An Estimate of the Outgassing of Space Payloads and Its Gaseous Influence on the Environment

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The outgassing of several space systems—including spacecraft instruments, spacecraft, the Shuttle bay, and a spent solid motor—is described. The outgassing was obtained from measurements in large vacuum chambers or, as for the Shuttle, implied from discrete measurements of the bay environment in orbit. The outgassing is expressed in terms of nitrogen, and described as a function of time. Its chemical composition obtained from mass-spectrometer measurements is also reported for some systems. The data are intended to provide a basis for estimating the following parameters of importance for instruments and payloads that have similar functions, weights, volumes, and designs: internal pressures, outgassing contribution to the environment, self-contamination, and contamination to nearby systems. In the future, with the full utilization of the Shuttle, there may be a need to put a payload in orbit that has not been tested in a vacuum chamber or extensively analyzed for outgassing. In such instances, an estimate of outgassing behavior in orbit may be provided on the basis of the data reported herein. In the following, the weights, volumes, and some of the scientific functions of the instruments for which outgassing data are available are indicated. Also, a brief description of the methods used to obtain the data is provided. General indications on how to use the data to obtain the internal pressure vs time for a payload, its self-contamination, the gaseous flow in its vicinity, the column densities in its field of view, and other environmental parameters are provided.

Introduction

THE evaluation of the pressure vs time in an instrument, the gaseous contamination hazards on a critical surface by certain molecular species of the outgassing, the gaseous environment created about the instruments, and other effects of gaseous sources in and out of a payload require a description of the outgassing sources produced by the payloads when in a vacuum. The description of the gaseous environment can be obtained from payload vacuum chamber tests, or by summing the outgassing rates from each material, if their outgassing rates are known from test measurements. Another alternative is to obtain measurement in space of the actual gaseous behavior of the payloads. All of these approaches have been used; however, each method involves considerable effort in the analysis of the measurements, a knowledge of the geometrical arrangements, and extensive measurements and expenses.

The outgassing data can be obtained from extensive measurements in a vacuum chamber or from a very detailed analysis of the payload components. The analyses employ components' outgassing data obtained from long and difficult tests of sample materials. In the analyses, outgassing behavior of components at different temperatures and configurations of sample tests, knowledge of the components' surface areas, view factors, system venting conductances, and the outgassing composition must be calculated and estimated.

In many cases, it is necessary to estimate the parameters well in advance of the flight or of the test-chamber measurements. In such cases, one may—with a knowledge of the geometry, configuration, and temperature of a payload instrument and with the availability of data on outgassing of major components of that payload—carry out an estimate of the outgassing source. This will provide an estimate of pressure vs time in the payload, the gaseous fluxes on internal and external surfaces, and the gaseous environment created around the payload. In addition, it is necessary for the evaluation of contamination hazards and the molecular column densities surrounding the payload to estimate the chemical composition of the outgassing. This is obtained from mass-spectrometer (M/S) measurements during the complete test of the payload or from M/S measurements for each component material and then summing the contributions. In all of these approaches, the results are very approximate due to the large number of materials, surface areas, temperatures, and geometric complexities of the payload. In many cases, the outgassing data for many materials are not available or are in a form not suitable for evaluation of the time-varying parameters. One must make use of data obtained using the ASTM E595-77 testing method employed to screen materials for space application. The use of that data cannot be used reliably for the derivation of material outgassing and its condensable content. However, using several assumptions, these data have been used to make estimates.[1]

It may become necessary, with the advent of the Space Shuttle and the space station, to predict those parameters which affect the payload itself and others in its vicinity, without vacuum test data or long-term analysis. This paper presents data on cumulative outgassing rates and chemical compositions measured for several payloads which have flown or will be flown. The availability of these data may provide a relatively rapid evaluation of the same parameters for other payloads. The data, with the appropriate modifications for the venting conductances of a payload under consideration, can provide the needed parameters with equal or better reliability than those obtained by analysis. For their use, in addition to a knowledge of the venting conductance of the payload, a comparison of the scientific functions, weights, and volumes of the payload being considered and those for which the data are available will be required. The available data were obtained from test measurements and, in a few cases, by analysis.

