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Redistribution of Particulates on a Payload During Flight Ascent

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REDISTRIBUTION OF PARTICULATES ON A PAYLOAD DURING FLIGHT ASCENT

by

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Abstract

The dislodgement, venting, and redeposition of particles on a surface caused by the vibroacoustic, gravitational, and aerodynamic forces have been estimated and the resulting areal obscurations of the surfaces have been calculated. The data on particle redistribution estimated to occur during a Shuttle launch have been employed to estimate the obscuration of a spacecraft's star tracker, as it is carried into orbit by the Shuttle. The approach used for that calculation has been generalized so that it can be employed for other applications where either the Shuttle or an Expendable Launch Vehicle (ELV) is employed for launch. Approaches for evaluating particle redistribution for other applications and for general use have been indicated.

Introduction

The redistribution of contaminant particles during spacecraft ascent has been investigated. The particles are those left within the launcher volume and on surfaces of both the launcher and the payload before launch. They escape cleaning efforts to remove them from the launcher at several stages of the flight preparation. The particle redistribution on surfaces and their release into an instrument's field of view is important to understand 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 into which they may escape. Some of the effects of particles on surfaces and in the spacecraft environment include: 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; and particle emissions of certain radiations which may be detrimental to certain instruments' observations.

This paper is concerned with the particulate redistribution during launch/ascent. The particles residing on launcher and payload surfaces at launch are dislodged, scattered, and redeposited by vibroacoustic, gravitational, and aerodynamic forces present during ascent. Some of the released particles are removed by gaseous venting; others will redeposit on surfaces according to the surface orientation with respect to the acceleration vector. In the following, the fractions of different-sized particles that are dislodged, redistributed, and vented are calculated. The interchange of particles from a particle-covered surface to another surface has been evaluated, indicating the resultant cleaning of one surface and the increased contamination of another surface. An estimate is given of the particles residing on a spacecraft surface when in orbit based on the original particulate conditions before launch.

The deposit of particles on a star tracker's optics has been calculated based on the original estimated conditions of the surfaces and on the assumption of the mechanism involved in the dislodging of the particles. The star tracker attached to a spacecraft mounted in the Shuttle bay is located within a conical horn, protected by a shutter that opens on command. The horn is directed at a 45° angle from the velocity vector of the launcher (Shuttle bay axis) and is located a few feet away from the Shuttle bulkhead, and near the lateral surface of the bay.

After providing a resume of the analysis results on particulate redeposits during Shuttle launch (as reported in Ref. 1) the particulate deposits on the star tracker lens of the spacecraft have been estimated. The calculations are based on the assumptions that the Shuttle surfaces are at a cleanliness level of about 750LV, and the clean surfaces receiving the dislodged particles are at a relatively clean level of 500LV. These levels are described in MIL STD 1246A, Rev. 2. The new cleanliness levels resulting from particle redistribution may cause an obscuration of an optical surface and, as in the case of the star tracker, may provide star obscuration, false star indication, and pointing errors. The calculations for the particle deposits and the relative obscurations indicated here are also intended to provide a guideline and a method to evaluate similar conditions expected during Shuttle launches or launches utilizing Expendable Launch Vehicles (ELVs). The sequence of the calculations which can be automated for computer use are shown. Suggestions on limiting the particulate contamination of critical surfaces have been offered. Some of the suggestions on improved cleaning for certain surfaces before launch may result in considerable monetary savings.

Summary and Conclusions for Shuttle Launch (Ref. 1)

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 13g rms in the frequency range of 20 to 2000 Hz experienced during Shuttle ascent by surfaces and systems are expected to release from surfaces all the particles in excess of 80-90μm in diameter, and only 1-2 percent of particles less than 10μm in diameter. 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 they are entrained by the outgassing molecules in the bay, thereby acquiring the energy of the outgassing which will be colliding with them. The undeposited particles will be moving randomly in this relatively tenuous gas, only rarely hitting a surface.

Two periods of releasing and resettling of particles are envisioned for the Shuttle launch. 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 minutes of ascent while venting of the bay volume is occurring. During the transonic region of flight (about 50 seconds after launch) with maximum mechanical disturbance at the surfaces and maximum vent velocity in the bay, released particles less than about 58μm will be entrained by the gas flow. Most of them may be directed to the vents where they are trapped by the vent filter if greater than about 35μm. Other particles entrapped in a turbulent flow will remain in random motion in the bay.

Released particles greater than 58μm 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's acceleration.

During the ascent stage, which terminates about 9 minutes after launch, additional particles are released and resettled. Aerodynamic drag in the Shuttle bay is no longer effective in moving the 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 redistributions may be expected during launch in the Shuttle or in an instrument:

- A surface facing opposite the acceleration vector will lose particles as the surface "cleans up." In orbit, that surface will have slightly fewer particles in the size range up to 36μm and considerably fewer particles of larger size than it had at launch. No particle greater than about 90μm will be left on that surface. Figure 1 shows this depletion. An expected undisturbed original cleanliness level of 750LV has been assumed.

- A surface looking into the velocity vector and located towards the rear of the craft recovers its own acceleration-released particles and collects particles released from other surfaces which are then accelerated towards the rear of the Shuttle or of the instrument. The increased number of particles on these surfaces are mainly those of diameters greater than 58μm. 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.

- A relatively clean surface (less than level 500) will be contaminated with particles from other surfaces greater than 58μm, and with few particles with diameters between 58 and 5μm. Figures 2 and 3 show the estimated final contamination levels on surfaces originally at 750 and 500LV. The field of view between these surfaces and the particle rejecting surface is one to one.

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 surfaces losing particulates to the one gaining particulates. View factor considerations must be used to estimate those gains and losses. Approaches to account for these are discussed later.

Application

As an application and a follow-on to the above, calculations have been carried out to estimate a star tracker's (ST's) obscuration which may result from the dislodging and settling of particles during Shuttle launch. The evaluation was precipitated by the request for a more careful cleaning of the Shuttle bay during launch preparation than the normal cleaning and inspection procedures. The requested cleaning involved a visual inspection of surfaces from a distance of 2 to 4 feet with a 50-foot cd light source, and the relative cleanings as required during the various stages of Shuttle launch preparation.

