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ANALYSIS OF THE PERFORMANCE OF THE SPACE ULTRAVACUUM RESEARCH FACILITY IN ATTACHED AND FREE-FLYER MODE

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16. ABSTRACT

The old concept of using the wake of a spacecraft to obtain an ultrahigh vacuum is revisited with a somewhat different emphasis. Since it is possible to configure a wake shield so that a surface of interest does not subtend any walls that could become contaminated, it appears that it should be possible to achieve a contamination-free, ultrahigh vacuum capability with infinite pumping speed even in the presence of high heat loads and moderate gas loads. With the new interest in developing thin films with precision controlled synthetic microstructures such as superlattices, mixed metal oxide high temperature superconductors, rare-Earth magneto-optical devices, and nano-crystalline alloys, the ability to work with a variety of different materials without cross contamination should be of significant importance. This paper analyzes the performance of the conceptual design for a Space Ultravacuum Research Facility (SURF), both in a Shuttle-attached mode and as a free-flyer. It is shown that even in the Shuttle-attached mode, it should be possible to obtain vacuum levels equivalent to 10^{-10} Torr with O and N_2 as the primary constituents. This should be sufficient to demonstrate the feasibility of the concept, particularly the infinite pumping speed and virtual elimination of contamination aspects. As a free-flyer the SURF will be limited primarily by the gas load associated with the process being performed. For chemical beam epitaxy (CBE) it is shown that equivalent vacuum levels of 10^{-14} Torr should be possible at 300 km.

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ANALYSIS OF THE PERFORMANCE OF THE SPACE ULTRAVACUUM RESEARCH FACILITY IN ATTACHED AND FREE-FLYER MODE

I. Introduction

An orbiting vehicle in low-Earth orbit travels several times faster than the average thermal speed of the residual atmospheric molecules. This produces a strong anisotropy in the directional flux of these molecules as observed from the spacecraft. Only a very small fraction of the lightest species (H and He) has any chance of overtaking an orbiting spacecraft from the rear; hence a nearly perfect vacuum can be created in the wake region of an orbiting plate which acts as a wakeshield. A surface located behind such a wakeshield, oriented toward the wake direction, would have no walls in its field of view that could become contaminated and release molecules in the presence of high heat loads. Furthermore, momentum considerations would prevent any molecule that leaves the surface of interest from ever returning. Thus, we could have a virtually contamination-free vacuum system that can accommodate high heat loads with an infinite pumping speed.

The concept of using the wake region of an orbiting vehicle to provide an ultrahigh vacuum (UHV) is by no means new. Kostoff first proposed this concept [1,2]. Wuenscher [3,4] mentioned this possibility in several of his early works on space processing. Melfi et al. [5] and Hueser and Brock [6] carried out detailed analyses of the vacuum environment in the vicinity of a hemispherical wakeshield deployed behind the Space Shuttle using a long boom or tether. Oran and Naumann [7,8] made order-of-magnitude estimates of the wake vacuum behind free-flying satellites. NASA sponsored several detailed studies [9,10] of such a facility in the late 1970's which confirmed the feasibility of obtaining ultrahigh vacuum by this technique. However, interest in this possibility waned because the concept at that time required the construction of a large ultravacuum chamber that would be pumped down and baked out on Earth, carried into orbit by the Shuttle, and then opened to the wake vacuum. This appeared to be prohibitively expensive and there did not appear to be sufficient user interest to justify continuation of the study. It was generally perceived that ultravacuum chambers on Earth were quite adequate for the processes envisioned at the time.

However, recent technological advances in developing materials with synthetic microstructures such as superlattices for electronic or photonic applications, mixed metal oxide thin films for high temperature superconducting devices, thin films with rare-Earth components for magneto-optical devices, and nano-crystalline alloys have placed more stringent demands on vacuum systems, particularly with regard to cross contamination. This becomes especially critical in applying molecular beam epitaxy technology to grow strained lattice systems for heterojunction devices with tailored bandgaps, mixed III-V/II-VI superlattices, etc. or in mixed oxide-high temperature superconductor systems that involve components with measurable vapor pressures. The ability to experiment with a wide variety of materials has been limited by the understandable reluctance of researchers to introduce materials such as Hg, Cd, Zn, Te, Se, P, As, Ba, etc. into their expensive UHV apparatus unless the facility is to be dedicated to the use of that specific material. A simple calculation will show that residual pressures as low as 10^{-16} Torr of certain contaminants can produce unwanted doping that can alter the electronic properties of other materials processed in the system. Even the use of a cryogenic cold wall may not be effective in trapping such components during processes that involve high heat loads because of photodesorption.

The pumping speed is also a limitation in many terrestrial UHV systems. Even with systems capable of 10^{-12} Torr, it is difficult to maintain much better than 10^{-6} to 10^{-7} Torr during processes such as chemical beam epitaxy (CBE) that involve a moderate gas load because of pump saturation.

The possibility of using a space vacuum facility for research in thin film technology and epitaxial crystal growth appears to offer an attractive alternative to some of the experimental difficulties encountered in ultra-vacuum processing, especially with regard to the virtual elimination of cross contamination and the ability to maintain good vacuum conditions in the presence of high heat and moderate gas loads. A new concept has evolved for simplifying the design and operation of a Space Ultravacuum Research Facility (SURF) which utilizes the space environment to clean and bake out the facility [11,12]. The SURF concept (Fig. 1) makes use of a large (~5 m dia.) shield that is convex on the wake side to minimize wall exposure to the sample surface, and to minimize the introduction of thermal molecules into the wake region where they could backscatter high-speed ambient atmospheric molecules into the region of interest.

To achieve its ultimate vacuum capabilities (~10^{-14} Torr), SURF would have to be a free-flyer. It could be deployed from the Space Shuttle and serviced in orbit, initially by the Shuttle and ultimately by the Space Station. It may be desirable (and less expensive) to conduct the first experiments with the SURF attached to the Shuttle using the remote manipulator arm. By flying the Shuttle belly-first and deploying the SURF in its wake, the larger area of the Shuttle can act as a primary shield as shown in Fig. 2. The Shuttle itself is a copious source of molecules which can degrade the vacuum conditions achievable by the SURF; however, it may still be possible to demonstrate certain features of the SURF concept such as its ability to handle high heat loads and gas loads with infinite pumping speed, and to avoid cross contamination by eliminating walls in the sample field of view.

The purpose of this paper is to establish the SURF concept by estimating its potential performance both as a free-flyer and in the Shuttle attached mode.

II. Analysis of the Wake Vacuum

Both the natural and the induced atmosphere surrounding a spacecraft are potential sources that can contribute to the influx of molecules into the wake region. Since the distribution of molecular velocities is highly anisotropic and mean free paths of such molecules are very long compared to the spacecraft dimensions, the more familiar state variables that are generally used to characterize a vacuum such as number density and pressure are not directly applicable. Instead, one must consider the directional flux of molecules incident on a surface of interest behind the wake shield.

The high-speed tail of the Maxwell-Boltzmann distribution of the ambient atmosphere that can overtake the spacecraft is an inherent limitation on the vacuum that can be achieved in the wake region. This background depends on the orbital altitude as well as on the solar activity which affects both the number density and kinetic temperature at different altitudes. As will be seen in the next section, the contributions from this source are highly species dependent. Only the lightest components (H and He) have any chance of overtaking the spacecraft.

The induced atmosphere is of more serious concern. In the attached mode, thermal molecules leaving the Shuttle can enter the wake region of the SURF past the shield and contribute to the number density in the region, but cannot impinge directly on the surface of interest because they are all moving away from the Shuttle. It is possible for two such molecules to collide in the wake region and for one to be backscattered into the region of interest; however, it can be shown that such collisions are highly unlikely at some distance away from the source; hence self-scattering from the induced atmosphere can be neglected [13].

The most significant contribution to the molecular flux in the wake region will be collisions between ambient atmospheric molecules, which have a high relative speed to the spacecraft, and any thermal molecules which happen to be in the wake region. The thermal molecules cannot be backscattered toward the surface of interest, but the ambient molecules can be, provided they are less massive than the thermal molecule they collided with. Therefore, it is the interaction of the ambient atmosphere with the induced atmosphere that sets the limit on the vacuum conditions achievable with the SURF.