As shown herein, the data on global outgassing rates vs time and its chemical composition modified for the venting conductances and temperature, if necessary, will provide an estimate of the following flight-system parameters: 1) internal pressure vs time to indicate operative constraints on high-voltage operations and other pressure-dependent functions; 2) internal self-contamination of the critical surface; 3) pressure, den-

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Table 1 Outgassing of some space systems

Space system	Volume, liters	Weight, kg	Internal pressure, Torr	Mass rate, g/s	Throughput Torr liters/s	Measurement
HRS instrument	1.78×10^3	~317	$3.2\times10^{-3}t^{-0.84}$	$1.88\times10^{-5}t^{-0.84}$	$5.2t^{-0.84}$	Internal pressure in vacuum chamber
FOC instrument	1.78×10^3	~317	$3\times10^{-3}t^{-1}$	$1.76\times10^{-5}t^{-1}$	$6t^{-1}$	Internal pressure in vacuum chamber
FOS instrument	1.78×10^3	~317	$1.4\times10^{-3}t^{-0.8}$	$8.22\times10^{-6}t^{-0.8}$	$1.04t^{-0.8}$	Internal pressure in vacuum chamber
HSP instrument	1.78×10^3	~317	$2\times10^{-4}t^{-0.77}$	$1.18\times10^{-6}t^{-0.77}$	$0.45t^{-0.77}$	Internal pressure in vacuum chamber
AE-D S/C	1.65×10^3	679	$2\times10^{-3}t^{-0.89}$	$1.18\times10^{-5}t^{-0.89}$	$0.69t^{-0.89}$	
CTS S/C	1.08×10^4	340		$2.12\times10^{-2}t^{-1.3}$	$12.4t^{-1.3}$	Flux in vacuum chamber
IMP-H S/C	3.15×10^3	260		$7.9\times10^{-2}t^{-1.5}$	$45.8t^{-1.5}$	
Gemini 2 S/C				1.4×10^{-2}	14.0	Early outgassing in vacuum chamber
Gemini 3 S/C				4.2×10^{-3}	4.3	
Apollo S/C				3×10^{-2}	30.6	
ATM S/C				1×10^{-1}	1.02×10^2	
ISIS		145		$1.47\times10^{-3}t^{-1}$	$1.3t^{-1}$	
Shuttle STS-3	Bay: 3.5×10^5		$2.32\times10^{-3}t^{-1}$	$0.22t^{-1}$	$130t^{-1}$	Orbit closed bay[a]
Thiokol motor Star 27 in. in diameter				$7.1\times10^{-3}t^{-1.62}$	$1.21t^{-1.62}$	Flux measured in vacuum chamber

[a] Closed bay pressure was estimated from limited pressure gages and mass spectrometer measurements.

sities, fluxes, and contaminations produced in the vicinity of the payload; 4) column or mass density in the field of view of the same or nearby payloads; 5) molecular scattering with the ambient gaseous environment or self-scattering of the outgassing source; 6) data on vent requirements of an external container to prevent high pressures and contamination; and 7) an estimate of the propulsive effect and flow distribution of outgassing exiting from a vent passage.

Outgassing Rates of Instruments

Table 1 includes the outgassing rates vs time of four scientific instruments. The instruments, which are included in the Space Telescope, have approximately the same weight and are packaged in a volume of about 1.78×10^3 liters. Those rates were obtained from measurements with ion gages calibrated in terms of nitrogen pressure of the instruments' internal pressures while thermovacuum tests were being carried out in larger vacuum chambers. The measured internal pressures vs time are shown in Fig. 1. The figure indicates the number of tests carried out on each instrument and the test durations. The pressure P vs time and the conductance C of each instrument calculated in terms of nitrogen at 293°C provided the throughput $Q = CP$ listed in Table 1. The conductances were carefully calculated to meet certain requirements for the installation of these instruments in the aft shroud of the Space Telescope.[2] To ensure appropriate selection when using these data for other instruments, a description of their locations, functions, and general configurations follows.

