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PARTICULATE CONTAMINANT RELOCATION DURING SHUTTLE ASCENT

by

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Abstract

The dislodgement, venting, and redeposition of particles on a surface in the shuttle bay by the vibroacoustic, gravitational, and aerodynamic forces present during shuttle ascent have been investigated. The particles of different sizes which are displaced, vented, and redistributed have been calculated; and an estimate of the increased number of particles on certain surfaces and the decrease on others has been indicated. The average sizes, velocities, and length of time for certain particles to leave the bay following initial shuttle doors opening and thermal tests have been calculated based on indirect data obtained during several shuttle flights. Suggestions for future measurements and observations to characterize the particulate environment and the techniques to limit the in-orbit particulate contamination of surfaces and environment have been offered.

Introduction

The redistribution of contaminant particles in the shuttle bay during ascent and the release to space of some of these particles following the bay doors opening in orbit have been investigated. The particles are left in the bay volume and on surfaces before launch. They escape cleaning efforts to remove them from the cargo bay and payloads at several stages of the flight preparation. The understanding of these particles' redistribution on surfaces and their release in the field of view of an instrument is important in view of the changes they may cause to the thermophysical properties of surfaces on which they deposit and to the optical degradation of the environment in which they may escape. Some of the effects of particles on surfaces and in the environment are: physical obscuration of a surface; scattering of radiation which changes the transmission properties of a surface and/or a volume; increased diffuse reflection of a surface; emission by the particles of certain radiations which may be detrimental to certain instruments' observations.

Figure 1 shows pictorially the particulate redistribution events which may occur during orbiter ascent. This paper is concerned with the particulate redistribution during launch/ascent and the particles released from the orbiter bay immediately following bay door opening and after certain orbiter operational tests. The particles residing in the bay at launch are dislodged, scattered, and redeposited by vibroacoustic, gravitational, and aerodynamic forces present during orbiter ascent. Some of the released particles are removed by the gaseous venting of the bay through the shuttle vents; others will redeposit on surfaces of the bay according to the surface orientation with respect to the orbiter acceleration vector. In the following, the fraction of particles of different size ranges dislodged, redistributed, and vented are calculated per unit surface area, irrespective of the original particulate distribution coverage. The interchange of particles from a particle-covered surface to another surface has been calculated. The resulting cleaning of one surface and the increased contamination of another surface have been estimated. An estimate of the particles residing on a surface in the shuttle bay when in orbit has been made based on the original particulate conditions before launch. Calculations of the diameters and velocities of the particles released from the orbiter into space immediately following the bay opening and the characteristics of those emitted during shuttle thermal tests and attitude changes have been carried out based on experimental data. Suggestions for future measurements of bay particulate conditions during and immediately after orbiter ascent have been offered with the intention of clarifying the generation and the mechanics of the particles during that phase of flight and of reducing the particulate contamination on future spacecraft.
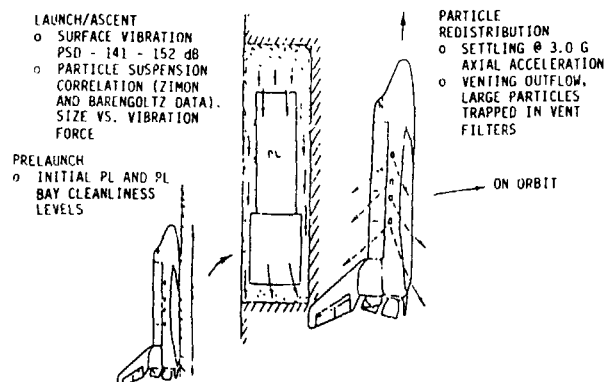

Figure 1. Particulate contaminant redistribution events.

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Particles Adhesion and Displacement Forces during Shuttle Ascent

Particles may be held on surfaces by the following adhesion forces (Ref. 1):
1. Van der Waals or molecular forces which are proportional to the particle dimensions;
2. Contact potential differences due to surface effects of dissimilar materials producing electrostatic forces proportional to the two-thirds power of the particle dimensions;
3. Coulomb forces arising from charges produced on the particle by external electric fields;
4. Capillary forces produced by water surface tensions also proportional to the size of the particles.

As concluded in Ref. 1, the adhesion force approaches the Van der Waals force during ascent when the adhesion force may change in a complicated manner. This force from experiments and analyses (Ref. 1, 2, 3 and 4) is expressed as $F = Kd$ where $K = 130 - 212$ dynes/cm. These K values apply to quartz particles of about 50μ diameter and for a 50-60% removal fraction of these particles from a glass surface. In this paper, the adhesion force will be assumed, for simplicity and for exploratory purpose, to be

$$F = 200 \, d \qquad \text{(dynes)} \qquad (1)$$

where d(cm) is the particle equivalent spherical diameter.

During shuttle ascent, the particles held on the surfaces will be acted upon by gravity, launch acceleration, vibroacoustic random accelerations, resonant frequencies accelerations, relative motion of surfaces, and gaseous flow momenta. The range of particle diameters, which could be released from the surfaces by forces equal or greater than the above adhesion force, can be estimated as follows:

a) Launch Accelerations
An estimate of the diameters of spherical particles which can be displaced can be obtained from the balance of forces acting on a particle of mass m(g) subjected to a force $F = kd$(dynes) and to an acceleration a(cm/s^2); i.e.,

$F - mg = ma$, so that $m = \dfrac{F}{a+g}$ and with the

substitution of $m = \rho_p V = \dfrac{\pi d^3}{6} \rho_p$, one obtains

$$d = \left[\frac{6K}{\pi \rho_p (a+g)} \right]^{\frac{1}{2}} \qquad \text{(cm)} \qquad (2)$$

The particles dislodged by this mechanism would have diameters larger than $d = 0.22$ cm (2200μ) for $K = 200$ dyne/cm, acceleration $(a+g) = 3g_c$

where $g_0 = 981$ cm/s^2, and an average particle density of $\rho_p = 2$ g/cm^3.

b) Random Accelerations
For payload systems and components, Goddard Space Flight Center suggests qualifications test levels of 12.9 grms for random vibrations in the range of frequencies of 20 to 2000 Hz (Ref. 5). This level reflects the power spectral density of accelerations for the entire frequency range of excitations. It is a generalized estimate of the response of components of moderate weight attached to a typical structure exposed to vibroacoustic levels in the empty STS cargo bay. The use of this acceleration in equation (2) indicates that the released particles would have diameters greater than 0.122 cm (1220μ).

c) Acceleration of Surfaces at Resonant Frequencies
The maximum acceleration of a harmonic oscillator at resonant frequency f_n is $a = 4\pi^2 f_n^2 x_0$ where x_0 is the amplitude of vibration. The diameter of the particles which could be released by this mechanism is

$$d = \left(\frac{6K}{4\pi^2 f_n^2 x_0 \rho_p \pi} \right)^{\frac{1}{2}} \qquad (3)$$

Accordingly, again using $K = 200$ dyne/cm, and $\rho_p = 2$ g/cm^3), the particle diameter which could be released is $d = 2.2/f_n \sqrt{x}$ (cm). A 100μ particle could be released by a following combination of frequencies and amplitudes: $f_n = 10$ Hz and $x_0 = 4.4$ cm; $f_n = 10^3$ Hz and $x_0 = .048$ cm; and $f_n = 2\times10^3$ Hz and $x_0 = .012$ cm. A 1μ particle would require a $f_n \sqrt{x} = 2.2\times10^4$ combination of frequency and displacement. As expected, the removal of smaller particles requires higher frequencies and amplitudes.