In the free-flying mode, Shuttle-induced molecules will be absent. By making the shield concave in the forward direction, intercepted ambient molecules that are reflected with thermal velocities are prevented from entering the wake region. Components that outgas are also located on the forward side of the SURF for the same reason. The only sources of thermal molecules in the wake region then will be outgassing from the shield itself and the molecules that evolve from whatever process that is carried out behind the shield.

A. Ambient Atmospheric Contribution

For an observer moving at velocity v_A in a gas whose molecules are in thermal equilibrium at temperature T, the directional flux is given by the drifted Maxwell-Boltzmann distribution function

$$\left(\frac{\partial\Phi}{\partial\Omega}\right)_\theta = \frac{n_A v_A}{\pi^{3/2}} \beta^{3/2} \int_0^\infty x^3 \, e^{-\beta(x^2 + 2x\cos\theta + 1)} \, dx \qquad (1)$$

where n_A is the number density, θ is the look angle relative to the velocity vector, and β is given by

$$\beta = \frac{Mv_A^2}{2\ RT}$$

where M is the molecular weight and R is the gas constant.

The orbital velocity at altitude H is given by

$$v_A^2 = \frac{g_{\odot} R_{\oplus}^2}{R_{\oplus} + H}$$

where $g_{\odot}$ is the acceleration at the surface of the Earth whose radius is $R_{\oplus}$. Numerically β is given by

$$\beta = 3760.82\left(\frac{6378}{6378 + H}\right) \frac{M}{T}$$

where H is expressed in km. Values for β are tabulated for H = 300 km in Table 1 for the various atmospheric species along with their number densities for the standard atmosphere [14] and for maximum and minimum solar activity [15]. The temperature was taken to be 1000 K for the standard atmosphere, 789 K for minimum solar activity, and 1480 K for maximum solar activity.

The maximum and minimum directional fluxes of the dominant atmospheric components are plotted in Fig. 3. Except for H and He, it is apparent that virtually no molecules can enter from angles greater than 90°.

The total flux incident on a flat plate oriented toward the wake direction (θ = 0) is given by

$$\Phi_{rear} = 2\pi \int_0^{\pi/2} \left(\frac{\partial\Phi}{\partial\Omega}\right)_\theta \cos\theta \sin\theta \, d\theta \tag{2}$$

which may be integrated to give

$$\Phi_{rear} = \frac{n_A v_A}{2} \left[\frac{e^{-\beta}}{(\pi\beta)^{1/2}} - \mathrm{erfc}(\beta^{1/2})\right]. \tag{3}$$

For $\beta >> 1$,

$$\Phi_{rear} = \frac{n_A v_A e^{-\beta}}{2(\pi\beta)^{1/2}} \left[\frac{1}{2\beta} - \frac{3}{4\beta^2} + \frac{15}{8\beta^3} - \frac{105}{16\beta^4} + \ldots\right]. \tag{4}$$

Note that as $\beta \to 0$ the expression reduces to the well-known result,[1]

$$\Phi_{rear} = \frac{n_A}{2}\left(\frac{2\ RT}{\pi M}\right)^{1/2} = \frac{n_A}{4}\left(\frac{8\ RT}{\pi M}\right)^{1/2} = \frac{n_A\langle v\rangle}{4} \tag{5}$$

where $\langle v\rangle$ is the average thermal speed.

Similarly, the total flux on a plate oriented at 90° to the flight path and shielded from molecules approaching at less than 90° is given by

$$\Phi_{side} = \int_0^{\pi} d\Phi \int_0^{\pi/2} \sin\theta \sin\phi \left(\frac{\partial\Phi}{\partial\Omega}\right)_\theta \sin\theta\, d\theta$$

or (6)

$$\Phi_{side} = 2\int_0^{\pi/2} \sin^2\theta \left(\frac{\partial\Phi}{\partial\Omega}\right)_\theta d\theta\ .$$

The integrated fluxes incident on both a rear- and side-looking plate are tabulated in Table 2 along with the equivalent pressure for the case of standard atmosphere at 300 km.[2] Note that H and He are the only species that have any possibility of overtaking the orbiting spacecraft. It is also interesting to note that the flux of H incident on a plate is relatively insensitive to orientation. The somewhat higher flux as θ approaches 90° is offset by the cutoff at $\theta = 90°$. For He and heavier species the influx of molecules is considerably greater as θ approaches 90°, but their number is still so small as to be insignificant.

B. Backscattering from Thermal Molecules

The major source of molecules entering the wake region is backscattering of ambient molecules by collisions with thermal molecules in the induced atmosphere of the spacecraft.

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(1) Hueser and Brock [6] obtain a result similar to eq. (3) except for the factor $(\pi\beta)^{1/2}$ in the denominator. Without this factor, the flux does not reduce to the proper value as $\beta \to 0$.

(2) By equivalent pressure we mean that pressure of an ideal gas at equilibrium with a chamber whose walls were at 300 K that would produce the same number of collisions per unit time on the surface in question. This is given numerically by

$$p(\text{Torr}) = \frac{\Phi(\text{cm}^{-2}\ \text{sec}^{-1})(MT)^{1/2}}{3.52 \times 10^{22}}\ .$$

Let n_o be the number density of thermal molecules in the vicinity of the spacecraft. The number of collisions that take place per unit time in an element of volume $dV = r^2 dr d\Omega$ is given by $n_A v_A \sigma_{Ao} n_o r^2 dr d\Omega$, where σ_{Ao} is the total scattering cross section. It is assumed here that the thermal velocities of the molecules in the induced atmosphere are much less than the relative velocities of the ambient molecules with respect to the spacecraft.

The probability that such a collision will scatter a molecule into solid angle $d\omega$ that subtends the area of interest dA is

$$\frac{1}{\sigma_{Ao}} \left(\frac{\partial\sigma}{\partial\omega}\right)_{\pi-\theta} d\omega,$$

where $d\omega = dA/r^2$ and $(\partial\sigma/\partial\omega)$ is the differential scattering cross section.

Therefore the number of scattered molecules crossing an element of area dA per unit time from solid angle $d\Omega$ or the directional flux is given by

$$\left(\frac{\partial\Phi}{\partial\Omega}\right) = n_A v_A \left(\frac{\partial\sigma}{\partial\omega}\right) \int_o^\infty n_o dr \tag{7}$$

assuming that the scattered molecule makes no additional collisions before it arrives at dA. The probability of such a molecule traversing a distance without colliding with another ambient molecule is $\exp(-r/\lambda)$ where the mean free path λ is given by

$$\lambda = \frac{\langle v_o \rangle}{n_A v_A \sigma_{Ao}} . \tag{8}$$

The average speed of the thermalized molecules $\langle v_o \rangle$ is given by

$$\langle v_o \rangle = \left(\frac{8\ RT}{\pi M}\right)^{1/2} = 145.5(T/M)^{1/2}\ (\mathrm{m\ sec^{-1}}).$$

Correcting for secondary scattering losses, the directional flux becomes

$$\left.\frac{\partial\Phi}{\partial\Omega}\right)_\theta = n_A v_A \left(\frac{\partial\sigma}{\partial\omega}\right)_{\pi-\theta} \int_{r_1}^\infty n_o e^{-(r-r_1)/\lambda} dr , \tag{9}$$

where r_1 is the distance from the observation point to the point at which the thermal molecules are shielded from the flux of ambient molecules.

C. Scattering Cross Sections

There does not appear to exist any direct measurements of the differential scattering cross sections for the atmospheric molecules of interest at the energies of interest, typically 5 eV. Foreman [16] has obtained potential functions for the repulsive forces between atoms from scattering data in the 100-eV range. The potentials have the form

$$U = Ae^{-ad}, \tag{10}$$

where d is the separation distance between the two particles and A and a are experimentally determined constants.