The four instruments—high-resolution spectrometer (HRS), faint object camera (FOC), faint object spectrometer (FOS), and high-speed photometer (HSP)—are located behind the primary mirror at the focal plane of the Space Telescope. The telescope is a f/24 Ritchie Chretian system with a 2.4-m aperture. Each of the scientific instruments is roughly the size of a phone booth, i.e., about 3 × 3 × 7 ft, and weighs about 700 lb. They all incorporate optical systems and sophisticated electronics, some with built-in microprocessors and advanced materials to provide the needed thermal and structural precision and stability. The size and sophistication of each of these Space Telescope instruments are comparable to the complete orbiting spacecraft of not long ago. Thus, these instruments are representative of the complexity and hardware included in present-day payloads. Reference 2 gives a detailed description of each Space Telescope scientific instrument.

Outgassing of Spacecraft

Table 1 includes outgassing data on the following spacecraft (S/C).

Atmospheric Explorer-D (AE-D)

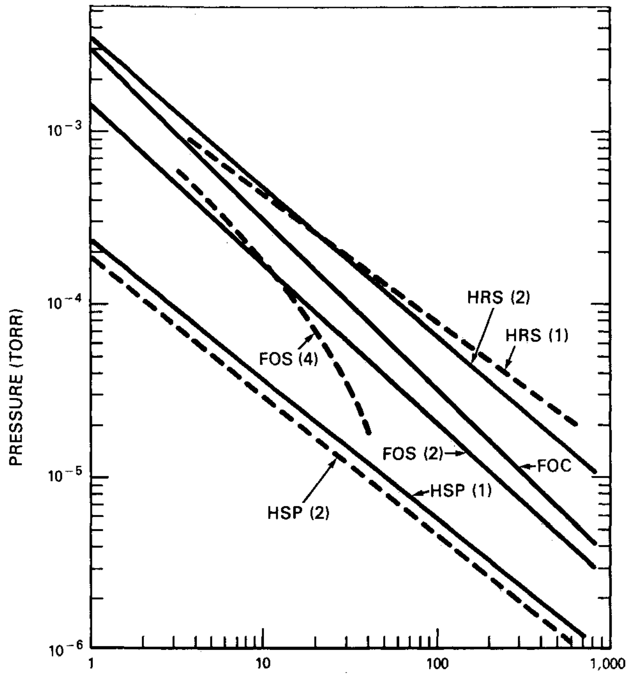
The outgassing rate of the AE-D S/C was obtained from the measurement of the internal pressure during the thermal vacuum with an ion gage and from an extensive evaluation of its venting conductance.[3] The AE-D was one of the three S/C of the Atmospheric Explorer program. It was launched on October 6, 1975, and carried 12 scientific instruments. These instruments are described in Ref. 4.

The AE-D S/C was a short, 16-sided polyhedron approximating a right cylinder of 136 cm in outside diameter, 114 cm high, and weighing 679 kg. As in the other AE S/C, the AE-D included an orbit-adjust propulsion system which consisted of three hydrazine thrusters providing the means to adjust the perigee and apogee altitudes and the circulation of the orbit. The S/C could be operated in the design and spin modes.

Canadian Technology Satellite (CTS)

The CTS outgassing data were obtained by integration of the outgassing flux measured by two back-to-back LN_2 cooled quartz crystal microbalances (QCMs) located 1 m from the surface of the S/C. One of the QCMs was facing the S/C, and the back QCM, faced the large wall of the test chamber. The QCMs indicated the accumulation vs time of the gaseous flux of molecules which condensed at the temperature of the crystals, in this case at about −190°C. The S/C was being rotated in step so that the QCM measured the flux from all S/C surfaces. The thermal test and outgassing measurement are described in Ref. 5. A polar plot of the flux, pressure, and density measured during the test is shown in that reference.

The CTS is a three-axis-stabilized S/C that orbits at synchronous altitude, performs an extensive series of communication experiments, and demonstrates the capability of a number of devices and techniques in space to advance communication technology. The satellite, with its expended apogee motor, weighs about 340 kg. Its approximate dimensions are: in the north-south direction, about 1.65 m; in the east-west, about 1.8 m; and from the motor tip to the gimbaled antennas, 1.6 m. These dimensions may be used to define an equivalent spherical satellite with a 137.25-cm radius.



