EROSION, GAS TRAPPING, AND REEMISSION AT THE FIRST WALL OF A FUSION REACTOR*

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Abstract

A survey of the literature up to the end of 1971 was made on sputtering, gas trapping, and reemission of hydrogen and helium in metals. The purpose of the work was to collect relevant data needed for an assessment of erosion, pumping, and emission of impurities of the first wall of a fusion reactor and to check for serious gaps.

Contents

*Translated from the German by R. G. Mansfield, Office of Language Services, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Today it is largely agreed that the first vacuum wall of a fusion reactor must consist of metal. Insulators may not be exposed to the radiation of neutrons, electrons, ions, and neutral particles coming from the plasma since the damage in them caused by radiation is sure to reach an intolerable level. Wherever insulators are unavoidable, they must be shielded against this radiation. The present literature study is therefore limited to effects on metals. Since insulator walls for current plasma experiments still play a large part, the plasma-wall interaction in the case of insulators is treated in a separate laboratory report by G. Haas [64].

1. Sputtering

By bombardment of the first vacuum wall with fast neutral particles, ions, and neutrons, atoms at the surface are knocked loose, and the wall is gradually eroded. Sputtering has two aspects in regard to the plasma-wall interaction: (1) destruction of the wall due to erosion and (2) contamination of the plasma by atoms and ions produced by sputtering.

In order to be able to assess the erosion of the wall by bombardment with particles, we must know the flux of particles on the wall as well as their composition and energy distribution and also the amounts of sputtering for the different species of particles and particle energies.

Determining factors in the contamination of the plasma are the nature, state of charge, and energy distribution of the particles emitted in sputtering. In the fusion reactor, the primary stream of particles incident on the wall is composed of

1. Atoms and ions of the fusion plasma (deuterium, tritium, helium)
2. Neutrons
3. Atoms and ions of the wall material, which are heated in the plasma and after neutralization by charge transfer reenter the wall with high energy
4. Atoms and ions of impurities (e.g., O or C which have their source in the oxide coating of the wall material or reach the surface by diffusion from the interior)

There is no accurate knowledge of the state of charge of the plasma particles that impinge on the wall. It is mainly dependent on the extent of ionization by irradiation of the gas located between the hot fusion plasma and the wall, the density and temperature of this gas, and the distance from the wall from which fast neutral particles formed by charge exchange can reach the wall without first becoming ionized [61, 62]. Just as uncertain is the energy distribution. It is determined by the temperature of the plasma in direct proximity to the wall and the temperature of the layers of plasma from which fast uncharged neutral particles reach the wall.

The elements vanadium, niobium, tantalum, and molybdenum and the alloys TZM (0.5%, 0.08% Zr, 99% Mo) and 80% Va + 20% Ti as well as various stainless steels have been considered as materials for the first vacuum wall. (Owing to its high reactivity, Ta plays a secondary role.)

The sputtering of the first vacuum wall of a fusion reactor has been treated in a series of papers [11-14, 44] which, however, deal mainly with the eroding effect, while the emission of particles into the plasma gets very little consideration. Moreover, all these articles are based on an incident particle energy of about 20 keV for atoms or ions and 14 MeV for neutrons.

It is more probable, however, that the mean energy of the atoms that impinge on the wall is smaller, as they come from colder boundary layers of plasma; in the case of neutrons, an appreciable "backshine" of low-energy neutrons must be considered.*

Reference is frequently made below to a further series of summarizing monographs and articles on sputtering [1-5].

1.1 Sputtering yields

The sputtering yield, S, gives the ratio of the number of atoms eroded away to the number of incident atoms or ions [2]. Sputtering is generally related to a loss in weight of the material. In some cases the target mass may remain constant or even increase, viz. when the total mass of incident particles collected by the target is greater than the total mass of particles lost by sputtering. This is the case especially if the sputtering yield is small and/or the probability of collection is great, e.g., in the case of sputtering by hydrogen or carbon.

a) Sputtering with H^+, D^+, and He^+. Sputtering yields with H^+, D^+, and He^+ are so small that they are difficult to measure owing to the high probability of collection in some cases, especially of hydrogen in some metals. The available data must therefore be considered with caution.

Sputtering yields for H^+, D^+, and He^+ in the energy range 0.1-100 keV are compiled in Figs. 1 and 2. Except for the measurements of Yonts et al. [9] which were made at 1100°C, these were all determined at room temperature. The measurements of Ken Knight et al. [27] were made with H_2^+ or H_3^+, and the sputtering yield was calculated by dividing the primary energy by 2 or 3. It may reasonably be assumed that an H_2^+ ion of energy E has the same sputtering yield as two H^+ ions, each having an energy of E/2. The same holds true for H_3^+, with 3 substituted for 2. From these measurements for 1- to 5-keV H^+ ions, sputtering rates are determined for Ag and Au which agree well with the values of Grønland and Moore [28] for Ag.

The plots of all measurements of sputtering are very similar in general. Between 1 and 10 keV the yields have a very flat maximum, but below 1 keV they drop off very abruptly while at higher energies they decrease slowly. The measurements of Gusev [25] for D^+ on tantalum are probably in error due to collected gas since they were performed by the weight loss method.

b) Sputtering with tritium. Because of the extensive safety measures needed in handling tritium, no measurements have been made with it before. In studies of wall erosion in fusion reactors [8,12,13] this point was not treated. Daniel et al. [11] attempted to estimate sputtering yields with tritium. They

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*After this report was prepared, a review by R. Behrisch was published in Nucl. Fusion 12: 695 (1972) in which the distribution of energy of the incident atoms and ions and neutrons were taken into account. Further reference is made to a paper by H. Vernickel, Nucl. Fusion 12: 386 (1972).