The requested cleaning for the entire Shuttle bay would have had a large cost impact. The analysis carried out here shows that it is not necessary to clean to that stringent a level the entire Shuttle bay—only the bulkhead and a small lateral area of the bay's cylindrical surface need to be carefully cleaned.

Analysis

The calculations for the obscurations and particle distributions on the STs are based on a modification of the results of the analysis briefly summarized above and fully described in NASA TM-87794, "Particulate Contaminant Relocation During Shuttle Ascent," dated June 1986. Figure 3 shows the accumulation of particles on a clean surface (prelaunch LV500) released by a surface at LV750 during Shuttle ascent. Those results, as indicated, are for a one-to-one field of view between receiving and depleting surfaces.

Figure 3 was obtained by assuming that for a direct view between a 1-square-foot surface at 750LV and a 1-square-foot surface at 500LV, the accumulation is characterized by the expression

$$A_T = N_O (1 + \psi)^2$$

for each particle size, where A_T is the number of particles accumulated on the receiving surface, N_O is the number of particles of that size on the releasing surface, and ψ is the percentage released for each size produced by the acceleration disturbance applied to them. This factor is based on experimental data as shown in Figure 4. The summations for each particle size, obtained by graphical integration of the Figure 3 distribution shown in Figure 6, are listed in columns 1, 2 and 3 of Table 1. The particles of diameter d_p are assumed to be of spherical shape, and to have an area A_p. The products of the number of particles per square foot, N_p, and the area A_p needed for the calculation of the areal obscuration are shown in column 4 of Table 1.

For the star tracker's (ST's) analysis, those results (columns) 1, 2, 3, and 4 of Table 1) have been modified to account for a larger particle-generating surface (as shown in Figure 7). The sketch in Figure 7 shows the location of the STs in the Shuttle bay, the configuration of the STs, the dimensions of the STs and the surfaces assumed to be contributing the particles. It is conservatively assumed that falling particles will enter both horizontal and vertical projections of the horn entrance, which is inclined at 45° from the vertical of the bay. The number and the corresponding sectional areas of the particles entering the horn are assumed to be 1.41 times those shown in Figure 3; i.e., a 1.4-square-foot surface at 750LV is shedding particles falling into the horn.

The various assumptions and alternatives which have been considered in the calculations to account for the baffles in the horn and the shutter opening and closing above the optical surface of the Star Tracker, are shown in Table 1 and in the Summary. The results are as follows:

Assumption 1

All the particles entering the horn fall on the shutter.

a. All the particles as per assumption 1, fall on the STs upon opening the shutter. The shutter and the STs have the same surface area (0.37 ft^2). The ST's obscuration will be 1.33 percent. Columns 5 and 6 of the table indicate the accumulation and obscuration.

b. Only a fraction of the particles on the shutter fall onto the ST upon opening the shutter. The shutter's opening is assumed to be carried out in 100 ms, while the shutter's moving leaves travel a distance of 4 inches. This motion will result in an approximately 2g force ($2d/t^2 \sim 2g$) applied to the particles on the shutter. The fraction of various-sized particles that have been released and have fallen onto the star tracker for 2g is based on data shown in Figure 4 and indicated in column 9 of Table 1. As a result, the ST's obscuration is 0.77 percent.

Assumption 2

Only the fraction of particles corresponding to the area ratio of the shutter area to the horn entrance area (0.37/1.41 = 0.26), deposits on the shutter (the other particles remain on the baffles). The particles and areas are shown by columns 7 and 8 of Table 1.

a. If all the particles on the shutter, as per assumption 2, fall on the STs, the obscuration will be 0.24 percent.

b. If only the fraction dictated by the 2g acceleration of the shutter (Table 1, column 13) falls on the STs, the obscuration is 0.14 percent. The particle distribution on the STs is as shown in Figure 8. The explanations for the columns are shown in Table 2; and the relative calculations to determine the amounts can be computerized.

Results and Recommendations

The results of the analysis, based on several assumptions of the launch vibroacoustic accelerations and particle adhesion forces on the surfaces, indicate a more probable ST obscuration of 0.24 percent. The obscuration is defined as the percentage of the ST's surface area covered by the projected areas of the surface particles assumed to be of spherical shapes. The 0.24-percent obscuration will be produced by a particle distribution approaching a surface cleanliness level of about LV600 for the large-sized particles. This level, as per MIL-STD-1246, implies that there is one particle of 600-μm diameter on the surface and a larger number of smaller sized particles according to a log normal distribution plotted on a log vs $\log^2$ set of axes. The 0.24-percent obscuration and corresponding particle size distribution, are considered acceptable for the star tracker performance, according to experts in the field.

On the basis of these estimates (and other considerations based on unpredictable surface conditions and releasing forces), the inspecting and cleaning of the Shuttle bay carried out according to the normal procedures was found to be acceptable, and the special inspecting and cleaning of all of the bay surfaces was unnecessary. It was suggested that special attention in this area be paid to surfaces located above the STs in the bay. These include the bulkhead surfaces and others located forward towards the Shuttle cabin, above the STs and the fixed spacecraft. In addition, it was recommended that the star trackers' shutters should be closed during launch, as intended. The shutters would provide an added protection against particle deposits on the STs. In fact, the shutter closing leaves could retain and prevent some of the smaller particles from falling on the STs during their opening motion. It was also noted that some available, low outgassing, tacky materials could be applied to the shutter leaves to capture and retain smaller particles.

References

1. Scialdone J.J. "Particulate Contaminant Relocation During Shuttle Ascent" Proceedings of SPIE, P. Glassford, Ed., Optical System Contamination, Orlando, Fla., May 1987 pg. 55. (Also NASA TM 87794, June 1986.)

2. MIL-STD-1246 B, Military Standard Product Cleanliness Level and Contamination Control Program, Dept. of Defense, 4 Sept 1987.

