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Particulate Contamination in a  
Space Instrument Application to a  
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ABATEMENT OF GASEOUS AND PARTICULATE CONTAMINATION IN A SPACE INSTRUMENT  
APPLICATION TO A SOLAR TELESCOPE

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Abstract

Contaminants from sources external or internal to an instrument may degrade its critical surfaces and/or create an environment which limits the instrument's intended performance. Analyses have been carried out to investigate methods to prevent the ingestion of external contaminants into the instrument and to limit the effect of the self-generated contaminants during ground, launch, orbiting and landing phases of flight. It is proposed that a positive pressure and purging flow of clean gas inside the instrument be maintained while on the ground, during launch, and for a period of time in orbit. The pressure to be maintained and the required purging flow are examined in terms of the effectiveness in preventing gaseous and particulate contaminants ingestion and the abatement of the self-generated contaminants. Considerations have been given to the venting requirements for the structural integrity of the instrument during launch, the limitations on the volume and the pressure of the purging gas to be carried along in orbit, and the requirements to operate the instrument after a reasonable time in orbit. The required venting area is established based on the internal volume of the instrument, the allowable pressure differential, and the rate of external pressure change during launch. Relationships have been developed for the time dependence of the diffusion of external contaminants into the volume in terms of the volume, vent area, depth of vent passage, volume characteristic dimensions, molecular mass of contaminants, and internal purging pressure. The exclusion of particulates is based on drag forces induced by the density and velocity of the purging gas. The volumetric flow requirements are established for the indicated vent area and purging pressure. The abatement of self-induced contamination is predicated on the partial suppression of the materials outgassing and the scattering and transport of its products out of the volume by the purging density and flow. Full internal outgassing occurs when the outside environment has improved, the purging is stopped, and the instrument is fully open. The results of the analysis have been applied to a telescope which is very sensitive to contaminant deposits on energy reflecting surfaces and to other equally contaminant sensitive systems.

It is proposed to utilize gaseous purging available from <sup>30000 PSI</sup> ~~compartments~~ attached to payloads or from service facilities on the Shuttle to prevent contamination of an instrument. The purge can disperse and prevent the entrance of external contaminants to critical locations of the instrument while it is on the ground and during launch, reentry and the early hours of the flight when contamination hazards are at their maximum. It can also prevent self-contamination of the instrument by reducing the outgassing of the internal surfaces, and by sweeping out those outgassed molecules and residual contaminants from surfaces. The benefits, limitations, and operational parameters have been discussed in the paper. An application of the purging is carried out for a large telescope which will be making solar observation from the Shuttle bay. Several factors which influence the choice of the purging parameters have been examined, namely: (1) the venting requirements necessary to limit the pressure differentials caused by the rapid pressure drop occurring during the transonic region of the launch, (2) the operational constraints on the length of time during which the purging and the natural self-outgassing of the instrument can be accomplished; (3) the quantity, volume and pressure of the purging gas which can be carried in orbit; (4) the gas flow which would not create in the bay a high pressure while the bay doors are closed; and would not be a source of propulsive effect. The analysis examines the following parameters: (1) the vent area requirements for the launch conditions; (2) the diffusion of external gases into a pressurized volume via a vent passage; (3) the partial pressure of external gases which can build-up in a volume under purging conditions; (4) the outgassing of materials in the volume under pressure; (5) the deposit of contaminant and its effect on the absorptive property of the surface; (6) the flow requirements to maintain a pressure in the volume and finally, (7) the sizes and velocities of particulates which can be stopped and blown away by the purge gas velocity and density. The results of the purging analysis as applied to the telescope protection during ground launch, orbit and deorbiting phases of the flight are reported. A summary and recommendation completes the paper.

Introduction

An instrument or a system may be degraded by gaseous and particulate materials deposited on its internal or external surfaces. The degradation results from changes in thermo-optical properties of the contaminated surfaces. The contaminant modifies the absorption, reflectance and scattering of the incoming radiations. The instrument performance may be degraded also because of absorption, reemission and scattering of certain radiation by the molecular and particulate medium in its field-of-view. The contaminants may originate from several sources: residues of machining and assembly operation, handling; exposure to polluted environment; release of weakly bound molecules from materials under vacuum conditions; exhaust products of nearby propulsive or discharge systems; micrometeorites impacts on materials; abrasion of moving parts; oxidation/degradation of materials and others. Many precautions have been employed to reduce the generation of those contaminants and their effects in space flights. However, several have depended on the availability of time to allow the environment to become acceptable and the instrument to dissipate its own outgassing and clean itself. With the advent of the Shuttle, the environment of an instrument located in its bay is affected by other nearby systems and by the many service functions to be performed by the Shuttle. In addition, the time available for an instrument attached to the Shuttle to accomplish its mission, has been curtailed to the order of weeks at least for now. The delay tactic cannot be employed. On the other hand, the Shuttle has provided many other benefits: reflights with refurbishment of instruments and systems; hands-on in orbit for corrective actions and operation; and, more important, it can carry many payloads and ancillary devices and systems.

Venting Area

The flow fields surrounding a structure during atmospheric flights produce pressure distributions which determine the rates of energy and mass transfer through vents. The flow rates through the vents are sensitive to the pressure variations at the vents. Insufficient venting and improper locations may subject a compartment to high pressure differentials and structural failures. The differential pressures can be limited by using favorable vent paths, vent areas, orifice configurations and locations. A suitable approach to the vent of a compartment is to design the compartment to have a flow response time comparable or faster than the external flow field disturbance time. The author employs the following to estimate the pressure differential at a volume produced by an external pressure drop rate  $dP/dt$  occurring at a base pressure  $P_0$ . Assuming isothermal flow conditions and small pressure differentials, the conservation of mass applied to the gas in volume  $V$  venting through an orifice of area  $A$  and discharge coefficient  $C_D$  is  $d(\rho V)/dt = \rho v A C_D$ , where  $\rho$  is gas density and  $v$  its velocity at the orifice. The density in terms of pressure and temperature using the gas law is  $\rho = P/RT$  and its derivative is  $d\rho/dt = 1/RT \cdot dP/dt$ . The gas velocity is  $v = \sqrt{2gh} = \sqrt{2g(\Delta P/\rho)} = \sqrt{2gRT(\Delta P/P)}$ . The substitution of these expressions in the above relation where  $V$ ,  $A$  and  $C_D$  are constants, give

$$\frac{dP}{dt} = \frac{A C_D P}{V} \sqrt{2gRT (\Delta P/P)} \quad (1)$$

Solving for  $\Delta P$ , one has

$$\Delta P = \frac{1}{2gRT} \left( \frac{V}{A C_D} \right)^2 \frac{(dP/dt)^2}{P} \quad (2)$$

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or the ratio of  $V/AC_D$  which produces a pressure differential when the external pressure drop rate is  $dP/dt = P$  and the pressure is  $P = P_0$ , is given by

$$\left(\frac{V}{AC_D}\right) = \sqrt{2gRT(P_0 \Delta P/P^2)} \quad (3)$$

In this expression  $g = 9.81 \text{ (m/s}^2\text{)}$  is the acceleration of gravity,  $R = 29.2 \text{ (m}^2\text{/K)}$  is the gas constant for air and  $T \text{ (K)}$  is the gas temperature. The orifice coefficient  $C_D$  can be taken conservatively to be about 0.6. It can be shown that these relationships relate the time constant of the volume-orifice system with the time involved in the external flow field change. The evaluation of the required vent area requires a knowledge of  $\dot{P}$  and  $P_0$  and the specification of an acceptable  $\Delta P$ . Experimental measurements of pressures versus time on a spacecraft have been used to specify  $\dot{P}$  and  $P_0$ . Alternatively, flow field analyses based on configuration and trajectory of the vehicle have provided these parameters.

The above equation provides the size of the vent area which allows a certain pressure differential to occur in a volume during the launch phase of the flight. Unless the vent area can be changed during other phases of flight and on the ground, the area size so established, becomes basic to the purging flow requirements and the protection against contaminants in a system.

