SPACE STATION PARTICULATE CONTAMINATION ENVIRONMENT

E. R. Miller and K. S. Clifton

N88-25397

Space Science Laboratory, NASA Marshall Space Flight Center
Huntsville, AL 35812

Abstract. The origin of particulate contamination on the Space Station will mostly be from pre-launch operations. The adherence and subsequent release of these particles during space flight are discussed. Particle size, release velocity, and direction are important in determining particle behavior in the vicinity of the vehicle. The particulate environment at the principal science instrument locations is compared to the Space Shuttle bay environment. Recommendations for possibly decreasing the particulate contamination are presented.

Introduction

Spacecraft on-orbit particulate contamination is defined as solid particles or liquid droplets deposited on a surface or contained in a volume of interest. Most of this material originates during ground processing, that is, hardware manufacturing, assembly, testing, transportation, and launch site operations.

The hardware surface cleanliness requirement presently imposed on the Space Station hardware is level 750 as defined by MIL-STD 1246A prior to final assembly for delivery to space; see Figure 1.

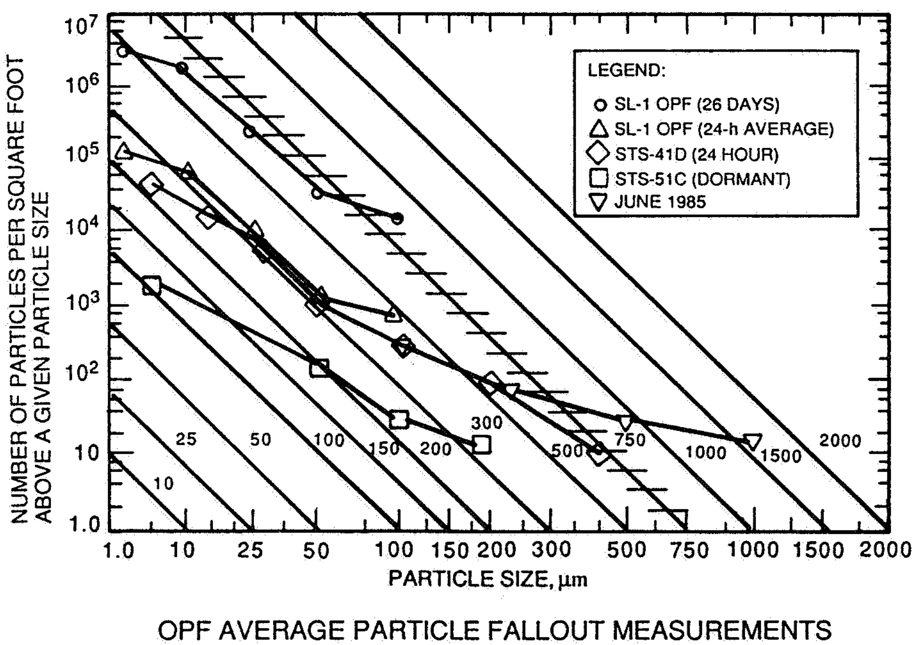

Fig. 1. Depiction of MIL-STD 1246A surface cleanliness levels. Level 750 is cross hatched for clarity. Also shown is typical actual fallout data in Orbiter Processing Facility (OPF).

To predict the Space Station particulate contamination environment we consider how these copious particles are adhered to the surfaces, what causes removal in the low-Earth orbit environment, and, once removed, what their likely behavior may be in the vicinity of the spacecraft. Also, since the main data base on large manned spacecraft has been gained from the Space Shuttle, we consider its relevant similarities and differences to the Space Station that may apply to the particulate environment.

Sources and Mechanisms

Barengoltz and Edgars (1975) determined that the dominant particle-to-surface binding mechanism in a vacuum environment is the van der Waals force. Further, they determined a mean adhesion of $F = 0.13\ d_p$ Newtons, where d_p is the particle diameter in meters, and found good experimental agreement using 22- to 110-μm-diameter glass beads on metal surfaces. Forces on the order of 10^3 to 10^4 g (where g is the Earth's gravitational acceleration) were required to remove half of the largest and smallest beads, respectively. Such large accelerations may be provided by meteoroid impacts.

