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DETERMINATION OF MOLECULAR CONTAMINATION PERFORMANCE FOR SPACE CHAMBER TESTS

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16. Abstract

The limitations of chamber tests with regard to the molecular contamination of a spacecraft undergoing vacuum test have been examined. The molecular flow conditions existing in the chamber and the parameters dictating the degree of contamination have been analyzed.

Equations and graphs have been developed to show the fraction of molecules returning to the spacecraft out of those emitted and to show other chamber flow parameters as a function of chamber and spacecraft surface molecular pumping and geometric configuration. Type and location of instruments required to measure the outgassing, the degree of contamination, and the returning flows are also discussed.

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INTRODUCTION

One characterization of vacuum chamber performance for the simulation of the environment of space is called permissiveness. This word was coined to describe the ability of the chamber to allow, as in space, only radiation heat transfer and to prevent the return of the outgassed molecules (ref. 1). These two characteristics of space are approximated by (1) providing a molecular density about the spacecraft sufficiently low that the probability of collisions between the molecules is extremely low and (2) having the chamber walls sufficiently cold to approximate the 4-K temperature of space. In the second case, the walls act also as a part of the pumping system. Restricting the discussion to the return of molecules to the spacecraft, although this is not divorced from the heat transfer problem, the reduction in molecular collision is obtained by evacuating until the mean free path of the gas molecules is in excess of the dimensions of the chamber. When this condition is met, the molecules should not interact with each other but will impinge on the chamber walls. At the walls they may be removed at the pumping system ports; immobilized by one of the surface effects, such as adsorption, condensation, or cryosorption; or they may be reflected with random directions back into the volume of the chamber. Some of these reflected molecules hit the spacecraft surfaces and may be retained; others will strike other parts of the walls, and the process is repeated. A measure of the chamber performance in the prevention of molecules returning to the spacecraft is given by the self-contamination coefficient defined as the ratio of the molecules returned and immobilized at the spacecraft to those outgassed from the spacecraft. This parameter is a function of the relative dimensions of the spacecraft and chamber; the location of the test object; the outgassing products and their temperatures; the temperature of the walls; the number, sizes, and nature of the pumping devices; and the natures of the surfaces involved. In the construction of space chambers the self-contamination has been minimized, and the prevention of contamination has been quite effective. In fact, testing of spacecraft in these chambers has been invaluable in detecting operational problems and in insuring excellent performance of these craft in space. Recently, however, with the installation on spacecraft of contamination-sensitive experiments and instruments, considerations of chamber self-contamination performance have become more important. It has become necessary to establish the degree of contamination experienced during testing and to relate this to the self-contamination possible in space. In space, contamination of critical surfaces has been experienced and it appears that one of the possible reasons is the self-contamination occurring because, at least within relatively low orbits, space is not completely permissive (ref. 2).

It is the intent here to examine the flow conditions in a vacuum chamber containing a spacecraft under test, to examine the parameters affecting the contamination of the spacecraft, and to arrive at a determination of the degree of contamination. The following analysis considers the type and location of the instrumentation and the parameters that are important for the evaluation of contamination. The present method of nude gage measurements as a characterization of the space simulation is discussed and shown to be inadequate for the evaluation of the contamination performance. Further equations and graphs have been developed to show the effect of each of the spacecraft chamber characteristics. These graphs permit the evaluation of the chamber contamination performance with a few chamber measurements.

MOLECULAR KINETICS IN A CHAMBER

If the mean free paths of the molecules outgassed from the test object in a chamber are shorter than the chamber dimensions, molecular collisions occur. A very large number of molecules having random velocities and directions produce a statistically uniform gas density. Under these conditions, Boltzmann-Maxwell statics and the ideal gas law are valid. The pressures and fluxes as a measure of the momentum and number of molecules moving per unit area are uniform at all locations and directions. This condition is still partially valid when the gas mean free path is larger than the chamber dimensions in a chamber with no cold walls and with small ratio of pump inlet-to-surface area. There, the molecules emitted by the test object are reflected from the walls and subsequently collide. These collisions provide the randomness in direction and magnitude of velocity that is necessary for the omnidirectionality of pressure and flux. In contrast, large space simulation chambers with cryogenic surface and large port areas immobilizing and removing molecules produce directional molecular fluxes. The molecules leave the test object directed to the wall and ports and the momentum and density are not statistically uniform in all the directions. Because the fluxes are not omnidirectional, density and pressure are no longer related. One cannot use the pressure measurements in the chamber as an indication of the molecular incidence rate on a surface anywhere in the chamber.

Further, because the molecular incidence rate on the surface of the spacecraft is the parameter determining the rate of contamination, its value must be established using flux measuring devices at the locations of interest or inferred from equivalent measurements. Quartz crystal microbalances are ideal for flux determination. Tubulated ionization gages properly oriented and used as impact gages can provide equivalent pressure measurements that can be related to the directional fluxes. The density within these tubulated gages will reach a level at which the efflux of the molecules from the probe opening is equal to the influx of the molecules from the environment. The molecular influx is given by the molecular flux incident on the probe opening and the pressure, as a measure of the density and temperature in the gage, is related to the directional flux. The gas law,

$$P = nkT \qquad \mathrm{N\ m^{-2}} \tag{1}$$

where n is the gas density, k is the Boltzmann constant, and T is the gas temperature, is valid for the conditions in the gage. The formula for flux (mass flow per unit area) is

$$\Phi = \frac{1}{4} nmc \qquad \mathrm{kg\ m^{-2}\ s^{-1}} \tag{2}$$

where $m = M/N$ is the mass of the molecule and c, the average molecular velocity, is determined by

$$c = \sqrt{\frac{8kT}{\pi m}} \qquad \text{m s}^{-1} \tag{3}$$

Combining these equations, the flux may be found in terms of the pressure and temperature of the gage:

$$\Phi = \left(\frac{m}{2\pi kT}\right)^{1/2} P \qquad \text{kg m}^{-2}\ \text{s}^{-1} \tag{4}$$

The pressure read by this gage can be used to describe the incoming gas and indicate an equivalent gas pressure. This pressure will not be the pressure in the thermodynamic sense as an isotropic property relating force per unit area and independent of the orientation of the area.

