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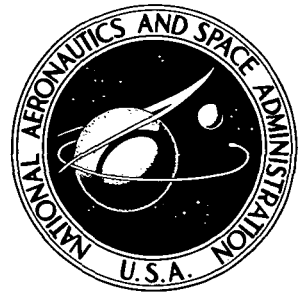

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DRAG COEFFICIENTS FOR SPHERES IN FREE MOLECULAR FLOW IN O AT SATELLITE VELOCITIES

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16. Abstract

The drag coefficients for the Echo I and Explorer XXIV spherical surfaces in an O environment have been experimentally determined over an energy range of 4 to 200 eV. The experiment was performed by generating a beam of atomic oxygen ions of the proper energy, neutralizing a portion of the beam, and then allowing only the neutral O particles to strike a very sensitive torsion balance. The momentum transferred to the surface was determined from the deflection of the torsion balance. At the lower energies, the more intense ion beam had to be used instead of the neutral beam. The drag coefficients are found to be slightly greater than 2 at energies corresponding to satellite velocities.

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DRAG COEFFICIENTS FOR SPHERES IN FREE MOLECULAR FLOW IN O AT SATELLITE VELOCITIES

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SECTION I
INTRODUCTION

One method of investigating the density of the earth's upper atmosphere is by observing the orbital decay of satellites. From a knowledge of the orbital parameters as a function of time one can infer the drag force produced by the atmosphere and hence it is possible to calculate the atmosphere density, if the drag coefficient is known. For the free-molecular flow conditions that exist for satellites in the upper atmosphere, a knowledge of the drag coefficient is equivalent to knowing the atmospheric composition and the manner in which individual molecules exchange momentum with the satellite surface. There is, however, very little experimental information available concerning molecule-surface interactions for relative velocities in the satellite range, and a consequent uncertainty in any corresponding theoretical calculation.

In April 1963 the University of Virginia began a program to study in the laboratory the transfer of momentum from atmospheric molecules to solid surfaces, especially for relative velocities in the satellite range and for surfaces that are samples of actual satellite material. The program has been sponsored by NASA Langley Research Center under Contract NAS1-2538. The original proposal [1] described the general approach used, and earlier reports have described the system developed to make the N_2 measurements [2], preliminary results for N_2 molecules on several surfaces [3], a study of various methods for producing a monatomic oxygen beam [4], and the final momentum transfer results for N_2 on surfaces of Echo I, Echo II, and unpainted Explorer XIX satellite material [5]. The present report describes the final momentum transfer results for atomic oxygen, O, on surfaces of Echo I and unpainted Explorer XXIV satellite material. Since much of

the experimental apparatus and procedure is similar to that presented in the final N_2 momentum transfer results report [5], some of the sections of that report are repeated here.

It was originally intended that measurements would also be made for several satellite surfaces which were painted with epoxy paint, but it was found that these electrically insulating surfaces could not successfully be employed with the present technique, since small electrical charges on these surfaces produced forces that tended to obscure the small forces that were to be measured. A brief discussion of estimated drag coefficients for the painted surfaces is given in the final section of this report.

Consider now the drag on a satellite moving through a rarefied atmosphere (free molecular flow) with a speed large compared to the thermal motion of the atmospheric molecules. The drag coefficient can then be expressed as [3]

$$C_D = \frac{F}{\frac{1}{2} A\rho v_o^2} = 2\left[1 + \frac{1}{A}\int_S \frac{P_m}{P_o} \cos\theta da\right] \qquad (1)$$

where F is the drag force, A is the cross-sectional area of the satellite projected on the plane normal to the direction of motion, ρ is the atmospheric density, v_o is the relative velocity of the satellite through the atmosphere, P_o is the corresponding molecular momentum, P_m is the average component of momentum of reflected molecules along the direction of motion (taken positive when opposite to P_o), θ is the angle of incidence of molecules (measured from the normal to the surface) striking an element of surface da, and the integral extends over the surface of the satellite. The above expression may therefore be used to calculate the drag coefficient for a body of convex shape (so that double reflections are not possible) moving through a one-component atmosphere if the

ratio P_m/P_o is known as a function of θ for a given v_o. If the atmosphere contains several components, then it is necessary to know P_m/P_o for each molecular species as well as the proportion of each present. To take a simple example, if one considers a flat plate moving so that its surface is normal to the direction of motion, then $\theta = 0$ for the entire surface and we get

$$C_D + 2\left(1 + \frac{P_m}{P_o}\right) \quad \text{(Flat Plate)}. \tag{2}$$

If the momentum of the reflected molecules is small compared to the incident momentum ($P_m/P_o \ll 1$) then $C_D \simeq 2$, whereas if the molecules are reflected back along the direction of v_o (specularly) with a speed equal to v_o, then $P_m = P_o$ and $C_D = 4$. One, therefore, would expect the measured value of C_D for a flat plate to be somewhere between these limits: $2 < C_D < 4$. For a convex body it is conceivable that for a considerable fraction of the surface P_m is in the same direction as P_o and hence is negative, leading to the possibility of values of C_D less than 2.

The present paper is concerned with the measurement in the laboratory of P_m/P_o as a function of v_o and θ for O atoms incident on several surfaces, and the calculation of drag coefficients from the results of these measurements. These drag coefficients should be valid for the situation of a body moving through a rarefied, stationary gas of O for surface conditions equivalent to those in the experimental system.

SECTION II
EXPERIMENTAL METHOD

Most of the techniques employed in making the measurements have been described in previous reports, but they will be briefly given again here for completeness.

The general procedure in measuring P_m/P_o is to produce a beam of atoms or molecules having a known energy corresponding to satellite velocities (the energy in the case of O atoms is 4-10 eV), allow the particles to strike a test surface at a chosen angle of incidence, and measure the component of force on the test surface along the beam direction. If the rate at which the particles strike the surface (part./sec.) is determined, then the force divided by the rate gives $(P_o + P_m)$, and since P_o is already known from a knowledge of the energy and mass of the beam particles, then one has sufficient information to determine P_m/P_o.

A. Equipment

A schematic drawing of the entire experimental system is shown in Figure 1. The apparatus is mounted in two separate vacuum chambers, a test chamber and a beam chamber, which has the ion source, a focusing and deflection section and a mass analysis section attached to it. Mounted inside the beam chamber is another electrostatic focusing and deflection section along with either the neutralization cell and electrostatic collection plates or another focusing section, depending on whether neutrals or ions were used to make a particular measurement. The test chamber contains the test surface which is mounted on a torsion balance used to measure the force produced by the beam on the surface. The test chamber is placed on a large concrete pier which is isolated from the laboratory floor to reduce mechanical

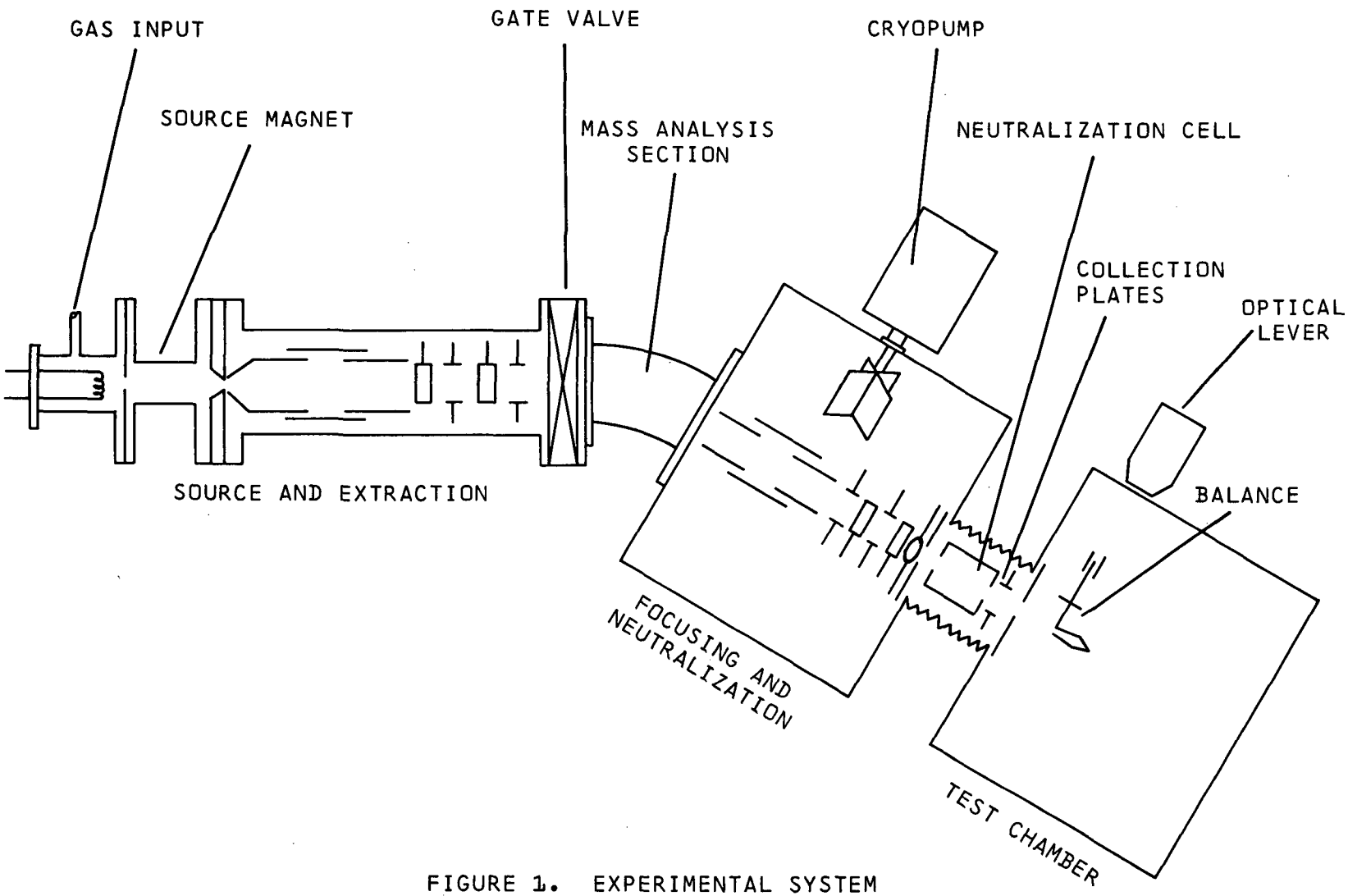


FIGURE 1. EXPERIMENTAL SYSTEM

vibrations in the torsion balance. The two chambers are connected by a metal bellows which allows movement of the beam chamber so that the beam can be moved with respect to the test surface. The beam chamber is pumped continuously by a diffusion pump, but the principal pumping during operation is provided by a 6600 l/sec. cryopanel which is cooled to approximately 20°K by a Malaker Cryomite mechanical refrigerator, providing an operating pressure in the beam chamber of 0.8-4 x 10^{-7} Torr. Background pressure is approximately 2 x 10^{-8} Torr.

