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ION AND FAST NEUTRAL BOMBARDMENT OF SURFACES IN CONTROLLED FUSION DEVICES

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ABSTRACT

The erosion of ferrous- and nickel-alloy walls in fusion reactors from impinging, energetic D-, T-, He-, and Ar - ions and neutrals is discussed. The two major mechanisms of erosion are sputtering and blistering. Pertinent data are reviewed to obtain estimated or experimental sputtering yields in the energy range 100 eV to 10 keV. The sputtering coefficients for Ar, He, and T are roughly 10^2, 10, and 1.5 times the value for D (at the same energy). Erosion from blistering is unimportant for Ar, unexamined for D or T, and probably comparable to sputtering for ~ 10 keV He.

I. INTRODUCTION

Ion and fast neutral bombardment (hydrogen isotopes, helium, impurities) of surfaces in controlled fusion devices affect the influx of cold particles to the plasma, the lifetime of reactor walls, and the tritium hold up and recovery route. Erosion due to the physical and chemical sputtering or blistering and embrittlement resulting from gas hold up may preclude reasonable wall lifetimes. Data on the sputtering coefficients for all plasma particles over a wide energy range are not available nor are hard numbers available to predict the identity, number, and energy distribution of the bombarding particles.

Erosion due to physical sputtering is strongly dependent on the mass and atomic number of both the bombarding species and the wall atoms as well as the energy and flux of the incoming energetic ions and neutrals. The implantation of energetic gaseous ions and neutrals produces drastic changes in the surface layers of metals: a large number of metal lattice vacancies and interstitials; a gas atom concentration that may equal the metal atom concentration; and electron excitation and thermal heating. The majority of these implanted gas atoms will be re-emitted at the bombarded surface for the metals that we consider, such as ferrous- and nickel-alloys, at temperatures around 500° C. Under certain unpredictable conditions some of this re-emission may result from the bursting of gas-filled bubbles that form in the surface layer by a coalescence of gas trapped at vacancies. This phenomenon, which is referred to as blistering, has recently been observed for He bombarding stainless steel[1] and nickel.[2] Some of the implanted hydrogen may migrate into the bulk of the metal wall and either become trapped at energetically favored sites, form a dilute solution in the metal, or be emitted at the unbombarded side. Too high a concentration of hydrogen in the bulk of the metal is undesirable because of degradation of mechanical strength by hydrogen embrittlement (especially important on cool down) and the desire to keep the tritium inventory as low as possible.

The aim of Sec. II is to indicate the gross characteristics of the bombarding particles impinging on the first wall. In Sec. III we present pertinent sputtering data, make necessary extrapolations to obtain estimates for needed sputtering coefficients and then calculate the wall erosion resulting from possible bombardment situations. The problem of blistering is addressed in Sec. IV. Finally in Sec. V we summarize the implications of our analysis to both reactors and experimental plasma devices and the areas where more experiments are needed.

II. THE BOMBARDING SPECIES

A D-T reactor plasma such as that proposed by the Princeton Reactor Studies Group (PR SG) contains D^+, T^+, Ar^{18+}, and impurities, e.g., Fe^{26+}, with an average energy of about 15 keV and He^{2+} ions with energies from 3.5 MeV down. The average He^{2+} energy in this burning plasma is expected to be in the range 10-50 keV.[3] Our reference to ~ 10 keV ions is meant to include these 10-50 keV He^{2+} ions. The question of how many ~ 10 keV particles reach the first wall is difficult to answer and model-dependent. (The lowest estimate is essentially none.[3]) Bombardment of the first wall by $\gtrsim$ 10 keV ions may result from plasma instabilities. Bombardment by ~ 10 keV neutrals, primarily D and T, can result from charge exchange if cold neutrals or partially-stripped ions enter the burning plasma. (The probability of He^{2+} acquiring two electrons via charge exchange is thought to be low so that bombardment by $\gtrsim$ 10 keV—He neutrals may be negligible.)

Possible sources of neutrals or partially-stripped ions entering a burning plasma are re-fueling by injection of neutral pellets or neutral beams as well as neutrals coming from the first wall or divertor region. A proposed model[4] for the divertor and scrape-off region keeps unwanted neutrals from the burning plasma; however, it is probably overly optimistic to assume that no neutrals will get to its edge. In this model[4] the first wall will also be bombarded by ions and neutrals having energies characteristic of the scrape-off region (~ 5 eV) and the transition region between the burning plasma and scrape-off region (~ 5 eV to 10 keV).

The damage to the first wall from bombardment is assumed to be directly proportional to the flux, for a given energy and identity of bombarding particles. (It is essentially independent of the charge on the particle so that damage from ions and neutrals of the same species and energy will be similar.) Since uncertainties exist in the fluxes, energies, and identity of the particles that will bombard the various regions of the first wall, we consider the damage associated with a wide span of energies.

Using existing experimental data we will estimate erosion rates for assumed fluxes to indicate required limits on these fluxes commensurate with reasonable first wall lifetimes.