3. Hamberg, O. "Particulate Fallout Predictions for Clean Rooms" The Journal of Environmental Sciences, May/June 1982.

Product Cleanliness Levels from MIL-STD-1246A

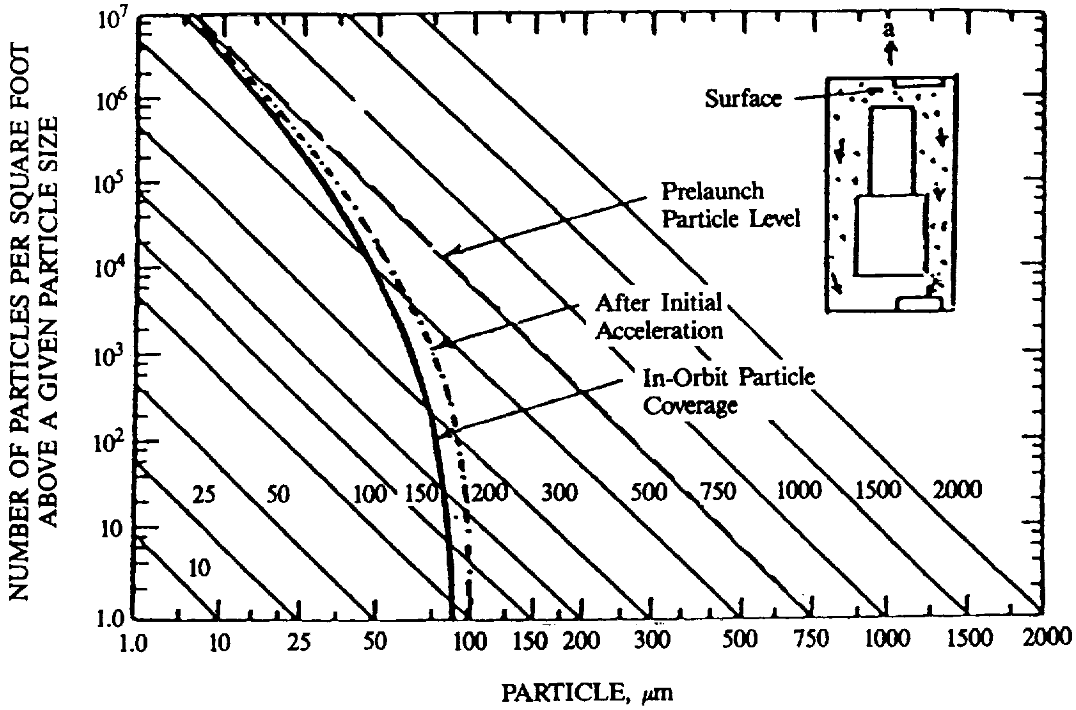


Figure 1. Particle depletion during Shuttle ascent from a surface not facing the acceleration vector, contaminated to a 750 LV of MIL-STD-1246A.

Product Cleanliness Levels from MIL-STD-1246A

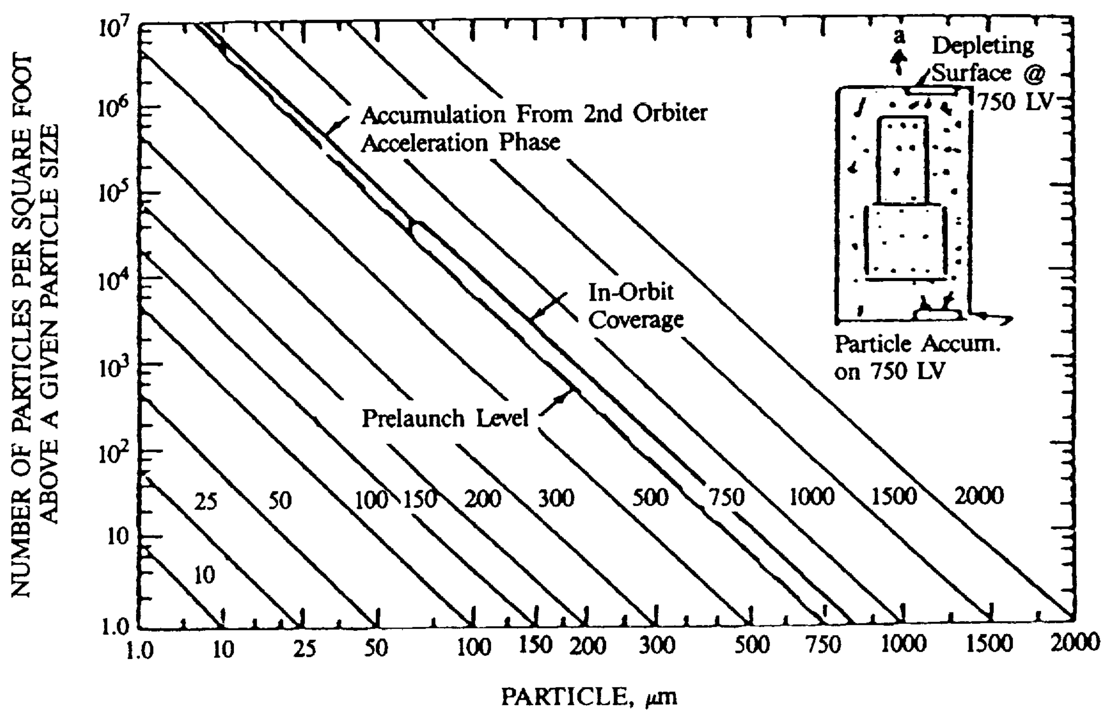


Figure 2. Particle accumulation during Shuttle ascent on a surface facing the acceleration vector at a prelaunch LV 750, from a depleting surface also at 750 LV with a one-to-one field of view.