The ion source is a magnetically confined oscillating electron bombardment type, patterned after the design of Carlston and Magnuson [6]. The pressure of the O_2 gas in the ion source is in the low micron range and the anode current is typically around 10 ma at an anode voltage of 150 eV. The ion beam is extracted from the ion source through a 0.6-mm diameter hole by an extraction potential of 300 volts.

After extraction the beam is focused and enters the mass analysis section, where the O^+ ions are separated from the O_2^+ ions by a transverse magnetic field. A mass spectrograph of ion collection current versus voltage across the electromagnet is shown in Figure 2. After more focusing and deflection in the beam chamber, the O^+ ion beam is decelerated to the proper energy and enters the neutralization cell which is located inside the bellows joining the two chambers. Within the neutralization cell, charge transfer takes place with the neutralizing gas krypton, and the beam leaving the cell is composed of O^+ ions that were not neutralized, neutralized O atoms, and a small number of low-energy Kr atoms from the neutralizing gas. The charged particles are removed from the beam by a transverse electric field created by two parallel plates. The neutralizing efficiency of O^+ in Kr gas is only about 10% of that achieved with the N_2 measurements and the O^+ ion beam intensity is only about 15 to 20% of the N_2^+ beam

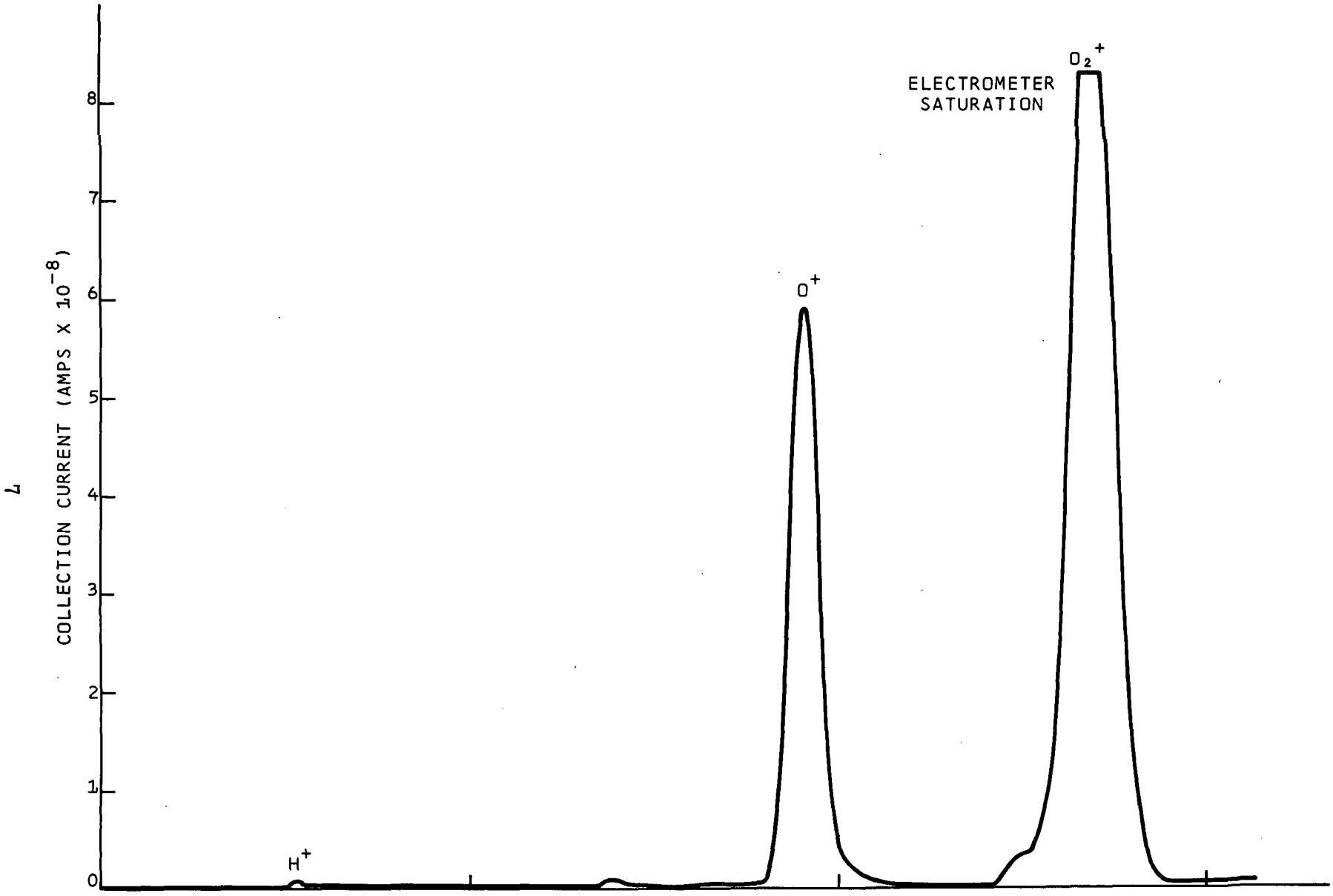


FIGURE 2. TYPICAL MASS SPECTROGRAPH

intensity previously obtained. The resulting neutral O beam flux was such that reliable data could be gathered down to only about 20 to 25 eV energy. To achieve data down to the desired energies, the neutralization cell was replaced by focusing elements and the ion beam was utilized directly to perform the measurements. This will be explained in more detail later.

The torsion balance which is used to measure the force produced by the beam on the test surface was patterned after one described by Pearson and Wadsworth [7] and uses electrostatic damping and an optical lever [8] for measuring the angular deflection of the balance arm. This balance is relatively rugged but is capable of detecting forces as small as 2×10^{-8} dyne. The balance configuration used in our work is shown in Figure 3. The torsion fiber is 10-micron tungsten, and both damping plates are mounted on the same end of the balance arm. The test surface is mounted on the other end of the balance arm along with a momentum trap for measuring the beam flux. The procedure is to allow the beam to enter the momentum trap, measure the balance deflection, and calculate the beam flux under the assumption that the molecules leaving the trap have a Maxwellian velocity distribution which is characteristic of the temperature of the trap. (The results are not very sensitive to the precise validity of this assumption since the average momentum of nearly thermally accommodated molecules leaving the trap is much less than that of the incident molecules.) The beam is then moved upward mechanically so that it strikes the test surface and the balance deflection is again observed, giving the force produced by the beam. This method of measuring the beam flux has the advantage that the absolute calibration of the balance is not needed, since two balance deflections are being compared in order to find the average momentum transferred to the test surface by the molecules of the beam. In each measurement the ion beam is turned on and