d) Air Stream Particles Displacement
An estimate of the gas venting flow and its velocity is needed to estimate the aerodynamic forces acting on a particle attached to a surface of the shuttle bay. The bay is vented via eight vents, each having an approximate area of 0.062m^2. The maximum pressure differential ΔP between the internal bay pressure and the external pressure during launch is approximately 0.7 psi. This differential, which exists for a few seconds, occurs 50-60 sec into launch, when the external pressure P_0 is about 9 psi. The

flow at the vents is, therefore, subsonic and can be estimated using Torricelli's equation as

$$Q = A\psi \sqrt{2gRT_0 \frac{\Delta P}{P_0}} = 24A\psi \sqrt{\frac{T_0 \Delta P}{P_0}}$$

$$= 72.3A \qquad (m^3/s) \qquad (4)$$

where $\psi = 0.63$ is the discharge coefficient, $T_0 = 293°K$ is the gas temperature, and $R = 29.26$ m/°K is the gas constant for air.

The flow at each vent is about 4.3 m^3/s; and

the total vent flow is about 34.65 m^3/s. The air velocity at the vent is

$$V = \alpha \left(\frac{2gRT_0 \Delta P}{P_0}\right)^{\frac{1}{2}} = 112.27 \quad (m/s) \qquad (5)$$

where $\alpha = 0.9$ is the velocity discharge coefficient. Assuming a bay sectional area of

about 18 m^2, the gas velocity in the bay may be about 3 m/s. The velocity will be higher within restrictions provided by payloads and systems. For these conditions, the Reynolds

number for a particle of diameter $d = 10^{-2}$cm,

gas velocity $V = 3 \times 10^2$ cm/s, air density

$\rho = 7.83 \times 10^{-4}$ (g/cm^3), and viscosity

$\mu = 1.84 \times 10^{-4}$ dyne/cm^2·s is $R_e = \frac{\rho V d}{\mu} = 12.76$.

The drag coefficient C_D for spherical particle

at this Reynold's number is $C_D = 24/Re \sim 2$

(Ref. 6) so that the drag on a particle having a diameter d(cm) not too different from

$d = 10^{-2}$cm, will be approximately

$$F = C_D A\rho \frac{V^2}{2} = \frac{\pi d^2}{4} \rho V^2 = 84.5d^2 \quad (dynes) \quad (6)$$

The ratio of this force to the Van der Waals adhesion force is about 0.42d. A high gas velocity is needed to remove a particle of micron size from a surface even if only a component of the adhesion force needs to be overcome. Furthermore, the small particles on the surface are submerged, for the most part, in a boundary layer of air where the velocity is slower than in the rest of the gas. Some particles may move some distances along the surfaces in the direction of the air flow, and a very few could leave the surface due to fluctuations of the air velocity in the vicinity of the particle (Ref. 7). In any event, the gas flow provides an additional force to remove from the surfaces and accelerate the particles.

Particles Displaced During Ascent

These calculations show that very large accelerations are needed for removal of micron size particles. However, test data show that accelerations in the range of those expected during orbiter ascent can release some fractions of the small size particles. Figure 2, taken from Ref. 8, presents test results obtained by several authors showing the fraction of resident particles for each size range that may be released from the surface and put in temporary suspension by certain acceleration forces. As pointed out by the authors, the data are subject to considerable uncertainty and provide order of magnitude indications on real conditions. The data obtained from Ref. 1, 2, 4, and 9 were correlated by Ref. 8 using a statistical method developed by Ref. 1. There are two periods during launch when particles on surfaces have a good probability of being displaced, resettled, and carried into the filter vents. The first period covers about 2 minutes of the launch acceleration profile, during which the orbiter accelerates to about 3g and the bay volume is vented to the atmosphere as shown in figure 3. Maximum venting occurs during the transonic region of the flight, when vibration and the pressure differential between bay and the external pressure are at their maximum. The velocity of the exhausting air in the bay as indicated is at about 3 m/s. The particles originally in the bay volume and those released from the surfaces by vibroacoustic accelerations and by other forces will be engulfed in the exhausting gas flow. As shown later, some of these particles will be carried into the vents; others, the larger ones, will strike and settle on the lower rear of the orbiter on surfaces perpendicular to the direction of the orbiter acceleration. Those settled on the surfaces will not be displaced again because the direction of the acceleration is in a direction restraining them. The second period, as shown on the acceleration profile, occurs after about 2 minutes into flight when the orbiter resumes its acceleration. The acceleration reaches about 3g at 7 minutes into the flight. It remains constant at that value for about 1 minute, and then it drops to a negligible value.

The vibroacoustic forces during this last propulsive period may be more effective in displacing particles attached to surfaces. The surface tension forces that help in retaining particles on the surfaces may become negligible because of the evaporation of the medium between the particles and the surfaces. In any case, those particles released during this last period will have an acceleration of 3g and may acquire velocities of about 32 m/s at the bay aft-bulkhead, which is about 18m below the bulkhead.
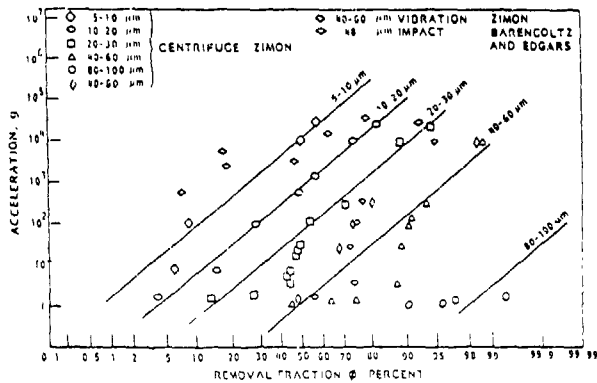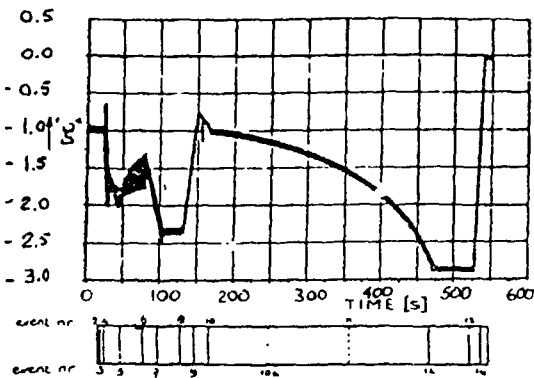
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Figure 2. Particle resuspended fraction vs acceleration test data — glass particles on s. steel (Ref. 8).