LEGEND:

INSTRUM	DATE OF TEST	TEST DURAT.	COMMENTS
HRS1	4/83	440 HRS.	
FOC	3/82-12/80	170 HRS.	
HSP1	12/82	430 HRS.	
HSP2	5/84	240 HRS.	
FOS2	7/83	200 HRS.	DATA FROM TEST FOLLOW.
FOS4	7/84	30 HRS.	← 19 DAYS TEST-AVG. 2 GAGES
HRS2	9/84	468 HRS.	

Fig. 1 Space Telescope instrument internal pressures vs time at ambient temperature.

Interplanetary Monitoring Platform H (IMP.H)

The outgassing rates for this S/C were obtained[6] by two tabulated ion gages mounted on a frame attached to the gimbal rotating the S/C at 5 rpm. The gages facing opposite directions—one, the S/C; the other, the chamber wall—were located approximately 66 cm from the S/C surface. They were shielded to prevent heat radiations and instrumented with thermocouples. The pressure measurements by the gages were converted into fluxes and outgassing rates of N_2 as shown in Ref. 6.

The IMP S/C was a 16-sided, 1.57-m-long prism divided into three bands—the central bands included the electronic boxes of the experiments. The S/C weighed 260 kg with the empty motor case, and solar panels covered a major portion of its surface. It carried a plasma-wave experiment antenna, a magnetometer, and attitude control system booms which were all in their folded configurations for the tests. The sequence, duration, solar aspect, and other details of the test cycle are indicated on the chamber pressure vs time profile in Ref. 6.

Gemini, Apollo, and Apollo Telescope Mount

The data for these S/C were obtained from Ref. 8 which indicates a single outgassing rate. Outgassing rates obtained from vacuum chamber measurements appear to indicate that those rates apply to the early hours of vacuum exposure. The rates, somewhat larger than those for the other payloads, may reflect earlier (before 1969) S/C constructions when contamination was not recognized as a major problem.

International Satellite for Ionospheric Study (ISIS)

The outgassing rate of this small satellite (~145 kg) launched during 1965-1967 was estimated from available space chamber test data not intended for the evaluation of this parameter. The estimate was obtained using the method of conductance, which consists of the comparisons of pumpdown curves with and without the S/C and a knowledge of the chamber pumping speed. It indicates order of magnitude and may be representative of the outgassing of small payloads.

Shuttle Bay Gaseous Environment

The Shuttle bay molecular environment was obtained, as indicated in Ref. 7, from a limited number of measurements in the Shuttle bay, reported in Refs. 9 and 10, and from calculations of the venting conductances of the Shuttle bay. The time-dependent pressure in the Shuttle bay with the bay doors closed, and the outgassing rates indicated in Table 1, are baseline approximate values which do not include leaks, dumps, or other transient events.

The pressure equation reflects the interpolation of the gaseous measurements made with a thermocouple gage on the STS-1 and measurements carried out on the STS-3 flight with the gage of the Plasma Diagnostic Package (PDP) and the neutral ion-mass spectrometer of the induced environment contamination measurements (IECM). The thermocouple (V07P9084A), located in midfuselage, made measurements with the bay doors closed during the first 2.2 h of the STS-1 flight. The PDP gage provided pressure data at 126 h of the STS-3 flight when the bay was temporarily closed.[9] The M/S provided indications on the total pressure 167 h into the STS-3 flight when the bay doors were closed.[10] The nitrogen equivalent outgassing rates were derived using the pressure-time data and the calculated venting conductance of the bay. These data regarding the Shuttle should be considered preliminary, reflecting normal temperatures and a Shuttle bay with a limited payload complement as carried on the STS-1 through -5 flights.

Solid Propellant Motor Outgassing

This motor was used as the apogee kick motor for the CTS. The data reported here are those of a motor that had been fired and subsequently attached to the S/C for the proper dynamic and thermal simulation during test. The motor had been fired several months before the vacuum test. The dimensions of the motor were 69.34 cm in diameter and 121.92 cm long, weighing 332.04 kg when loaded with 305.36 kg of propellant. Other data are given in Ref. 11. The outgassing data were obtained from the vacuum chamber measurements of the flux emanating from the CTS S/C. As indicated previously, the outgassing flux was obtained with QCM at LN_2 temperature located 1 m from the motor exit. The total mass rate at the motor exit is an average at the centerline axis of the motor and at 45 deg on each side of the axis. The distribution appeared to follow a cos θ to a 6.98 power for angles between 0 and 45 deg. The molecular constituents were assumed to have an average molecular mass of $M \sim 100$ g/mole for the calculation of the outgassing parameters.