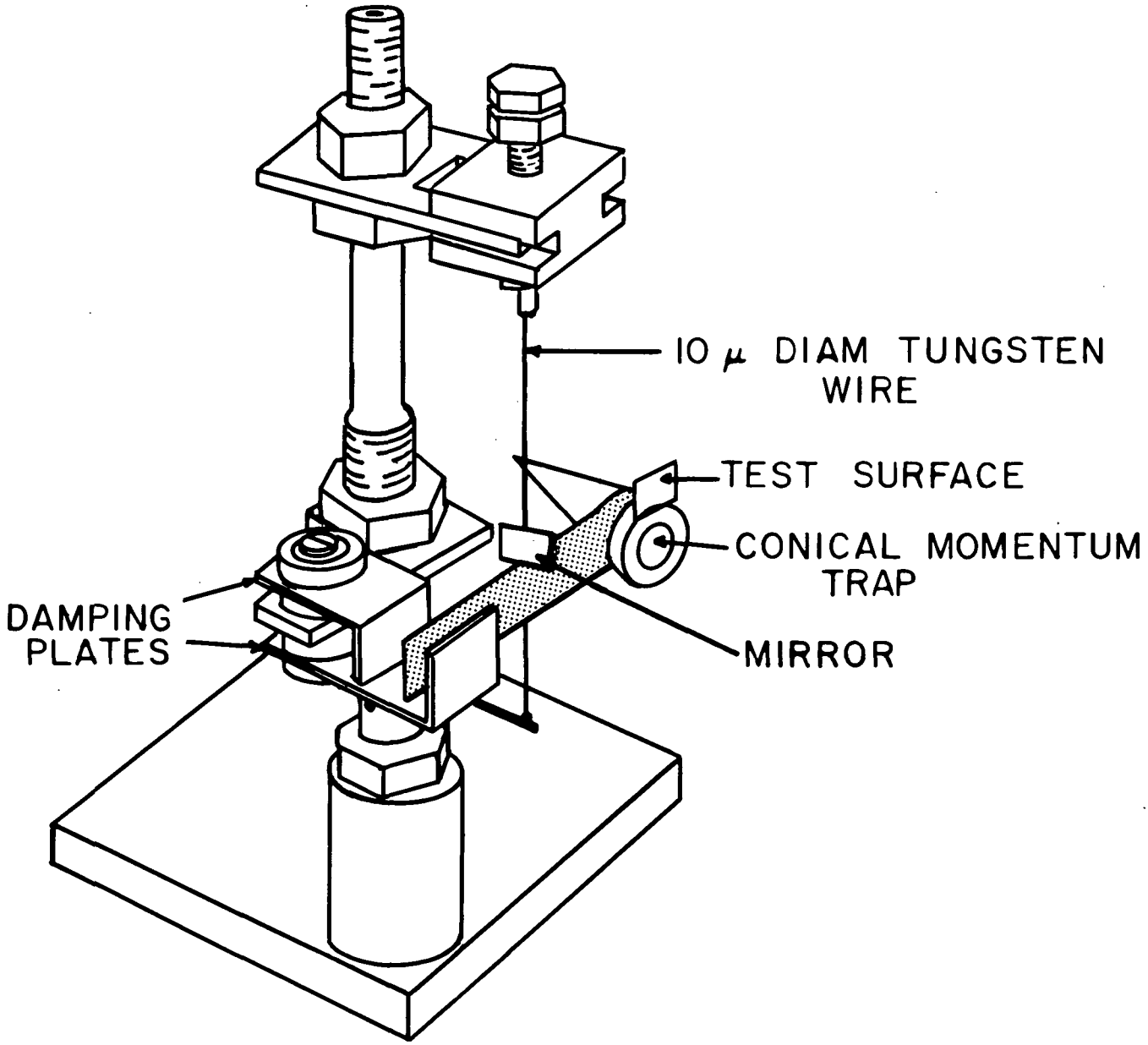


FIGURE 3. TORSION BALANCE

off and the resulting balance deflection is taken as a measure of the force of interest. The effect of all forces on the balance other than that produced by the beam (such as that caused by the neutralizing gas) are thus eliminated. The momentum trap is 4.1-cm long with an apex angle of 22° and with a 0.9-cm diameter hole. The ratio of the hole area to the total internal surface area of the cone is 0.052, so that one would expect entering molecules to experience, on the average, around 20 collisions with the surface of the box before leaving. This means that if one assumes that the thermal accommodation coefficient for a single collision of a molecule with the inner surface of the cone is greater than around 0.2, the assumption that the molecules leaving the box have an average velocity that is characteristic of the box temperature is well satisfied. Although there have been no measurements of the accommodation coefficient in the eV energy range, the measurements at thermal energies [9] indicate that for gas covered surfaces the accommodation coefficient is generally greater than 0.5. Theoretical consideration of the particle-surface interaction as being hard-sphere at eV energies also leads one to think that the accommodation coefficient for these studies (with or without adsorbed gases) will be in excess of 0.5. All measurements described here were performed with test surfaces at room temperature.

As stated earlier, the principal difficulty in using the electrical acceleration method, described in the previous section, is in achieving an adequate beam flux for detection by the torsion balance. One is concerned, then, with a signal-to-noise problem where the signal is the force produced by the beam on the test surface and the noise is that of the torsion balance. As an example of the magnitudes involved for a 10-eV O beam with a flux of 2×10^9 atoms/sec. (calculated from the ion current measured at the collection plates and an estimated

3% neutralization efficiency), the force produced on the test surface would be about 7×10^{-8} dyne, under the assumption that the reflected molecules carry away negligible momentum. If the reflected molecules have appreciable momentum compared to the incident momentum, the force would then be larger. The minimum measured rms noise of this type of torsion balance is around 2×10^{-8} dyne [7], and this figure is just about equal to what one expects for the Brownian motion of the balance vane.

The most important characteristic of the balance is its noise level expressed in force units. The period of the balance in its torsional mode is also a consideration since this determines the length of time required for oscillations to be damped out after the beam is allowed to deflect the balance. It is also desirable to have the balance reasonably rugged so that a minimum amount of time is spent in construction and testing of each new balance.

With a 10-micron tungsten torsion fiber the balance is sturdy enough to be constructed without special equipment and can be handled easily. A typical rms noise level in angular units for this balance is around 5×10^{-7} radians, or, expressed in units of force, it is 4×10^{-8} dynes. At times of minimum external disturbance, the noise level of the balance was found to be about equal to the Brownian limit of 2×10^{-8} dyne. The larger noise values result from pressure variations due to the irregular pumping characteristics of the diffusion pump and from vibrations reaching the balance. The torsional period of the balance depends on the moment of inertia of the vane assembly which is slightly different for each new balance but a typical value for the period is 15 seconds.

In a measurement the beam is allowed to strike the test surface and the balance deflection is recorded. The beam chamber is then moved downward mechanically so that the beam enters the momentum trap, and the corresponding balance

deflection is recorded. The ratio of these two deflections then gives

$$R = \frac{P_o + P_m}{P_o + P_a}, \tag{3}$$

where P_a is the momentum due to the atoms leaving the momentum trap and has a maximum calculated value for these experiments of around 0.07 P_o. If one assumes that the molecules collide with the walls of the momentum trap a sufficiently large number of times that they are in thermal equilibrium with the walls and leave with a corresponding velocity and angular distribution, then by knowing the temperature of the walls, P_a can be calculated, and

$\frac{P_m}{P_o}$ can be easily computed from

$$\frac{P_m}{P_o} = R\left(1 + \frac{P_a}{P_o}\right) - 1. \tag{4}$$

A straightforward investigation of the dependence of the ratio P_m/P_o on the angle of incidence would involve mounting the test surfaces on the balance vane so that the beam molecules strike the surface at the chosen angle, but with the beam direction still perpendicular to balance vane. This means that the balance must be modified or reconstructed for each new angle. At angles of incidence less than 30° this procedure was followed with success. At larger angles, however, it was found that the combination of the mass of the momentum trap and that of the larger test surface needed to intercept all of the beam passing through the collimating aperture caused the balance to be intolerably noisy. Since all the surfaces studied gave essentially identical results it was decided that the measurements at larger angles would be performed by eliminating the

momentum trap and using one of the surfaces studied earlier (at $\theta = 0°$) as a reference surface, thereby reducing the mass mounted on the balance arm. The ratio P_m/P_o for the larger angles can thus be obtained by comparing deflections for the inclined surface and the reference surface, and then using the results obtained previously which provided a comparison of the reference surface with the momentum absorber. If the deflection for the inclined surface divided by the deflection for the reference surface is called S, then

$$S = \frac{P_o + P_m}{P_o + P_m^o} = \frac{1 + \frac{P_m}{P_o}}{1 + \frac{P_m^o}{P_o}}, \tag{5}$$

where P_m^o is the value of P_m for the reference surface for $\theta = 0$. Also,

$$R^o = \frac{P_o + P_m^o}{P_o + P_a} = \frac{1 + \frac{P_m^o}{P_o}}{1 + \frac{P_a}{P_o}}, \tag{6}$$

where R^o is the value of R for the reference surface at $\theta = 0$. Eliminating P_m^o/P_o between expressions for S and R^o and solving for P_m/P_o one gets

$$\frac{P_m}{P_o} = S\, R^o \left(1 + \frac{P_a}{P_o}\right) - 1. \tag{7}$$

This is the expression normally used for obtaining P_m/P_o for the larger angles of incidence where one is comparing the force on an inclined surface to that on a reference surface. The above expressions were employed for all of the N_2 measurements.

Regardless of whether atomic oxygen entering the momentum trap sticks, recombines or does not react with the surface, for an incident beam with energies over 4eV, P_a/P_o is theoretically less than 0.07, and in this report P_a is assumed equal to 0. In the case that P_a/P_o is higher than zero, the corresponding drag coefficient would not be increased by more than 3%. Hence, for a test surface mounted with the momentum trap, it is assumed that:

$$\frac{P_m}{P_o} = R - 1, \tag{8}$$

and for the larger angles of incidence where one is comparing the force on an inclined surface to that of a reference surface,

$$\frac{P_m}{P_o} = S\ R^o - 1. \tag{9}$$

To perform the desired measurements in a reliable manner, the signal-to-noise ratio should be at least 10. As mentioned earlier, the force or the resulting deflection from a 10-eV O beam is about three times the noise background of the torsion balance. Thus measurements were possible using the method utilized for the N_2 results, and called the D.C. method for neutrals, down to about 75 eV. An A.C. or swinging method could be utilized down to about 20 eV before the balance noise and drift became too severe, and the D.C. method using O^+ ions rather than neutrals was employed down to 4 eV. These three techniques will now be described more thoroughly.

B. D.C. Method (Neutrals)

The neutralization cell exit is located about 10 cm from the test surface on the torsion balance.

This allows a considerable distance within which the neutral beam can diverge appreciably, especially at the low energies where the ion beam before neutralization is expected to be rather divergent. The diameter of the beam at the test surface at low energies was found to be around 1-1.5 cm. Since it is difficult to construct a satisfactory balance with the test surface and the entrance aperture of the momentum trap as large as this, some means was necessary to collimate the neutral beam before it reached the balance. This was accomplished by placing two 0.65-cm dia. collimating holes, one above the other, just before the balance. The diameter of the holes is such that all of the beam passing through the top hole will strike the test surface and all of the beam passing through the bottom hole will enter the momentum trap. The measurement is then performed by closing the bottom hole with a shutter, allowing a portion of the beam to pass through the upper hole and strike the test surface, and recording the corresponding balance deflection. The beam chamber is then moved downward a distance equal to the separation between the two holes, the top hole is closed and the bottom one opened, the same portion of the beam is allowed to pass through the bottom hole and enter the momentum trap, and the balance deflection is recorded. The ratio of these two deflections, then, gives the value of R.

Because of the nature of the method used to produce the beam there are forces on the balance in addition to the desired force. This requires that the method used to obtain the balance deflection should eliminate any effects due to these extraneous forces. First, there is a force on the balance produced by Kr gas effusing from the neutralizing cell, which may be considerably larger than that caused by the particles of interest. Second, there can be a force produced by high-energy neutral particles that were produced by charge transfer of beam ions in the residual gas of the beam chamber at points within the electrostatic focusing system where the ion energy is higher

than the desired energy. One must then have a method of obtaining balance deflections which are due only to the desired neutral beam atoms and are not affected by the magnitude of these extraneous forces. This is accomplished by allowing all of these particles to strike the balance and then measuring the balance deflection that results when the particles of interest are prevented from reaching the balance. This in effect allows one to ignore the effect of the unwanted particles. The O atoms of interest (which in previous discussion we have called the beam) are prevented from reaching the balance by changing the potential on an electrode just before the neutralization cell so that the ions cannot enter the cell. This eliminates the force on the balance caused by the neutral atoms formed by neutralization of these ions, but does not affect the forces due to the effusing gas molecules and the high-energy neutrals. The corresponding balance deflections caused by turning the ion beam on and off in this manner at 30-second intervals is then the desired deflection. This procedure is, of course, repeated for both the test surface and the momentum trap.