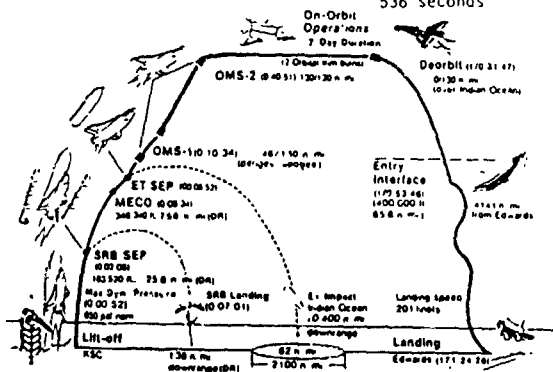| Ascent event:	Time (seconds):
1. Pre-launch	-
2. SSME ignition	6.5
3. SRB ignition	10.5
4. High-Q Boost	20.
5. Throttle-down SSME's	28.
6. Throttle-up SSME's	2C.
7. Max Boost	32.
8. SRB Deca_	13.
9. SRb Separation	10.
10.)	
10a.) Throttle up for 3 'G'	310.
11.)	
12. Throttle for 3 'G'	60.
13. SSME shut down and decay	12.
14. E.T. separation	14.
	536 seconds

Figure 3. Acceleration versus time history for ascent phase.

They will remain in the bay in the absence of an effective gas flow and, on striking a surface, may bounce in a zero g environment. The bouncing will continue until their kinetic energies are dissipated by collisions among themselves and by their anelastic collisions with surfaces. An estimate of the particle speeds required for bouncing and or settling is discussed later.

Particles Vented During the First Two Minutes of Flight

For an estimate of the particles released from bay surfaces that will remain in the bay or will be transported to the vents by the vent gas, an analogy with the cascade impactor design has been used. According to Ref. 10, the separation of particles in a cascade impactor can be characterized by the ratio of the forces of inertia and drag of the particles entrained in the gas jet. The cascade impactor consists of a nozzle through which air laden with particles of diameter D exits at velocity V and of a particle collector plate located perpendicular to the nozzle at a distance L. The inertia to drag force is referred as Stokes number, St and is defined as

$$St = \rho_p V D^2 / 18\mu L \qquad (7)$$

where ρ_p is the particle density, μ is the gas viscosity. It has been found empirically that for St ~0.2, the probability that a particle of diameter D will strike the collector plate rather than follow the deflected air stream is

50% and the particle diameter is $D_{50} \sim \left[\dfrac{\mu L}{\rho_p V}\right]^{\frac{1}{2}}$.

The reference indicates that to account for pressure lower than standard, a coefficient C which increases with decreasing gas density should be included in the denominator of the equation for D_{50}. For the shuttle conditions, the Stokes

number—i.e., the ratio of the particle inertia to the drag force—is

$$St = 2mg/\rho_a \ V^2 \ AC_D = \frac{4}{3} \ \frac{\rho_p \ gd}{\rho_a \ V^2 C_D}$$

$$= \frac{\rho_p d^2 g}{18\mu V} \qquad (8)$$

where d(cm) is the particle diameter, A its cross sectional area, μ is the gas viscosity, V is the gas velocity, ρ_p the particle density and the drag coefficient $C_D = 24/R_e = \dfrac{24}{Vd} \dfrac{\mu}{\rho_a}$ consistent with the gas velocity, gas density $\rho_a (gr/cm^3)$ and for a spherical particle. The

diameters of the particles having a 50% probability to follow the gas are then

$$D_{50} = \left[\frac{18}{g}\frac{\mu V}{\rho_p} (St)\right]^{\frac{1}{2}} \quad (cm) \qquad (9)$$

The same relation can also be obtained taking the ratio of the particle "relaxation time"

$\tau = d^2\rho_p/18\mu$ (Ref. 11) to the gas acceleration

time, t = V/g. The gas acceleration time used for the cascade impactor is t = L/V. The

substitution of $g = 3g_o = 2943 \text{ cm/s}^2$, $\rho_p = 2$

gr/cm^3, St = 0.2, and $\mu = 1.84 \times 10^{-4}$ dynes/

$cm^2 \cdot s$ indicates that the 50% diameter is $D_{50} =$

$3.35 \times 10^{-4}(V)^{\frac{1}{2}}(cm)$. The diameter is less than

58µ when a max gas venting velocity of

3×10^2 cm/s, which lasts about 5 sec, is used. The definition of $D_{50} = 58µ$ may be stated in a

different form: 50% of particles with diameter less than 58µ will be transported to the filters and 50% of those of diameter larger than 58µ will remain in the bay. However, a general conclusion may be that most of the particles with diameters larger than 58µ will remain in the bay after this initial period of launch. These could include particles which had become sufficiently large as a result of water super-saturation on them, but that would return to their original small diameters after a subsequent sublimation of the condensate. Supersaturation occurs on critical particle diameters as a result of a rapid, adiabatic gas expansion.

Particles Released and Retained by a Surface During Orbiter Ascent

The percentage of particles (ψ) in each diameter range released from a surface exposed to a 12.9 grms vibroacoustic acceleration, the same as the value employed for testing, is obtained from the figure 2 and is plotted in figure 4. These particles under the orbiter acceleration may fall on lower surfaces, where they will be held by the same acceleration. For the first 2 min of ascent, some of the released particles (<58µ dia.) will be dragged to the vents where those of less than 35µ dia. will vent out of the bay and those of diameters between 35µ and 58µ dia. will remain on the filters (the bay filters have a 35µ GBR glass bead rating

A tabulation of the percentages of particles released and remaining on the surface for each size range was prepared. The actual number of particles released and retained depends on the

original particle distribution per unit area of the surface. The MIL-STD-1246A defines the product cleanliness on the basis of the number of particles on a component. The number of particles per square foot of surface for all particles of specified size or larger plot as a straight line on log versus log^2 scales. The particulate cleanliness level is defined by the line crossing the abscissa. For example, Level 750 crosses the abscissa at one 750µ part.per square foot. Figure 5 shows the number of particles in each range remaining on an upper bay surface, $R_1 = N_o(1-\psi)$, after the initial 2 min acceleration,

based on an assumed initial particulate density N_o (particle/ft²) corresponding to the surface

cleanliness level 750 of the MIL-STD-1246A. After the initial removal, the second period of acceleration, also having a value of about 13 grms vibroacoustic acceleration, will release an additional fraction of the particles. The particles remaining on the surface after these accelerations,

$R_t = (1-\psi)^2 N_c$, are shown by the lower curve in

figure 5. This shows that a surface will retain a large number of small particles while releasing all particles larger than about 85-90µ.
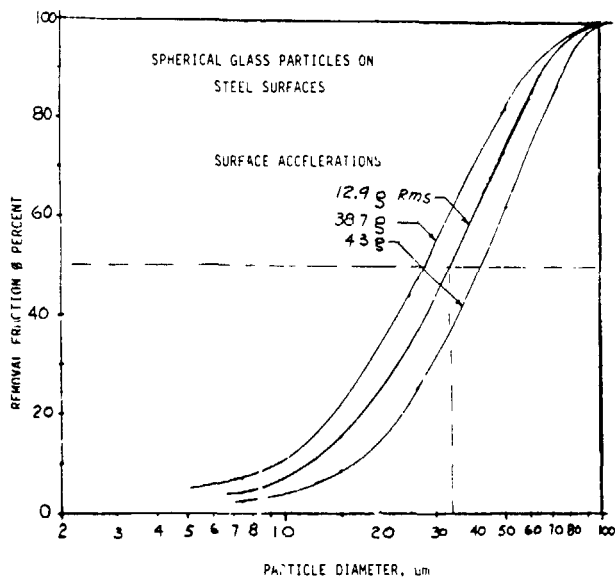

Figure 4. Fraction of particles removed by surface vibration.