Outgassing Chemical Composition

Data are scarce with regard to the outgassing chemical composition. Indications of the normal gas composition in the Shuttle bay were obtained from the M/S measurements on STS-2, -3, and -4 and Spacelab 1 as reported in Refs. 10, 12, and 13. Table 2 shows the percentage compositions recorded in the STS-3 with the bay doors open and closed at 7, 94, and 167 h mission elapsed time (MET). The H_2O partial pressures corresponding to the return fluxes measured on the STS-4 with the bay door open at 5 and 140 h MET are indicated, as is the composition of the Reaction Control System (RCS) engine firing obtained during the M/S mapping of the STS-4. Thus, it appears that the outgassing composition for those flights may consist of less than 3.3% of H_2O and less than 0.15% for materials with 45-150 amu. With regard to the percentages of the high amu materials, one can reason that many of the materials in the bay are of the same nature as the polymeric

Table 2 Mass spectrometer measurements of outgassing masses, % of total

		STS-3 and -4 Shuttle bay				
		7.2 h[a]	167 h	94 h Reaction Control System Engine Firing	FOS instrument[c]	
amu	Gas	Open bay	Closed bay	Open bay	12 h	36 h
2	H_2	–	–	4.2		
4	H_e	24.9	18	–		
16	CH_4	5.5	3.53	–		
18	H_2O	1.6	3.3	23	48	32
17	NH_3	–	–	Trace		
28	N_2+CO	65	73	70	41.2	62
30	NO	0.05	–	–		
32	O_2	0.03	0.41	–	4.06	4.5
40	Ar	1.4	1.21	–		
44	CO_2	1.5	0.07	Trace	0.03	0.3
45-150	Hydrocarbon	0.02	0.15[b]		0.012	0.005

[a]Mission elapsed time. [b]Includes a large Freon leak. [c]Martin Marietta Co. data. NOTE: H_2O count rates in the open bay of STS-4 indicate source densities approximately equivalent to pressures of 7.7×10^{-9} and 1.5×10^{-10} Torr during return flux measurements at about 5 and 140 h MET. The H_2O time constant (1/e) was about 10 h.

materials, e.g., the adhesive RTV-566, paint S-13G, and other similar materials. The vapor pressure of these materials (methyl-pheniltrisiloxane) at normal temperatures is about 3×10^{-8} Torr (Ref. 2) which would be maintained in the bay with closed doors. This partial pressure, when compared to the M/S measurements' total pressure of 8.2×10^{-6} at 167 h MET with closed doors,[10,12] indicates that the outgassing fraction of these materials could have been less than about 0.36%. With the bay open, the preceding partial pressure would be less and the fraction of these components would approach the value of 0.02% measured with the doors open at 7 h MET. One may assume, therefore, that the partial pressure of molecules of high molecular masses, which may be a surface contaminant hazard, is less than 0.1% of the total pressure at all times. This is in accordance with the material selection criteria, which state that materials for space use should produce not more than 0.1% volatile condensable material on a 25° C collector when the sample material is at 125°C for 24 h in a vacuum. The available M/S measurements on these flights[10,12,13] indicated very low levels of molecules of high molecular masses (>50 amu). Molecules of high masses which were identified included those from trichlorethylene, Freon 12, and other hydrocarbons typical of chemically cleaned surfaces.[12] A relatively large flux of Freon 21 was indicated during the STS-4 flight. Masses greater than 50 amu were measured on the Spacelab 1 flight and were attributed to fractionation of tetrafluoroethane (C_2F_4) and Freon 114 ($C_2Cl_2F_4$).[13]

Measurements made with the M/S in the large space chamber at Martin Marietta Corporation while the FOS was being tested indicated the fraction of the molecular environment at 12 and 36 h after initiation of the vacuum test. Within the difficulties making these measurements, one can see from the data that the contaminants with mass greater than 45 amu have the same order of magnitude indicated in the Shuttle bay. This seems to indicate that the contaminant partial pressures and, consequently, their fraction of the total outgassing may be 10^{-3}-10^{-4} of the total outgassing.