Molecular Mass Rates From Spacecraft and Chamber Walls

A spacecraft undergoing test in a space chamber under steady-state conditions outgasses a mass rate q_{mo} (measured in kilograms per second). If this mass is emitted uniformly from the surface A_m, the flux is

$$\Phi_{\text{mo}} = \frac{q_{\text{mo}}}{A_m} \qquad \text{kg m}^{-2}\ \text{s}^{-1}$$

The chamber walls, because of their outgassing or leakage, emit a mass rate q_{co} that may be produced by a uniform flux

$$\Phi_{\text{co}} = \frac{q_{\text{co}}}{A_c}$$

where A_c is the chamber internal surface. However, the total mass rates from the spacecraft q_m and from the chamber wall q_c include not only their own outgassing but also fractions of their outgassings that have been reflected and intercepted again. (See fig. 1.) The total rate from the spacecraft is

$$q_m = q_{\text{mo}} + (1 - \eta_m)Bq_c \tag{5}$$

The second term in the right of the equation represents the fraction of the total mass originating at the wall q_c that intercepts the spacecraft with probability B and is reflected by the spacecraft surface having a reflection coefficient $(1 - \eta_m)$. The coefficient η_m is the capture coefficient of the surface of the spacecraft for the gas. This and the capture coefficient of the chamber wall η_c will be discussed later. The probability B will also be defined.

The total mass rate leaving the chamber wall is

$$q_c = q_m(1 - \eta_c) + (1 - \eta_c)(1 - B)q_c + q_{\text{co}} \tag{6}$$

The first term on the right is the fraction of the total mass from the spacecraft reflected by the chamber walls. The second term represents the fraction of the total mass from the chamber walls that does not impinge on the spacecraft and does not stick on other areas of the chamber wall. The third term is the outgassing from the chamber walls.

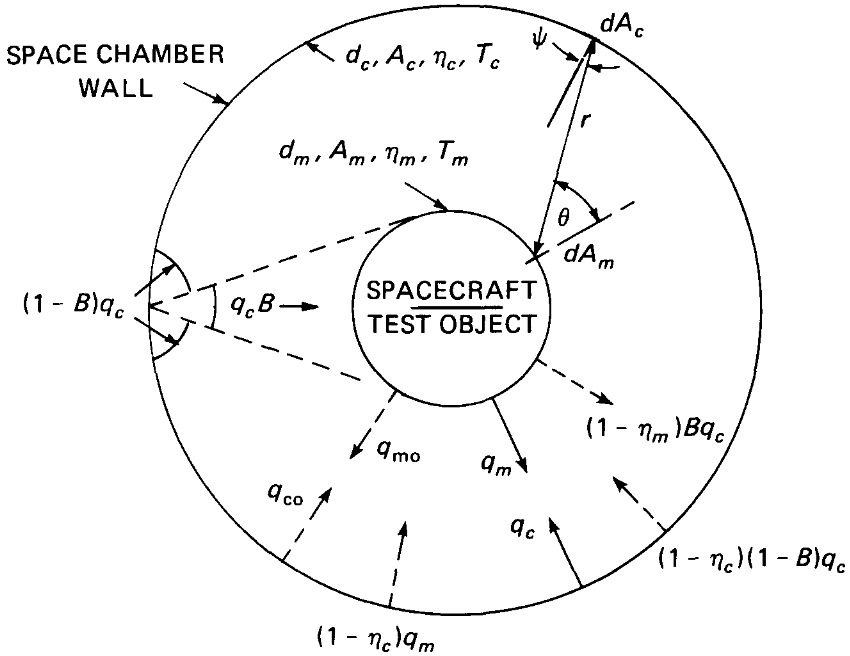

Figure 1.—Chamber geometry and assumed flows. (d_m = diameter of test object; T_m = surface temperature of test object; d_c = diameter of chamber; and T_c = wall temperature of chamber.)

The simultaneous solution of the two equations gives the following relations. The total mass rate from the spacecraft is

$$q_m = \frac{q_{mo}[1 + B(1 - \eta_c)/\eta_c] + q_{co}[(1 - \eta_m)/\eta_c]B}{1 + \eta_m B(1 - \eta_c)/\eta_c} \tag{7}$$

and the total mass rate from the chamber is

$$q_c = \frac{q_{mo}(1 - \eta_c)/\eta_c + q_{co}/\eta_c}{1 + \eta_m B(1 - \eta_c)/\eta_c} \tag{8}$$

These equations can be simplified further by introducing the dimensionless parameter

$$Z = \frac{1 - \eta_c}{\eta_c} B \tag{9}$$

which includes the capture coefficient of the chamber walls and the geometric factor B expressing the probability that the molecules randomly leaving the chamber will hit the spacecraft surface. As will be shown later, this parameter turns out to be the number of times a molecule emitted from the spacecraft will return to it, or the ratio of the mass returned to the vehicle out of the total outgassing when the outgassing or leakage from the chamber and the capture coefficient of the vehicle are both zero.

The two previous equations with this parameter reduce to

$$q_m = \frac{q_{\mathrm{mo}}(1 + Z) + q_{\mathrm{co}}[(1 - \eta_m)/\eta_c]B}{1 + \eta_m Z} \tag{10}$$

and

$$q_c = \frac{q_{\mathrm{mo}}Z/B + q_{\mathrm{co}}/\eta_c}{1 + \eta_m Z} \tag{11}$$

Ratio of Mass Rates, Fluxes, and Pressures

The ratio of the mass rate leaving the wall to the mass rate leaving the spacecraft is given by

$$\frac{q_c}{q_m} = \frac{Z/B + q_{\mathrm{co}}/q_{\mathrm{mo}}\eta_c}{1 + Z + (q_{\mathrm{co}}/q_{\mathrm{mo}})[(1 - \eta_m)/\eta_c]B} \tag{12}$$

Because $q_c = \Phi_c A_c$ and $q_m = \Phi_m A_m$, where Φ is the flux or mass rate per unit area with the restrictions indicated previously regarding the meaning of the pressure, the following relations obtained from equation (4) can also be used:

$$\frac{\Phi_c}{\Phi_m} = \frac{P_c}{P_m}\sqrt{\frac{T_m}{T_c}}$$

$$= \frac{q_c}{q_m}\,\frac{A_m}{A_c} \tag{13}$$

(The subscripts have the same meaning as before; i.e., *c* for chamber and *m* for spacecraft.)

Spacecraft Outgassing in Terms of the Mass Rates From the Spacecraft and the Chamber

The outgassing rate from a spacecraft can be determined from the measurement of the total mass flow q_m originating at the spacecraft and a knowledge of the chamber outgassing q_{co}, the capture coefficients η_m and η_c, and configuration probability B. From the relation for q_m, one obtains

$$q_{\mathrm{mo}} = q_m\left(1 + \eta_m Z - \frac{q_{\mathrm{co}}}{q_m}\,\frac{1 - \eta_m}{\eta_c}B\right)\frac{1}{1 + Z} \tag{14}$$

This may also be obtained by measurement of the total mass flow q_c from the chamber wall:

$$q_{\mathrm{mo}} = q_c\frac{B}{Z}\left(1 + \eta_m Z - \frac{q_{\mathrm{co}}}{q_c\eta_c}\right) \tag{15}$$

Again these relations can be transformed into fluxes or equivalent pressures. It should be noted that the two equations include the total outgassing mass of the chamber walls. This can be determined provided Z, B, and η_m are known for the system by making simultaneous readings of q_m and q_c.