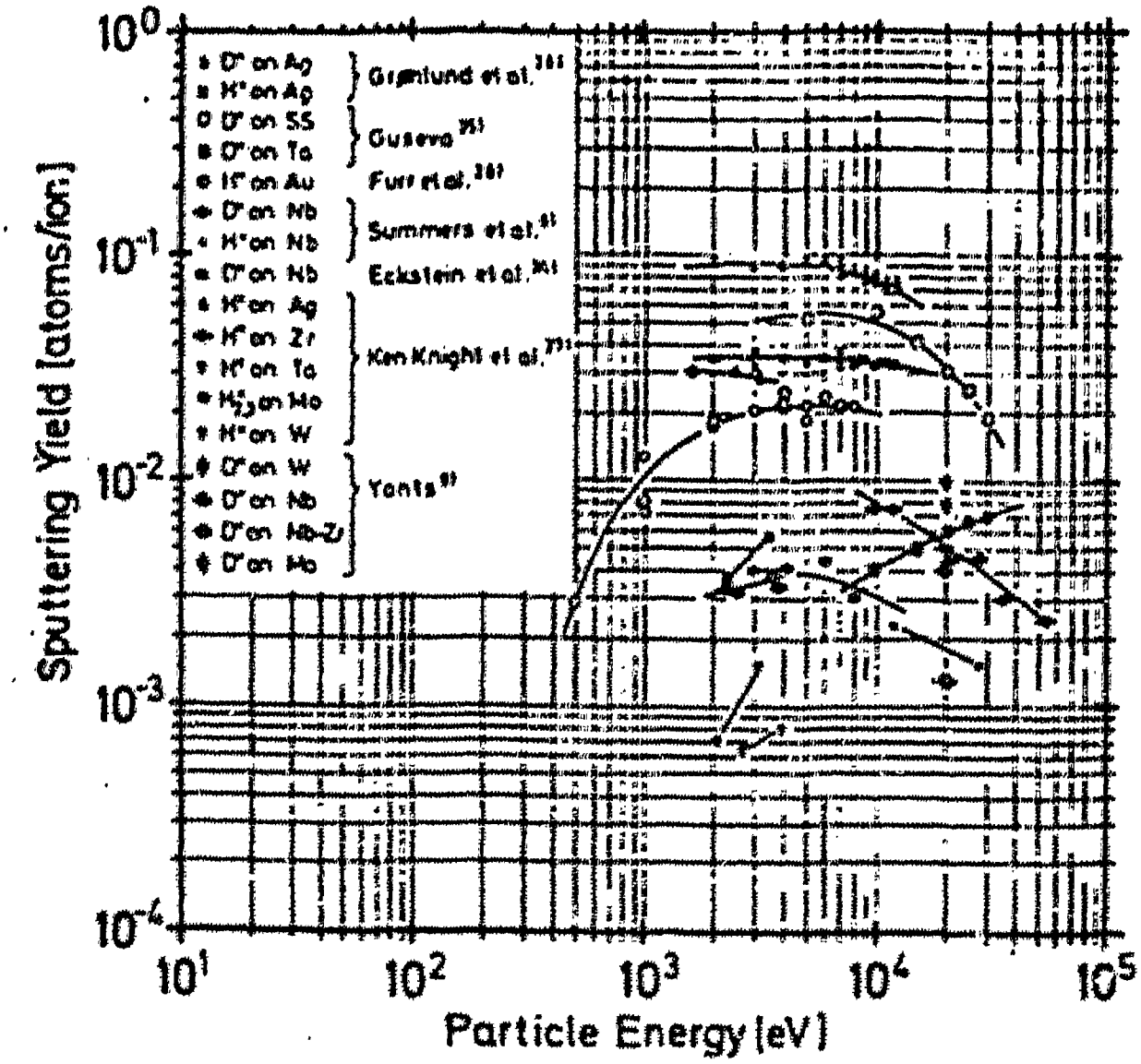


Fig. 1. Sputtering yields from various metals upon bombardment with H^+ and D^+.

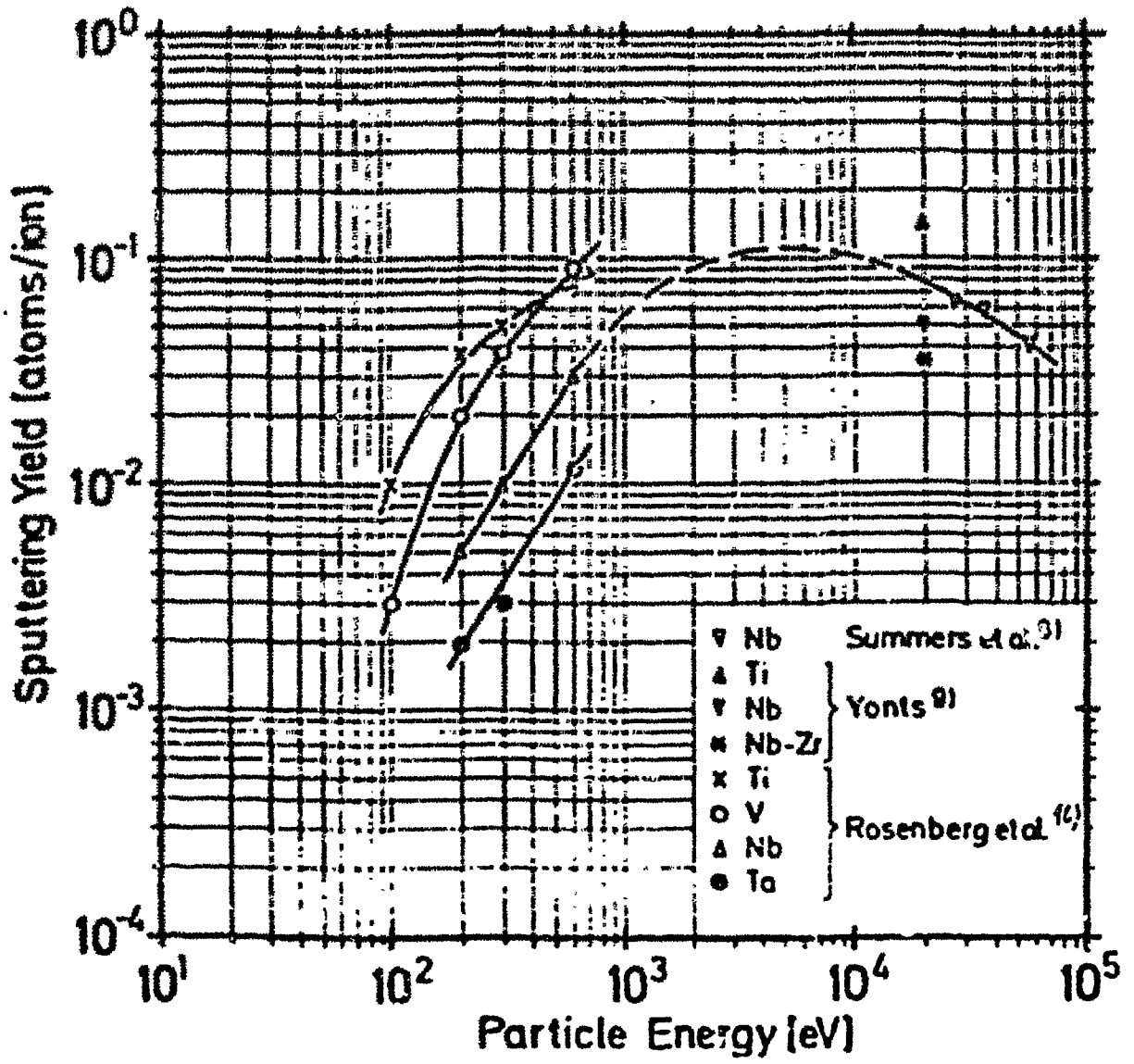


Fig. 2. Sputtering yields from various metals upon bombardment with He^+.

arque that the ratio of the sputtering yields with T and D should correspond to the ratio of the sputtering yields with H_3^+ [27]:

$$S_{T^+}/S_D \qquad S_{H_3^+}/S_{H_2^+} \approx 1.5$$

This estimation is not justified physically since the processes of collision in the case of sputtering with molecular ions differ from those with atomic ions. As Knight and Wehner [27] have shown, the molecular ions split up into their atomic components in passing through the surface, whereby the total energy is evenly distributed over all components.