Using this potential function along with conservation of energy and angular momentum in the center of mass system, the closest approach d_o is related to the impact parameter δ by

$$Ae^{-ad_o} = \left(1 - \frac{\delta^2}{d_o^2}\right)KE' \tag{11}$$

where KE' is the kinetic energy in the center of mass system. In order to produce backscatter in the lab system, a large scattering angle is required in the center of mass system, hence $\delta << d_o$. The closest approach distance may be obtained by

$$d_o = -\frac{1}{a}\left[\ln\left(\frac{KE'}{A}\right) + \ln(1 - \delta^2/d_o^2)\right] \tag{12}$$

or

$$d_o \approx -\frac{1}{a}\left[\ln\left(\frac{KE'}{A}\right) + \frac{\delta^2}{d_o^2}\right]. \tag{13}$$

Since $KE' << A$ and $\delta^2 << d_o^2$, the distance of closest approach is only slightly dependent on the impact parameter for collisions that produce backscatter. Therefore, a hard sphere approximation may be applied for collisions of interest with the result that scattering in the center of mass system will be isotropic with a differential scattering cross section given by

$$\left.\frac{\partial\sigma}{\partial\omega}\right)c/m = \frac{\sigma_{Ao}}{4\pi} = \frac{\pi d_o^2}{4\pi} = \frac{d_o^2}{4}. \tag{14}$$

Using the potential function parameters obtained by Foreman for atomic oxygen colliding with other gases, the differential scattering cross sections in the center of mass system are listed in Table 3.

Transforming back to the lab system in which the outgassing molecule with mass M_o is considered to be at rest, the differential scattering cross section is given by

$$\left.\frac{\partial\sigma}{\partial\omega}\right)_{\pi-\theta} = \frac{d_o^2}{4}\left[\frac{1 + \gamma^2(\cos^2\theta - \sin^2\theta)}{(1 - \gamma^2 \sin^2\theta)^{1/2}} - 2\gamma\cos\theta\right] , \tag{15}$$

where $\gamma = M_A M_O^{-1} \varepsilon^{-1/2}$ for ambient molecules with mass M_A scattered by thermal outgassing molecules and ε is the coefficient of restitution. Note that if $\gamma > 1$ scattering at angles >90° is not possible. For the thermal outgassing molecules, eq. (15) also applies but in this case $\gamma = \varepsilon^{-1/2} > 1$ and no backscattering is possible.[3]

Normalized values of diffential cross sections as a function of θ for different values of γ are shown in Fig. 4.

D. Induced Atmosphere

Assume an omnidirectional source emitting Q thermal molecules per second. The number density from such a source at some distance ℓ is given by

$$n_o(\ell) = \frac{Q}{4\pi\ell^2} \langle\frac{1}{v}\rangle \tag{16}$$

assuming no collisional losses. For a Maxwell-Boltzmann distribution the average inverse molecular speed is given by

$$\langle\frac{1}{v}\rangle = \frac{4}{\pi\langle v\rangle} , \tag{17}$$

where $\langle v\rangle$ is the average molecular speed.

Assume the molecules are shielded from collisions with ambient molecules by some form of structure until they reach a distance ℓ_1 from the source point. After a thermal molecule encounters a high-speed ambient molecule, it is scattered forward with much higher than thermal velocity and is no longer effective in backscattering ambient molecules. Therefore the number density of thermal molecules is given by

$$n_o(\ell) = \frac{Qe^{-(\ell-\ell_1)/\lambda}}{\pi^2\ell^2\langle v\rangle} . \tag{18}$$

Now let the source Q be located some Z_o in front of the wakeshield as shown in Fig. 5. Putting this into eq. (9) yields

$$\left.\frac{\partial\Phi}{\partial\Omega}\right)_\theta = n_A v_A \left(\frac{\partial\sigma}{\partial\omega}\right)_\theta \frac{Q}{\pi^2\langle v\rangle} \int_{r_1}^{\infty} \frac{e^{-(\ell-\ell_1)/\lambda}\, e^{-(r-r_1)/\lambda}}{\ell^2}\, dr \tag{19}$$

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(3) By analogy, a pool ball at rest struck by the cue ball cannot be made to move backward because of momentum considerations.

where

$$\ell = [r^2 + Z_o^2 + 2rZ_o \cos\theta]^{1/2} . \tag{20}$$

If the structure shielding the thermal molecules has radius r_o, the shielding distance r_1 is $r_1 = r_o/\sin\theta$ and $\ell_1 = r_1 \ell/r$.

If λ is sufficiently large so that the scattering loss terms may be neglected, the integral may be evaluated in closed form

$$\int_{r_1}^{\infty} \frac{dr}{\ell^2} = \frac{1}{Z_o \sin\theta} \left[\frac{\pi}{2} - \tan^{-1} \left(\frac{r_1 + Z_o \cos\theta}{Z_o \sin\theta}\right)\right]. \tag{21}$$

For $Z_o \sin\theta << r_1$, this further reduces to

$$\int_{r_1}^{\infty} \frac{dr}{\ell^2} \rightarrow \frac{1}{r_1 + Z_o \cos\theta} . \tag{22}$$

These simplified expressions are useful to estimate an upper bound on the backscatter flux.[4] On the other hand, if $r \approx \ell$, the integral becomes

$$\int_{r_1}^{\infty} \frac{e^{-2(r-r_1)/\lambda}}{r^2} dr = \frac{1}{r_1} \left[1 - \frac{2r_1}{\lambda} e^{2r_1/\lambda} Ei(2r_1/\lambda)\right]. \tag{23}$$

The exponential integral function Ei(x) is defined

$$Ei(x) = \int_{x}^{\infty} e^{-u} \frac{du}{u} = -\varepsilon - \ln x + x - \frac{x^2}{2 \cdot 2!} + \frac{x^3}{3 \cdot 3!} - \frac{x^4}{4 \cdot 4!} \cdots \tag{24}$$

where ε is Euler's number, $\varepsilon = 0.577215665$. For $x >> 1$, it is convenient to use the semiconvergent asymptotic series

$$Ei(x) = e^{-x} \left[\frac{1}{x} - \frac{1}{x^2} + \ldots\right]. \tag{25}$$

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(4)For example, if we ignore scattering losses and take $Z_o << r_o$, the directional flux from backscattered ambient molecules becomes

$$\left(\frac{\partial\Phi}{\partial\Omega}\right)_\theta = \frac{n_A v_A}{\pi^2 \langle v \rangle} \left(\frac{\partial\sigma}{\partial\omega}\right)_\theta \frac{\sin\theta \cos\theta}{r_o + Z_o \sin\theta \cos\theta} .$$

For the general case, the integral in eq. (19) is evaluated numerically from $r = r_1$ to a point r_2 at which the difference between r and ℓ becomes arbitrarily small. The final term is then obtained from the expression

$$\int_{r_2}^{\infty} \frac{e^{-2(r-r_1)/\lambda}}{r^2} dr = \frac{1}{r_2} \left[e^{-2(r_2-r_1)/\lambda} - \frac{2r_2}{\lambda} e^{2r_1/\lambda} Ei(2r_1/\lambda)\right] . \qquad (26)$$

E. Source Terms

There are a number of sources of thermal molecules on the Shuttle that must be evaluated to determine their contribution to the backscatter.

1. The ram flux. Each element of surface facing the ram direction encounters $n_A v_A$ molecules cm^{-2} sec^{-1} of residual atmosphere. For a standard atmosphere, this represents 7.4×10^{13} N_2 cm^{-2} sec^{-1} or 1.3×10^{20} molecules sec^{-1} most of which become thermalized and are readmitted in the forward direction. With the Shuttle flying belly-first, only a small fraction of these molecules will enter the wake region with thermal velocities because of the relatively flat underside of the vehicle presented to the ram flux. Therefore, this contribution will be small compared to cabin gas leakage.

2. Cabin gas leakage. Typically, some 1.5 kg of cabin gas per day leaks from seals in the crew cabin. This represents 3×10^{20} N_2 molecules sec^{-1} and 6.5×10^{19} O_2 molecules sec^{-1}. Lacking any specific orientation of such leaks, this source will be assumed to be isotropic.

