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PREDICTING SPACECRAFT SELF-CONTAMINATION IN SPACE AND IN A TEST CHAMBER

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16. Abstract

The self-contamination of a spacecraft (defined as the return and deposition of outgassed molecules on its critical surfaces, either in orbit or while undergoing vacuum test) is considered. Theoretical relations for the flux, density, and pressure of the emitted gas as a function of altitude, radius, and distance from the spacecraft surface are developed. The flux of the outgassed molecules that return to the emitting surface is also obtained and shown to be dependent on altitude, spacecraft dimensions, and the magnitude of outgassing. The rate of condensation and the time for the formation of a monolayer of the returning molecules can be calculated.

The self-contamination of a spacecraft undergoing vacuum chamber test is also theoretically examined and compared with the equivalent parameters for orbit conditions. It is concluded that, depending on the dimensions of the spacecraft relative to those of the chamber and the wall capture coefficient, ground tests conducted in the more usual space simulation chambers can provide returning fluxes and self-contamination comparable to those occurring in space up to an altitude of about 400 km. For higher altitudes and return fluxes less than 10^{-3} of those emitted, the chamber test can produce a greater contamination. In this case, the ground results can be related to those obtained in space, provided that the wall capture coefficient is known or if the ratio of returned to emitted flux at the spacecraft surface is measured.

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FOREWORD

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This document contains data so expressed because the use of the SI equivalents alone would impair communication. The non-SI units, given in parentheses following their computed SI equivalents, are the basis of the measurements and calculations reported here.

CONTENTS

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INTRODUCTION

The accumulation of molecules on a surface may change the optical properties of that surface. In general, this contamination consists of water vapor and medium- to high-molecular-weight organic materials having low vapor pressures. Low-molecular-weight organic materials that have very high vapor pressures (i.e., that are volatile) at room temperatures are not likely to remain on surfaces. The surface temperatures of an orbiting spacecraft are generally higher than the condensing temperatures, and these materials should not present a problem. However, experiments utilizing detectors cooled to temperatures of 175 K (−98°C) or lower have recently been flown. At these temperatures, most gases will condense upon and lower the efficiency of optical surfaces.

In orbit, a spacecraft can become self-contaminated, and deterioration of optical, thermal, and electric systems may occur. Self-contamination in space, when not produced by direct impingement of desorbed molecules on critical surfaces, has been thought of as being produced by a cloud consisting of emitted gases and particulate matter surrounding the spacecraft. Various theories have been suggested to confirm the existence of this so-called cloud and to evaluate its nature. Radiation pressure, aerodynamic drag, solar wind, charge drag, and Lorentz forces have been invoked as the mechanisms retaining the cloud of emitted gas around the spacecraft. Flight experiments have been few, and their results are inadequate for establishing the presence of this cloud or determining its characteristics. In this paper, the atmosphere that forms around an orbiting spacecraft as a result of material outgassing is described, and the fraction of outgassed molecules that return the surface of the spacecraft as a result of their collisions with ambient neutral particles is calculated. Curves showing the dependence of the cloud and the fraction of returning molecules on spacecraft size and altitude are also given.

Self-contamination of a spacecraft undergoing tests in a space chamber is examined. This contamination results from the return flux of desorbed (i.e., outgassed) molecules reflected by the chamber walls; it is governed by the capture coefficient of the chamber wall surface and the geometry of the spacecraft and the chamber. The two conditions are evaluated, and an attempt is made to predict and model the tests in such a way that the terrestrial environment will be similar to the space environment. The time required for a monolayer to form on a cold surface in space is correlated with the time required in the test chamber. This correlation indicates, within the limits of the idealized analysis, the duration of testing necessary to reproduce the space contamination. It is expected that the analysis can help in predicting alterations of thermal and optical properties of a surface.

ORBITING SATELLITE

Concentration of Outgassing Around the Satellite

With the assumptions that the density around a spherical spacecraft of radius R is such that the majority of the radially desorbed molecules do not collide with each other and that the trajectory of each molecule is straight until it collides with an ambient molecule, the density (Reference 1) is

$$n_D = \frac{N_D e^{-x/\lambda_D}}{4\pi(R+x)^2 v_D} \quad (\mathrm{cm}^{-3}) , \tag{1}$$

where

N_D = the number of molecules per second emanating from the spacecraft, which can be obtained from any of the commonly used measures of outgassing, for example, Q (torr-l-s^{-1}), or $\dot{m}$ (g-s^{-1}),

x = the radial distance in the direction of motion away from the satellite,

λ_D = the mean free path (MFP) of the desorbed molecules in the condensation region of the orbiting spacecraft,

v_D = the mean thermal velocity of the desorbed molecules.