Product Cleanliness Levels from MIL-STD-1246A

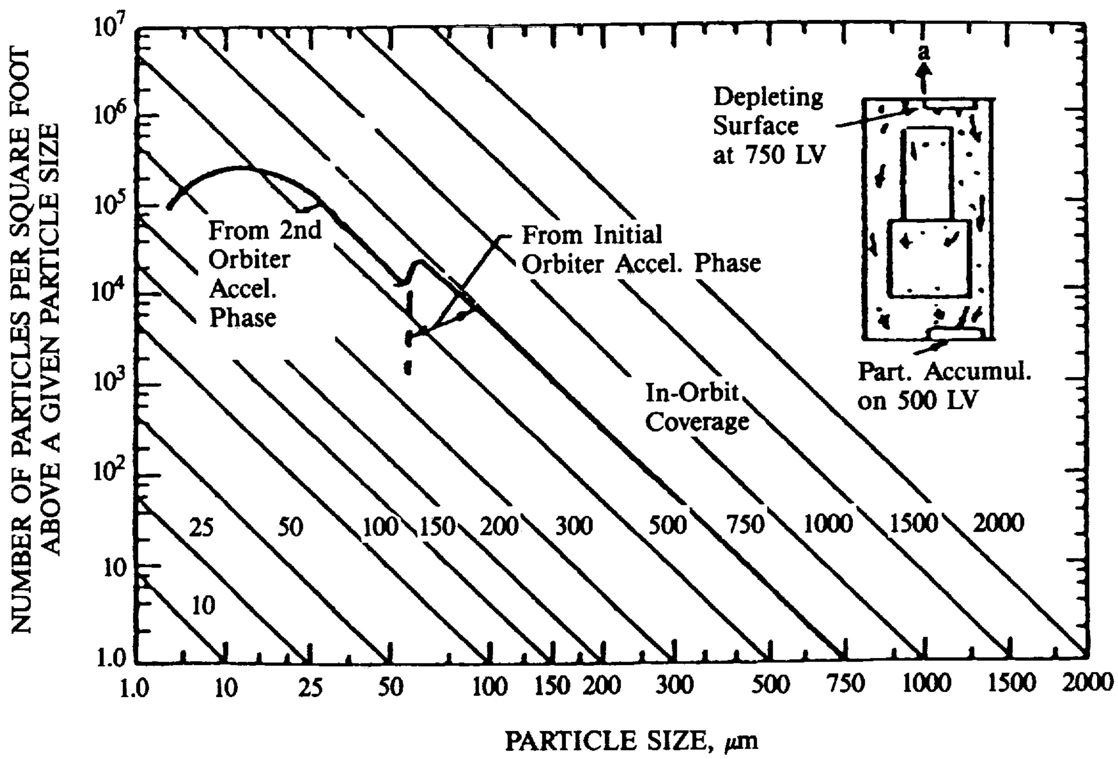


Figure 3. Particle accumulation during Shuttle ascent on a clean surface (prelaunch LV 500) facing acceleration from a depleting surface at LV 750 — one-to-one field of view.

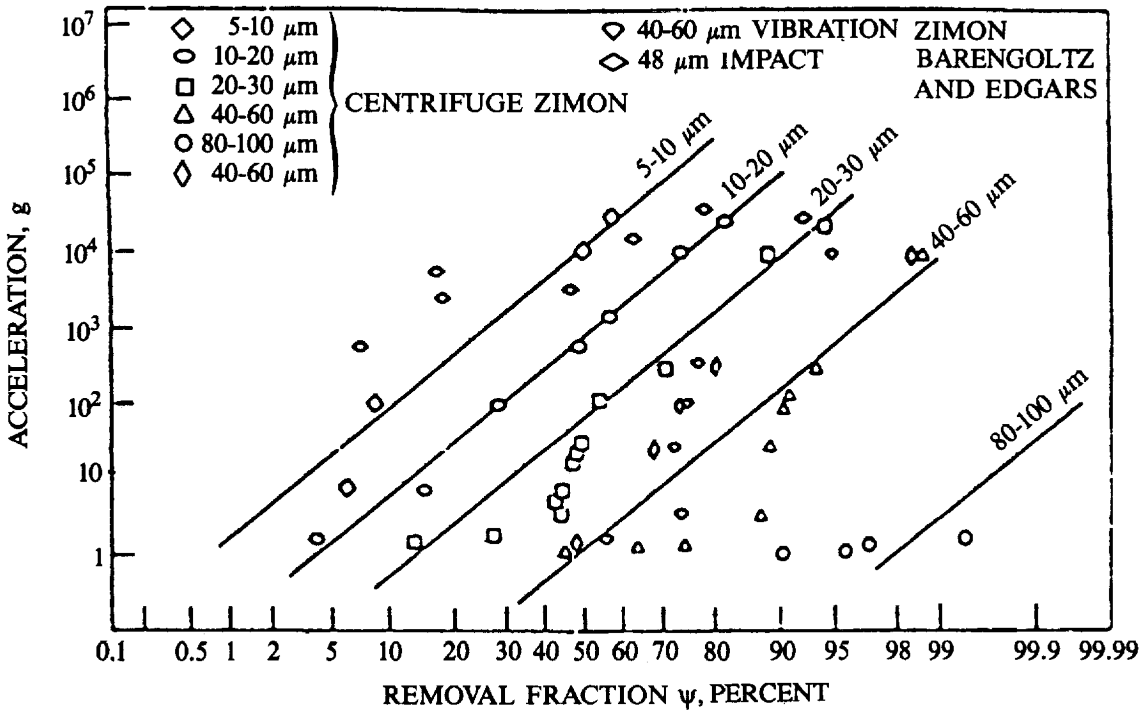


Figure 4. Particle resuspended fraction vs. acceleration test data — glass particles on stainless steel (Ref. 8).