More simply, q_c should be established independently; one method would be by measuring the rate of pressure rise when the chamber is empty and secured. However, the outgassing or leakage from the chamber should be negligible under cryogenic wall conditions and that term in the equations can be neglected. This would not be true during warming of chamber walls when evaporation of condensation from the walls occurs.

SELF-CONTAMINATION PERFORMANCE PARAMETERS

As a measure of the self-contamination in a chamber, several parameters may be defined (refs. 1 and 3 to 5). C_s indicates the ratio of the mass rate impinging and absorbed by the spacecraft to the spacecraft total outgassing. For $q_{co} = 0$,

$$C_s = \frac{q_c B \eta_m}{q_{mo}}$$

$$= \frac{Z\eta_m}{1 + \eta_m Z} \tag{16}$$

Another parameter similar to C_s is the ratio of the mass rate returned to the spacecraft to its outgassing rate; i.e.,

$$\alpha = \frac{q_c B}{q_{mo}}$$

$$= \frac{q_m - q_{mo}}{q_{mo}}$$

$$= \frac{Z}{1 + \eta_m Z} \tag{17}$$

Both relations are obtained from previous equations properly modified. The parameter α is equal to C_s/η_m. Other important parameters will result from these equations when simplifications and substitutions are performed.

C_s and α are shown in table 1 together with other relations obtained by parametric variations of the controlling coefficients. Before these are discussed, however, the capture coefficients η_m and η_c and the configuration probability B will be discussed.

Configuration Factor

The configuration factor B represents the probability that molecules departing the chamber walls according to the cosine law strike the spacecraft. The factor, analogous to the energy interchange factor in radiant energy transfer, accounts for the geometric relationship between surfaces. The configuration factor between two elements of areas dA_c and dA_m separated by a distance r is

$$B_{A_c \to A_m} = \frac{1}{A_c} \int_{A_c} \int_{A_m} \frac{\cos\theta \cos\psi}{\pi r^2} \, dA_c \, dA_m \tag{18}$$

The calculation of this double integral can be performed in closed form for several simple geometric arrangements; tables listing these values are available (refs. 6 and 7). Computer programs using finite differences, contour integrals, and combinations of these two techniques are available and provide numerical values for all practical geometric arrangements (ref. 8). The reciprocity theorem relating the configuration factor from one area to the other is very helpful in these calculations. It states that

$$B_{A_c \to A_m} A_c = B_{A_m \to A_c} A_m \tag{19}$$

The configuration factor B for the probability of molecules from a larger sphere (diameter d_c) impinging on a concentric smaller sphere (diameter d_m) is $B = d_m^2 / d_c^2$. For two infinite concentric cylinders of diameters d_c for the larger and d_m for the smaller, $B = d_m / d_c$; and for two parallel infinite planes, $B = 1$.

Capture Coefficient

The capture coefficient indicates the fraction of the mass removed by a surface to the mass that has impinged on the surface. The gas may be removed by pumps and by a combination of molecular condensation, adsorption, and entrapment on the surface. Molecular condensation is obtained when the vapor pressure of the condensed gas at the temperature of the surface is less than the gas phase pressure. In general, chamber walls are maintained at liquid nitrogen temperatures (77 K), gaseous helium temperature (20 K), and a combination of these two. In the case of two temperatures, the colder surfaces at 20 K are shielded in a variety of ways by warmer walls (77 K) (ref. 3). This arrangement approaches the condition of space to simulate radiation heat transfer and provide sufficient cold surface for condensation of most of the gases emitted by the spacecraft, and is economically acceptable. In some cases, cryosorption employing cryopumping of condensables and cryosorption of noncondensables is obtained with liquid-helium-cooled molecular sieve materials. Surface adsorption exists when the surface exposed to the gas is at temperatures precluding condensation; i.e., the vapor pressure of the gas corresponding to the surface temperature is higher than the gas partial pressure. In this case, a few monolayers of gas are held on the surface by physical forces of intermolecular nature. Other methods of removing gases at surfaces exist but are not of general applicability in large space simulation vacuum chambers. The capture coefficient of the chamber walls η_c can be described as the sum of the capture coefficients provided by the pumps η_p and the cold walls η_{cryo}. Each is the ratio of the removed mass to the impinging mass (flux times area). The mass removed by the pumping system is a function of the pumping port, the temperature and nature of the gas, and the pump type. This mass will be $\Phi_m A_p \delta$ where Φ_m is the flux impinging, A_p is the pumping port area, and δ is a coefficient accounting for the geometry of the pumping port and the pump limitations. The pump capture coefficient then will be

$$\eta_p = \frac{\Phi_m A_p \delta}{\Phi_m A_c} = \frac{\delta A_p}{A_c} \tag{20}$$

where A_c is the total surface area of the chamber. For a small chamber this coefficient is generally less than 0.1; for larger chambers it is generally less than 0.01 (ref. 9). The condensation mass on the cold surface A_r can be expressed as the difference between the impinging and evaporated masses modified by a condensation coefficient β. If the gas has a pressure P and temperature T and its saturated pressure is P_s at the temperature T_s of the surface, the condensed gas will be

$$\beta(\Phi_m - \Phi_e)A_r = \beta A_r \Phi_m \left(1 - \frac{P_s}{P}\sqrt{\frac{T}{T_s}}\right) \tag{21}$$

where Φ_e is the evaporated flux. In addition, a factor γ must be included in equation (21) to account for the geometric arrangement, hence reflecting the probability that a molecule actually reaches the surface on which condensation occurs. The capture coefficient for the condensation can then be expressed as

$$\eta_{\text{cryo}} = \frac{\beta\gamma\Phi_m\,[1 - (P_s/P)\sqrt{T/T_s}]\,A_r}{\Phi_m A_c}$$

$$= \beta\gamma \left(1 - \frac{P_s}{P}\sqrt{\frac{T}{T_s}}\right)\frac{A_r}{A_c} \tag{22}$$

where A_c is the chamber internal shroud area.