Applications

The selection of the appropriate volumetric rate $Q(t)$ listed in Table 1 will have to be based on the volume, mass, and scientific functions of the payload (P/L). A perusal of those values shows that classes of P/Ls have similar outgassing rates. In any case, the data will provide a satisfactory estimate, probably better than a prolonged analytical estimation and comparable to those obtained from a vacuum test.

The data reflect outgassing at normal temperature ($T_0 \sim 293$ K). The throughput at higher or lower temperature T(K) can be estimated by modifying the given throughput Q_0, i.e.,

$$Q = Q_0 \exp - E/R\left(\frac{1}{T}-\frac{1}{T_0}\right) \quad \text{Torr liters/s} \qquad (1)$$

where $R=1.987$ cal/mole/K is the gas constant and E (cal/mole) is the outgassing activation energy. A 10% increase in absolute temperature will result in an approximate tenfold increase in throughput for a nominal activation energy of about 10 kcal/mole.

After the selection of $Q(t)$ and its modification for temperature, if necessary, the following parameters can be estimated.

1) The pressure vs time in a P/L can be calculated knowing $Q(t)$ and the venting conductance C of the P/L, which can be calculated using any of the classical formulas for the molecular conductances of geometrical passages.

The pressure is then

$$P(t) = Q(t)/C \quad \text{Torr} \qquad (2)$$

2) The outgassing molecular density in the P/L for isotropic conditions and constant temperature will be

$$n(t) = P(t)/KT \quad \text{cm}^{-3} \qquad (3)$$

where $P(t)$ (Torr), T (K) is the gas temperature, and $K=1.04\times10^{-19}$ Torr cm^3/molec/K is the Boltzmann constant.

3) The incident molecular flux on surfaces exposed to the random motion of the gas molecules is given by $\phi_D = n(t)v/4$ which, with the substitution for the average velocity v, becomes

$$\phi(t) = \frac{n(t)}{4}\left(\frac{8RT}{\pi M}\right)^{1/2} = \frac{3.5\times10^{22}P(t)}{(TM)^{1/2}} \quad \text{cm}^{-2}\text{s}^{-1} \qquad (4)$$

where $R=8.134\times10^7$ erg/K/gmole is the gas constant and M (g/mole) is the mass per mole of the gas (28 g/mole for N_2) and T (K). The corresponding mass flux per unit area will be

$$\dot{m} = \phi(t)\frac{M}{N} \quad \text{g/cm}^2\text{/s} \qquad (5)$$

where $N=6.023\times10^{23}$ molec/mole is Avogadro's number.

Contamination

Deposits on a surface of unwanted molecules defined here as contaminant will occur when a partial pressure of the contaminant is present in the environment. The accumulation may proceed until a balance is established between the molecules arriving and leaving the surface. If the conditions are such that the partial pressure P of the contaminant in the environment is less than the saturated vapor pressure P_s of the same contaminant at the temperature of the surface, an accumulation will occur by an adsorption process. The Langmuir absorption isotherm predicts that the accumulation will be

$$\sigma=\gamma\phi_i\tau \qquad \mathrm{g/cm^2} \tag{6}$$

where γ is a coefficient close to 1, ϕ_i (g/cm^2/s) [Eq. (5)] is the gaseous impinging flux, and τ the residence time. The residence time is $\tau=\tau_0 \exp E/RT$, where $\tau_0 \sim 10^{-13}$ s is an oscillation period of the molecule on the surface, E (cal/mole) is the activation or binding energy of the molecule on the surface at temperature T (K), and R (cal/mole/K) is the gas constant. A desorption of the contaminant occurs when the flux ϕ_i is removed. In this case, the deposited material leaves the surface according to

$$\sigma=\sigma_0 e^{-t/\gamma\tau} \qquad \mathrm{g/cm^2/s} \tag{7}$$

which is obtained by integrating Eq. (6), and where σ_0 is the initial equilibrium deposit and γ a sticking coefficient. A more accurate evaluation of the deposit coverage can be obtained by using the Brunauer-Emmett-Teller (BET) relation

$$\sigma=\sigma_m\frac{C\phi_i/\phi_L}{(1-\phi_i/\phi_L)[1+(C-1)\phi_i/\phi_L]}=\left(\frac{1}{1-P_i/P_L}\right)_{C\to\infty} \tag{8}$$