Generally four or five measurements are taken with the beam striking the test surface, then a similar number with the beam entering the momentum trap, and then another set with the test surface. The average for the test surface is then compared to the average for the momentum trap. The fact that a complete measurement includes two sets for the test surface tends to minimize the effect of slowly changing beam conditions.

C. Swinging Method (Neutrals)

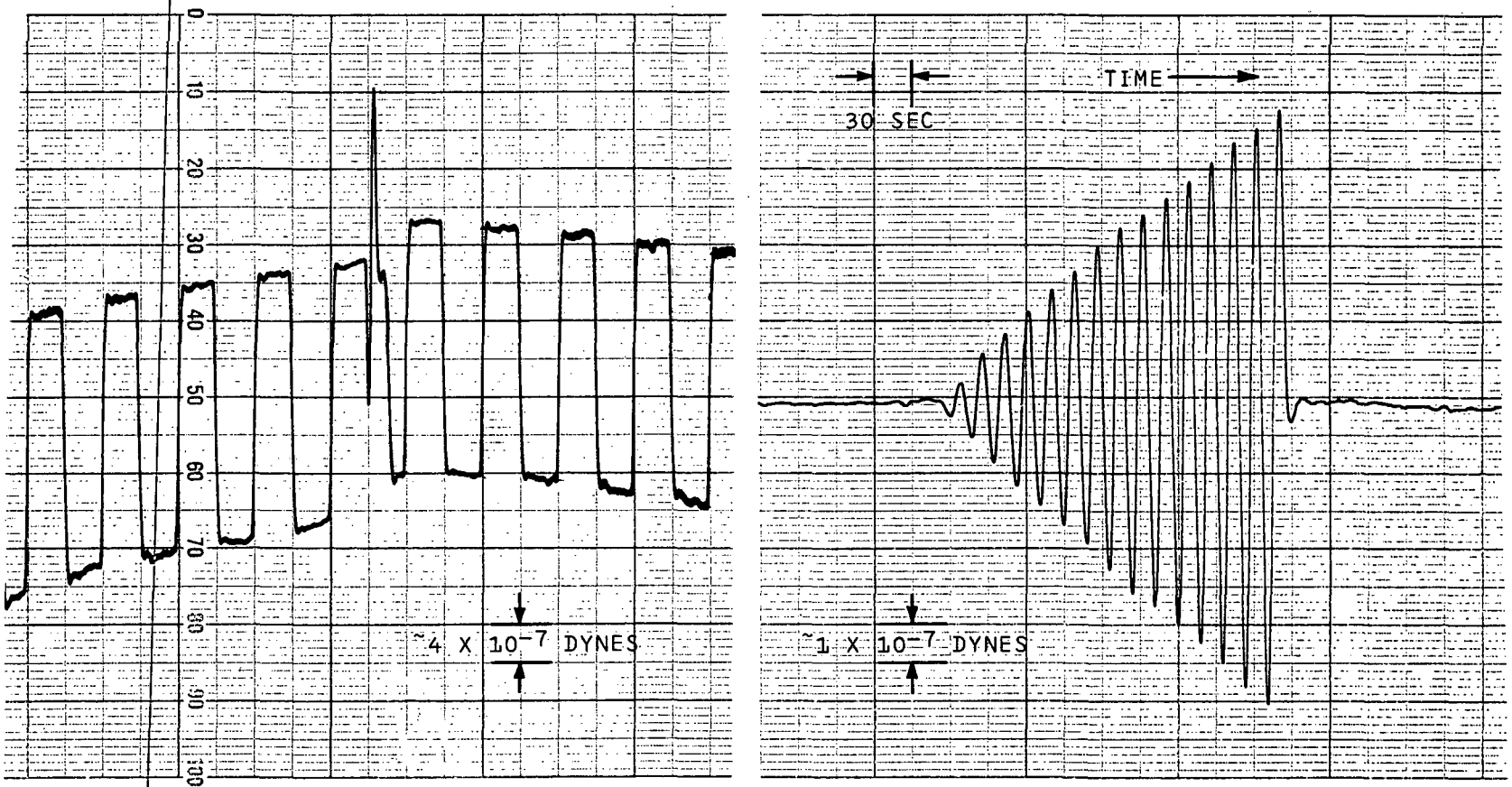
At beam energies of less than about 75 eV, the deflection of the torsion balance was not sufficient when compared to the background noise deflections to make reliable measurements, so an A.C. or swinging method was utilized. Briefly, the technique

used is to remove the damping from the torsion balance and turn the beam on and off in phase with the natural resonant frequency of the balance. In essence a constant force is applied in phase with a simple harmonic motion, thus causing the amplitude of the motion (rotation of the balance arm) to build up at a constant rate. A recorded trace of the amplifier output as this "in phase" cycling procedure is performed is shown in Figure 4 along with a typical trace of the D.C. method. As before, a number of these "build-ups" are recorded with the beam striking the test surface, then a similar number with the beam entering the momentum trap, and then another set with the test surface. The slope of the plot of the magnitude of the rotation of the balance versus the number of swings then yields the average rate of the build-up. The slope is generally determined by a computer program using the least-squares method. A ratio of the average of the slopes for the two beam positions then gives the desired value of R.

Results using this technique compare within experimental error to results obtained using the D.C. method at the higher energies and reliable data is possible for neutral O atoms down to about 20 eV.

D. D.C. Method (Ions)

The mechanics or procedure for this method is identical to the D.C. method for neutrals, however advantage is taken of the fact that the ion beam intensity is much greater than the neutral beam intensity, thus permitting large signal-to-noise ratios down to less than 4 eV. The possibility of using ions rather than neutrals is based on the idea that positive ions are neutralized by an electron attracted from the surface immediately prior to impact on a conducting surface. The electron is attracted from the surface due to the electrostatic force when the ion is several angstroms away [10-11]. Our data



DC METHOD

AC OR SWINGING METHOD

FIGURE 4. TYPICAL DATA TRACES

taken at energies greater than 20 eV indicate excellent agreement with neutal data. However, a small energy correction of about 2 eV must be made to take into account the effect of the attraction of the ion due to the electrostatic image force prior to the neutralization. The ion beam, neutralized near the target surface, receives an additional energy, ΔE, where $\Delta E = \frac{3.6}{d}$ eV and d in Angstroms is the distance from the target. It is assumed that d is 1.8 Å.

When a measurement is made with ions instead of neutrals striking a test surface mounted at an angle, anouther phenomenon must be considered. As the ion approaches an angular suface, the electrostatic image force tends to bend the parth of the ion and cuase the trajectory to be more normal to the surface. The closer the ion comes, the greater the force and the more the trajectory changes, until the ion is neutralized several angstroms from the surface. The neutralized ion then continues on a straight-line path to the surface. The amount of the trajectory change is, of course, dependent upon the angle of the surface and the energy of the incoming ion. As an example, a 4 eV 0 ion approaching a 75° surface, measured from the normal to the approach direction, is bent so that the actual impact occurs as though the surface was at 53°. From a measurement standpoint, this presents a difficulty, since the measured deflection of the torsion balance due to momentum exchange is not due to the desired component along the actual ion impact direction, but rather is that along the original ion beam direction.

To circumvent this problem encountered with measurements using ions on angular surfaces, the following procedure is utilized. Data for curves of momentum transfer ratio versus energy at a given angle are taken for N_2, N_2^+, and O^+. For a given energy, the corrected impact angle, due to the bending trajectory of the ion, of both O^+ and N_2^+ are nearly the same, i.e., less than one-half a degree difference even for a 75° test surface. Assuming that the neutralized N_2 molecule and O atom behave in a similar manner at the surface, i.e., the

reflected momentum patterns are similar for the same angle of incidence on the same surface for identical energies, then the ratio of measured S values for N_2 to N_2^+ multiplied by the S value for O^+ yields the desired value of S for neutral O for the desired angle of incidence of the test surface. This procedure is followed for all the non-zero angle of incidence ion results, and the validity of the above assumption is indicated by the excellent agreement of the ion and neutral data for the Echo I surface.

To enhance the ion beam intensity, especially at the low energies, the neutralization cell was replaced by a lens and focusing section. This enabled the ions of desired energy to travel about 5 cm instead of 17 cm before striking the test surface and thus reduced the loss of beam intensity due to space charge spreading. Because of the changed angular geometry and to reduce the possibility of part of the beam missing the target, the size of the collimating aperture at the shutter was lowered from 6.5-mm to 4-mm diameter. However, it was found that some of the beam did in fact miss the angular surface, so the torsion balance was electrically insulated to enable the measurement of the ion current striking the surfaces. The balance deflections were then normalized to these currents to take into account the portion of the ion beam which did not strike the angular surface.