The coefficient of condensation β for gases at about 300 K ranges from about 0.6 to 0.95 for condensation on surfaces at temperatures between 9.5 and 77 K (refs. 10 to 14). The geometric coefficient γ is dependent on the design of the array. In many cases this can be approximated using the various closed-form solutions for orifices and pipes. Statistical methods such as the Monte Carlo method have been used or can be used to evaluate the probability of molecules reaching the cold surfaces (ref. 15). That portion of equation (22) within parentheses approaches 1 if the vapor pressure is an order of magnitude lower than P corresponding to the case of no reevaporation. Finally, the ratio A_r/A_c cannot be greater than 1 in equation (22); but by providing several surfaces from which molecules noncondensed on first impact can rebound, the energy of the molecules is reduced and can be subsequently trapped. In effect, because of multiple reflections, this provides an improvement on the coefficient of condensation β. The total capture coefficient for a chamber wall reflecting the various parameters discussed is therefore the sum of the two capture coefficients η_p and η_{cryo}; i.e.,

$$\eta_c = \delta\frac{A_p}{A_c} + \beta\gamma\left(1 - \frac{P_s}{P}\sqrt{\frac{T}{T_s}}\right)\frac{A_r}{A_c} \tag{23}$$

The first term varies from 0.01 to 0.1 as mentioned. The second term has been calculated using the Monte Carlo method for three configurations of radiation-shielded cryopump geometries normally employed in chamber design. Its value when β and the term in parentheses are equal to 1 varies from 0.25 to 0.45 (refs. 3 and 16). The shielding surfaces protecting against heat loads from inside and outside the chamber are usually near 100 K. The cryopump surfaces are at 20 K. If a design does not include shields or baffles, the second term reduces to the condensation coefficient β; and when $P_s \ll P$, the capture is quite effective for the condensable gases.

In summary, the following generalizations are made about the capture coefficients of space chambers:

1. The coefficient, when no refrigeration is provided, is less than 0.1 for small chambers, less than 0.01 for large chambers, and is about 0.8 for unshielded cryopumping surfaces.
2. Special unshielded chambers with special geometric surface configurations (Jet Propulsion Laboratory Molsink) have been reported (ref. 9) to have a capture coefficient approaching 0.98.
3. The coefficient for molecules condensing on 20-K surfaces (noncondensable) is about 0.3 when these surfaces are shielded by surfaces at temperatures near 100 K.

The capture coefficient η_m of the object under test will be a function of the temperature, nature of its surface, and the nature and temperature of the gas. If the surface is at room temperature ($\approx$293 K), the coefficient may be quite small and little adsorption may occur. Cold surfaces, of course, will have a capture coefficient dictated by the condensation coefficient and the evaporation effect.

Vacuum Chamber Parameters

Table 1 shows the various relations for chamber flows in terms of the coefficient Z, the capture coefficient of the test item η_m, and geometric configuration B. The parameter Z includes the chamber capture coefficient η_c and B. The equations are in dimensionless form and relate the mass flow from chamber and spacecraft to the outgassing of the spacecraft and chamber. In addition, the performance parameters of contamination C_s and α are shown in the tabulation.

Two major groupings for these relations are shown in table 1: one includes the leakage and/or outgassing from the chamber walls (i.e., $q_{co} \neq 0$) and the other is for $q_{co} = 0$. For the case of $q_{co} = 0$, the parameters have been also evaluated for the limiting conditions of $\eta_c = 1$, $\eta_c = 0$, $\eta_m = 1$, and $\eta_m = 0$ and for the combinations of $\eta_c = 1$ and $\eta_c = 0$ each for both $\eta_m = 1$ and $\eta_m = 0$. For the case of $q_{co} \neq 0$, the spacecraft would experience a chamber-induced contamination in addition to self-contamination. The degree of induced contamination would be in direct proportion to the amount of chamber wall leak, which either should not exist or should be a very negligible amount if the chamber is performing as intended. It is expected that the chamber has been checked for leaks and properly degassed prior to each test. But, if leaks from the walls, backflow from the pumps, or wall outgassing should exist during a test, the values of q_m and q_c would be higher than expected, with a corresponding indication of high self-contamination and poor chamber performance.

Parameters for the Case $q_{co} = 0$

The parameter that appears in all of the relations describing the contamination performance in a space chamber is Z. (See eq. (9).) As shown in table 1, Z represents the attenuation or amplification factor to be applied to the spacecraft outgassing to obtain the amount of outgassed material returning to the spacecraft when no other source of gas exists in the system (i.e., $q_{co} = 0$), and the capture coefficient of the spacecraft η_m is equal to zero. Also for this case, Z can be interpreted as being the number of times a molecule emitted by the spacecraft impinges on it before it is removed by the

Table 1.—Kinetics in a Space Chamber

Parameter	General relation	$q_{co} = 0$								
		$\eta_c \neq 0, \eta_m \neq 0$	$\eta_c = 1$	$\eta_c = 0$	$\eta_m = 1$	$\eta_m = 0$	$\eta_c = 1$		$\eta_c = 0$	
							$\eta_m = 1$	$\eta_m = 0$	$\eta_m = 1$	$\eta_m = 0$[a]
Z	$\frac{B(1-\eta_c)}{\eta_c}$	$\frac{B(1-\eta_c)}{\eta_c}$	0	∞	$\frac{B(1-\eta_c)}{\eta_c}$	$\frac{B(1-\eta_c)}{\eta_c}$	0	0	∞	∞
q_c	$\frac{q_{mo}Z/B + q_{co}/\eta_c}{1+\eta_m Z}$	$\frac{q_{mo}Z}{B(1+\eta_m Z)}$	0	$\frac{q_{mo}}{B\eta_m}$	$\frac{q_{mo}}{B}\frac{Z}{1+Z}$	$\frac{q_{mo}Z}{B}$	0	0	$\frac{q_{mo}}{B}$	∞
q_m	$\frac{q_{mo}(1+Z) + q_{co}B(1-\eta_m)/\eta_c}{1+\eta_m Z}$	$\frac{q_{mo}(1+Z)}{1+\eta_m Z}$	q_{mo}	$\frac{q_{mo}}{\eta_m}$	q_{mo}	$q_{mo}(1+Z)$	q_{mo}	q_{mo}	q_{mo}	∞
$\frac{q_c}{q_m}$	$\frac{Z/B + q_{co}/q_{mo}\eta_c}{1+Z+(q_{co}/q_{mo})[(1-\eta_m)/\eta_c]B}$	$\frac{Z}{B(1+Z)}$	0	$\frac{1}{B}$	$\frac{Z}{B(1+Z)}$	$\frac{Z}{B(1+Z)}$	0	0	$\frac{1}{B}$	$\frac{1}{B}$
$\frac{q_c}{q_{mo}}$	$\frac{Z}{B(1+\eta_m Z - q_{co}/q_c\eta_c)}$	$\frac{Z}{B(1+\eta_m Z)}$	0	$\frac{1}{B\eta_m}$	$\frac{Z}{B(1+Z)}$	$\frac{Z}{B}$	0	0	$\frac{1}{B}$	∞
$\frac{q_m}{q_{mo}}$	$\frac{1+Z}{1+\eta_m Z - (Bq_{co}/q_m)(1-\eta_m)/\eta_c}$	$\frac{1+Z}{1+\eta_m Z}$	1	$\frac{1}{\eta_m}$	1	$1+Z$	1	1	1	∞
$\alpha = \frac{q_c B}{q_{mo}}$	$\frac{Z + (q_{co}/q_{mo})(B/\eta_c)}{1+\eta_m Z}$	$\frac{Z}{1+\eta_m Z}$	0	$\frac{1}{\eta_m}$	$\frac{Z}{1+Z}$	Z	0	0	1	∞
$C_s = \alpha\eta_m$	$\frac{Z\eta_m + (q_{co}/q_{mo})(\eta_m/\eta_c)B}{1+\eta_m Z}$	$\frac{Z\eta_m}{1+\eta_m Z}$	0	1	$\frac{Z}{1+Z}$	0	0	0	1	0
$\frac{P_e}{P_m}$	$\frac{1}{2}\left(1+\frac{A_m}{A_c}\sqrt{\frac{T_c}{T_m}}\frac{\alpha}{B}\right)$	$\frac{1}{2}\left(1+\frac{A_m}{A_c B}\sqrt{\frac{T_c}{T_m}}\frac{Z}{1+Z}\right)$	$\frac{1}{2}$	$\frac{1}{2}\left(1+\frac{A_m}{A_c}\sqrt{\frac{T_c}{T_m}}\frac{1}{B}\right)$	$\frac{1}{2}\left[1+\frac{A_m}{A_c}\sqrt{\frac{T_c}{T_m}}\frac{Z}{B(1+Z)}\right]$	$\frac{1}{2}\left[1+\frac{A_m}{A_c}\sqrt{\frac{T_c}{T_m}}\frac{Z}{(1+Z)B}\right]$	$\frac{1}{2}$	$\frac{1}{2}$	[b]1	∞

