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GAS FLOW ANALYSIS DURING THERMAL VACUUM TEST OF A SPACECRAFT

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16. Abstract

The self-contamination of the IMP-H spacecraft, while it was undergoing thermal and solar vacuum tests, has been investigated in conjunction with the outgassing evaluation and detection of molecular flow anomalies occurring in the test chamber. The pressures indicated by two tubulated ionization gauges—one pointing to the spinning spacecraft and the other toward the chamber wall—were used to calculate flow kinetics in the vacuum chamber. The fluxes of emitted molecules and chamber-wall-reflected molecules were monitored during the entire test. Representative equations and graphs are presented. Test results indicate that from 3 to 9 of every 100 emitted molecules returned to the spacecraft surface; that self-contamination by non-condensable gases was more severe than that by condensable gases; and that outgassing of the spacecraft was approximately 1.18×10^{-2} g/s after 10 hours and 1.18×10^{-3} after 90 hours of vacuum exposure. Pressure readings and temperatures can be used to establish the rate of outgassing that returns to, and possibly contaminates, the spacecraft surface. Testing deficiencies have been identified, and the type and location of instruments required to measure the outgassing, the degree of contamination, and return flow are discussed.

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GAS FLOW ANALYSIS DURING THERMAL VACUUM TEST OF A SPACECRAFT

John J. Scialdone
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INTRODUCTION

Spacecraft carrying contamination-sensitive experiments and surfaces have required strict control to prevent contamination occurring either on the ground or in space. An investigation of self-contamination (defined as the return of spacecraft outgassed molecules to the spacecraft surfaces) was conducted while the IMP-H spacecraft was undergoing thermal and solar vacuum tests. The fluxes of emitted and chamber wall reflected spacecraft molecules were monitored during the entire test.

During the test of a spacecraft in a thermal-vacuum simulation chamber, the sink of space is not completely reproduced. The limitations in size, wall temperatures, and pumping devices of the chamber preclude a simulation that corresponds 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 maximize the molecular sink ability of the chamber were included in the design of some special chambers. Recent papers by Scialdone (References 1 and 2) show that the return of outgassed molecules in a chamber may or may not be greater than in space. The return of outgassed molecules depends on the contamination performance of the chamber with respect to the orbiting altitude of the spacecraft under test.

The test described in this paper was conducted in a space environment simulator (SES) and the results obtained validate the above considerations. Quantitative values are given to the chamber performance in terms of its pumping performance and degree of self-contamination imposed on the spacecraft. The outgassing of the spacecraft versus time, hence the potential amount of contamination that a critical spacecraft surface might experience, are indicated. Also, a comparison is made of the chamber test self-contamination to the theoretical self-contamination in orbit. As an unexpected benefit, the measurements carried out in this test allowed for estimates of the leakage of certain gas sources located in the spacecraft.

MOLECULAR KINETICS IN A CHAMBER TEST

When the mean-free paths of the molecules, including those molecules emitted by the spacecraft enclosed in a chamber, are shorter than the chamber dimensions, intermolecular collisions occur. In order for these intermolecular collisions to occur, the chamber normally has small pumping ports compared to its internal surface area, and its surfaces are not cooled to provide molecular pumping. Under these conditions, the intermolecular collisions provide the randomness in direction and magnitude necessary to establish omnidirectional fluxes and pressures in the chamber. In contrast, directional molecular fluxes exist when the mean-free path of the molecules is larger than the governing spacecraft-chamber dimensions. This condition normally exists when the chamber has large pumping ports and the walls operate at cryogenic temperatures. The cryogenic walls immobilize and remove the molecules reaching these surfaces. For these conditions, the density and momentum are not statistically uniform in all directions, and the density and the pressure are not related. Nude gauge pressure measurements in the chamber cannot be used as an indication of the uniformity of density and of the molecular incidence rate on a surface anywhere in the chamber. Flux-measuring instruments at the location of interest must be used to establish the molecular incidence rate, which is the source of probable contamination. In this chamber test, properly oriented tubulated ionization gauges have been used to provide pressure measurements at discrete locations from the spacecraft. These equivalent pressure measurements have been related to directional fluxes. In fact, the density developed in these gauges corresponds to an equilibrium between the efflux of molecules out of the gauges' openings and the influx of the molecules from the environment incident on the opening. The density in the gauge, recorded as pressure, indicates the incoming flux, which can be expressed as an equivalent pressure of the incoming gas. It is understood that this pressure is dependent on the gauge orientation (that is, the pressure is not an isotropic property). The relations used to extract the incident flux from the gauge pressure readings are as follows: The gas law, $P = nKT$, and the flux rate relation, $\Phi = 1/4n\ mc$, can be combined to obtain the flux in the gauge in terms of the pressure, P, temperature, T, and molecular mass of the gas, m. The flux relation, taking the average molecular velocity of the gas in the gauge as $c = \sqrt{\frac{8KT}{\pi m}}$, where K is the Boltzman constant, is

$$\Phi = \left(\frac{m}{2\pi KT}\right)^{1/2} P \tag{1}$$

This is also the flux impinging on the gauge opening and is representative of the directional flow in the chamber.

The directional fluxes to be measured in the space chamber where a spacecraft is being tested are a function of the outgassing property of the spacecraft, the nature of the pumping surfaces, and the geometric relation between chamber and spacecraft. The total rate of gas leaving the spacecraft, q_m, is given by Garwin (Reference 3) and Scialdone (Reference 4)

$$q_m = q_{mo} + (1 - \eta_m)\, B\, q_c \tag{2}$$

where q_{mo} is the total rate of outgassing originating from the spacecraft, B is the configuration factor or probability that molecules departing from the wall according to the cosine law strike the spacecraft, and η_m is the capture coefficient of the spacecraft surfaces. The total mass rate leaving the chamber walls is q_c and may be found as

$$q_c = q_m (1 - \eta_c) + (1 - \eta_c)(1 - B)\, q_c \tag{3}$$

when there is no leakage or outgassing from the chamber walls. The additional term η_c in this equation represents the capture coefficient of the chamber, and it includes the pumping system and cryogenic wall entrapment of molecules. The simultaneous solution of the two equations results in these equations:

$$q_c = q_{mo} \frac{Z}{B(1 + \eta_m Z)} \tag{4}$$

and

$$q_m = q_{mo} \frac{(1 + Z)}{(1 + \eta_m Z)} \tag{5}$$

where Z is given by

$$Z = B \frac{(1 - \eta_c)}{\eta_c} \tag{6}$$

The ratio, q_c/q_m, which is the measurable quantity in the chamber, is

$$q_c/q_m = \frac{Z}{B\,(1 + Z)} \tag{7}$$

The ratio of the mass returned to the spacecraft surfaces to the outgassing mass $q_{m\,o}$ is given by:

$$a = \frac{q_c B}{q_{m\,o}} \approx Z \tag{8}$$

when Z is much less than one. In the present tests, the value of Z has been obtained from measurements of q_c/q_m knowing B. In turn, the equivalent capture coefficients or pumping ability of the chamber, η_c, was then evaluated from Z. The spacecraft outgassing, $q_{m\,o}$, as indicated later, was obtained from the measurement of q_m and the knowledge of Z. The determination of the ratio q_c/q_m was obtained in terms of the pressures indicated by two tubulated pressure gauges located at approximately the same distance from the spacecraft but facing opposite directions. Thermocouples attached to the two gauges provided indications of the gauge temperatures. One has, from the conservation of mass and the assumption of uniform fluxes from the spacecraft and chamber walls, that

$$\frac{q_c}{q_m} = \frac{\Phi_c A_c}{\Phi_m A_m} = \frac{\Phi_3 A_3}{\Phi_2 A_2} \tag{9}$$