#### Penetration and Diffusion of an External Gas into a Pressurized Volume

The mass increase with time into a volume  $V \text{ (cm}^3\text{)}$  via a film of thickness  $d \text{ (cm)}$  and area  $A \text{ (cm}^2\text{)}$  of a gas at density  $\rho_0 \text{ (g/cm}^3\text{)}$  can be expressed by the equation

$$V \frac{d\rho}{dt} = \frac{DA}{d}(\rho_0 - \rho) \quad (4)$$

where  $D \text{ (cm}^2\text{/s)}$  is the diffusion coefficient of the entering gas through another gas representing the film. The solution of this equation for  $\rho = \rho_0$  at  $t = 0$ , which can be verified by substitutions, is

$$\rho = \rho_0(1 - e^{-t/\tau}) \quad (5)$$

where  $\tau_D = dV/DA \text{ (s)}$  is the time constant which corresponds to the time when  $\rho/\rho_0 = (1 - 1/e) = 0.632$ . The diffusion coefficient from kinetic theory of gases, (reference 1) is  $D = \lambda c/3$  where  $c \text{ (cm/s)}$  is the average velocity of the gas, and  $\lambda \text{ (cm)}$  is the mean free path of the gas. The velocity is given by  $c = \sqrt{8kT/\pi m}$  and the m.f.p. by  $\lambda = kT/\pi\sqrt{2}\delta^2 P$  where  $k$  is the Boltzman constant and the characteristics of the gas are given by the temperature  $T \text{ (K)}$ , the molecular mass  $m \text{ (g/molec)}$ , the molecular diameter  $\delta \text{ (cm)}$  and  $P \text{ (torr)}$  is the pressure. The expression for the diffusion coefficient with these substitutions becomes

$$D = \frac{2}{3} \frac{1}{\delta^2 P} \sqrt{\frac{k^3 T^3 N}{\pi^3 M}} \quad (\text{cm}^2/\text{s}) \quad (6)$$

where  $N$ , the Avogadro number and  $M$  the mole mass have replaced  $m = M/N$ . An equivalent value or reduced mass of  $M$  and  $\delta$  is needed to calculate the diffusion coefficient of two gases. The diameter  $\delta$  must reflect combined forces between the two molecules in addition to the molecular sizes. Experimental data are available in the literature (references 2 and 3) giving the coefficient  $D_0$  for several combinations of gases at a temperature  $T_0$  and pressure  $P_0$ . An approximate value of the coefficient at different temperature  $T$  and pressure  $P$  and for the gases having an equivalent molecular mass  $M$  can be calculated by modifying the theoretical expression for  $D$ , i.e.

$$D = D_0 \frac{P_0}{P} \left(\frac{M}{M_0}\right)^{1/2} \left(\frac{T_0}{T}\right)^{3/2} \quad (7)$$

The experimental value of  $D_0$  for  $\text{H}_2\text{O}$  diffusing into air at atmospheric pressure ( $P_0 = 760 \text{ torr}$ ) and at  $T = 273 + 20 = 293\text{K}$  is  $D_0 = 0.24 \text{ cm}^2/\text{s}$

The time constant  $\tau_D = dV/AD$  applicable to the diffusion of a gas through a layer,  $d$  of air into a volume  $V$  can be written with the above substitutions as,

$$\tau_D = \frac{dV}{AD} = \frac{P}{D_0 P_0} \left(\frac{M_0}{M}\right)^{1/2} \left(\frac{T}{T_0}\right)^{3/2} \frac{dV}{A} \quad (8)$$

and for water vapor diffusing into air at  $20^\circ\text{C}$ , the time constant is  $\tau_D = (P/0.24P_0)(dV/A)$ . This expression which reflects the pressure, the opening area, the passage thickness and the volume, has been plotted in Figure 1 in terms of  $V/A$  and pressure  $P$ . The plot is for  $d = 1 \text{ cm}$  so that for other values of  $d$ , one should multiply by  $d \text{ (cm)}$  and for other temperature and masses by the ratio shown by the theoretical equation for  $D$ .

The previous time constant reflects the penetration through the entrance to the volume. It may be necessary for a large volume to consider the variation of the density  $\rho$  at a location  $\ell$  from the surface of the volume or in the present case from the surface immediately after the entrance. This can be estimated using the time dependent, one dimension diffusion equation  $d\rho/dt = D d^2\rho/dx^2$  where  $D$  is the diffusion coefficient. The solution of this equation for the uniform diffusion of the density  $\rho_0$  from a large surface to a surface  $2\ell$  distant from it is (reference 1, page 581).

$$\frac{\rho}{\rho_0} = 1 - \frac{8}{\pi^2} \left[ e^{-(\pi^2 D/4\ell^2)t} + e^{-(9\pi^2 D/4\ell^2)t} + e^{-(25\pi^2 D/4\ell^2)t} + \dots \right] \quad (9)$$

It is shown that for  $Dt/\ell^2 > 0.089$ , the second term in bracket is less than 2% of the first term.

Hence for long time  $t$  and relatively small  $\ell$ , the solution to a first approximation can be written as

$$\frac{\rho}{\rho_0} = 1 - \frac{8}{\pi^2} e^{-t/\tau_D} \quad (10)$$

where  $\tau_D = 4\ell^2/\pi^2 D$  is a characteristic time. For  $t = \tau_D$  the density is  $\rho \approx 0.70 \rho_0$ , so  $\tau_D$  has not the same significance of the time constant defined as the time when  $\rho \approx 0.64 \rho_0$ . The error which will be made with the assumption that the characteristic time has the same meaning of the usual time constant, can be determined by its comparison to the penetration time constant. This pseudo-time constant can be expressed with the substitution for  $D$  as

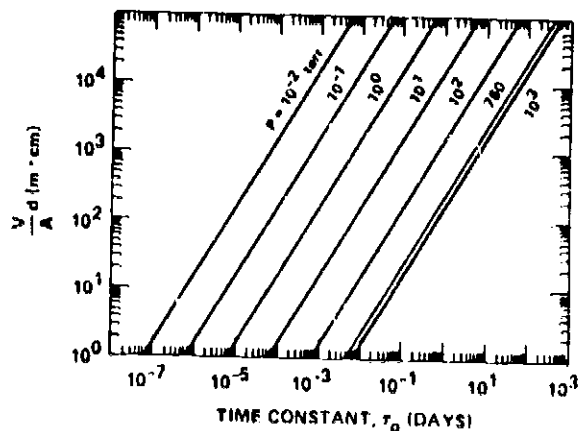


Fig. 1 Time constant for penetration of  $\text{H}_2(\text{g})$  in a volume  $V \text{ (m}^3\text{)}$  with air at pressure  $P \text{ (torr)}$  via an opening of area  $A \text{ (m}^2\text{)}$  and depth  $d \text{ (cm)}$

$$r_D = \frac{4R^2}{\pi^2 D} = \frac{P}{P_0 D_0} \left( \frac{M_0}{M} \right)^{1/2} \left( \frac{T}{T_0} \right)^{3/2} \left[ \frac{4R^2}{\pi^2} \right] \quad (11)$$

The above has been plotted in Figure 2 for the diffusion of water vapor into air at 20°C in terms of the pressure P and for R varying from 0.2 m to 6 m.

With the above assumptions, the total time constant  $\tau$  for a gas to penetrate the entrance of the volume, fill it up and diffuse to a distance R, is the sum of the two time constants since the flow resistances are in series, or

$$\begin{aligned} \tau &= \tau_p + \tau_D = \frac{Vd}{DA} + \frac{4R^2}{\pi^2 D} \\ &= \frac{P}{P_0 D} \left( \frac{M_0}{M} \right)^{1/2} \left( \frac{T}{T_0} \right)^{3/2} \left[ \frac{Vd}{A} + \frac{4R^2}{\pi^2} \right] \end{aligned} \quad (12)$$

A comparison of the values of  $\tau_p$  and  $\tau_D$  can be obtained by using these data:  $V = 350 \text{ m}^3$ ,  $A = 0.5 \text{ m}^2$ ,  $d = 0.1 \text{ m}$ ,  $R = 2.5 \text{ m}$ ,  $P = 760 \text{ torr}$  and  $D_0 = 0.24 \text{ cm}^2/\text{s}$ . These values are representative of the shuttle bay and the time constants which may represent the time for the diffusion of water vapor in the shuttle bay at the normal condition of pressure and temperature. It is found that  $\tau_p$  is about 33.7 days and  $\tau_D$  about 0.305 day indicating a total time constant of about 34 days. The time constant, disregarding the diffusion, would be about 3.6 days with  $d = 10^{-2} \text{ m}$ . This compares favorably to the time constants obtained from a series of experiments on humidity infiltration in a volume via thin orifices (reference 4).

