PREVENTION OF PRIMARY MIRROR CONTAMINATION BY HELIUM PURGING (U)
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Prevention of Primary Mirror Contamination by Helium Purging

R. R. HERM, B. R. JOHNSON, and S. J. YOUNG
Chemistry and Physics Laboratory
Laboratory Operations
The Aerospace Corporation
El Segundo, CA 90245

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Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
Los Angeles, CA 90009-2960
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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

KEVIN O'BRIEN, Capt, USAF
MOIE Project Officer
SD/CNS

JOSEPH HESS, GM-15
Director, AFSTC West Coast Ofc
AFSTC/WCO OL-AB
Telescopes mounted on space platforms may be subject to performance degradation by the condensation of gaseous species on cryogenically cooled optical surfaces. Attenuations of the flux of impinging contaminants by a purging counterflow of helium (He) gas at the telescope entrance aperture have been calculated by a Monte Carlo procedure that follows individual trajectories selected at random. The calculations involve no significant approximations and should be quite accurate. In particular, multiple-collision trajectories are treated, employing the best available information on the atomic and molecular collision cross sections. Extensive calculations on protection of the Shuttle-mounted CIRRIS I and CIRRIS IA telescopes are presented which illustrate the extent of protection afforded.
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I. INTRODUCTION

The interference by molecular contaminants in the environment to the proper performance of space-based infrared telescopes mounted on the Shuttle Orbiter has been discussed by a number of authors. Contaminants include natural atmospheric species, primarily oxygen (O) atoms at Shuttle altitudes, as well as molecules released by the Shuttle. These include water (H$_2$O), nitrogen (N$_2$), oxygen (O$_2$), carbon monoxide (CO), carbon dioxide (CO$_2$), other trace molecular species, and hydrogen (H$_2$) and helium (He), although these latter two will not normally interfere with the telescope's operation. Potential interference effects include background radiation from excited molecules (and possibly from interactions of O atoms with surfaces, i.e., "Shuttle glow"), as well as degradation in optical performance due to condensation on sensitive optical components, specifically the cryogenically cooled primary mirror. The objective of the work reported here was to analyze the degree to which a purge flow of incondensible He gas could protect against such contamination of the primary mirror of the AFGL CIRRIS (Air Force Geophysics Laboratory Cryogenic Infrared Radiance Instrument for Shuttle) telescope.

Either He or neon (Ne) could potentially be used as the incondensible purge gas. Although Ne should have better efficiency by virtue of its higher mass, He has been the gas chosen in virtually all discussions, analyses, and implementations of the purge concept to date. One practical reason in the case of CIRRIS is the use of a liquid He cryogen so that the He gas is already available at flow rates up to 0.02 g/sec. Early analyses of the He purge concept, reviewed in Refs. 2 through 4, demonstrated its feasibility, but were too approximate to calculate or measure its efficiency reliably. These early analyses had to assume a simple hard-sphere differential

---

^Actually, the rate of gaseous He boil-off from the cryogen is considerably faster, but only 10% of that gas is used in the He purge flow in the current CIRRIS design.
scattering cross section. Accurate differential cross sections $\sigma(\theta)$ for the scattering of He atoms by O atoms reported in Ref. 3 show properties very different from the simple hard-sphere approximations. References 4 and 5 provide the only analyses that use the accurate He-O scattering cross sections calculated in Ref. 3. Because itformulates the problem in terms of scattered O atoms that miss the mirror rather than those that hit it, Ref. 4 avoids the unrealistic limit of only partial purge efficiency, even in the limit of infinite He density which appears in Ref. 5. However, both calculations employ a single-collision approximation and are, consequently, invalid at high purge-flow conditions.

The goal of the present study is to calculate the He purge-flow efficiency without the limitations of the previous studies. Specifically, a Monte Carlo calculation is made of the efficiency of the He purge, as a function of He gas flow rate $m$, in protecting the primary mirror. The calculation is valid for any arbitrary number of collisions between He atoms and an incoming contaminant atom or molecule. The best available information is used to calculate highly reliable scattering cross-section functions, and purge protection is calculated for impinging contaminant molecules released from the Shuttle Orbiter, as well as for impinging atmospheric O atoms.
II. PROCEDURE

Calculations were done for the CIRRIS I and CIRRIS IA telescopes. The geometry, taken from Ref. 4, is shown in Fig. 1 for CIRRIS I. The computer code developed in this study can treat the case of He injection within the telescope, or He ejection from orifices in front of the telescope that make any angle $\omega$ with the sensor axis. All calculations reported here were done for the purge apparatus used on CIRRIS I and CIRRIS IA, an injector ring, with $\omega = 30^\circ$, about the circumference of the sensor entrance aperture. A plane wave of incident contaminant molecules of mass $m_c$ approaches the sensor with speed $v_c$ at an angle $\gamma$ to the sensor axis. The purpose of the He purge gas is to deflect incoming contaminants that would otherwise hit the mirror at the rear of the sensor. Detailed analyses are presented for $N_2$ and $H_2O$, the two most troublesome contaminant species. Contaminant molecules may collide with He gas within the telescope and in the "plume," i.e., in front of the telescope. However, He density falls off rapidly in the plume with increasing distance from the sensor. In these calculations, collisions were considered within a hemispherical plume region of 100 cm radius centered on the sensor aperture.

The temperature of the CIRRIS primary mirror is 20 K; an analysis presented later in this report indicates that even $N_2$ will condense at this temperature. The temperature of the walls of the CIRRIS telescope varies from about 20 K near the primary mirror to about 40 K near the sensor aperture. Contaminants such as $N_2$, which condense only at very low temperature, will not condense along the telescope wall except at the back near the primary mirror. On the other hand, the vapor pressure of $H_2O$ is negligible even at 40 K. Accordingly, it was assumed that an impinging $H_2O$ molecule sticks to the first surface it hits, mirror or wall. This same assumption has been made in all previous treatments of the He purge concept. It should be noted that a record of the profile of contaminant deposition along the sensor wall was kept for all calculations reported here. Consequently, it would be possible in the
Fig. 1. Purge Geometry for CIRRIS I
future to examine sensitivity to this assumption of a sticking coefficient of unity by allowing contaminants to reflect, after partial accommodation, from various wall positions.

A. HELIUM FLOW FIELD

The spatial dependence of the He number density and velocity distributions are necessary input functions for the calculations of the He purge efficiency. These functions were modeled by assuming thermal effusion of He from the ejection ring shown in Fig. 1. Perturbations of the flow field that resulted from He-He collisions outside of the ejection ring were ignored. Possible perturbations of the He flow field, which resulted from collisions with contaminants or atmospheric species, were also ignored. This latter condition should be an excellent approximation at the Shuttle Orbiter altitude, 380 km, planned by CIRRIS, although it could break down at much lower orbital altitudes.

The temperature of the He in the ejection ring in CIRRIS IA may vary from \( \sim 220 \) to \( 273 \) K. This relatively high temperature results because boil-off from the liquid-He cryogen is used as a coolant for an electronics box before it enters the ejector ring. Most of the calculations were carried out for a He ejection temperature \( T_{\text{He}} \) of 273 K. However, some calculations were carried out for a much lower ejection temperature, \( T_{\text{He}} = 20 \) K, in order to examine the sensitivity of He purge efficiency to ejection temperature.

At any point in the plume, the He number density was computed by summing the effusion contribution from sources on the circumference of the ejection ring and effusion from the sensor entrance aperture. The He number density within the sensor, assumed to be a constant within the sensor volume, was calculated by equating rates of effusion into and out of the sensor aperture. In order to save computer time and render the purge problem computationally tractable, all effusing He was assumed to move at an average thermal speed of

\[
\bar{v}_{\text{He}} = (8 kT/m_{\text{He}})^{1/2}
\]
Within the plume, the distribution in directions of He motion was obtained by summing all effusion contributions. As noted above, there is a distribution in temperatures within the sensor. In treating the He flow field, however, this was treated as one temperature, $T_w$. The distribution in speeds within the plume could be bimodal, corresponding to the sensor and ejection-ring temperatures. The speed distribution anywhere within the sensor consisted of He moving at $v_{He}$ from Eq. (1), with a random distribution in directions.

Figure 2 shows a comparison between the predictions of this number density model and measurements reported in Ref. 4 for a 0.0405-g/sec ring ejection of 300 K argon (Ar) gas in a 1/1.78-scale CIRRIS I model. The agreement at large distances is encouraging because model and measurements are steady-state results for the same mass flow rate $\dot{m}$, so that the integrals of the net outward flux, over any bound surface containing the aperture, have to be equal. The discrepancy at smaller distances might be due to noneffusive real source flow, purge-purge collisions in the real flow, as well as experimental error. The approximation of effusive flow from the orifices in the ejector ring would result in the largest uncertainty in He densities in this region, i.e., within and immediately in front of the sensor aperture. In order to examine the sensitivity of purge efficiency results to He flow-field uncertainties, calculations were actually carried out as a function of the steady-state density, denoted $N_{He}$, of He within the sensor. Additional sensitivity studies could be carried out by examining noneffusive source flow velocity distributions. However, this was not pursued because the effect should be very small in comparison to uncertainties introduced by the approximate treatment of the CIRRIS IA geometry, which is discussed later.

**B. COLLISION CROSS SECTIONS**

A contaminant or atmospheric species changes speed, usually slowing down, each time it collides with a He atom. The collision cross sections are needed for a wide range of relative collision speeds, $v = |\vec{v}_c - \vec{v}_{He}|$, in order to follow many collisions between incoming contaminants and He purge atoms. Differential and total cross sections
Fig. 2. Measured (Ref. 4) and Modeled (see text) Centerline Number Densities for Subscale Ar Ring Injection. $Z > 0$ measures distance in front of sensor aperture. Results for $Z < 0$ indicate values within the sensor.
\[ \sigma(v) = 2\pi \int_0^\pi \sigma(\theta,v) \sin \theta d\theta \] (2)

for the scattering of O atoms from He atoms were calculated in Ref. 3 by solving the quantum mechanical Schrodinger equation for the best information available in the literature on the central force interaction potential \( V(r) \). Sensitivity analyses reported in Ref. 3 illustrate inconsequential errors in \( \sigma(\theta,v) \) and \( \sigma(v) \) that result from the assumption of a single central force potential and from possible errors in the potential function. The literature indicates that the interaction potentials between He and the molecules CO, \( \text{N}_2 \), \( \text{H}_2\text{O} \) are only weakly anisotropic. To an excellent approximation, they can be analyzed as isotropic systems; i.e., the interaction potential is assumed to depend only on \( r \) and not on the orientation (central field approximation) of the molecule. The total and differential scattering cross sections for these "isotropic cases" (i.e., He + \( \text{N}_2 \), He + CO, and He + \( \text{H}_2\text{O} \)) were calculated quantum mechanically by means of the standard techniques described in Ref. 3. Results for the total scattering cross section are shown in Fig. 3. Appendix A provides plots of the differential cross sections and describes the interaction potentials used.