The MFP for a molecule emitted parallel or perpendicular to the orbit velocity vector is approximated, respectively, by

$$\lambda_{D_\parallel} = \frac{v_D}{v_0 + v_D} \lambda_0$$

and

$$\lambda_{D_\perp} = \frac{v_D}{(v_0^2 + v_D^2)^{1/2}} \lambda_0 , \tag{2}$$

where λ_0 is the ambient MFP and v_0 is the spacecraft velocity. However, $\lambda_{D_\perp}$ practically coincides with $\lambda_{D_\parallel}$ for near-earth orbits, where $v_D \ll v_0$. The values of λ_0 and v_0 are both determined for a given orbiting altitude.

Expressing Equation 1 in terms of flux, and substituting $\lambda_{D_\parallel}$ for the parallel-emitted molecules, one obtains for the emitted flux,

$$\phi_D = \frac{N_D \exp\left[-\left(\frac{v_D + v_0}{v_D}\right)\frac{x}{\lambda_0}\right]}{4\pi(R+x)^2} \qquad (\mathrm{cm}^{-2}\text{-}\mathrm{s}^{-1}) . \tag{3}$$

The outgassing concentration given by Equation 1 with the substitution of $\lambda_{D_{\parallel}}$ of Equation 2 is plotted parametrically in Figure 1 as a function of distance, spacecraft radius, and orbit altitude. (The value of the thermal velocity employed for the calculations was 0.4 km-s^{-1}).

Although pressure in the thermodynamic sense, or as an isotropic property relating to a force per unit area (independent of the orientation of the area), has no meaning here, in a practical way the gas conditions can be described by the pressure sensed by an open-end probe located in the molecular stream and oriented toward the gas source. The pressure sensed by the probe is related to the molecular flux and is a function of the density and temperature of the gas. The pressure inside this probe will reach a level so that the efflux of the molecules through the probe opening is equal to the influx of the molecules from the environment. The molecular influx is the value of the molecular flux incident on the probe opening. With these assumptions, the nonisotropic concentrations and fluxes obtained here can be transformed to "equivalent pressure" through the equation of state, $P = nkT$, used as a definition rather than as an equation.

