for the impact of high energy resonant charge exchange neutrals on the wall. The energy distribution of backscattered neutrals differs significantly from that of ions. High amounts of gas may be trapped in the first wall, but a reemission factor of one will be attained for most materials after a short starting period. High trapping efficiencies for hydrogen even at very high doses are found in materials like Ti and Zr. This may be helpful in increasing the pumping efficiency of a divertor.

PACS numbers: 28.50.R, 61.80.K

INTRODUCTION

The three principal physical goals of controlled thermonuclear reaction (CTR) research are to obtain a sufficiently stable plasma, to heat this plasma to ignition temperature, and to avoid excessive interaction of the hot plasma with the solid wall of the containing vessel. As plasma stability and temperature have been considerably increased over the last years, plasma–wall interaction has become a more and more important problem. It forms a substantial part of the experimental programs of magnetically confined near future plasma devices, e.g., PLT, PDX,[1] ASDEX, and JET.[2]

Besides the radiation damage inflicted on the wall material by the high energy neutrons the most serious effects arise from the bombardment of the first wall surface with energetic ions and neutral atoms from the plasma. This bombardment of 50–10^5 eV hydrogen and up to 3.5-MeV helium introduces high-atomic-number impurities into the plasma due to sputtering, blistering, and desorption and at the same time causes erosion of the first wall which may eventually limit its lifetime.

Both aspects of plasma–wall interaction in magnetically confined devices have been stressed in recent review papers.[3–6] Recent calculations of wall erosion[7,8] arrive at values between 10^{-3} and several tenths of a millimeter per year, depending on the assumed sputtering and blistering yields and the efficiency of a divertor, i.e., a specific configuration of the magnetic field by which the outer boundary layer of the plasma is scraped off and steered along the magnetic field lines into a dumping chamber to be pumped away. But it was shown by Behrisch *et al.*[6] that in a steady state reactor which necessarily includes refuelling the current of working gas particles (deuterium and tritium) to the first wall can only be significantly reduced by a divertor if refuelling can be performed without producing many charge exchange neutrals.

It has further been shown by Duechs *et al.*[9] that the introduction of impurities due to sputtering is a very serious problem which probably limits the burning time of a reactor to 100 particle confinement times (i.e., the average time a particle stays in the plasma) even if a divertor is used.

Some of the principal results of these calculations are given in the following part. In a second part a survey of recent results on the principal ion surface interaction processes involved is given.

INFLUENCE OF IMPURITIES ON THE PLASMA

Small concentrations of high-atomic-number impurities dominate the effective charge,

$$Z_{\text{eff}} = 1 + \sum_{z=2}^{z_{\max}} f_z (Z^2 - Z),$$

of the plasma and thus determine its resistivity and transport processes, $f_z = n_z/n_e$ being the ratio of densities of particles with atomic number Z and of electrons. This effect is considered helpful in present day tokamaks as it increases the ohmic heating input power and it may also diminish anomalous transport due to trapped particle modes in future neutral-beam-

heated tokamaks.[10] Also, impurities are deliberately introduced into the plasma in design studies of fusion reactors[11,12] to thermally stabilize the plasma. But there is an upper limit to impurity concentration above which ignition of a reactor is prevented due to radiation losses.[13,14] Figure 1 shows the maximum tolerable impurity concentration in a D–T plasma as a function of the atomic number of the impurities. At the critical concentration f_c (full drawn curve) the α-particle energy due to fusion reactions is equal to the radiation losses. The values of f_c by Kaminsky[4] assume critical radiation losses equal to 10% of the α-energy. It is seen that for materials like Fe, Ni, and Nb, f_c must be below several percent whereas for low-Z materials like carbon $f_c \sim 10\%$ is tolerable.

IMPURITY CONCENTRATION AND WALL EROSION IN A REACTOR

The importance of the interaction of charged and neutral particles from the plasma with the first wall and the close correlation between wall erosion and impurity concentration in the plasma can be demonstrated by a simple model.[6,7,9]

We assume a steady state reactor with divertor and neutral particle refuelling. The total currents of charged particles of type ν (ν=H, He, impurities) (no difference is made between hydrogen isotopes) that hit the first wall are determined by the currents $n_\nu \cdot V/\tau_\nu$ leaving the plasma (n_ν particle densities in the plasma, $n_H = n_D + n_T$; V—plasma volume; τ_ν—particle confinement times) multiplied by a factor ϵ_ν giving the fraction of particles that hit the wall instead of being removed into the divertor. Additionally, a fraction A_1 of the refuelling current F_1 is released to the first wall as a fast neutral particle current A_1F_1 due to resonant charge exchange. A current F_0 of predominantly neutral hydrogen atoms returns from the wall to the plasma due to backscattering and reemission. A fraction A of these particles again releases fast charge-exchange neutrals from the plasma boundary to the first wall. This gives rise to a further neutral current AF_0 to the wall. While $0 < A_1 \lesssim 0.5$ depending on the energy of the neutrals in the refuelling current and on the plasma parameters, A may well attain values above 0.5. Finally, the neutron current has to be taken into account. Additionally we assume that: (a) helium and impurities are distributed uniformly over the plasma; (b) there is no backflow from the divertor, although it could easily be included in the model; (c) evaporation and desorption may be neglected.