The He + \( \text{CO}_2 \) system is strongly anisotropic, and the "central field approximation" could not be used in the present study. The differential cross section in this case was calculated by means of the infinite order sudden (IOS) approximation. The interaction potential \( V(r,\alpha) \) is a function of the separation distance \( r \) and the angle \( \alpha \) between the line of center and the axis of the \( \text{CO}_2 \) molecule. In the IOS approximation, \( \alpha \) is regarded as a parameter and not a dynamical variable. For a fixed value of the parameter \( \alpha \), the potential is a function only of \( r \) and is thus "isotropic." This "isotropic" scattering problem, for a fixed \( \alpha \), is then solved by the partial-wave method to obtain a differential cross section \( \sigma(\theta,\alpha) \), which is also a function of the parameter \( \alpha \). It has been shown elsewhere that the desired "total" (elastic plus inelastic) differential scattering cross section is, to an excellent approximation, given simply by the orientation average over \( \alpha \):

\[ \sigma(\theta) = \frac{1}{2} \int_0^\pi \sigma(\theta,\alpha) \sin(\alpha) d\alpha \] (3)
Fig. 3. Calculated Total Cross Sections for Scattering of He from H₂O, CO₂, N₂, O, and CO as a Function of Relative Collision Speed v
In the present work, the above integral was calculated numerically by means of the trapezoidal rule, with an integration spacing of \(\Delta \alpha = 22.5^\circ\). By making use of symmetry, the integration range was reduced from 0 to \(\pi\) to 0 to \(\pi/2\). Thus, four separate partial-wave calculations to compute \(\sigma(\theta, \alpha_i)\) for \(\alpha_i = 22.5^\circ, 45^\circ, 67.5^\circ,\) and \(90^\circ\) (\(\alpha = 0^\circ\) need not be calculated because of the \(\sin \alpha\) factor) were calculated to obtain each differential scattering cross-section curve for \(\text{He} + \text{CO}_2\), shown in Appendix A. Again, the total scattering cross-section results are shown in Fig. 3.

C. MONTE CARLO CALCULATIONS

A Monte Carlo calculation was made for contaminant molecules impinging at angle \(\gamma\) with speed \(v_c\) (see Fig. 1). The transmission

\[
\tau = \frac{\text{number of contaminants striking mirror with He flow}}{\text{number of contaminants entering sensor without He flow}} \quad (4)
\]

is the quantity of interest in analyzing readily condensible contaminants, such as \(\text{H}_2\text{O}\). For contaminants that condense only at the primary mirror, viz \(\text{N}_2\), the quantity of interest is the sensor acceptance

\[
\eta = \frac{\text{number of contaminants entering sensor with He flow}}{\text{number of contaminants entering sensor without He flow}} \quad (5)
\]

The Monte Carlo technique is a well-known procedure\(^{10-13}\) wherein unspecified parameters are chosen at random, and a large number of individual trajectories of contaminants are followed as they transverse the He flow field, in order to provide a statistically reliable result.

Specifically, the calculation placed a control surface normal to the impingement direction in front of the sensor at a point where the He plume density was \(\sim 1\%\) of its centerline value at the sensor aperture. The area of the control surface through which the contaminants impinged was typically twice that of the sensor aperture, in order to allow for scattering of contaminants into, as well as out of, the sensor aperture. A record was kept for each calculation of the number of trajectories where the He actually
scattered an impinging contaminant into the sensor aperture. This was always a small fraction of the trajectories, a fact confirming that the control surface area was sufficient to account for this effect. This was further verified in a few calculations where other control areas were used.

The spatial position of the contaminant, as it crossed normal to the control surface, was chosen at random. The contaminant was allowed to move along a straight-line trajectory $s$ for a distance $\ell$ before a collision took place. The free path length $\ell$ was calculated from the randomly chosen variable, $0 < x < 1$, as

$$\frac{1}{v_c} \int_0^{\ell} <v\sigma(v)> n(r)dr = -\ln x$$

where

$$<v\sigma(v)> = \int_0^{\infty} v\sigma(v)\rho(v)dv$$

is the numerical average of the total collision rate constant over the probability density distribution in relative collision speed, viz, $\int_0^{\infty} \rho(v) dv = 1$. The quantity $\rho(v)$ has two forms -- one for outside the sensor, where the He velocity field is determined by effusive flow from the ejector ring and sensor aperture, and one for inside the sensor, where the He velocity field is random in direction. In both cases, $\rho(v)$ is for the mean-speed distribution approximation $f(v_{He}) = \delta(v_{He} - v_{He})$. If the resultant straight-line trajectory corresponded to hitting the sensor wall, hitting the mirror, or exiting the He plume to free space, the result was recorded and the motion of the next incoming contaminant was followed.

If the solution for $\ell$ resulted in a position in the He plume or in the He gas within the sensor, a collision had taken place. After the collision, the contaminant left this position on a new straight-line trajectory with a new velocity $v'_c$, i.e., in a new direction and at a new speed, and the procedure was repeated to find a new trajectory length. First, however, the new contaminant velocity $v'_c$ was calculated from the old known contaminant
velocity $\vec{v}_c$ by invoking conservation of energy and linear momentum in the collision. For this calculation it was necessary to specify the precollision direction of motion of the He atom involved in the collision, as well as the center-of-mass scattering angles, $\theta$ and $\phi$, produced by the collision. A value for the azimuthal angle $\phi$ was chosen randomly, i.e.,

$$\phi = 2\pi x$$  \hspace{1cm} (8)

The polar scattering angle $\theta$ was chosen by randomly selecting a cumulative scattering probability, i.e., by solving

$$P_c(\theta) = \frac{2\pi}{\sigma} \int_0^\theta \sigma(\theta')\sin\theta'd\theta' = x$$  \hspace{1cm} (9)

for $\theta$ when $x$, as usual, is randomly chosen between 0 and 1. Rigorously, the He direction should be chosen randomly. This was done for collisions within the sensor. For collisions within the plume, however, the He direction was taken as the most probable one for that particular spatial position in order to reduce computation time. The effect of this approximation on the computation should be negligible.

In this manner, trajectories of a large number of impinging contaminants were followed to arrive at statistically significant results for $r$ and $\eta$. Each trajectory was made up of an arbitrary number of straight-line trajectories, with intervals between collisions determined randomly. After each collision, the new contaminant velocity was determined randomly, consistent with conservation of linear momentum and energy.

Equation (9) indicates that the differential cross section only enters the Monte Carlo calculation of $r$ through the cumulative scattering probability distribution $P_c(\theta)$. Figure 4 shows plots of this function for He + CO$_2$ for three different collision velocities. For all of the Monte Carlo calculations reported here, $P_c(\theta)$ was fit to

$$\cos\theta = 1 - 2P_c(\theta)^n, \ n > 1$$  \hspace{1cm} (10)
Fig. 4. Plots of $P_{c} = (2\pi/\sigma) \int_{0}^{\theta} \alpha(\theta') \sin\theta' d\theta'$ for He + CO$_2$ for Three Relative Collision Speeds $v$
As $n$ goes to unity, the scattering would approach isotropic, hard-sphere scattering. As $n$ goes to infinity, the scattering is more and more closely confined to a region around $0^\circ$. These two limiting scattering behaviors, isotropic and pure forward, are also shown in Fig. 4. Figure 5 shows the dependence of $n$ on collision speed for He + H$_2$O, He + N$_2$, and He + CO$_2$, inferred by fitting the data in the Appendix to Eq. (10). The fact that $n$ is much greater than unity over the range of collision speeds of interest here illustrates the failure of the hard-sphere scattering approximation for this particular problem.
Fig. 5. Parametric Fit (Scattering Parameter) of $\cos \theta = 1 - 2p^n$ (see text) for He + $H_2O$, He + $N_2$, and He + $CO_2$
III. ESTIMATED CONTAMINATION LEVEL

The characteristics of the expected contaminants are necessary input conditions for the He-purge transmission calculations. At an orbital altitude of 380 km and a velocity of \( v_0 = 7.7 \times 10^5 \text{ cm/sec} \), O atoms will be the most abundant atmospheric species. For standard atmospheric conditions, they will be present at a density of \( n = 1.7 \times 10^8 \text{ cm}^{-3} \), corresponding to a flux of \( F = v_0 n = 1.4 \times 10^{14} \text{ cm}^{-2} \text{ sec}^{-1} \). However, they could reach the CIRRIS primary mirror only for a telescope line of sight that makes a small angle \( \beta \) with the direction of the orbital velocity \( v_0 \), whereas the CIRRIS IA mission plans specify that \( \beta > 90^\circ \). For these large values of \( \beta \), the O atoms incident along the telescope axis will be negligible. Indeed, it can be shown that the incident flux decreases very rapidly with increasing \( \beta \) as

\[
f = K \left[ a(2a^2 + 3) \left( \text{erf}(a) + 1 \right) \exp(-c^2 \sin^2 \beta) + \frac{2}{\pi^{1/2}}(a^2 + 1) \exp(-c^2) \right]
\]

where \( K = 1.6 \times 10^{12} \text{ O atoms cm}^{-2} \text{ sr}^{-1} \text{ sec}^{-1} \), \( a = c \cos \beta \), and \( c = 7.0 \) is the ratio of \( v_0 \) to the most probable O atom thermal speed. At \( \beta = 0^\circ \), \( f = 2.2 \times 10^{15} \text{ O atoms cm}^{-2} \text{ sr}^{-1} \text{ sec}^{-1} \), whereas \( f < 5 \times 10^{-8} \text{ O atoms cm}^{-2} \text{ sr}^{-1} \text{ sec}^{-1} \) for any \( \beta \) between 90\(^\circ\) and 180\(^\circ\), i.e., attenuated by more than 23 orders of magnitude. It should also be noted that, by virtue of the comparable masses and similar cross-section behaviors indicated in the Appendix, He purge results that are calculated here for \( \text{H}_2\text{O} \) would be approximately valid for O atoms as well.