E. Surface Condition

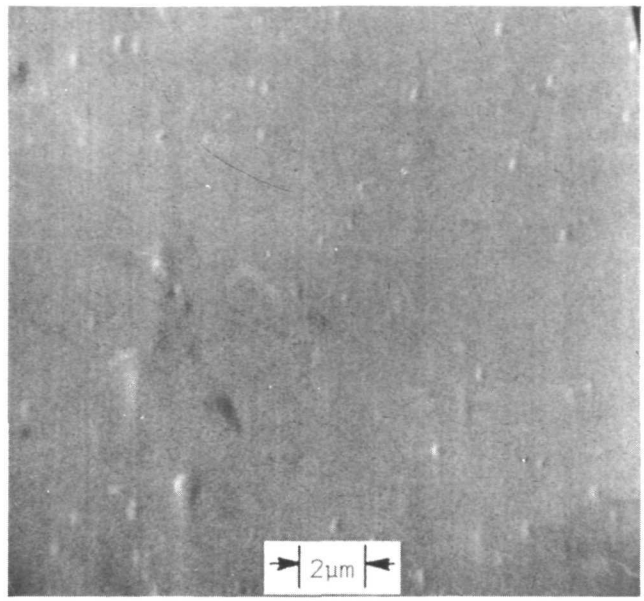
The measurements were performed for several different test surfaces. The entire question of surface condition in experiments such as these involves a number of uncertainties. In considering the application of the measurements to satellite studies of the density of the earth's upper atmosphere, one would like to make the measurements using samples of actual satellite surfaces which have the same surface condition as

that of the satellite in orbit (especially regarding adsorbed gases on the surface). There are two reasons why this desirability cannot be achieved at present. First, the condition of the satellite's surface is to a large extent unknown. It depends on the preparation of the satellite, its environment in orbit, and possible continual emission of gases from portions of the satellite. Second, even the most advanced laboratory techniques are not presently capable of specifying precisely the condition of a surface under study. It is possible, however, that some aspects of the molecule-surface interaction are not especially sensitive to the exact nature of the surface, particularly aspects that involve averages over a number of parameters. Since the momentum transfer measurements described here provide a rather coarse study of the interaction, the following philosophy has been adopted with regard to surface condition. The measurements are performed for several test surfaces, but the exact condition of the surface is not rigidly controlled. The surfaces are handled carefully before placing them in the vacuum system so as to prevent their being contaminated by oils, fingerprints, etc., but no attempt is made to remove adsorbed gases from the surfaces after they are in the vacuum system and the measurements are performed at pressures (5×10^{-7} - 1×10^{-6} Torr) such that a clean surface (no adsorbed gases) cannot be maintained. If the results of the measurements indicate that only the gross character of the surface (such as surface roughness) affects the momentum transfer, then one might conclude that the surfaces can be adequately characterized for this particular type of measurement. Measurements that investigate finer details of the interaction, such as the angular and velocity distribution of the reflected particles, may require considerably more accurate surface characterization.

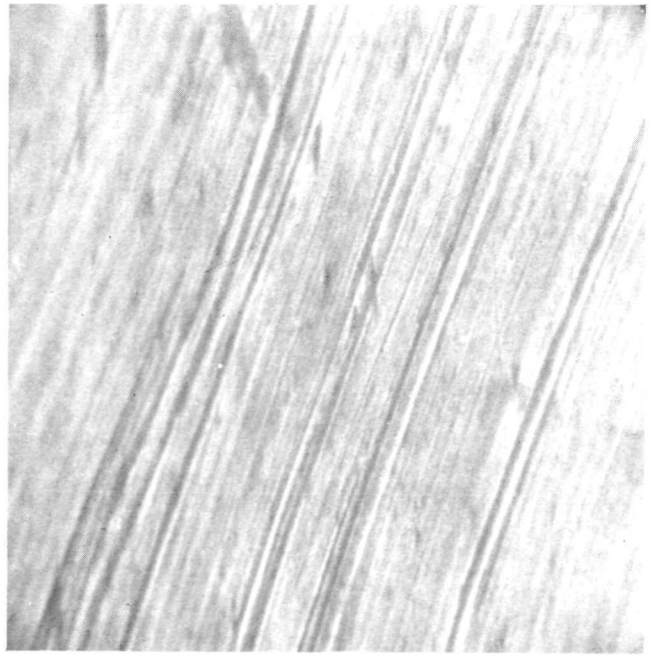
SECTION III
RESULTS

The objective in these measurements is to investigate P_m/P_o as a function of molecule energy and angle of incidence for two test surfaces. The surfaces used were samples of material used in the earth satellites Echo I and Explorer XXIV (no paint). Photomicrographs of these surfaces taken with a scanning electron microscope to show the gross roughness are shown in Figure 5. The results of the measurements are presented in Figures 6-8, in which the ratio P_m/P_o is plotted versus the incident energy E_o. The measurements extend up to an energy of 200 eV since these results are rather easily obtained and they indicate the high energy limit of the momentum transfer. One of the principal factors in determining the nature of the particle-surface interaction is the ratio of the masses of the incident molecule and the surface atoms that it strikes. For this reason a measurement was previously made for a gold surface (mass number 197) at $\theta = 0°$ to see if the results are affected by a large change in the mass number of the base material. The fact that the results for gold were essentially the same as for the other surfaces indicates that under the conditions of these measurements the interaction with adsorbed gases appears to predominate.

In Figure 6 for the Echo I surface error bars are shown for the measurements at $\theta = 0°$ and $\theta = 75°$, and are representative of the corresponding uncertainties in the other measurements. The error bars give the standard deviation in the mean value of P_m/P_o as calculated from a number of measurements at a given energy, and therefore represent the result of random fluctuations from the mean value caused by system noise, etc. No inclusion has been made of possible systematic errors in the measurements, but it is felt that these should be small since the measurements involve a comparison of two determinations



ECHO I



EXPLORER XXIV
(NO PAINT)