The theories of R. S. Pease as well as those of Goldman and Simon [2] for the sputtering of light ions are valid only for the range of high primary energies (ie. that of Rutherford back-scattering). The sputtering yield is determined by the cross-section for displacement of atoms

$$\sigma_c = \frac{\pi e^4 \Lambda Z_1^{\,2} Z_2^{\,2}}{4 E_1 E_d} \left(1 - \frac{E_d}{E_1}\right)$$

and the mean energy of the "primary recoils," i.e., the mean energy which on impact with a primary ion is transferred to an atom of the lattice,

$$\bar{E} = \frac{E_d}{1 - \frac{E_d}{\Lambda E_1}} \ln \frac{\Lambda E_1}{E_d}$$

The expression $\Lambda = 4M_1 M_2/(M_1 + M_2)^2$ is the maximum energy transfer factor on collision of two particles with masses M_1 and M_2. Z_1 and Z_2 are the atomic numbers of the particles, and E_d is the energy of displacement. The cross-section for displacements accordingly increases approximately in proportion to $M_1 Z_1^{\,2}$. The value of $\bar{E}$ is only slightly dependent on M_1. Therefore we can expect a dependence of the sputtering yield which is proportional to $M_1 Z_1^{\,2}$. This estimation also agrees with the sputtering theory of Thompson [65] which is also valid for low primary energies. From this we obtain the ratios

$$\frac{S_{T^+}}{S_{D^+}} = 1,5 \quad \text{and} \quad \frac{S_{T^+}}{S_{He^+}} \approx 0,2$$

The measured sputtering yields for D^+ and He^+ [8] and the expected values for tritium if the calculation is based on one of the above ratios are shown in Table 1.

From this estimate we obtain values differing by a factor of 2 to 5, depending on whether the measured sputtering yields for D^+ and He^+ in niobium are used as the starting point. The reason for this is the greater deviation of the measured sputtering yields for He from theory [8]. However, smaller sputtering yields

for niobium with hydrogen and helium than would be expected from Pease's theory were found by Summers and coworkers, while those for silver were higher [2].

Table 1. Estimated sputtering yield for tritium on niobium from measurements for D^+ and He^+ on niobium [8]

E [keV]	S_{D^+}	S_{T^+} $\frac{S_{T^+}}{S_{D^+}} = 1,5$	S_{He^+}	S_{T^+} $\frac{S_{T^+}}{S_{He^+}} = 0,2$
20	0,005	0,0075	0,07	0,014
40	0,003	0,0045	0,06	0,012
60	0,0015	0,0023	0,055	0,011

All theories of sputtering for light ions fail to consider the sputtering due to back-scattered primary particles. That the effect of these is appreciable has been shown experimentally by Behrisch and Weissman [45]. Therefore it appears meaningless to make more accurate estimates of the sputtering yields with tritium by means of the various theories. (In principle, the back-scattering is contained in the theory of Sigmund [7]. The integral-differential equations, however, were not evaluated for this case prior to this time. At present, Weissmann is making an attempt at numerical evaluation.)

c) Self-sputtering. Sputtering yields by heavy ions can be higher than those with light ions by several orders of magnitude. Although the flux of fast heavy atom particles on the wall is probably small, these could, nevertheless, contribute appreciably to the erosion. Figure 3 shows self-sputtering yields of various elements with 45-keV ions according to Almen and Bruce [17]. The metals V, Nb, and Mo, which are of interest as wall materials in particular, show only slight sputtering. The absolute values, of course, are too low by a factor of about 0.5, probably because of surface contamination. Summers et al. [8] have measured self-sputtering yields of niobium in the range of energies between 10 and 80 keV (Fig. 4). The value of Almen and Bruce [17] is denoted by $\angle$. In contrast to sputtering with light ions, the sputtering yield continues to increase up to energies above 100 keV. The theories of Sigmund [7], curve a, and of Almen and Bruce [17], curve b, to be sure, show the true general trend, but the absolute values differ from experiment. Self-sputtering yields are not known in the region of special interest below 10 keV.

d) Sputtering due to contamination. Very little is known about this. In many cases a layer is built up by the bombarding ions on the surface, which acts as a protective layer and decreases the sputtering yield in comparison with the material with a clean surface. For example, in bombardment with carbon, an increase in target weight is observed [17] which can be explained by the buildup of a layer of carbon on the surface. Similarly,

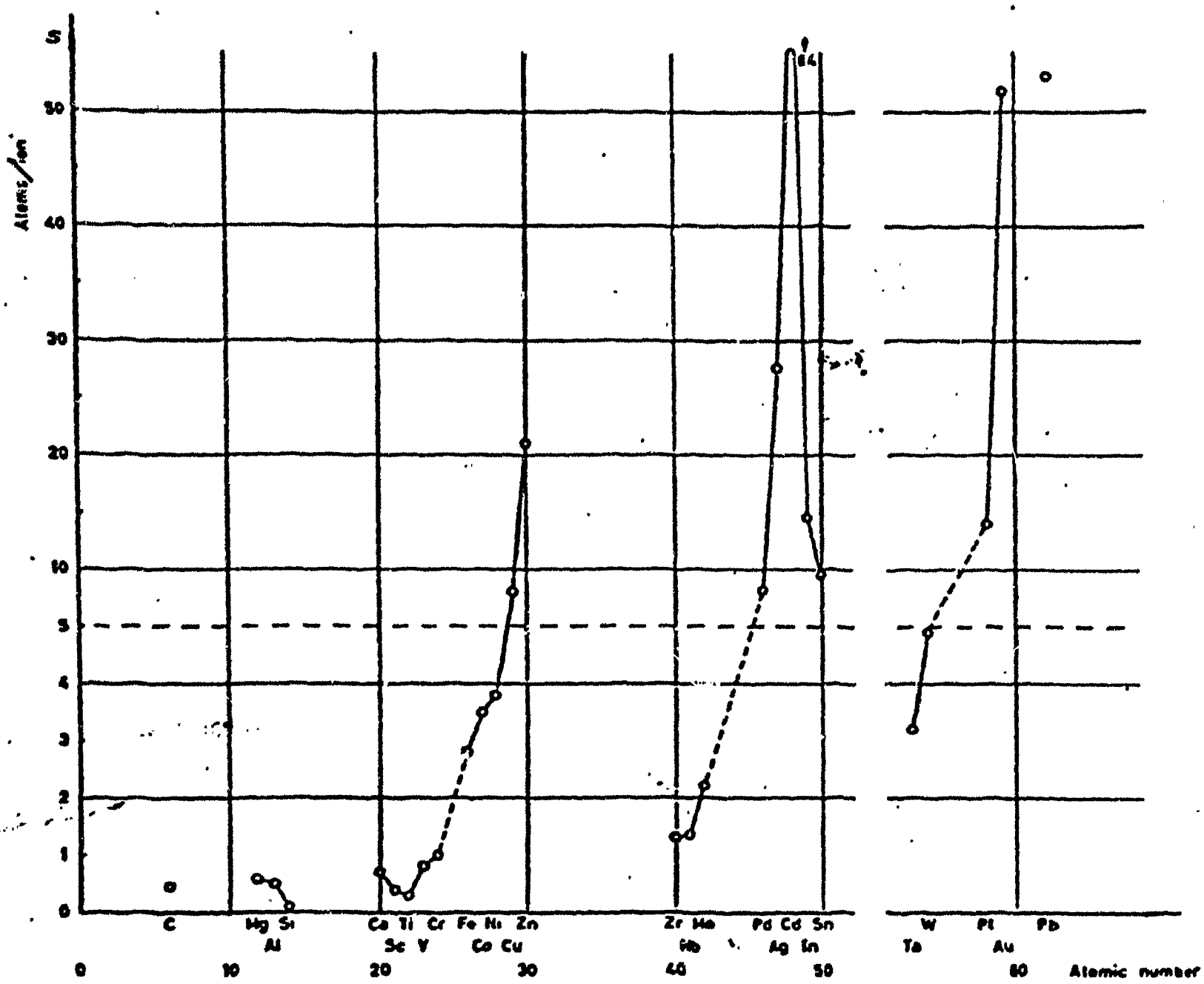


Fig. 3. Self-sputtering yield for materials, using 45 keV ion energy [17].