In a further study, Barengoltz (1980) estimated the number of contaminant particulates released by such impacts on the Shuttle orbiter, using a total surface area of 1200 m^2 arbitrarily contaminated with 10^6 (10 to 100-μm-diameter) particles m^{-2}. He concluded that impact-released sources would provide an estimated 5.7×10^3 particles day^{-1} with typical release velocities of 3 cm s^{-1}. These impact-released particles are fairly uniform in size range due to the competing factors of fewer large particles which can be removed by the numerous small meteoroids and the more populous small particles which require impacts of larger but less numerous meteoroids.

Barengoltz also analyzed the "backsplash" particles (ejecta) by meteoroid impact cratering. These particles are estimated to be mostly small (2-10 μm) and numerous (~10^5-10^7 day^{-1}) with relatively high velocities (~500 m s^{-1}).

Scialdone (1987), Clifton and Owens (1987), and Green et al. (1987) have discussed particle release by thermally-induced forces such as differential thermal expansion ("oil-canning") and friction between surfaces ("creaking"). Such forces could also be mechanically induced. Using a time decay of possible thermally-induced release of particles observed by the IECM on Spacelab 1, Scialdone derived an extremely slow average particle velocity of 1.5×10^{-3} cm s^{-1}.

Another release mechanism mentioned by Scialdone is the so-called radiometric force, or that force created when a particle is differentially heated (e.g., by sunlight) causing directional outgassing resulting in an accelerating force. Other sources include: (1) spacecraft and payload mechanical operations such as door/aperture cover opening and closing, instrument slewing/pointing, release/attach mechanisms, remote manipulating systems; (2) engine firings; (3) fluid vents and leaks; (4) astronaut EVA; and (5) spacecraft proximity and rendezvous operations. Simpson and Witteborn (1977) discuss several of the above sources and mechanisms in more detail.

For Space Station, operational controls may be applied for so-called quiescent periods. The sources that pertain during these periods are: (1) instrument mechanical operations, (2) fluid vents and leaks from the spacecraft and instruments, (3) thermal shock by terminator crossings (sunrise and sunsets), (4) instrument heating and cooling operations, and (5) meteoroid impacts.

The operations that occur during non-quiescent periods may be important due to relocation of particulate material that may subsequently be removed during quiescent operations.

Shuttle, Space Station Similarities and Differences

The obvious similarities that the Space Station will share with the Shuttle orbiter that relate to the particulate contamination environment are: (1) both are manned vehicles having pressurized volumes, (2) both fly in low-Earth orbit, and (3) both serve as a platform for a diverse mixture of science experiments.

The differences are extensive and significant. (1) The Space Station will have repeated long period (weeks) cycles of quiescent operations, whereas the Shuttle typically has hours of similar operations. (2) The Space Station maintains attitude without engine firings, whereas the Shuttle requires almost constant attitude correction using vernier engines and requires orientation of the payload bay for various pointing requirements. (3) The Space Station will undergo only slow thermal environment (solar angle) changes, while the Shuttle payload bay experiences large thermal excursions depending on attitude to Sun, Earth, or deep space. (4) Experiments on Space Station are at large distances from expansive areas (such as photovoltaic arrays, thermal radiator, and manned modules) compared to Shuttle bay experiments. (5) The Space Station has a long on-orbit stay time (20-30 years) with months for its experiments, compared to days for Shuttle.

Shuttle Data

The Induced Environment Contamination Monitor (IECM) Camera/Photometer Experiment operated continuously throughout the STS-2, -3, -4, and -9 missions, stereoscopically recording particles and background within a 32° field-of-view. During a total of 378 hours of observations, over 18,000 frames of data were recorded by the two cameras (Clifton and Benson, 1988). However, not all of the recorded frames were conducive for particle detection, most often due to adverse lighting considerations, and the number of frames for which contamination measurements could be made was sharply reduced. Contaminant particles with radii in excess of 10 μm were recorded on over 1800 frames or approximately 42 percent of the data suitable for contamination measurements. Much of the higher activity came during the very early portions of the missions when high contamination levels are anticipated.

The results indicated high particle concentrations early in the mission decaying to a quiescent rate equivalent to approximately 500 observable particles per orbit (Clifton and Owens, 1987). With exposures normalized to 1 s, the probability of the cameras recording one or more particles at any given time was 36 percent. The average stay time for a particle was 5 s. It is evident that particle production was related to both Shuttle and experiment activities. The contamination that was observed varied greatly from frame to frame in both nature and extent, with bursts of particle activity observed frequently throughout the missions. During the cold test of STS-9, however, contamination activity was minimal as compared to the warmer and more active phases of the mission. During this cold test, only 3 frames out of 330 showed in excess of 5 particles, while 282 frames showed no evidence of contamination at all. Thermal effects were evident in producing particles during the cold test, with the preponderance of particles observed within 15 min of orbital sunrise.