III. SPUTTERING

When energetic particles bombard target materials with energy above a threshold value (~ 10 eV), they penetrate the surface and initiate a transfer of energy to target atoms so that some of them are ejected from the surface. This process is referred to as sputtering. The number of ejected target atoms per incident particle is the sputtering coefficient. The incident particles in most sputtering experiments have been ions, however, the sputtering yield is assumed to be independent of the charge on the bombarding particle.

A qualitative picture of sputtering from a random target follows. An impinging particle undergoes a series of collisions in the target; atoms that recoil with enough energy undergo secondary collisions, thereby creating another generation of recoiling atoms. The incident particles and energetic recoil atoms have the possibility of getting back-scattered out of the target surface with an appreciable fraction of their initial energy. Since the second generation of scattered target atoms have much lower recoil energy and consequently shorter range, only those located originally within a few atomic layers of the surface will retain sufficient energy to overcome the surface binding force and be ejected. The majority of the sputtered atoms result from these secondary collisions in the surface region. Hence the sputtering yield depends primarily on: (1) the energy deposited in the surface region of the target by both the bombarding particle and energetic recoil atoms and (2) the surface binding energy.

The surface binding energy depends on surface impurities, absorbed or adsorbed gas, and the crystallographic plane or planes at the surface. Thus sputtering yields are dependent on the existing surface conditions. The temperature of polycrystalline targets is not likely to be a significant factor as long as its well below the melting point. In the case of reactive bombarding species, such as hydrogen, chemical forces may play a significant role in the sputtering process and molecules like NiH could be ejected.

The maximum energy that can be transferred in a two-body collision is limited by conservation of momentum and energy to $4m_1m_2/(m_1 + m_2)^2 E_1$, where m_1 and E_1 are the mass and energy of the incident particle in the reference frame where the second particle of mass m_2 is at rest. When $m_1 = m_2$ all of the energy can be transferred. The transferred energy decreases as the mass ratio m_1/m_2 departs from one; this is reflected in similar decreases in sputtering yields; however, this simplified model does not quantitatively give the mass dependence of the sputtering yields.

The sputtering yield exhibits a maximum when the angle of incidence is about 60° - 70° from normal.[5] Most sputtering data are for normal incidence; incidence at ~ 60° from normal could increase the yield by an order of magnitude.

A representative curve showing the dependence of the sputtering coefficient S(E) on the energy E is shown in Fig. 1. The rather broad maximum which occurs around 1 keV to 10 keV reflects the energy region where the increasing penetration depth of the bombarding particle results in a smaller fraction of its total energy being deposited in the surface region.

Available Data

A number of review articles on sputtering contain collections of existing data and details of various theoretical models.[5-11] No pertinent sputtering data found for the PRSG proposed first wall alloy, Nimonic P.E.16 containing primarily 44% Ni, 17% Cr, 1% Ti, 3% Mo, and 35% Fe; however, its sputtering coefficient is not likely to differ appreciably from that of Fe and Ni. (The available sputtering coefficients for these two metals are within a factor of two.) Figures 2-8 are plots of the more pertinent sputtering data to the first wall erosion of ferrous- or nickel-based alloys.

Guseva's data[12] on the sputtering yields for stainless steel bombarded by 5 - 30 keV D^+ (Fig. 2) show that S is essentially the same at 5 and 10 keV and decreases at higher energies.

The most extensive collection of sputtering data comes from Wehner and co-workers,[13-16] who measured the sputtering yields for the inert gases over the energy range 0 to 600 eV and for H_2^+ and H_3^+ with an energy of 7 keV on many metal targets. Their data for He[13,14] and Ar[13,15] bombardment of Fe, Cr, and Ni are plotted in Figs. 3 and 4. Similar values for Ar bombardment have been reported by Weijsenfield et al.[17] No data were found for hydrogen in this low energy range; however, later in this section we will scale some data on silver to estimate a value for 700 eV D. Figures 5 and 6 are plots of the sputtering yield of 300 eV He^+,[14] and 7 keV H_2^+,[16] as a function of the atomic number of the target material. A strong periodic dependence of the yield exists in metals for all bombarding ions with maxima occurring at Cu, Ag, and Au, which is correlated to the filling of the 3d, 4d, and 5d shell. This consistency gives us a certain amount of confidence in scaling the rather extensive sputtering data of Gronlund and Moore[18] on silver shown in Figs. 7 and 8 to obtain estimated sputtering yields on iron and nickel.

The sputtering yield for molecular ions such as 7 keV H_2^+ in Fig. 7 is used to calculate the yield for 3.5 keV H^+ by assuming that the energy is equally divided between the H nuclei which then sputter independently. Similarly the data for 2 keV H_3^+ on silver in Fig. 8 can be used to obtain sputtering yields for 700 eV H^+ on silver. This implies that the sputtering yield for H and D is roughly constant over the energy range 1 keV to 12 keV with the value of D falling off more at the higher energies than that for H. Also the value for D is more than twice the value for H.