Additional Particles Acquired by a Surface During Orbiter Ascent

From the same tabulations of the released particles, the particles which may accumulate on a lower bay surface can be evaluated. Figure 6 shows the resulting distribution

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$A_1 = N_0(1+\psi)$ on a surface assumed to be at the

N_0, corresponding to the 750 initial level,

which has received particles released from an upper surface also originally at 750 cleanliness level. As a result of the first acceleration, which includes venting, the surface receives only a small fraction of particles less than 58μ, since those were directed by gas flow to the vent filters. The filters stop particles greater than 35μ (filter sizes) and allows smaller particles to go out of the bay. During the second accelerating period, all the released particles can drop on another surface, since the air flow will no longer remove particles from the bay. As shown by the plot, there is a small additional degradation of the surface receiving and holding those particles; and the total accumulation is $A_T = N_0[(1+\psi)+\psi(1-\psi)]$. The degradation is more pronounced in the distribution for particle greater than 58μ. In fact, in that region, the surface level may change from the assumed 750 Lv to about 800 Lv. However, the new surface cleanliness level acquired by a clean surface (less than Lv 500) exposed to the falling particulate during ascent is shown in figure 7. The initial acceleration produces a level of about 700 for the particle range between 58 and 100μ dia. and 750 for those ranges beyond 100μ. The subsequent second period of acceleration adds the particle of diameters less than 58μ. The distribution for dia. less than 58μ corresponds to about 500-550 Lv showing the discontinuity in distribution at 58μ.
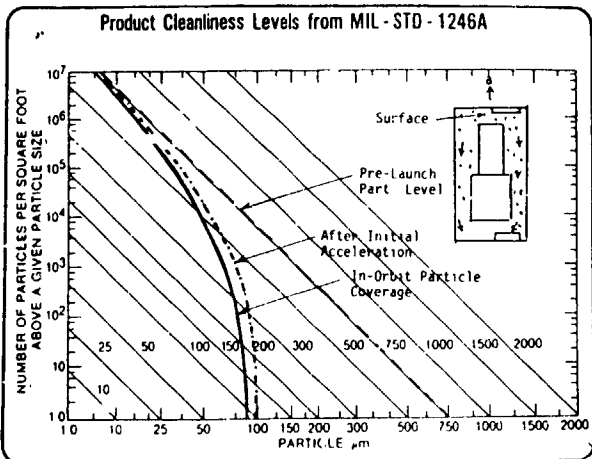

Figure 5. Particles depletion during shuttle ascent from a surface not facing the acceleration vector, contaminated to a 750 Lv of MIL-STD-1246A.
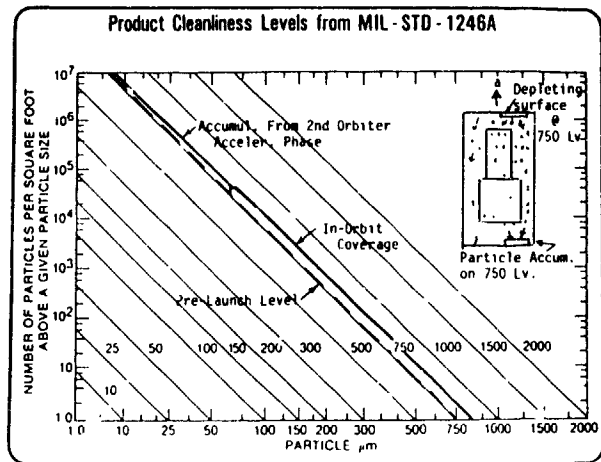

Figure 6. Particles accumulation during shuttle ascent on a surface facing the acceleration vector at a pre-launch Lv 750, from a depleting surface also at 750 Lv with a one-to-one field of view.
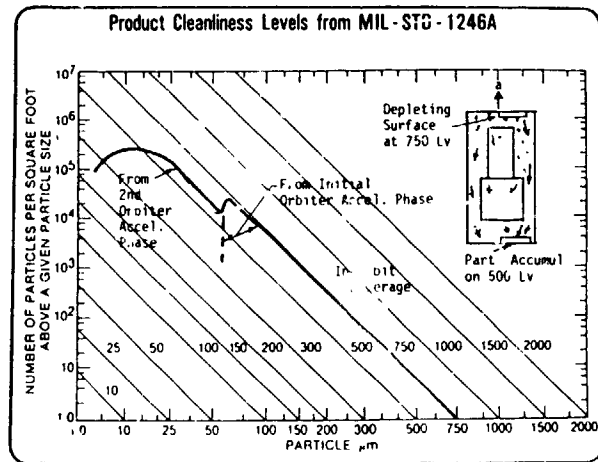

Figure 7. Particles accumulation during shuttle ascent on a clean surface (pre-launch Lv 500) facing acceleration from a depleting surface at Lv 750 — one-to-one field of view.

Rebounding of Particles and Brownian Motion

The particles displaced during the early 2 min of the flight and not transported to the filters will settle on surfaces restrained by the orbiter acceleration. During the second phase of the acceleration, additional particles will be shaken from surfaces. Those particles

may acquire velocities given by $v=(2gh)^{\frac{1}{2}}$ where h is the fall distance. For a fall of about 18m and a 3g acceleration, the velocity is 32.54 m/s. Those particles with sufficient kinetic energies to overcome the adhesion force potentials and the collision anelastic energy losses will rebound at impact. The rebound may continue for a period of time since, by that time, the orbiter is no longer accelerating. The particles will rebound if their kinetic energies ($\frac{1}{2} mv^2$) exceed the adhesion force potential of the particle on the surface, $P = FZ$ where $F = 200\ d$ is the adhesion force and $Z = 5\times10^{-8}$ cm is the range of the adhesion force. For conservation of energy and momentum, both linear and angular, the particle will rebound when the vertical velocity component of impact meets the following criteria (Ref. 4).

$$v^2 > \frac{2P}{m} \frac{1-e^2}{e^2} \qquad (10)$$

where m is the particle mass and e is the coefficient of restitution. For a particle of density, $\rho_p = 2$ gr/cm^3 and a conservative e = 0.8 for the impact of a quartz particle on a quartz surface, the particle of diameter $d(\mu)$, will rebound if its velocity is $V > \frac{32.7}{d}$ (cm/s).

According to these criteria, a 1μ dia. particle will rebound when its velocity is V>32.7 cm/s while a 100μ dia. rebounds when V>0.327 cm/s. Eventually, the particles on colliding with the surfaces will stop when the above criteria have been met. However, the particles in the bay will be engulfed in a gaseous density produced by the outgassing which may be equivalent to about 10^{-2} torr pressure, 1 hour after launch. At this pressure, the mean free path of the molecules is $\lambda \sim 2\times10^{-1}$ cm and the mean velocity of the molecules is $4.5-5.0\times10^4$ cm/s. The mean time between collisions is about 4.2×10^{-6} sec. Therefore, many collisions will occur between molecules and particles during the 1-2 hours of closed bay door conditions. The particles will be losing energies and will randomly move following a Brownian motion with mean velocities according to statistical mechanics and thermal energies of $v = \left[\frac{3KT}{m}\right]^{\frac{1}{2}}$. This mean velocity amounts to 0.11 cm/s for a 1μ dia particle and 3.5×10^{-3} cm/s for a 10μ dia particle at T = 293°K.