#### Equilibrium Partial Pressure of a Contaminant Gas in a Volume Under Purging Condition

The partial pressure P of a gas at pressure  $P_0$  infiltrating and diffusing in a volume, while a purging flow Q is opposing the infiltration, can be obtained from the equation expressing a mass balance in the volume under isothermal conditions,

$$V \frac{dP}{dt} = C(P_0 - P) - QP \quad (13)$$

where C is the conductance for the inflow of the contaminant. Rearranging the equation and noting that  $C/V = 1/\tau$  is the infiltration and diffusion time constant and  $Q/V = 1/t_p$  is the change of purged volume per unit time, the above equation can be written

$$\frac{dP}{dt} = \frac{P_0 - P}{\tau} - \frac{P}{t_p} \quad (14)$$

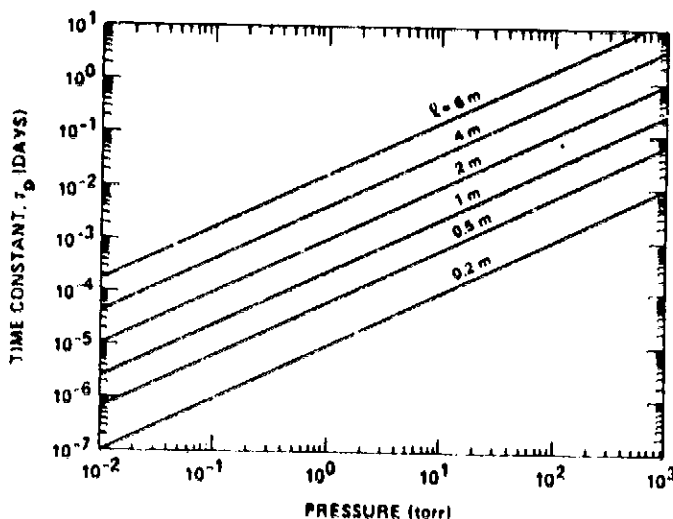


Fig. 2 Pseudo-time constant for  $\text{H}_2\text{O}$  diffusing to a distance R(m) in a large section volume containing air at pressure P (torr).

This equation can be solved to provide the contaminant pressure in the volume as a function of time. However, the equilibrium maximum pressure, which can occur when  $dP/dt = 0$ , will be

$$P = \frac{t_p}{t_p + \tau} P_0 \quad (15)$$

If  $t_p \ll \tau$ , and one ignores the diffusion portion of the infiltration time constant, the contaminant pressure in the volume as given by the above equation can be approximate by  $P \sim (D/\rho v d) P_0$  where D is given by equation (7), v is the exit velocity of the purging gas at density  $\rho$  and d is the depth of the passage.

#### Effect of Pressure on Outgassing of Materials

The outgassing of materials is characterized by:

- The nature of the material; for a given material, the outgassing is a function of the surface treatment and the atmospheric composition to which it was exposed.
- The outgassing is proportional to the surface area and increases exponentially with temperature and decreases slowly with time and apparently never becomes zero at ambient temperature.
- The outgassing rate of a material is independent of the total gaseous pressure on the surface when this pressure is less than about  $10^{-3}$  torr. This behavior has not been established with complete certainty but it is valid as a first approximation.

The effect of the total pressure on the outgassing can be evaluated by considering the "survival relation" which gives the probability of the number of molecules N out of a total  $N_0$  which will reach a distance x from their origin given that the mean free path of the gas is  $\lambda$ . The equation is  $N = N_0 e^{-x/\lambda}$ . The number of molecules which will have made a collision and are scattered within the distance x are,  $N_0 - N = N_0(1 - e^{-x/\lambda})$  so that for  $x = \lambda$ , 64% of the molecules will be scattered. The mean free path or average distance per collision for a gas at density n ( $\text{cm}^{-3}$ ), pressure P (torr) and temperature T (K) is given by  $\lambda = 1/\sqrt{2} n \sigma = kT/\sqrt{2} \sigma^2 P$  (cm) where k is the Boltzmann constant and  $\sigma$  (cm) is the effective molecular diameter. A plot of  $\lambda$  as a function of pressure for several gases is shown in Figure 3. A large size

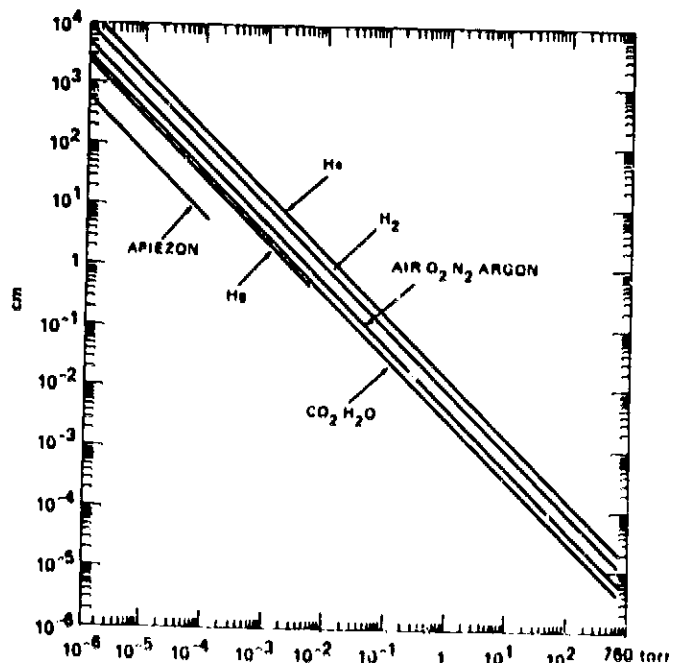


Fig. 3 Mean free path as a function of pressure at 20°C

molecule or a chain of molecules as those released by polymeric materials, would have a smaller mean free path than that offered by air or N<sub>2</sub> to a similar molecule. The mean free path for a N<sub>2</sub> purging pressure at 1 torr is about 4x10<sup>-3</sup> cm and 64% of the outgassed molecules would be scattered within this distance. A large fraction of those scattered molecules would return to their surface of origin and the outgassing rate would be reduced. Few data are available to indicate the reduction of outgassing or of distillation-evaporation at high total pressures. Dushman (reference 1, page 21) reports data obtained by Hickmann on the distillation of Octoil at temperatures of 368, 383 and 393K with residual air pressures on the Octoil varying from 3x10<sup>-4</sup> to 5x10<sup>-2</sup> torr. The data show for example that when the saturated vapor pressure of the Octoil was 1x10<sup>-2</sup> torr, and the air pressure on the surface was 5x10<sup>-2</sup> torr, the rate of distillation was 20% of that with a residual gas pressure of 3x10<sup>-4</sup> torr. Another evidence of the effect of pressure on reducing outgassing can be obtained by comparing the rate of evaporation of water under vacuum and at atmospheric pressure. A semi-empirical equation for the evaporation of water per unit area when the atmospheric pressure is P<sub>0</sub> is reference (5).

$$W_a = \frac{\alpha}{P_0} (P_s - P_{va}) \quad (\text{kg/hr/m}^2) \quad (16)$$

where  $\alpha = 24 \text{ kg/hr/m}^2$  for no wind conditions and  $\alpha = 29$  when wind exists, P<sub>s</sub> is the saturation vapor pressure of the water at temperature T, and P<sub>va</sub> the vapor pressure in the air. This equation can be compared to the rate under vacuum given by the Langmuir equation

$$W_v = 5.833 \times 10^{-2} \sqrt{M/T} (P_s - P_{va}) \quad (\text{g/cm}^2/\text{s})$$

$$= 5.18 \times 10^2 (P_s - P_{va}) \quad (\text{kg/hr/m}^2) \quad (17)$$

where M = 18 (g/mole), T = 293K and P (torr). If one lets P<sub>va</sub> = 0 in both the equations, their ratio indicates that

$$W_a = \frac{4.63 \times 10^{-2}}{P_0} W_v \quad (18)$$

where P<sub>0</sub> (torr). This relation which has been plotted in Figure 4 for convenience, indicates that at P<sub>0</sub> = 760, W<sub>a</sub> = 6.09x10<sup>-5</sup> W<sub>v</sub> and the two rates are equal when P<sub>0</sub> = 4.62x10<sup>-2</sup> torr. According to reference (6) the rate of water evaporation at STP is probably 10<sup>-2</sup>-10<sup>-3</sup> the rate under vacuum and according to reference (7) is about 10<sup>-4</sup>. In any case, all these considerations show that the outgassing will be reduced considerably under a total pressure which provides a small mean free path. Two more effects of high pressure are important. The survival relation shows also that the flux  $\phi = \phi_0 e^{-x/\lambda}$  at a distance x from the source when the m.f.p. is  $\lambda$ , so that at x = 10 $\lambda$  for example, the contaminant outgassing is a very small fraction of the surface flux and it

