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Publication Date

1981-10-01

LBL-13515

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Accelerator & Fusion Research Division

Presented at the 9th Symposium on Engineering Problems of Fusion Research, Chicago, IL, October 26-29, 1981

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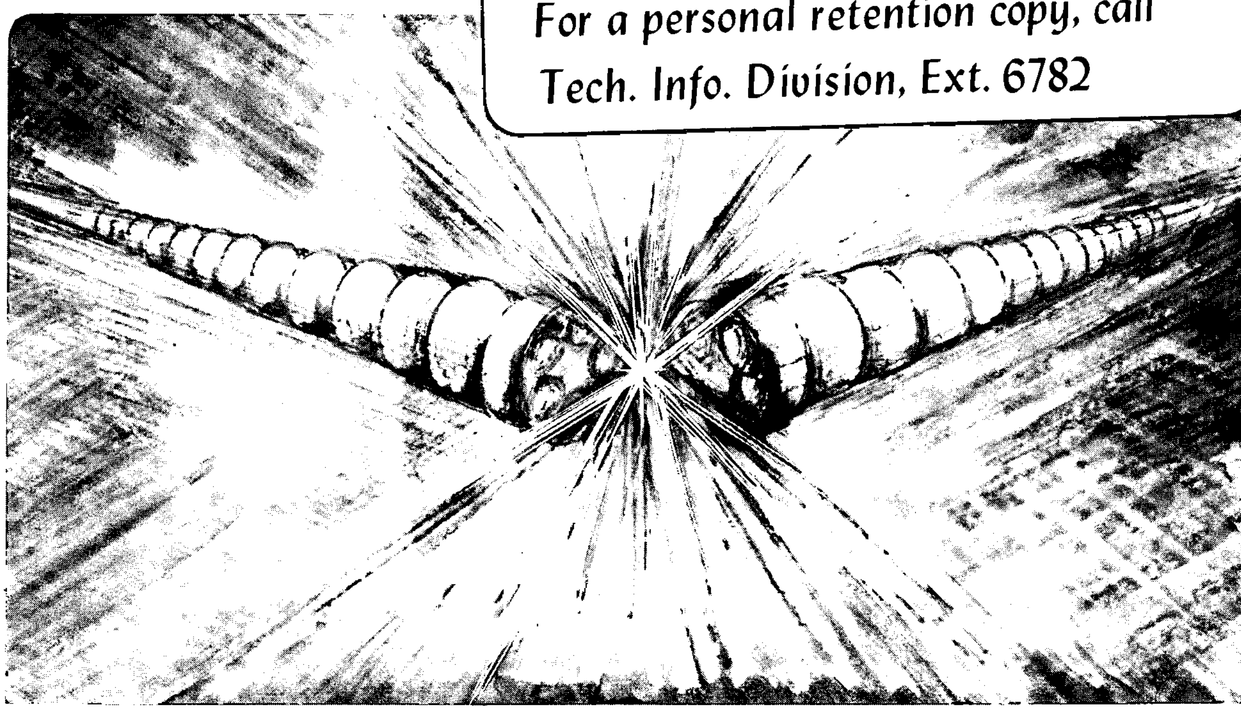
October 1981



Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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SPUTTERING EROSION ESTIMATES FOR NBETF BEAM DUMPS

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Abstract

To stop multi-second high-energy hydrogen or deuterium beams in neutral injection systems, thin-skin actively cooled dumps made of Cu, Mo, or W are contemplated. For the Neutral Beam Engineering Test Facility (NBETF), the design goal for the life of the beam dumps is 25,000 thirty-second pulses, with a fluence of 10^{23} deuterons/cm^2. From a review of the literature on sputtering and blistering, we estimate that an erosion allowance of 0.13 cm for Cu, 0.02 cm for Mo, and 0.004 cm for W has to be incorporated in the beam-dump design.