The diffusion coefficient of these particles is

$$D = \frac{kT}{3\pi\eta d} = \frac{2.4\times10^{-7}}{d} \qquad (cm^2/s)$$

where $d(\mu)$, and they may travel a mean distance of $X=(Dt)^{\frac{1}{2}}$ cm. Then, a 1μ particle during an hour could travel a distance of 0.3 cm and a 100μ dia of 0.03 cm. Therefore, some of the particles in the range of 1-100μ diameter, having lost most of their initial kinetic energies on bouncing, may be randomly moving among the outgassing molecules, traveling at very low speeds for short distances without contacting a surface. Small accelerations provided by the orbiter attitude changes should have negligible effect on the floating particles in the bay. A measure of their response to disturbances is provided by the particle relaxation time, $\tau = d^2\rho_p/18\mu$ already mentioned.

As expected, small particles respond immediately to changes, while larger ones have very long response times (1μ dia, $\tau = 10^{-5}$ sec; 10μ, $\tau = 10^{-3}$ sec).

Particles Leaving the Orbiter Bay - Experimental Data

When the orbiter bay doors are opened, the particles moving randomly in the bay will diffuse out of the bay. The particle depletion can be represented by the following differential equation

$$V \frac{dn}{dt} = -nvA \qquad (11)$$

where $V \sim 1\times10^4$ ft^3 (2.83×10^8 cm^3) is the bay volume, $A \sim 86\times10^6$ cm^2 is the bay doors' aperture area, $n(cm^{-3})$ is the particles' concentration, and v (cm/s) is their velocities. The solution of the equation for an initial density, n_0 at t = 0 is

$$n = n_0 \exp\left(-\frac{Avt}{V}\right)$$
$$= n_0 \exp(-t/\tau) \quad (cm^{-3}) \qquad (12)$$

where $\tau = \frac{V}{Av}$ (hr) is the e-folding time. Also, the rate of particles leaving the bay is

$$\frac{dn}{dt} = -\frac{n_0}{\tau} \exp(-t/\tau) \qquad (cm^{-3}hr^{-1}) \qquad (13)$$

The on-orbit particle environment has been probed with the camera-photometer during the STS-2,3,4 and STS-9 missions. The camera-photometer, which is one of the measuring instruments of the Induced Environmental Contamination Measurements (IECM) package, takes on film 32° FOV stereo pictures of particles as small as 25μ at a distance of 20m when the particles are illuminated by the Sun against the dark sky or Earth background. Figures 8 and 9 (Ref. 12, 13, and 14) show the time history of the particles seen by the camera during those missions. Figure 8 indicates the percent number of frames showing particles versus time for the first 48 hours of flight. The percentage of frames showing more than 10 particles/frame appears to drop with an e-folding time of about 9.5 hrs. The bay doors in these flights have been opened at about 2-2.5 hr mission elapsed time (Met), and the frame takings have been initiated at about 4.5 hrs Met. Particles from water dumps and other operations are not recorded in these frames. The same plot for the STS-9 mission, figure 9, shows an e-folding time, which has been estimated to be about 15 hrs. Figure 9 shows also a second burst of particles with a corresponding decay. This second event, which started at 55 hrs MET, will be discussed later. Using the time constant of τ = 9.5 hrs for missions STS 2-3-4 and the time constant definition, one calculates that the average velocity

of the escaping particles was

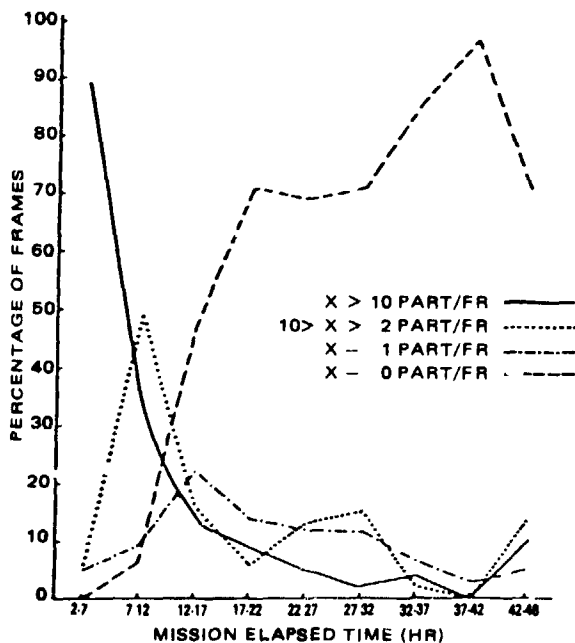$$v = \frac{V}{A_T} = 3.45 \times 10^{-1} \text{ m/h } (9.61 \times 10^{-3} \text{ cm/s}).$$

Figure 8. Summary of particulates observed during the first 48 hours of STS–2,–3, and –4. (Ref. 12).
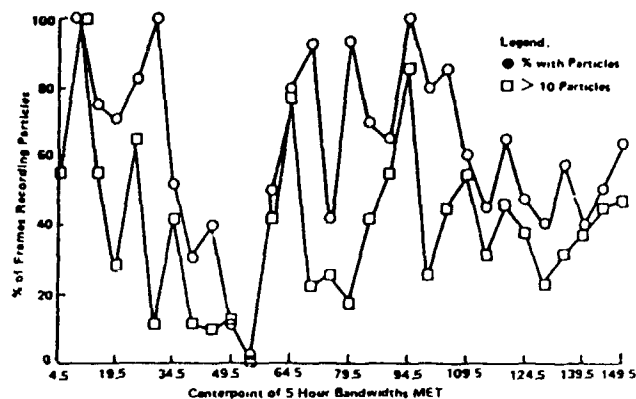

Figure 9. Percentage of STS–9 camera-photometer frames showing particles (ref. 14).

The average mass of the particle can be estimated by equating its kinetic energy to its thermal energy. The average mass of the above particles at a temperature of T = 298°K is m =

$$\frac{3KT}{v^2} = 1.33 \times 10^{-9}$$

where K = 1.38×10^{-16} ergs/K/g

is the Boltzmann constant.