From the particle balance equation we obtain the following relation for the impurity concentration $c_i = n_i/n_H$:

$$c_i = \frac{\gamma_i \tau_i}{n_H} \sum_j \frac{F_j S_j}{(1-\gamma_i \epsilon_i S_i)}, \tag{1}$$

where F_j are the currents of hydrogen, helium, and neutrons to the first wall per unit volume of the plasma; S_j are the respective erosion yields due to sputtering and blistering; τ_i is the impurity confinement time; γ_i is the probability for an impurity atom leaving the wall to reach the plasma; c_i is related to the impurity concentration $f_z = n_z/n_e$ commonly used in plasma physics (Fig. 1) as $c_i = f_z(1 - zf_z)$ in case the impurity atoms are fully ionized.

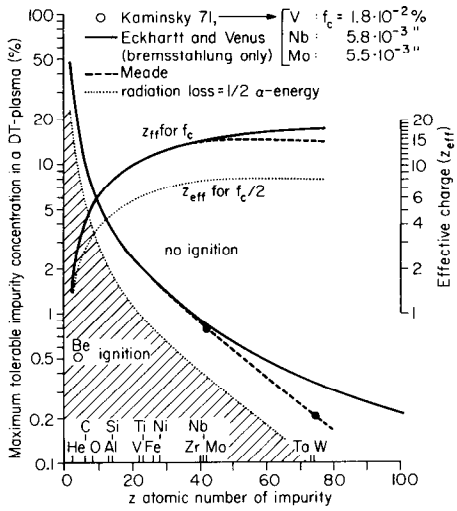

FIG. 1. Critical impurity concentration f_c and corresponding effective charge Z_{eff} for a D–T fusion plasma.

The currents are given similarly to Behrisch *et al.*[6]:

(a) deuterium, tritium

$$F_H = \frac{n_H}{\tau_H} \times \frac{\epsilon_H(1-f) + (1-\epsilon_H)A_1}{(1-AR_H)(1-f) - (1-R_H)A_1}; \tag{2a}$$

(b) helium

$$F_{He} = \frac{\epsilon_{He}}{1 - R_{He}\epsilon_{He}} \left(\frac{f}{2}\right) F_1; \tag{2b}$$

(c) neutrons

$$F_n = (f/2)\alpha F_1; \tag{2c}$$

where f is the fractional burnup of the total throughput F_1, R_H and R_{He} are the combined reflection and reemission coefficients for hydrogen and helium from the first wall, and α is the neutron current through the wall in units of the source current. (This definition of f differs from that used in Ref. 6. Also, a steady state hydrogen density n_H is assumed here, while $(1-f)n_H$ is taken in Ref. 6.) In deriving Eq. (2a) a refueling current of

$$F_1 = \frac{1 - A_0R_H - \epsilon_H R_H(1-A_0)}{(1-A_0R_H)(1-f) - (1-R_H)A_1} \times \frac{n_H}{\tau_H}$$

was assumed.

The current of working gas particles to the wall (2a) consists of two parts. The second one which is due to refuelling increases with divertor efficiency $(1-\epsilon_H)$. This shows that the divertor alone cannot efficiently reduce first wall bombardment by working gas particles. Additionally, the neutral impact due to

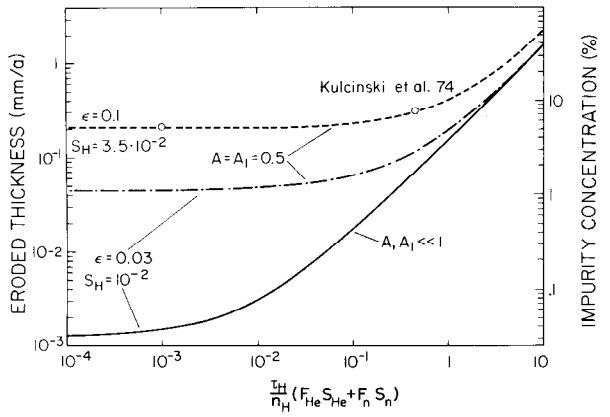

FIG. 2. Wall erosion in mm/yr and impurity concentrations c_i calculated from Eqs. (1) and (3) for a steady state tokamak reactor with divertor (UWMAK I [11]) as a function of helium and neutron contribution to wall erosion.

refuelling has to be kept small, e.g., by using high energy particles for refuelling ($E>100$ keV).