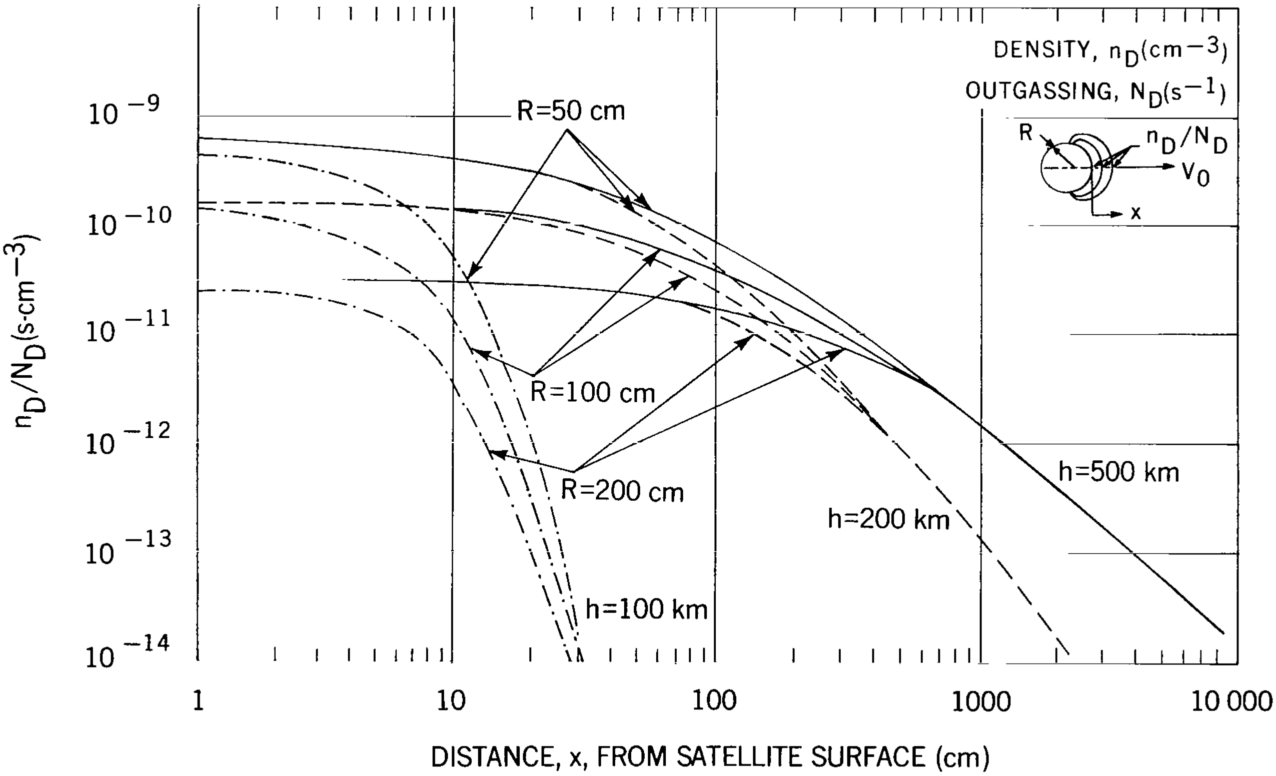

Figure 1—Concentration of outgassing molecules vs. distance from spacecraft.

Flux and Density of Molecules Returning to the Satellite Surface

The difference between the number of molecules that reach distance x and $x + \Delta x$ represents the number of molecules that have collided with ambient molecules in the interval Δx. If this number is divided by the shell area $4\pi(R + x)^2$, one obtains the number of collisions Δn occurring at distance x in a volume having a unit base and Δx thickness (Reference 1). Further, if these Δn are summed for $0 \leqslant x \leqslant \infty$, the total number of molecules per unit time that will have collided in the unit semi-infinite column in front of the spacecraft is the flux

$$\phi'' = \int_0^\infty \frac{N_D e^{-x/\lambda_D}}{4\pi(R + x)^2 \lambda_D} dx$$

$$\approx \frac{N_D}{4\pi\lambda_D R} \qquad (\mathrm{cm}^{-2}\text{-}\mathrm{s}^{-1}) \tag{4}$$

for $\lambda_D \gg R$. After collision, the velocity of the molecules is less than the velocity of the spacecraft; hence, the molecules are reacquired by the spacecraft. If the average velocity of approach is ν_n, the apparent density of the returning molecules at the spacecraft surface will be

$$n'' = \frac{N_D}{4\pi\lambda_D \nu_n R} \qquad (\mathrm{cm}^{-3})\ . \tag{5}$$

Ratio of Emitted to Returned Molecules

The fraction of the desorbed molecules that return to the spacecraft surface in the region of condensation is given by the ratio of Equation 3 (taken at $x = 0$) and Equation 4:

$$\frac{\phi''}{\phi_D} = \frac{R}{\lambda_0}\left(\frac{\nu_D + \nu_0}{\nu_D}\right) \tag{6}$$

Similarly, the ratio of the densities of emitted and returned molecules can be obtained from Equations 5 and 1.

Figure 2 is a plot of the ratio of the returning flux to the emitted flux as a function of altitude. The altitude, as mentioned, determines ν_0 and λ_0 in Equation 6. The ratio decreases rapidly with altitude, reaching a practically constant value at altitudes greater than 1000 km; it increases with the radius of the satellite. The density, which decay in the same manner as the flux, is also plotted in Figure 2, for an estimated return velocity equal to one-half the orbital velocity (Reference 1).