The corresponding average diameter of the

particle of density ρ_p = 2 gr/cm³

is d = $\sqrt[3]{\frac{6m}{\pi \rho_p}}$ = 1.09×10^{-3} cm (10.9μ)

For the STS-9 time constant of τ = 15 hrs, the corresponding calculated particle parameters

are: velocity v = 6.08×10^{-3} cm/s; mass

m = 3.32×10^{-9} g and diameter d = 2.48×10^{-3} cm (14.8μ). From the above equations, one can calculate that the concentration of particles remaining in the bay will be 1% of the initial after 4.6τ; i.e., after 43.7 hrs for the STS 2-3-4 missions and 69 hrs for the STS-9. After those elapsed times, the likelihood of not seeing particles is 99.48%. These calculations appear to confirm the data points and likelihood plots shown in the two figures. One should note that the calculated average diameters of the particles leaving the bay, 10 and 15μ, are small and must have been released during the second period of acceleration; otherwise they could have been vented out by gas flow. Furthermore, figures 10 and 11 of Ref. 12, 13, and 15 show the distribution of particles collected on the IECM passive sample array, which was positioned perpendicular to the Z axis (parallel to the bay doors). The plots indicate three principal peaks near 4, 12, and 22μ diameters which are within the statistical distribution of the

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diameters calculated here. The justification for those particles having deposited on the array may be that they had lost their energies by collisions and settled on the array surface on which they had impinged. The drift velocities of the particles leaving the bay have not been measured. The velocities of the particles, as estimated from the camera photometer observations, are much higher than these calculated drift velocities.
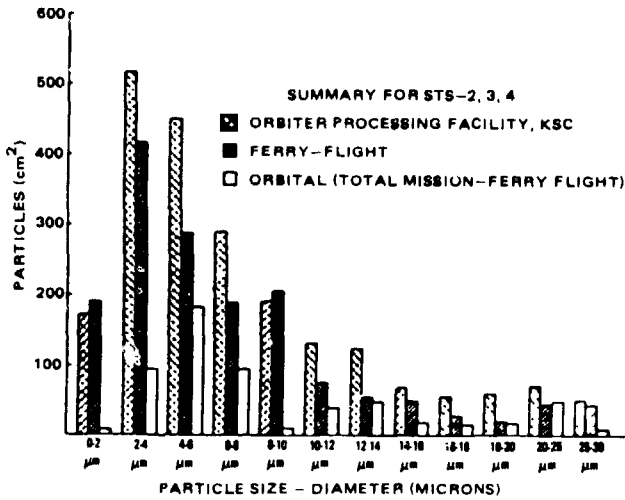

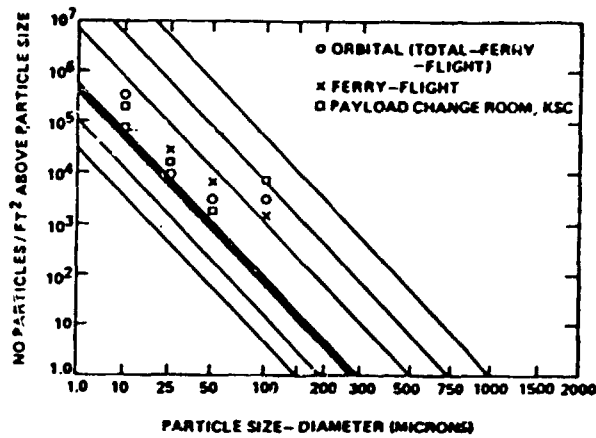Figure 10. Passive sample array particle distributions (Refs.. 12, 13, 15).

Figure 11. Passive sample array: particle-size distributions for STS-4, combined mission operations (Refs. 12, 13, 15).

The rate of particles leaving the bay is

$$\dot{n} = - \frac{n_0 V}{\tau} \exp(-t/\tau) \ (hr^{-1}) \qquad (14)$$

where $\dot{n}$ (hr^{-1}) is the rate at time $t(hr)$,

$n_0 V (particle)$ is the total number of particle

at time zero and $\tau(hr)$ is the time constant. The time required for the rate to drop to a value n is $t = - \tau \ln \frac{n_0 V}{\dot{n}\tau}$ (hr), which requires a knowledge of τ and of n_0, which is the density of drifting particles in the bay when doors are opened.

From the above calculations indicating particles of mean diameters of 10-15μ drifting out of the bay at velocities of $9-6 \times 10^{-3}$ cm/s, one may also conclude that particles greater than three to four times the above diameters released during the last stage of the orbiter acceleration lose sufficient energy and settle on surfaces.

Other Particles Ejected from Bay

The camera photometer data in figure 9 indicate a recurrence of particles in the field of view at about 55 hr Met of the STS-9 mission when the initial particle emission appeared to have subsided. That emission took longer than the first to decay and appeared to have a time constant of the order of 75 hrs. The reason for this second emission not experienced on other flights may be found by comparing the frames with particles plot versus time of figure 9 with the plot of figure 12. Figure 12 shows the temperature of the Quartz Crystal Microbalance (QCM), which measured in bay molecular contamination and indicates shuttle attitudes and other operations versus time experienced during that flight mission (Ref. 16). A shuttle cold test was carried starting at about 34 hr Met and terminating at about 57 hrs. The QCM temperature had dropped to -83°C at that time. The cold test was followed immediately by multiple attitude changes lasting till about 85 hours Met. The attitude changes were resumed at 95 hrs MET, but these were not preceded by the cold test followed by the sudden increase in temperature as had occurred at 57 hrs Met. A close examination of the frame plot in figure 9 shows a corresponding behavior for particle emission. At about 55-57 hours, there was a sudden increase of frames with particles, which lasted up to 95 hrs Met. During that period, a drop of frames with particles is not apparent. A decay does appear after 95 hrs Met, which may be estimated to have a time decay of 50-75 hrs. Using the same procedure as before, the velocity of these particles at a temperature of 273K and for a $\tau = 60$ hrs is 1.52×10^{-3} cm/s. The corresponding mass is 4.89×10^{-8}g, and the mean diameter is 36.2μ. These particles, larger than those calculated for the initially released

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particles (10-15μ), must have been generated by the sudden temperature excursions and the attitude changes. Motions experienced by the shuttle immediately before and during particle release, differential thermal displacements of materials, contractions and expansions of surface occlusions, and friction between surfaces could have generated these larger particles. Speculation that the particles seen in the camera field of view during this period could have been produced by frozen water particles exhausted from the attitude control engines and from water dumps should be excluded. Those frozen ice particles would have considerable exhaust velocities and would have dispersed rapidly, not remaining in the field of view for hours. In fact, water dumps particles were observed to have e-folding times of about 5 min as shown in figure 13, Ref. 12.

Other particle release mechanisms should be investigated, such as: the diminished attraction force of particles on surfaces, thermal shock desorption of particles, meteoritics impact release and generation of surface particles, radiometric force, and electric fields changes reducing the coulombic forces between particles and surfaces.

...icles Velocities as Seen by the Camera/Photometer

The particles leave the shuttle bay along random directions and at velocities of $6-9 \times 10^{-3}$ cm/s. When outside of the bay, they are accelerated by drag forces caused by the rarefied atmosphere at density ρ_a. The acceleration of a particle of diameter d, density ρ_p, moving at the velocity v of the orbiter, ignoring the particle small exit velocity, is

$$a = \frac{F}{m} = \frac{3}{4} C_D \frac{\rho_a}{\rho_p} \frac{v^2}{d} \qquad (cm/s^2) \qquad (15)$$