where $\sigma_m=(\rho N/M)^{2/3}$ is the monolayer density (cm^{-2}) for full surface coverage, which is characterized by the contaminant density ρ, Avogadro's number N, and the mass of the mole M. The other parameters in the foregoing equation are $C=\exp(E-E_v/RT)$, where E_v is the heat of evaporation of the contaminant, E the binding energy of the first layer of molecules to the surface, $\phi_i \simeq P_i$ the impinging flux of molecules at a partial pressure P_i, and $P_L \simeq P_s$ the flux leaving the surface, which is at a saturated vapor pressure P_s.

For the cases of condensation ($P_i>P_s$) and evaporation ($P_i<P_s$), the material on the surface at time t is

$$\omega=\gamma\int_{t_0}^{t}\phi_i\mathrm{d}t-\int_{t_0}^{t}\phi_L\mathrm{d}t \qquad \mathrm{g/cm^2} \tag{9}$$

where t_0 is the initial time when exposure of the surface to the impinging flux [$\phi_i=m_i$ (g/cm^2/s)] occurs and γ is a sticking (accommodation) coefficient. These fluxes are expressible in terms of pressure, temperature, and molecular mass, using the Langmuir expression

$$\phi=\frac{1}{4}nv=(5.83\times10^{-2}\sqrt{M/T}P=kP \qquad \mathrm{g/cm^2/s} \tag{10}$$

where P (Torr) is the pressure and k the expression in parentheses. With these substitutions, the deposit on the surface will be

$$\omega=k_i\cdot\gamma\int_{t_0}^{t}P_i(t)\mathrm{d}t-K_L\int_{t_0}^{t}P_L(t)\mathrm{d}t \qquad \mathrm{g/cm^2} \tag{11}$$

where $P(t)$ indicates that those pressures may be a known function of time. Equations (6) and (11) can be used to calculate the deposits of each contaminant on the surfaces as a function of time.

Deposits from Instruments' Outgassing

The condensable fraction of the outgassing from the instruments may be estimated to be on the order of 0.1-0.01% of the total outgassed material, as discussed previously. This fraction is based on the material selection criteria, which require that materials used for space application produce less than 0.1% condensable deposit on a surface at 25°C when that material is maintained at 125°C for 24 h in a vacuum of 10^{-6} Torr. The calculations for contaminant deposits can be made assuming partial pressures P_i of both 0.1 and 0.01% of the total pressure P.

Additional considerations can be made to characterize probable contaminants. A variety of materials in the instruments will be outgassing. Most of the outgassing, however, will originate from pottings, sealants, encapsulants, and coatings. These may be represented by RTV-566, a silicone sealant; RTV-602, also a silicone sealant; S-13G, a thermal-control paint that includes RTV-602 sealant; and DC-704 silicone oils. These materials are representative of methylpheniltrisiloxane (MPT), which, according to Ref. 14, has equivalent vapor pressures: $\log P_L=11.025-5570/T$, where P_L (Torr) and T (K). The slope of the equation provides data on the energy; i.e., $E=5570R/0.434=25.065$ kcal/mole, where $R=1.978$ cal/mole-K is the gas constant and $0.434=1/\ell n 10$ accounts for the logarithmic representation of the equation. The equivalent molecular mass is given as 484 g/mole. Other materials normally found as contaminants are dibutyl phthalate, which has a vapor pressure of about 10^{-4} at 25°C, and ethylhexyl phthalate (EP), which has a pressure of 2×10^{-7} at the same temperature. Both are relatively high-pressure materials, and their deposits would leave the surfaces before those of the RTV silicone. Reference 14 provides data on equivalent vapor pressures and corresponding evaporation energy for several materials.

The deposit of water on cold surfaces can be calculated in the same manner. The partial pressure of H_2O in the environment provides the impinging flux, and the vapor pressure of water at surface temperature provides the flux of the water leaving the surface.