The effect of the return flux on the total "equivalent pressure", at the surface of the satellite is an important consideration. The total pressure P_t produced by the outgassing is given by the sum of the equivalent pressures of the emitted molecules P_D and of the returned molecules P''. In normalized form, this is given by

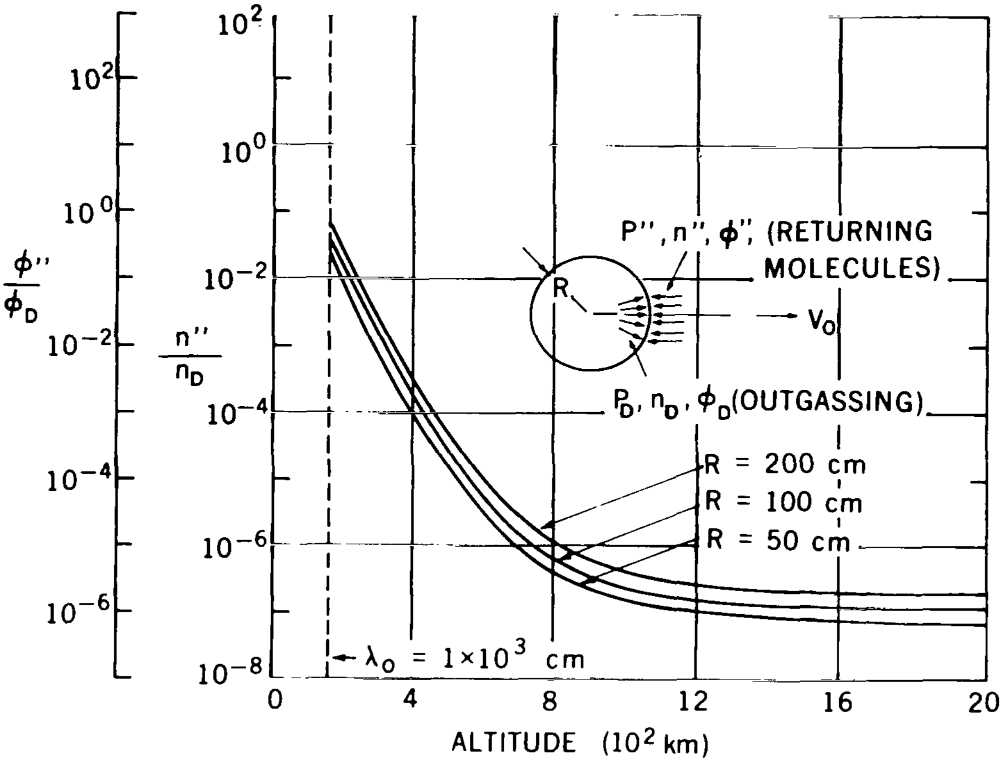

Figure 2—Returning flux vs. altitude.

$$\frac{P_t}{P_D} = 1 + \frac{\phi''}{\phi_D}\sqrt{\frac{T_n}{T_D}}$$

$$= 1 + \frac{R}{\lambda_D}\,\frac{\nu_n}{\nu_D}\ , \qquad (7)$$

which is obtained by substituting $(P''/P_D) = (\phi''/\phi_D)(\nu_n/\nu_D)$, given by the previous equations. It is readily seen that the effect of the returned molecules is undetectable if one attempts to measure the pressure. The total pressure is produced almost entirely by the desorbed molecules, and a pressure measurement would be insensitive to the returned molecules because of the relative dimensions of R and λ_D at the altitudes under consideration (i.e., $\lambda_D \gg R$).

Contamination Caused by the Returning Flux and Time for Monolayer Formation

The returning molecules may enter an opening or impinge on surfaces upon which they may deposit as adsorbate or condensate. If the pressure exerted by the contaminant gas on the surface is less than the saturation vapor pressure (of the same contaminant) corresponding to the temperature of the surface, a few monolayers or a fraction of one may form on that surface. An equilibrium between molecules arriving and leaving the surface will be established. The number of adsorbed molecules per unit area is given by $\sigma = \alpha_s \phi'' \tau$, where α_s is the sticking coefficient and τ is the average residence time for the molecule on the surface. According to Frenkel's relation, this last parameter is a function of the heat of adsorption of the gas and of the surface temperature. The adsorption decreases exponentially with the temperature and increases exponentially with the heat of adsorption. For condensation to occur, the partial pressure P'' of the contaminant must be higher than the saturation vapor pressure P_s of the contaminant corresponding to surface temperature T_s. The saturation pressure is given by the Clapeyron relation. The rate of condensation is given by the difference between the impinging flux and the evaporating flux as dictated by the saturation pressure. If P_s is more than an order of magnitude less than P'', the evaporation can be disregarded, and the rate of condensation will be