A summary of experimental sputtering yields for H^+, D^+, He^+, Ar^+, Fe^+, Ni^+, and Cr^+ bombardment of Fe, Ni, Cr, and stainless steel targets is given in Table I. Except for Ar^+ on Fe we can see that the existing data fail to cover a wide spectrum of energies. Sputtering data for Fe, Cr, and Ni bombarding ions are of interest since sputtered wall atoms may become energized in the plasma and return to the wall to produce additional sputtering. Assuming that the data on silver and iron scale as in Figs. 5-8 we estimate sputtering yields on iron- nickel-chromium alloys in the energy range 1 keV to 10 keV to be 0.03 for D, 0.04 for T, 0.3 for He, and 2.0 for Ar. These values are expected to be good to better than an order of magnitude and, in fact, the value obtained this way falls within a factor of two of the experimental data in Fig. 2 for D on stainless steel. We feel less certain about scaling and extrapolating the sputtering data for H to estimate the yields for D and T at energies below 1 keV; however, we assume that they fall off linearly below 1 keV.

Wall Erosion

For a twenty year lifetime the wall erosion rates cannot appreciably exceed 10^{-2} cm/year. The yearly erosion rate from sputtering by particle i with energy E is

$$T_i(E) = C\ S_i(E)\ J_i(E) = 3.8 \times 10^{-16}\ \frac{\text{cm sec}}{\text{year atom}}\ S_i(E)\ J_i(E)$$

$$C = (3.16 \times 10^7\ \frac{\text{sec}}{\text{year}})\ n^{-1}$$

$$n \cong 8.4 \times 10^{22}\ \frac{\text{atoms}}{\text{cc}} \quad .$$

Here T_i is the thickness that is eroded in cm/year; C is a constant that varies with the atomic density of the wall, n, as shown and is assigned a value that is typical of ferrous- and nickel-alloys, $S_i(E)$ is the sputtering coefficient of projectile i with energy E in atoms/ion, and $J_i(E)$ is the flux in ions (or neutrals)/cm^2 sec .

The fluxes $J_i(E)$ that produce a yearly erosion rate of 0.01 cm/year using the above equations together with experimental data or our estimates for $S_i(E)$ for D, T, He, and Arcat two characteristic energies are given in Table II. The maximum acceptable (D,T) flux at 100 eV is about 5×10^{15} ions/cm^2. This energy was chosen as typical of the erosion rate from low energy particle bombardment and is in a region where the sputtering scales roughly linearly with energy. The existence of a plasma sheath near the walls that is ~ 4 kT_e (T_e is the electron temperature) results in multi-charged ions bombarding the walls at higher energies and producing more damage. Table II shows that if 8% of the bombarding ions are 200 eV He^{2+}, the erosion rate doubles, and if 2% are argon, the erosion rate increases by a factor of two or more depending on the ionization states of the argon.

The erosion rate in the 1 - 10 keV region is not expected to vary much with the bombarding energy (see Table I). The data for D on stainless steel[12] and H, D, and He on silver (Figs. 7 and 8) both support this. If all of the plasma ions leaving the PRSG reactor were to uniformly hit the first wall once, the flux would be 1.5×10^{15} ions/cm^2-sec. (This is the number of exiting particles divided by the first wall area.)

These calculations suggest that the wall erosion rate from D, T, and He particles that escape from the plasma will be tolerable provided: (1) these escaping particles strike the wall no more than once before they are pumped. (The divertor should prevent most of them from striking the wall even once.), (2) there are not locally high fluxes such as at the divertor entrance or near the refueling entrance, and (3) the estimated sputtering yields are accurate. The higher sputtering coefficient for argon necessitates a correspondingly lower flux that bombards the first wall. As mentioned earlier ~ 10 keV argon and helium bombardment of the first wall occurs primarily by instabilities in confinement and not by charge exchange with neutrals.

Erosion by the sputtered wall particles (e.g., Fe and Ni), will be negligible as long as their bombarding energy is below ~ 1 keV. The divertor and scrape-off region[4] is designed to prevent bombardment of these ions at higher energies.

In concluding this section on erosion by sputtering we wish to re-emphasize the lack of sputtering data on the proposed first wall alloy, and the uncertainty of the particle fluxes and energies that will bombard the wall. The combination of these two unknowns prevents an accurate prediction of the first wall erosion rate due to sputtering at this time.

IV. BLISTERING AND ASSOCIATED PHENOMENA

Blistering, pitting, flaking, and exfoliation of surfaces subjected to bombardment by H^+, D^+, and He^+ have been reported for both metals and insulators.[1,2,23-28] The available data indicate that blistering is favored by a low gas solubility and a high number of radiation-produced lattice vacancies which promotes the coalescence of the injected gas and vacancies to form gas-filled bubbles. The region at which bubble growth initiates corresponds to the projected range or penetration depth for the bombarding ion (10^3 Å for ~ 10 keV H or He).