External Induced Environment

The outgassing flowing out of the P/L will be given by

$$Q(t)=P(t)C \qquad \text{Torr liters/s} \tag{12}$$

where $Q(t)$ is the throughput listed in Table 1, $P(t)$ (Torr) is the pressure inside the P/L, and C (liters/s) is the venting conductance. More precisely, $Q(t)$ is the value in the table minus the throughputs which will be depositing on internal surfaces. This can be given by

$$\Sigma(q_i-q_L)=\Sigma\frac{992.5}{\sqrt{TM}}\gamma A_i[P_i-P_L] \qquad \text{Torr liters/s} \tag{13}$$

where $\gamma\sim1$ is the condensation coefficient, A_i the surface areas on which condensation occurs, P_i the contaminant partial pressure impinging on the surfaces, and P_L the partial of the contaminant at the surface temperature.

The throughput Q leaving the P/L may be impinging directly on an external surface and may produce a density in the external environment sufficient to contaminate nearby surfaces and obscure sufficiently the viewing of an optical instrument. The surface flux will be a function of the surface view factor to the outgassing source, or it may be a function of other passage or obstructions that may prevent the gas from expanding freely in space. In either case, the preceding expressions can be used with available computer modeling programs, e.g., Ref. 15, or with the equations indicated below, which include several simplifying assumptions to evaluate the various parameters describing the environment.

The density drop with distance from an assumed hemispherical gaseous source can be estimated by

$$\frac{n}{n_0}=\frac{3}{2}\exp\left(\frac{-4\alpha R}{\lambda_0}\right)(1+\alpha)^{-2} \tag{14}$$

where $\alpha=x/R$ with x (m) being the distance from the surface of the hemisphere of radius $R(m)$ where the density is n_0 (cm^{-3}) $=Q/CKT$ and λ_0 the gas mean-free path at the flight orbit.

The return flux ϕ_R, produced from the scattering of the emitted molecular flux ϕ_D with the ambient molecules and particles having a mean free path λ_0, can be estimated using the relation

$$\phi_R = \phi_D (R/\lambda_0)[(v_s/v_D + 1)] \sim 21(R/\lambda_0)\phi_D \qquad \mathrm{cm^{-2}s^{-1}} \qquad (15)$$

where $v_s = 8$ km/s is the orbit velocity and $v_D \sim 0.4$ km/s is the average velocity of the emitted molecules.

The scattering flux of the outgassed molecules among themselves is approximately given by

$$\phi_{ss} = 1.78 \times 10^{-2}(\sigma R/v_D)\phi_D^2 \qquad \mathrm{cm^{-2}s^{-1}} \qquad (16)$$

where σ (cm^2) is the average cross section of the outgassing molecules.

The molecular column density N_c (cm^{-2}), representing the number of molecules in a column with a 1-cm^2 cross section extending from the source to infinity, can be estimated using the relation

$$N_c = \left(\frac{\lambda_0}{v_s}\right)\phi_R \sim \left(\frac{R}{v_s}\right)\phi_D \sim nR \qquad \mathrm{cm^{-2}} \qquad (17)$$

where all of the terms have been defined previously.

The propulsive effect of the outgassing emanating from a vent is

$$F = \dot{m}v = \left[\frac{QM}{P_0 V_0}\right]v \qquad \text{dynes}$$

where $\dot{m}$ (g/s) is the throughput, M (g/mole) is the mole mass of outgassing, $P_0 = 760$ Torr, $V_0 = 22.4$ liters/mole, and v is exit velocity of the gas which is a function of the temperature and molecular mass. The propulsive component of the flow out of the vent must be considered in the calculation of this parameter. The geometry of the vent and the flow regime establish the flow distribution and the propulsive component. For a thin orifice and a flow in the molecular regime, the exit flow has a cosine distribution. Other geometries for the same flow regime produce distributions described by some power of the cosine.

Conclusions

The experimentally measured outgassing vs time of a number of instruments, spacecraft, and a motor has been provided. The scientific instruments of sizes comparable to early spacecraft are of recent design and include approved materials. The outgassing data, with appropriate modifications for temperature and ventings, are intended to provide the tools to estimate the internal pressure, self-contamination, and external gaseous environment created by payloads. The data will be especially valuable for estimating the outgassing of payloads which are not or will not be exposed to vacuum testing before flight, and for predicting the global environment produced by several payloads in a confined volume. The application of the data for the calculation of the pressures, contamination, column densities, and other parameters which are dependent on the outgassing of a payload has been shown.

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