3. H_2O/outgassing. The porous tiles that provide thermal protection system can soak up moisture during launch preparation, especially if subjected to heavy rain. The Induced Environment Contamination Monitor (IECM) flown on STS-2, -3, and -4 measured the forward scattered flux of H_2O when the payload bay was facing the ram direction using a collimated mass spectrometer [17]. From eq. (9) the directional flux of these scattered molecules is given by

$$\frac{\partial\Phi}{\partial\Omega}\Big)_\theta = n_A v_A \left(\frac{\partial\sigma}{\partial\omega}\right)_\theta \int_0^{\infty} n_o dr. \qquad (27)$$

For elastic scattering of thermal molecules the γ term in eq. (15) is 1 and the differential scattering cross section reduces to

$$\frac{\partial\sigma}{\partial\omega}\Big)_\theta = \frac{\sigma_{Ao}}{\pi} \cos\theta.$$

The observed directional flux at $\theta = 0$ early in the STS-4 mission was 2.1×10^{14} H_2O cm^{-2} sec^{-1} sr^{-1} and eventually decayed to 6.5×10^{12} cm^{-2} sec^{-1} sr^{-1}. Similar results were obtained on STS-2, which, like STS-4, had been subjected to heavy rain prior to launch. On the other hand, STS-3, which had remained fairly dry, observed backscatter fluxes ranging from 1.0×10^{12} cm^{-2}

sec^{-1} sr^{-1} early in the mission to 2.6 x 10^{11} cm^{-2} sec^{-1} sr^{-1} late in the mission. For v_A = 7.72 x 10^4 cm sec^{-1}, n_A = 1.3 x 10^9 molecules cm^{-3}, and σ_{Ao} = 9 x 10^{-16} cm^2, the corresponding integrated column densities are shown in Table 4. The respective source functions are obtained by treating the Shuttle as a uniform disc Lambertian emitter with radius R_o = 7.2 m. The column density along the normal of such a disc can be shown to be [13]

$$\int_0^\infty n_o dr = \frac{8Q}{\pi^2 \langle v_o \rangle R_o}.$$

For $\langle v_o \rangle$ = 5.94 x 10^5 cm sec^{-1}, the calculated values for Q are also given in Table 4.

4. Flash evaporator. Approximately 4 kg of H_2O must be evaporated per hour to provide cooling for the avionics in the attitude envisioned. This amounts to 3.7 x 10^{22} H_2O molecules sec^{-1}. Most of these molecules can be deflected into the forward direction by raising the elevons above the evaporator vents which are located on the sides of the fuselage just forward of the body flap as shown in Fig. 2. The effectiveness of this shielding by the elevons was demonstrated by the fact that no change in backscattered H_2O flux was noted in the IECM measurements on STS-2, -3, or -4 when the flash evaporation was operated [17].

5. VCS firings. The vernier control system (VCS) thrusters will consume approximately 1 kg of fuel per hour to maintain the prescribed attitude. The primary combustion products are N_2, H_2O, and oxides of nitrogen. This produces some 3.6 x 10^{21} N_2 molecules sec^{-1} and 2.4 x 10^{21} H_2O sec^{-1}. None of the thrusters fire upward relative to the payload bay, but a portion of the plume from the rear thrusters impinges on the wings which could create a significant source of thermal molecules that can enter the wake region. Since the H_2O molecules from this source should be included in the ram backscatter measurements made by the IECM, we must conclude that only a small fraction of the thruster plume molecules become thermalized by this mechanism.

6. Outgassing from the shield. A clean and well baked-out stainless steel surface should outgas at a rate lower than 10^8 molecules cm^{-2} sec^{-1} [9]. For a 5 m diameter shield this would amount to 2 x 10^{13} molecules sec^{-1}.

7. Process molecules. For a typical crystal growth by chemical beam epitaxy (CBE), the source flux is 10^{16} H_3As cm^{-2} sec^{-1} and 10^{16} $(CH_3)_3Ga$ cm^{-2} sec^{-1}. These gases react to form GaAs with the release of H_2 and CH_4. Since none of the gas reaction products are massive enough to backscatter O or heavier atmospheric constituents, they will not degrade the wake vacuum. However, as many as half the primary molecules may not react. Since all of the molecules that do not react will be in the wake region, the effective Q will be taken as 10^{16} $H_3As(M_o = 36)$ and 10^{16} $(CH_3)_3Ga(M_o = 118)$.

F. Prediction of Wake Vacuum

Using the values for Q from each of the various sources described in the previous section, the differential backscattered flux for each atmospheric component is obtained from eq. (19). Figure 6 shows the directional flux of O scattered from N_2, O_2, and H_2O emissions from the Shuttle for a standard atmosphere at 300 km. The integrated values on a side-facing and rear-facing surface are given in Table 5. Again it may be seen that the increased flux as the look angle approaches 90° is offset by the cutoff provided by the shield.

Finally the total flux of each atmospheric component incident on a rear-facing surface behind the wakeshield is given in Table 6 for both the Shuttle-attached mode and the free-flyer mode. This total includes both the over-taking flux and the backscattered flux from all of the thermal molecules in the wake region. The range of values reflects the variations in atmospheric composition due to solar activity.

III. Conclusions

The wake environment of an orbiting spacecraft has been estimated using a simple single-collision model. This approach seems justified because the mean free paths are long compared with characteristic dimensions of the spacecraft. The source terms for thermal molecules originating from the Space Shuttle were obtained from measured crew cabin loss rates and from molecular backscatter measurements made on the early flights using a collinated mass spectrometer. The present SURF wakeshield concept confines most of its thermal molecules to the forward side of the shield. The only thermal molecules introduced into the wake region by the SURF will be outgassing from the shield surface and molecules introduced by the process being carried out.

In the attached mode the wake environment will be governed primarily by the induced environment of the Shuttle. The calculations indicate that it should be possible to obtain vacuum levels equivalent to 10^{-9} Torr or better at 300 km even under worst-case assumptions for ambient atmospheric density and Shuttle outgassing. This should be sufficiently low to carry out some precursory vacuum experiments to demonstrate the infinite pumping speed in the presence of high heat and gas loads, and to test the assumptions made in this estimate.

The largest uncertainties are probably in the source terms of thermal molecules from the Shuttle. The source terms for H_2O obtained from ram scattering measurements on early Shuttle flights were consistent with the values obtained from direct survey measurements in which the mass spectrometer package was picked up by the remote manipulator arm and turned to measure the direct molecular flux eminating from the Shuttle. In addition to H_2O, some heavier gases such as Freon were detected but at much lower levels. Unfortunately it was not possible to obtain meaningful values for N_2 and O_2 by this method because of the background from the ambient atmosphere. Direct wake measurements were also attempted on these early flights using the IECM mass spectrometer. The high instrument background ($\sim 10^{-10}$ Torr) created by the getters in the collimator and the inability of the instrument to observe atomic oxygen directly limited the usefulness of these measurements [13].

The scattering cross section is another source of uncertainty. The value assumed in this analysis, 9×10^{-16} cm^2, is somewhat smaller than the 3×10^{-15} cm^2 value typically assumed for computing mean free path in the atmosphere at ambient temperatures. At 5 eV, however, it seems reasonable to expect that deeper penetration into the potential field surrounding the molecules would be required to produce a backscatter in the laboratory system. Since the potential data from which this estimate was made are extrapolated from 100 eV, some uncertainty exists. Perhaps a greater uncertainty is involved in the assumption that the collisions are elastic. There is sufficient energy available in the center of mass system to excite rotational and vibrational modes. This would limit the amount of kinetic energy available after a collision which reduces the backscatter in the laboratory system. However, there is also evidence [18] that the thermal molecules in the vicinity of the Shuttle are already in excited rotational and vibrational states which may also influence the cross section. The possibility also exists that de-excitation may occur in such collisions which could make more energy available and allow lighter molecules to backscatter heavier molecules.

Finally, the neglect of multiple collisions requires some checking. This has been attempted using a Monte Carlo calculation; however, the collisions are too sparse for this to be an effective technique. Perhaps a better approach would be some form of hybrid technique as suggested by Moore [9].

