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Sputtering in the Upper Atmosphere

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Measurements have been made on the sputtering rates of surfaces in the upper atmosphere The measurements were carried out on two Air Force satellites that orbited at about 200 km above the earth At this altitude a satellite sweeps out an intense beam of molecules from the upper atmosphere which impact with energies ranging up to about 10 ev We are studying these impacts to determine the sputtering effects they will have on surfaces

On these two flights, sputtering measurements were made on Au and Ag surfaces Laboratory studies at 30 ev,[1] the lowest energy at which we have been able to make sputtering

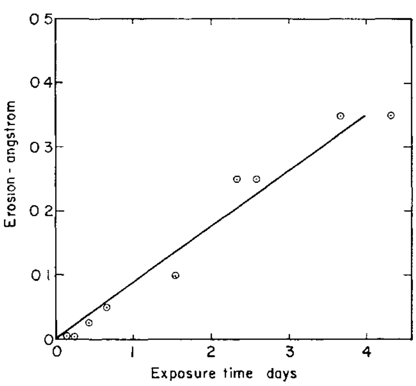

Fig 1 Erosion of Au in the upper atmosphere

Received December 16, 1963 The research reported in this paper was sponsored in part by the Air Force Missile Develop ment Center, Air Force Systems Command, under Contract AF29(601) 5997, and the Office of Naval Research, Contract 3157(00) Satellite flights were carried out under the auspices of the Air Force System Division and the Air Force Cambridge Research Center The authors wish to thank L L Letterman, F W Groesbeck, J H Miller, D Sprague, and J R Talley for their generous help, needed in the making of these measurements

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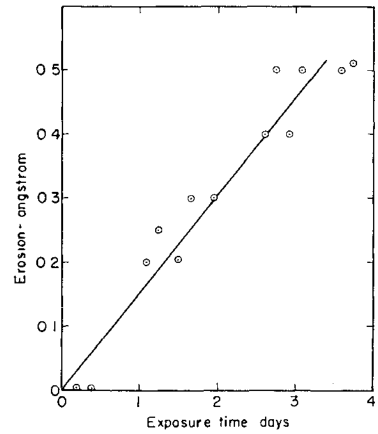

Fig 2 Erosion of Ag in the upper atmosphere

measurements, show that these two metals have the highest sputtering yield of any materials investigated Hence, knowing the yields for these two metals in the upper atmosphere would place a limit on the yield for other surfaces

The crystal-oscillator method was used in the measurements The material to be studied is plated on a quartz crystal, and the rate at which it is sputtered off by particle impacts was determined from the change in the oscillator frequency This method for measuring small mass changes has been previously described [2 3] With it, it is possible to measure the average erosion of 0 01Å from a surface

The total thickness of gold eroded from a surface as a function of exposure time in the upper atmosphere is shown in Fig 1 This erosion measurement was made for the air stream impacting a 30° angle relative to the plane of the surface The erosion rate for a gold surface as determined from Fig 1 is 0 1 ± 0 05 Å/day

The total thickness of silver eroded from a surface as a function of exposure time is shown in Fig 2 Here the measurement was made for the air stream impacting at normal incidence to the plane of the surface The erosion rate for a silver surface as determined from Fig 2 is 0 15 ± 0 05 Å/day

From the erosion rate for a surface, one can calculate its sputtering yield in the upper atmosphere [3] The composition of the upper atmosphere is mainly N_2,[4] and one finds the sputtering yield μ in Au atoms ejected per incident N_2 molecule to be

$$\mu \approx 1 \times 10^{-6}\ \mathrm{Au}/\mathrm{N_2}$$

This yield occurs at 9 ev, the energy of impact of N_2 on a satellite at 200 km

The sputtering yield for Au as measured here is within a factor of two of that measured on Discoverer 26 [2] The measurement on Discoverer 26 was to determine the sputtering yield of Au for a surface positioned at normal incidence to the air stream As a result of these two measurements, it can be concluded that there is no significant difference in the erosion of a surface as a function of its angle to the air stream

The sputtering yield for Ag as determined from the data given in Fig 2 is

$$\mu \approx 2 \times 10^{-6}\ \mathrm{atoms}/\mathrm{N_2}$$

The higher yield for an Ag over that of Au is in agreement with laboratory measurements at higher energies [1] The Ag surface flown on the satellite had been exposed to the atmosphere at the launch site for several days prior to launch, and it most probably had reacted with sulfur compounds in the air to form Ag_2S This layer of Ag_2S would have sputtered at a greater rate than Au because of the more optimum transfer of energy to Ag_2S by N_2