Reference 16 reports results from a mass spectrometer flown on the Shuttle Orbiter. The inlet of the mass spectrometer was collimated to a narrow field of view, 0.1 sr, of the space environment so that molecules outgassing from Orbiter surfaces could not reach it by a straight-line trajectory. Contaminants entering the CIRRIS telescope are under the same geometric constraint; contaminants enter either instrument only by virtue of some other transport mechanism, such as self-scattering or scattering from atmospheric...
0 atoms. Detected contaminants reported in Ref. 16 include H$_2$, He, diborane, (B$_2$H$_6$), methane (CH$_4$), N$_2$, CO, O, monomethyl hydrazine (CH$_3$N$_2$H$_3$), H$_2$O, CO$_2$, nitric oxide (NO), O$_2$, hydrogen chloride (HCl), and propane (C$_3$H$_6$). With the possible exception of N$_2$, which is discussed later, H$_2$O was the dominant species. This same predominance of contaminant H$_2$O was also observed$^{17}$ by a different mass spectrometer instrument on one Shuttle flight; in this case, however, outgassed molecules could reach the mass spectrometer directly by collisionless, straight-line trajectories.

Table 1 lists the H$_2$O contamination levels reported in Ref. 16 for Space Transportation System (STS) flights 3 and 4. The source of this H$_2$O was outgassing from Shuttle Orbiter surfaces. Typically, outgassing rates are high immediately after launch and decay over a period of many hours to a steady value. Values listed in Table 1 are approximate 100-hr averages for the sensor perpendicular to the wind direction, i.e., for $\beta = 90^\circ$. There have also been a number of predictions of the expected Orbiter contaminant environment. Two representative predicted values$^{18,19}$ are also included in Table 1 to indicate that the measured values conformed to reasonable expectations.

Thus, CIRRIS IA will probably have to contend with a contaminant H$_2$O environment similar to that present on STS flight 3, i.e., $\sim 3 \times 10^{11}$ H$_2$O molecules cm$^{-2}$ sr$^{-1}$ sec$^{-1}$. However, there is no doubt that the contaminant H$_2$O environment was worse on STS-4 because of the hail and rain experienced by Columbia during the STS-4 prelaunch preparation. It is therefore prudent to take the STS-4 environment, $\sim 7 \times 10^{12}$ H$_2$O molecules cm$^{-2}$ sr$^{-1}$ sec$^{-1}$, as the postulated worst-case environment for the CIRRIS IA mission.

Transmission through the He purge flow depends on the speed $v_c$ of the incident contaminant. This, in turn, depends on the mechanism that transports the contaminant from its source to the sensor aperture. For a contaminant of mass $m_c$ that escapes from the Shuttle Orbiter and scatters off an atmospheric O atom of mass $m_0$ back toward the sensor

$$v_c = 2[m_0/(m_0 + m_c)] v_0 \cos\beta$$

(12)
<table>
<thead>
<tr>
<th>Source</th>
<th>H$_2$O Flux (cm$^{-2}$ sr$^{-1}$ sec$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Outgassing - STS-3</strong></td>
<td></td>
</tr>
<tr>
<td>Ref. 16 Mass Spectrometer Measurement</td>
<td>$3 \times 10^{11}$</td>
</tr>
<tr>
<td>Ref. 18 Calculation</td>
<td>$1 \times 10^{11}$</td>
</tr>
<tr>
<td>Ref. 19 Calculation</td>
<td>$2 \times 10^{10}$</td>
</tr>
<tr>
<td><strong>Outgassing - STS-4</strong></td>
<td></td>
</tr>
<tr>
<td>Ref. 16 Mass Spectrometer Measurement</td>
<td>$7 \times 10^{12}$</td>
</tr>
<tr>
<td><strong>Vernier Engine Firing</strong></td>
<td></td>
</tr>
<tr>
<td>Ref. 17 Mass Spectrometer Measurement$^b$</td>
<td>$0.4 - 4 \times 10^{14}$</td>
</tr>
<tr>
<td>Ref. 18 Calculation</td>
<td>$1 \times 10^{14}$</td>
</tr>
<tr>
<td>Ref. 19 Calculation</td>
<td>$1 \times 10^{13}$</td>
</tr>
</tbody>
</table>

$^a$These are approximate values for a sensor line of sight perpendicular to the wind. Actual values reported in Refs. 16 through 19 were scaled to those at 380 km by assuming contaminant return flux to be proportional to atmospheric density.

$^b$Calculated by assuming a 2π-steradian field of acceptance for the mass spectrometer.
for $0^\circ < \beta < 90^\circ$. This expression fails, of course, near $\beta = 90^\circ$, where it predicts that $v_c$ goes to zero. The contaminant flux from this mechanism would also be $\beta$ dependent, peaking at $\beta = 0^\circ$ and dropping to zero at $\beta = 90^\circ$. Reference 16 does provide some qualitative data on this $\beta$ dependence. The values in Table 1 from Ref. 16 refer to some $\beta = 90^\circ$. Data in Ref. 16 actually indicate that the $H_2O$ return flux varies by a factor of $\sim 80$ between $\beta = 0^\circ$ and $90^\circ$. Calculations reported in Ref. 19 are in reasonable agreement, giving a factor of $\sim 25$ for this variation in $H_2O$ return flux. The variation in $H_2O$ return flux with $\beta$ is probably a sharp function of $\beta$. In the absence of any better information, and in order to make a conservative estimate of the $H_2O$ return flux, however, the $H_2O$ return flux used to estimate $H_2O$ film build-up on the CIRRIS IA primary mirror is taken to be

$$\frac{dH_2O(\beta)}{dH_2O(\beta \rightarrow 90^\circ)} = \frac{1 + (79 \cos \beta)}{1}, \quad 0^\circ < \beta < 90^\circ$$

and

$$\frac{dH_2O(\beta)}{dH_2O(\beta \rightarrow 90^\circ)} = \frac{1 + (79 \cos \beta)}{1}, \quad \beta > 90^\circ$$

(13)

where $dH_2O(90^\circ) = 7 \times 10^{12} H_2O$ molecules cm$^{-2}$ sr$^{-1}$ sec$^{-1}$ (STS-4 result). For $\beta > 90^\circ$, the return flux is due to self-scatter of two or more collisions with the wind, and it should return with speeds comparable to or less than thermal speeds of outgassed molecules. Thus, for angles $\beta > 90^\circ$, $v_c$ is taken as $\sim 6 \times 10^4$ cm/sec, the average thermal speed of $H_2O$ at 300 K.

The CIRRIS IA mission plan currently specifies that no engine in the Orbiter may fire while the telescope is uncapped. This includes the small 25-lb-thrust vernier control system (VCS) engines. In order to estimate the consequences if this requirement were relaxed, the contaminant environment produced by these engines has also been considered. The largest source of uncertainty is the return speed of molecules that are produced when these engines fire, as there are neither measurements nor calculations of this parameter. Along the axis of the plume, the flow velocity is $\sim 3.5 \times 10^5$ cm/sec. However, molecules that return to the Orbiter bay probably originate
from the wings of the plume flow field. Here, plume flow velocity may be less than the flow velocity along the axis. Again, however, there are neither measurements nor calculations of velocities in this region of the plume of this engine. In any case, plume molecules can return to the Orbiter Bay because of collisions with the atmosphere at a wide range of speeds $v_c$ that correspond to the range in possible geometries of motor location and thrust direction in relation to the Orbiter's attitude and the sensor's line of sight.

For $\text{H}_2\text{O}$, a reasonable range of return speeds is $v_c = 0.6 - 5 \times 10^5 \text{ cm/sec}$. Reference 17 measured density spikes of $\text{H}_2\text{O}$ and $\text{N}_2$, but not of CO or CO$_2$, associated with firings of these VCS engines. The corresponding return fluxes are listed in Table 1; the range in values quoted corresponds to the range of uncertainties in $v_c$. Recently, Ehlers$^{20}$ reported calculations of the return flux as a function of VCS engine location. His calculations exhibit a large variation in return flux, by approximately a factor of 40, as the angle between the Orbiter's velocity and the instrument's line of sight varies between 10° and 90°, in approximate agreement with the factor estimated in Table 1. When converted to an altitude of 380 km, however, the absolute magnitude of his calculated return fluxes are lower by approximately a factor of ten than the estimate given in Table 1. Here again, the estimate in Table 1 is used to calculate the rate of cryodeposit buildup in order to provide the more conservative, worst-case analysis. However, it is important to note that the observations reported in Ref. 17 included contributions from the vernier engines on the rear of the Orbiter. The plumes of these motors impact, at least partially, on the wings of the Shuttle. Thus, it is quite possible that data from Ref. 17 represent an unrealistic worst case for the CIRRIS mission because direct scattering of plume molecules from the Orbiter wing could have contributed significantly to the observations reported in Ref. 17, whereas it could not contribute return flux along the CIRRIS line of sight. For this reason, cryodeposit buildup rates based on Ehlers' return fluxes are also discussed later.