I. Introduction

The development of high-energy hydrogen and deuterium beams for neutral injection systems has to deal not only with the problem of generating and directing such beams but also with the problem of how to stop them. For example, the Neutral Beam Engineering Test Facility (NBETF) at the Lawrence Berkeley Laboratory has been designed for the development of deuterium neutral-beam sources with energies up to 170 keV, currents of 65 A, and pulse lengths of 30 sec with a 10% duty cycle.[1] The long pulses dictated the choice of actively cooled heat absorption panels - thin metal surfaces backed by high-velocity water - for the beam dumps.[2] Anticipated peak power densities normal to the beam are as high as 30 kW/cm^2. The dumps, which will be inclined to reduce power densities on the surfaces to the design value of 2 kW/cm^2, will be exposed to fluxes of 0.7 x 10^{17} deuterons/cm^2-sec for 170 keV beams or 1.4 x 10^{17} deuterons/cm^2-sec for 80 keV beams (fluences of 2 to 4 x 10^{18} deuterons/cm^2/pulse). The NBETF design goal for panel life is 25,000 beam pulses. With an expected cumulative fluence of 10^{23} cm^{-2} during the life of a panel, erosion of the thin surface by deuteron bombardment has to be considered in the design of the heat absorption panels, along with the usual heat-transfer, thermal-stress and water-channel-erosion considerations. Our goal was to specify an erosion allowance - the additional thickness of material required on the surface facing the beam to compensate for the erosion expected after a fluence of 10^{23} deuterons/cm^2 - for the panels.

The candidate materials for the heat absorption panels are Cu, Mo, and W because of their high thermal conductivity. We were unable to find, in the literature, sputtering data directly applicable to the design conditions of these dumps. In this paper we consider information in the literature on the fluence and angle-of-incidence dependence of sputtering and the exfoliation of blisters. From this we estimate an erosion allowance for the NBETF beam dumps.

This work was supported by the Director, Office of Energy Research, Office of Fusion Energy, Development and Technology Division, of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

II. Sputtering at Normal Incidence

Recent review articles[3-8] on sputtering by light ions summarize the current status in detail. Most sputtering measurements have been made for normal incidence. For Mo and W experimental results are available only to 10 keV;[3] for Cu results havebeen reported to several MeV.[5] A semi-empirical model can be used to extrapolate to higher energies;[8] the energy dependence tends toward E^{-1} at high energies. The fluences used for sputtering measurements for hydrogen and deuterium tend to be quite high - typically 10^{20} - 10^{21} cm^{-2} - because of the small sputtering coefficients. Sputtering coefficients for Cu, Mo, and W bombarded by H^+ or D^+ are shown in Fig. 1.[9-14]

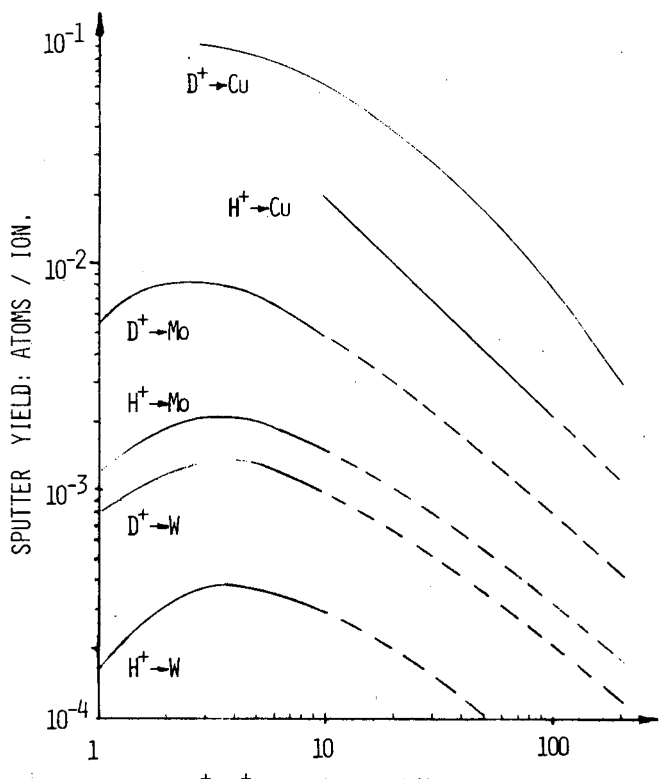

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Fig. 1: Sputter yields (atoms/incident ion) for normal-incidence H^+ and D^+ bombardment of Cu, Mo, and W. The solid lines represent experimental data from the literature: H^+ on Cu (Refs. 9, 10); D^+ on Cu (Refs. 11, 12); H^+, D^+ on Mo (Ref. 13); H^+, D^+ on W (Refs. 4, 14). The dashed lines are extrapolations.