Subscript 3 refers to parameters of the flow originating from the chamber and directed to the spacecraft. Subscript 2 refers to the flow originating from the spacecraft and directed to the chamber wall. The change in subscripts has been made to provide agreement with the designation of parameters shown on computer-plotted curves described later. The quantities $\Phi_3 A_3$ and $\Phi_2 A_2$ are measured at the same location in the chamber ($A_3 = A_2$) by the tubulated gauges. So, from the previous relation of the flux in terms of pressure, one obtains

$$\frac{q_c}{q_m} = \frac{\Phi_3}{\Phi_2} = \frac{P_3}{P_2}\sqrt{\frac{T_2}{T_3}} \tag{10}$$

The determination of the outgassing was obtained from the relation for q_m (Equation 5), which for $\eta_m \approx 0$ will give

$$q_{mo} = \frac{1}{1+Z} q_m \tag{11}$$

This expression, changed to flux and measured by a flux, Φ_{mo}, at a diameter, d, rather than d_m of the surface, reduces to:

$$\Phi_{mo} = \frac{q_{mo}}{A_m} = \left(\frac{1}{1+Z}\right)\frac{q_m}{A_m} = \frac{1}{1+Z}\left(\frac{d}{d_m}\right)^2 \Phi \tag{12}$$

$$= \left(\frac{1}{1+Z}\right)\left(\frac{d}{d_m}\right)^2 \left(\frac{m}{2\pi K T_2}\right)^{1/2} P_2$$

when it is assumed that the flux is inversely proportional to the square of the distance from the test specimen. It is apparent that if $Z \ll 1$, $q_{mo} \approx q_m$, and the flux measured by the gauge facing the spacecraft corresponds to the outgassing flux.

MAIN TEST OBJECTIVES AND DESCRIPTION OF TEST FACILITY AND SPACECRAFT

The test results and analysis reported here were an adjunct to the verification of the thermal design of the IMP-H spacecraft under solar vacuum conditions. The test was to establish temperatures experienced by the spacecraft under 100 percent sun stabilization and shadow periods. Solar aspect angles (the angle between direction of the sun and spacecraft spin axis) of 75°, 90°, and 105° were simulated with the spacecraft in vacuum spinning at a nominal 5 rpm. Another objective was the evaluation of electronics performance under the simulated orbital conditions. The tests reported here were intended to establish the parameters of self-contamination, the evaluation of outgassing, and molecular flow anomalies occurring in the chamber. The setup for this secondary test had to be kept to a minimum, based on the limitations imposed by the main test objectives.

The IMP-H spacecraft shown in Figure 1, which was photographed previous to the tests, is a 16-sided, 1.57-m long prism divided into 3 bands–the central bands include the electronic boxes of the experiments. The spacecraft weighs 260 kg with the empty motor case, and solar panels cover a major portion of its surface. It carries a plasma wave experiment antenna, a magnetometer, and attitude control system (ACS) booms which were all in their folded configurations for the tests. The spacecraft orbit is planned to be

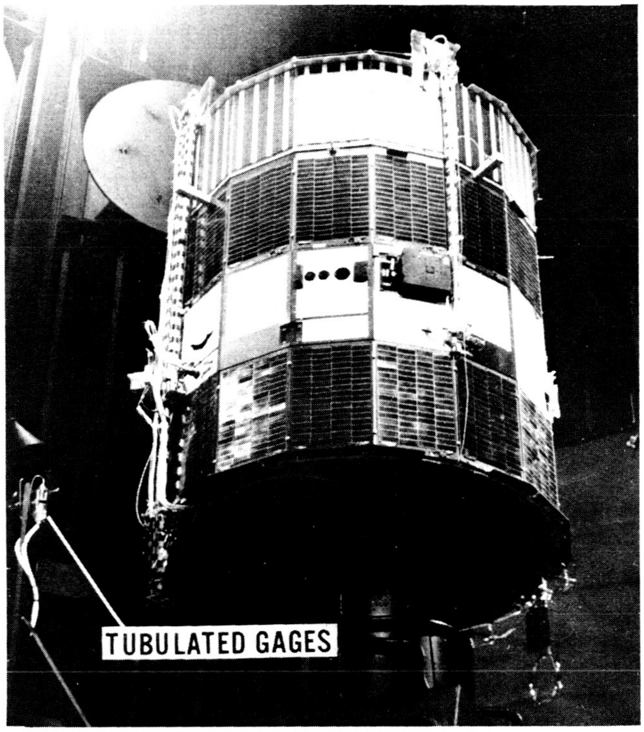

Figure 1. IMP-H spacecraft in the SES space chamber.

inclined 28° to the equator with an apogee of 38 earth radii and a perigee of 32 earth radii, with a period of 12 days and a sun angle of 90° ± 5°. Its objectives in space are: (a) to continue the study of radiation environment of the cislunar space; (b) to study interplanetary magnetic fields in relation to particle flux from the sun; (c) to monitor solar flares; and (d) to further the development of inexpensive spin stabilized spacecraft for interplanetary investigations. The sequence, duration, solar aspect, and other details of the test cycle are indicated on the chamber pressure versus time profile (Figure 2).

The test was carried out in the space environment simulator (SES) which has nominal dimensions of 8.38 m in diameter and 12.19 m in height, with a nominal volume of 1372 m^3. The chamber is provided with 8 Roots blowers, 8 mechanical pumps, seventeen 0.8-m (32 in) diffusion pumps (4×10^4 ℓ/s each). In addition, there is 18.6 m^2 of surface in a Santeler type arrangement which may be cooled by helium at 20 K. The chamber shroud made of aluminum with Cat-A-lac black finish can be controlled with nitrogen from 75°C to −190°C. The solar simulation is provided by one hundred and twenty-seven 3.5-kW Hg - Xe arc lamps illuminating a test plane of 6.1 m diameter with 1 solar constant. Spin and aspect angle for payload are provided by a liquid nitrogen cooled gimbal. Instrumentation data handling for 2500 channels of data collected every 100 seconds, and real-time plotting capability for 130 channels is available at the data handling center (known locally as Data Central). Alphatron and ion gauges are used to monitor the chamber pressure.