In addition to $\text{H}_2\text{O}$, $\text{N}_2$ is probably also an important contaminant molecule in the vicinity of the Orbiter. However, the information on the return flux of this contaminant is very limited. Owing to an instrumental
background at mass 28, Ref. 16 reported no data on \( \text{N}_2 \) return flux except at small \( \theta \) angles, where impingement of atmospheric \( \text{N}_2 \) is important. Reference 17 reports \( \text{N}_2 \) and \( \text{H}_2\text{O} \) densities that are in a ratio of \( \sim 0.02 \) in the absence of a VCS firing, and \( \sim 1 \) in the transient spike in the presence of a VCS firing. In the absence of a VCS firing, it is not clear what fraction of either of these \( \text{N}_2 \) or \( \text{H}_2\text{O} \) signals corresponds to a return flux. In a recent paper recommending environment estimates for the Orbiter bay, Scialdone\textsuperscript{21} recommends an on-orbit \( \text{N}_2/\text{H}_2\text{O} \) ratio of \( \sim 40 \), in clear disagreement with results measured in Ref. 17. Thus, in the absence of data on the \( \text{N}_2 \) return flux, the value adopted here is the calculated flux reported in Ref. 19 for \( \theta = 90^\circ \). This was adjusted to a corresponding flux at the CIRRIS altitude of 380 km by correcting linearly for differing atmospheric densities to give

\[
f_{\text{N}_2}(\theta) = 1 \times 10^{11} \text{ N}_2 \text{ molecules cm}^{-2} \text{ sr}^{-1} \text{ sec}^{-1}, \theta > 90^\circ \quad (14a)
\]

Here, \( v_c \) is taken as \( 4.6 \times 10^4 \) cm/sec, the average thermal velocity of \( \text{N}_2 \) at 300 K. This should represent a conservative overestimate of the actual \( \text{N}_2 \) return flux, because Ref. 19 calculated it for an \( \text{N}_2 \) release corresponding to the maximum possible atmospheric cabin leakage rate that NASA specifications permit. Again, the \( \theta \) dependence of this \( \text{N}_2 \) flux is assumed to have the forms

\[
f_{\text{N}_2}(\theta) = f_{\text{N}_2}(\theta = 90^\circ) (1 + 49 \cos \theta), 0^\circ < \theta < 90^\circ \quad (14b)
\]

Once more, this is a conservative overestimate, with the \( \theta = 0^\circ/\theta = 90^\circ \) ratio exceeding that calculated in Ref. 19 by a factor of \( \sim 2 \).

A. **CRYODEPOSIT BUILDUP RATE**

For a contaminant like \( \text{H}_2\text{O} \), which sticks to the sensor walls, film buildup on the primary mirror is due solely to molecules that strike the mirror first. Consider \( \text{H}_2\text{O} \) impinging through a point on a hemisphere of radius \( r \) that is centered on the sensor aperture. The solid angle subtended by the sensor aperture is \( \text{A} \cos \gamma/r^2 \), where \( \text{A} \) is the aperture area. Then, the number of \( \text{H}_2\text{O} \) molecules that pass through a small area on this hemisphere and would enter the sensor in the absence of any He flow is given by
\[ f(\gamma, \phi) \left( A \cos \gamma/\pi^2 \right) r^2 \sin \gamma d\gamma d\phi \]

For the case considered here, where the areas of the mirror and the sensor aperture are the same, the average number of H\textsubscript{2}O molecules condensing per second per cm\textsuperscript{2} of mirror becomes

\[ C = \int_0^{\pi/2} \int_0^{\pi/2} \tau(\gamma) f(\gamma, \phi) \sin \gamma d\gamma d\phi \]  

(15)

As discussed in Table 2, the factor of \( \cos \gamma \) is included in the \( \tau(\gamma) \) values that are calculated.

Clearly, \( f(\gamma, \phi) \) can be calculated from the \( f(\theta) \) expressed in Eqs. (13) and (14). In view of the approximate nature of this assumed \( \cos \beta \) functional dependence, however, the angular flux dependence was ignored in evaluating Eq. (15) to obtain

\[ C = f \tau(0) B \]  

(15a)

where

\[ B = \frac{2\pi}{\tau(0)} \int_0^{\pi/2} \tau(\gamma) \sin \gamma d\gamma \]  

(16)

Nevertheless, the value of \( f \) in Eq. (15a) will be calculated for the particular value of the angle \( \beta \) between \( \hat{\gamma}_0 \) and the sensor line of sight. Then, the rate of contaminant film buildup, in cm/sec, is given by

\[ \dot{\xi} = CM/6 \times 10^{23} \rho \]  

(17)

where \( M \) is the molecular weight and \( \rho \) is the density.

As will be discussed later, \( \text{N}_2 \) represents the opposite case of a molecular contaminant having a temperature-dependent vapor pressure that prevents condensation on the warmer sensor walls but that allows condensation.
Table 2. Summary of All He Purge Efficiency Calculations

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a d
Table 2. Summary of All He Purge Efficiency Calculations\(^a\) (Continued)

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<td>44</td>
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<td>0.0017\pm0.0017</td>
<td>0.805\pm0.037</td>
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Table 2. Summary of All He Purge Efficiency Calculations\textsuperscript{a} (Continued)

<table>
<thead>
<tr>
<th>Run</th>
<th>Species</th>
<th>$v_c$ \text{ cm/sec}</th>
<th>$\gamma$</th>
<th>$\alpha$, $\mu$, $T_{He}$, $T_w$, $N_{He}$, $N_{He}$ \text{ 10$^{13}$/cm$^3$}</th>
<th>$N$</th>
<th>$N_w$</th>
<th>$N_{ol}$</th>
<th>$N_{lo}$</th>
<th>$c^c$</th>
<th>$n^d$</th>
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<tbody>
<tr>
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<td>$N_2$</td>
<td>5.8</td>
<td>60</td>
<td>0.02 273 77</td>
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<td>1000</td>
<td>0</td>
<td>0</td>
<td>0.001</td>
<td>0.046\pm0.021</td>
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<td>0.017\pm0.005</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>64</td>
<td>$H_2O$</td>
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<td></td>
<td>32</td>
<td>421</td>
<td>32</td>
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<td>30</td>
<td>6</td>
<td>444 6 0</td>
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<td></td>
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<tr>
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<td></td>
<td>40</td>
<td>1500</td>
<td>1 666 1</td>
<td>0.001\pm0.001</td>
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<tr>
<td>67</td>
<td></td>
<td>10</td>
<td>1000</td>
<td>126 371 57 125</td>
<td>0.250\pm0.020</td>
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<td>68</td>
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<td>0.6</td>
<td>1</td>
<td>30 0 204</td>
<td>0.002\pm0.002</td>
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</tr>
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<td>69</td>
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<td>111</td>
<td>0</td>
<td>0.001</td>
<td>0.111\pm0.011</td>
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</tr>
</tbody>
</table>

\textsuperscript{a} $\alpha$, $v_c$, $\gamma$, $N_{He}$, $T_{He}$, $T_w$, $c$, and $n$ have been defined in the text. Other symbols are as follows:
- $N$ = number of trajectories sampled
- $N_{tr}$ = number of trajectories that terminate on mirror
- $N_{wi}$ = number of trajectories that terminate on wall
- $N_{ol}$ = number of trajectories that would have missed mirror with no He flow, but hit with He flow
- $N_{lo}$ = number of trajectories that would have hit mirror with no He flow, but missed with He flow

Other counts of interest are as follows:
- $N_{en} = N_{tr} + N_{wi}$ = number of trajectories entering sensor
- $N_{hit} = N_{wi} - N_{ol}$ = number of trajectories that would have hit mirror with no He flow and hit with He flow
- $N_{miss} = N - N_{wi} - N_{lo}$ = number of trajectories that would have missed mirror with no He flow and missed with He flow

\textsuperscript{b} As noted in the text, sensor wall temperature varies between ~70 and 40 K. Calculations were done for $T_w$ (the effective temperature of He within the sensor) of 20 and 77 K, which bounds this range. Note that $T_w$ does not enter the calculation when $N_{He} = 0$. 

\textsuperscript{c} $c$ = number of trajectories that would have hit mirror with no He flow, but hit with He flow

\textsuperscript{d} $n$ = number of trajectories that would have missed mirror with no He flow, but missed with He flow
Table 2. Summary of All He Purge Efficiency Calculations\(^a\) (Continued)

\[ t = f \cos \theta / N \]

\[ N = \frac{N_0 + N_1 / \sqrt{2}}{N_0 N_1} \]

\[ \sigma = f \cos \theta / N \]

\[ N = \frac{N_0 + N_1 / \sqrt{2}}{N_0 N_1} \]

\[ \sigma = f \cos \theta / N \] is the transmittance [Eq. (4)] and its standard deviation. Note that a \( N^{1/2} \) contribution to the standard deviation in \( t \) and \( \sigma \) was ignored. The factor \( f \) accounts for the size chosen for the control area. Its value is \( f \), with the following exceptions:

<table>
<thead>
<tr>
<th>Run</th>
<th>( t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>1.351</td>
</tr>
<tr>
<td>10</td>
<td>0.667</td>
</tr>
<tr>
<td>11</td>
<td>0.310</td>
</tr>
<tr>
<td>12</td>
<td>1.114</td>
</tr>
<tr>
<td>14</td>
<td>0.667</td>
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<td>50</td>
<td>4</td>
</tr>
<tr>
<td>58</td>
<td>4</td>
</tr>
</tbody>
</table>

When \( N = 0, t = f \cos \theta / N \) defines a one-standard-deviation upper bound on \( t \).

\[ \sigma = f \cos \theta / N \]

\[ N = \frac{N_0 + N_1 / \sqrt{2}}{N_0 N_1} \]

\[ \sigma = f \cos \theta / N \]

\[ N = \frac{N_0 + N_1 / \sqrt{2}}{N_0 N_1} \]

\[ \sigma = f \cos \theta / N \]

*Runs 1 through 6 are early preliminary CIRRIS I calculations, with \( \theta = 60 \) and various combinations of He injection and barrel pressure as follows:

<table>
<thead>
<tr>
<th>Run</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Injection plume + barrel plume + barrel</td>
</tr>
<tr>
<td>2</td>
<td>Injection plume + barrel plume + barrel</td>
</tr>
<tr>
<td>3</td>
<td>Injection plume + barrel plume alone</td>
</tr>
<tr>
<td>4</td>
<td>Barrel alone</td>
</tr>
<tr>
<td>5</td>
<td>Injection plume alone</td>
</tr>
<tr>
<td>6</td>
<td>Barrel + barrel plume alone</td>
</tr>
</tbody>
</table>

*Run 7 tests results reported in Ref. 2. \( R = 18.127 \) cm, \( L = 206 \) cm, and hard-sphere scattering were used for this run only.

*Runs 8 through 26 employ CIRRIS I geometry. \( R = 6.4 \) cm, \( L = 96 \) cm.

*Runs 27 through 29 and 31 through 69 employ CIRRIS IA geometry. \( R = 16.23 \) cm, \( L = 96 \) cm.