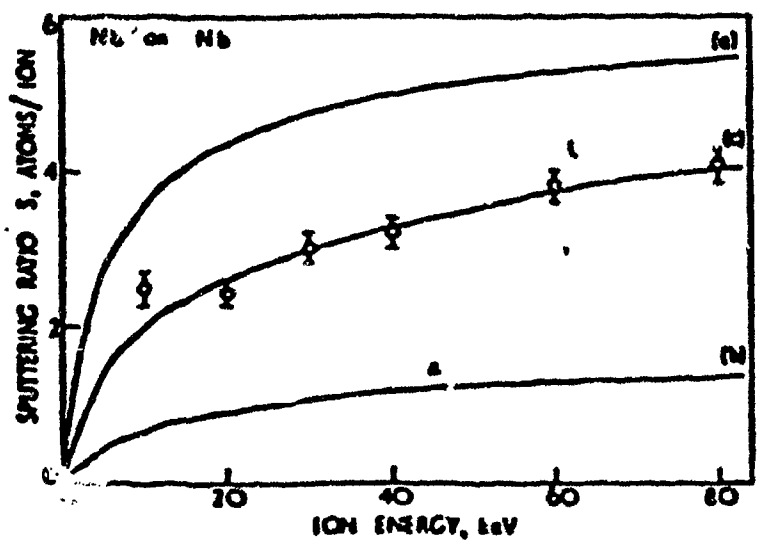


Fig. 4. Self-sputtering yields of niobium as a function of ion energy [8].

oxygen forms an oxide layer which results in lower sputtering rates. More will be said about this in the section on contaminated surfaces.

e) Sputtering by charged and uncharged particles. Nearly all known measurements of sputtering have been made with ions. In the fusion reactor, however, some strike the wall in the neutral state. What effect can the state of charge have on sputtering? Weiss et al. [5] have found greater sputtering yields with 10-keV neutral H and He than in the case of the singly charged ions H^+ and He^+. However, the result may possibly be explained by the presence of high-energy heavy neutral particles in the unanalyzed primary beam.

At low energies the potential for interaction between bombarding particles and atoms of the lattice can be dependent on the state of charge. On the other hand, there is great probability that the bombarding particle at low energy will be neutralized before reaching the surface [18,19]. The probability of neutralization is a function of the velocity, v, of the ion perpendicular to the surface,

$$P_n = 1 - \exp(-v_o/v)$$

For He^+, $v_o \approx 10^7 - 10^8$ cm/sec. Below this velocity the ions are neutralized before reaching the surface, i.e., in the case of He^+ at energies below 1-10 keV. Below this energy no effect of the state of charge on sputtering may be expected. To my knowledge, no values of v_o have been determined for hydrogen. However, a similar behavior may be expected. The state of charge should therefore have no effect on the sputtering yield.

f) Sputtering by neutrons. Sputtering yields by neutrons have been measured by various authors; Garber et al. [20-22] have observed sputtering yields of 3×10^{-3} atom per fast neutron in forward sputtering with 14-MeV neutrons on a gold single crystal. Sputtering yields of other metals can be derived only indirectly from these studies. Thus for Mo a sputtering rate for fast reactor neutrons was determined which is a factor of about 10 lower than that for Au. Norcross et al. [23] found for fast reactor neutrons on Au a sputtering yield of $(1.0^{+}_{-}\ 0.3)\times10^{-4}$, hence one which is significantly lower than that of Garber et al. (also by activation analysis).

Finally, Keller [24] gives upper limits for the rates of sputtering of Cu, Au, W, In, and Mo with 14-MeV neutrons:

Cu :	S	$3,9\cdot10^{-2}$	W :	S	$1,1\cdot10^{-2}$	In :	S	$3,6\cdot10^{-4}$
Au :	S	$6\cdot10^{-4}$				Mo :	S	10^{-4}

Sigmund's theory [7] of sputtering gives the yield for sputtering with neutrons:

$$S_n = 2\Lambda g N \sigma_n \langle \nu(E) \rangle$$

where $\Lambda = 3/(4\pi^2 N C_o U_o)$; U_o is the binding energy of a target atom which leaves the surface perpendicularly; C_o is a constant of the material; g is a factor of the geometry; N is the density of atoms in the target; σ_n is the total cross-section for neutrons; and $\langle \nu(E) \rangle$ is the mean value of the com-

ponent of "recoil energy" which goes into elastic collisions determined over the whole "recoil energy" spectrum. For $\langle \gamma(E) \rangle$ = 4 keV (Munich reactor), Sigmund obtains $S_n = 1 \times 10^{-5}$ for Au. For 14-MeV neutrons he estimates values between 10^{-4} and 10^{-3}.

Keller estimates the sputtering yield due to neutrons as follows: Only those atoms which have undergone collision and which are located in a surface layer with a thickness x ($\sim$100 Å) cause sputtering. The fraction of the incident neutron flux which collides with an atom of the target in the layer x is $1 - \exp(-\sigma_n Nx)$. This value is multiplied by the self-sputtering yield S_s according to Almen and Bruce [17] and gives

$$S_n = \left[1-\exp(-\sigma_n Nx)\right] 4{,}24 \times 10^{-10} N R^2 E \frac{1}{4} \exp\left(-11{,}2 E_B / 2\sqrt{M}\right) \quad \text{atoms/neutron}$$

where R is the impact cross-section at the ionic energy E (in m); E_B is the binding energy (in eV); and M is the mass of the metal atom. For 14-keV neutrons on Mo we obtain a sputtering yield of $S_n \approx 10^{-6}$ atom/neutron.

All measurements and theoretical estimates permit no statement concerning the exact sputtering yield with neutrons. However, we can assume values of less than 10^{-3} with reasonable certainty for the difficultly fusible metals.

g) Sputtering of alloys. Guseva [25] caused sputtering of stainless steel with D^+. The values are plotted in Fig. 1. The maximum sputtering yield is between 5 and 10 keV. It is a factor of about 8 higher than that for Nb.

Borovik et al. [55] found a sputtering yield of 9×10^{-3} with 35-keV H^+ on stainless steel. This was determined gravimetrically by the increase in weight of the collector.

In the case of sputtering of alloys, the components with the lowest sputtering yield become concentrated in the surface layer. The sputtering yield, after a certain time of acceleration, should drop to a value that corresponds to the new composition of the target surface (Tarng and Wehner [29]).

h) Effect of surface structure on the sputtering yield. The sputtering yield decreases with increasing roughness of the surface (Rosenberg and Wehner [16]) because more sputtered atoms are trapped again and cannot leave the target. This effect is stronger at lower energies because then the material on the average is emitted at flatter angles with respect to the surface [30]. Thus, for example, the sputtering yield of a threaded rod amounts to only 50% of that of a smooth rod (100 eV Ar^+ Ni), although the sputtering yield due to the oblique incidence on the threaded surface would have to be higher than in the case of perpendicular incidence. There are two reasons for this: The atoms sputtered at an oblique angle of incidence are preferentially emitted in the forward direction and hence strike on the wall again somewhere in the furrow; and atoms omitted obliquely to the target are caught by the neighboring turn of the thread. The porosity of the target also lowers the sputtering yield. Martinenko [31], in the sputtering of Mo and W with 200- to 500-eV Cd^+, finds for porosities of 50% or greater sputtering yields approximately 50% of that of the massive target.