Sputtering rates are influenced by surface roughness of the target. In general, sputtering rates for polished surfaces increase with fluence (by as much as a factor of 4) as the surface is roughened by sputtering,[7] but appear to reach a steady-state value for fluences above 10^{19} cm^{-2}. For W a decrease in sputtering with increased fluence has been observed.[7] The sputtering coefficients shown in Fig. 1 are the results of high-fluence measurements which should be representative of steady-state (rough-surface) conditions applicable to fluences as high as the 10^{23} cm^{-2} of interest for the beam dumps.

III. Angular Dependence of Sputtering

For sputtering by heavy ions, the sputtering yield increases with a $\cos^{-1}$ dependence, where is the angle with respect to normal incidence.[15] For near-grazing incidence (θ 85°) the sputtering yield falls below the $\cos^{-1}$ value. Similar behavior is observed for sputtering by hydrogen and deuterium from low and intermediate Z targets.[3,6] For Mo[16] (Fig. 2) and W[17] the sputtering yield can be 3 to 4 times greater than the $\cos^{-1}$ relation would predict.[3] This is attributed to contributions from interactions of not only incoming ions but also reflected ions that suffer a hard collision near the surface.[3] Results for the angular dependence of sputtering are limited to energies below 8 keV. Since the reflection coefficient decreases at high energies,[18] we would expect the deviation from the $\cos^{-1}$ dependence to decrease at high energies.

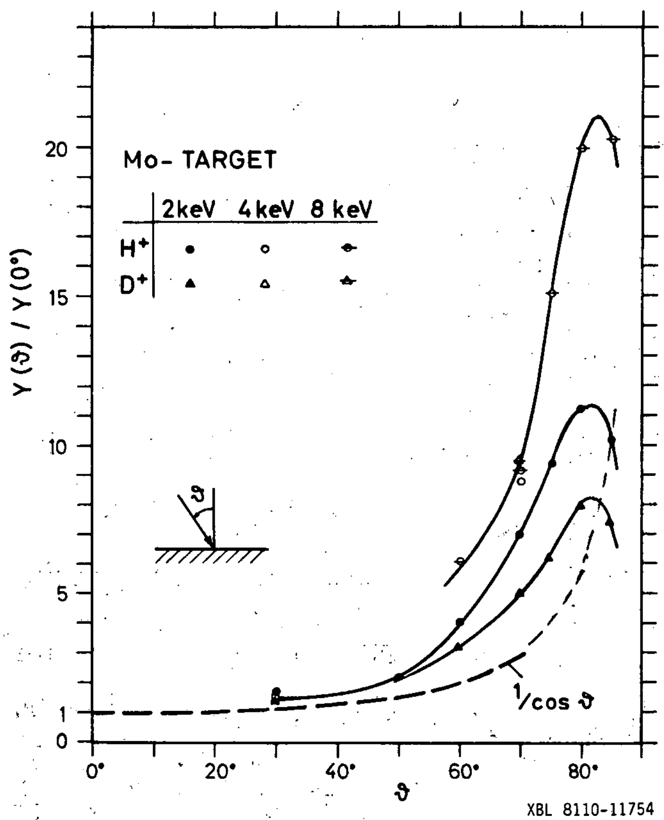

Fig. 2: The variation of sputtering yield with angle of incidence for H^+, D^+ on Mo (Ref. 16). The dashed line indicates a $\cos^{-1}$ dependence.

IV. Blistering and Exfoliation

The bombardment of surfaces by energetic hydrogen, deuterium, and helium beams creates blisters, which at sufficiently high fluences rupture, exfoliate, and contribute to surface erosion. The relevant parameters for blistering are discussed in the review article by Das and Kaminsky:[19] The formation, size, and exfoliation of blisters depends on the projectile ion and its energy, the permeability of the implanted gas in the target, the target temperature, and the yield strength of the target material. Blistering by H^+ or D^+ bombardment is not as severe as for He^+, and most of the blistering studies have been with He beams. Blisters range in size from 10 to 1 mm and have a skin thickness of the order of 10^{-3} mm. Blisters form at fluences of 10^{17} - 10^{19} cm^{-2}. As blisters rupture and exfoliate with increased fluence, new blisters of smaller diameters appear; this process may continue for 3-6 generations, until the surface becomes porous and blister formation ceases (usually at a fluence about ten times greater than that for the onset of blistering).[18] Thus, erosion by blistering is a self-limiting effect.