*Run 51 was not applicable to this problem and is deleted.
on the primary mirror. In this case, a steady-state $N_2$ density develops in the sensor according to

$$n_{ss} = 2 \frac{f n(0) B'}{v}$$

(18)

where

$$B' = \frac{2\pi}{\bar{n}(0)} \int_{0}^{\pi/2} n(\gamma) \sin \gamma d\gamma$$

(19)

$v$ is the average $N_2$ thermal speed of $1 \times 10^4$ cm/sec at 20 K, and a factor of 2 enters because $N_2$ enters only one end of the telescope but is removed at both ends. In this case, the cryodeposit growth rate, in cm/sec, is given by

$$\dot{t} = 0.25 n_{ss} \frac{\bar{v} M}{6} x 10^{23} \rho$$

(20)

for $n_{ss} > n_{ss}^0$

and

$$\dot{t} = 0$$

for $n_{ss} < n_{ss}^0$

where $n_{ss}^0 = 4.8 \times 10^6$ cm$^{-3}$ is the number density corresponding to the vapor pressure of $N_2$ at 20 K, the temperature of the primary mirror.

B. SIGNIFICANT CRYODEPOSIT THICKNESS

Clearly, some small contamination buildup on the primary mirror can be tolerated. However, the critical thickness associated with the onset of significant degradation in sensor optical performance is not well defined. A careful definition of this critical thickness would itself require a study comparable in effort to the present analysis of He purge efficiency. This section is restricted to a review of the very limited published information on this question and to a rough estimate of the thickness of cryodeposit films which might begin to affect the optical performance of the CIRRIS telescope.

Both absorption and scattering by the contaminant film can adversely affect optical performance. Absorption is well understood. The thickness of an ice deposit, for example, should be less than $\sim 0.1$ um (1000 A) in order to prevent significant absorption of radiation within the
H$_2$O absorption bands. However, the scatter properties of condensed films are only poorly characterized. For the SIRE (Satellite Infrared Experiment) sensor, which had off-axis rejection requirements similar to those of CIRRIS, it was estimated that cryodeposit thicknesses up to 2 $\mu$m would produce insignificant scatter. A similar estimate of 1 $\mu$m for the SIRTF (Shuttle Infrared Telescope Facility) is given in Ref. 1. However, the basis of these estimates is not documented; they probably refer to a homogeneous smooth deposit.

Reference 24 specifies a bidirectional reflectance distribution function (BRDF) scatter performance for the primary mirror of CIRRIS of $10^{-4}$ sr$^{-1}$ at $\theta = 1^\circ$, with a $\theta^{-2}$ rolloff. These authors mention, but do not reference, measurements that indicate that 2 to 10 $\mu$m of contaminant buildup can cause a degradation by a factor of 10 to 100 in this mirror's scatter performance.

Reference 25 reports measurements at $\lambda = 10.6$ $\mu$m of BRDF mirror scatter increase produced by $\sim$ 1 to 20-$\mu$m cryodeposits of various species. Oxygen deposits consistently caused an increase in scatter with increased deposit thickness. For example, the data indicate that an O$_2$ deposit of 1.7 $\mu$m would degrade the BRDF to the CIRRIS specification of $1.8 \times 10^{-5}$ sr$^{-1}$ at 2.3$^\circ$. In contrast, N$_2$ deposits as thick as $\sim$ 25 $\mu$m did not ordinarily produce any measurable BRDF change. In a few cases, however, BRDF increased by $\sim$ 10 to 100. This was presumably associated with the formation of an N$_2$ frost, as opposed to that of a transparent, continuous, homogeneous smooth film.

In one case, the scatter from an N$_2$ film increased markedly after partial evaporation, perhaps because of some recrystallization that greatly increased scatter centers. Subsequent N$_2$ deposition onto this film increased the scattering markedly. This worst-case N$_2$ behavior would indicate that the N$_2$ cryodeposit must not exceed $\sim$ 0.05 $\mu$m (500 A) in order to meet the CIRRIS BRDF requirement. Because better information is not available, this is the safe limit recommended here for contaminants other than H$_2$O that do not absorb appreciably. It is probably a conservative limit because it is based upon the worst N$_2$ behavior observed. Moreover, it is also subject to considerable uncertainty because it is arrived at from an assumption that BRDF increase is
proportional to cryodeposit thickness $t$ from molecular dimensions to dimensions comparable to the wavelength $\lambda$ of the incident radiation. In reality, there are neither data nor theories to support such a linear, or other particular functional, extrapolation.

Reference 25 also reports five measurements of water vapor depositions, with $t = 3$ to $5 \mu m$, on mirrors at temperatures from 27 to 74 K. Three of these measurements revealed no increased mirror scatter. However, two other cases revealed a mirror scatter increase $> 10^5$, i.e., one much larger than that due to the $N_2$ frost. A linear thickness extrapolation of this behavior gives an $H_2O$ thickness limit of $\sim 6 \times 10^{-5} \mu m$ (0.6 A) before the CIRRIS BRDF requirement is exceeded. However, this linearly extrapolated thickness limit seems unrealistically small, which indicates the failure of a linear extrapolation in at least this case. Before any contamination, the best available, state-of-the-art, super-polished mirrors, with BRDF at $\lambda = 10 \mu m$, considerably better than the CIRRIS requirement, have $26$ root-mean-square (RMS) roughnesses of 10 to 50 A. Electromagnetic boundary-value theoretical expressions given in Ref. 26 for mirror BRDF can be used to estimate RMS surface roughness limits for $H_2O$, which should be highly reflective at wavelengths where it absorbs strongly. These theoretical expressions depend a great deal on the surface roughness correlation length as well. They would indicate a $\sim 0.01 \mu m$ surface roughness for a correlation length assumed to be much less than a wavelength $= 0.1 \mu m$ at $\lambda = 2.7 \mu m$ (a wavelength near the short-wavelength edge of the CIRRIS band where water is highly absorbing), in order to meet the CIRRIS BRDF requirement at one degree. In the absence of any better information, a critical thickness limit estimate of $0.01 \mu m$ (100 A) is adopted here for $H_2O$ deposition on the CIRRIS primary mirror.
IV. MONTE CARLO HELIUM-PURGE EFFICIENCY RESULTS

A summary of all of the Monte Carlo calculations is given in Table 2. The He purge efficiency depends on a number of variables, viz sensor geometry, molecular identity, impact speed $v_c$, impact direction $\gamma$, He mass flow rate $\dot{m}$, number density of He within the sensor $N_{He}$, and temperatures of the He effusion sources $T_{He}$ and $T_w$. In general, these results show the following general trends in transmission of contaminants through the He purge:

(a) $\tau$ decreases monotonically with increasing $\dot{m}$ or $\gamma$ or $N_{He}$;
(b) $\tau$ increases monotonically with increasing $v_c$ or $T_{He}$;
(c) $\tau$ (CIRRIS IA) > $\tau$ (CIRRIS I); and
(d) $\tau$ ($CO_2$) > $\tau$ ($N_2$) > $\tau$ ($H_2O$), other variables being equal.

These trends are discussed in more detail in the remainder of this section.

One striking feature of the results listed in Table 2 is that the purge flow of He provides very significant protection against impinging contaminants in some cases. This is most striking for CIRRIS I. In many of these cases, no contaminants reached the mirror and only an upper limit could be set on $\tau$. An example is the case of $H_2O$ impinging at $v_c = 6 \times 10^4$ cm/sec, with $\dot{m} = 0.02$ g$_{He}$/sec and $\tau < 0.002$ (run 27). Indeed, $\tau < 0.001 \pm 0.001$ for this case because this was the value calculated for a much higher impingement speed, $v = 8 \times 10^5$ cm/sec (run 26). In fact, an examination of wall deposition numbers in the different calculations indicates that $\tau$ << 0.001 for thermal $H_2O$ at $\dot{m} = 0.02$ g$_{He}$/sec, perhaps by orders of magnitude. Figure 6, for example, shows results for $H_2O$ impinging at orbital velocity. Out of 2000 trajectories followed, one reached the mirror, whereas 371 others deposited along the sensor wall with an approximate exponential decay. In contrast, not a single one out of a total of 1000 trajectories even entered the aperture for thermal $H_2O$ in run 27. Thus, in some cases the He purge flow does indeed sweep aside completely the impinging thermal contaminants. The assumption discussed earlier of a unit sticking coefficient is clearly inconsequential for these cases.
Fig. 6. Histogram of $\text{H}_2\text{O}$ Deposition along the CIRRIS I Sensor Wall
The remainder of the discussion presented here concentrates on CIRRIS IA, the instrument that will be used on an upcoming flight. Both CIRRIS I and CIRRIS IA were modeled as telescopes with a separation \( T = 94 \text{ cm} \) between the sensor aperture and the primary mirror. Figure 7 compares the CIRRIS I and IA entrance apertures. The CIRRIS IA aperture is approximately elliptical, with an area \( A = 345 \text{ cm}^2 \), whereas the CIRRIS I aperture was circular, with \( A = 222 \text{ cm}^2 \). Because the Monte Carlo trajectory program required a circular aperture, the CIRRIS IA aperture was modeled in these calculations as circular, with a diameter equal to the major diameter of the ellipse and an area \( A = 829 \text{ cm}^2 \). At a given flow rate \( \dot{m} \), the He attenuates incoming contaminants more efficiently for CIRRIS I than for CIRRIS IA, because there is less sensor aperture area to protect and because deflections through smaller angles, on average, will cause the contaminant to miss the sensor aperture or strike the inside sensor wall. Thus, the CIRRIS IA results presented here, based upon the much larger circular aperture area, are conservative in underestimating the actual attenuation that is due to the He gas. In view of the values of the three areas, in fact, the results presented here for CIRRIS IA should be very conservative, with the real CIRRIS IA behavior closer to that of CIRRIS I than are the computed results for CIRRIS IA.

Figure 8 illustrates some of these remarks. The transmission is a strong function of He flow rate. The He provides considerably more protection for the CIRRIS I geometry than for the CIRRIS IA geometry. Even for CIRRIS IA, however, at the planned flow rates of 0.02 \( \dot{m}_\text{He}/\text{sec} \), the He flow still provides significant protection against \( \text{H}_2\text{O} \) impinging at low speed.

Increasing the He ejection temperature \( T_{\text{He}} \) should increase the He momentum while decreasing the steady-state density in front of the sensor. The effect on impinging contaminants can be seen in Table 2 by comparing runs 27 versus 34, 32 versus 33, and 28 versus 39. Apparently the density change is more important. In all cases, \( T_{\text{He}} = 20 \text{ K} \) was considerably more effective than \( T_{\text{He}} = 273 \text{ K} \), and had a particularly big effect on the \( \text{N}_2 \) acceptance.