[a] This condition is not real because it implies no sink, only a source in the chamber.

[b] If $1/B = A_m/A_c$ (concentric spheres) and $T_c \approx T_m$.

chamber sink. Figure 2 has been plotted to show the variation of Z with the geometric factors B and η_c. The figure and table 1 indicate that for η_c approaching zero, Z approaches infinity; whereas if η_c approaches one, Z tends to zero. The condition of $\eta_c = 0$ implies no pumping in the chamber; consequently, with the presence of a gas source, a steady increase in chamber pressure would exist. It is apparent from the figure that for a chamber with small η_c, and for many of the usual chamber spacecraft arrangements as embodied in parameter B, Z will be greater than 1. That is, the molecules will return more than once to the spacecraft before they are removed. The determination of Z can be made by measuring at the spacecraft surface the fluxes from the chamber walls and the spacecraft. This is discussed later.

The general expression for the fraction of the outgassing molecules returning to the spacecraft α is given by equation (17). If the object capture coefficient equals zero, for example, when its surfaces are at relatively high temperatures, $\alpha = Z$. The product $q_c B$ is the fraction of gas from the chamber wall that impinges on the test object. This is the total amount of the outgassing q_{mo} that may contaminate the object under test. Figure 3 has been plotted to show the effect of the test object capture coefficient η_m upon α as a function of the chamber object characteristic Z. It shows that α is not sensitive to η_m for values of $Z < 1$. Large values of η_m reduce the amount returned to the object when $Z > 1$. If the object is also a perfect sink ($\eta_m = 1$) and Z approaches infinity ($\eta_c = 0$), whatever emerges from the object is reacquired by it. For $Z < 10$, not all of the emitted gas is reacquired by the object. The measurement of the coefficient α is obtained by taking the ratio of the fluxes to and from the object near the object surface where any molecules from the chamber walls will surely impinge on the object.

The fraction of the spacecraft outgassing that returns to and is immobilized on the spacecraft is the self-contamination coefficient C_s given by equation (16). It is the product of the previous parameter α and the capture coefficient of the object. There will be no contamination if $\eta_m = 0$ and/or $Z = 0$ ($\eta_c = 1$). If $\eta_m = 1$, then

$$C_s = \alpha = \frac{Z}{Z+1}$$

Figure 4 shows C_s as a function of Z and η_m. This figure, as the previous one for α, shows that for small values of Z and/or η_m, the self-contamination $C_s \approx \eta_m Z$. At small values of Z, the nonlinearity of the functions for α and C_s is no longer strong. The determination of the self-contamination can be made by measuring the rate of condensation on the surface of the spacecraft and by measurement of the outgassing flux emitted by the spacecraft. As will be apparent later, the flux originating from the spacecraft is the outgassing source only when the simulation is good; i.e., when Z is small; otherwise, it includes also a portion of the flux reflected from the walls. The measurement of C_s would be appropriate when, for example, the spacecraft included a cold surface such as a radiation cooler on which condensation could easily occur.

Under steady-state conditions, the mass rate from the test object q_m is greater than the outgassing rate q_{mo}. The relation between these is obtained from equation (7). The ratio q_{mo}/q_m is plotted in figure 5 as a function of characteristic Z and capture coefficient η_m. The outgassing quantity may be a large fraction of the measured quantity q_m from the spacecraft when Z is large and the capture coefficient η_m is less than 1. Conversely, if $\eta_m = 1$ and/or Z is small, the two quantities coincide.

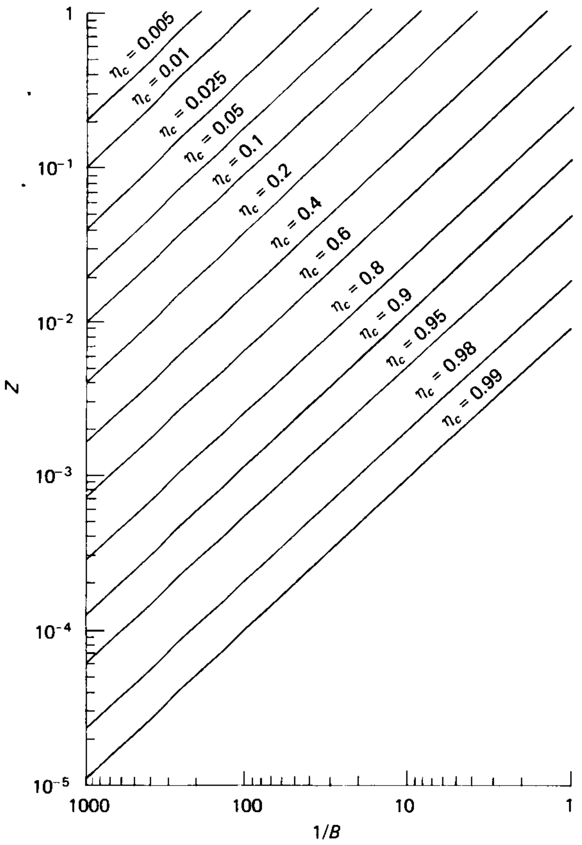

Figure 2.—Variation of Z as a function of B and η_c.