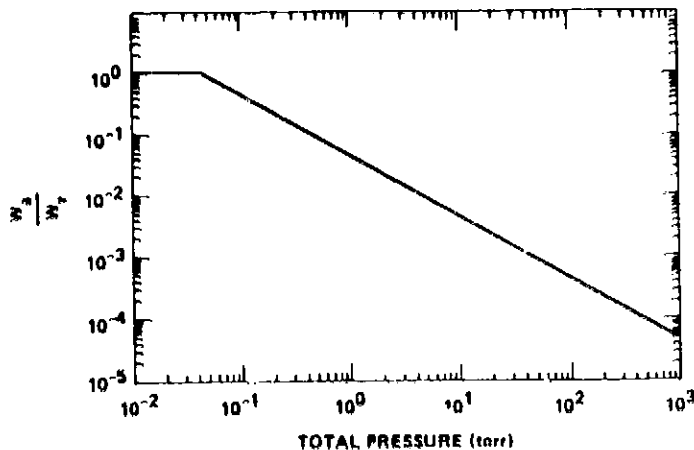


Fig. 4 Estimated fraction of maximum material outgassing rates as a function of the total pressure on the surface.

has been mixed randomly within the gas. If a purging is present these scattered molecules will be also transported by the purging flow

#### Particles Rejection by a Vent Gas

The velocities of particulates approaching an instrument may be

- Terminal velocities of particles falling in a gravity field through a medium at density  $\rho$  and viscosity  $\eta$ . As shown in Figure 5, terminal velocities of large particles (~0.1 cm) may be 4-5 m/s at normal ambient conditions.
- Velocities which the particles have acquired from a gaseous medium as for example by wind or by cleanroom air flows. Particles velocities in horizontal cleanroom facilities may be of the order of 1 m/s.
- Velocities of particles produced by propulsive systems. These particles may approach sonic velocities or supersonic velocities ( $v = \sqrt{2\gamma RT/\gamma-1}$ ) of gases at T(K) with specific heat ratios  $\gamma$  which can be of the order of 2-3 km/s.
- Velocities of particles ejected from the impact of meteorites on surfaces. The meteorites may be traveling at average velocities of 15-20 km/s. Some ejecta may acquire these velocities if the meteorites have sufficient energy to overcome the various forces holding the particles (van der Waals, Coulombic, adhesion, etc.) and to impart a kinetic energy to the released particles. However, it is estimated that in general particles released in orbit by the Shuttle are a few meters per sec (reference 8).
- Velocities of particles ingested via Shuttle filters during reentry which could have values approaching reentry velocities.

In order to evaluate the effectiveness of a purging gas in preventing particles from entering an instrument via a vent area, the following analysis has been carried out.

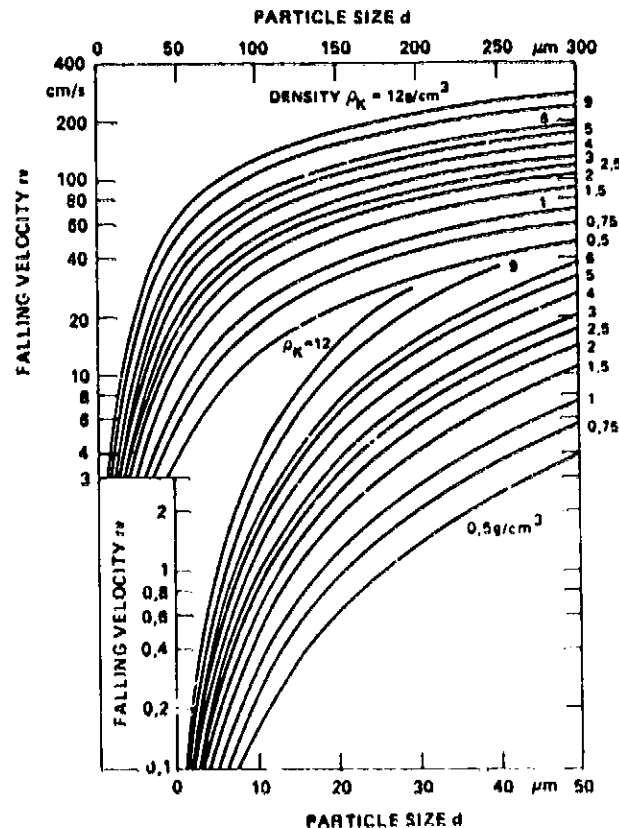


Fig. 5 Falling velocity of spherical particles in air.

The terminal velocity of a falling particle is obtained when the particle weight equals the drag force on the particle i.e., when  $mg = F_D$ . The drag force is a function of the Reynold's number  $R = \rho v d / \eta$  where  $\rho$  ( $\text{kg/m}^3$ ),  $\eta$  ( $\text{Pa}\cdot\text{s}$ ) are the medium density and viscosity respectively,  $v$  ( $\text{m/s}$ ) and  $d$  ( $\text{m}$ ) are the velocity and diameter of the particle. The dynamic viscosity varies with temperature and will vary with pressure when the particle dimensions are comparable to the mean free path in the medium. For a  $R < 10$ , the drag force is given by Stokes law,  $F_D = 3\pi\eta v$ . For  $10 < R < 10^3$ , the drag is  $F_D = C_D(\pi d^2/4)\rho v^2$  where  $C_D$ , the drag coefficient is a function of  $R$  and the shape of the particle (reference 9). The terminal velocities are then given by

$$v_t = \frac{\rho_p g d^2}{18 \eta} \quad (\text{m/s}) \quad (19)$$

if Stokes law applies or, in the other case by

$$v_t = \sqrt{\frac{4}{3} \frac{d}{\rho} \frac{\rho_p g}{C_D}} \quad (\text{m/s}) \quad (20)$$

In these equations  $\rho_p$  ( $\text{kg/m}^3$ ) is the density of the particle. If one assumes that a particle is moving at a velocity  $v_e$  through a gas moving in the opposite direction at velocity  $v_a$ , the drag force on the particle will be  $F_D = k(v_a + v_e)$ . The constant  $k$  is the constant in Stokes force and  $(v_a + v_e)$  is the velocity of the particle relative to the gas stream. The equilibrium equation in that case will be  $k(v_a + v_e) = mg$ . If  $v_a = 0$ , then  $v_e = v_t$ , the terminal velocity. For  $v_a \neq 0$ , dividing  $k(v_a + v_e) = mg$  by  $kv_t = mg$ , one obtains  $v_a + v_e/v_t = 1$ . This indicates that to stop the approaching particle ( $v_t = 0$ ), one needs a gas velocity  $v_a = -v_e$ . For the purge gas to make the particle move away with a velocity equal and opposite the terminal velocity ( $v_e = -v_t$ ), one needs a purge gas velocity ( $v_a = 2v_t$ ), i.e., two times the terminal velocity.

For the calculations on the sizes of the particles which can be stopped by a purge flow, one may assume conservatively, that only those which can be given a velocity  $v_a/2 = v_t$  will be prevented from entering the instrument. This assumption should insure that the arresting will occur far from the vent exit and compensate for the fact that the above analysis applies to the case of Stokes drag and not the case when the drag is proportional to the square of the particle velocity. With these assumptions, the size of the particles which can be prevented from entering can be estimated using the previous equations for terminal velocities with the substitution  $v_t = v_a/2$ , i.e.,

$$d = \sqrt{\frac{18\eta}{\rho_p g} \frac{v_a}{2}} \quad (\text{m}) \quad (21)$$

or

$$d = \frac{3}{4} \frac{C_D \rho}{\rho_p g} \left(\frac{v_a}{2}\right)^2 \quad (\text{m}) \quad (22)$$

The appropriate equations to be used is determined by the Reynolds number. One may note that the maximum velocity of a gas at the throat of an orifice will be a sonic velocity ( $\sim 310$  m/s for Nitrogen gas at normal temperature). So, certain particles moving at these velocities can be stopped by the purging flow.