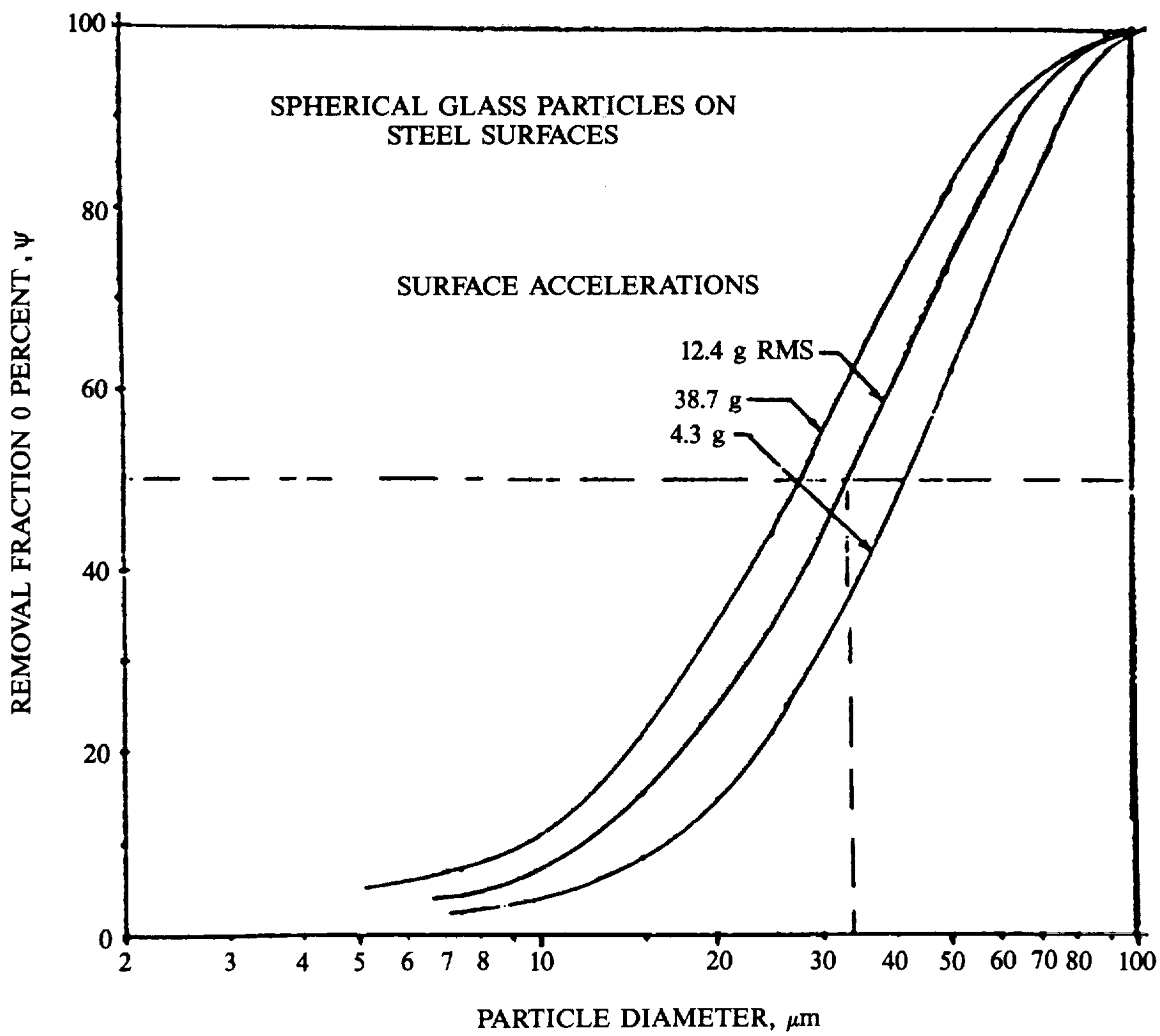


Figure 5. Fraction of particles removed by surface vibration.

Product Cleanliness Levels from MIL-STD-1246A

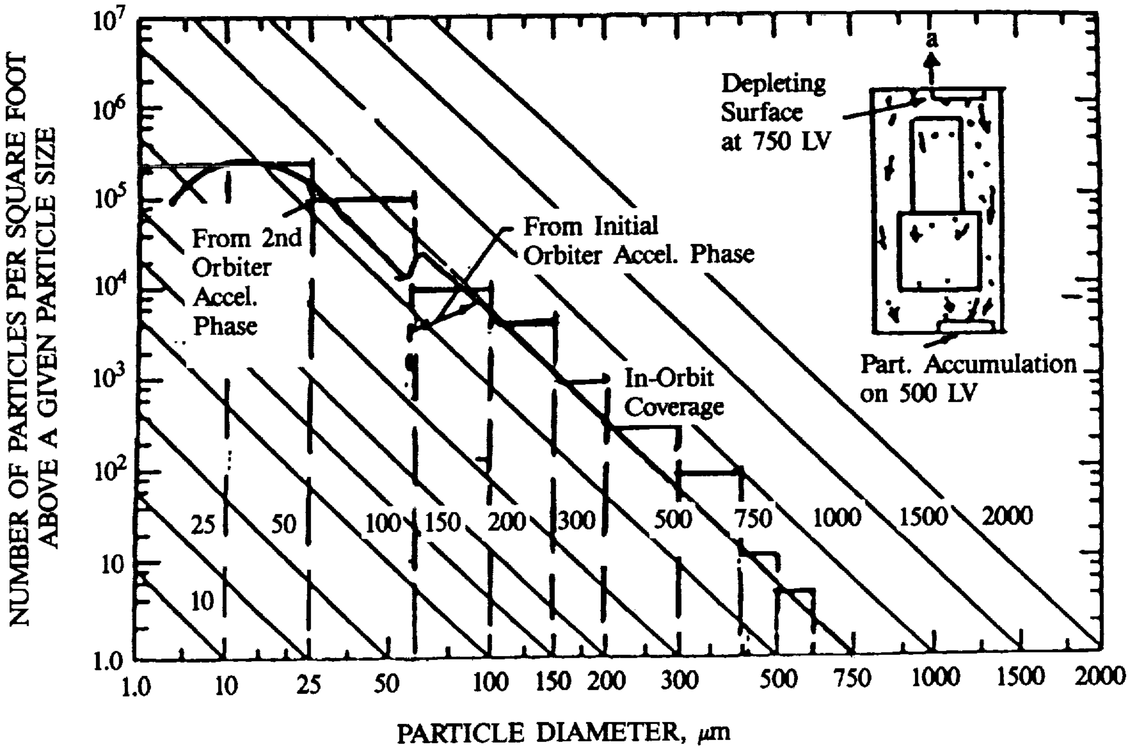


Figure 6. Particle accumulation during Shuttle ascent on a clean surface (prelaunch LV 500) facing acceleration from a depleting surface at LV 750 — one-to-one field of view.