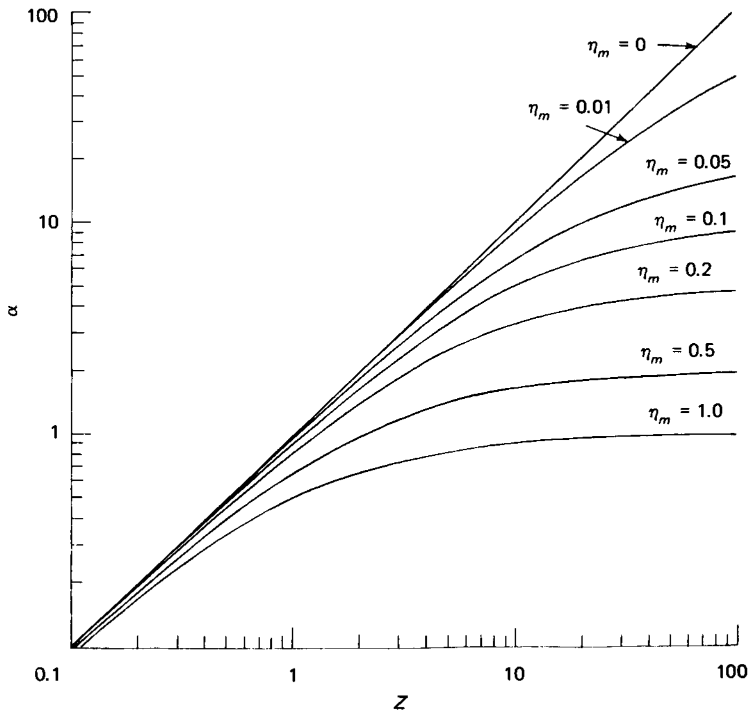

Figure 3.—The effect of variation of η_m on α.

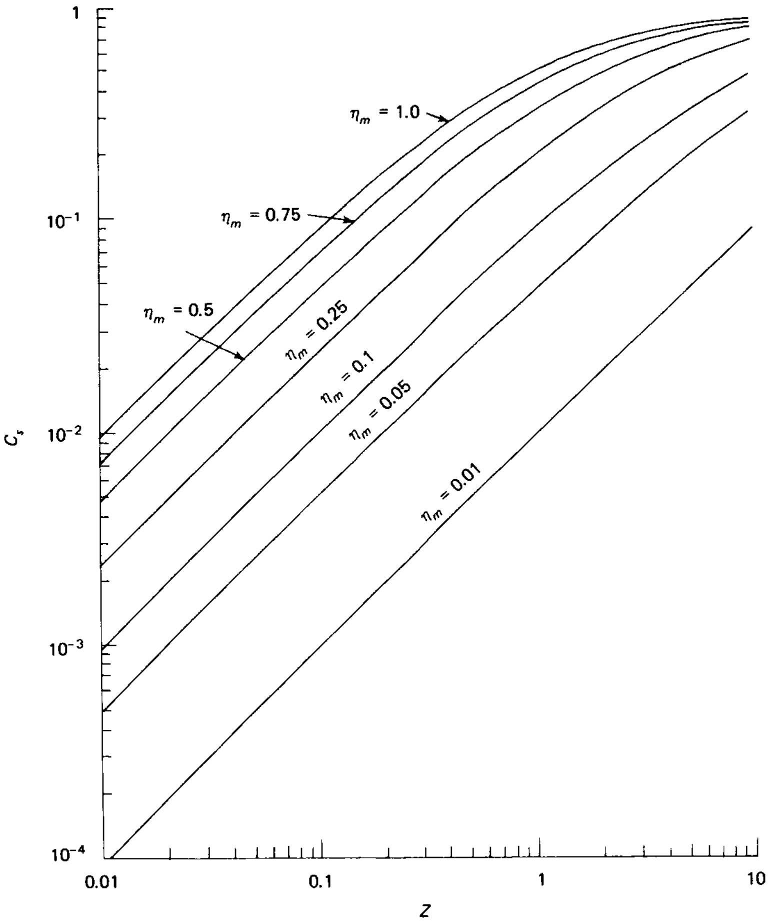

Figure 4.—C_s as a function of Z and η_m.

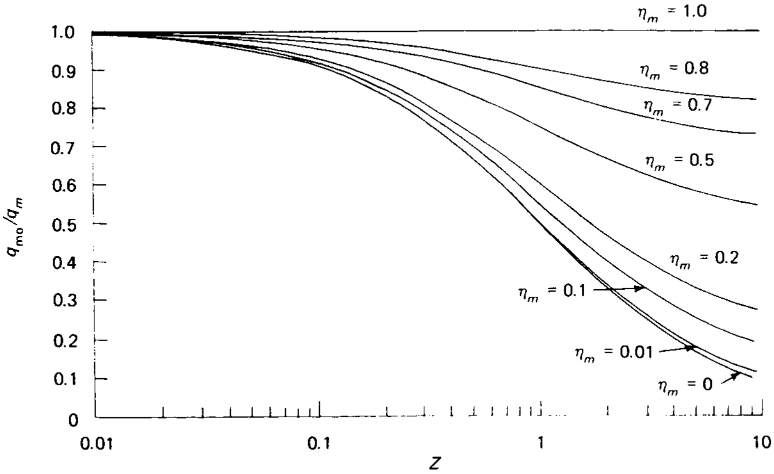

Figure 5.—q_{mo}/q_m as a function of Z and η_m.

The outgassing q_{mo} in terms of the flow at the chamber walls q_c directed to the spacecraft is obtained from equation (15). If the return flow is measured at the spacecraft surface, it would be q_cB. In that case the ratio of the returned to outgassed flow would reduce to the parameter $\alpha = q_cB/q_{\mathrm{mo}}$. Furthermore, the two expressions for q_m and q_c as a function of q_{mo} reduce to

$$q_m = (1 + Z)q_{\mathrm{mo}}$$

and

$$q_cB = Zq_{\mathrm{mo}}$$

when $\eta_m = 0$. The mass flow at the chamber wall q_c directed to the interior of the chamber is related to the flow leaving the spacecraft q_m by the relation derived from equation (12) for $q_{\mathrm{co}} = 0$.