#### Rejection of Natural Atoms and Molecules at the Entrance of an Open Instrument

An instrument open to space such as a telescope, is exposed to the flux of the natural atomic and molecular gases. The flux which is the product of the density and the relative velocity between the instrument and gas can be very high when the instrument is pointing into the velocity vector of the spacecraft. As recently reported in reference (10), fluxes of atomic oxygen at Shuttle orbital altitudes have been sufficiently high to cause oxidation and aging of several materials. The losses have been quite high considering the relatively short time ( $\sim 3 \times 10^4$  s) exposure of the materials to the high oxygen fluxes.

The avoidance of these high fluxes into an instrument or over a surface can be prevented with a low purging non-contaminating gas. The purge gas must scatter and reflect the incoming gas within a convenient distance from a criti-

cal surface. This purging gas, as reasoned in reference (11), or by using a modified "survival equation" should have a mean free path

$$\lambda \approx \frac{L v}{v_p} \quad (23)$$

where  $L$  ( $\text{cm}$ ) is the distance within which the scattering has to occur,  $v$  ( $\text{cm/s}$ ) is the purging gas velocity and  $v_p$  ( $\text{cm/s}$ ) the relative velocity of the natural gas with respect to the instrument or surface ( $v_p \sim 8$  km/s in the velocity vector). The pressure corresponding to  $\lambda$  is given by the relation indicated previously or obtained from Figure 3.

#### Flow Requirements and Exit Flow Velocities

The contamination prevention against gaseous and particulate contaminants either external or internal to an instrument is predicated on the internal pressure and the exit velocity of the purging gas. The purging gas is either dry air or gaseous nitrogen. The quantity of purge gas is a function of the vent area,  $A$  ( $\text{m}^2$ ) the pressure to be maintained  $P$  (torr) upstream of the vent area and the downstream pressure  $P_0$  (torr). For air or nitrogen, when  $P_0 > 0.53P$  the viscous flow of gas at standard pressure and temperature (SPT) from an orifice with small pressure differentials is given by

$$Q = \psi A v = \psi A \sqrt{2gRT_0(P-P_0/P_0)} \quad (\text{m}^3/\text{s}) \quad (24)$$

which is obtained from the Torricelli equation. The coefficient  $\psi$  which accounts for a velocity coefficient and vena contracta, may vary from 0.64 to 0.98 for an orifice. The other parameters are the temperature of the gas  $T_0$  (K), the acceleration of gravity  $g$  ( $\text{m/s}^2$ ) and the gas constant  $R = 29.26$  ( $\text{m}^3/\text{K}$ ) for air. The flow velocity at the exit for the same conditions of  $P_0 > 0.53P$  is

$$v = \alpha \sqrt{2gRT_0(P-P_0/P_0)} = 24\alpha \sqrt{T_0(P-P_0/P_0)} \quad (\text{m/s}) \quad (25)$$

The velocity coefficient  $\alpha$  is about 0.98 for an orifice. The continuum gas flow rate at SPT when  $P_0 < 0.53P$  is from the "Fliegner equation" using  $A$  ( $\text{m}^2$ ),  $T$  (K) and  $P$  (torr),

$$Q = 4.34 C_D \frac{AP}{\sqrt{T_0}} \quad (\text{m}^3/\text{s}) \quad (26)$$

where  $C_D$  is the discharge coefficient. The above for  $T_0 = 293\text{K}$  reduces to  $Q = 0.253 C_D AP$  ( $\text{m}^3/\text{s}$ ) =  $15.22 C_D AP$  ( $\text{m}^3/\text{min}$ ). This equation normalized with the volume has been plotted in Figure 6. The normalization provides the number of volume changes per unit time,  $Q/V$  ( $\text{m}^3/\text{m}^3/\text{min}$ ) or the time needed for one complete volume change  $t_p = V/Q$  (min) as a function of the purging pressures and the sizes of the orifice. The plot includes also the flow required when molecular flow conditions exists. This occurs when the gas m.f.p. is about 10 times the diameter of the orifice. The flow of atmospheric air at  $20^\circ\text{C}$  is then  $Q = 8.8 AP$  ( $\text{m}^3/\text{min}$ ). The exit flow velocity for the continuum flow regime when  $P_0 < 0.53P$  is sonic at the orifice and is given by

$$v = \alpha \sqrt{\frac{2\gamma}{\gamma+1} P T_0} = 18.3\alpha \sqrt{T_0} \quad (\text{m/s}) \quad (27)$$

where  $\gamma = c_p/c_v = 1.4$  is the ratio of the specific heats for air, and  $\alpha = 0.98$  is the velocity coefficient. The other parameters are as indicated above.

#### Contaminant Deposits and Its Optical Effect

The deposit on a surface by a contaminant with a vapor pressure less than the saturated vapor pressure corresponding to the temperature of the surface can be estimated using the Langmuir equation for adsorption or more accurately using the B.E.T. relation reference (12). The Langmuir adsorption isotherm is

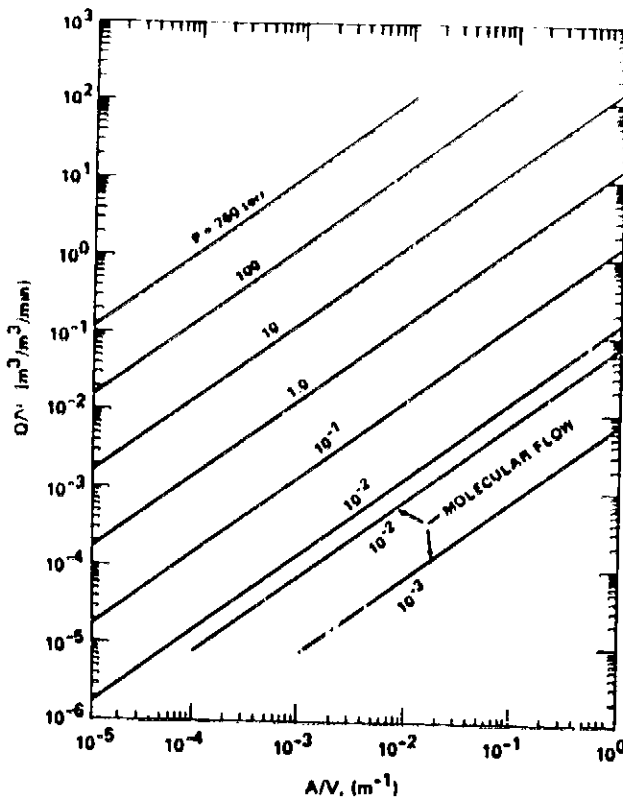


Fig. 6 Volume air changes  $Q/V$  ( $\text{min}^{-1}$ ) versus vent area volume ratio  $A/V$  ( $\text{m}^{-1}$ ) as a function of internal pressure.

$$\sigma = \gamma \phi = \gamma (5.83 \times 10^{-2} \sqrt{M/TP}) \tau_0 e^{E/RT} \quad (\text{g/cm}^2) \quad (28)$$

where  $\gamma \approx 1$  is a sticking coefficient,  $\phi$  ( $\text{g/cm}^2/\text{s}$ ) is the flux of contaminant impinging on the surface,  $M$  ( $\text{g/mole}$ ) is its molecular mass,  $T$  ( $\text{K}$ ) its temperature,  $P$  ( $\text{torr}$ ) its partial pressure and  $\tau$  is a residence time of the molecule on the surface. The residence time is  $\tau = \tau_0 e^{E/RT}$  where  $\tau_0 \approx 10^{-13}$  (s) is an oscillation period of the molecule on the surface,  $E$  ( $\text{cal/mole}$ ) is the activation or binding energy of the molecule on the surface at temperature  $T$  ( $\text{K}$ ) and  $R$  ( $\text{cal/moleK}$ ) is the gas constant. The activation energy may have a value approximately the same as the heat of evaporation if the adsorption involves physical forces and if many layers of deposit have been accumulated on the surface. Or, it may be several times the heat of evaporation if the adsorption involves chemical bonding.