One of the primary determinants in the number of particles detected appears to be the direction of the velocity vector. The residual atmosphere at orbiter altitudes acted very much as an 8 km s^{-1} wind both inhibiting and enhancing the observation of particles. For the most part, very little contamination was observed during periods of the STS-4 and STS-9 missions in which the orbiter velocity vector had a co-elevation of less than 70°. On the contrary, large number of particles were often recorded with the velocity vector at high co-elevations.

In addition to variations of particle activity, frames often differed greatly in the populations of particle sizes that they exhibited. For example, the mean particle radii of water-dump particles as compared to non-dump-associated particles were 102 and 53 microns, respectively. The mean total velocity for particles observed in 18 selected frames was ascertained at 1.2 m s^{-1} with a mode at 0.8 m s^{-1} and a median of 1.0 m s^{-1}. (It should be noted that the selection of frames was intended to provide a sampling of different conditions that produced contamination.) Particles traveling with the mean velocities observed are often already under the influence of atmospheric drag. A number of curved particle tracks can also be observed as the particles tend to align themselves with the velocity vector. In one frame in which particles were shielded from the velocity vector, particles indicated an initial velocity on the order of 0.2 m s^{-1} or less with velocities gradually increasing as the particle-to-spacecraft distance increased. This effect, i.e., the low initial velocity increasing with distance, appears to be a general one, particularly for radial velocities.

Not unexpectedly, strong enhancements of particles were observed during water dumps. The appearance of "snowstorm" events was independent of velocity vector direction and occurred during each water dump event. However, the duration of the settling periods following water dumps did show a variability evidently dependent upon the velocity vector. For the best measured cases, nominal contamination rates were reached approximately 30 min following cessation of the dump, with an e-folding time of 5 min.

Space Station Particulate Contamination

The predominant areas of the Space Station are the solar photovoltaic arrays and dynamic collectors (~4000 m^2), the pressurized modules (~1000 m^2), and the thermal radiators (~500 m^2). If it is assumed that the number of released particles is proportional to surface area, as predicted from meteoroid impacts and perhaps to some degree from thermally-induced forces, it is important to determine where the particles are transported, especially in relation to sensitive viewing instruments located, say, on the upper and lower booms of the dual keel Space Station.

Assuming elastic collisions, a released particle will undergo an acceleration, a, due to atmospheric drag

$$a = 3 \frac{\rho_a}{\rho_d} \frac{V^2}{d} ,$$

where ρ_a = atmospheric density (~1 x 10^{-14} g cm^{-3} at 350 km), ρ_d = particle density, V = Space Station velocity (~8 x 10^5 cm s^{-1}), and d = particle diameter. The distance a particle will travel released into RAM is proportional to the release velocity squared, ν_o^2. For example, a 100-μm-diameter particle, ρ_d = 1, ν_o = 10 cm s^{-1}, will travel 0.26 m before coming to rest and begin turning around. For the same particle with ν_o = 100 cm s^{-1}, the distance will be 26 m (a 50-μm particle with ρ_d = 2 g cm^{-3} will behave similarly), and for a 200-μm particle, ρ_d = 1, the respective distances will double. The optimum RAM release direction, in order for a particle to travel to the upper or lower boom locations (estimated to be 30 to 50 m or more from the major surface areas) is ±45°, requiring release velocities to be increased by $\sqrt{2}$ from a RAM normal surface, or to be released from a surface ±45° from RAM. Release at other angles into RAM will require higher velocities to reach the boom regions. Particles released in the wake cannot reach the experiment areas but could possibly be detected by instruments viewing in the wake direction. In this area-dependent scenario, particle release velocity is a very important parameter for contamination in the vicinity of the experiment locations, as is the release direction.

As stated previously, Barengoltz (1980) predicts average particle velocities of ~3 cm s^{-1} while Scialdone arrives at a much lower figure. Data from the IECM indicate an upper limit to the average release velocity of about 20 cm s^{-1}. Corroborative evidence of low release velocities is the data from IECM showing very little contamination when the Shuttle bay was oriented within 70° of RAM.