FIGURE 5. PHOTOMICROGRAPH OF SURFACES

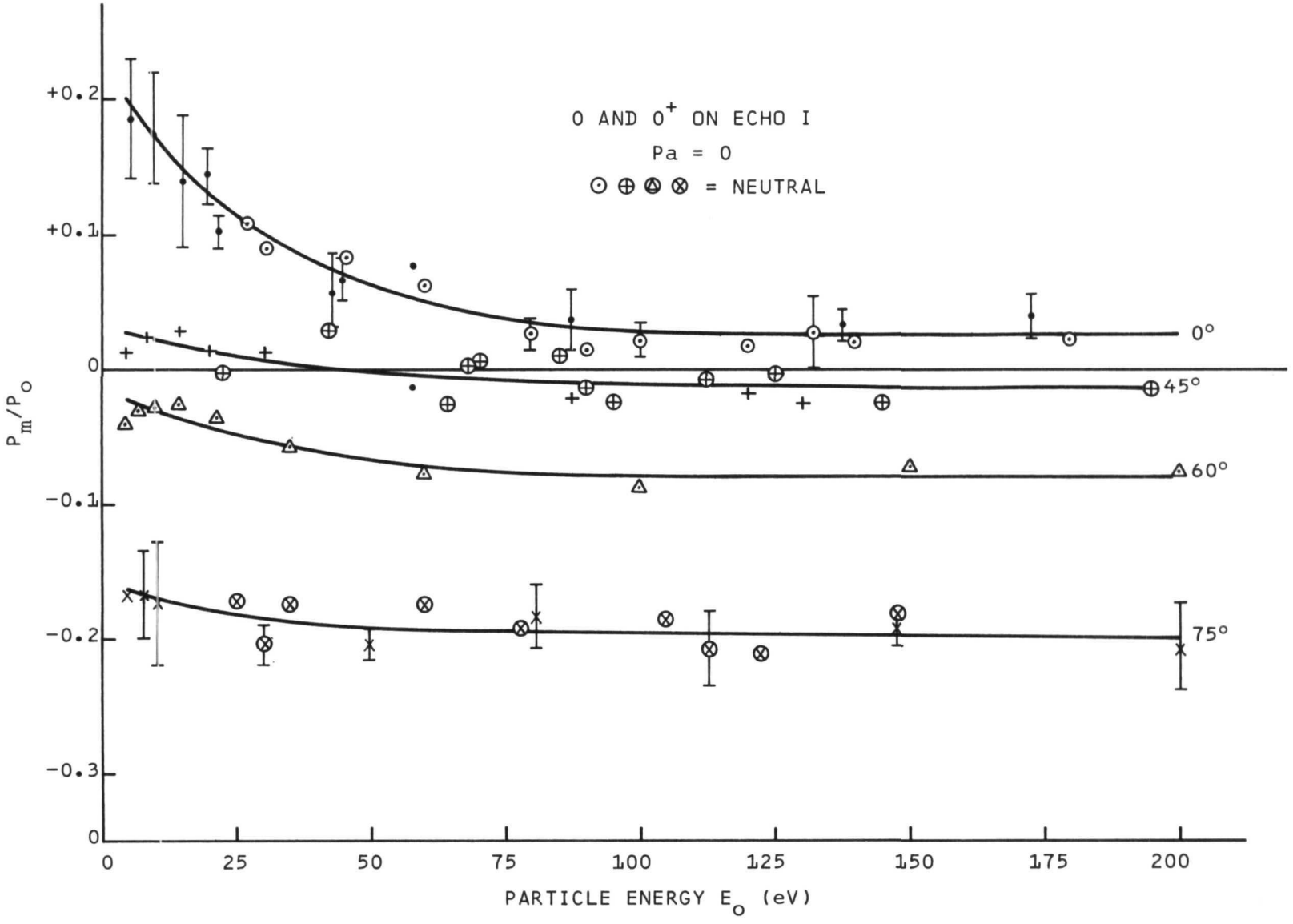


FIGURE 6. MOMENTUM TRANSFER RESULTS FOR ECHO I

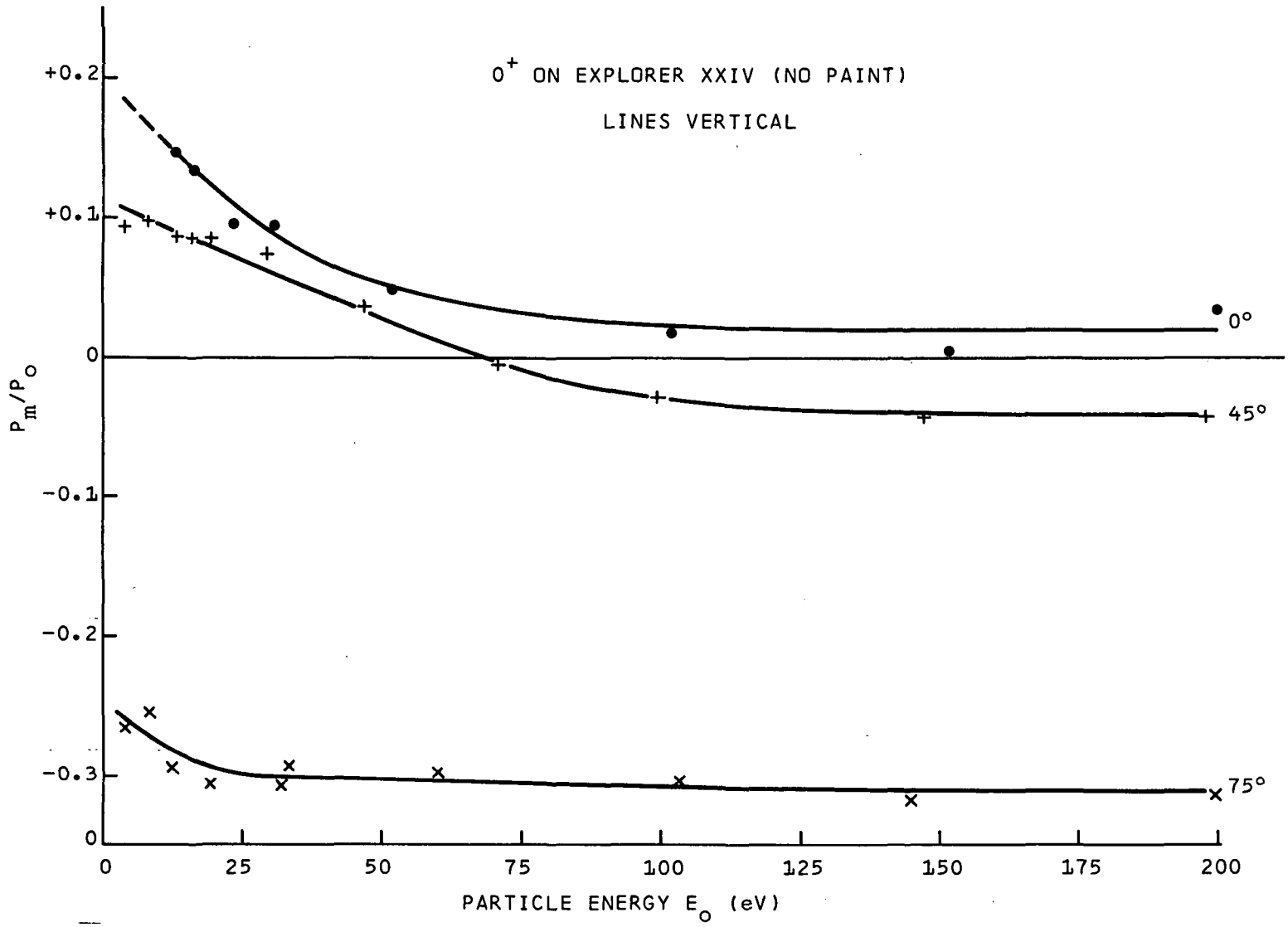


FIGURE 7. MOMENTUM TRANSFER RESULTS FOR EXPLORER XXIV (LINES VERTICAL)

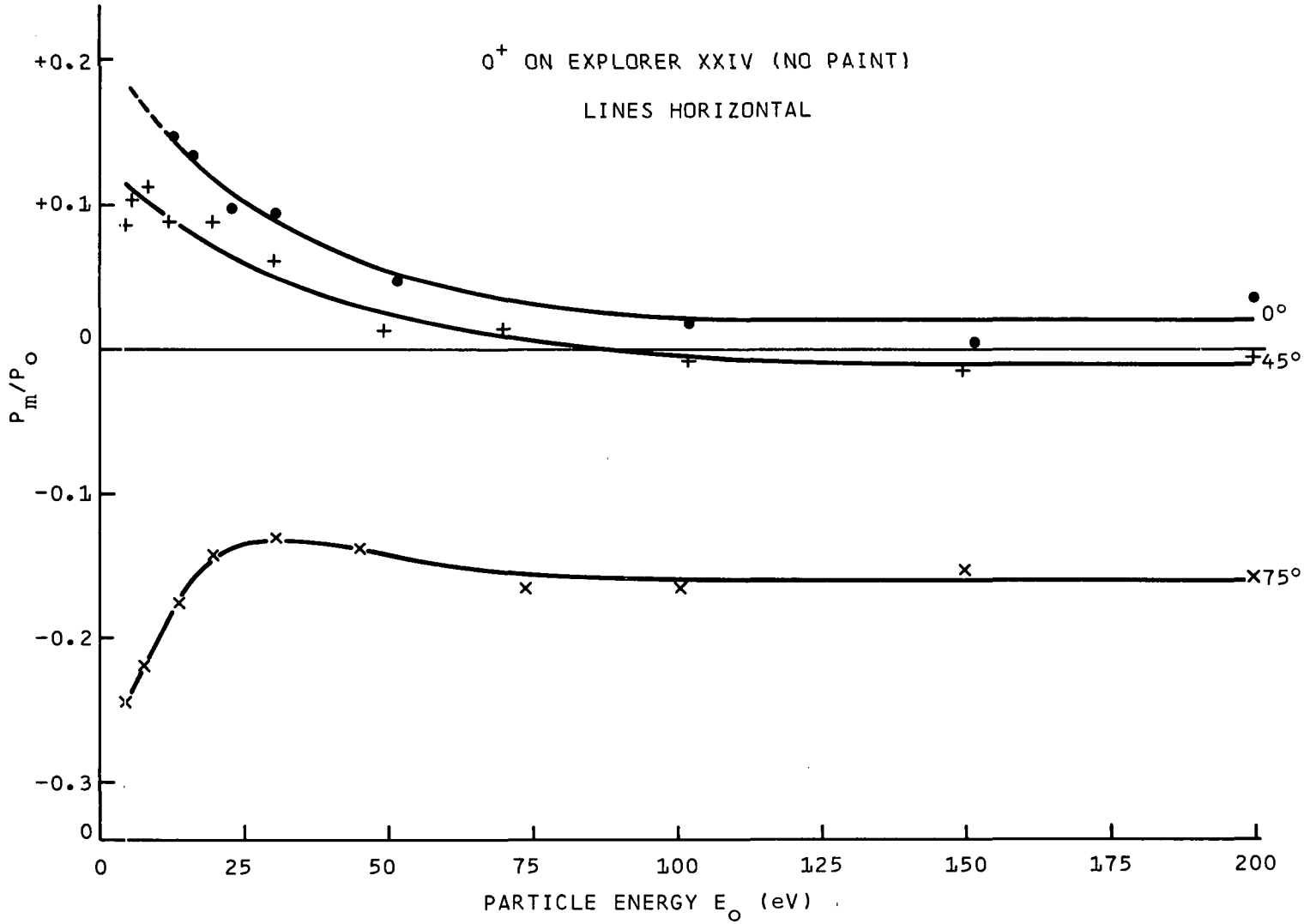


FIGURE 8. MOMENTUM TRANSFER RESULTS FOR EXPLORER XXIV (LINES HORIZONTAL)

of the same type of quantity (balance deflection) which were repeated a number of times for each surface and angle over a period of several months.

It is seen in the photomicrograph of the Explorer XXIV surface in Figure 5 that there is a pattern of parallel grooves and ridges. It was found that for the measurements of P_m/P_o for this surface at the larger angles, the orientation of this pattern affected the results. The measurements shown in Figure 7 for 45° and 75° were taken with the grooves vertical (projection of the grooves on the normal to the beam direction is vertical), while those of Figure 8 were taken with the grooves horizontal.

Drag Coefficients

One of the purposes of these measurements has been to allow one to calculate drag coefficients for bodies moving in free-molecular flow with speeds in the satellite range. With the experimental results of the last section and Equation (1) one can calculate drag coefficients for a body of any convex shape. In this section such calculations for spherical bodies are performed.

In order to do the integration indicated in Equation (1) over a sphere, it is necessary to know P_m/P_o as a function of θ. Figure 9 shows a typical plot of P_m/P_o versus $\cos\theta$ taken from Figure 6 for two energies. For a sphere, Equation (1) can be written as

$$C_D = 2\left[1 + 2\int_0^{\frac{\pi}{2}} \frac{P_m}{P_o} \sin\theta\cos\theta d\theta\right]. \qquad (10)$$

Taking the data points of Figure 9 and fitting them with straight-line segments (three or less) in the range $0.26 \leq \cos\theta \leq 1.00$ one can easily calculate the contribution to the drag