The drag coefficient C_D depends on the ratio of the speed of the particle and those of the natural particle and on the specular or diffuse reflectivity of the particles (Ref. 17). Its value varies between 2 and 4 and the acceleration is $a = \frac{\rho_a}{\rho_p} \frac{v^2}{d}$ if one assumes, for simplicity, $C_D = 2.66$. The particle should acquire a
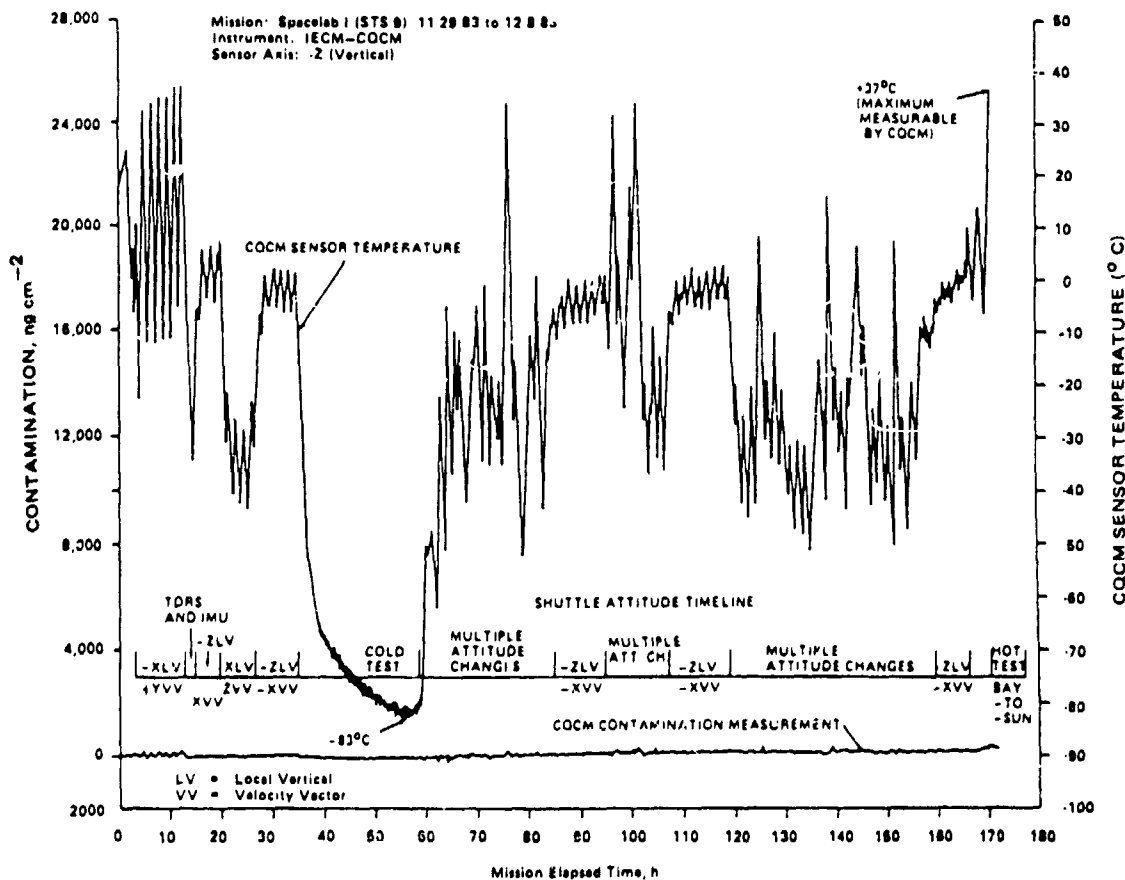

Figure 12. IECM CQCM surface contamination measurements and sensor temperature (Ref.16).

velocity $v = (2aL)^{\frac{1}{2}}$ with respect to the orbiter in the direction of the acceleration, where L is the distance the particle travels parallel to the orbiter. The distance depends on the distance r of the particle from the observation point (bay) and on the FOV angle α of the observer. It is approximately, $L = 2rtn\,\alpha/2$ and the observed velocity is then

$$v = \left[4\frac{\rho_a}{\rho_p}\frac{V^2}{d} rtn\,\alpha/2\right]^{\frac{1}{2}} \quad cm/s \qquad (16)$$

indicating that the velocity is proportional to the square root of the ratio of the observation distance to the particle diameter. The camera photometer with a FOV angle of $\alpha = 32°$, taking about 24 frames/hour would have indicated, for a 25µ particle, a velocity of 1.49 m/s if photographed at 20m distance and 0.33 m/s if at 1m distance. The numerical values for the other parameters for the calculations are $\rho_p = 2$ gr/cm^3 $\rho_a = 7.65\times10^{-14}$ gr/cm^3 at 241 km orbit (Ref. 18), and $V = 8.5\times10^5$ cm/s. These calculated velocities seem to be confirmed by the recent evaluation of the camera photometer measurements (Ref. 19) and are in good agreement with those reported for the Skylab (Ref. 20). When out of the bay, the particles will be accelerated and will be losing energy with respect to the orbiter. The particles move away from the orbiter and enter eccentric orbits. As seen from the orbiter, the particles will move down behind and then in front of and up the orbiter. The continuous loss of energy by rag will lower the particles orbit continuously changing their distances from the orbiter. Figure 14, taken from Ref. 21, shows the orbits as a function of time and distance for a 100µ dia particle released from a spacecraft with a velocity of 3 m/s at various angles from the orbit zenith. Other orbit plots in terms of directions, velocities, drag coefficients, and time are shown in Ref. 22, 23, and 24.

Summary and Conclusions

Particulate contaminants on shuttle bay surfaces and on surfaces of payloads carried by the shuttle will be resuspended during shuttle ascent by vibroacoustic, gravitational, and aerodynamic loadings.

Random mechanical accelerations of about 13 g rms in the frequency range of 20 to 2000 Hz experienced during ascent by surfaces and systems are expected to release from surfaces all the particles in excess of 80-90µ dia. and only 1-2% of particles less than 10µ. These particles--depending on the direction of the releasing surface with respect to the acceleration vector--will fall back on the surface, fall on another surface properly

positioned with respect to the velocity vector, or be transported to the vent filters. Also, if they have sufficient falling kinetic energy, they may bounce from surface to surface until either they deposit on a surface or are entrained by the outgassing molecules in the bay acquiring the energy of the outgassing molecules which will be colliding with them. The particles not deposited will be moving randomly in this relatively tenous gas only rarely hitting a surface.

Two periods of releasing and resetting of particles are envisioned. During these two periods, the random acceleration forces have magnitudes of about 13g rms including some peak magnitudes of about 39g.

An initial number of particles will be released during the initial 2 min of ascent while venting of the bay volume is occurring. During the transonic region of flight with max mechanical disturbance at the surfaces and max vent velocity in the bay, released particles less than about 58µ, will be entrained by the gas flow. Most of them may be directed to the vents where they are trapped if greater than about 35µ. Others capped in a turbulent flow will remain in random motion in the bay.
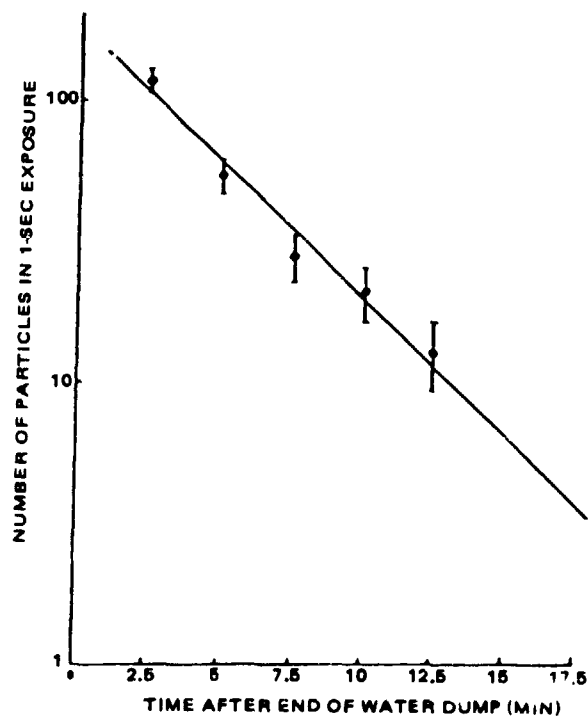