Many factors are expected to influence the growth, migration, and eventual rupture of these bubbles. These include temperature, implantation rate and depth, re-solution probability of precipitated gas, radiation damage, local stress, yield strength, and target microstructure including grain size, crystallite orientation, and precipitated solid phases such as carbides. Unexpectedly high surface temperatures may develop due to subsurface bubbles lowering the thermal conductivity and result in evaporation, enhanced bubble growth, or surface rupture at a lower dose. Presently, the theoretical models for formation, growth, and rupture of gas bubbles cannot predict the magnitude and nature of the surface damage thus produced and experimental data on blistering of iron- or nickel-alloys are scant. The short range (50 Å) and high sputtering coefficient for 10 keV argon imply that it will not cause blistering. On the other hand, we expect blistering to occur from bombardment with $\gtrsim$ 10 keV He and do not know about bombardment with ~ 10 keV H, D, or T.

Bauer and Thomas[1] have found that 300 keV He implanted in stainless steel in the temperature range -50° C to 500° C produces a large amount of surface flaking after a critical He dose of 10^{18} atoms/cm^2 whereas at temperatures above 600° C it results in ruptured surface blisters after doses of 5×10^{17} atoms/cm^2. Their helium ion flux was 6×10^{13} ions/cm^2-sec. A similar dependence has been reported by Erents and McCracken for molybdenum bombarded by 36 keV He^+ ions;[2] the temperature ranges differed but the critical dose was still ~ 5×10^{17} He atoms/cm^2.

We will roughly estimate the wall erosion from He blistering by assuming that (1) the injected He collects in bubbles at a distance beneath the surface determined by the penetration depth and (2) after a critical dose (~ 10^{18} ions/cm^2-sec) the gas pressure becomes sufficient to result in the exfoliation of this retaining surface. The penetration depth or projected range for 6 - 60 keV He in Fe or Ni is given by

$$R(\text{Å}) = 31\ E(\text{keV})$$

which we calculate using the theory of Shiott[29] for light ion ranges R as a function of energy E. The yearly erosion rate, B, is

$$B(\text{cm}) = \frac{R(\text{Å})}{10^8\ \text{Å/cm}} \cdot \frac{J(\text{ions/cm}^2\text{-sec})}{10^{18}\ \text{ions/cm}^2} \cdot 3.1 \times 10^7\ \text{sec/year}$$

$$= 3.1 \times 10^{-19}\ R.J$$

where R is the range in Å, J is the flux in ions (or atoms)/cm^2-sec. Substitution for R in terms of E gives

$$B = 9.6 \times 10^{-18} \cdot J \cdot E\ \text{cm/year} \quad .$$

Thus bombardment with 10^{14} He ions/cm^2-sec at 50 keV causes an estimated erosion of 0.05 cm/year or 10^{14} He ions/cm^2-sec at 10 keV causes an estimated erosion of 0.01 cm/year due to blistering. The sputtering-associated erosion in either case is estimated to be 0.01 cm/year.

Hydrogen is known to permeate through metals and have a higher solubility than helium. This is the basis for predicting that blistering from hydrogen implantation will occur less often and require larger doses. This has been somewhat verified by the observation that 250 keV D^+ bombardment of 700° C Nb produces blistering after a fluence of ~ 10^{19} ions/cm^2 and that the surface damage is less severe than from 500 keV He bombardment. However, blistering in niobium from implanted D was unexpected and indicate the important role that radiation damage and kinetic effects must play in bubble formation. A simple steady state diffusion model using the diffusion coefficient for D in undamaged Nb would predict a maximum implanted D concentration of ~ 10^{-2} appm, well within the solubility limits.

The fact that deuterium-bombarded Nb blisters suggests that deuterium-bombarded iron- and nickel-based alloys may also blister. However, experiments will be necessary to determine if blistering does occur and if significant wall erosion occurs by this mechanism. Also the simultaneous bombardment of D,T, and He could result in synergistic effects associated with changes in the bombarded surface region due to the presence of two injected gases. (The projected ranges for 10 keV D, 10 keV T, and 20 keV He are essentially the same.)

V. DISCUSSION

Limited experimental data are available on pertinent sputtering yields and blistering of iron, nickel, and their alloys subjected to ion bombardment with H^+, D^+, He^+ or Ar^+. The sputtering data were obtained before blistering from injected H, D, and He had been observed. The study of blistering and associated phenomena is in the stage of characterizing the dependence of the surface damage on a few parameters—fluence, temperature, target material; information is not yet available to forecast the cumulative wall damage and erosion from long term particle bombardment. The large threshold dose ($\gtrsim 10^{17}$ ions/cm^2-sec), microscopic size ($\sim 10^{-6} - 10^{-3}$ cm), and impulsive gas release with surface rupture typical of blistering make it difficult to ascertain whether possible erosion contribution from blistering were measured in some of the early sputtering experiments.[12,14,16,19] Considerations of the depth of bubble formation and associated fluence required for surface damage allows us to estimate that blistering and sputtering produce a comparable amount of wall erosion for 10 keV He^+ bombardment and that the erosion from blistering becomes dominant at higher energies. Blistering from H and D bombardment of Fe, Ni, and their alloys has not been observed but could occur.