For sputtering with hydrogen and helium ions, no such measurements are known. Since the surface of a target can become very rough under certain conditions owing to formation of bubbles, the very small sputtering yield of hydrogen could be attributed in part to the roughness of the surface. Thereby, of course, it is a matter of a second-order effect. Here eventually an effect of temperature on the sputtering yield is possible since at high temperature the surface has a different appearance than at a low temperature. Measurements at low energies should be the main ones made.

i) Sputtering of contaminated surfaces. The principal contaminants of the surface of a wall are probably films of oxide. Further, layers of carbon can build up on the surface with time owing to the low sputtering yield. Measurements of the sputtering yields of metals by hydrogen or helium ions in the region of energies below 20 keV in the presence of surface layers are not known. Smith et al. [32] have found that the sputtering of Cu with 500-keV He^+ becomes smaller by a factor of 100, when there is a film of carbon of 10^{17} atoms/cm^2 on the surface.

A thin layer of gallium was proposed by Parker [33] for decreasing the sputtering yield of tantalum. This process proved useful mainly at low energies (below 100 eV) and hence in the neighborhood of the threshold energy. Layers of oxide could also contribute to the decrease of the sputtering yield [2]. However, here also there are no known measurements with hydrogen ions. Still, it is probable that an oxide layer is not stable under bombardment with hydrogen ions, so that it does not act as a protective layer.

j) Threshold energy. The ionic energy below which sputtering no longer takes place is called the threshold energy. Measurements of the threshold energy are extremely difficult since very small sputtering yields must be measured. A summary of the important articles is found in ref. 2.

Since the energy transferred on impact is a function of the ratio of the masses of the ion and the atom of the lattice, a dependence of the threshold energy on this ratio may be expected. The measurements, however, do not show this dependence. Instead, there is a nearly linear relation between the threshold energy and the heat of sublimatation of the target. The threshold energies of most metals on sputtering with noble gases are between 10 and 35 keV.

The lowest thresholds were measured by Morgulis and coworkers [35]. According to these measurements the threshold energies for helium are between 11 eV (Sb) and 20 eV (W). The measurements, however, are probably conditioned by the presence of doubly charged ions in the plasma of the gas discharge. Without question, the threshold energy depends on the condition of the surface. Henschke [34] distinguishes two extreme values: as a maximum the threshold energy for a complete plane and as a minimum the threshold energy for detaching an isolated atom on a complete plane.

k) Effect of target temperature on sputtering. It is generally agreed that sputtering of metals is caused by cascades of impacts which are produced in the lattice by the incident ion. Even less is known about the mechanism

of propagation of an impact cascade in the lattice. Most important, it has not yet been decided what share the focusing series of impacts [2,3,5] has in the propagation of the cascade. Therefore it is not possible at present to estimate the effect of temperature on the sputtering yield. Several interdependent factors are involved:

1. Due to rising temperature, the propagation of the focusing series of impacts is impeded by the thermal vibrations of the atoms of the lattice.

2. Lattice defects heal completely more easily at high temperature, and thus the crystal order of the bombarded material will be higher at high temperature than at low.

3. At high temperatures, less injected gas is packed up; the surface is thus in a purer condition.

In most cases a slight increase in sputtering with increasing temperature is observed; however, the effect is insignificant as long as the temperature is not close to the melting point [5]. Carlston et al., in the sputtering of Mo, W, and Ta with 2- to 10-keV Ar^+, find an increase in the sputtering yield of 26, 28, and 39%, respectively, in the temperature range 350 to 1000°K.

Beginning at about $0.8T_m$ (T_m = melting temperature), the sputtering yield shows a great increase [46]. This increase can be explained by evaporation from so-called "thermal spikes."

1) Dependence of sputtering yield on the angle of incidence. Sputtering yields have been measured as a function of the angle of incidence formed with the normal to the surface by Summers et al. [8] for the system $D^+ \rightarrow$ Nb. The results of the measurements agree with expected $(\cos\theta)^{-1}$ distribution but can also be described by a $(\cos\theta)^{-2}$ distribution owing to the relatively high error of measurement (Fig. 5).

The dependence of the sputtering yield on the angle for the self-sputtering of Nb was measured by the same authors. The found

$$S(\theta) = S_o (\cos\theta)^{-3/2}$$

in good agreement with the theoretical result of Sigmund [7], who predicted

$$S(\theta) = S_o (\cos\theta)^{-1.6}$$

An increase in the sputtering yield with the angle of incidence, however, is found only for angles that are not too great. For $\theta \gtrsim 50°$, $S(\theta)$ reaches a maximum for many target-ion combinations and at greater values of θ again decreases [2,5]. Summers et al. [8] have measured sputtering yields of niobium with hydrogen and helium only up to $\theta \sim 60°$; therefore the position of the maximum cannot be determined from their measurements.

1.2 Emission of material produced by sputtering

In the plasma contamination and the recycling process, the state of charge, the angular distribution, and the energy distribution of the sputtered material play a significant role.