If we assume uniform distribution of the particle currents to the wall and neglect redeposition of eroded material, the erosion in time t is given by

$$d=\bar{v}_{at}(V/O)t\sum_j F_jS_j/(1-\gamma_i\epsilon_iS_i), \qquad (3)$$

where $\bar{v}_{at}$ is the volume of a wall material atom, and V/O the ratio of plasma volume to surface area of first wall.

In Fig. 2 wall erosion according to Eq. (3) is given for the data of UWMAK I[11]: $V/O=200$ cm, $n_H=8\times10^{13}$ cm^{-3}, $f=7.2\%$, $\tau_H=14$ sec, $\bar{v}_{at}=1.17\times10^{-23}$ cm^3 for stainless steel 316 as wall material. $\tau_H=\tau_{He}=\tau_i$, $\epsilon_H=\epsilon_{He}=\epsilon_i$, $\gamma_i=1$, and $R_H=R_{He}=1$ are assumed. The wall erosion per year is plotted over the sputtering contribution of He and neutrons. In the lower curve very efficient ionization of all neutral particles entering the plasma ($A, A_1\ll1$) was assumed whereas the upper curves are obtained for $A=A_1=0.5$. The result shows that neutral-particle refuelling may in unfavorable cases increase wall erosion by more than an order of magnitude. The upper curve has been calculated with Kulcinski's assumptions[8]: $\epsilon=0.1$, $S_H=3.5\times10^{-2}$ including erosion by blistering. The open circle corresponds to his assumed values for helium and neutron sputtering: $\alpha=2.3$, $S_n=0.14$, $S_{He}=1.15$ including blistering. The high neutron sputtering yield is based on measurements of Kaminsky *et al.*[16,17] If $S_n<10^{-3}$ as was found by several other investigators[6] the contribution of neutron sputtering to wall erosion may be neglected. A wall erosion of $d\simeq0.1$ mm/A would allow for operation of a reactor for a limited number of years, probably not for a lifetime of 30 years, without replacement of the inner wall. But irradiation embrittlement and swelling are probably more restrictive to first wall lifetime than erosion.[15] About an order-of-magnitude-higher values of wall erosion estimated previously[3,18] are based on a higher wall loading assumed in older reactor designs. The present example gives doses of up to 4×10^{22} particles cm^{-2} yr^{-1} for hydrogen and 2×10^{20} cm^{-2} yr^{-1} for helium.

A more pessimistic picture is obtained if we look at the impurity concentration c_i for the same assumptions as given above. Since Eqs. (1) and (3) differ only by a constant factor, the result is given by the same curves as those for wall erosion. On the right side of Fig. 2, c_i is given in percent. Even with the rather optimistic assumptions of $\epsilon=0.03$ and $S_H=0.01$, we obtain $c_i>1\%$ over the whole range if the contribution of refuelling to neutral wall bombardment is high. Comparing this to Fig. 1 it is seen that such high impurity concentrations are only tolerable for very low Z material. Kulcinski's assumptions lead to $c_i>5\%$.

It has already been pointed out earlier by Düchs *et al.*[9] and Vernickel[7] that steady state operation is not feasible without a divertor. The simple model calculation shows that ion surface interaction may be critical to the performance of a fusion reactor primarily with respect to impurity concentration in the plasma. Sputtering and possibly blistering by the working gas particles and helium are found to be the main sources of impurity buildup. The current of charge-exchange neutral particles hitting the first wall probably contributes the major part. It depends largely on the energy and charge distribution of hydrogen particles leaving the wall due to backscattering.[7,8] For a better understanding of the basic ion–solid interaction processes involved, experiments have been performed during the last few years bombarding well defined solid surfaces with ion beams of known energy and composition. Some of the more recent results are reported in the following section.

SPUTTERING

The results of the preceding paragraph have shown how critical wall erosion will be for the performance of a fusion reactor. Sputtering of refractory metals by light ions has been extensively studied during the last years,[3,19–21] but the higher tolerable impurity concentration seems to favor wall materials of low atomic number like different types of carbon, carbides, aluminum, and vanadium.[22] However, stainless steel and some nickel alloys are favorite wall materials at least in prototype reactors[11] because of their well known mechanical and thermal properties. Unfortunately, the agreement between sputtering theory and experiments is unsatisfactory for light ions,[23–25] so that we have to rely mainly on the measured data. Figure 3 shows sputtering yields for stainless steel measured by different authors and methods.[26–35] The measurements show that a broad sputtering maximum is found for light ions between 1 and 10 keV. To lower energies the sputtering yield decreases rapidly but there are no data available for hydrogen isotopes below 500 eV. Sputtering yields of low-Z materials are collected in Fig. 4. A large discrepancy is observed in the sputtering yields for carbon by hydrogen. This may partly be due to a temperature effect because some of the data[28,31] were obtained with high current densities.

While in metals temperature does not influence sputtering yields as long as $T \lesssim 0.7 T_m$ (T_m = melting temperature),[36] in carbon very high yields are observed around 600°C due to bombardment with hydrogen ions.[37,38] This is explained by the formation of volatile hydrocarbon compounds. There are not yet enough data available to assess this chemical sputtering effect in the nonmetallic low-Z materials but it may well limit their applicability as first wall material.