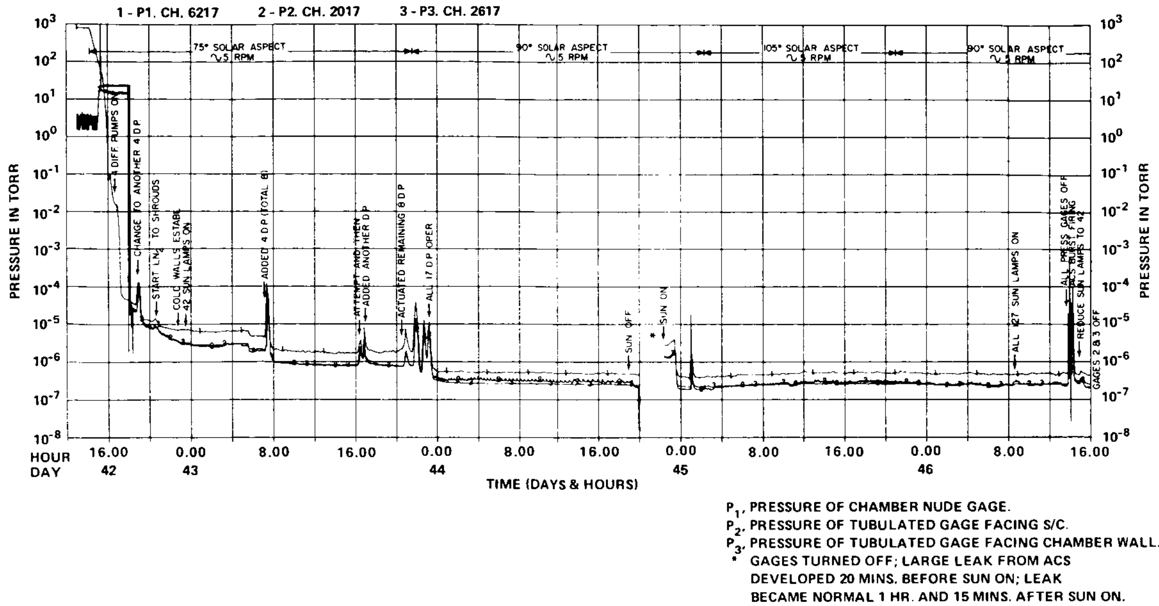

Figure 2. Test pressure profile and test events.

FLUX MEASUREMENT INSTRUMENTATIONS

As shown in Figure 3, two tubulated gauges mounted on a frame attached to the gimbal and facing opposite directions were located at approximately 66 cm from the spacecraft surface at a height corresponding to the spacecraft electronic compartment deck. These gauges, made of Pyrex with a 1.9-cm diameter, and a 5.6-cm long Kovar tubulation with two tungsten filaments, were calibrated before and after the test with nitrogen gas at ambient temperatures. The calibration is performed using two volumes separated by a calibrated orifice. The pressure in one of the volumes is measured with a Baratron gauge previously calibrated against a MacLeod gauge. The volumes are maintained at different pressures with diffusion and mechanical pumps.

The gauges, mounted on a nonrefrigerated frame and shielded to prevent heat radiation, were also instrumented with thermocouples. A nude ionization gauge for chamber pressure monitoring was located at a 9-m level and about 1.2 m from the chamber wall. Calibration of the gauge was also performed prior to testing. The readings of the gauges and thermocouples were made automatically every 100 seconds and stored on magnetic tape. The range switching was made manually. The tubulated gauges were located between the spacecraft and chamber walls. However, they were in the shadow of the spacecraft when the solar aspect was other than 0°. In that case, the return flux gauge was looking at the LN_2 cooled bottom of the chamber.

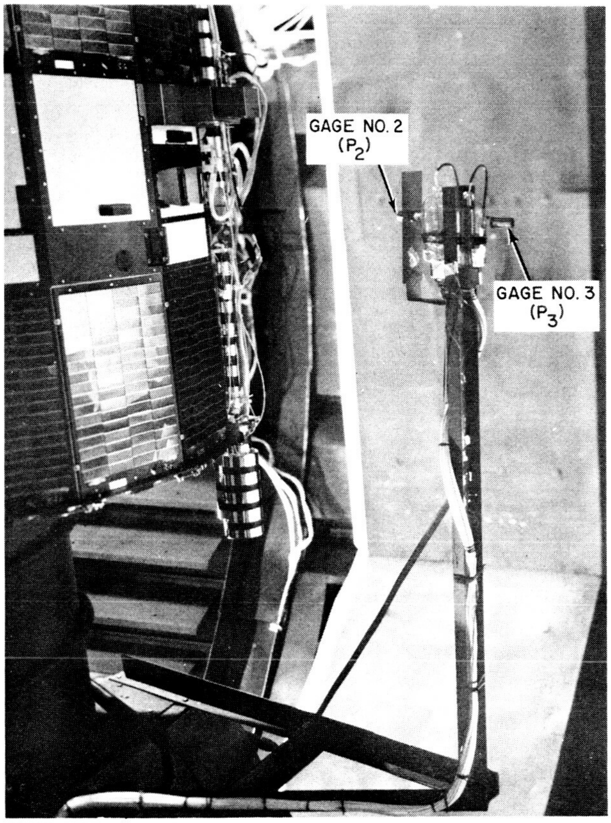

Figure 3. Tubulated pressure gauges mounting.

TEST PROCEDURE AND COLLECTED DATA

The main test objectives were carried out according to the procedure described in Greyerbiehl (Reference 5). The curves in Figure 2 were plotted by the computer utilizing the data stored in Data Central. The curve labeled 1 is the pressure of the nude ionization gauge monitoring the chamber pressure. The curve labeled 2 is the pressure indicated by the tubulated gauge facing the spacecraft, and 3, the pressure of the gauge facing the wall. The plot shows gauge calibration events, solar aspect of the spacecraft, its rpm, methods of pumping at various stages, solar intensity settings, and solar beam scan. The pressures shown on this curve are indicated pressures. The pressures, rotational speed, and other parameters were also monitored manually during the test. From these observations, it was noted that gauge 2, facing the spacecraft, was oscillating from a minimum to a maximum of pressure within a span of about 3 seconds. The periodicity of the oscillation corresponded to the period of revolution of the spacecraft. By appropriate timing of the event, it was possible to establish that the excursion of pressure corresponded to the passage in front of the gauge of an area of the spacecraft where sources of gas leakage were possible. In fact, the location corresponded to a location where Freon 14, needed for the ACS, or isobutane gas, needed for one of the experiments (MAE), were stored.