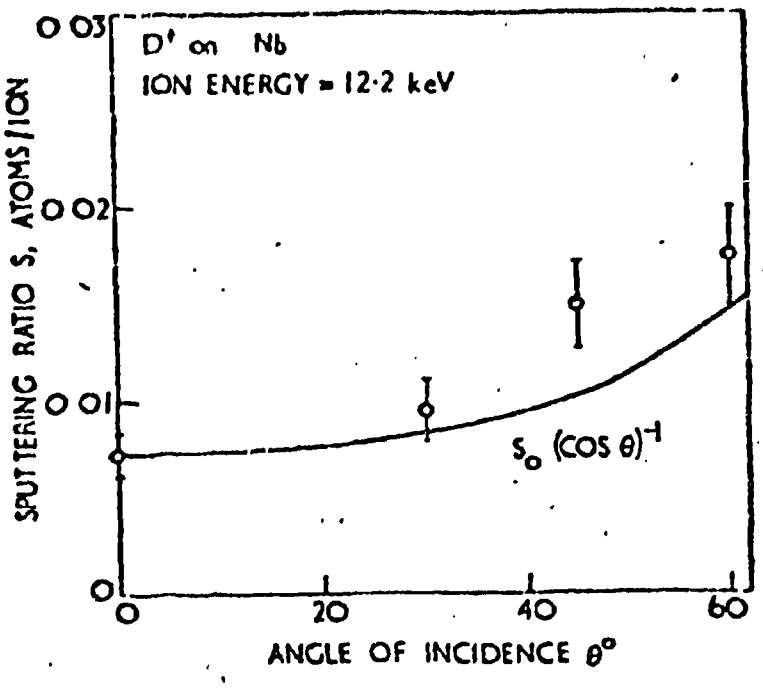
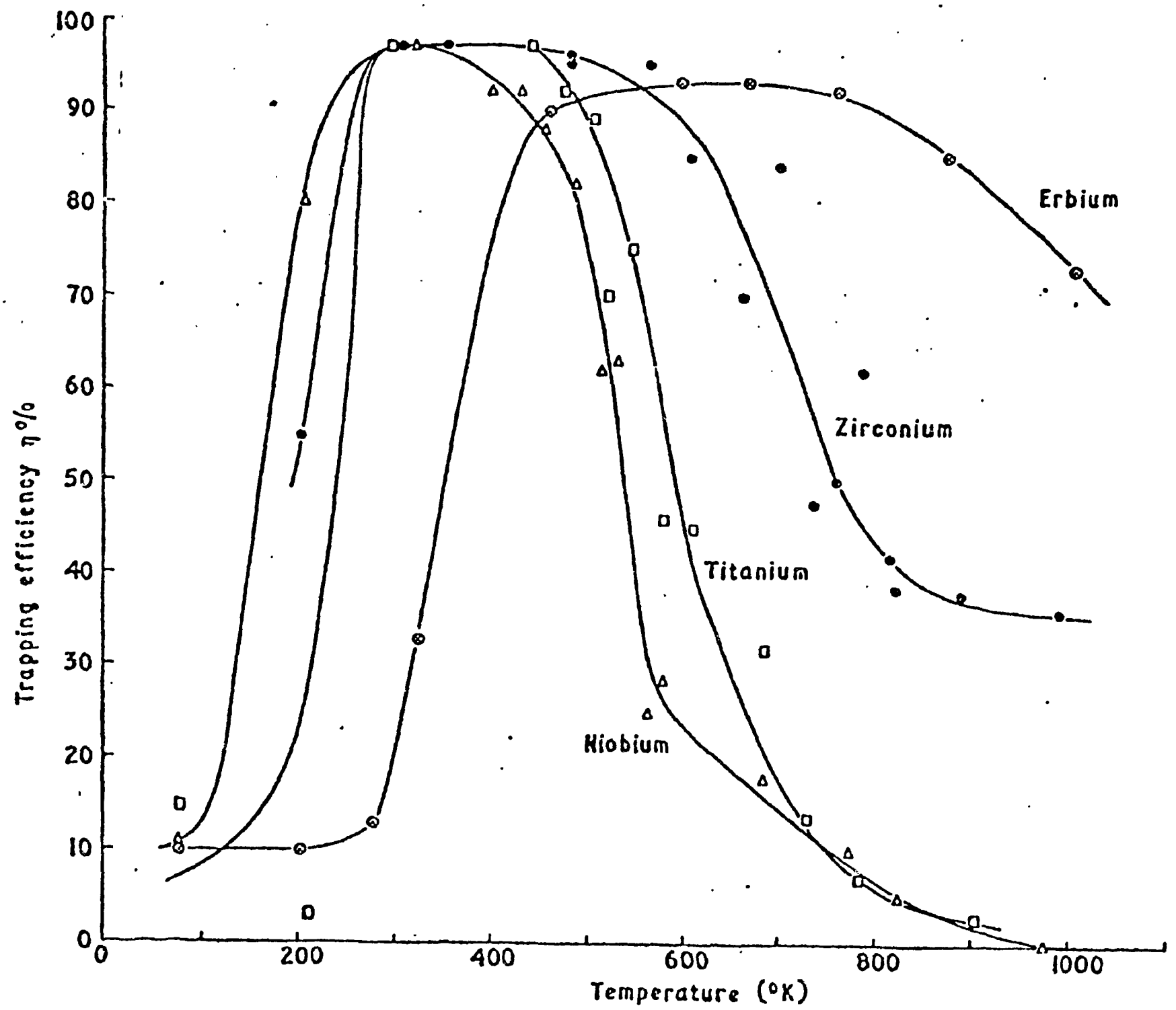


Fig. 5. Sputtering yield of Nb with D^+ as a function of the angle of incidence [8].

Fig. 6. Gas absorption of deuterium in Nb, Ti, Zr, and Er as a function of temperature, 1000 sec after beginning of the bombardment; current density 0.7 mA/cm^2 [54].



As has been long known [2], in the erosion of metals the bulk of the material that is eroded away is neutral. Normally, the fraction of ionized sputtered atoms increases with contamination of the surface by chemically active adsorbates [37-39].

The crystalline structure of the material (e.g., its texture) is of great importance for the angular distribution of the material removed in sputtering. Only very little is known about angular distributions in sputtering with hydrogen and helium ions. Grønland and Moore [28] with 9-keV D^+ on Ag find a distribution which corresponds approximately to the cosine law and which in the case of oblique incidence of the ions shows a slight bulge in the forward direction. Wehner and Rosenberg [30], on bombarding various metals with 0.1- to 1.0-keV Hg^+ find that at small bombarding energies the sputtered particles show a distribution that is far below the cosine distribution, i.e., the flat exit angle is given preference over the exit angle perpendicular to the surface. Conversely, in sputtering with high-energy primary particles, a distribution of sputtered particles above the cosine distribution is found.

The energy distribution of the sputtered atoms has been measured many times but not for sputtering with hydrogen ions. Stuart and Wehner [40] find for atoms emitted perpendicularly to the surface a distribution of velocities which approximates a Maxwell distribution, having its maximum at a few eV. This maximum is shifted to higher energies with increasing energy of the impinging ions. The mean energy of the sputtered atoms, however, at a primary energy of about 1 keV reaches a constant value, although the sputtering yield continues to rise with the energy and the high-energy tailing-off portion of the curve is more pronounced. In addition, the energy of emission decreases with smaller mass of the bombarding particles. The authors explain this by the assumption that the light ions penetrate deeper into the material before they transfer energy in a collision with atoms of the lattice. Thereby the particles sputtered by light ions suffer a greater energy loss before they leave the surface. The same authors have made the further observation that the energy of the sputtered atoms increases with the angle that the emitted particles form with the target surface. Finally, Stuart et al. [41] find that the mean emitted energy is lower, the greater the sputtering yield of the material. Heavy target atoms have higher emission energy while light ones have a higher emission velocity.

Thompson [42], in sputtering of Au with Ar^+ and Xe^+ (43 and 66 keV, respectively), finds that the energy distribution of the sputtered atoms is a function of $1/E^2$ between 10 and 1000 keV. In the region of particular interest---that of the maximum distribution---between 1 and 10 eV, reproducibility is poor.

Measurements of the energy distribution of Oechsner [43] for 900-eV Ar^+ on various metals are in good agreement with the results of Stuart and Wehner.

The energy distributions of sputtered atoms on bombarding with hydrogen

have not been measured prior to now. The energy of the sputtered ions does not permit any conclusions, as they constitute only a very small fraction.

1.3 Problems of the wall in divertors and on limiters

For various reasons, one of which is also the high rate of erosion of the first vacuum wall by sputtering, at present a fusion reactor without a divertor appears impracticable. In this case a large part of the load on the wall by bombardment with particles is shifted onto the walls of the divertor. In a continuously operating 5-MW(th) reactor some 10^{23} ions per second with a mean energy of about 20 keV would flow into the divertor. It appears possible to provide surfaces in the divertor which are large enough to keep the flux of energy per surface within tolerable limits. But here also the erosion of the wall by sputtering will limit the lifetime. In particular, atoms of the wall material which has been eroded away can become heated in the plasma and then contribute appreciably to the sputtering. It will be necessary to direct the flux of particles onto the wall of the divertor at places on which the wall material is especially thick or which can be easily replaced from outside.