The angle of incidence of the ions is another parameter determining sputtering yields. On smooth surfaces the yield is approximately proportional to $1/\cos\theta$ (Ref. 20) (θ—angle between beam and surface normal). Cohen[27] has estimated that the sputtering yield due to the angular distribution of the charge-exchange neutral flux in a reactor is increased by approximately 85% above the yield for normal incidence. Surface roughness, developing after high dose bombardment may modify this effect. Since the accuracy of measured data is only within a factor of 2 it appears justified to neglect these effects at the moment.

The use of very rough surface structures for the first wall in order to reduce sputtering yields has been discussed recently. Cramer *et al.*[39] have calculated that the yield from a honeycomb surface structure may be a factor of 3 to 4 smaller than that of a flat surface. But most of the sputtering yield measurements with light ions have been made with rather high doses where surface structures due to sputtering are already rough on the μm range as will be shown in the next paragraph. So measured sputtering yields already contain some surface roughness effect, reducing the benefit to be expected from the honeycomb structure.

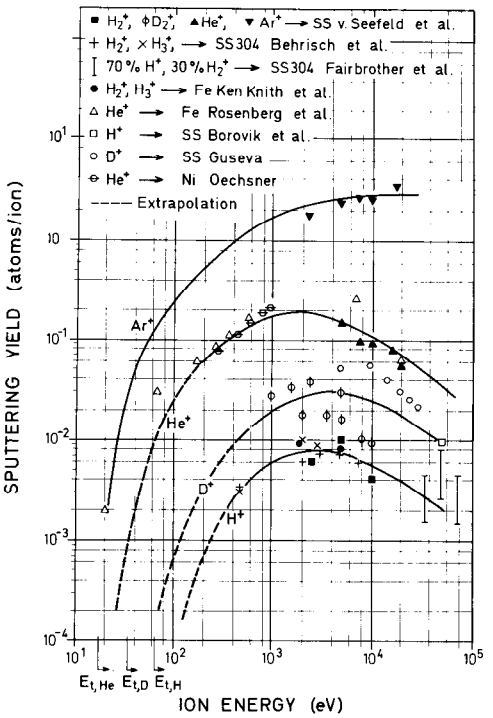

FIG. 3. Sputtering yields of H^+, D^+, He^+, and Ar^+ on stainless steel.[26–35] E_t are threshold energies below which no sputtering is observed.

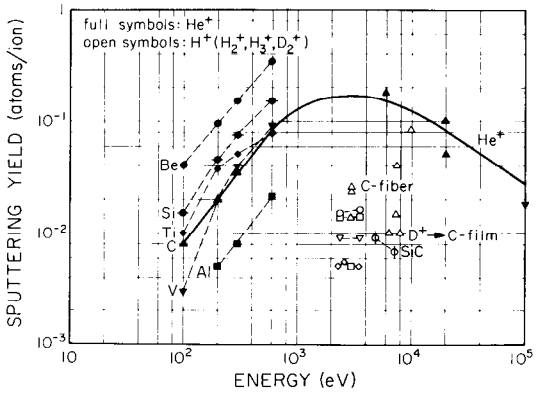

FIG. 4. Sputtering yields of H^+, D^+ (open dots), and He^+ (full dots) on low-Z materials.[26–28,31,34]

BLISTERING

A more controversial subject in the discussion of wall erosion is the contribution due to blistering. Kulcinski *et al.*[8] estimate that it is almost as large as sputtering by ions. Blistering has been the subject of detailed studies recently[40–43] which have lead to a more profound understanding of the mechanisms involved.

Light ions with energies as low as several hundred eV can penetrate a solid surface and are trapped deep inside the material. Depending on the diffusion of the implanted gas, high concentrations may build up in the range of the ions. After implanting a critical dose, this gas filled surface layer becomes unstable resulting in the appearance of domelike blisters at the surface or, at higher energies, in a complete peeling of the implanted layer, called flaking or exfoliation.[44,45] The latter effect is combined with a strong gas burst, leading originally to the assumption that a high gas pressure builds up inside the material which finally overcomes the mechanical strength of the material.[40,46] Recent measurements[47] have shown that this model has to be modified. Comparing depth profiles of implanted 1–15 keV ^3He ions to the thickness of the blister covers ("deckeldicke") it is seen that the depth of maximum helium concentration is usually about a factor of 3 smaller than the deckeldicke. In Fig. 5 implantation profiles measured by $^3He(d, p)^4He$ reaction in Nb are compared to the deckeldicke observed by double-aligned Rutherford backscattering.[48] These results can be explained by the formation of stress between the implanted surface layer and the bulk material due to swelling. The stress finally leads to rupture near the interface of the implanted and unimplanted region. The formation of large gas bubbles has been observed in this interface[49] probably causing mechanical weakening of the material. Also after blistering the maximum of the helium concentration stays in the covers [Fig. 5(c)], indicating that only a minor amount of the total implanted gas quantity is released during blister formation.