The energy transfer coefficient is $4m_1m_2/(m_1 + m_2)^2$, where m_1 is the molecular weight of the impacting particle, and

m_2 is the atomic weight of the surface atom For a relatively heavy atom such as Au, the energy transfer is poor when the impacting particle is N_2 As a consequence, one would expect the Ag_2S surface to have a higher sputtering yield than Au

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Technical Comments

Comment on "Propulsion Application of the Modified Penning Arc Plasma Ejector"

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In a recent paper,[1] results of a brief analytical and experimental treatment of the modified Penning plasma accelerator are presented which purport to show that devices of this general class are not attractive for propulsion purposes The writers have previously called attention to a number of factors that render the conclusions of Ref 1 invalid§ and wish to criticize again the more significant points These include use of a single-fluid model in the theoretical approach which cannot account for the essential features of the problem, neglect of dominant diffusion processes in the interpretation of observed experimental trends, and use of a cold cathode discharge that can be shown by a priori arguments to be inherently inefficient and cannot be considered for propulsion purposes

Criticism of Theory

In the theoretical treatment of the effect of the exit fringing magnetic field on the divergence of the exhaust beam, it is stated in Ref 1 that "the foregoing calculations are certainly of the simplest type that can be applied in a basically complex plasma situation, and it is reasonable to question their validity " The writers wish to underscore this statement For example, the plasma model employed is that of a uniform, single-component, MHD flow in which transport coefficients are assumed to be scalar quantities In the problem considered, however, if a fluid model is to be employed it is necessary that the model consist of a two component flow with spatial inhomogeneities allowed, with tensor transport properties, and with coupling between the ion and electron fluids caused only by means of volume electrostatic fields and not by collisions Such a flow is indeed complex and, yet, still does not allow for the effects of a nonthermal velocity distribution; hence, it is generally desirable to adhere to the self consistent, individual-particle approach (e g , Refs 2 and 3) Virtually all of the essential details of the physical processes occurring in the plasma are lost when the single-fluid simplifications employed in Ref 1 are applied

Ion densities of $10^{12}/cm^3$ and electron energies of the order of 10 ev are representative of typical beam conditions for practical propulsion devices of this type Using the calculations of Ref 1, one then arrives at electron mean free paths (μ) on the order of 30 cm, a distance large compared to characteristic apparatus dimensions Both of these lengths are large compared to the electron cyclotron radius (~0 03 cm) Hence, for conditions of interest for propulsion, electrons having an appreciable transverse kinetic energy are trapped on field lines (in a classical sense) and can migrate across field lines as a result of $\mathbf{E} \times \mathbf{B}$ drifts (Hall currents) or diffusion (either classical or anomolous) If one adopts the fluid model, this implies that conductivity is a tensor property of the medium and cannot be considered simply (as in Ref 1) the reciprocal of the resistivity The conductivity transverse to a magnetic field is reduced by a factor $(\nu/\omega)^2$ for $\nu/\omega \ll 1$ from the values used in Ref 1 The reduction by a factor of 3 in conductivity (taken in Ref 1 from Spitzer) to account for the magnetic field is appropriate only when applied to resistivity and only under conditions of $\nu/\omega > 1$ Furthermore, the use of the Spitzer formula for the conductivity along the magnetic field implies that the energy gain between collisions is small, i e , when $E\mu > kT/e$, the theory is not valid In order for the plasma source to operate as a propulsion device, it is necessary that electric fields accelerate ions and that these electric fields exist over the source dimensions; hence, for conditions of interest, $Ee\mu/kT \approx 30$ Clearly the conditions needed for the concept of a scalar conductivity to be meaningful do not exist in the propulsion version of the Penning source where Hall effects are important and where the energy gain between collisions can be greater than the energy of random electron motion

In the theory of Ref 1, it is assumed that currents due to electron motions exert $\mathbf{J} \times \mathbf{B}$ forces on the plasma, causing changes in the momentum of the ions However, it must be understood that, because an essentially collisionless situation exists, the only way in which the motion of the ions can be

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Received July 30 1963

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§ Discussion following presentation of Ref 1 at the ARS Electrical Propulsion Conference, Berkeley, Calif , March 14–16, 1962