A plasma-surface problem of a somewhat different type occurs in pulsed machines when, toward the end of the discharge, the plasma becomes unstable and within a few milliseconds to microseconds falls onto the wall. Then some 100 Joules/cm^2 in a pulse is transferred to the uppermost layers of atoms of the wall. If the energy cannot be conducted away within the short time by heat conduction, a thin surface layer is heated within a short time to such a high temperature that evaporation of material occurs. In apparatus similar to the Tokomak, even now the main source of erosion appears to be volatilization. Materials of high melting point and/or low vapor pressure and high heat conductivity are best suited to this stress. Curves of vapor pressure for metals may be found in the literature [66].

2. Chemical Interactions

Chemical reactions with the wall material take place:

1. On bombardment of the wall with energetic particles of chemically active elements, e.g., oxygen. Mainly surface layers are built up, which have an effect on the sputtering yield (see above) or desorb by bombardment with other particles.

2. In chemical sputtering, when the surrounding gas reacts with the wall material to form a volatile compound. Thus the wall is eroded. Such processes have not been found with the metallic wall materials and gaseous components of interest (principally hydrogen).

3. Upon dissolving of large amounts of gas, when the structure of the metal wall and its mechanical properties can be changed considerably. This is the case especially in the highly hydrogen-dissolving metals vanadium, niobium, and tantalum. At high temperatures (above 600oC), which the wall of a fusion reactor will have, however, the achievable equilibrium concentrations of hydrogen in the wall are too small to produce such changes.

Thus chemical reactions will probably not be involved at the first vacuum wall, as far as the interface between plasma and wall are considered. Processes on the opposite side, which under certain conditions are cooled with liquid lithium, are not treated here.

3. Injected and Diffused Gas, Back Diffusion, Bubble Formation

There are several aspects to this complex problem:

1. Fast neutral particles from the plasma (principally hydrogen and helium) penetrate into the wall and can either dissolve in the lattice or, after reaching a saturated concentration, be deposited in the form of bubbles.

2. If the pressure in the bubble becomes too high, it bursts on the surface (blisters). The gas contained in it is then liberated in a fraction of a second. The formation of bubbles is mainly a function of the solubility and rate of diffusion of the gas in the lattice.

3. By sputtering, particles previously injected into the wall and embedded or dissolved in the lattice are set free and can return to the gas space.

4. Finally, part of the injected gas, through diffusion, reaches the surface again and goes back into the vacuum. From processes 2, 3, and 4 together, the probability of pick-up for the bombarding gas is determined. It depends on the kind of bombarding particles, the wall material, the primary energy, the primary intensity, and the wall temperature.

5. Between the outer gas pressure (in the vacuum) and the concentration of the gas in the wall, an equilibrium is established. This can result in the condition that, on first filling of a reactor, a large part of the hydrogen at first disappears in the wall. In addition, relatively small fluctuations of temperature in the wall lead to relatively large emission or absorption of gas.

6. Finally, it must be considered that all data on solubility, diffusion constants, etc. that have been measured on the annealed, unbombarded material have only limited significance for us because all these values change under bombardment. Solubility and binding energy depend especially on the concentration of lattice defects. Processes of diffusion under the action of radiation take place appreciably more easily than in undisturbed material.

3.1 Pick-up and re-emission of injected high-energy gas atoms (hydrogen, helium)

Light, high-energy particles with energies greater than 1 keV are back-scattered on the surface of a solid to only a slight extent. The major part penetrates through the surface into the lattice. Part of these penetrating atoms are back-scattered by collisions with atoms of the lattice and

leave the lattice with relatively high energy (discussed in ref. 63); the remainder come to rest in the lattice and diffuse through it until the atoms either reach the surface or are collected in a bubble.

The depth at which the atoms come to rest depends on the primary energy. Schiøtt [48] has calculated the theoretical ranges for hydrogen in metals. However, the theory was derived for amorphous substances, so that in polycrystalline material in some cases appreciably greater ranges (up to a factor of 10) can occur as a result of the lattice guiding effect. Measurements of the depth of penetration of hydrogen in metals are very difficult since the hydrogen, after penetration, becomes distributed throughout the entire lattice owing to diffusion. The measurements of Chu and Friedman [50], who measured the depth of penetration of 20-keV D^+ in gold and aluminum by means of the D-D reaction, yielded depths of penetration of 4-5000 Å. For the depth of penetration (projected range) of 20-keV D^+ in niobium, Schiøtt found a value of 1700 Å [51].

The overall probability of pickup, η , of hydrogen and helium ions on various metals has been measured many times. A review of the measurements with noble gases up to about 1965 is found in the paper of Carter and Colligon [5]. The initially high values of η for noble gases gradually drop after reaching a bombardment dose of 10^{15}-10^{16} cm^{-2} to very small values when saturation is reached.

Hydrogen behaves in an altogether different way. McCracken and coworkers [52-54] found that η is a function of the bombardment dose as well as of the target temperature. Very high values are found for the metals in which hydrogen dissolves readily (V, Nb, Ta). Figure 6 shows η as a function of the temperature for a high bombardment dose. Above 500°K, η drops off sharply and at the expected wall temperatures, above 800°K, is less than 10% for niobium. In Figs. 7 and 8 the probabilities of re-emission for 18-keV D^+ on nickel are plotted as a function of the bombardment dose for various temperatures and dose rates. The probabilities of pick-up are appreciably lower than for niobium in the medium temperature range; however, they are higher than expected for annealed nickel on the basis of the experimentally determined diffusion constants.

Thermal desorption spectra show that there are many discrete activation energies at which the injected deuterium is again emitted, and these delayed re-emissions can be correlated to the capture of incident ions in various configurations of damage by irradiation. Measurements of Borovik et al. [55] on stainless steel show a similar behavior (Fig. 9).

In contrast to hydrogen, helium has a negligible solubility in most metals. Under bombardment, however, just as in the case of hydrogen, diffusion is impeded by capture on different configurations of irradiation damage [56].

Formation of bubbles. It has been shown that the mechanism of re-emission of the injected gas in many cases cannot be explained by diffusion even if increased binding energies of the injected ions at sites of irradiation damage are considered. With a large number of metals, bombardment with H^+, D^+, and He^+ at doses of 10^{17}-10^{18} cm^{-2} results in the formation of bubbles. These burst on the surface and thus emit their gas into the vacuum.