In a passive mode, the free-flying SURF should be able to attain vacuum levels well below 10^{-14} Torr for all species except H which has a sufficient probability of overtaking the vehicle to produce an equivalent pressure of $\sim 10^{-14}$ Torr. The actual background from O will depend on how effectively the shield can be cleaned using the 10^{14} O atoms cm^{-2} sec^{-1} from the ram flux and solar bakeout to degas the shield surface. Also to be considered are non-equilibrium processes in the residual atmosphere which may produce energetic molecules from photodissociation. Such a process could allow some O atoms to overtake an orbiting spacecraft.

In an active mode, the vacuum levels will be governed by the evolution of process gases. It should be remembered that, even with infinite pumping speed, the vacuum is degraded in proportion to the gas load. Unlike conventional chambers, however, the evolved molecules are lost forever. Instead they induce new species, primarily atomic oxygen. As may be seen from Table 6 the equivalent pressures may be held to the low 10^{-14} Torr range at 300 km for modest gas loads associated with CBE. The equivalent pressures are directly proportional to the gas load and the number density of atmospheric molecules. If it is necessary to accommodate higher gas loads, the vacuum may be improved by going to a higher altitude. Since the scale height for O is 60 km, a 1/e improvement can be obtained for each scale height increase in altitude. For example, operating at 500 km would allow 10^{-14} Torr to be maintained at gas loads of 3×10^{18} cm^{-2} sec^{-1}. Processes involving light gases, such as He atom surface spectroscopy, do not degrade the vacuum as long as the molecular weight is equal or less than 16.

From this first-order analysis is appears that the Space Ultravacuum Research Facility using the wakeshield concept is capable of attaining a unique vacuum environment in terms of the elimination of contamination and its ability to maintain ultravacuum conditions in the presence of high heat and moderate gas loads.

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Table 1. Atmospheric Composition at 300 km

Species	Standard		Solar Minimum		Solar Maximum	
	β	$n_A(cm^{-3})$	β	$n_A(cm^{-3})$	β	$n_A(cm^{-3})$
H	3.592	1.05×10^5	4.553	4.66×10^5	2.427	1.00×10^4
He	14.37	7.57×10^6	18.21	8.57×10^6	9.707	5.26×10^6
O	57.47	5.43×10^8	72.84	3.62×10^8	38.83	1.86×10^9
N_2	100.57	9.59×10^7	127.46	3.52×10^7	67.95	5.48×10^8
O_2	114.94	3.94×10^6	145.68	1.15×10^6	77.66	1.73×10^7
A_r	143.68	1.57×10^4	182.10	3.92×10^3	97.08	2.67×10^5

Table 2. Integrated Fluxes and Equivalent Pressures on Rear-Facing and Side-Facing Surfaces in the Wake Region from Overtaking Molecules

Species	Side-Facing		Rear-Facing	
	$\Phi(cm^{-2}\ sec^{-1})$	p(Torr)	$\Phi(cm^{-2}\ sec^{-1})$	p(Torr)
H	4.4×10^{7}	2.2×10^{-14}	3.4×10^{7}	1.7×10^{-14}
He	1.8×10^{4}	1.8×10^{-17}	7.9×10^{3}	7.8×10^{-18}
O	6.6×10^{-14}	1.3×10^{-34}	1.4×10^{-14}	2.7×10^{-35}
N_2	1.3×10^{-33}	3.5×10^{-54}	1.9×10^{-34}	5.0×10^{-55}
O_2	2.8×10^{-41}	7.8×10^{-62}	3.6×10^{-42}	1.0×10^{-62}
Ar	3.0×10^{-56}	9.5×10^{-77}	3.3×10^{-57}	1.0×10^{-77}

Table 3. Scattering Cross Section Parameters

Interaction	A (eV)	b ($Å^{-1}$)	KE' (eV)	d_o (Å)	σ_{Ao} (cm^2)
$O \rightarrow N_2$	541	3.012	3.18	1.71	9.14×10^{-16}
$O \rightarrow O_2$	1870	3.670	3.33	1.72	9.34×10^{-16}
$O \rightarrow H_2O$	1484	3.724	2.65	1.70	9.07×10^{-16}

Table 4. Observed Backscatter of H_2O Molecules from Early Shuttle Flights and Inferred Source Term

Mission	$(\partial\Phi/\partial\Omega)_o$ Obs. (H_2O cm^{-2} sec^{-1} sr^{-1})	$\int_0^\infty n_o\,dr$ (H_2O cm^{-2})	Q (H_2O sec^{-1})
Early STS-3	1.0×10^{12}	3.5×10^{12}	1.9×10^{20}
Late STS-3	2.6×10^{11}	9.0×10^{11}	4.9×10^{19}
Early STS-4	2.1×10^{14}	7.3×10^{14}	3.9×10^{22}
Late STS-4	6.5×10^{12}	2.3×10^{13}	1.2×10^{21}

Table 5. Back-Scattered Atomic Oxygen Flux and Equivalent Pressure for Shuttle-Attached Mode

Source Q	Side-Facing		Rear-Facing	
	Φ(cm^{-2} sec^{-1})	p(Torr)	Φ(cm^{-2} sec^{-1})	p(Torr)
3.0×10^{20} N_2	7.5×10^{9}	1.5×10^{-11}	8.3×10^{9}	1.6×10^{-11}
6.5×10^{19} O_2	2.0×10^{9}	3.9×10^{-12}	2.3×10^{9}	4.5×10^{-12}
3.9×10^{22} H_2O	2.4×10^{11}	4.8×10^{-10}	1.6×10^{11}	3.2×10^{-10}
Total	2.5×10^{11}	5.0×10^{-10}	1.7×10^{11}	3.4×10^{-10}

Table 6. Wake Environment at 300 km

Mode	Species	Total Flux (molecules cm^{-2} sec^{-1})	Equivalent Pressure (Torr)
Shuttle-attached[(a)]	H	$1.4 \times 10^{7}-3.7 \times 10^{7}$	$6.9 \times 10^{-15}-1.8 \times 10^{-14}$
	He	$4.2 \times 10^{9}-6.8 \times 10^{9}$	$4.1 \times 10^{-12}-6.8 \times 10^{-12}$
	O	$1.1 \times 10^{11}-5.8 \times 10^{11}$	$2.3 \times 10^{-10}-1.2 \times 10^{-9}$
	N_2	$2.9 \times 10^{7}-4.5 \times 10^{8}$	$7.5 \times 10^{-14}-1.2 \times 10^{-12}$
Free-flyer[(b)]	H	$1.4 \times 10^{7}-3.7 \times 10^{7}$	$6.9 \times 10^{-15}-1.8 \times 10^{-14}$
	He	$2.5 \times 10^{5}-1.0 \times 10^{6}$	$2.4 \times 10^{-16}-9.8 \times 10^{-16}$
	O	$7.2 \times 10^{6}-3.7 \times 10^{7}$	$1.4 \times 10^{-14}-7.4 \times 10^{-14}$
	N_2	$1.4 \times 10^{6}-8.1 \times 10^{6}$	$3.7 \times 10^{-15}-2.1 \times 10^{-14}$

(a) $Q = 3 \times 10^{20}$ N_2 sec^{-1} + 6.5×10^{19} O_2 sec^{-1} + 3.9×10^{22} H_2O sec^{-1}