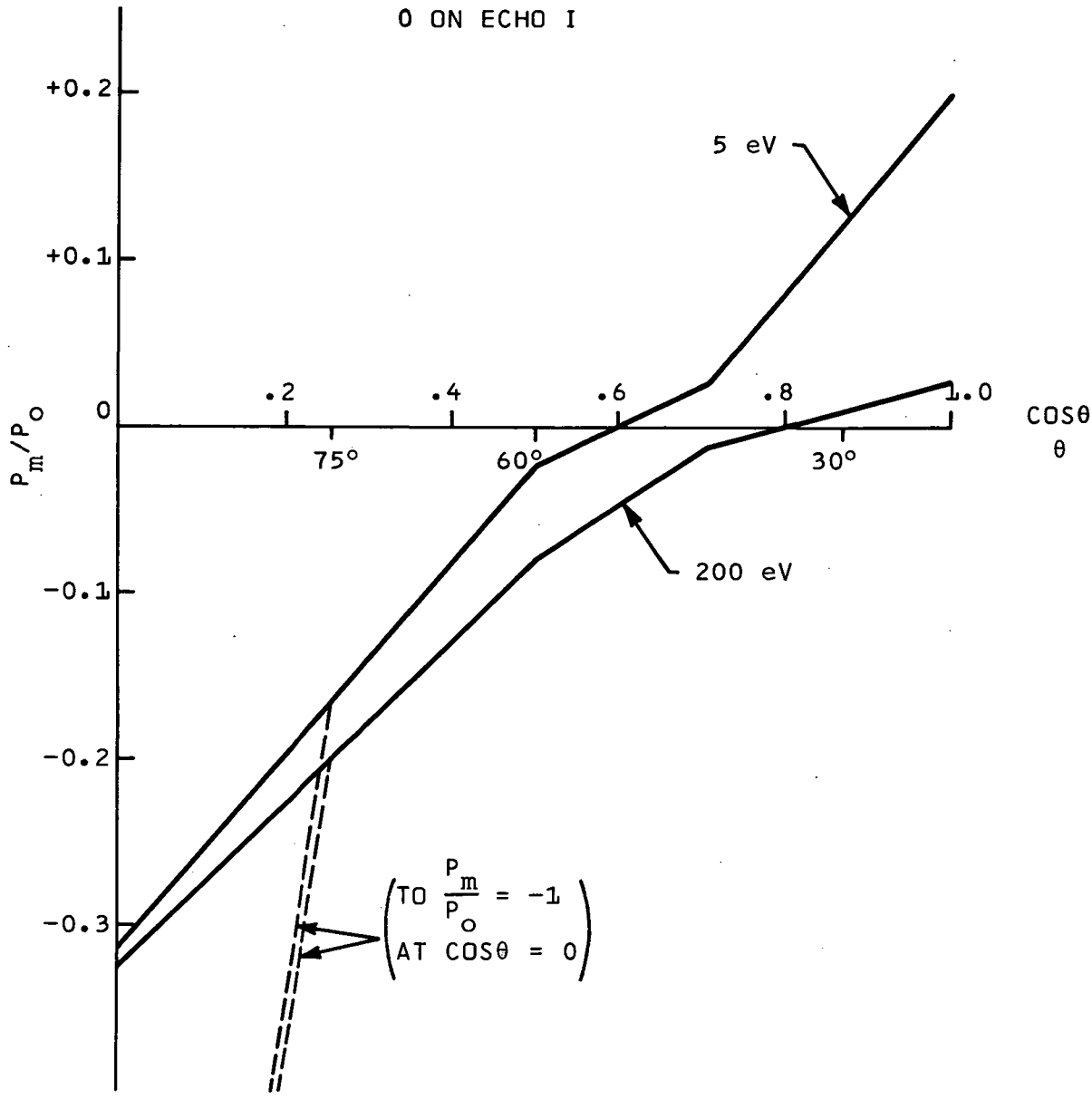


FIGURE 9. TYPICAL RESULTS AS A FUNCTION OF COSθ

coefficient for parts of the sphere where θ is less than 75°. Since no data was taken for angles greater than 75°, then some extrapolation to larger angles must be used. Consider two such extrapolation procedures as bounds on the actual behavior of the curve in this region: (1) an extension of the straight-line segment used for angles slightly less than 75° to angles $75° \leq \theta \leq 90°$ will give the upper bound to the actual curve; and (2) a straight line drawn from the data point at 75° to $P_m/P_o = -1$ at $\theta = 90°$ will give the lower bound. Plots of the drag coefficients obtained by these two methods are shown in Figures 10 and 11. It is seen that the two extremes in extrapolation amount to about a ±1 percent difference in the value of the drag coefficient.

In Figure 12 the curves of drag coefficient for O versus energy have been plotted for the Echo I and Explorer XXIV surfaces, and for comparison, the N_2 results on the Echo I surface are also shown. These represent averages of the two limiting extrapolation procedures, and for the case of Explorer XXIV, an average also of the two orientations of surface grooves (or lines). It is seen in Figure 12 that for a given energy (or velocity) the value of C_D for the two surfaces vary by less than 2%. A large part of this variation is probably attributable to differences in gross surface roughness as observed in the microphotographs of Figure 5. When a surface like that of Explorer XXIV is mounted at some angle and has the lines or grooves oriented in a horizontal direction, then from a momentum exchange viewpoint, the angle effectively appears to be less than the measured angle. See Figure 13. The result would be a higher value of P_m/P_o when compared to a "smooth" surface or a surface with the lines oriented vertically. This effect was also noticed in the N_2 momentum transfer results.

The error bars in the low energy data (shown typically in Figure 6)would lead to about a ±2 percent uncertainty in the