We estimate from existing sputtering data that bombardment of the first wall with a relatively large flux (5×10^{14} ions/cm^2-sec) of 10 keV (D,T) neutrals or ions will erode the first wall 0.01 cm/year, however, for a similar erosion rate the flux of 10 keV argon must be down by two orders of magnitude and the flux of 10 keV He down by one order of magnitude. The erosion rates are expected to remain essentially constant over the energy range 1 - 10 keV and decrease approximately linearly with energy below 1 keV. The plasma sheath potential ($\sim 4\ kT_e$) can result in significant acceleration of ions prior to wall bombardment and add significantly to the erosion rate from low temperature (~ 25 eV) plasmas, especially when multi-charged He- and Ar-ions are present.

No experimental data exist on nickel and iron alloys under prolonged and/or simultaneous bombardment with H-, D-, He-, and Ar-ions or neutrals in the energy range 5 eV to 50 keV. Such experiments are needed since the erosion from combined bombardment is unlikely to be the sum of separate erosion rates—especially when blistering occurs.

Experimental programs are needed to study the bombardment of proposed first wall alloys at expected operating temperatures with H^+, D^+, and He^+ at energies from ~ 50 keV down. It is hoped that in our presentation of experimental data on Fe, Ni, and Cr and subsequent use of it to estimate erosion rates of ferrous- or nickel-alloys that the scarcity of data and uncertainty in our estimated erosion rates were noted. In addition to measuring gross erosion rates, such a program should aim at characterizing and understanding the factors that determine both (1) the migration, hold up and re-emission of the injected H, D, and He atoms and (2) the energy and identity of material eroded from the surface. This is important because of possible plasma contamination and interest in anticipating the hold up or migration through the first wall of tritium.

Experimental Plasma Devices

The influx of cold neutral atoms (metal and H) from the limiters and vacuum walls are affecting quasi-steady-state plasma discharges such as the ATC and ST Tokamaks. The prospect of higher plasma temperatures resulting from a lowering of the radiative energy losses through Bremsstrahlung and line radiation make it desirable to minimize high Z impurities in the plasma either by using a magnetic divertor or "low-contaminating" materials for the limiter and vacuum walls. The concentration of metal impurities entering the plasma depends on the energy, charge, and spatial distribution of metal particles ejected from the limiter and divertor under the existing set of bombardment conditions. Such detailed information on sputtering (or possibly blistering or evaporation) is not generally available. The sputtering yields for 300 eV He and 7.5 keV H_2^+, for a variety of metals, as plotted in Figs. 5 and 6, provide a somewhat reliable gauge for judging the relative contaminating tendency of materials for interior use in plasma devices.

The sputtering yields for bombardment with light particles, such as H or He, decrease with increasing atomic weight of the target material; the sputtering yields for any bombarding particle on transition metal targets increase with the filling of the d-electron shell reaching maxima at Cu, Ag, and Au. A comparison of sputtering yields from stainless steel and gold (used in ORMAK is of interest but inconclusive since for 300 eV He^+ bombardment apparently the increase in mass dominates the filling of the d-electron shell since the yield for Au is one-half the yield for Fe. On the other hand, for bombardment with 7.5 keV Hg^+ (3.7 keV H^+) the reverse is true with the yield for Au being twice the yield for Fe. The advantage of gold-plating the walls is questionable for future higher-energy plasma devices, especially for H plasmas.

Limiters, which receive the heaviest particle bombardment, are usually made from Mo or W, both of which are heavy early transition metals and have low sputtering yields. These metals might make interesting liners for plasma devices as divertors since they are low-sputtering metals and do not form stable hydrides.

The use of the earliest transition metals for interiors in plasma devices is certainly suggested by their low-sputtering yields in Figs. 5 and 6. However, Ti, V, Zv, Nb, and Ta form stable metal hydrides at low temperatures which may result in a deterioration of mechanical properties. Numerous papers and books on the metal hydrides are available[30-32]; however, the characteristics of metal hydrogen reactions at low temperatures (< 300° C) are poorly described and very sensitive to small details such as impurity content.

In conclusion we would like to point out that experimental programs characterizing the interaction of energetic H and He particles with metal surfaces are pertinent both to reactor technology and to current experimental plasma devices.