(b) $Q = 10^{16}$ H_3As sec^{-1} + 10^{16} $(CH_3)_3Ga$ sec^{-1}

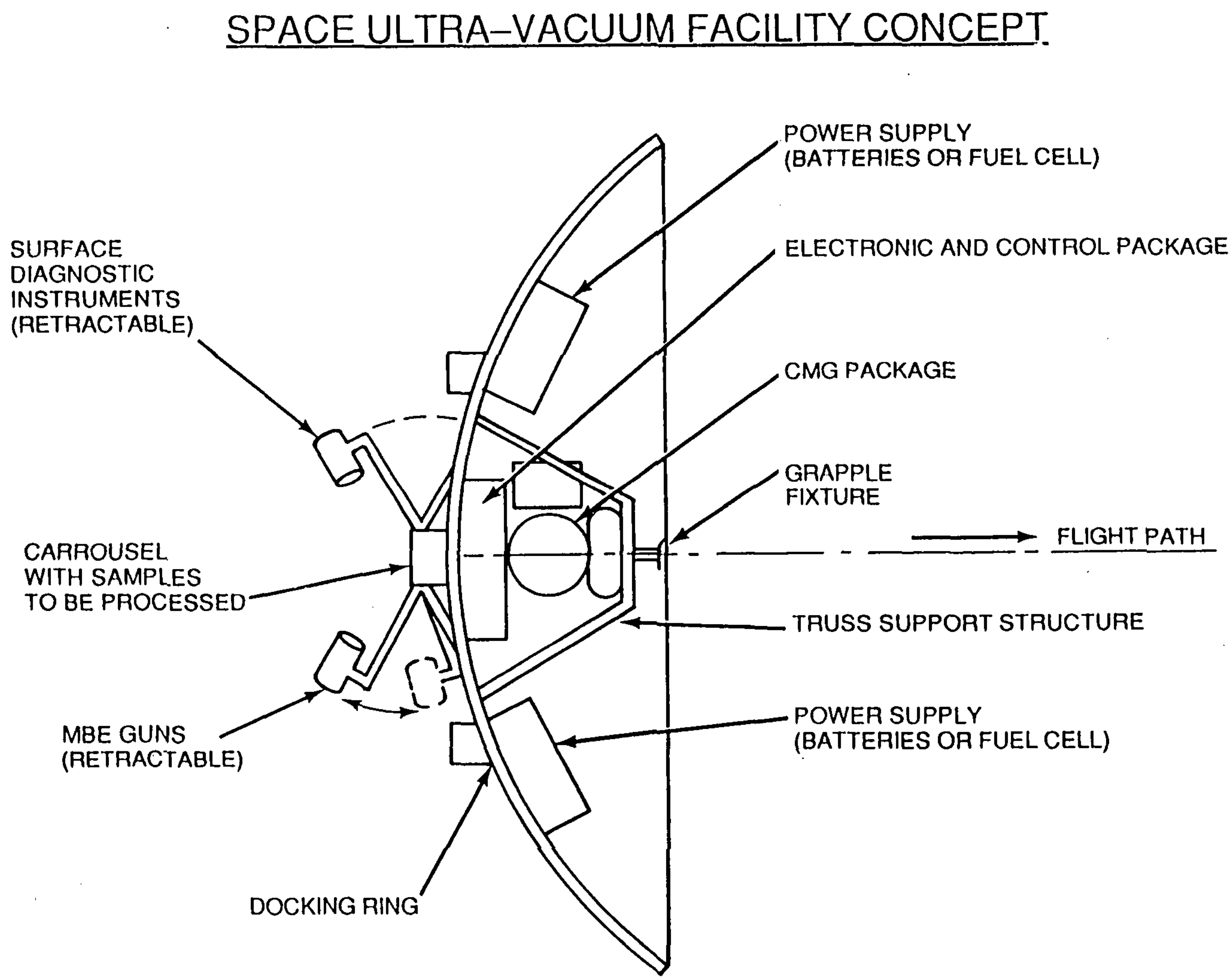

Fig. 1. Space Ultravacuum Concept. The umbrella shape with the concave side oriented toward the velocity vector prevents outgassing molecules from power and control components and ambient atmospheric molecules encountered by the shield as it moves through the ambient atmosphere from entering the wake region. Also a surface of interest oriented in the wake direction has no sources of contamination in its field of view.

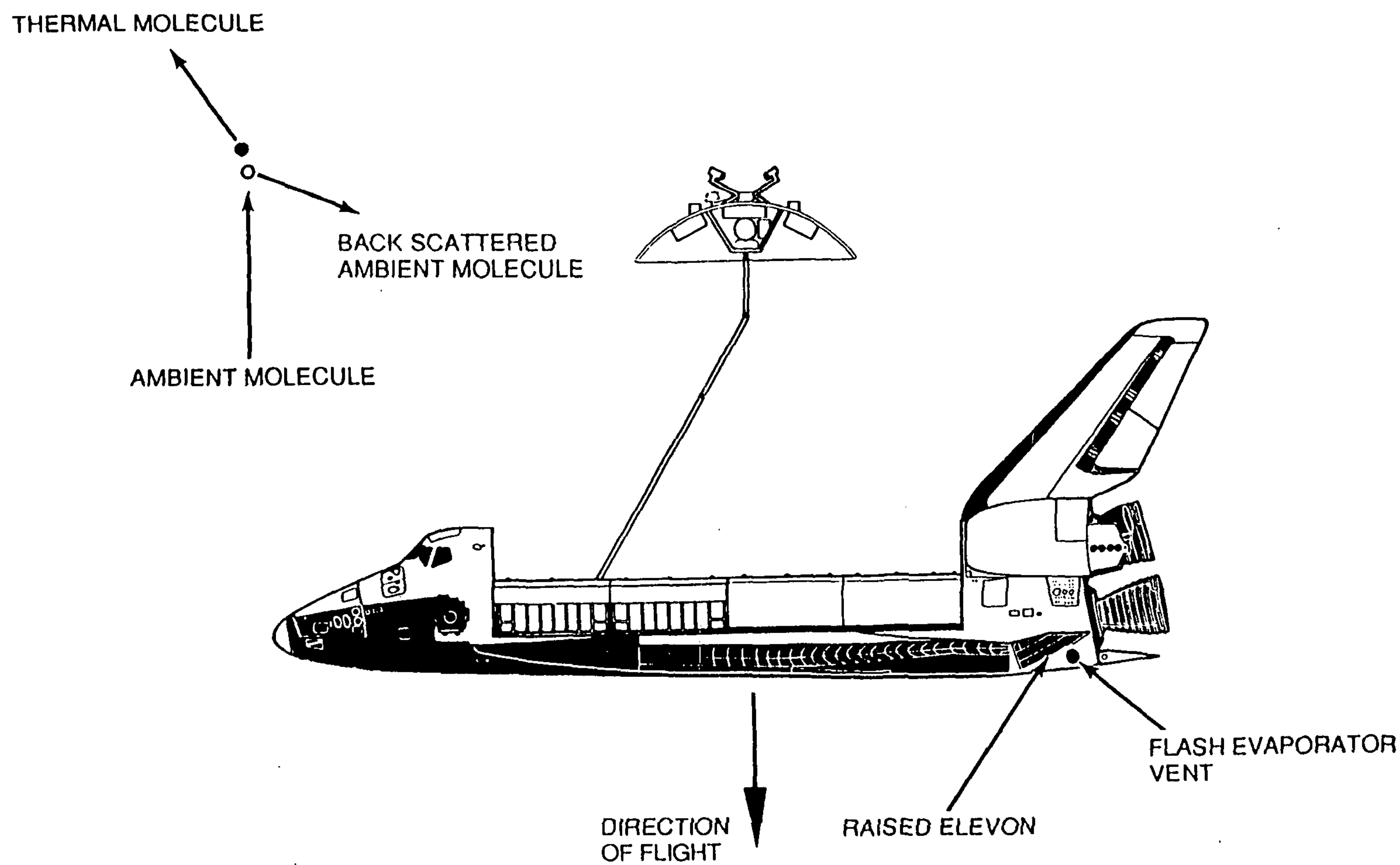

Fig. 2. SURF operating in the Shuttle-attached mode. The Shuttle itself is a copious source of thermal molecules from outgassing, cabin leaks, thruster firings, and operation of the flash evaporator. Such molecules cannot impinge directly on a surface of interest behind the shield, but the ultimate vacuum that can be achieved will be limited by backscatter of atmospheric molecules from the Shuttle-induced atmosphere. It may still be useful, however, to operate initially in this mode, which is considerably less expensive than a free flyer, in order to test the concept and to obtain more insight into the molecular dynamics involved.