$$\begin{aligned} \nu &= \alpha \phi'' \\ &= \alpha \frac{P''}{kT_n} \frac{v_n}{4} \\ &= \frac{\alpha P_D v_D}{4kT_D} \left(\frac{\phi''}{\phi_D} \right) \qquad (\text{cm}^{-2}\text{-s}^{-1}) \,, \end{aligned} \tag{8}$$

where α is the coefficient of condensation. This expression is obtained by multiplying the expression for the rate of condensation by ϕ''/ϕ_D and then dividing by $(\phi''/\phi_D) = (P''/P_D)(v_D/v_n)$, which is given by previous relations.

The time required for the accumulation of a monolayer of molecules on a surface is given by

$$\begin{aligned} t &= \frac{N_m}{\nu} \\ &= \frac{4kT_D}{\alpha v_D} \frac{N_m}{\left(\frac{\phi''}{\phi_D} \right) P_D} \qquad (\text{s}) \,, \end{aligned} \tag{9}$$

where N_m is the number of molecules per centimeter-square in a monolayer and P_D is the desorbed-molecule pressure at the surface, determined (from Equation 1) by

$$\begin{aligned} P_D &= n_D kT_D \\ &= \frac{N_D kT_D}{4\pi R^2 v_D} \,. \end{aligned}$$

Figure 3 shows the time required for monolayer formation as a function of the coefficient of self-contamination C_S, which is equal to ϕ''/ϕ_D, and of the outgassing pressure P_D, which is a measure of the spacecraft outgassing.

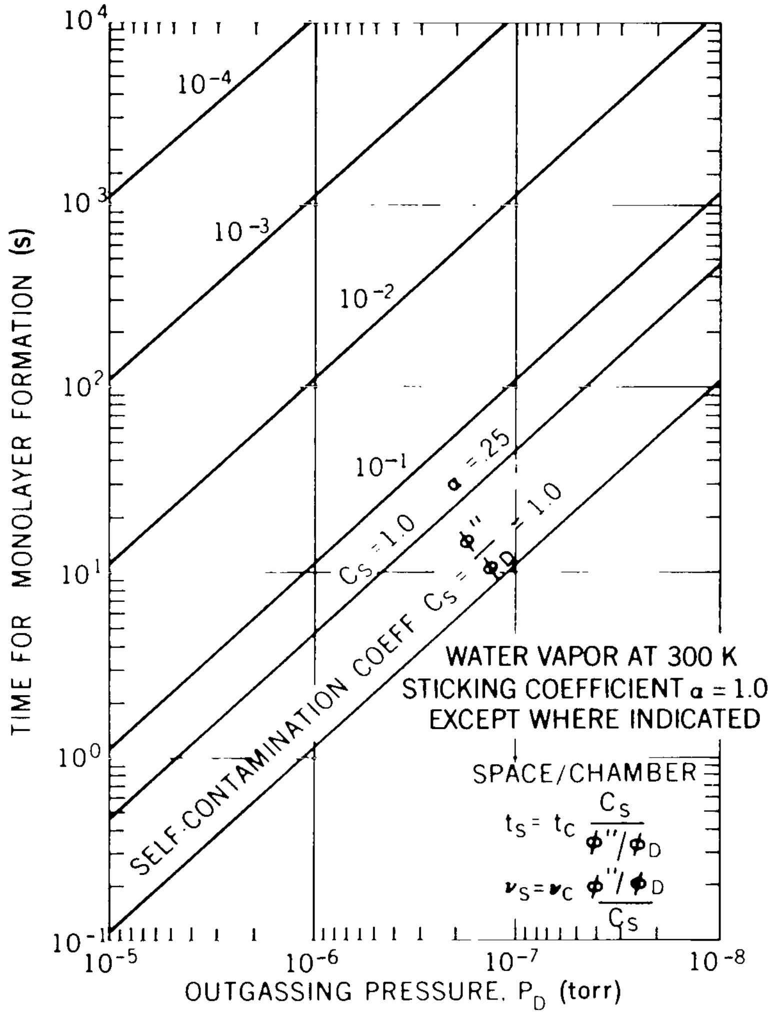

Figure 3—Time required for monolayer formation as a function of the coefficient of self-contamination C_S, and of outgassing pressure P_D.