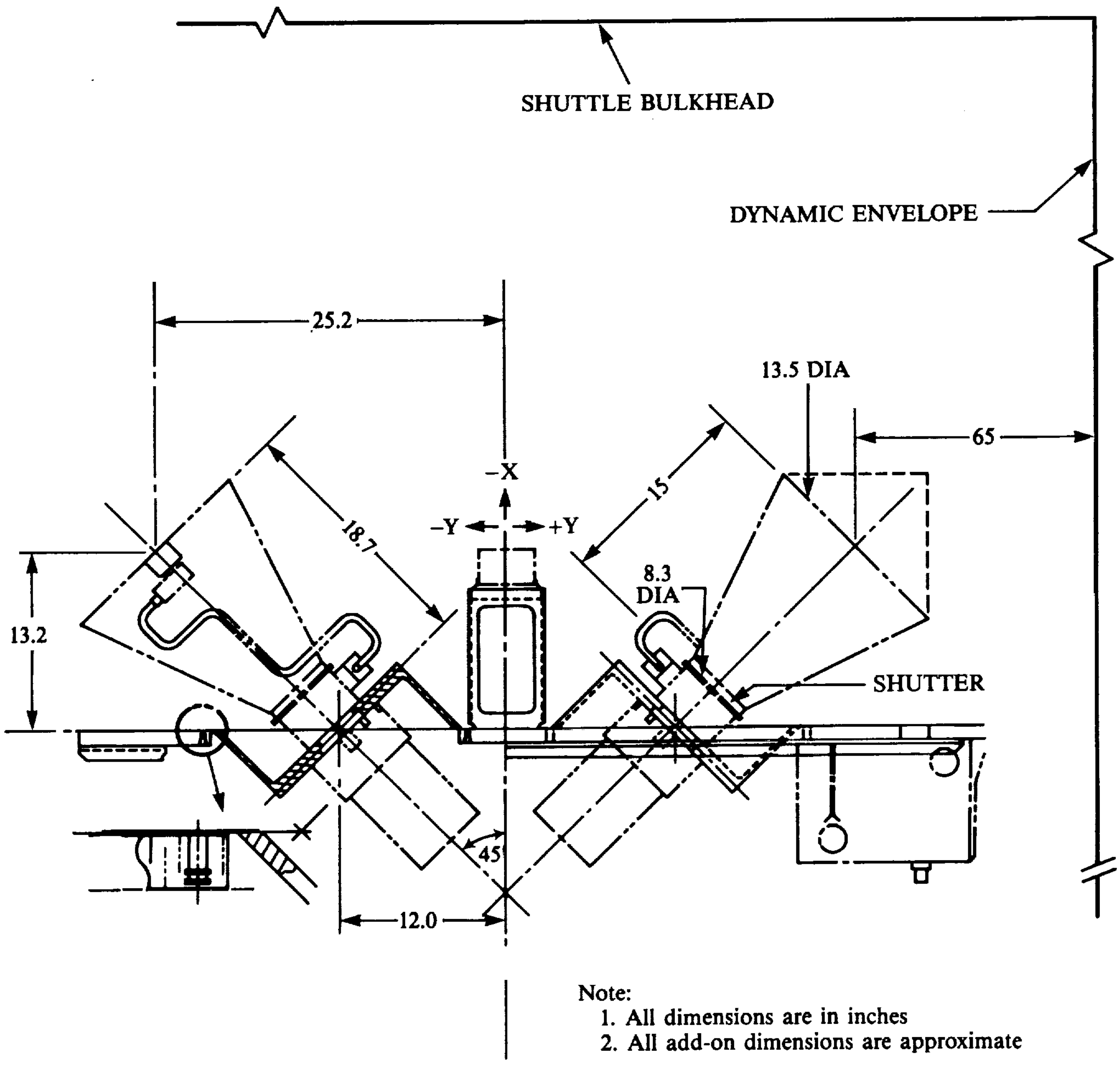
Data & Assumptions:

Shutter Area, $A_s = \frac{\pi}{4} (8.3)^2 = 0.37 \text{ Ft}^2$

Horn Entrance Area, $A_H = \frac{\pi}{4} (13.5)^2 = 1.0 \text{ Ft}^2$

Horn Entrance Projected Area, $A_p = A_H (\text{Cos } 45 + \text{Sin } 45) = 1.41 A_H = 1.41 \text{ Ft}^2$