Sample strip chart records of these events were taken as a precaution against possible omission of the fluctuation in the main data collection system. The charts show periods of 12.27 s to 12.37 s between pulses, which correspond to the spacecraft rotations of 4.89 and 4.85 rpm (5 rpm was the nominal speed). The magnitude of the pressure pulses varied from about $\Delta P = 3.5 \times 10^{-7}$ torr at the early stage of testing, to $\Delta P = 6.5 \times 10^{-8}$ torr toward the end of the test. The glass temperatures of the gauges were recorded as a function of time. These remained practically constant at about 36° to 38°C. The ratio of the two gauge temperatures was about 1.02, with the temperature of the gauge facing the spacecraft about 1 degree higher than that of the gauge facing the wall.

Figure 4 reproduces to a larger scale the actual pressures of the two gauges. It shows that for several stretches of time, the pressure, P_3, of the gauge facing the walls was slightly higher than P_2, facing the spacecraft. This is apparent in Figure 5 which shows the ratio P_3/P_2. The cyclic behavior of the pressure P_2 is immediately noticeable in these graphs. The periods of 20 to 25 minutes recorded by these graphs are the beat periods resulting from the rotation period of the spacecraft (nominal 12 s, 5 rpm) not being an exact submultiple of the data sampling rate (100 s). With the spacecraft rotating at 4.85 rpm (12.37 s period), the beat in the data would have been the noted 20-minute period.

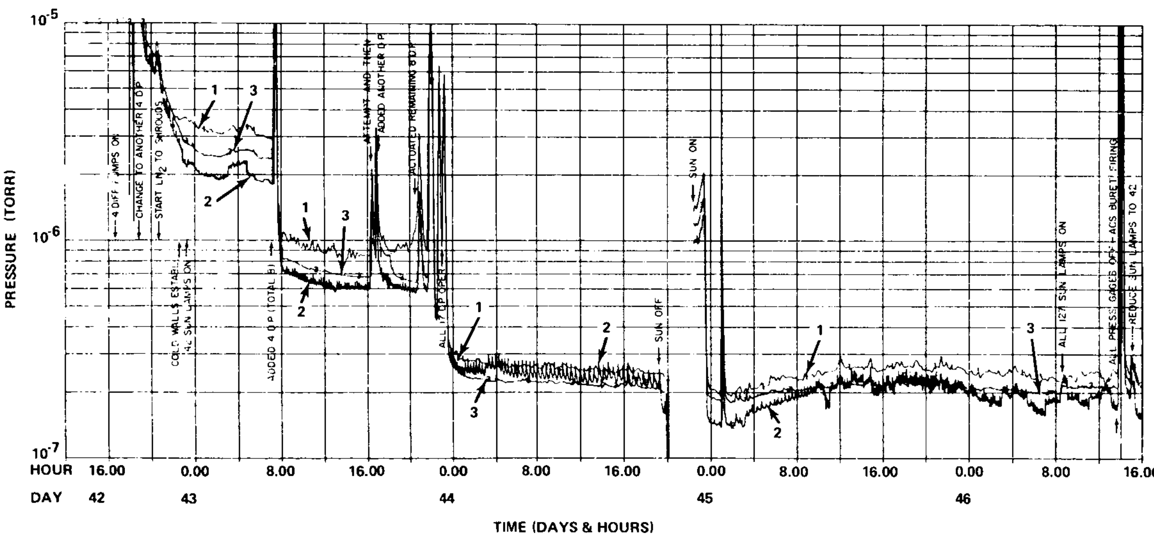

Figure 4. Pressure profiles measured by the gauge P_2 facing the spacecraft and P_3 facing the chamber wall.

The plots show correlation with the conditions and events existing in the chamber as a result of the changes in pumping and solar simulation. Drops in pressure ratios (P_3/P_2) are noticeable when the chamber walls are cooled to LN_2 temperatures, and the number of diffusion pumps in operation is changed from 4 to 8, 9, and finally 17. When all of the 17 pumps are operating, the pressure ratio becomes less than 1, indicating that the return flux is less than the emitted flux. Beam scans, increasing solar flux and firing of jets affect the ratio in the sense of increasing it as would be expected.

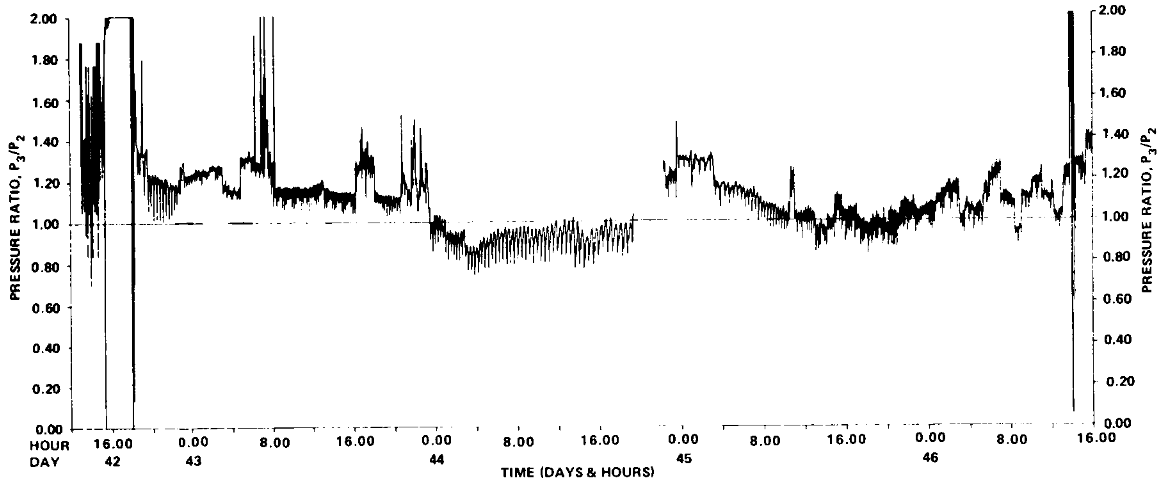

Figure 5. Ratio of the pressures P_3/P_2 versus time.

REDUCTION OF COLLECTED DATA AND RESULTS

Self-Contamination and Chamber Capture Coefficient

Figure 6 shows the ratio of the fluxes indicated by the gauges. The curve was obtained by modifying the pressure ratio by their temperatures. As shown by Equation 10, the flux ratio is

$$\frac{\Phi_3}{\Phi_2} = \frac{P_3}{P_2}\sqrt{\frac{T_2}{T_3}}$$

The temperatures which were monitored continuously during the test remained constant at 36° to 37°C. Small transients occurred during application and removal of the sun. As expected, the flux ratio shows the same behavior as the pressure ratio.