The amount of material removed from the surface due to blistering depends to a large extent on ion

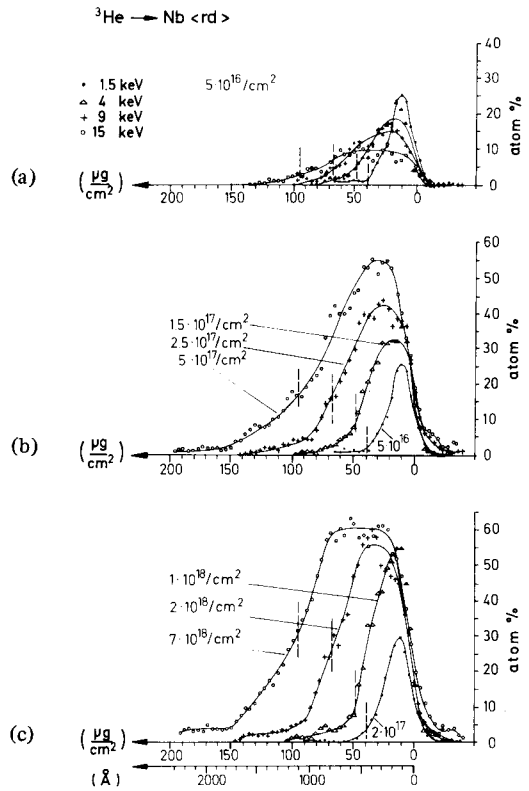

FIG. 5. Implantation profiles of ^{3}He in niobium[47]: (a) total dose much lower, (b) just below, and (c) several times higher than the critical dose for blistering. The dotted lines indicate the "deckeldicke" as measured by double aligned Rutherford backscattering.[48]

energy. With He on niobium no breaking away of blister covers is observed below 8 keV; at 15 keV up to 8% break away; and at energies above 100 keV usually the major part of the bombarded surface is exfoliated. To determine the erosion yield due to blistering it is essential to investigate at much higher than critical doses. It was observed earlier[50] that after bombardment with very high doses blisters disappear. This effect has been confirmed in Nb.[51] Figure 6 shows a polycrystalline Nb surface after bombardment by different doses of 9-keV He ions as observed in a scanning electron microscope. It is seen that after the first blister generation is gradually sputtered [Figs. 6(b) and 6(c)] the surface becomes increasingly rough [Fig. 6(d)]. The final and probably equilibrium structure consists of ridges and grooves in the micron range reflecting the orientation of the bombarded grain [Fig. 6(e)]. No second generation of blisters is found.

This result can be explained by the following simple model. After sputtering the first blister generation, a broad helium distribution is formed in the surface layer extending from the surface to the maximum range of the ions. This layer is so heavily damaged that newly implanted helium can escape along cracks or porosities or, as was suggested by Wilson,[52] by diffusion along neighboring damage sites. This is confirmed by the observation that helium trapping decreases almost to zero after the first blister layer is formed.[53] In Fig. 7 the amount of trapped helium is shown as a function of bombardment dose at different primary energies. The respective critical doses for blistering are indicated by arrows. At very low doses the trapping efficiency is close to 100%. Probably only the kinetically backscattered particles (see next paragraph) leave the target. At doses much lower than the critical dose for blistering trapping starts to decrease. At the critical dose trapping efficiency has reached almost zero as indicated by the very slow increase in the number of trapped particles. Apparently the mechanism of helium release starts long before and independently of blister formation.

These results imply that blistering may be completely avoided by deliberately implanting a broad helium distribution in the target. This is shown for a niobium sample in Fig. 8. The polycrystalline target was bombarded with subcritical doses of He ions at lower energies before applying a higher than critical dose at higher energy [Figs. 8(b) and 8(d)]. It is seen that only a few small blisters are produced due to this procedure whereas heavy blistering is observed after applying the same high energy dose to a virgin surface [Figs. 8(a) and 8(c)].

Since in a fusion reactor the depth distribution of incident particles due to their energy and angular