Shutter Area/Horn Proj. Area or $\frac{A_s}{A_p} = \frac{.37}{1.41} = 0.26$



Note:
1. All dimensions are in inches
2. All add-on dimensions are approximate

FIGURE 7
FIXED HEAD STAR TRACKER DATA & ASSUMPTIONS

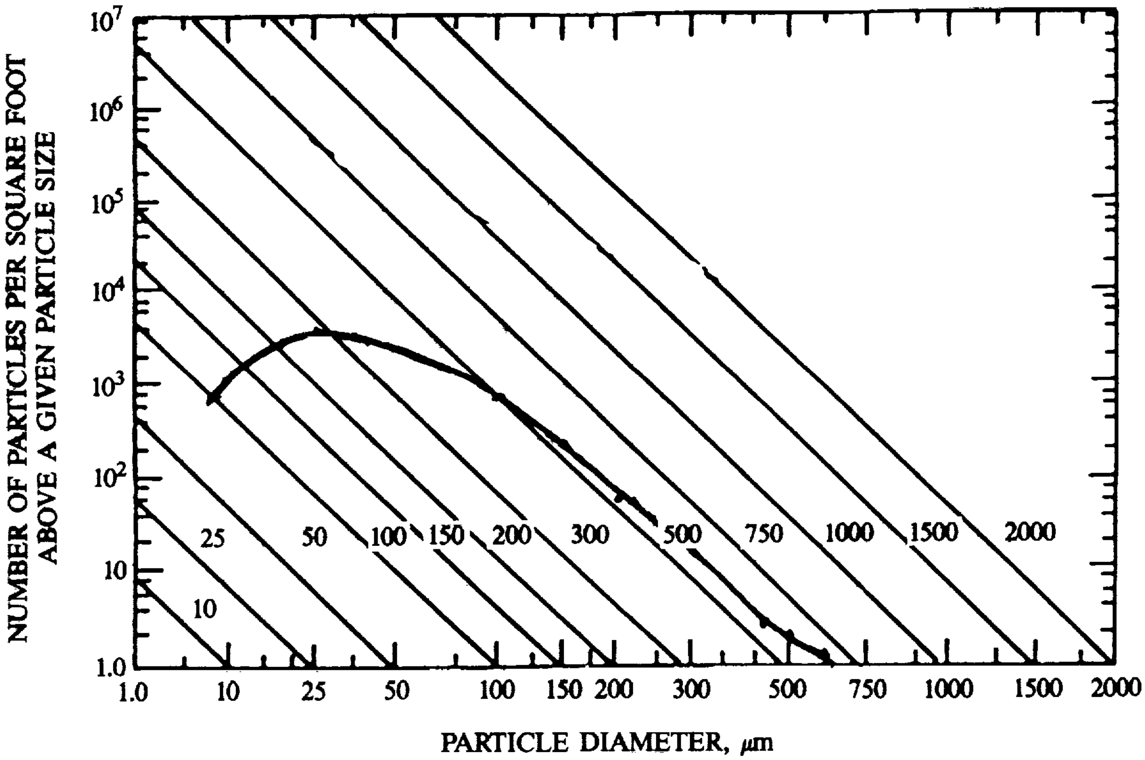


Figure 8. Distribution of particles on the ST optics originally at 500 LV, produced by the fraction of the particles on the shutter (26% of total entering the horn) released by 2g acceleration while opening the shutter; per assumption 2 b.

Table I
Calculations to Estimate Obscuration and Distribution of Particles on Star Tracker

*Particles on 1 ft^2 Surface Origin. @ LV 500 Fallen From an LV750 Surface				Particles Entering Horn		Fraction of Particles on Shutter		% Drop From Shutter @ **2g	Particles Fallen on Star Tracker		Fraction Particles on Star Tracker	
1	2	3	4	5	6	7	8	9	10	11	12	13
d_p (μ)	A_p (μ^2)	N_p (ft^{-2})	N_pA_p (μ^2)	1.41 N_p	1.41 N_pA_p (μ^2)	0.26 N_p	0.26 N_pA_p (μ^2)	ψ%	1.41 N_p ψ	.41 $N_pA_p\psi$	.26 $N_p\psi$	.26 $N_pA_p\psi$
10	78	5^5	3.9^7	7.05^5	5.49^7	1.30^5	1.01^7	1	7.05^3	5.5^5	1.3^3	1.0^5
25	4.87^{-2}	2^5	9.74^7	etc.	etc.	etc.	etc.	12	etc.	etc.	etc.	etc.
55	2.36^3	1^4	2.36^7	↓	↓	↓	↓	50				
100	$7.8^{\ 3}$	5^3	3.90^7					100				
150	1.75^4	1^3	1.75^7					100				
200	3.12^4	3^2	9.36^7					100				
300	7.02^4	1^2	7.02^6					100				
400	1.24^5	1^1	1.24^6					100				
500	1.95^5	8^0	1.56^6					100				
600	$2.8^{\ 5}$	5^0	1.40^6					100				
750	4.38^5	1^0	4.38^5	1.41^0	6.17^5	2.6^{-1}	1.13^5	100	1.41^0	6.17^5	2.6^{-1}	1.13^5
* From $A_T = N_O(1+2\psi-\psi^2)$ or Fig. 7 in Ref. TM87794			$\Sigma=3.21\times10^8\mu^2$ $= 3.46^{-3}ft^2$		$\Sigma=4.59^8\mu^2$ $=4.94^{-3}ft^2$		$\Sigma=8.35^7\mu^2$ $=8.98^{-4}ft^2$	**a $=2s/t^2=2g$ s=4 in, t=10^2ms		$\Sigma=2.67^8\mu^2$ $= 2.87^{-3}ft^2$		$\Sigma=4.81^7\mu^2$ $=5.17^{-4}ft^2$

Obscurations

A. Particle from 1 ft^2 @ 750 to 1 ft^2 @ 500LV $= \dfrac{3.46 \times 10^{-3}}{1} = 0.34\%$.

B. 1a. All particles from 750LV entering horn on shutter and then on STs $= \dfrac{4.94 \times 10^{-3}}{0.37} = 1.33\%$.

C. 2a. Fraction of total particles entering falling on shutter and then on STs $= \dfrac{8.98 \times 10^{-4}}{0.37} = 0.24\%$.

D. 1b. The fraction ψ of particles on shutter falling on STs due to 2g $= \dfrac{2.87 \times 10^{-3}}{0.37} = 0.77\%$.

E. 2b. The fraction ψ of particles on shutter (26% of total) falling on STs $= \dfrac{5.17 \times 10^{-4}}{0.37} = 0.14\%$.

Table II
Calculation—Procedure

1. Distribution of particles on a 500-LV surface, deposited from a 750-LV surface when exposed to the Shuttle environment, d_p (μ) their diameters.
2. The section area of those particles A_p.
3. N_p, the number per ft^2.
4. N_pA_p, the total obscuration area μ^2 = (3)(2).
5. Particles entering the horn from horizontal and vertical, component of horn entrance A (cos 45 + sin 45) = 1.41 A = 1.41 ft^2; 1.41 N_p = 1.41 • (3)
6. Area covered by particles in horn 1.41 N_pA = 1.41 • (3)(2).
7. Fraction of particles on shutter out of those entered the horn.

   i.e., $\dfrac{\text{area shutter}}{\text{area project horn}} \times N_p = 0.37/1.41 \cdot (3) = 0.26\ N_p$
8. Total area on Shutter 0.26 N_pA_p = (7) × (2)
9. % Drop from Shutter on opening with accel $a = \dfrac{2s}{t} = 2g$, ψ from figures 4 & 5.
10. No. of particles = 1.41 $N_p\psi$ = (5) × (9) on star tracker.
11. Area of particles on star tracker = $1.41 N_p\psi A_p$ = (10) (2).
12. 0.26 $N_p\psi$ = (7) • (9) particle on star tracker.
13. 0.26 $N_p\psi A_p$ = (12) × (2).