Figure 9 illustrates that \( \text{H}_2\text{O} \) transmission shows appreciable dependence on the steady-state density of He within the sensor. The model of
Fig. 7. Normal View of Sensor Apertures. The CIRRIS I aperture is circular, $R = 8.4$ cm. However, the CIRRIS IA elliptical aperture was modeled by a larger circular aperture, $R = 16.25$ cm.
Fig. 8. Transmission of H$_2$O Contaminant as a Function of He Flow Rate $\dot{m}$, for Runs 34, 43, 44, 56, and 57
Fig. 9. Transmission of H$_2$O Contaminant as a Function of Steady-State He Density in the Sensor for Runs 44 through 47. The arrow indicates that $N_{He} = 0.55 \times 10^{14}$ cm$^{-3}$ for true effusion of He out of the ejector ring.
Effusion of He from the ejection ring into the sensor actually predicts \( N_{\text{He}} = 0.55 \times 10^{14} \text{ cm}^{-3} \), so that the true value is likely to be somewhere between this number and zero. Contaminant buildup rates that are estimated later represent the conservative analysis where \( N_{\text{He}} \) is taken as zero. In reality, the buildup of \( \text{H}_2\text{O} \) should be significantly slower than the estimates for \( \text{H}_2\text{O} \) provided later in this report, as a result of a finite \( N_{\text{He}} \). The buildup rate of \( \text{N}_2 \), however, should show very little or no dependence on \( N_{\text{He}} \), because the He must deflect the \( \text{N}_2 \) before it enters the sensor. There might be a small dependence associated with the small increase in He density in front of the sensor, as a result of effusion from the sensor for a finite \( N_{\text{He}} \).

The transmission of \( \text{H}_2\text{O} \) is plotted versus He flow rate for two speeds of contaminant approach in Fig. 10. This illustrates that \( \tau \) exhibits an initial, Beer's-law exponential decrease with increasing \( \dot{m} \), but that significant deviations from this simple dependence appear in the \( v_c = 6 \times 10^4 \text{ cm/sec} \) results, where the attenuations are clearly well beyond the single-collision regime. Figure 11 illustrates the very strong dependence of \( \tau \) on speed of approach for \( \text{H}_2\text{O} \). This is reproduced in Fig. 12, where results for \( \text{N}_2 \) and \( \text{H}_2\text{O} \) are compared. This illustrates that the contaminant transmission is more sensitive to impact speed \( v_c \) than to molecular identity. For this reason, the investigation of sensitivity to collision cross sections was not pursued beyond that represented by runs 7, 48, and 54. Comparisons of runs 54 and 33 are interesting, however. Run 54 was done for a total cross section independent of \( v \), with a value equal to that for \( \text{H}_2\text{O} \) at \( v = 8 \times 10^5 \text{ cm/sec} \) but with an isotropic, hard-sphere differential cross section. In contrast, run 33 refers to the correct \( \text{H}_2\text{O} \) cross sections, so that the total cross section increases after the first collision has slowed the \( \text{H}_2\text{O} \) down. Nevertheless, run 54 produced much larger attenuations than did run 33 (\( \tau = 0.12 \) and 0.43, respectively), which indicates that an assumed hard-sphere, isotropic differential cross section severely overestimates the role of hard, wide-angle collisions.

As noted earlier, \( \text{H}_2\text{O} \) is expected to return with an approximate thermal-speed distribution characteristic of the outgas source for \( \beta > 90^\circ \). In orbit, Orbiter surface temperatures can vary from \( \sim 200 \) to \( 375 \text{ K} \), depending
Fig. 10. Transmission of H₂O Contaminant as a Function of He Flow Rate for Two Impingement Speeds v_c, for Runs 33 through 36, 43, and 44.
Fig. 11. Transmission of $\text{H}_2\text{O}$ versus $v_c$, for Runs 33, 34, 37, 38, 50, and 58. The corresponding angle $\beta$, calculated from Eq. (12), is plotted along the top axis.
Fig. 12. Transmission versus $v_c$ for H$_2$O and N$_2$. The H$_2$O results are the same as in Fig. 11; the N$_2$ results are from runs 39, 49, 52, and 53.

CIRRIS IA:

$T_{He} = 273 \text{ K}$

$\gamma = 0$

$\dot{M} = g_{He} / \text{sec}$

$N_{He} = 0$
on solar illumination. Figure 11 indicates small transmissions, <0.01, for average thermal return speeds corresponding to these surface temperatures. In order to test for sensitivity to the high-velocity tail of the Boltzman speed distribution, however, the $\tau (v_c)$ behavior shown in Fig. 11 was averaged over a thermal speed distribution to obtain a thermally averaged transmission $\bar{\tau}$. The results shown in Fig. 13 indicate $\bar{\tau} < 0.01$ for $T < 375$ K.

In order to evaluate Eqs. (16) and (19), $\tau$ and $n$ were evaluated as a function of $\gamma$. The results are shown in Figs. 14 and 15 for $H_2O$ and $N_2$. Integration of the $\tau(\gamma)$ for $H_2O$ at $v_c = 8 \times 10^5$ cm/sec, shown in Fig. 14, yielded

$$B_{H_2O} = 0.18$$

(21)

The calculations of $\tau(\gamma)$ and $B$ were not carried out at lower $H_2O$ impact speeds because of the very large computation time that would have been required to achieve good statistics. Instead, the value of $B$ given in Eq. (21) was used in evaluating Eqs. (15a) and (17) for the buildup rate of $H_2O$ contaminant film at all $v_c$ values. Again, this should be a conservative estimate, since $B$ would be expected to decrease with decreasing $v_c$. Runs 33 versus 67 and 34 versus 68 in Table 2 support this expectation, although the statistics are poor. It is also of interest to compare Eq. (21) with a rough estimate of $B = A/L^2$. For the CIRRIS IA model employed here, this rough estimate gives $B = 0.09$, whereas it gives $B = 0.04$ if the real CIRRIS IA area is used. Again, these comparisons serve to emphasize that the results calculated here overestimate conservatively the actual contamination buildup.

The $N_2$ acceptance results shown in Fig. 15 indicate a much weaker dependence on $\gamma$. Indeed, the He purge has very little effect on acceptance at the highest velocity studied, $5.8 \times 10^5$ cm/sec; in the absence of He, the behavior would have been $1.0 \cos \gamma$. Acceptance results for $H_2O$ are included in Fig. 14 to illustrate that this behavior in Fig. 15 is not peculiar to $N_2$. Indeed, the results in Fig. 14 illustrate that He does little to prevent fast-impinging contaminants from entering the sensor, but that it does serve to
Fig. 13. Thermally Averaged $\tau$ for $H_2O$, Obtained by Averaging the $\tau(v_c)$ Behavior Shown in Fig. 11 over a Thermal Speed Distribution.
Fig. 14. Transmission and Acceptance versus $\gamma$ for $H_2O$ for Runs 33 and 64 through 67

CIRRIS IA:

- $H_2O$
- $m = 0.02 \text{ g He sec}$
- $v_c = 8 \times 10^5 \text{ cm/sec}$
- $T_{He} = 273 K$
- $N_{He} = 0$
CIRRIS IA:

$N_2$
$m = 0.02 \text{ a}_{\text{He}} / \text{sec}$
$T_{\text{He}} = 273 \text{ K}$

$N_{\text{He}} = 0$

$\gamma$

$\gamma$

$0.04 e^{-2.35 \gamma}$

$0.97 \cos \gamma$

$0.1$

$10$

$10^{-2}$

$10^{-3}$

$1.0 \times 10^5 \text{ cm/sec}$

$4.8 \times 10^4 \text{ cm/sec}$

Fig. 15. Acceptance versus $\gamma$ for $N_2$, for Runs 39, 52, 53, 59 through 63, and 69. The dashed line is a fit to the $v_c = 4.8 \times 10^4 \text{ cm/sec}$ data that were used to evaluate Eq. (19).
deflect most of them into the walls. The results in Fig. 15 clearly show that $B'$ of Eq. (19) is $2\pi$ at $v_c = 5.8 \times 10^5 \text{ cm/sec}$. The dashed line fit to the results for $v_c = 4.8 \times 10^4 \text{ cm/sec}$ gives $B' = 0.9$. A functional form was assumed to join these two limits:

$$B'_{N_2} = 0.9 + (5.4 \cos \theta)$$  \hspace{1cm} (22)$$

where $\theta$ is calculated from Eq. (12).
V. CONTAMINANT BUILDUP RATE AND CONCLUSIONS

Figure 16 shows the buildup of $H_2O$ computed from Eq. (17) with the Orbiter worst-case $H_2O$ environment specified in Eq (13). For a total $H_2O$ thickness goal of $< 0.01 \mu m$ and a $\sim 100$-hr period during which CIRRIS IA will be uncapped on orbit, growth rates of $\dot{t} \leq 10^{-4} \mu m/hr$ should be acceptable. Thus, Fig. 16 indicates there is no problem associated with $H_2O$ buildup for the current CIRRIS IA mission plan: $m = 0.02 \, g_{He}/sec$, $\beta = 90$ to $180^\circ$, and there are no VCS motor firings. Figure 16 also illustrates that $H_2O$ contamination would increase significantly if the sensor were pointing into the hemisphere containing the incoming wind. The second curve is included in Fig. 16 to illustrate what part of this increase in $\dot{t}_{H_2O}$ with decreasing $\beta$ is due to the $v_c$ dependence of $\dot{t}$, rather than to the $\beta$ dependence of $f_{H_2O}$. The functional dependence of $f_{H_2O}(\beta)$ is essentially unknown except at $\beta = 0$ and $90^\circ$. Thus, the true $\dot{t}$ probably lies between the two curves shown in Fig. 16, although it must approach the curve labeled $\dot{t}$ as $\beta$ goes to $0^\circ$. Clearly the CIRRIS IA mission plan is wise; it would be unwise to plan to collect all data at any angle $\beta < 90^\circ$. If, however, it might be desirable to collect some limited data at $\beta < 90^\circ$, Fig. 16 can be used to estimate the corresponding contamination penalty. It is evident that some data collection at angles $\beta < 90^\circ$ would be acceptable.