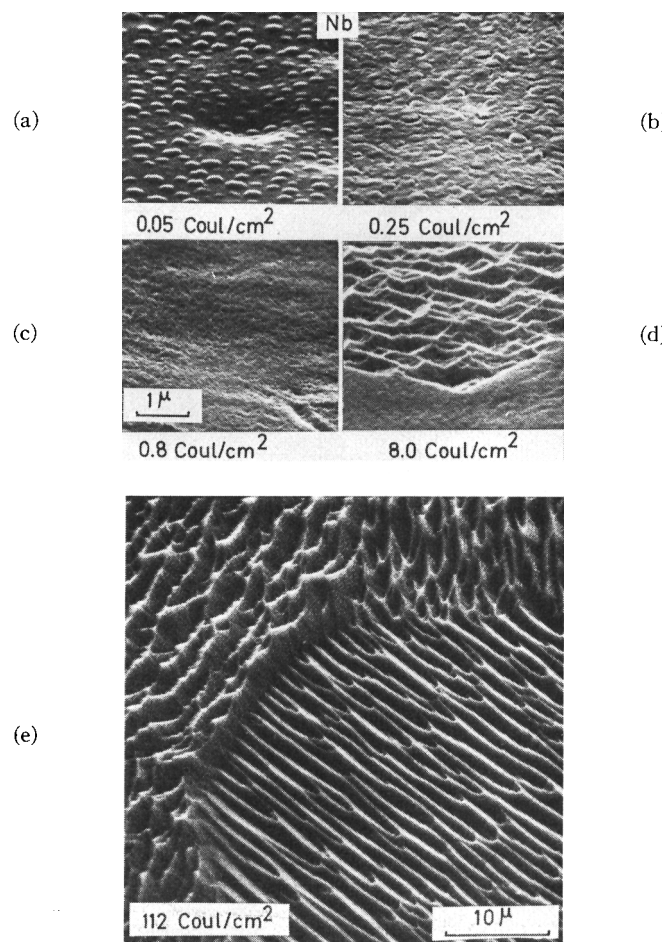

FIG. 6. Polycrystalline niobium surface after bombardment with increasing doses of 9-keV He at room temperature (1 C≙6.25 $\times 10^{18}$ He^+ ions).

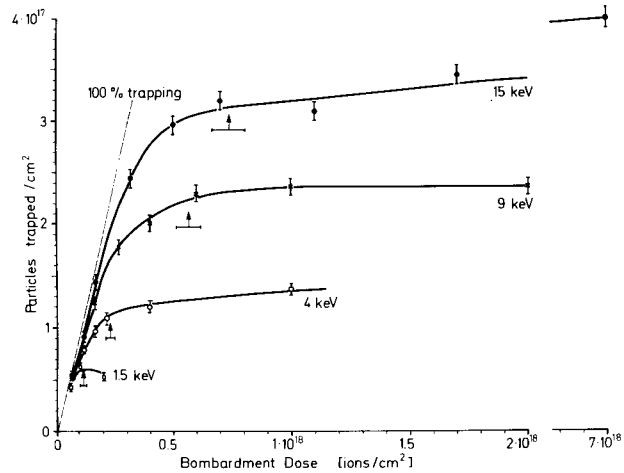

FIG. 7. Amount of trapped ^{3}He particles in a niobium single crystal as a function of dose for different energies at room temperature as measured by ^{3}He$(d, p)^4$He reaction.[53] Arrows indicate critical doses for blistering.

distribution is very broad, we can expect that no blisters are formed. It should be stressed at this point that these results have still to be confirmed at higher energies and for other materials but it seems very likely that we can neglect blistering as an erosion mechanism in a fusion reactor.

BACKSCATTERING AND REEMISSION

The back-flow of working gas particles and helium to the plasma is determined by (a) the total reemission coefficient R, (b) the energy and angular distribution of the emitted particles, and (c) their charge state.

If a beam of energetic light ions hits a solid, the particles penetrate the surface. Inside the solid their trajectory is determined by a sequence of binary collisions with target atoms, in which the particle is deflected from its original direction. On its path through the solid it suffers energy loss due to excitation of target electrons and ionization of target atoms, and due to elastic collisions with target atoms. Finally, the particle is either completely stopped in the target or emerges from the surface with some residual kinetic energy. The latter particles are called backscattered.

Particles that are stopped inside the solid may either be permanently trapped or may leave the solid by way of diffusion. The trapped particles build up a high gas concentration in the target which under certain conditions leads to blistering, as has been discussed above. They can escape through the heavily damaged surface (Fig. 7) or are released when the solid matrix is sputtered away. So, in a steady state reactor a reemission factor $R \simeq 1$ may be assumed. The particles released due to diffusion and sputtering of the solid matrix have the thermal energy of the wall ($\sim$0.1 eV) and are mostly neutral.

Particles backscattered with higher than thermal energy may leave the target either neutral or positively or negatively charged. In the case of hydrogen, the particles traverse the solid as ions.[54,55] Their charge state after leaving the surface depends on the probability of electron pickup in the tail of the electron distribution at the target surface. This has been found experimentally to be hardly dependent on the target atomic number.[56–60] Figure 9 shows the fraction of positively charged hydrogen atoms as a function of the emerging energy between 5 and 150 keV. Only on Be the charged fraction is found about 10% higher than in the other materials. Below 40 keV the neutral fraction prevails. The dependence on the angle of emergence is also very small.[60]