For the case when the contaminant gas partial pressure is greater than its saturated vapor pressure at the surface which exists in general, when cryogenic surfaces are present, the accumulation on the surface is a condensation process and can be calculated by summing the net flux

$$\sigma = \int_{t_0}^{\infty} (\gamma \phi - \phi_s) dt = k \int_{t_0}^{\infty} (\gamma P - P_s) dt \quad (\text{g/cm}^2) \quad (29)$$

where  $\phi$  is the incident flux and  $\phi_s$  is the flux of contaminant departing the surface at its saturated conditions.

The optical effect of contaminant deposits on a surface is difficult to evaluate because one must know the complex index of refraction of the contaminant and substrate. The effect changes with the radiation wavelength, the contaminant thickness and distribution on the surface. An estimate of the absorption at certain wavelengths by contaminants can be obtained by applying the Lambert relation. The loss of incident intensity through a thickness  $t$  ( $\text{\AA}$ ) of material which has an absorption coefficient  $\alpha$  ( $\text{\AA}^{-1}$ ) at certain wavelengths is

$$\frac{I - I_0}{I_0} = (1 - e^{-\alpha t}) \quad (10)$$

The absorption coefficient will change if the chemical nature of the deposit is modified by certain radiations or energetic particles.

#### Application

The results of the previous analysis have been applied to the contaminant protection of a solar telescope which will be carried in space by the Shuttle. The telescope will remain in orbit for about a week and will be making sun observations from the Shuttle bay. Solar energy in the telescope will be very high and part of it must be rejected via mirrors back into space. Contaminants on those surfaces can affect negatively the rejection requirements and introduce instrument loss of sensitivity in several regions of the spectrum, especially in the U.V. region. The telescope tube with communicating volumes has been estimated to have a volume of about  $16 \text{ m}^3$  and to be about 6 m long. The telescope closure door which for protective reasons will remain closed during ground, launch, initial orbital phase and return, has a diameter of 1.3 m.

The calculations and application of the theory which follow are preliminary. However, they indicate that the proposed purging is feasible and can protect the telescope against gaseous and particulate contaminants external and internal to the telescope, during the most critical periods of contaminant hazards. These periods are ground operations, launch, early hours in orbit and return from orbit.

The results of the calculations which are indicated below have been shown in summary form in Table I.

#### Telescope Tube Vent Area Requirements

The vent area required to prevent a hoop pressure differential across the tube can be estimated from equation (3). With the assumption that the tube structure can withstand a maximum  $\Delta P = 0.25$  psi (13 torr) while flying through the transonic regime of the flight at an ambient pressure of about 14 psi and the rate of pressure drop is about 0.457 psi/s (reference 13), the required volume vent area ratio with a coefficient of about 0.6 is  $V/A = 1.67 \times 10^3 C_D \sim 10^3$ . The required vent area for  $V = 16 \text{ m}^3$  is then  $A = 159 \text{ cm}^2$  ( $24.7 \text{ in}^2$ ). This total area will govern the entrance of contaminants and the purging flow through all of the operational phases of the telescope unless provisions are made to limit the area during other operational phases of the instrument.

#### Ground Purging Protection

If one decided to maintain a purge pressure of  $P = 773$  torr (0.25 psig) in the telescope and the entrance of contaminant is through the previously calculated  $159.6 \text{ cm}^2$  with an assumed pipe depth of  $d = 8$  cm, the time constant for a contaminant to infiltrate the passage and diffuse to a location  $\ell = 6$  m away, is given by equation (12). The time constant for water vapor which has a diffusion coefficient  $D_0 = 0.24 \text{ cm}^2/\text{s}$  at 760 torr and normal temperature has been calculated to be about 46.38 days where 39.2 days were taken by the contaminant to move through the passageway. The time constant for a contaminant having an  $M = 400$  g/mole will be 218 days. These are the lengths of time required for the contaminants to build up to 64% of their external concentration if no purging flow existed. However, the required flow of purge gas to maintain 773 torr in the telescope with the external pressure at 760 torr (14.7 psi) will be  $Q = 0.53 \text{ m}^3/\text{s}$  at STP as calculated using equation (24). The exit velocity from equation (25) will be  $v = 52.6$  m/s and the time for one change of volume will be  $t_p = V/Q = 30$  sec. The equilibrium maximum partial pressure of contaminant ( $M = 400$  g/mole) which can exist in the telescope will be  $7.5 \times 10^{-6}$  of its external pressure and for water vapor  $1.3 \times 10^{-6}$ . These were calculated using equation (15). Therefore, there should be no contamination while the telescope is being purged.

Table 1  
Summary of SOT Purging Requirements

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Purge Cavity: Volume =  $16 \text{ m}^3$ , Length = 6 m, Cavity Door =  $1.3 \text{ m}^2$ , Accept.  $\Delta P = 0.25 \text{ psi}$   
Shuttle Flight: Max  $\Delta P/\Delta t = 0.457 \text{ psi/s}$  at 14 psi  
Vent Requirements w/Cavity Door Closed:  $V/A = 10^3$ , depth  $d = 8 \text{ cm}$

Parameter	Ground*	Launch	Orbit		Deorbit Landing	Comments
			0-1 hr	1-24 hr		
Vent Area ( $\text{cm}^2$ )	159 (24 $\text{in}^2$ )	159	159	$1.3 \times 10^4$	159	Vent area required for $\Delta P < 0.25 \text{ psi}$ during launch phase
Purge Press (torr)	13 (0.25 psi)	$P_{\text{AMB}} + 1$	1		$P_{\text{AMB}} + 1$	$P_{\text{AMB}}$ = variable pressure in bay
Purge Volume Rate ( $\text{m}^3/\text{s}$ )	0.53	$0.14 - 4.2 \times 10^{-3}$	$4.2 \times 10^{-3}$	-	$4.2 \times 10^{-3} - 0.14$	Quantity for 1 hr purge: $0.1 \text{ m}^3$ at 2000 psi
Flow Velocity (m/s)	52.6	14.6 - 309	309	-	309 - 14.6	
Time/Volume Change	30 sec	114.3 sec - 1.05 hr	1.05 hr	-	1.05 hr - 114.3 sec	
Contaminant Infiltration Time Constants	46d 218 d	45.6d - 144 hr 214d - 6.78 hr	1.44 hr 6.78 hr	0 0	1.44 hr - 45.6d 6.78 hr - 214d	$\text{H}_2\text{O}$ $M = 400 \text{ kg/mole}$
Fraction of Contamination Pressure in Volume at S. State	$7.5 \times 10^{-6}$ $1.3 \times 10^{-6}$	$2.9 \times 10^{-5} - 0.42$ $6.1 \times 10^{-6} - 0.13$	0.42 0.13	- -	$0.42 - 2.9 \times 10^{-5}$ $0.13 - 6.1 \times 10^{-6}$	$\text{H}_2\text{O}$ $M = 400 \text{ kg/mole}$
Pressure in Bay (torr)	-	$761 - 3 \times 10^{-2}$	$3 \times 10^{-2}$	-	$3 \times 10^{-2} - 761$	Pressure produced by purge w/bay door closed
Purge Gas Mean Free Path (cm)	$6 \times 10^{-6}$	$6 \times 10^{-6} - 4 \times 10^{-3}$	$4 \times 10^{-3}$	-	$4 \times 10^{-3} - 6 \times 10^{-6}$	In cavity
Internal Outgassing	$6 \times 10^{-5}$	$6 \times 10^{-5} - 4 \times 10^{-2}$	$4 \times 10^{-2}$	$\phi_{\text{vac}}$	$4 \times 10^{-2} - 6 \times 10^{-5}$	Fraction of rates in vacuum
Gas Contamination Deposit	-	-	3 - 10 Å		-	On $20^\circ\text{C}$ -degradation: 8% absorption at U. V.
Dia. of Particles Blown Away (cm)	1.2	$9.5 \times 10^{-2} - 1.4 \times 10^{-1}$	$1.4 \times 10^{-1}$	-	$1.4 \times 10^{-1} - 9 \times 10^{-2}$	Maximum dia. for particles at 26 m/s (ground) & 155 m/s (orbit)

\*Ground purge as shown provides large protection at expense of large flow. Purge pressure can be lowered.