VACUUM CHAMBER TESTING—SPACECRAFT SELF-CONTAMINATION

The design of vacuum chambers for spacecraft is based on the expectation that in space there exists only a negligible probability that an emitted molecule will collide with another and return to the spacecraft. Accordingly, it is expected that self-contamination may occur only through direct molecular encounter between two surfaces that can "see" each other. Thus, chamber walls are designed to minimize the return of desorbed molecules; that is, they act as molecular sinks, much in the same manner as they do for radiation.

Molecular self-contamination in a chamber bears no direct dependence upon the chamber pressure or upon the mean free path of the gas in the chamber. (However, pressure as a measure of density is significant for gas conduction and radiation heat transfer effect and for voltage breakdown.) The mean free path which is so important to the calculations of self-contamination in space has no comparable significance in a vacuum chamber, because for a relatively low gas pressure (or density), the mean free path of the molecules exceeds the dimensions of the vacuum chamber. The molecules emitted by the spacecraft will collide with the chamber walls; and if the walls are not a perfect sink, some molecules will be reflected. These returned molecules constitute the contaminating molecules and may provide an additional contamination not present in space. For a test chamber from which gas is removed only by pumps, the probability that a molecule is removed is roughly the ratio of the area of the pumping port to that of the entire projected chamber wall. This ratio is no more than 0.01 for large chambers. For cryopumped chambers with a refrigerated but nonpumping shield, the capture probability may be about 0.3, and for an unshielded cryopump surface, about 0.8 (References 2 and 3). Molecules not captured on the first encounter with the wall will leave the walls randomly; some will impinge upon the spacecraft, and others with other parts of the walls. A quasi-equilibrium condition is established when molecules are removed from the chamber after a number of collisions with the walls and spacecraft. For this condition of equilibrium, Chuan (Reference 2) derives a self-contamination coefficient C_S, defined as the ratio of the molecules returning to the test object after collision with the chamber wall to those emitted from the test object. The derivation, involving form factors and properties of surfaces, is based on the assumption that the chamber and spacecraft are concentric spheres and that the gas emission from the spacecraft and the chamber walls is uniformly distributed. This coefficient C_S is given by

$$C_S = \frac{1}{1 + \dfrac{\eta_c}{1 - \eta_c} \dfrac{1}{\eta_m} \dfrac{A_c}{A_m}}, \tag{10}$$

where

η_c = the chamber wall capture probability,

η_m = the spacecraft surface capture probability,

A_c = the surface area of the chamber,

A_m = the surface area of the spacecraft.

It is apparent from its definition that C_S corresponds to the flux ratio ϕ''/ϕ_D (Equation 6), which was derived for self-contamination in space.

Figure 4 is a plot of C_S as a function of the ratio of spacecraft to chamber diameter, for various values of the wall capture coefficient η_c. The value of η_m depends on the properties of the spacecraft surface and upon the nature of the contaminating molecules; Figure 4 has been plotted for η_m = 0.5.

The equivalent pressure in the chamber measured by a nude ionization gage at the spacecraft surface and caused by molecules coming directly from the spacecraft and by molecules returning from the walls was also derived. The equation, normalized by the surface pressure produced by the effusion rate

$$P_D = \frac{\dot{m}}{4\pi R^2}\left(\frac{2\pi k T_m}{M}\right)^{1/2} ,$$

is

$$\frac{P_e}{P_D} = 1/2 \left\{1 + C_S \left[\frac{1 + (T_c/T_m)^{1/2}}{\eta_m} - 1\right]\right\} \tag{11}$$