Figure 7 shows the calculated values of Z. These were obtained from Equation 7 in terms of the flux ratios (Figure 6) and configuration factor B, that is

$$Z = \frac{B}{1 - B\Phi_3/\Phi_2}(\Phi_3/\Phi_2)$$

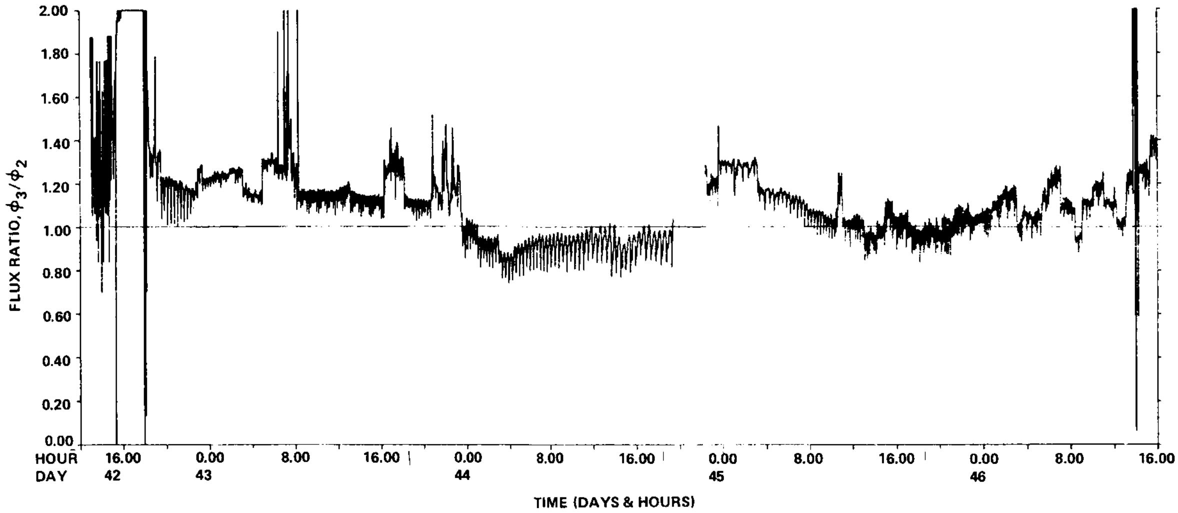

Figure 6. Flux ratio, Φ_3/Φ_2 versus time.

The value of B, relating the geometries of the chamber walls with those of the spacecraft, were obtained by a Ravfac computer program. This program utilizes finite difference methods, contour integrals, and combinations of these two to calculate the configuration factor between areas. For the different aspects of the spacecraft relative to the chamber axis, the computer indicated a value of B = 0.03486. A value of B = 0.037 can be obtained from the relation

$$B = \frac{d_m^2}{D_c^2}$$

where d_m is the diameter of the spacecraft and D_c, that of the chamber which is appropriate for the configuration of infinite concentric cylinders or concentric spheres.

The parameter Z, grouping the geometric configuration and the gas molecules capture coefficient of the chamber, is also the ratio of the gas molecules returned to the spacecraft to those which left it. Hence, it is a parameter which indicates the degree of self-contamination existing during test. It can be interpreted as expressing the number of times a molecule which left the spacecraft returns to it before eventually being trapped or removed from the chamber. The actual contamination of a spacecraft would be the product of $Z \times \eta_m$ where η_m is the capture coefficient of the gas molecules on the spacecraft surfaces. Figure 7 shows that, during the test, the parameter Z varied between 3×10^{-2} and 9×10^{-2} at the location under investigation. The larger value existed during initial pumping when 4 diffusion pumps were used. The minimum value of 3×10^{-2}, indicating that 3 out of 100 molecules were returning to the spacecraft, existed when all 17 pumps and cryogenic walls were activated. The value 3×10^{-2} corresponds, as per

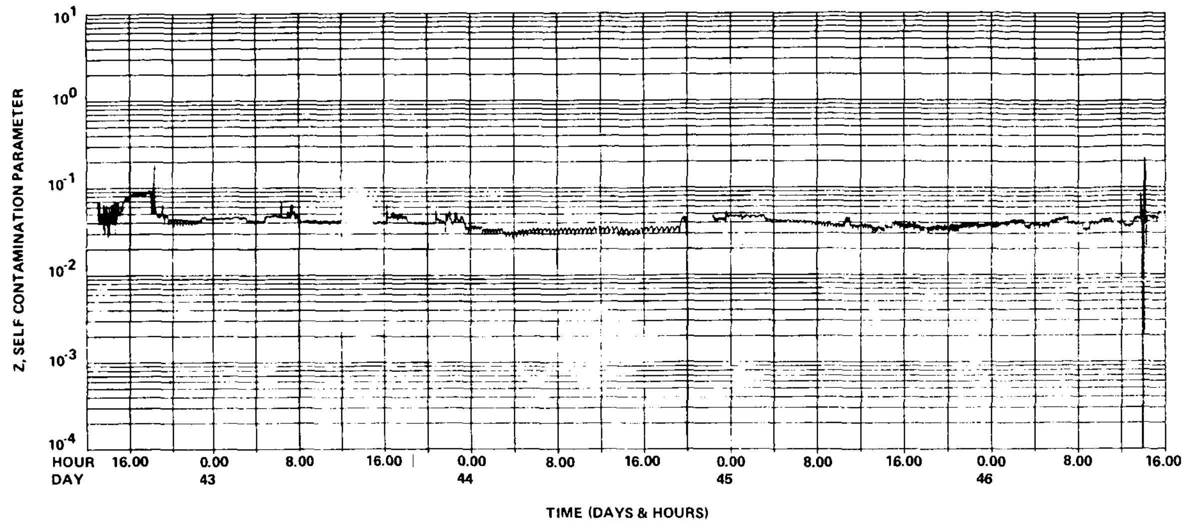

Figure 7. Ratio of molecules returned to spacecraft to those which left as a function of time, Z versus t.

Scialdone (Reference 1), to a self-contamination which would exist on the frontal area of a spacecraft orbiting at about 300 km. Figure 8 shows the chamber capture coefficient, η_c, versus time. This was obtained from the definition of Z, that is, $\eta_c = B/Z + B$, both B and Z being previously determined. The coefficient varied from 0.3 to about 0.55.