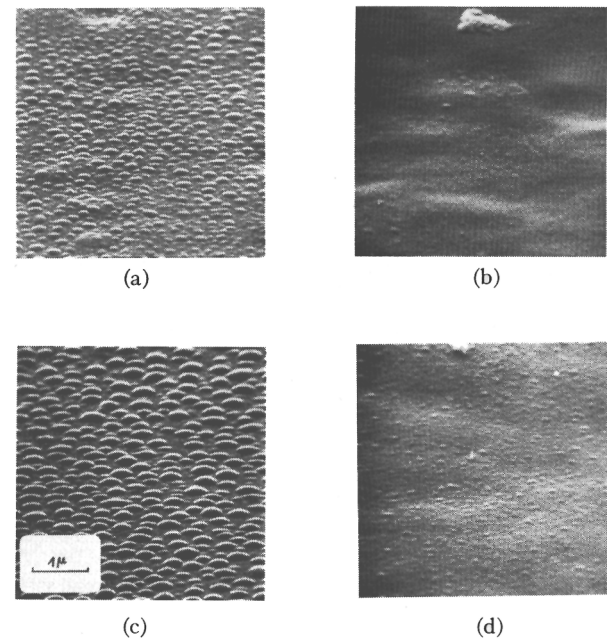

FIG. 8. Surface structure of polycrystalline Nb after bombardment with He^+ ions of (a), (b) 6 keV, 1×10^{18} He^+/cm^2, (c), (d) 9 keV, 1.5×10^{18} He^+/cm^2 at room temperature.[51] In (b) the sample was preimplanted with

0.5 keV	5×10^{17}	He^+/cm^2
1 keV	2×10^{17}	He^+/cm^2
2 keV	1.2×10^{17}	He^+/cm^2
3 keV	1.2×10^{17}	He^+/cm^2
4 keV	1.5×10^{17}	He^+/cm^2

in (d):

0.5 keV	5×10^{17}	He^+/cm^2
1 keV	2×10^{17}	He^+/cm^2
2 keV	1.2×10^{17}	He^+/cm^2
4 keV	1.5×10^{17}	He^+/cm^2
6 keV	2×10^{17}	He^+/cm^2

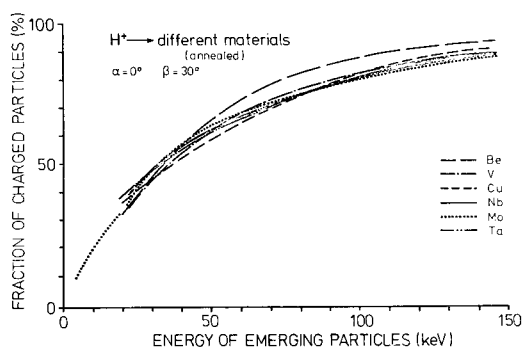

FIG. 9. Fraction of positively charged backscattered hydrogen from different metals.[60] α—angle of incidence; β—angle of emergence.

At energies below 5 keV considerable influence of target material and angle of emergence is found[61] for hydrogen backscattered from metals. Generally more than 80% of the backscattering particles are neutral in this energy range.

Backscattered energy distributions of high energy light ions (H, He, $E \geqslant 100$ keV) have been an object of study since the times of Rutherford.[62] The energy distributions of the scattered particles extend from zero to the primary energy reduced by the kinematic collision factor. They are well described theoretically by the Rutherford model of backscattering in one single collision.[63,64] For low energies, hydrogen below 50 keV, helium below 100 keV, this simple model breaks down. Multiple collisions have to be taken into account and no analytical theory is available.

Also experimental difficulties in measuring energy distributions of scattered particles including neutrals increase with decreasing energy. In the energy range below 10 keV which is most relevant for plasma wall interaction, solid state detectors are no longer applicable. Only very few measurements exists in this energy range.[61,66–68] The energy analysis of the neutral component is performed either by ionizing a part of the neutrals in a gas-filled stripping cell or by using a time of flight method with a chopped primary beam. A typical energy spectrum of hydrogen scattered from niobium is shown in Fig. 10. It contains the distributions of the positive and negative scattered ions as well as the total energy distribution of all particles including the neutrals. Two interesting features are apparent: the energy distributions of charged and neutral particles differ markedly. The neutral particles have a sharp peak around 1 keV. It is not yet clear whether the energy distribution goes to zero for very low energy or whether a finite fraction leaves the target with essentially thermal energy. Improvement of the stripping cell method allows measurements down to 150 eV for hydrogen.[69] Calculations of energy distributions of scattered particles by computer simulations[70,71] also show the maximum near 1 keV but the details for the distribution depend largely on the assumed stopping cross sections which are not well known in this energy range.