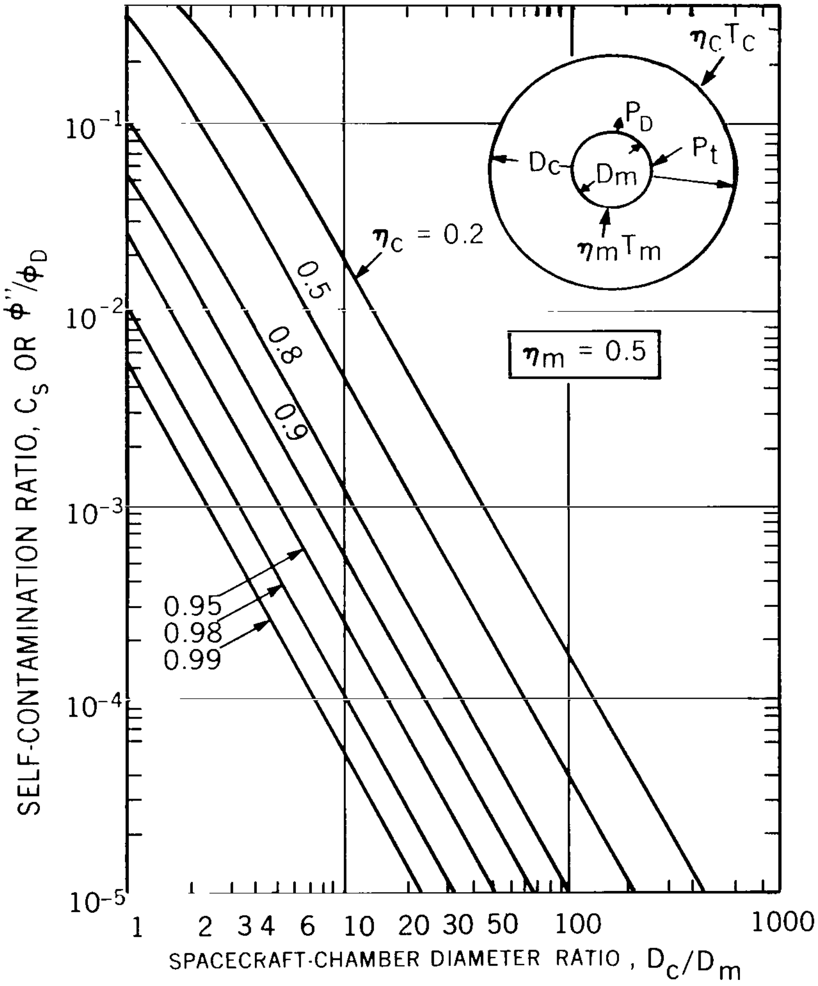

Figure 4—Coefficient of self-contamination C_S vs. ratio of spacecraft to chamber diameter.

where subscript m refers to spacecraft conditions and c to those of the chamber. The equation shows that the pressure (or density) measurement is insensitive to changes in C_S for values less than 0.2. In fact, taking as an example $T_c/T_m = 0.5$ and $\eta_m = 0.5$, the equation shows that in reducing C_S from 0.2 to 0.02, the pressure P_e would be reduced by a factor of 1.41. Another tenfold improvement in $C_S = 0.002$ would yield only an additional 6-percent reduction. Therefore, pressure is not a meaningful parameter for evaluation of self-contamination in a vacuum chamber. This was seen to be true (in fact, much more so) for self-contamination in an actual space environment.

COMPARISON OF SELF-CONTAMINATION IN SPACE AND IN A TEST CHAMBER

The various relations that apply to self-contamination in space and in a test chamber have been indicated. For both conditions, it has been shown that measurement of the pressure at the surface of the spacecraft is not sufficiently indicative of the degree of self-contamination. It has also been pointed out that whereas densities expected to occur in space can be reproduced in a vacuum chamber, the mean free paths are severely limited by the dimensions of the chamber. In space, the number of returned molecules is governed by the "reduced" ambient mean free path; in the vacuum chamber, the number of returned molecules is governed mainly by the interior surfaces of the chamber. However, in both cases, the flux ratio of returned molecules to emitted molecules can provide a meaningful contamination parameter. For equal degrees of self-contamination occurring in a vacuum chamber and in space, the coefficient C_S will be equal to the ratio ϕ''/ϕ_D. In this case, and with the appropriate substitution from Equations 10 and 6, the required wall capture coefficient must be

$$\eta_c = \frac{1 - \dfrac{R}{\lambda_D}}{1 + \dfrac{R}{\lambda_D}\left(\dfrac{A_c}{\eta_m A_m} - 1\right)}$$

$$\approx \frac{1}{1 + \dfrac{R}{\lambda_D}\,\dfrac{A_c}{\eta_m A_m}} \qquad (12)$$