The maximum value was experienced when all pumps were in operation. The chamber capture coefficient, determined here from the gauges indicated fluxes and B, is an equivalent coefficient which does not differentiate between the condensable and noncondensable gases. One does not know the composition of the gas leaving and returning to the spacecraft. The gas returning to the spacecraft had to consist mainly of those gases which did not condense on the liquid nitrogen cooled shroud. The pumping of these could be done by the diffusion pumps, and only a negligible amount by the chamber surfaces, since the 20 K helium-cooled panels were not activated during this test. An estimate of the pumping of those noncondensed gases can be obtained by taking the ratio of the diffusion port area, 5180 cm^2, to the entire surface area of the chamber, 288×10^4 cm^2, and assuming that the transmission coefficient of the pump is one. This estimate indicates that the chamber capture coefficient of the noncondensables could be about 7×10^{-3} for four pumps in operation, 1.4×10^{-2} for eight pumps, and 3.6×10^{-2} for 17 pumps. The resulting value of Z for the noncondensables could then be about 0.91 when all 17 pumps were in operation. This implies that out of 100 noncondensable emitted molecules, 91 returned to the surface. Since the gauge could not distinguish between gauges, we cannot confirm these results or establish the amount of outgassed noncondensable molecules which returned to the spacecraft. In the future, mass spectrometers should be used in a manner similar to the tubulated gauges, to differentiate between gases. In order that one may get a qualitative indication of the amount of condensables and noncondensables returning to the spacecraft,

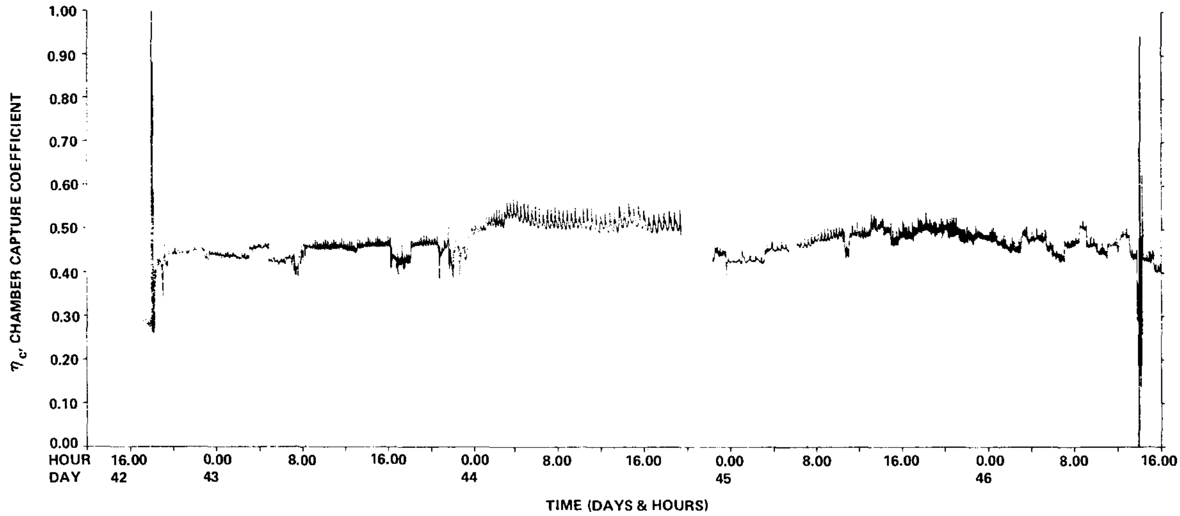

Figure 8. Chamber capture coefficient, η_c versus time.

Table 1 has been prepared. It shows the calculated fractions of condensables and noncondensables leaving and returning to the spacecraft for the respective values of Z which may have existed in the chamber. The Z of the condensables is predicated on an assumed capture coefficient of 0.9 which could be expected in the present test. The calculation shows that the condensable gas measured by a gauge facing the spacecraft would be about the same as the gas which left the spacecraft. The return, however, would be only about 0.1 of the emitted flux. On the other hand, the amount of noncondensable read by a gauge facing the spacecraft would be almost two times the emitted noncondensable flux, and the return, about 26 times the emitted flux. The noncondensable fluxes are predicated on a Z = 0.91 obtained as indicated previously. The table also shows the results of the calculation for an assumed outgassing composition of 96 percent condensable and 4 percent noncondensable gas. It shows that for the above Z's, the mass seen by the gauge facing the spacecraft would consist of 92.6 percent condensable and 7.4 percent noncondensable. The return would be almost reversed, 10 percent condensables and 90 percent noncondensables. Further, the equivalent Z obtained without differentiation of gas type would be 4.05×10^{-2}. This value is comparable to the range of values obtained in testing. These calculations show the importance of being able to differentiate the gas composition. One would have to be concerned mainly with the returning condensable gases for the prevention of contamination.

Spacecraft Outgassing, Degree of Contamination

Figure 9 shows the outgassing flux, Φ_0, versus time, obtained from the pressure indicated by the gauge facing the spacecraft. This pressure employed in Equation 12 allows one to calculate the flux at the spacecraft surface. The curve shows that at the end of 10 hours of

Table 1

A Calculation of Contamination Parameters Accounting for Condensable and Noncondensable Gases.

	Condensable	Non-condensable	Total	Remarks
Capture coefficient, η_c	0.9	3.6×10^{-2}		
Configuration factor B	3.48×10^{-2}	3.48×10^{-2}		For this test
Z	4.25×10^{-3}	9.14×10^{-1}		Equation 6
Outgassing, q_{mo}	q_{moc}	q_{mon}	$q_{mo} = q_{moc} + q_{mon}$	
Mass rate leaving s/c, q_m	$\sim 1.0\, q_{moc}$	$1.914\, q_{mon}$	$q_m = 1.0\, q_{moc} + 1.914\, q_{mon}$	Equation 5
Mass rate return to s/c, q_c	$\sim 1.22 \times 10^{-1} q_{moc}$	$26.22\, q_{mon}$	$q_c = 1.22 \times 10^{-1}\, q_{moc} + 26.22\, q_{mon}$	Equation 4
Equivalent Z_e			$Z_e \approx q_c B / q_{mo}$	Equation 8
EXAMPLE: Assume $q_{moc} = 96$, $q_{mon} = 4$ and Z as above:				
Outgassing, q_{mo}	96	4	100	
Mass leaving, q_m	96	7.64	103.64	
Mass returning, q_c	11.7	105	116.7	
Ratio of masses leaving to total	92.6 percent	7.4 percent		
Ratio of mass returning to total	10.0 percent	90 percent		
Equivalent Z_e			$\frac{116.7}{100} \times 3.48 \times 10^{-2} = 4.05 \times 10^{-2}$	

vacuum exposure, the outgassing was on the average of about 1.2×10^{-7} g/cm²/s; after 20 hours about 4×10^{-8} g/cm²/s. After this period, a quasi-steady outgassing rate of 1-2 $\times 10^{-8}$ g/cm²/s was measured. The total outgassing of the spacecraft can be estimated by multiplying the above by an estimate cylindrical surface of 9.85×10^{4} cm² for the spacecraft. If this is done, the loss of gas (equivalent air) per unit time at the beginning of the test was about 1.1×10^{-2} g/s and toward the end of the test about 1×10^{-3} g/s. These values are not out of line. In fact, taking total pumping area of the chamber as 2.32×10^{6} cm², and pressure as 5×10^{-7} torr, one calculates the outgassing flow as $Q = 1.96 \times 10^{-2}$ g/s. This assumption of uniform outgassing is almost certainly not true. It could have been verified by installing several gauges around the spacecraft and taking an average of the outgassing rate to estimate the total outgassing. The discontinuities in the generally decaying curve are directly related to the changes in the pumping system or solar simulation. The flux rate of the returning molecules on the spacecraft surfaces can be calculated, knowing Z and the outgassing. This flux, Φ_R, which was a potential contaminating flux for the present test, is shown in Table 2. A spacecraft surface sufficiently cold to condense these returning molecules could have been contaminated at the indicated rates, (10^{-9} to 10^{-10} g/cm²/s). Contamination on warmer surfaces might consist of a few monolayers.