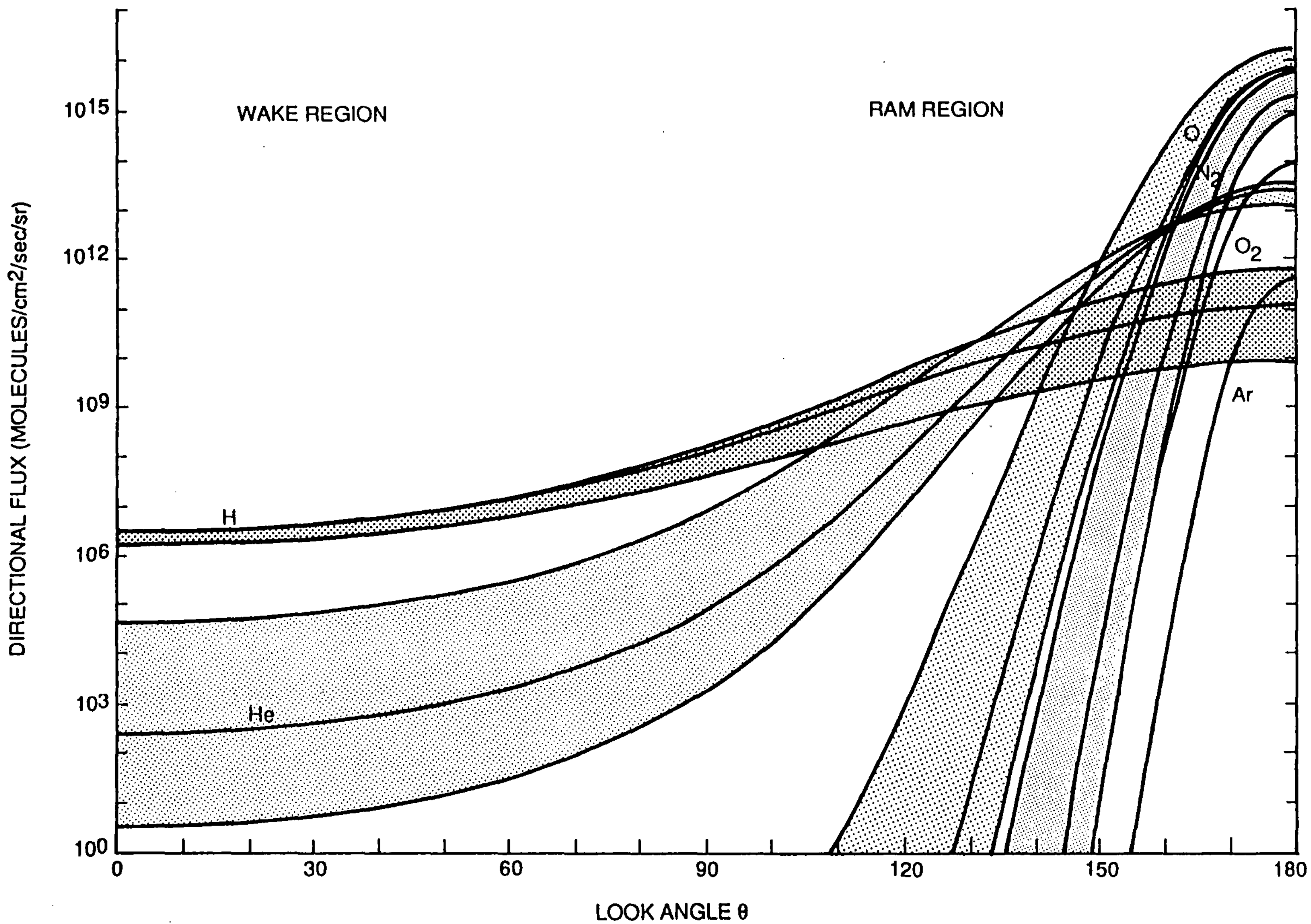

Fig. 3. Directional flux of ambient molecules from an orbiting spacecraft at 300 km. The envelops about the dominant species represent the variations due to solar variations. From this distribution it is apparent that no species heavier than He can enter the wake region.

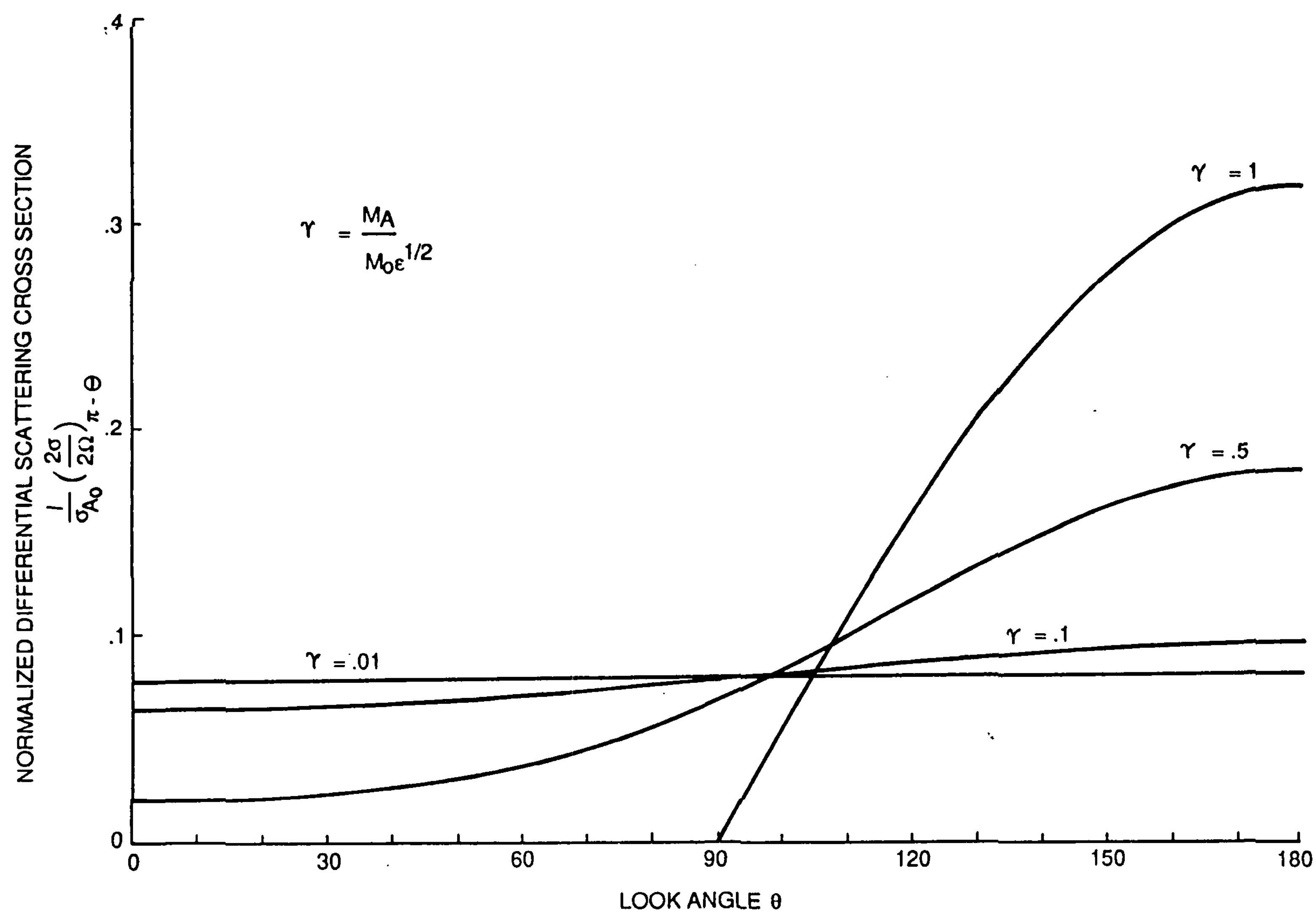

Fig. 4. Normalized differential scattering cross section as a function of look angle for different values of the parameter γ. Backscatter is only possible for $\gamma < 1$ which implies that the mass of the high-speed ambient molecule must be less than the product of the mass of the thermal molecule and the coefficient of restitution in order for the ambient molecule to be backscattered. The thermal molecule cannot be backscattered under any circumstance.