This indicates that for reproduction of the conditions in a 200-km orbit in which the expected contamination coefficient ϕ''/ϕ_D is 10^{-1} (Figure 2), the capture coefficient for $A_c/A_m = 10$ ($D_c/D_m \approx 3.16$) and a spacecraft surface coefficient $\eta_m = 0.5$ must be approximately 0.31 (see Figure 4). As was mentioned, this value can be obtained in a cryopumped chamber with a refrigerated but nonpumping shield. For a 400-km orbit and a self-contamination of 10^{-3}, η_c must be 0.98. This capture coefficient is not generally obtainable, and more contamination would be expected in the vacuum chamber than in orbit. According to Reference 4, the Molesink chamber at Jet Propulsion Laboratories has a self-contamination coefficient of 4×10^{-4} for a diameter ratio of 10; this self-contamination, corresponding to a 500-km orbit (Figure 2), requires a wall capture coefficient of approximately 0.95.

In view of this discussion, the self-contamination produced in a vacuum chamber could be made similar to that in space if the wall capture coefficient could be adjusted in relation to the ratio of the chamber to spacecraft diameter. Obviously, this is neither practical nor possible for the simulation of high-altitude orbits. Consequently, in many cases the contamination in space cannot be reproduced in a vacuum chamber and must be inferred from test results.

Spacecraft self-contamination can be calculated from vacuum chamber results if the capture coefficient and ratio of diameters are known. Alternatively, the average ratio of the emitted and returned fluxes obtained with quartz crystal microbalances or tubulated ion gages will give the self-contamination directly. If this parameter is known, other measurements (e.g., emitted pressure, outgassed quantity per unit time, number of monolayers of contaminants, and the time of monolayer formation) in the chamber test can be related by simple ratio to the same quantities that will be obtained in space. For example, consider t_c to be the time required for a contaminant to form a layer of a certain thickness during chamber test; then, if C_S and ϕ''/ϕ_D are known, the time t_s required for the same accumulation in space (assuming identical temperature and rate of outgassing) will be

$$t_s = t_c \frac{C_S}{\phi''/\phi_D} \quad . \tag{13}$$

Furthermore, if the rate of condensation on a cold surface on the spacecraft is established during test, the equivalent rate in space will be

$$v_s = v_c \frac{\phi''/\phi_D}{C_S} \quad . \tag{14}$$

Other parameters (e.g., total contaminant deposition and outgassing rates) can be estimated. However, in projecting expected space results from chamber test results, one must take into account the effect of spacecraft rotation and the fact that the estimated contamination in space applies only to the frontal area of the spacecraft (i.e., the condensation region).

CONCLUSION

Molecules outgassed from the spacecraft in the direction of the velocity vector produce a concentration that diminishes with distance from the surface. The drop is a function of the altitude and the spacecraft radius: For a 100-km orbit, the outgassing concentration at a distance of 10-cm from the surface is diminished one order of magnitude; at 500 km, the decay to one order of magnitude occurs approximately 2 m from the surface.

Spacecraft self-contamination decreases rapidly with orbit altitude. The ratio of the returned to the emitted molecular flux varies from one-half at 160 to 170 km down to one-millionth or less at 1000 km and higher. On the other hand, self-contamination during vacuum chamber tests may be greater than or less than that in space, depending on chamber/spacecraft dimensions and chamber wall capture coefficient. Tests conducted in conventional vacuum chambers can provide returning contaminating fluxes comparable to those expected in space up to an altitude of about 400 km. For higher altitudes involving return fluxes less than 10^{-3} of those emitted, the chamber tests can produce a greater contamination than that in space.

Self-contamination in a vacuum chamber and in space can be related. The condensation rates and time of monolayer formation can be established, provided that the chamber capture coefficient is known or, better, if the returned and emitted fluxes are measured in the chamber. For both space and test conditions, self-contamination can be determined by measurement of the emitted and returned fluxes. Pressure measurements are not sensitive to the returning molecules and cannot indicate self-contamination.

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National Aeronautics and Space Administration
Greenbelt, Maryland, October 22, 1971
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