A. Obscuration on surface @ LV 500 from particles fallen from surface at LV 750, 1 ft^2 to 1 ft^2.

$$OBS = \frac{\Sigma(4)}{1} = \frac{3.46 \times 10^{-3}}{1} = 0.34\%$$

B. Obscuration from all particles from LV 750 enter horn, on shutter then on star tracker.

$$OBS = \frac{\Sigma\ (6)}{\text{area shutter}} = \frac{4.94 \times 10^{-3}}{0.37} = 1.33\%$$

C. Obscuration produced by particle falling on shutter only and then on star tracker.

$$OBS = \frac{\Sigma\ (8)}{\text{area shutter}} = \frac{8.98 \times 10^{-4}}{0.37} = 0.24\%$$

D. Obscuration on star tracker by particles on shutter release by g force.

$$OBS = \frac{\Sigma\ (11)}{\text{area shutter}} = \frac{2.87 \times 10^{-3}}{0.37} = 0.77\%$$

E. Fraction ψ of particles of shutter falling on ST $= \dfrac{\Sigma\ (13)}{0.37} = 0.14\%$.

Appendix

Approach

The following suggestions may be of help in carrying out estimates of particulate redistribution during launch, or from dynamic events which can displace particles.

1. Obtain an estimate of the initial distribution of particles on the surfaces of the vehicle and of the payload. This can be obtained by microscopic observations and by counting of particles at several locations on the surfaces; by using a sticky tape to lift particles; and by assuming the surface conditions from past experience and history of the surface exposure. With regard to the latter approach, based on clean-room classes described in MIL SPEC 209 on the exposure time at those conditions and on other parameters reflecting type of facility and operations, an estimate of the surface distribution is given in Reference 3. The method makes use of measured data obtained at various facilities.

2. Obtain data on vibroacoustic loads, aerodynamic forces, applied accelerations, and any other forces applied to surfaces holding the particles. Also, obtain venting data to provide gaseous velocities within the vehicle and around the payload. Estimate the impact velocities of released particles on surfaces, and duration of these parameters.

3. Obtain experimental data on particle dislodgement given the nature of the surface and particles, and of applied forces or accelerations. The available data show the percentage particle removal fraction (ψ) versus acceleration and particle diameter. Figures 4 and 5 of Reference 1 show a collection of experimental results for quartz particles on steel plates.

4. The redistribution of particles on a surface resulting from applied forces to that surface can be estimated given the above experimental data. The released particles may return to the emitting surface and one should consider the trajectories of the particles following the release. The particles remaining on the surface after a certain number have been released as dictated by a coefficient ψ, can be evaluated using the relation

   $$R_1 = (1 - \psi) N_O$$

   where N_O (particle/ft^2) is the density on the surface of a specified particle diameter. The calculations can be repeated for additional applied forces which are described by different release coefficients, ψ_n. The expression for the sequence is

   $$R_N = N_O (1 - \psi_1)(1 - \psi_2) \ldots (1 - \psi_n)$$

5. The particles removed from the surface may add to the particles on another surface. Those adding from a first removal are $A_1 = N_O (1 + \Psi_1)$ and for successive additions, $A_N = A_{N-1} + \psi_n R_N$. These calculations can be done in tabular fashion according to the sequence of removal from one surface and addition on the other. Of course, the removed particles may not fall on a surface of interest. The relative view between the surface, the direction of the acceleration, obstacle, etc., must be considered. The removed particles may be entrained by gaseous venting flow and may or may not be transported away by that flow. The transport is dependent upon the particle inertia and the drag on it applied by the gas flow. The ratio of these two is referred to as the Stoke's number. One example of this evaluation is carried out in Reference 1, where it was calculated that 50 percent of the particles with diameters less than 58μm released from the Shuttle bay will be transported by the gas flow to the vent during the initial few seconds of the launch.

6. Accumulation on a surface depends upon many factors. The particles fall in a direction defined by the vehicle acceleration and the acceleration of gravity. The particles impinging on a surface may or may not stay on that surface. They may bounce on it and eventually stay, or they may fall after the bounce onto another surface. The bouncing will occur if the kinetic energy of the falling particles exceeds the adhesion force potential of the particle on the surface. The calculations can be carried out using Equation 10 of Reference 1, and the discussion indicated there. The inclination of the receiving surface with respect to the trajectory of the falling particle can be accounted for by assuming that, in those cases, the vector component of the adhesion force is the effective force holding the particle. One may assume that particles bounce on a surface and the bounce directions are represented by a cosine distribution. As a result, a number of particles may return on that surface, and another portion—as determined by the cosine distribution—may fall somewhere else. The cosine distribution for bouncing can also be used when the particles move in a zero-g environment and strike a surface.

   Where a direct view between the releasing and the receiving surfaces exists, and both have the same surface areas, the redistribution of particles is straightforward. When there may be focusing (contribution from a large area to a small receiving area) one may assume that the accumulation on the small area is K times that for a one-to-one arrangement. The factor K is the ratio of the surface areas. For example, in the Shuttle case, one may assume that accumulation of particles released from the bay on the rear bulkhead during launch is 18 times the one-to-one ratio because the surface of the upper bulkhead and the cylindrical area of the bay together is approximately 18 times that of the rear bulkhead. Obstacles in the path of particles must be considered by checking the bouncing on the obstacle, the trajectories' redistribution after bounce, and the retention of particles on that obstacle. Assumptions about redistribution may have to be made. As an example, in the evaluation of particles entering the star tracker located at an angle from the acceleration axis, it has been assumed that the areas contributing the released particles are the sum of the projection of the vertical and horizontal areas of the star tracker entrance area.

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15. Supplementary Notes

16. Abstract

The dislodgement, venting, and redeposition of particles on a surface caused by the vibroacoustic, gravitational, and aerodynamic forces have been estimated and the resulting areal obscurations of the surfaces have been calculated. The data on particle redistribution estimated to occur during a Shuttle launch have been employed to estimate the obscuration of a spacecraft's star tracker, as it is carried into orbit by the Shuttle. The approach used for that calculation has been generalized so that it can be employed for other applications where either the Shuttle or an Expendable Launch Vehicle (ELV) is employed for launch. Approaches for evaluating particle redistribution for other applications and for general use have been indicated.

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