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TABLE I. Sputtering yield data on Fe, Cr, Ni

Target Fe	Yield[+]
7.5 keV H_2^+	0.024[a]
8.0 keV H_2^+	0.017[a]
7.5 keV H_3^+	0.030[a]
8.0 keV H_3^+	0.022[a]
6-30 keV D^+	0.05-0.02[b*]
35 keV H^+	0.009[c*]
36 keV (H^+, H_2^+)	0.009[d*]
51 keV (H^+, H_2^+)	0.016[d*]
75 keV (H^+, H_2^+)	0.009[d*]
100 eV He^+	0.030[e]
600 eV He^+	0.170[e]
100 eV Ar^+	0.20[f] 0.1[g]
600 eV Ar^+	1.26[f] 0.9[g]
1000 eV Ar^+	1.4[h,g]
2000 eV Ar^+	2.0[h*]
5000 eV Ar^+	2.5[h*]
1.1 keV Fe^+	1.1[i]
45 keV Fe^+	2.9[i]
Target Ni	
7.2 keV H_2^+	0.037[a]
7.5 keV H_2^+	0.035[a]
7.2 keV H_3^+	0.058[a]
7.5 keV H_3^+	0.058[a]

TABLE I (Continued)

Target Ni (Cont'd)	
100 eV He^+	0.028[e]
600 eV He^+	1.18[e]
100 eV Ar^+	0.28[f] 0.25[g]
600 eV Ar^+	1.52[f] 1.5[g]
1000 eV Ar^+	2.1[g,h]
1.0 keV Ni^+	1.0[i]
45 keV Ni^+	3.8[i]
Target Cr	
100 eV He^+	0.030[e]
600 eV He^+	0.20[e]
100 eV Ar^+	0.30[f]
600 eV Ar^+	1.30[f]
45 keV Cr^+	1.0[i]

+ The yield is per bombarding particle where H_2^+ is counted as one bombarding particle

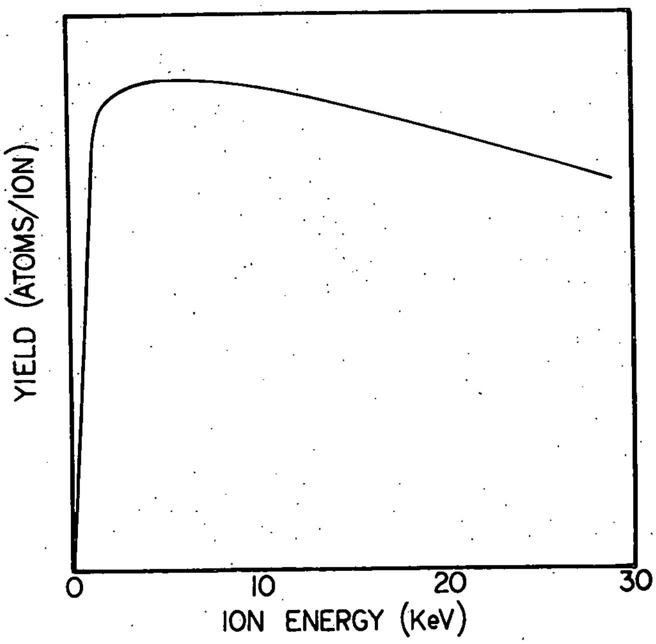
* stainless steel
a ref. 16
b ref. 12
c ref. 22
d ref. 19
e refs. 13, 14
f refs. 13, 15
g ref. 17
h ref. 21
i ref. 20

TABLE II

Bombarding Particle	S(atoms/particle)[a]	J(particles/cm^2-sec)[b]
100 eV D	0.005	5×10^{15}
100 eV T	0.007	4×10^{15}
100 eV He	0.04	7×10^{14}
200 eV He	0.07	3×10^{14}
100 eV Ar	0.3	9×10^{13}
200 eV Ar	0.6	4×10^{13}
1-10 keV D	0.05	5×10^{14}
1-10 keV T	0.07	4×10^{14}
1-10 keV He	0.3	9×10^{13}
1-10 keV Ar	2.0	1×10^{12}

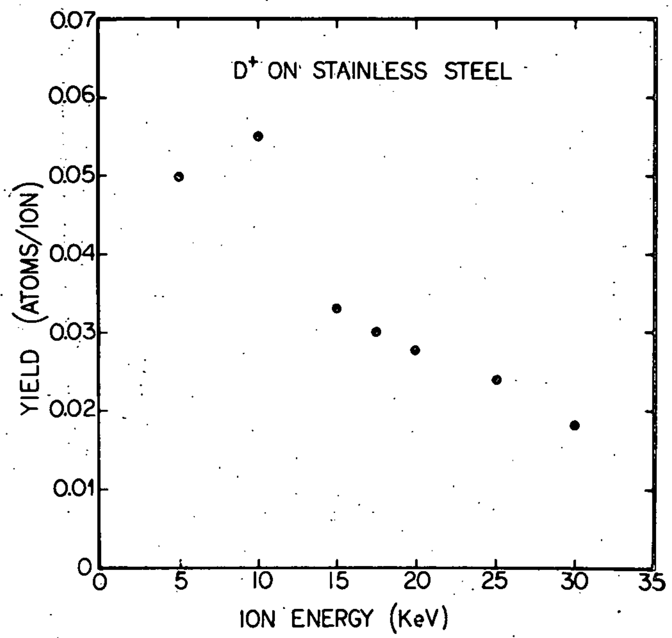
a Estimated values. See sputtering section

b Flux that is expected to produce an erosion rate of 0.01 cm/year.