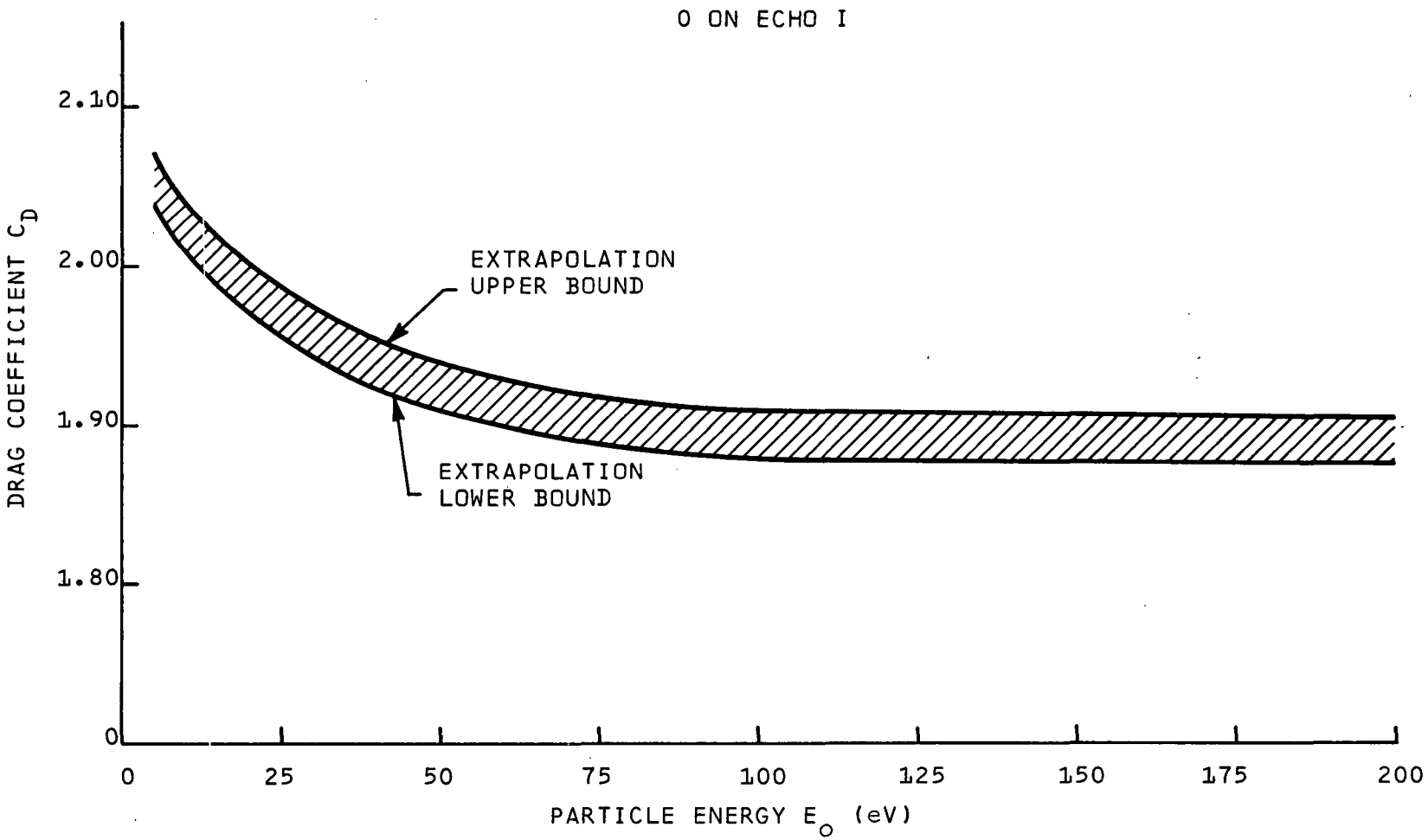


FIGURE 10. DRAG COEFFICIENTS FOR ECHO I

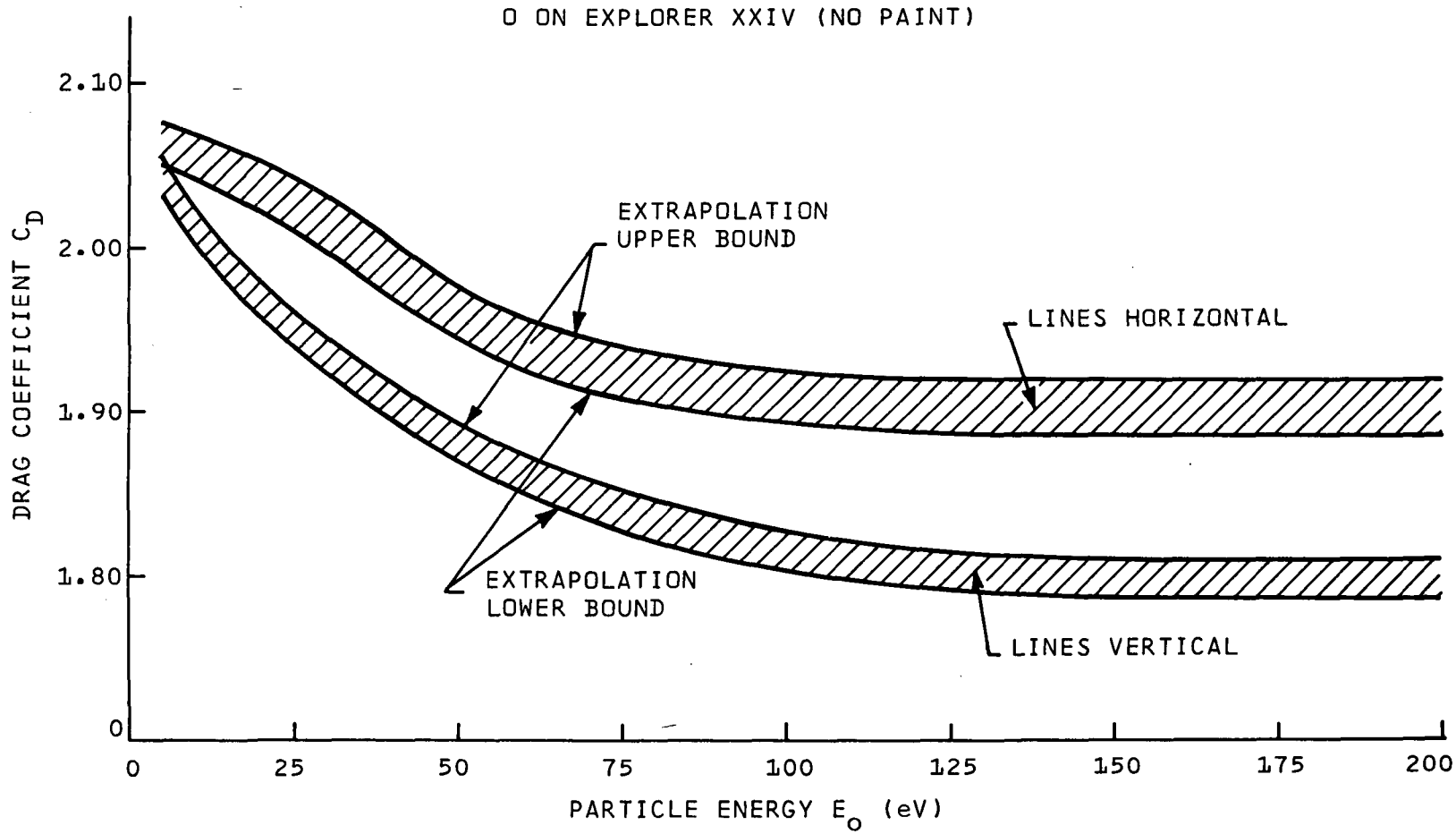


FIGURE 11. DRAG COEFFICIENT FOR EXPLORER XXIV

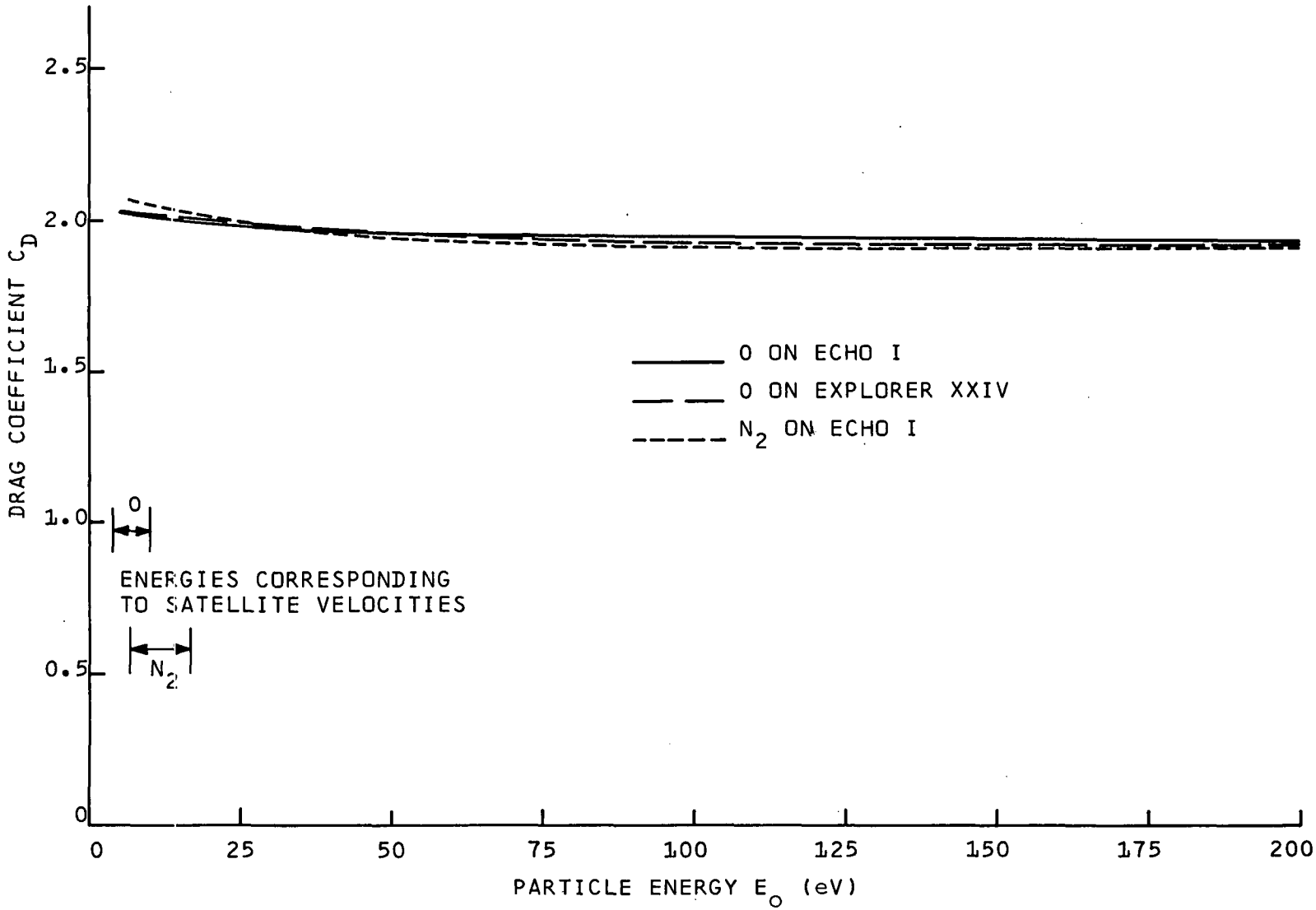


FIGURE 12. AVERAGE DRAG COEFFICIENTS

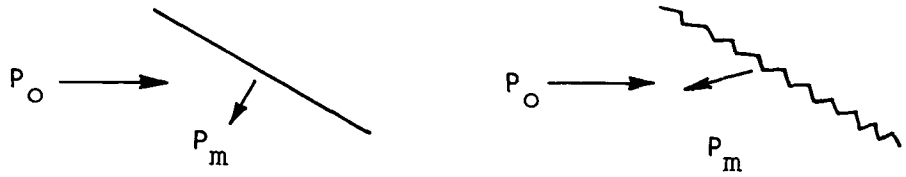


FIGURE 13. SIDE VIEW OF SMOOTH SURFACE AND SURFACE WITH GROOVES HORIZONTAL

drag coefficient, which along with the uncertainty in the large angle extrapolation procedure would lead to a total uncertainty in the drag coefficients of about ±3 percent for the lowest energies of the curves of Figure 12.

Consider now the question of estimating drag coefficients for surfaces other than those for which measurements were described above. From the fact that the $\theta = 0°$ results seem rather insensitive to both the base material of the surface and the gross surface roughness, the variation in value of drag coefficient seen for the surfaces in Figure 12 probably comes about mainly due to the different large angle behavior of the results. It is very likely that surface contour differences are what lead to this behavior, although the distance scale on which these contour differences are most important is not known. A good guess for an unknown surface might be arrived at by comparing a photomicrograph of the surface with those shown in this report and in the N_2 report [5], and from the appearance of the surface roughness, estimate the drag coefficient by inspection of the measured results.

SECTION IV
CONCLUSIONS

The drag coefficients for the Echo I and Explorer XXIV spherical surfaces in an O environment have been experimentally determined over an energy range of 4 to 200 eV. The following results were noted:

1. The drag coefficients studied are seen to be slightly greater than 2 at energies corresponding to satellite velocities.
2. The value of the drag coefficients for O on the two surfaces vary by less than 2%, and much of this variation is probably attributable to effects of differences in gross surface roughness.
3. The value of the drag coefficients for N_2 and O on the Echo I surface differ by less than 1.5%.
4. The value of $C_D \simeq 2$ for spheres obtained from both the N_2 and O experimental results comes about because the appreciable positive values of P_m/P_o for small angles is to a large extent cancelled by the negative values at larger angles. A body of a different shape might therefore give values of C_D which are significantly different from 2.
5. The validity of using ions instead of neutrals to increase the beam intensity for momentum measurements is justified by theory and by the excellent experimental results observed when both ions and neutrals were used on several different surfaces.

REFERENCES

1. Boring, J. W., "The Experimental Determination of Aerodynamic Drag on Solid Surfaces Simulating Satellite Motion," proposal AST-NASA-38-62U, Research Laboratories for the Engineering Sciences, University of Virginia, September 1962.

2. Boring, J. W., "A System for Investigating Molecule-Surface Interactions at Satellite Velocities," report EP-4018-128-65U, Research Laboratories for the Engineering Sciences, University of Virginia, November 1965.

3. Boring, J. W., "Momentum Transfer to Solid Surfaces by N_2 Molecules at Satellite Velocities," report EO-4018-139-67U, Research Laboratories for the Engineering Sciences, University of Virginia, February 1967.

4. Boring, J. W., "A Study of Systems for Producing High-Energy Monatomic Oxygen Beams," Report EP-4018-138-66U, Research Laboratories for the Engineering Sciences, University of Virginia, September 1966.

5. Boring, J. W. and Humphris, R. R., "Drag Coefficients for Spheres for Free Molecular Flow in N_2 at Satellite Velocities," report EP-4018-159-69U, Research Laboratories for the Engineering Sciences, University of Virginia, February 1969.

6. Carlston, C. E. and Magnuson, G. D., "High Efficiency Low-Pressure Ion Source," Rev. Sci. Instr. 33, 905 (1962).

7. Pearson, S. and Wadsworth, N. J., J. Sci. Instr. 42, 150 (1965).

8. Jones, R. V., J. Sci. Instr. 38, 37 (1961).

9. Kaminsky, M., Atomic and Ionic Impact Phenomena on Metal Surfaces, (Academic Press, New York 1965).

10. Carter, G. and Colligan, J. S., Ion Bombardment of Solids, (American Elsevier Publishing Co., Inc. 1968).

11. Arifov, U.A., Interaction of Atomic Particles with a Solid Surface, (Consultants Bureau, New York 1969).

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