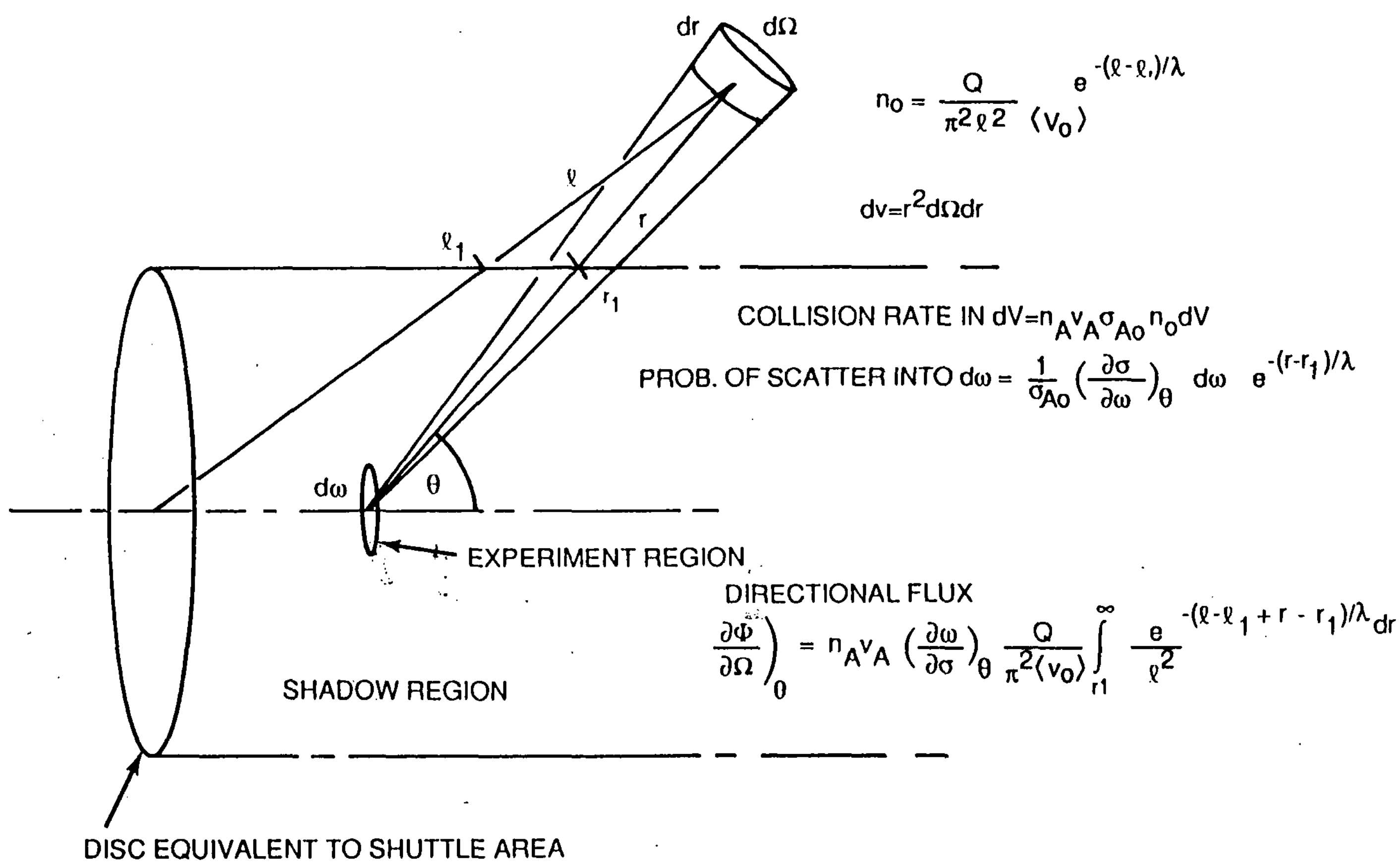

Fig. 5. Geometry for computing the backscattered flux at some point behind a shadowing disc.

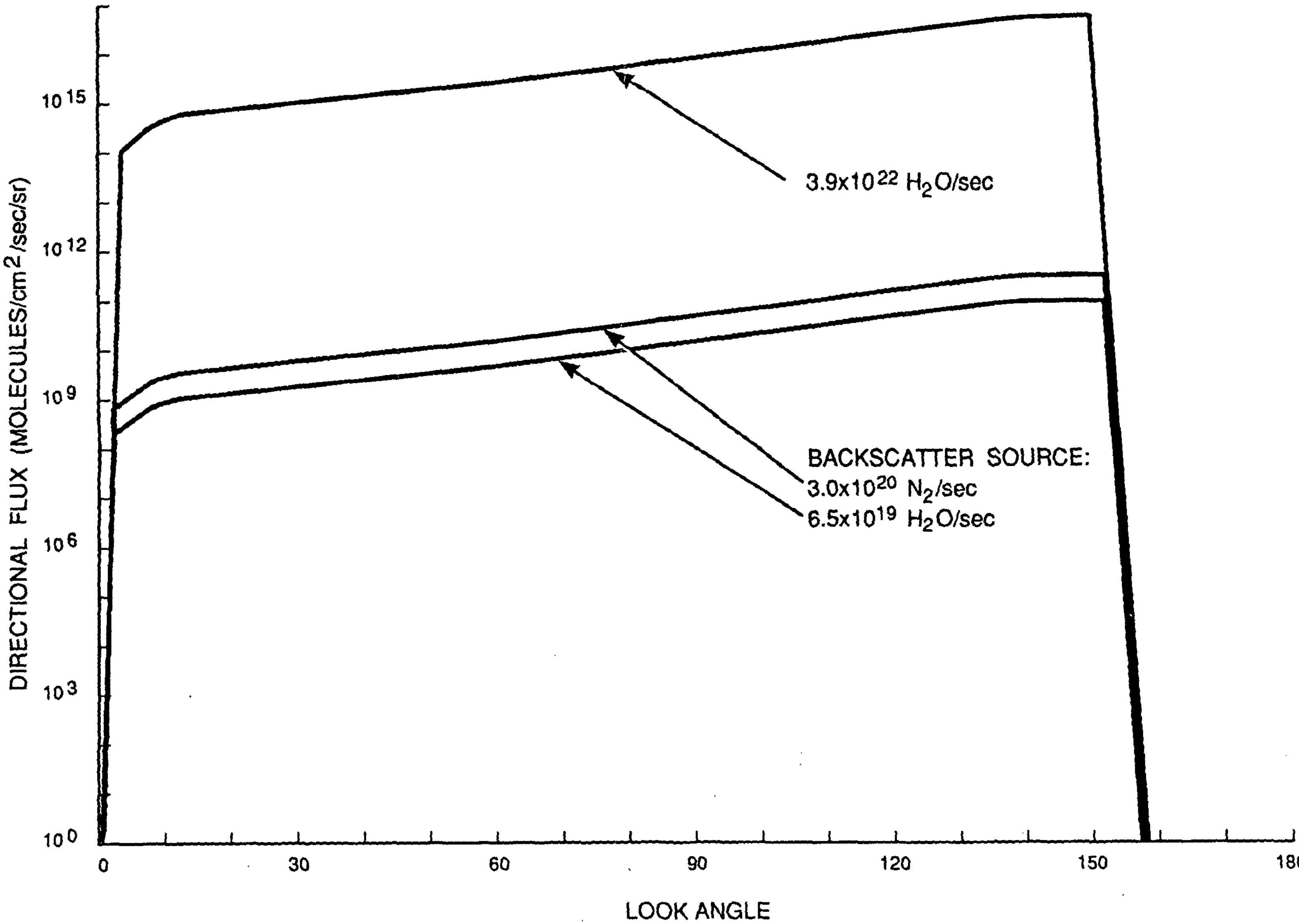

Fig. 6. Directional flux of ambient O atoms scattered by the Shuttle-induced atmospheric constituents. The cutoff at 155° represents the shielding by the equivalent disc of the Shuttle from an observing point some 15 m behind the centerline of the payload bay.

APPROVAL

ANALYSIS OF THE PERFORMANCE OF THE SPACE ULTRAVACUUM RESEARCH FACILITY IN ATTACHED AND FREE-FLYER MODE

By Robert J. Naumann

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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