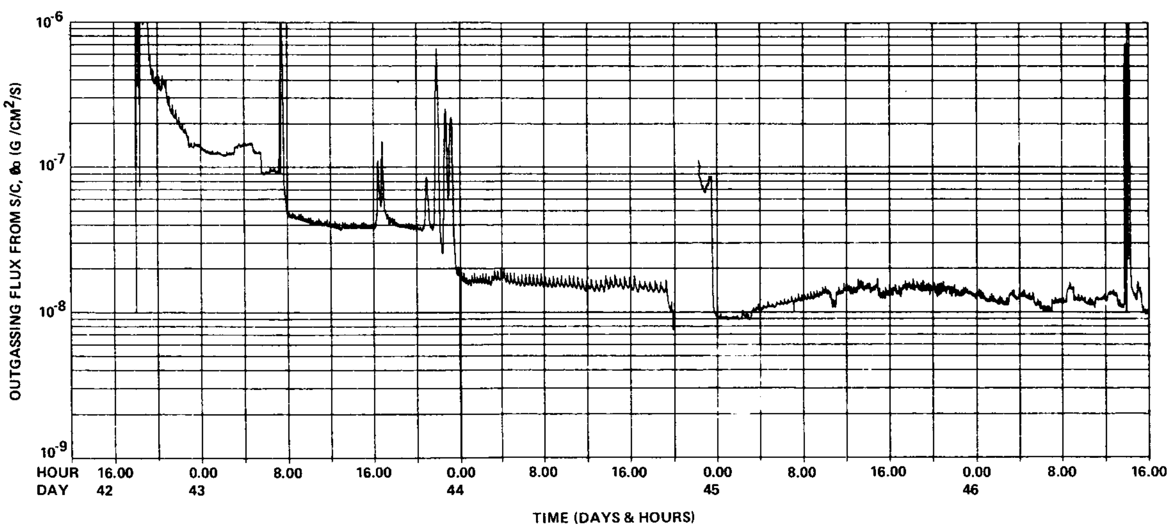

Figure 9. Spacecraft outgassing flux, Φ_0 versus time.

Estimate of the Amount of Localized Leak

Figure 9 indicates that the difference between maximum and minimum values of the outgassing which was caused by the localized leak was about 5×10^{-9} g/cm²/s at T + 20 hours, 3.7×10^{-9} at T + 43 hours, and 2.9×10^{-9} at about T + 73 hours. These values are

Table 2

Summary of Contamination Performance and Indicated Localized Leak.

Time (Hrs.)	Self Cont. Coeff. Z	Capt. Coef. η_c	Outgas. Rate Φ_0 (g cm^{-2} s^{-1})	Return Rate Φ_R (g cm^{-2} s^{-1})	Total Outgas. W_0 (gs^{-1})	Total Return W_R (gs^{-1})	Localiz. Leak (atm cm^3 s^{-1})		
							ΔP_2	@ 1 = 0	@ 1 = 78.8 cm
0 + 10 (43d.00h.)	4.5×10^{-2}	0.44	1.2×10^{-7}	5.40×10^{-9}	1.18×10^{-2}	5.31×10^{-4}	1.49×10^{-7}	1.56×10^{-4}	9.20×10^{-4}
20 (43d.10h.)	4.1×10^{-2}	0.46	4.2×10^{-8}	1.74×10^{-9}	4.14×10^{-3}	1.70×10^{-4}	6.52×10^{-8}	6.85×10^{-5}	4.03×10^{-4}
30 (43d.20h.)	4.0×10^{-2}	0.47	3.8×10^{-8}	1.52×10^{-9}	3.74×10^{-3}	1.50×10^{-4}	3.28×10^{-8}	3.44×10^{-5}	2.02×10^{-4}
40 (44d. 6h.)	3.2×10^{-2}	0.54	1.8×10^{-8}	5.76×10^{-10}	1.77×10^{-3}	5.66×10^{-5}	4.69×10^{-8}	4.92×10^{-5}	2.89×10^{-4}
50 (44d.16h.)	3.3×10^{-2}	0.53	1.6×10^{-8}	5.29×10^{-10}	1.58×10^{-3}	5.21×10^{-5}	4.73×10^{-8}	4.96×10^{-5}	2.91×10^{-4}
60 (45d. 2h.)	4.5×10^{-2}	0.43	9.0×10^{-9}	4.05×10^{-10}	8.86×10^{-4}	3.99×10^{-5}	9.50×10^{-9}	9.98×10^{-6}	5.86×10^{-5}
70 (45d.12h.)	3.5×10^{-2}	0.49	1.4×10^{-8}	4.90×10^{-10}	1.38×10^{-3}	4.84×10^{-5}	2.46×10^{-8}	2.58×10^{-5}	1.51×10^{-4}
80 (45d.22h.)	3.8×10^{-2}	0.48	1.3×10^{-8}	4.95×10^{-10}	1.28×10^{-3}	4.86×10^{-5}	4.04×10^{-8}	4.24×10^{-5}	2.49×10^{-4}
90 (46d. 8h.)	4.0×10^{-2}	0.47	1.2×10^{-8}	4.80×10^{-10}	1.18×10^{-3}	4.73×10^{-5}	1.51×10^{-8}	1.58×10^{-5}	9.32×10^{-5}

in agreement with those obtained using the pressure variations noted with a Brush analog recorder. The location of the leak is not known because the gauges could not scan the cylindrical length of the spacecraft. However, the amount of leakage can be bracketed by considering that it had to be produced by a leak either at the extreme edge of the cylinder or at the center of the spacecraft, that is, opposite the gauge. In order to do this, one can calculate from the geometry the view factor F_{ER} of the gauge from the leak location at these two points. This relates the leakage at the surface Q_E to the leak measured by the gauge Q_R, that is, $Q_E = Q_R/F_{ER}$. For two areas, A_E on the spacecraft, and A_R, the gauge tubulation area, located at a distance, r, from each other, and both directed at an angle, β, from r, the view factor will be

$$F_{ER} = \iint \frac{1}{A_E} \frac{\cos\beta \cos\beta \, dA_E \, dA_R}{\pi r^2} = \frac{\cos^2\beta \cdot A_R}{\pi(\ell^2 + a^2)}$$

where a is the distance of the gauge from the spacecraft surface (66 cm) and ℓ is the normal to this distance along the spacecraft surface (ℓ_{max} = 78.8 cm). The leak for the two geometries can be

$$Q_E = \frac{\pi(\ell^2 + a^2)}{\cos^2\beta \cdot A_r} Q_R = \begin{cases} 4.8 \times 10^3 \, Q_R & \text{for } \ell = 0 \\ \text{or} & \\ 2.81 \times 10^4 \, Q_R & \text{for } \ell = 78.8 \text{ cm} \end{cases}$$