The size of particles which will be rejected by the purge gas have been calculated using equation (22) with  $v_p = 52.6 \text{ m/s}$ ,  $\rho = 1.22 \text{ kg/m}^3$ ,  $\rho_p = 2.6 \times 10^3 \text{ kg/m}^3$  for sand and  $C_D \sim 0.5$  for the drag coefficient in the range of  $10 < R < 10^2$  applicable to a spherical particle (reference 9). The calculation indicates that the particle size which could be blown away will be as large as 1.2 cm. The Reynolds number is about 21730 for that size particle, and for a dynamic viscosity for the air at normal temperature of  $\eta = 18.1 \times 10^{-6} \text{ Pa}\cdot\text{s}$ .

It is apparent from these results that by using a 0.25 psig purging, one is overprotecting the volume at the expense of a large amount of purging gas. One may want to reduce the pressure and/or reduce temporarily the vent area during ground operation.

#### Launch Phase Protection

During the launch phase using a pressure controller, the purging pressure should be maintained at about 1 torr higher than the decaying external pressure. This will provide a flow out of the volume which will provide an obstacle to external contaminants. The flow will be  $0.14 \text{ m}^3/\text{s}$  with a velocity of 14.6 m/s at start of the launch phase as calculated using equations (24) and (25). When the external pressure  $P_0 < 0.53 \text{ torr}$  (in orbit), the flow will be  $Q = 4.2 \times 10^{-3} \text{ m}^3/\text{s}$  [equation (26)] and the velocity will be 309 m/s [equation (27)]. The time constant for infiltration at 761 torr (on the ground)

will be  $\tau = 45.6 \text{ days}$  for water and 214 days for  $M = 400$ , and with the purge period of  $t_p = 114.3 \text{ s}$  the maximum pressure of these contaminants in the telescope will be  $2.9 \times 10^{-5} P_0$  and  $6.1 \times 10^{-6} P_0$ , respectively. The particle sizes which will be rejected under these conditions will have diameters up to  $9.5 \times 10^{-2} \text{ cm}$  with velocities up to 14 m/s. These results indicate that one could use the 1 torr purging pressure during ground operations and the telescope would be sufficiently protected.

#### In Orbit Protection

At the end of the launch phase and in orbit, the purging pressure will be 1 torr and the bay pressure will be less than 0.53 torr. The in orbit purge pressure must provide a sufficiently high pressure to prevent incoming gaseous and particulate contaminants; arrest to a large extent the internal outgassing; and be as low as possible so that the required amount of gas is a minimum. This last requirement is important for the limitation on the amount of gas to be carried, and for the pressure which can be established in the Shuttle bay while the bay doors are closed. The one torr pressure was selected with these considerations in mind.

The purge flow under these conditions, will be  $4.2 \times 10^{-3} \text{ m}^3/\text{s}$  and its exit velocity, 309 m/s. This flow rate is equivalent to  $Q = 3.18 \times 10^3 \text{ torr l/s}$  being emitted in the bay. The bay with closed doors has a venting area of



about  $0.5 \text{ m}^2$  which corresponds to a conductance in the viscous region of  $C = 20 \text{ A} = 10 \times 10^4 \text{ l/s}$  (reference 1). The equilibrium pressure in the bay is then  $P = Q/C = 3.18 \times 10^{-2} \text{ torr}$ . This pressure may be cause for some concern. Voltage breakdowns under certain conditions could occur. However, other analyses have indicated that the bay pressure does not drop below this value until about 20 minutes in orbit. It drops to about  $10^{-3}$  torr and remains at that level for considerable time. Therefore, the additional pressure does not change substantially the bay pressure. After the bay doors open, the bay purging induced pressure will drop substantially. It appears that the flow is acceptable based on these considerations and the fact that the purging will last a limited amount of time as will be discussed later. If it is found unacceptable, one may provide an automatic partial closure of the vent area to limit the flow of gas into the bay. It is to be noted that the purging flow will also have some beneficial effects in arresting, mixing and transporting the outgassing in the Shuttle bay.

The time constant  $\tau$  as calculated for  $P = 1 \text{ torr}$ , for the infiltration of contaminants will be 1.44 hours for water and 6.78 hours for  $M = 400$ . These values and the volume change time of 1.05 hour limit the maximum partial pressures of the water and that of the real contaminant ( $M = 400$ ) to 0.42 and 0.13 respectively of their in bay pressures. These values were obtained by substitution in equations (12) and (15) of  $P = 1 \text{ torr}$ ,  $V/A = 10^3 \text{ cm}$ ,  $d = 8 \text{ cm}$ ,  $l = 6 \times 10^2 \text{ cm}$ ,  $D_0 = 0.24 \text{ cm}^2/\text{s}$ ,  $p_0 = 760 \text{ torr}$ ,  $T = T_0$ ,  $M_0 = 18 \text{ g/mole}$  and  $M = 400 \text{ g/mole}$ .

While this purge is on, at  $P = 1 \text{ torr}$  ( $\lambda = 4 \times 10^{-3} \text{ cm}$ ), the outgassing of the internal surfaces will be about 4 percent of the values they would have if the total pressure on those surfaces was less than  $4.6 \times 10^{-2}$  (equation (18)). Also, some of the molecules outgassed will be transported out of the volume by the purge flow. One can reason that if the outgassing material inside the telescope is of the same nature of the many polymeric materials (such as RTV-566 adhesives, S-13G paints and others) which have a saturated vapor pressure of about  $P_s = 3 \times 10^{-8} \text{ torr}$  at normal temperature, then the actual vapor pressure in the purged volume will be less than  $4\% \times 3 \times 10^{-8} = 1.2 \times 10^{-9} \text{ torr}$ .

One must add to this pressure, the pressure created by the infiltration of the external contaminants. The in bay partial pressure of a similar contaminant cannot exceed its saturated vapor pressure of  $3 \times 10^{-8} \text{ torr}$ . In fact, it must be less as dictated by its venting out of the bay, via the shuttle side vents. It will be even less when the bay doors are open. If one assumes, however, conservatively that the outside contaminant partial pressure is  $3 \times 10^{-8}$ , then the infiltrated contaminant could have a maximum pressure of  $3 \times 10^{-8} \times 0.13 = 3.6 \times 10^{-9} \text{ torr}$  in the volume. The total partial pressure of the contaminant in the volume will be summing the infiltrated and the self-produced,  $P = 3.6 \times 10^{-9} + 1.2 \times 10^{-9} = 4.8 \times 10^{-9} \text{ torr}$ . This pressure determines the rate of impingement of contaminant on a surface in the volume. Since  $P$  is less than  $P_s$ , only an adsorption process can occur and the relationship to be used for the accumulation of deposits on a surface is given by equation (28). The polymeric material which is being considered as the contaminant (Methyl-Phenyl-Trisiloxane) has an activation energy of about 20 kcal/mole and  $M = 400 \text{ g/mole}$ . Its sojourn time on a surface at  $T = 293$  will be:  $\tau = 10^{-13} \frac{20000}{1.98 \times 293} = 8.3 \times 10^5 \text{ s}$ . The rate of impingement will be  $5.83 \times 10^{-2} (400/293)^{1/2} \times 4.8 \times 10^{-9} = 3.269 \times 10^{-10} \text{ g/cm}^2/\text{s}$  and the deposit which can occur will be  $d = \tau \phi = 3.27 \times 10^{-10} \times 8.3 \times 10^5 = 2.71 \times 10^{-8} \text{ g/cm}^2$  with the sticking coefficient taken as one. The deposit will have a thickness of about  $3 \text{ \AA}$  assuming a density approximately equal to that of the water ( $\rho = 1 \text{ g/cm}^3$ ). As the flux diminishes, some of this deposited contaminant may actually leave the surface.