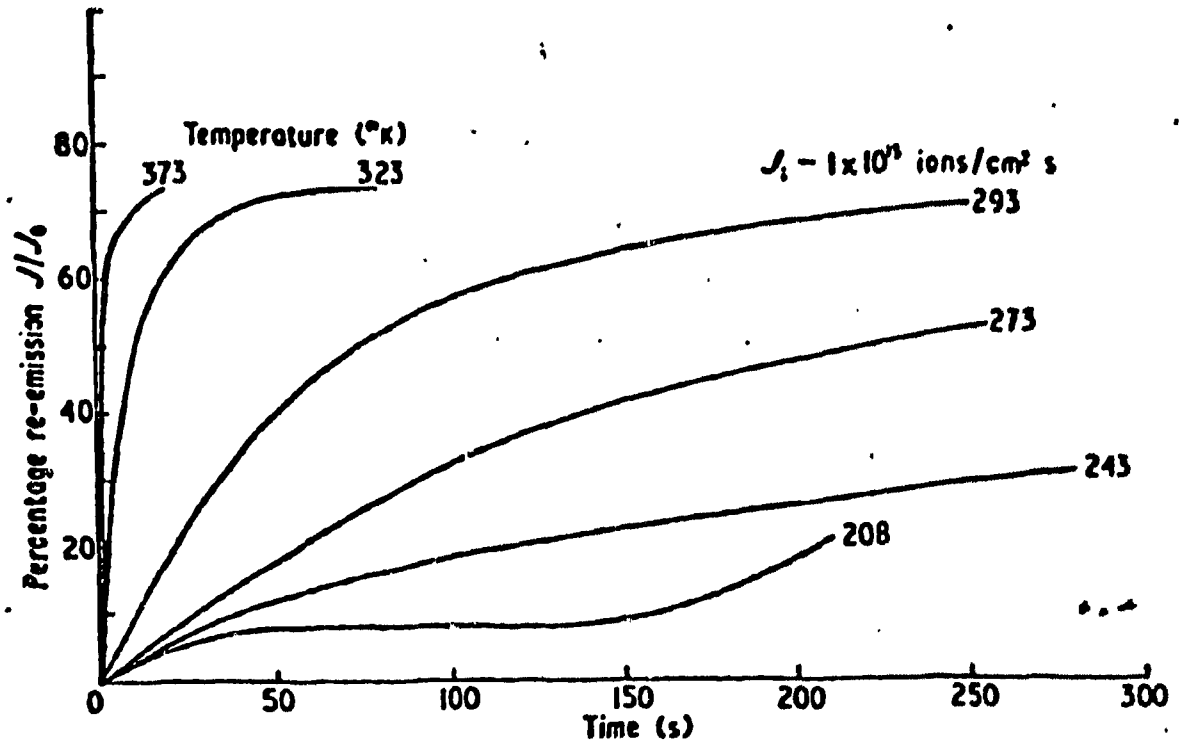


Fig. 7. Re-emission probability of deuterium on nickel as a function of bombardment time at different target temperatures [54].

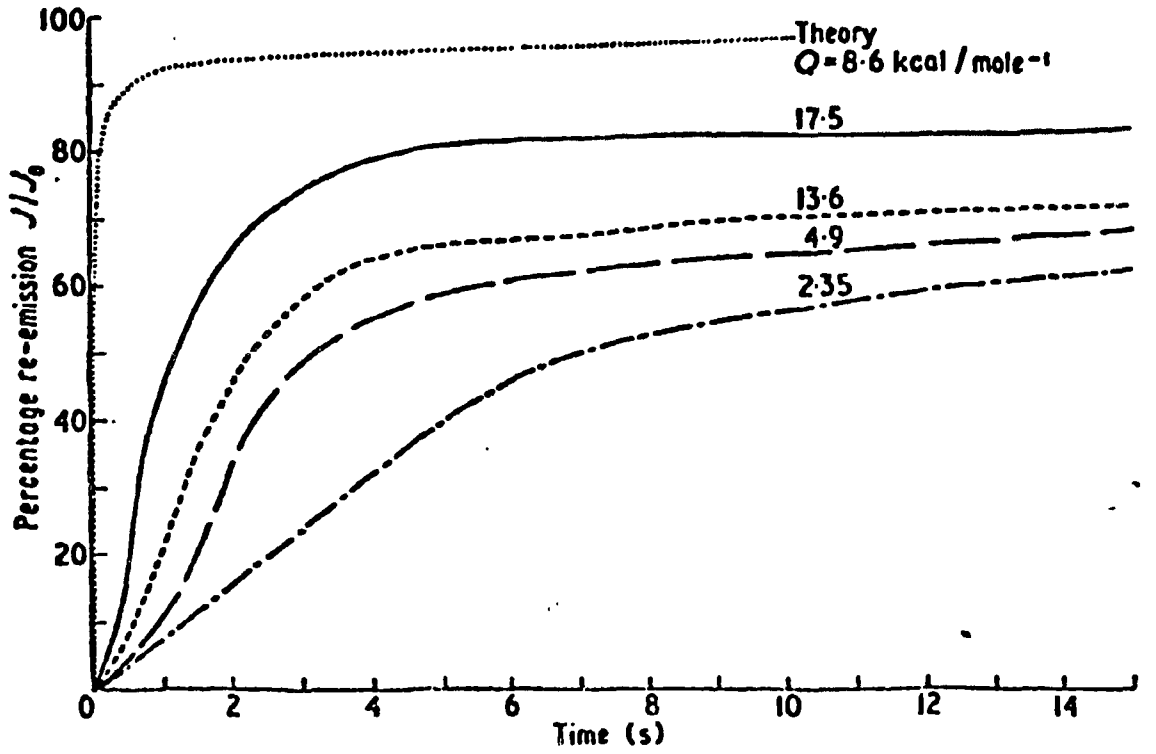


Fig. 8. Re-emission probability of deuterium on nickel as a function of bombardment time for various D^+ fluxes (in 1014 ions/cm2.sec) at 373oK [54].

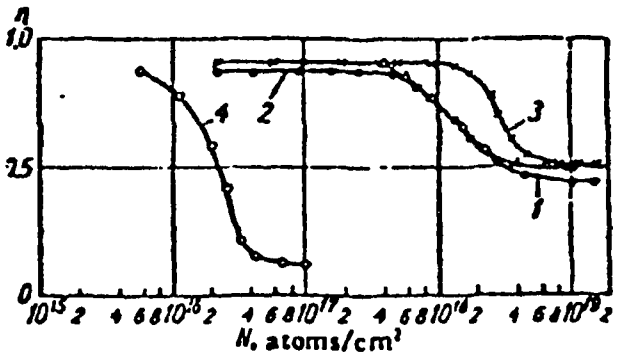


Fig. 9. Re-emission probability of H^+ on high-grade steel at different temperatures.

Formation of bubbles was observed with hydrogen ions on copper and beryllium [57], with deuterium on copper [58], and with helium on niobium [57].

On the other hand, in the case of metals that have a high solubility for hydrogen---e.g. V, Nb, and Ta---even after bombardment with doses of 10^{19} to 10^{20} cm^{-2}, no trace of bubble formation is observed.

This formation of bubbles has not received much study in the past. Above all, very little is known about the size of the bubbles and their number per unit of surface area as a function of dose, dose rate, temperature, and structure of the metal. Further, the problem has not yet been solved as to whether the pits formed on breaking of the bubbles result in a fissuring of the surface which is great enough that, under certain conditions, the wall strength is impaired. Experiments performed previously in most cases do not go beyond total bombardment doses of 10^{19} to 10^{20} cm^{-2}. However, these doses are too small for the total life of a reactor wall.

4. Unsolved Problems

This study has shown that, for the wall problem in fusion reactors, some processes must still be studied in greater datail---processes which are almost sure to have an important influence. These are,briefly,

a) Sputtering with D, T, and He in the range of energies from 10 eV to 10 keV.

b) Distribution of energies of the atoms eroded away on bombarding with light ions.

c) Bubble formation in metals on bombardment with hydrogen and helium ions as a function of the energy, dose, dose rate of bombardment, and target temperature.

d) Erosion of metal surfaces with impingement of hot plasma; problems of the limiter and divertor.

e) Distribution of energies of back-scattered light ions in the energy region below 10 keV.

List of Important Unsolved Problems

1. Sputtering yields with D, T, and He in the energy range below 10 keV.

2. Energy distribution of sputtered metal ions on bombardment with light ions.

3. Formation of bubbles in metals on bombardment with hydrogen and helium ions; threshold energy for bubble formation.

4. Erosion of metal surfaces by impingement of hot plasma.

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