The ratio q_c/q_m is independent of η_m and depends only on the geometry and the pumping characteristics of the chamber. A plot of this relation is shown in figure 6. It shows that better simulation (small q_c/q_m) is obtained when the chamber is large relative to the testing object and Z is small ($\eta_c \to 1$). The ratio, which can be expressed as a flux or equivalent pressure ratio, may be greater

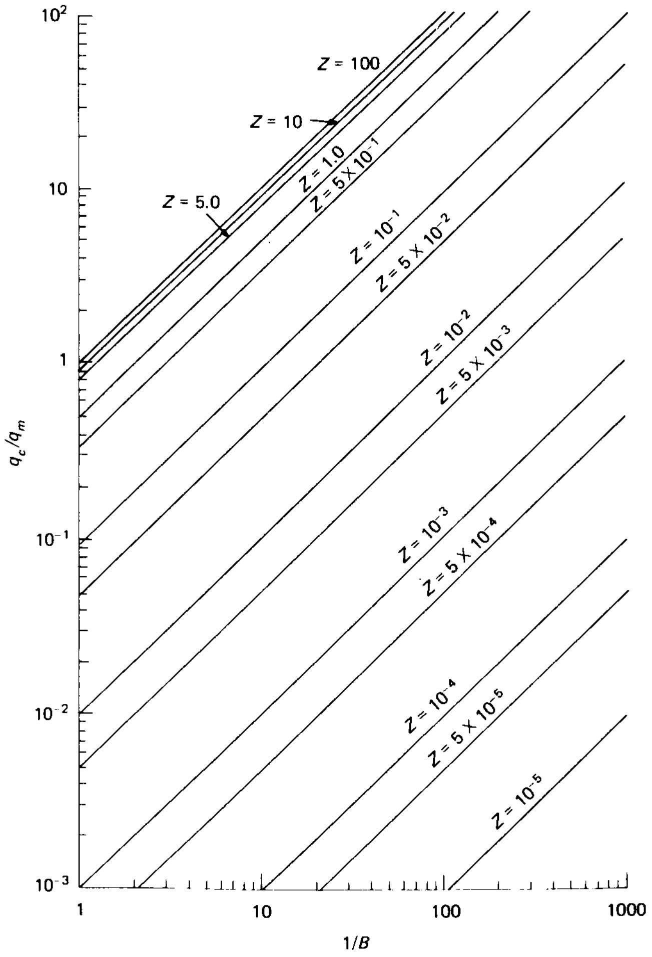

Figure 6.—q_c/q_m as a function of B and Z.

than 1 for many of the values of $1/B$ when $Z > 0.001$; i.e., for most of the values of η_c. This is to be expected because q_c includes not only what goes to the spacecraft but also quantities going to other parts of the chamber walls. The measurement of q_c at the walls and q_m at the spacecraft will not permit the determination of the contamination performance parameters unless the configuration factor B is known. If the return flux is measured at the spacecraft, as mentioned before, one would be reading q_cB, and the expression for the return to the emitted ratio would be equal to $Z/(1 + Z)$. Consequently, measuring both leaving and returning quantities at the spacecraft surface permits the determination of Z.

NUDE GAGE PRESSURE MEASUREMENTS IN THE CHAMBER

The pressure obtained with a nude ionization gage in a space chamber is not very sensitive to the direction of the existing flows and cannot indicate the degree of self-contamination simulation. The gage will measure an equivalent pressure produced by the flux densities at the location of measurement and a variation of flux in one of the directions is not apparent with this type of measurement. The gage, however, does indicate the existing degree of gas density, which is a parameter of importance for other simulation effects: gas conduction, voltage breakdown, surface material effects, evaporation, etc. The equivalent pressure read by a nude gage in a space chamber can be estimated by the following method. The density n (per cubic meter) between the walls and the test object should be probably an average of the densities produced by the molecules originating from the two directions (ref. 17); i.e.,

$$n = \frac{n_m + n_c}{2} \tag{24}$$

Also the temperature of the ensemble of molecules should be a weighted average of the object and walls; i.e.,

$$T = (T_m n_m + T_c n_c) \frac{1}{2n} \tag{25}$$

The equivalent pressure from the gas law is then

$$\begin{aligned} P_e &= nkT \\ &= \frac{k}{2}(n_m T_m + n_c T_c) \\ &= \frac{1}{2}(P_m + P_c) \end{aligned} \tag{26}$$

Because

$$\frac{P_c}{P_m} = \frac{q_c A_m}{q_m A_c} \sqrt{\frac{T_c}{T_m}}$$

equation (26) can be expressed in any of the forms for q_c/q_m indicated in table 1; therefore,

$$\frac{P_e}{P_m} = \frac{1}{2}\left(1 + \frac{A_m}{A_c}\sqrt{\frac{T_c}{T_m}}\,\frac{q_c}{q_m}\right)$$

$$= \frac{1}{2}\left[1 + \frac{A_m}{A_c}\sqrt{\frac{T_c}{T_m}}\,\frac{Z}{B(1+Z)}\right] \tag{27}$$

Additional substitutions for the ratio are $q_c/q_m \approx \alpha/B = C_s/\eta_m B$ when Z is small; i.e., when $q_m \approx q_{\mathrm{mo}}$.

Table 1 shows that the equivalent pressure varies from one-half the effusive pressure P_m at the surface of the object to a fixed value when $\eta_c = 0$ and $\eta_m = 1$. The fixed value becomes 1 if $B = A_m/A_c$, as for concentric spheres, and $T_c/T_m = 1$. On the other end, if $\eta_m = 0$, the pressure is one-half the effusive pressure when $\eta_c = 1.0$ and infinity when $\eta_c = 0$. Infinite pressure is not real because for those conditions ($\eta_m = 0$ and $\eta_c = 0$) there would be no sink in the system, only a source of gas.

To show the insensitivity of this gage to improved conditions of self-contamination in the chamber (small Z, C_s, and α), figure 7 has been plotted. The plot shows the pressure ratio as a function of the several indicators of self-contamination performance and of the wall object temperature ratio. The figure indicates that the pressure ratio will hardly change for values below 0.2 on the abcissa.