An important quantity is the total fraction of incident particles which is backscattered. The kinetic

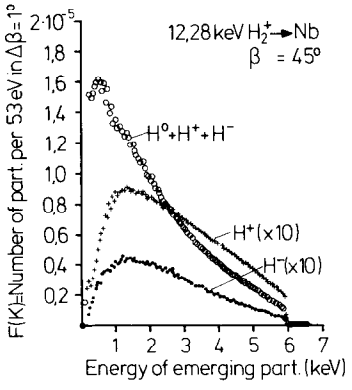

FIG. 10. Energy distribution of positive, negative, and neutral backscattered hydrogen emerging at 45° to the surface normal.[65]

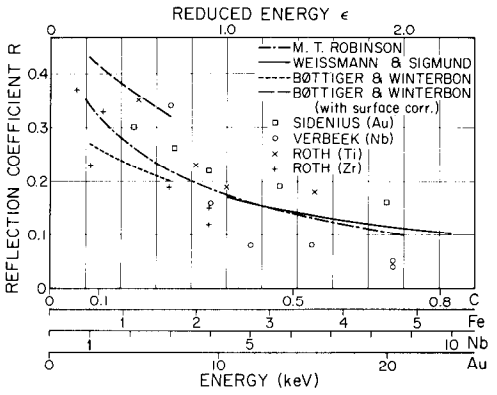

FIG. 11. Kinetic reflection coefficient for hydrogen on different materials as a function of reduced energy $\epsilon = a/b$.[25,66,71,72,74,75] Real energies for some materials are given on the lower abscissa.

reflection coefficient has been obtained from measured energy distributions[66] and by proportional counter technique.[72] Results are shown in Fig. 11 as a function of reduced energy[73] $\epsilon = a/b$, where a is the Thomas–Fermi screening radius and b is Bohr's collision parameter. Theoretical calculations of $R(\epsilon)$ have been made by solving transport equations for amorphous material.[25,75] The results are yet preliminary, but they already show that for most metals $0.05 < R < 0.5$ for energies between 1 and 10 keV. No measurements have yet been made below 1 keV and some computer simulation studies are under way in this energy range. At higher energies they are in reasonable agreement with results of transport theory.[71]

The trapping efficiency of working gas in the dumping plates of a divertor may largely influence the backflow of neutral gas to the plasma. Up to now most measurements of trapping efficiency for hydrogen and helium ions have been performed with rather low total doses.[76,77] Recent measurements show that the fraction of hydrogen that is not kinetically reflected is almost 100% trapped in Ti and Zr up to doses of approximately 10^{20} cm^{-2}. This result was obtained by measuring the weight change of a target after a very high dose hydrogen bombardment.[74] Reflection coefficients calculated from these results are included in Fig. 11. They agree well with kinetic reflection coefficients obtained theoretically and experimentally.

Helium on the other hand is not trapped in any material at doses higher than $\sim 10^{18}$ cm^{-2}.

CONCLUSIONS

Simple model calculations show that sputtering by energetic neutral particles which are formed in the plasma by resonant charge exchange probably is the main source of impurities in the plasma and of wall erosion. It may prohibit steady state operation of the reactor and enforce exchange of the first wall material during the reactor lifetime.

Divertor action does not efficiently reduce wall erosion and plasma impurity buildup if refuelling with neutral particles contributes appreciably to the charge-exchange neutral current to the wall.

Impurity levels tolerable in the plasma are significantly higher for low-Z materials, but properties of these materials at high temperature and energetic hydrogen bombardment are not yet sufficiently studied.

Wall erosion and impurity concentrations can be effectively reduced by keeping the temperature of the plasma boundary low ($\lesssim$100 eV) where sputtering yields are small. Data on low energy sputtering yields are very scarce.

Blistering due to hydrogen and helium bombardment of the solid wall does not contribute to erosion for energies below 20 keV if the incident particles have a broad energy and angular distribution. This is expected to be true also at higher energies. Experiments should be performed with ion or neutral beams of broad energy distributions ($\sim$50 eV up to 100 keV for hydrogen and up to 3.5 MeV for helium).

A considerable fraction of the incident plasma particles are backscattered from the first wall with higher than thermal energies. Most of these particles leave the wall as neutrals and can penetrate deep into the plasma giving rise to high-energy charge-exchange neutrals.

Except for this kinetically reflected fraction hydrogen can be very efficiently trapped ($\sim$100%) in materials like Ti and Zr. This can possibly be used to increase the pumping efficiency of the divertor.

Desorption of impurity layers by particles and radiation may be an important process in the starting period of a reactor. It has not been discussed here since conditions are not sufficiently defined.

ACKNOWLEDGMENTS

I want to thank my colleagues of the plasma-wall-interaction group at Max-Planck-Institut für Plasmaphysik, Garching. The work of this group constitutes a large part of this report. Especially, Dr. Vernickel contributed critical comments on the first part of the manuscript, Dr. Behrisch, Dr. Eckstein, Dr. Roth, and Dr. Verbeek have given helpful advice and provided unpublished data. Special thanks are due to Dr. J. W. Mayer and Dr. M-A. Nicolet for giving me the opportunity of writing this report in the stimulating scientific atmosphere of Caltech. Finally, I am highly indebted to Carol Norris for excellent typing of my almost unreadable manuscript.

*Work supported in part by the U. S. National Science Foundation.

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