With regards to the infiltration of particulates, those particles which are directed toward the vent at velocities of about 154 m/s and have diameters up to  $1.4 \times 10^{-3} \text{ cm}$  will be rejected by the purge gas. The calculations have been carried out using equation (21) with  $\eta = 18.1 \times 10^{-6} \text{ Pa}\cdot\text{s}$ ,  $\rho_p = 2.65 \times 10^3 \text{ kg/m}^3$  and  $v = v_0/2 = 154.5 \text{ m/s}$ . The Reynold's number was calculated to about 38, using a density  $\rho = \rho_0/760 = 1.6 \times 10^{-3} \text{ kg/m}^3$  for the gas. These estimates indicate that the protection of the telescope surfaces against contaminants can be provided with 1 torr. What remains to be determined is the length of time the purging should be carried out. This time is limited by the gas consumption and by the operational constraints. It is suggested that the purging be carried out for about an hour. The total amount of gas which will be used is about  $0.1 \text{ m}^3$  at a pressure of 2000 psi. After one hour in orbit, the total bay pressure with the bay doors open is estimated to be about  $10^{-4}$  torr (without purging) and the contaminant outgassing rates should drop by an order of magnitude (the outgassing rates often drop one order of magni-

tude after one hour in vacuum and 2 orders in about 10 hours). Further, with the bay open, the partial pressure of the characteristic contaminants discussed previously should be considerably less than  $10^{-8} \text{ torr}$ . It is to be noted that many of the materials used will meet the criteria that their contaminant fractions be 0.1% of their mass loss when exposed at  $125^\circ\text{C}$  for 24 hours. So, also based on this criteria, the partial pressures of contaminants should be 1 order of magnitude lower than that of the total pressure. At the end of one hour, while the purging is being terminated, the telescope should be raised from the bay, pointed away from the velocity vector, the cabin, the engines and from the sun. The closure door should be fully open in this more rarefied environment which exists out of the bay. Full outgassing of the internal surfaces will result. However, the contaminant pressure in the telescope will be set by the conductance of the closure door (1.3 m dia.) and the outgassing surfaces, so  $P \sim P_s (A_p/A_c)$  where  $P_s$  is the vapor pressure of the contaminant ( $P_s \sim 10^{-8} \text{ torr}$ ),  $A_p$  is the exposed surfaces of the outgassing sources and  $A_c$  is the open door area. The pressure  $P$  cannot be greater than  $P_s$  and in fact, it will be much less due to the large vent area and the relatively small area of the organic materials. Under these conditions no additional deposits can occur on surfaces at  $20^\circ\text{C}$  or higher. Some deposits could occur only at a surface near and facing directly a source. This condition should be prevented whenever possible by blocking the field-of-view. This venting condition should be maintained as long as possible to ensure the depletion of most of the outgassing, before solar observation is carried out. Previous experiences would suggest that one should allow at least 24 hours for the outgassing rate to become reasonably small.

As indicated, the maximum deposit of contaminant after having taken all the above precautions, should not exceed  $3 \text{ \AA}$ . Assuming, however, that the deposit is about  $10 \text{ \AA}$ , an estimate of the effect that this thickness would have on the absorption at  $1215 \text{ \AA}$  radiation indicates, using equation (30), that the loss in transmittance would be about 8.7%. The absorption coefficient was taken to be  $\alpha = 9 \times 10^{-3} \text{ \AA}^{-1}$  which was the average of the results on transmittance at that wavelength of many materials used in space application (reference 14).

#### De-Orbit and Landing Phase

A purging could be employed during the returning phase of the flight. It would provide: (1) protection against particulates, and other gases and vapors ingested by the Shuttle during the re-entry; (2) a heat conductive medium to transfer heat out of the telescope; and (3) eliminate some of the expenses necessary for the refurbishment of the telescope. One would need to maintain a purging pressure slightly higher than the bay ambient pressure which would be increasing as the Shuttle descends. The purge supply system should have a response time as fast as the pressure increases in the bay and would require a pressure controller performing the reverse function of the one used for the launch phase. A method to restrict the telescope venting passage before the reentry could facilitate this protective approach. This is possible because during reentry pressure changes occur more gradually than those during launch. The parameters for the two extremes of purging, in orbit and on ground, with 1 torr pressure differentials are indicated in the summary table.

#### Conclusions and Recommendations

A method has been developed to evaluate the protection offered by gaseous purging of an instrument against external and internal gaseous and particulate contaminants. The protection is needed while the instrument is on the ground and in the Shuttle bay during launch, reentry and orbiting. Operational and other restrictions have been considered in the development.

The analysis of the results indicates that maintaining a pressure of about 1 torr above the external environment in the instrument may afford sufficient protection against infiltration of gaseous and particulate contaminants and abate sufficiently the internal self-generated contaminant outgassing. The vent dimensions which are dictated by pressure differentials developed during launch, establish the purge gas flow and the gas quantity needed for the purging.

The prevention of contaminants infiltration has been evaluated in terms of the time constant for a gas to infiltrate a vent, diffuse in the volume and the purge time for one volume change. The contaminant pressure which can

be built in the volume is a function of the diffusion coefficient of a gas into another at different pressure, the size of the volume, the vent area and its length and a characteristic dimension of the volume.

The self-contamination is prevented by the high pressure which reduces the outgassing rates of the materials in the volume. The total contaminant pressure in the volume is obtained by the superposition of the infiltrated and self-generated pressures. The total contaminant deposit on a surface can be estimated based on the pressure, chemical properties and the temperature of the surface being contaminated. In turn, an estimate of the optical degradation of that surface is obtained using experimental data on the absorption of the contaminant at certain wavelengths.

The protection against particulate contaminants entering the volume is provided by the drag forces on the particles produced by the velocity, density and viscosity of the purge gas at the vent exit.

The purge gas flow rates and velocities have been calculated in terms of the pressure differential, gas temperature and molecular masses. Considerations on the pressures which the purge flow would produce in the Shuttle bay, on the amount of stored gas which can be carried along and on the length of time during which purging and free outgassing can be carried out without interfering with the instrument operational requirements, have been taken into account.

The findings of the analysis have been applied to a solar telescope which has a volume cavity of about  $16 \text{ m}^3$  with an aperture door with an area of about  $1.3 \text{ m}^2$  to be opened on command. The summary Table I indicates the purging requirements, the suggested times for purging and free outgassing, and the protection which the purge will offer. The vent area which is needed because of structural integrity during shuttle launch, has been calculated to be about  $24 \text{ in}^2$ . During ground operations and launch, the venting through the above area with a passageway about  $8 \text{ cm}$  long of the nitrogen gas at a few torr higher than the ambient pressure, offer ample protection against gaseous and particulate contaminants. In orbit the purging at  $1 \text{ torr}$ , will limit external and internal contaminant pressure to about  $0.1$  the pressures which would be otherwise expected. Particles of diameter up to  $0.1 \text{ mm}$  with speeds up to  $150 \text{ m/s}$  will be prevented from entering the volume. The purging is expected to induce in the Shuttle bay with doors closed a pressure of about  $2 \times 10^{-2}$  torr. The amount of purge gas for the recommended one hour purging is equivalent to  $0.1 \text{ m}^3$  at  $2000 \text{ psi}$ . The purging and the subsequent full venting are expected to allow contaminant deposits on volume surfaces of about  $3\text{--}10 \text{ \AA}$ . A  $10 \text{ \AA}$  deposit can produce about  $8\%$  absorption of UV radiations.

The following recommendations, based on the above analysis and other experiences, can be offered:

- Internal and external surfaces should be maintained free of gaseous and particulate deposits during the various phases of manufacturing, assembly, tests, etc.
- Materials employed with the instrument should be selected to have low outgassing rates with a minimal fraction of condensable products.
- The exposed surfaces in the instrument of organic materials should be a minimum.
- Critical surfaces should be shielded from known outgassing sources.
- Critical surfaces should be kept (with heaters) at temperature slightly higher than the others. The heaters may also be needed to maintain the system at certain temperatures, if it is exposed to the cold of space.
- Ground purging should be carried out with pressures a few torr higher than the total ambient pressure.
- Launch and reentry purging requires a variable pressure one torr higher than the environment pressure.
- The purge pressure while in orbit is about one torr and the purge should continue for about one hour. The amount of purge gas for the telescope will be about  $0.1 \text{ m}^3$  at  $2000 \text{ psi}$ .

- The volume, while the purge is being terminated, should be lifted from the bay and fully vented with the vent pointed away from the sun, velocity vector, engine, cabin.
- The passive, full vent outgassing should be allowed to continue for about 24 hours or longer before exposing the volume to the sun and initiate operations.
- Methods to restrict the vent passage either manually or automatic should be explored. Partially closing the vent, on ground, in orbit and reentry could save large amounts of purge gas and offer additional protection. In orbit, the purge induced pressure in the bay would also be reduced.
- The depth of the vent passage should be as long as permissible. This would extend the infiltration time constant.
- The closure door of the volume should be tight during purging as to prevent additional loss of purging gas or pressure.

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