The acceptance $n$ of $N_2$ is plotted versus $v_c$ in Fig. 17. This was used in conjunction with $f_{N_2}(\beta)$ from Eq. (14) and $B_{N_2}(\beta)$ from Eq. (22) to calculate the $N_2$ steady-state densities (shown in Fig. 18) within CIRRIS IA from Eq. (18). For a CIRRIS IA primary mirror temperature of $20 \, K$, condensation begins at $n_{gs} = 5 \times 10^6 \, N_2$ molecules $cm^{-3}$, or $\beta = 87^\circ$. This figure also indicates that condensation would not take place under any condition at a wall temperature greater than $24 \, K$. Thus, condensation takes place only at the mirror except for some small part of the wall near the mirror which may have temperatures of $20$ to $24 \, K$. For small $\beta$ values, the $N_2$ film thickness growth rate, calculated from Eq. (20), is shown in Fig. 19. The estimated-safe $N_2$
Fig. 16. Buildup of $H_2O$ Contaminant-Film Thickness, Calculated from Eq. (17) for the STS-4 Worst-Case Environment Specified in Eq. (13) and Shown as $t$. The other curve shows that part of the $\beta$ dependence which is due to the $v_c$ dependence of $t$. 
Fig. 17. The Acceptance $n$ for $N_2$ versus $v_c$ for Runs 39, 49, 52, and 53
Fig. 18. Steady-State $N_2$ Density within CIRRIS IA versus $\beta$ from Eq. (12) for $f_{N_2}(\beta)$ from Eq. (14) and $B_{N_2}(\beta)$ from Eq. (22). The right vertical axis shows the maximum temperature at which the corresponding number density shown on the left axis would produce condensation.
Fig. 19. Growth Rate of $N_2$ on the CIRRIS IA Primary Mirror, Calculated from Eq. (20), for the $n_{ss}$ Dependence Plotted in Fig. 18
thickness discussed earlier was 0.05 μm, so that t should be less than $5 \times 10^{-4}$ μm/hr for a 100-hr mission. Again, the mission constraint of $\beta > 90^\circ$ is well-advised. Figure 19 may be used to estimate the contamination consequences if any data are collected at smaller $\beta$ angles.

Buildup rates of H$_2$O and N$_2$ contaminant films that would be produced by continuous firing of a VCS engine are given in Table 3 for the worst-case return-flux estimates based on observations reported in Ref. 17. As discussed earlier, there is considerable uncertainty, given a large range of possible return speeds and H$_2$O and N$_2$ fluxes. As shown in Table 3, this produces a large range of uncertainty in possible contaminant-film buildup rates. The VCS engines are used when the Shuttle Orbiter is not in the stable gravity gradient mode; they are operated in a pulsed mode with a duty factor $D_f$ much less than unity. The corresponding film buildup rate is obtained by multiplying the entry in Table 3 by $D_f$. For a typical $D_f = 0.01$, the thickness buildup rates given in Table 3 may be read as total buildup during the 100 hr that CIRRIS IA is uncapped. Even these worst-case estimates indicate that H$_2$O buildup is not a problem, but that N$_2$ buildup may be a problem.

A more careful analysis of N$_2$ buildup requires a detailed consideration of geometry, because $v_c$ and $f$ depend on the location and thrust direction of the VCS engine in relation to the Shuttle Orbiter's attitude and the sensor's line of sight. Table 4 provides such an analysis versus $\beta$ for a typical case, a CIRRIS IA line of sight straight up out of the cargo bay. Return speeds were calculated from conservation of linear momentum and energy for an N$_2$ plume molecule that returned as a result of a single collision with an O atom. These are only estimates. In reality, a spread of return speeds would be produced because of multiple collision effects and a spread in the intersection angle of the collision partners. Combining the $v_c$ values with the transient N$_2$ signals reported in Ref. 17 gives the worst-case $f_{N_2}$ and $t$ entries in Table 4. Even these worst-case entries indicate that VCS engines

---

*It should be noted that N$_2$ evaporation while the motor is off is too slow, given the 20 K temperature of the primary mirror, to be of any consequence.*
Table 3. Worst-Case Estimates of H$_2$O and N$_2$ Growth Rates on the CIRRIS IA Primary Mirror Due to the 25-lb-Thrust VCS Engine$^a$

<table>
<thead>
<tr>
<th>Species</th>
<th>$v_c$, $10^5$ cm/sec$^b$</th>
<th>$f$, $10^{14}$ cm$^{-2}$ sr$^{-1}$ sec$^{-1}$</th>
<th>Thickness Buildup $t$, $\mu$m/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O</td>
<td>0.6</td>
<td>0.4</td>
<td>$6 \times 10^{-5}$</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>5</td>
<td>4</td>
<td>$3 \times 10^{-2}$</td>
</tr>
<tr>
<td>N$_2$</td>
<td>0.5</td>
<td>0.4</td>
<td>$2 \times 10^{-3}$</td>
</tr>
<tr>
<td>N$_2$</td>
<td>4</td>
<td>3</td>
<td>$1$</td>
</tr>
</tbody>
</table>

$^a$Thickness buildup rate refers to continuous engine burn:

$m = 0.02$ g$_{He}$/sec; $T_{He} = 273$ K; $N_{He} = 0$

$^b$As discussed in the text, this is the estimated range of possible return speeds and worst-case fluxes.
Table 4. Best Estimates of $N_2$ Growth Rates on the CIRRIS IA Primary Mirror Due to the 25-lb-Thrust VCS Engine

<table>
<thead>
<tr>
<th>$\beta$, deg</th>
<th>$10^5 v_c$, cm/sec</th>
<th>Worst Case $^{c}$</th>
<th>Best Estimate $^{d}$</th>
<th>Worst Case $^{e}$</th>
<th>Best Estimate $^{d}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>3.4</td>
<td>28</td>
<td>1.2</td>
<td>0.8</td>
<td>$1 \times 10^{-2}$</td>
</tr>
<tr>
<td>120</td>
<td>2.5</td>
<td>21</td>
<td>0.4</td>
<td>$4.1 \times 10^{-1}$</td>
<td>$2.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>150</td>
<td>1.0</td>
<td>8</td>
<td>0.14</td>
<td>$5.2 \times 10^{-2}$</td>
<td>$2.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>180</td>
<td>-</td>
<td>4</td>
<td>0.09</td>
<td>$1.2 \times 10^{-3}$</td>
<td>$8.4 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

$^{a}$Thickness buildup rate refers to a continuous single-engine burn for line of sight straight up out of cargo bay: $m = 0.02 \text{ gHe/sec}$, $T_{\text{He}} = 273 \text{ K}$, $N_{\text{He}} = 0$.

$^{b}$Estimate for single plume O-atom collision. $v_c$ actually depends on the location of the particular VCS engine relative to the velocity vector. Entries given are for the engine that gives the largest $v_c$. A single collision cannot return $N_2$ along $\beta = 180^\circ$. $v_c = 5 \times 10^4 \text{ cm/sec}$ was used for $\beta = 180^\circ$.

$^{c}$is based upon the transient $N_2$ signal measured in Ref. 17.

$^{d}$is calculated from Refs. 20 and 27, as described in the text.
can be safely fired at $D_f = 0.01$ during the entire CIRRIS IA mission so long as $\beta \geq 150^\circ$. Moreover, the best-estimate entries in Table 4 indicate that contamination buildup due to VCS engine firings at a typical $D_f = 0.01$ will be inconsequential so long as the sensor is looking into the aft hemisphere, i.e., if $\beta > 90^\circ$. These best estimates were calculated by extrapolating the $\beta = 0$ to $80^\circ$ calculations reported in Ref. 20 with the approximate $\beta = 0$ to $180^\circ$ return flux angular distribution reported in Ref. 27. Work reported in Ref. 28 indicates that even this should overestimate the $N_2$ return flux at these large $\beta$ angles, because $N_2$ is heavier than the $O$ atom collision partner.
REFERENCES


15. B. R. Johnson, S. J. Young, and R. R. Herm, to be published.


Differential cross sections have been calculated by the method described in Ref. 3 for the scattering of He atoms by \( \text{H}_2\text{O}, \text{N}_2, \text{CO}, \text{and CO}_2 \). Results are presented here as plots of \( \sigma(\theta,v) \), in units of \( \text{Å}^2/\text{sr} \), as a function of polar scattering angle \( \theta \). Some plots are presented versus collision energy, \( E = \mu v^2/2 \), rather than collision speed. For completeness, results on He-O are also included here. The He-O potential function given here is correct; there is an error in the potential function that appears in Ref. 3.

Potential Energy Functions

For He + O(\(^3\)P):

\[ V(r) = \tanh(ar^{-6}) \ V^F(r) + \tanh(br^{-6}) \ V^A(r) \]

where:

\[ V^F(r) = Ae^{-Br} \]

\[ V^A(r) = \epsilon\left[\frac{6}{a-6} \exp\left\{-a\left(\frac{r}{r_m}\right)^{-1}\right\}\right] - \frac{a}{a-6} \left(\frac{r}{r_m}\right)^{-6} \]

and where

\[ a = 102.0 \ \text{bohr}^6 \]
\[ b = 0.001 \ \text{bohr}^{-6} \]
\[ A = 378 \ \text{eV} \]
\[ \beta = 3.744 \ \text{Å}^{-1} \]
\[ \epsilon = 2.48 \times 10^{-3} \ \text{eV} \]
\[ \alpha = 13.772 \]
\[ r_m = 3.08 \ \text{Å} \]
For He + CO and He + N₂:

Both potentials⁶ are a parametrized form called the Simons-Parr-Finlan-Dunham (SPFD) potential given by

\[ V(r) = \epsilon \left[ b_0 \left( \frac{r - r_m}{r_m} \right)^2 \sum_{i=1}^{3} b_i \left( \frac{r - r_m}{r_m} \right)^i - 1 \right] ; \frac{r}{r_m} < 1.6 \]

\[ = - \epsilon C_6 \left( \frac{r}{r_m} \right)^{-6} \quad \frac{r}{r_m} > 1.6 \]