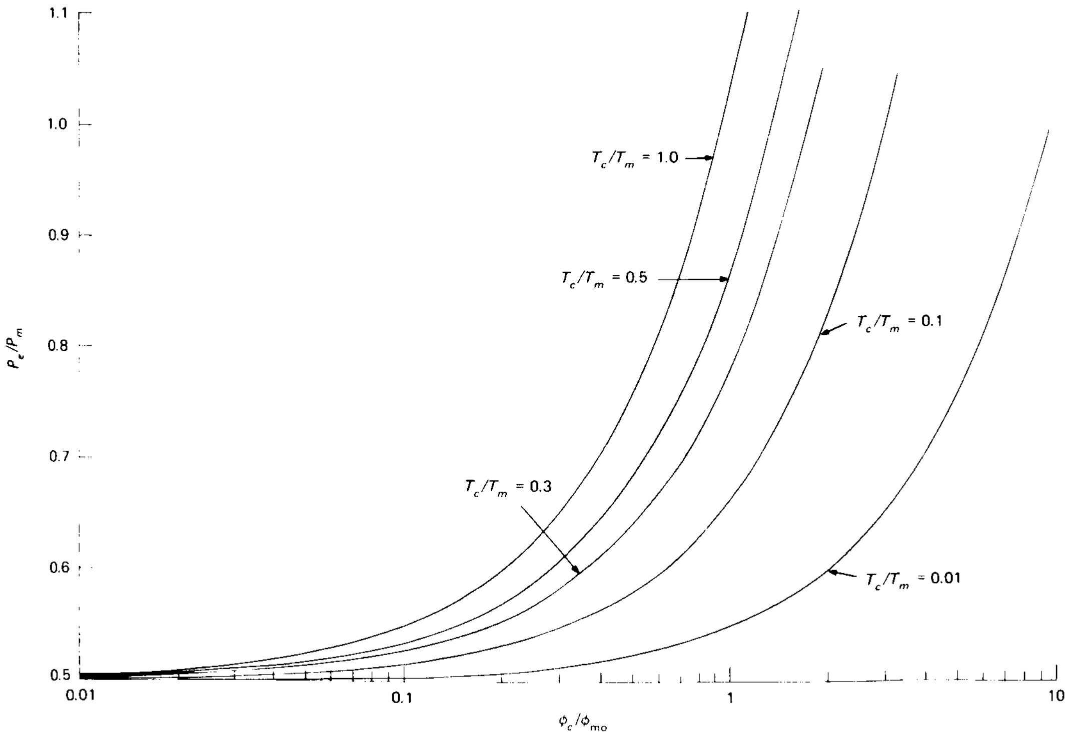

Figure 7.—Pressure ratio as a function of flux and temperature ratios.

The limiting value of $P_e = \frac{1}{2}P_m$ represents the intermediate pressure between the pressure at the spacecraft and the zero pressure at the walls. The assumption about density is open to question for geometries other than two parallel planes (ref. 17), but it should not be too much in error. The same result for parallel planes can be obtained by integrating for $u < 0$ and $u > 0$ the Boltzmann-Maxwell distribution function of a gas with velocity components **u**, **v**, and **w**.

CONCLUSIONS

The sink of space is not always reproduced during test of a spacecraft in a thermal vacuum simulation chamber. The limitations in size, wall temperatures, and pumping devices preclude a simulation corresponding in all cases to the property of space to diffuse, according to the orbiting altitudes, the molecules emitted by the spacecraft. The result is that during simulation tests molecules from the spacecraft are reflected by the chamber walls back to the spacecraft where they may contaminate critical surfaces. This deficiency of the chamber tests was recognized some time ago and methods to increase to a maximum the molecular sink ability of the chamber were included in some special chambers. A number of recent papers by the author shows that return of outgassed molecules in a chamber may or may not be more than in space. This depends on the contamination performance of the chamber with respect to the orbiting altitude of the spacecraft under test. In recent years, spacecraft carrying contamination-sensitive instruments and surfaces have required a strict control in the prevention of contamination at all levels on the ground and in space. In this paper, the limitations of vacuum chambers in regard to self-contamination have been explored to understand the various parameters, the flow kinetics, and the methods of measurements necessary to establish the contamination performance. Ultimately, the results of contamination obtained in a test must be related to the conditions to be expected in space and the extent of contamination damage that may result.

The properties of the chamber that control the return of the molecules to the object under test are the capture coefficient of the chamber and the geometric configuration factor between chamber and test object walls. These coefficients are grouped in a single parameter Z whose value may vary from zero to infinity. The minimum value corresponds to perfect pumping of the chamber, which results when the capture coefficient is 1. The maximum is when no pumping occurs. The pumping ability is improved when the chamber has a large number of pumps, an unrestricted passage to the very cold surfaces existing at the chamber walls, and the test object offers a small surface area in comparison to the chamber walls.

The number of molecules returning to the spacecraft compared with the number emitted by it, or the number of times a molecule emitted returns to the spacecraft before it is pumped out of the chamber, is designated by α and is a function of the parameter Z. This ratio α, which establishes the probable contamination of the spacecraft, becomes Z when $Z < 1.0$.

The actual self-contamination C_s, defined as the ratio of the molecules impinging and immobilized at the spacecraft to those outgassed by it, is the product of α and the capture coefficient of the spacecraft surface. Little contamination occurs when Z and the capture coefficient approach zero. The capture coefficient approaches zero if the spacecraft surface is at a high temperature with respect to molecules striking the surface.

In regard to molecular fluxes existing during testing, there are two main directional flows: one originating from the spacecraft and directed to the walls and another directed in the opposite direction. The flux from the spacecraft is greater than the flux due to its outgassing. The quantity of gas leaving the walls is greater than the quantity impinging on the spacecraft. Flows in a chamber can be related to each other by simple transfer functions. The outgassing source q_{mo} is attenuated by $1/(\eta_m Z + 1)$ and amplified by Z to give the return flow at the chamber walls, by Z/B to give the return at the spacecraft surface, and by $Z + 1$ to give the actual flow from the spacecraft q_m. The flow from the spacecraft q_m used as source or input is attenuated by $1/(1 + Z)$ and amplified by the same gains as above to give the return flows.

Chamber spacecraft contamination performance parameters Z and α can be established during a vacuum test by the simultaneous measurements with flux measuring devices, such as quartz crystal microbalances or tubulated ion gages, of the fluxes leaving and returning at several angular and longitudinal positions in the vicinity of the spacecraft. The measurement of the return flux at the chamber walls would require the knowledge of the configuration factor B for the determination of α and Z.

The self-contamination C_s can be determined by comparison of actual contamination on a critical surface, either existing or installed on the spacecraft surface, to the flux emitted by the spacecraft. The installation of a cold finger at the chamber walls to collect material from the spacecraft and chamber will not indicate the degree of self-contamination. Cold fingers facing opposite directions could be used to establish total contamination for the test period and the chemical composition of the gases in the system. Mass spectrometers arranged in the same manner would provide the double function of measuring the fluxes and identifying the materials.

The contamination parameter Z or α can be established in advance for a test if, from previous tests, the equivalent capture coefficient for a pump setup at a particular wall is known and the configuration factor can be estimated by computation. However, the degree of possible contamination can only be established by measuring one of the fluxes in the chamber.

Nude ionization gages in a chamber will not identify the degree of contamination performance of the chamber.

The deterioration of a surface or a malfunction due to return flow during test can be related to the occurrence or nonoccurrence of these conditions in space using the α or Z parameter in conjunction with a similar parameter estimated for space conditions (ref. 18).

In conclusion, the limitations of chamber tests with regard to molecular contamination have been examined. The parameters controlling the contamination have been considered in order to provide a clearer understanding of the contamination that may occur during chamber testing. A dimensionless parameter embodying geometry and pumping ability of the chamber describing potential contamination during test can be determined by appropriate in-chamber measurements. The equations and the graphs show the flow relations and lead to an understanding of the conditions existing in the chamber.

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