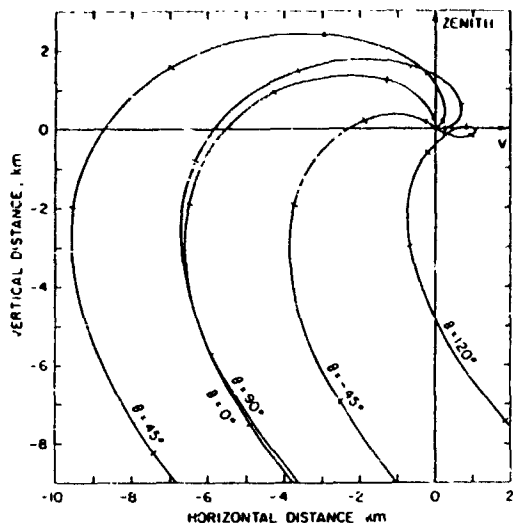Figure 13. Particle count decay after water dump termination (Ref. 12).

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Figure 14. Trajectories as viewed from the spacecraft are given for a dust particle with $r_d = 100$ μm and $V_o = 3$ m/sec at a 350-km altitude and average atmospheric density. The tick marks represent times of 100 sec, 500 sec, 1000 sec, 1500 sec, 2000 sec, etc. θ is the angle from the zenith of the initial particle velocity vector V_o. (Ref. 21).

Released particles greater than 58μ will resettle on the surface of origin if the surface is normal and facing the velocity vector. Those released from surfaces parallel and/or not facing the velocity vector will drop on surfaces facing the vector by virtue of the shuttle acceleration.

During the second stage of the ascent, which terminates about 9 min after launch, additional particles are released and resettled. Aerodynamic drag in the bay is no longer effective in moving particles; and those released either will be accommodated on the surface by the shuttle acceleration or will be floating about in the bay in a zero g environment.

The following particle redistributions may be expected during launch in the shuttle or in an instrument:

- A surface facing opposite the acceleration vector will lose particles as it cleans up. In orbit, that surface will have slightly less particles in the size range up to 36μ and considerably less particles of larger size than it had at launch. No particle greater than about 90μ will be left on that surface.

- A surface looking into the velocity vector and located toward the rear recovers its own acceleration released particles and collects particles released from other surfaces which

are accelerated toward the rear of the shuttle or of the instrument. The increased number of particles on these surfaces are mainly those of diameter greater than 58μ. The number of particles per unit area may double for this range if there is a one-to-one view factor between the rejecting and accepting surfaces. If the area of the surfaces releasing particles is K times the area of those surfaces receiving particles, then the accommodation is approximately K times the or for the one-to-one view factor. For the shuttle bay, the distribution per unit area on the aft surface of the bay may be approximately 18 times that for the double distribution obtained for the one-to-one view factor.

- A relatively clean surface (less than Level 500) will be contaminated with particles from other surfaces greater than 58μ, and with few particles with diameters between 58 and 5μ.

- The redistribution of particles on surfaces assumed to have an initial distribution of particles corresponding to Level 750, with a surface correspondence of a one-to-one, has been indicated. These assumptions can be changed since the losses and gains of particles are provided in terms of the percentage of the density/unit area in the specific particle size range. The gain on a unit surface can be estimated by modifying the results for a one-to-one relation by the area ratio of the surface losing to the one gaining particulates.

- Some small particles <58μ, which did not enter the vents or were released during the second phase of acceleration, are entrained in the outgassing molecules and move randomly in the bay where the outgassing mean free path is a few tens of cm. After about 2 hours in orbit when the bay doors are opened, those particles which have mean diameters of 10-15μ leave the bay with

  average velocities of about 1×10^{-2} cm/s. Outside of the bay, these particles are decelerated with respect to the orbiter by drag forces and will be moving away from the velocity vector. The camera-photometer observing these particles at various distances from the bay will see the particle moving at about 1.5 m/s if the particle is 20m away and about 0.33 m/s if at 1m away. These bay released particles lose energy with respect to the shuttle and enter a different orbit.

- Particles of mean diameter of about 36μ which had deposited on surfaces and/or did not leave the bay will be made to leave the

  bay at velocities of 1.5×10^{-3} cm/s by

thermally induced effects. Thermal shock, differential thermal expansions, friction between surfaces, photodesorption, thermophoresis, desorption from surfaces, and other mechanisms can be the cause of these additional emissions, which have been observed by the camera photometer in one of the shuttle flights.

Recommendations

1. Clean the bay surfaces and payloads to optimum level of cleanliness before launch. Protect the clean surfaces whenever possible.

2. Surfaces normal to the acceleration vector should be as clean as possible, since they will receive additional particles from other surfaces above them not facing the acceleration vector.

3. The bay doors should be opened as soon as possible to allow particles floating in the bay to exit. This will limit the settling of those particles on surfaces.

4. Provide particulate shields, covers, and doors on surfaces normal to acceleration. The covers should firmly enclose the protected surface preventing particles carried by turbulent venting flow from entering the spacing between cover and surface.

5. Optical observations out of the bay should be carried out after the source of particles leaving the bay is depleted. The time constant (1/e drop in number) is about 10-15 hours. The time to wait for the number of particles leaving the bay to be a few percent of the initials is therefore 40-50 hours after bay opening. This delay in observation may also be necessary after an initial thermo-shock of the shuttle bay.

6. Suggested measurements and data collections which may provide additional understanding of the release and redistribution of particles in the bay are:

a. Photomicrograph control surfaces located on bulkhead and aft of the bay, before launch, after rocket boosters' separation (2 min), after tank separation. Analyze these photos for particles redistributions as a function of ascent stages.
b. Analyze the particulates on a filter vent before launch and in orbit. The sample filter could be replaced in orbit and returned to ground in a protected enclosure.
c. Inspect and check visually for particulate deposits in the aft bay and bulkhead after shuttle flights to note gross differences in deposits.
d. Use particle deposition instruments located at strategic locations in the bay and

timed to operate at specific periods of the ascent to provide particulate density data in the bay at various times.
e. Use QCMs with sticky surfaces to collect particulates at various bay locations during ascent.
f. Use optical systems to get data on particulate density in the bay as a function of time while bay doors are closed and when opened.

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16. Abstract

The dislodgement, venting and redeposition of particles on a surface in the shuttle bay by the vibroacoustic, gravitational, and aerodynamic forces present during shuttle ascent have been investigated. The particles of different sizes which are displaced, vented, and redistributed have been calculated; and an estimate of the increased number of particles on certain surfaces and the decrease on others has been indicated. The average sizes, velocities, and length of time for certain particles to leave the bay following initial shuttle doors opening and thermal tests have been calculated based on indirect data obtained during several shuttle flights. Suggestions for future measurements and observations to characterize the particulate environment and the techniques to limit the in-orbit particulate contamination of surfaces and environment have been offered.

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