The parameters are

<table>
<thead>
<tr>
<th>He + CO</th>
<th>He + N₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_m )</td>
<td>3.70 Å</td>
</tr>
<tr>
<td>( r_m )</td>
<td>3.65 Å</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>2.28 × 10⁻³ eV</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>2.27 × 10⁻³ eV</td>
</tr>
<tr>
<td>( b_0 )</td>
<td>39.2</td>
</tr>
<tr>
<td>( b_0 )</td>
<td>31.9</td>
</tr>
<tr>
<td>( b_1 )</td>
<td>-5.10</td>
</tr>
<tr>
<td>( b_1 )</td>
<td>-4.72</td>
</tr>
<tr>
<td>( b_2 )</td>
<td>11.31155006</td>
</tr>
<tr>
<td>( b_2 )</td>
<td>10.05959840</td>
</tr>
<tr>
<td>( b_3 )</td>
<td>-9.73209667</td>
</tr>
<tr>
<td>( b_3 )</td>
<td>-8.52603029</td>
</tr>
<tr>
<td>( C_6 )</td>
<td>1.52</td>
</tr>
<tr>
<td>( C_6 )</td>
<td>2.10</td>
</tr>
</tbody>
</table>

\( b_1 \) and \( b_3 \) are determined by smoothness conditions.\)

For He + H₂:

This is also an SPFD potential⁷ with the following parameters:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_m )</td>
<td>3.38 Å</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>2.27 × 10⁻³ eV</td>
</tr>
<tr>
<td>( b_0 )</td>
<td>31.4</td>
</tr>
<tr>
<td>( b_1 )</td>
<td>-6.15</td>
</tr>
<tr>
<td>( b_2 )</td>
<td>17.6202007</td>
</tr>
<tr>
<td>( b_3 )</td>
<td>-18.5110554</td>
</tr>
<tr>
<td>( C_6 )</td>
<td>2.30</td>
</tr>
</tbody>
</table>
For He + CO₂:

This potential is a Morse-Spline-Van der Walls (MSV) potential\(^6\) with parameters that are functions of the angle \(\gamma\), as follows:

\[
V(r, \gamma) = \varepsilon \exp\left[-\beta(r - r_m)/r_m\right] \left[\exp\left[-\beta(r - r_m)/r_m\right] - 2\right] \quad (r < r_1)
\]

\[
V(r, \gamma) = (r_2 - r) \left[S_1(r_2 - r)^2 + S_3\right] + (r - r_1) \left[S_2(r - r_1)^2 + S_4\right] \quad (r_1 < r < r_2)
\]

\[
V(r, \gamma) = -\frac{C_6}{r^6} - \frac{C_8}{r^8} \quad (r > r_2)
\]

where

\[
\varepsilon = \varepsilon_0 + \varepsilon_2 P_2(\cos \gamma)
\]

\[
r_m = r_{m0} + r_{m2} P_2(\cos \gamma)
\]

\[
C_6 = C_6(0) + C_6(2) P_2(\cos \gamma)
\]

\[
C_8 = C_8(0) + C_8(2) P_2(\cos \gamma)
\]

The function \(P_2(\cos \gamma)\) is the second-order Legendre polynomial and the values of the parameters are

\[
\varepsilon_0 = 1.05 \text{ meV}
\]

\[
\varepsilon_2 = -0.67 \text{ meV}
\]

\[
r_{m0} = 3.84 \text{ Å}
\]

\[
r_{m2} = 0.99 \text{ Å}
\]

\[
C_6(0) = 9.98 \text{ eV Å}^6
\]

\[
C_6(2) = 2.31 \text{ eV Å}^6
\]

\[
C_8(0) = 46.4 \text{ eV Å}^8
\]

\[
C_8(2) = 48.4 \text{ eV Å}^8
\]

\[
\beta = 4.59
\]

\[
r_1 = (1 + \frac{\ln(2)}{\beta}) r_m
\]

\[
r_2 = 1.6 r_m
\]
The spline parameters $S_1$, $S_2$, $S_3$, and $S_4$ are determined by smoothness conditions at $r_1$ and $r_2$; i.e., the potential and its first derivative are continuous at these points.
HELIUM - OXYGEN DIFFERENTIAL CROSS SECTION

E0 = .02 ELECTRON VOLTS
HEL IUM - OXYGEN DIFFERENTIAL CROSS SECTION
HELIUM - OXYGEN DIFFERENTIAL CROSS SECTION
HELIUM - OXYGEN DIFFERENTIAL CROSS SECTION
HELIUM - OXYGEN DIFFERENTIAL CROSS SECTION
EN = 0.60 ELECTRON VOLTS

HEL IUM - OXYGEN DIFFERENTIAL CROSS SECTION
HELIUM - OXYGEN DIFFERENTIAL CROSS SECTION
HELIUM - OXYGEN DIFFERENTIAL CROSS SECTION
HELIUM - OXYGEN DIFFERENTIAL CROSS SECTION
HELIUM - OXYGEN DIFFERENTIAL CROSS SECTION

EN = 1.66 ELECTRON VOLTS
HEL IUM - H2O DIFFERENTIAL CROSS SECTION
\( u = 2.5 \times 10^{-4} \text{ cm/sec} \)

**HELIUM - H2O DIFFERENTIAL CROSS SECTION**

80
HELIUM - H2O DIFFERENTIAL CROSS SECTION

v = 4.2E-04 CM/SEC
HELIUM - H$_2$O DIFFERENTIAL CROSS SECTION

$\nu = 6.5 \times 10^{-4} \text{ cm}^2 \text{ sec}^{-1}$
$u = 2.5 \times 10^{-5} \text{ cm-sec}$

**HELIUM - H2O DIFFERENTIAL CROSS SECTION**
HELIUM - N2 DIFFERENTIAL CROSS SECTION
U = 2.5E-04 cm-SEC

HELIUM - N2 DIFFERENTIAL CROSS SECTION
HELIUM - N2 DIFFERENTIAL CROSS SECTION
HELIUM - N2 DIFFERENTIAL CROSS SECTION

V = 6.5E-04 CM/SEC
HELIUM - N2 DIFFERENTIAL CROSS SECTION
HELIUM - N2 DIFFERENTIAL CROSS SECTION
HELIUM - N2 DIFFERENTIAL CROSS SECTION
HELIUM - CO DIFFERENTIAL CROSS SECTION

$U = 1 \times 10^4 \text{ cm} \cdot \text{sec}$
HELIUM - CO DIFFERENTIAL CROSS SECTION
HEL IUM - CO DIFFERENTIAL CROSS SECTION
HELUM - CO DIFFERENTIAL CROSS SECTION

\( V = 1.0 \times 10^{-6} \text{ cm/sec} \)
HELIUM - CO DIFFERENTIAL CROSS SECTION
HELIUM - CO DIFFERENTIAL CROSS SECTION

$U = 4.0 \times 10^{-5}$ CM-SEC
HELIUM - CO DIFFERENTIAL CROSS SECTION

\[ U = 6.5 \times 10^{-5} \text{ cm/SEC} \]
HELIUM - CO2 DIFFERENTIAL CROSS SECTION
HELIUM - CO2 DIFFERENTIAL CROSS SECTION
HELIUM – CO2 DIFFERENTIAL CROSS SECTION

U = 4.0E-04 CM/SEC
HELIUM - CO2 DIFFERENTIAL CROSS SECTION
HEL IUM – CO2 DIFFERENTIAL CROSS SECTION
HELIUM - CO2 DIFFERENTIAL CROSS SECTION

$U = 2.5 \times 10^{-5}$ CM/SEC
U = 4.0E-05 CM/SEC

HELIUM - CO2 DIFFERENTIAL CROSS SECTION
The Aerospace Corporation functions as an "architect-engineer" for national security projects, specializing in advanced military space systems. Providing research support, the corporation's Laboratory Operations conducts experimental and theoretical investigations that focus on the application of scientific and technical advances to such systems. Vital to the success of these investigations is the technical staff's wide-ranging expertise and its ability to stay current with new developments. This expertise is enhanced by a research program aimed at dealing with the many problems associated with rapidly evolving space systems. Contributing their capabilities to the research effort are these individual laboratories:

**Aerophysics Laboratory:** Launch vehicle and reentry fluid mechanics, heat transfer and flight dynamics; chemical and electric propulsion, propellant chemistry, chemical dynamics, environmental chemistry, trace detection; spacecraft structural mechanics, contamination, thermal and structural control; high temperature thermomechanics, gas kinetics and radiation; cw and pulsed chemical and excimer laser development including chemical kinetics, spectroscopy, optical resonators, beam control, atmospheric propagation, laser effects and countermeasures.

**Chemistry and Physics Laboratory:** Atmospheric chemical reactions, atmospheric optics, light scattering, state-specific chemical reactions and radiative signatures of missile plumes, sensor out-of-field-of-view rejection, applied laser spectroscopy, laser chemistry, laser optoelectronics, solar cell physics, battery electrochemistry, space vacuum and radiation effects on materials, lubrication and surface phenomena, thermionic emission, photosensitive materials and detectors, atomic frequency standards, and environmental chemistry.

**Computer Science Laboratory:** Program verification, program translation, performance-sensitive system design, distributed architectures for spaceborne computers, fault-tolerant computer systems, artificial intelligence, microelectronics applications, communication protocols, and computer security.

**Electronics Research Laboratory:** Microelectronics, solid-state device physics, compound semiconductors, radiation hardening; electro-optics, quantum electronics, solid-state lasers, optical propagation and communications; microwave semiconductor devices, microwave/millimeter wave measurements, diagnostics and radiometry, microwave/millimeter wave thermionic devices; atomic time and frequency standards; antennas, rf systems, electromagnetic propagation phenomena, space communication systems.

**Materials Sciences Laboratory:** Development of new materials: metals, alloys, ceramics, polymers and their composites, and new forms of carbon; non-destructive evaluation, component failure analysis and reliability; fracture mechanics and stress corrosion; analysis and evaluation of materials at cryogenic and elevated temperatures as well as in space and enemy-induced environments.

**Space Sciences Laboratory:** Magnetospheric, auroral and cosmic ray physics, wave-particle interactions, magnetospheric plasma waves; atmospheric and ionospheric physics, density and composition of the upper atmosphere, remote sensing using atmospheric radiation; solar physics, infrared astronomy, infrared signature analysis; effects of solar activity, magnetic storms and nuclear explosions on the earth's atmosphere, ionosphere and magnetosphere; effects of electromagnetic and particulate radiations on space systems; space instrumentation.