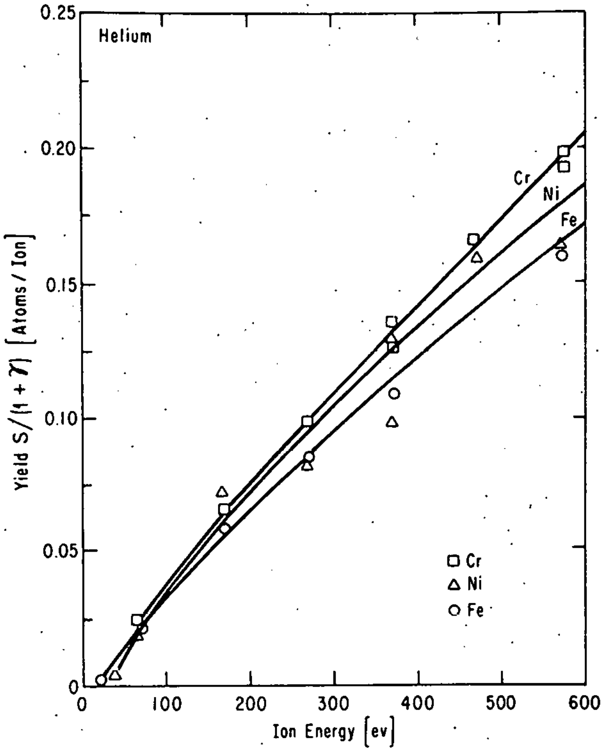
734223

Fig. 1. A representive sputtering curve to demonstrate the energy dependence of the yield.



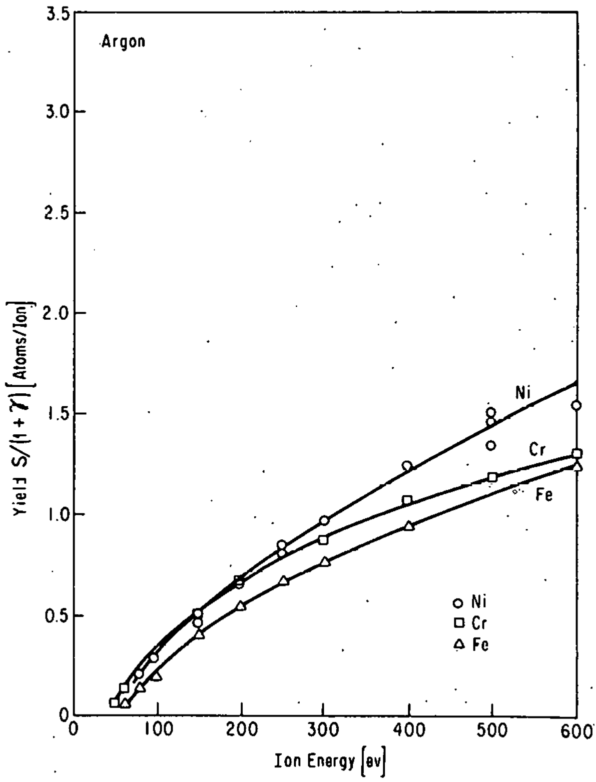
734222

Fig. 2. The sputtering yield for D^+ bombardment of stainless steel as a function of ion energy. Data from ref. [12].



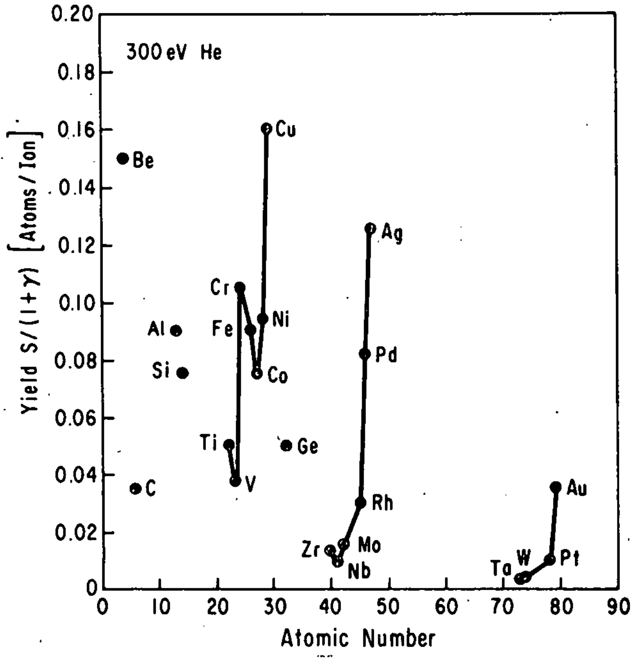
734218

Fig. 3. Sputtering yield (uncorrected for secondary electrons) of low energy He^+ on Cr, Ni, and Fe. Data from ref. [13].