Blistering of Cu[19,21] and Mo[19,22,23] has been observed for H^+ and D^+ bombardment and is not considered to be a major contributor to surface erosion.[4,7,19]

V. Erosion Estimates

The NBETF will have the capability of producing deuterium beams with energies up to 170 keV, but for estimating an erosion allowance operation at lower energies is more significant because: 1) The sputtering yield decreases with increasing energy (Fig. 1). 2) For optimum system efficiency, the panels will be oriented so that the power flux is 2 kW/cm^2; this results in higher fluences at lower energies. For our estimates of the erosion allowance we have chosen 80 keV deuterium beams incident on the beam-dump panels inclined 85° to reduce the power density to 2 kW/cm^2. For these conditions (near-grazing incidence) the flux is 1.4×10^{17} deuterons/cm^2-sec, and the fluence integrated over the design life of the panel (25,000 pulses of 30-sec duration) is 10^{23} cm^{-2}.

The sputtering results reported in the literature and shown in Fig. 1 were obtained at fluences of 10^{20} to 10^{21} cm^{-2} (Sect. II). These fluences are about two orders of magnitude higher than those required for blister formation, hence well above the fluence required for the cessation of exfolation (Sect. IV). The sputtering results of Fig. 1, which were determined from the weight loss of the target, should therefore include exfoliation losses. The variation with angle has been assumed to be $\cos^{-1}$; as discussed in Sect. III, this is a poor assumption for the low-energy results that have been reported, but should improve at higher energies as reflection becomes less significant.

The erosion estimates are presented in Table I. For Cu we estimate a loss of about 0.13 cm after a fluence of 10^{23} cm^{-2}. This is a significant loss and must be considered in the design; the extra thickness increases the temperature drop from the surface to the water interface and thus increases the thermal stresses and decreases the fatigue life of the panels.

For a given set of conditions, the lack of knowledge of the angular dependence of the sputtering coefficient is the main contributor to the uncertainty in the erosion estimate. However, for a development facility such as NBETF there are also large uncertainties in the anticipated energies and fluences. At 170 keV both the fluence and the sputtering yield will be smaller, and the erosion estimates will be reduced by one-third to one-fourth of the values in Table I. If the assumed beam optics are not achieved, the power densities will be reduced, and the panels will not be inclined as steeply to achieve 2 kW/cm^2 -- this will result in a reduced sputtering coefficient. On the other hand, neutral beams are usually an admixture of hydrogen or deuterium atoms of different energies: The molecular ions D_2^+ and D_3^+ produce D^0 at one-half and one-third the energy of D^0 produced from D^+ (at two and three times the flux). These low-energy components also have larger sputtering coefficients than the full-energy component, since the sputtering coefficient varies roughly inversely with the beam energy. This combination of increased flux and increased sputtering yield for the low energy fragments increases the erosion of the panels significantly. For example, a $D^+/D_2^+/D_3^+$ mix of 85%/10%/5% could result in an erosion rate 1.5 times greater than a pure D^+ beam.

In soliciting development contracts for beam dumps we have specified erosion allowances of 0.07, 0.01, and 0.01 cm (the erosion allowance for 170 kV operation) for Cu, Mo, or W panels. We plan to implement an erosion monitoring program for the panels used on NBETF, possibly exchanging panels from high-fluence locations with those in low-fluence locations if surface erosion becomes significant.

VI. Acknowlegements

This work was supported by the Director, Office of Energy Research, Office of Fusion Energy, Development and Technology Division, of the U. S. Department of Energy under Contract No. W-7405-ENG-48.

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Table I.

Erosion estimates for 80 keV deuterium beams incident on beam-dump panels. The angle of incidence is 85^o to reduce the power density to 2 kW/cm^2. The flux is 1.5 x 10^{17} deuterons/cm^2-sec and the fluence integrated over the design life of the panels (25,000 pulses of 30-sec duration) is 10^{23} cm^{-2}.

	Cu	Mo	W
Atomic Number	63.5	95.9	183.8
Density (gm/cm^3)	8.95	9.01	19.3
Atom Density (atoms/cm^3)	8 x 10^{22}	5.7 x 10^{22}	6.3 x 10^{22}
Sputtering Coefficient (atoms/ion) at 80 keV normal incidence	1 x 10^{-2}	1 x 10^{-3}	2 x 10^{-4}
at 85^o to normal	1 x 10^{-1}	1.1 x 10^{-2}	2.2 x 10^{-3}
Erosion Rate (atoms/cm^2-sec)	2 x 10^{16}	2 x 10^{15}	3 x 10^{14}
Design-Life Erosion Allowance (cm)	0.13	0.02	0.004