The leak rate indicated by the gauge, Q_R, can be obtained from the rate of pressure rise experienced by the gauge, that is, from $Q_R = V\Delta P/\Delta t$. The volume of the gauge was 250 ml and $\Delta t \approx 1.5$ seconds while the ΔP was available from the computer printout of P_2 and from the Brush recorder. Using the value of Q_R obtained from the pressure rise equation, the leakages for the Q_E calculated in this manner, and for a location either directly facing gauge P_2 or at the cylinder edges, are tabulated in Table 2. The values for the leak at the extreme edge are about six times as large as those at the center of the spacecraft. The leak in the spacecraft was most probably at about the same height as the gauge, and the smaller values reflect more closely the actual leakages. The only validation of these values is a reported 5.5×10^{-5} atm cm^3/s leak, measured sometime during the test by a mass spectrometer calibrated to detect an N_2 leak in an empty chamber with liquid nitrogen and all the pumps operative. Accordingly, the values calculated here and those obtained with the mass spectrometer give confidence that for this test the leakage was not a problem. Acceptable leak rates were 1×10^{-3} atm cm^3/s for either the isobutane contained in the MAE (Maryland Electron) experiment or the Freon 14 in the ACS system. However, for future leak detection, the present method should be verified by experiments. A larger number of pointing gauges at various locations, or gauges which can scan the surfaces should make it possible to locate the leak exactly and measure its magnitude. It is also felt that this method of measuring leakage may be a reliable adjunct to the present method of using a previously calibrated mass spectrometer.

IMP-H – SUMMARY OF THE TEST RESULTS

The results of the present test obtained with a single pair of pointing gauges indicate the following:

- The self-contamination parameter of the IMP-H spacecraft under the solar vacuum conditions to which it was exposed, varied from 3.2×10^{-2} to 9×10^{-2}. That is, 3 to 9 out of 100 emitted molecules were returning to the surfaces of the spacecraft. The smaller return occurred when all 17 diffusion pumps and the liquid nitrogen cooled surfaces were operative. These returns are comparable to the return expected to occur on the frontal surface of a satellite orbiting at an alatitude of about 300 km. In view of the fact that the IMP may have an initial perigee altitude of 600 to 1000 km, the ground test potential contamination was more severe than that expected in orbit. Since no malfunction of the type caused by contamination was experienced during test, no contamination problem should develop in space under the same conditions of testing.

- The self-contamination in the chamber of noncondensable gases was more severe. These gases were pumped out only by the diffusion pumps. LHe refrigerated panels which could condense some of these gases were not employed in this test. The pointing gauges could not differentiate between gases, and the self-contamination parameters for the noncondensable and condensable gases could not be determined. It can be estimated, however, that for the geometry of the system and the size of the pumping ports, the noncondensable self-contamination may have been about 91 percent under optimum condition of pumping. However, the return of noncondensable gas is of no concern as far as contamination of the spacecraft.

- The outgassing of the spacecraft, assumed to be uniform over the entire surface of the spacecraft, and assumed to be nitrogen, amounted to about 1.18×10^{-2} g/s after 10 hours of vacuum exposure and 1.18×10^{-3} after 90 hours. The rates of gas return to the spacecraft amounted to 5.3×10^{-4} g/s and 4.73×10^{-5} at these times.

- The leak of isobutane and/or Freon, expressed in equivalent nitrogen, varied from about 3.6×10^{-4} to 5×10^{-5} atm cm^3/s. The leak could have been about six times larger than the above if it was located at either the top or the bottom edge of the spacecraft cylindrical surface.

- The vacuum chamber during this test exhibited an equivalent capture coefficient varying between 0.3 to 0.55. The noncondensable capture coefficient may have varied from 7×10^{-3} to 3.6×10^{-2} or slightly better if some adsorption of these gauges by cooled surfaces is included. The capture coefficient for the condensable gases may have been close to 0.9.

CONCLUSIONS AND RECOMMENDATIONS

Directionally pointed tubulated gauges can indicate molecular fluxes in the direction of their pointing, a determination which is not possible with nude ionization gauges. In the space chamber, the tubulated gauges properly pointed can differentiate between the fluxes leaving the spacecraft under test and the fluxes directed to the spacecraft from the chamber walls. Further, the pressure readings and temperatures can be used to establish the rate of the spacecraft's own outgassing which returns to the spacecraft surface, and which may contaminate its critical surfaces if the conditions are appropriate. In addition, the self-contamination experienced in the chamber can be related to the expected self-contamination in space, or in more general terms, can establish if contamination may or may not occur in space. In conclusion, the present test has confirmed that tubulated gauge readings can provide, in addition to the self-contamination: (a) a determination of the spacecraft rate of outgassing, (b) the localization and amount of leakages which may exist and, (c) the pumping performance of the chamber as expressed by the chamber molecules capture coefficient.

The following deficiencies in the present test setup have been noted:

- Several gauges in pairs should be mounted at the same distance and along the surface of the spacecraft. This will establish the uniformity or nonuniformity of the spacecraft outgassing.
- The gauge should be carefully calibrated. The difference in readings between those gauges facing the spacecraft and the chamber wall may be quite small.
- If the two gauges could be mounted as close as permissible to the spacecraft surface, the self-contamination parameter could be determined without establishing the chamber spacecraft configuration factor. On the other hand, the differences in fluxes, hence in pressure readings between gauges, would be maximum if the gauge pointing toward the walls would be located near the chamber wall, and the gauge pointing toward the spacecraft would be near the spacecraft surface.
- The localization and measurement of a point leak could be established readily if the gauges could scan the surfaces. This would be a necessity when a few monitoring gauges are used.
- The ionization gauges cannot distinguish between condensable and noncondensable gases. Their use precludes the differentiation between the condensable and noncondensable gas flows. Small pointing mass spectrometers could permit this distinction. An alternative method would be to use cooled quartz crystal microbalances to measure quantitively the noncondensable accumulation of the leaving and returning gas for the duration of the test.

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