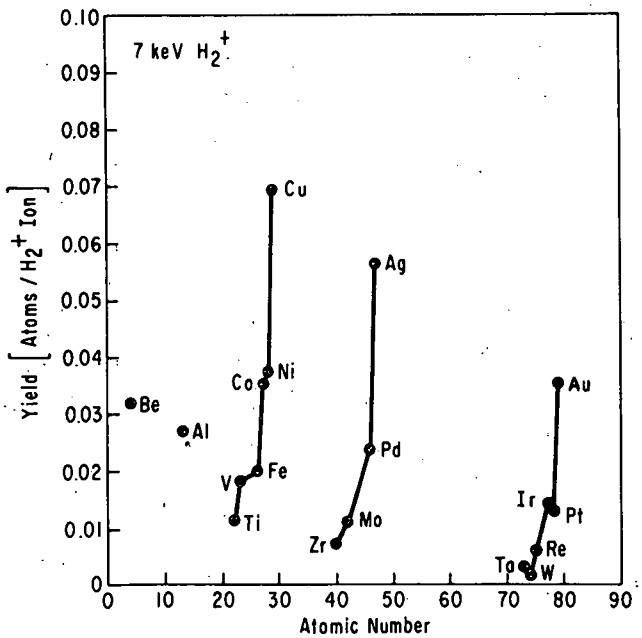
734219

Fig. 4. Sputtering yield (uncorrected for secondary electrons) of low energy Ar^+ on Cr, Ni, and Fe. Data from ref. [13].



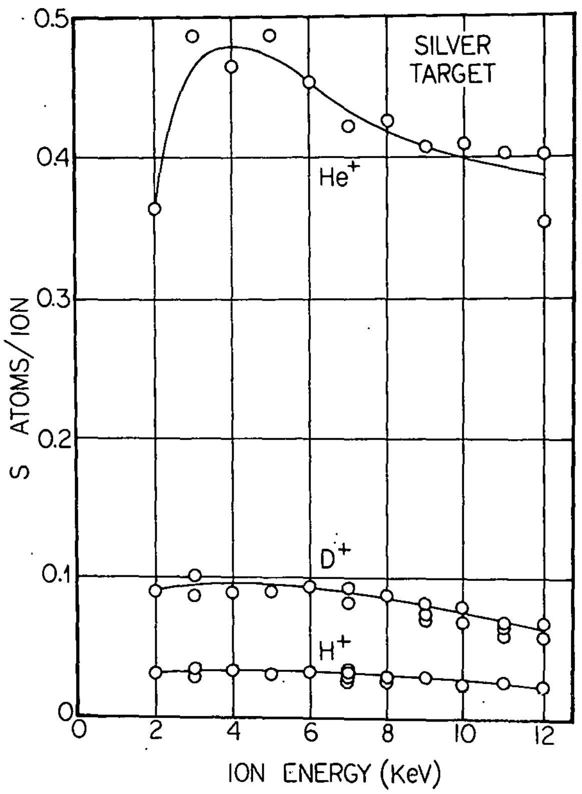
734216

Fig. 5. The sputtering yield for 300 eV He^+ bombardment as a function of the target's atomic number. The divisor (1+γ) indicates that the ion current was uncorrected for secondary electron yield γ. Data from ref. [14].



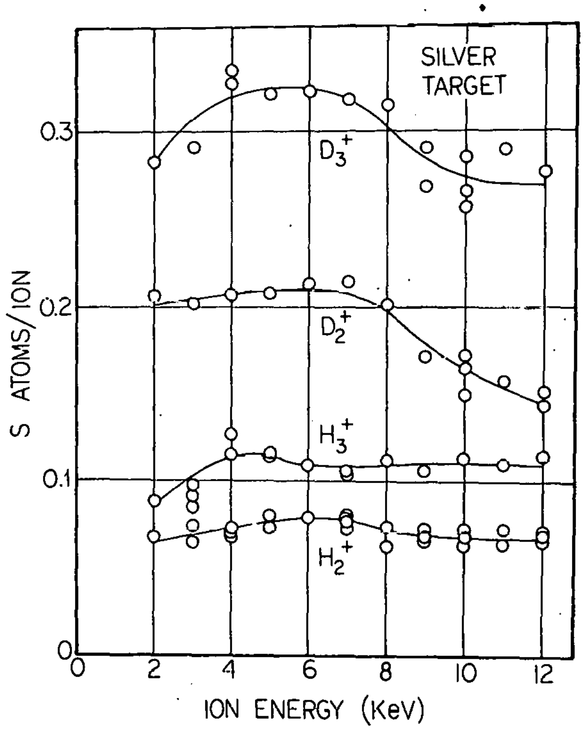
734217

Fig. 6. Sputtering yield for 7 keV H_2^+ bombardment as a function of the target's atomic number. Data from ref. [16].



734221

Fig. 7. Sputtering yield of He^+, D^+, and H^+ on silver as a function of energy.
Figure from ref. [18].



734220

Fig. 8. Sputtering yield of D_3^+, D_2^+, H_3^+, and H_2^+ on silver as a function of energy.
Figure from ref. [18].