The Barengoltz meteoroid impact model produces omni-directional particles, while particles released by thermal-related effects may favor the solar direction, e.g., in the general RAM direction for sunrise on Space Station and in the wake direction from sunset.

The IECM and Particle Analysis Cameras for Shuttle (PACS) (Green et al., 1987) data show a definite correlation of particulate events with instrument and system hardware operations. The Space Station instruments on the upper and lower booms will have similar mechanical operations (opening/closing of covers, slewing and pointing, extending/retracting). In addition, instrument gas venting and fluid leaks will probably occur. Also, meteoroid impact and thermal effects and particulate release mechanisms will apply to these areas. However, the linear arrangement of these instruments along a fairly open boom allows particles to be released in mostly unobstructed directions. In the case of Shuttle, Scialdone's decay model allows released particles to reflect from surfaces until they more or less directly escape from the bay. Also, on Space Station, there is less opportunity for shielding from RAM than for Shuttle bay released particles.

Both IECM and PACS data indicate particulate decay with time. The IECM data show an initial on-orbit decay to average levels in about 15 hours. Less obvious was Scialdone's 50- to 75-hour decay time constant from IECM data on Spacelab 1 after heatup from a long cold soak. The meteoroid model with an almost unlimited supply of particles of 100 μm diameter or less would not predict a significant decay except for the larger particles. It seems reasonable, however, that thermally- and radiometrically-released particles from surfaces undergoing repeated similar cycles would have some time constant. Most of the large areas of Space Station will be constructed on-orbit probably months before scientific instruments will be attached (even on the Phase I single boom). If we postulate a time constant of 1 week, particulate contaminants from these sources would be reduced by a factor of >50 per month.

Recommendations

Surface cleanliness specifications should be tighter for large areas, especially for the photovoltaic arrays (the dynamic solar power system will probably have a much better surface cleanliness requirement than level 750).

Use of low absolute values of solar absorptance and thermal emittance coatings will reduce diurnal temperature changes, thereby reducing particle release by thermal effects.

Extra cleaning should be required for instruments and equipment located on the upper and lower booms. Also, manifesting and placement of experiments must be considered (i.e., do not fly a particulate generator with an IR telescope, but if it must be done place them as far apart as possible in physical location and timelining of operations).

Do not locate satellite servicing facility near the upper boom as shown in some sketches of the full-up Space Station.

Verification and monitoring instrumentation for the Space Station particulate environment is highly recommended, especially to correlate particle production with various activities, ranging from science instrument operations to Shuttle tending. Monitoring demands a good centralized data base of all possible contamination-producing events in order that correlation studies can be performed and possible corrective action be taken. Such a data base does not exist for the Space Shuttle.

Conclusions

Particulate matter is tightly bound to surfaces in vacuo primarily by van der Waals molecular force. For space vehicles, most of this particulate matter originates during ground operations.

For Space Station quiescent operations, particles are probably released in proportion to surface areas that are mostly 30-50 m from the upper and lower boom areas.

The release mechanisms during quiescent periods are probably related to thermal effects (including radiometric), meteoroid impacts, and instrument mechanical operations.

The average release velocities are predicted and measured on the order of 20 cm s^{-1} or less, allowing transport distances of ~2 m for 200-μm-diameter particles with unit densities, or 4 m for 200-μm-diameter, density = 2 g cm^{-3}, etc. For release of particles larger than about 100 μm diameter, some decay time constant, much shorter than the many months between construction of the major area elements and the addition of sensitive instrumentation, seems to be warranted for all mechanisms other than meteoroid impacts.

Particulate release by instrument and nearby equipment operations will probably be less severe than from similar operations in the Shuttle bay, but remains a large concern.

Overall, the particulate contamination environment for the Space Station should be significantly less than for Space Shuttle.

References

Barengoltz, J., and D. Edgars, The relocation of particulate contamination during spaceflight, Jet Propulsion Laboratory, Pasadena, California, TM33-737, 1975.

Barengoltz, J., Particulate release rates from Shuttle orbiter surfaces due to meteoroid impact, J. Spacecraft & Roc., 17(1), 58-62, 1980.

Clifton, K. S., and J. K. Owens, Optical contamination measurements on early Shuttle missions, Appl. Opt., in press, 1987.

Clifton, K. S., and J. K. Owens, Analysis of contamination data recorded by the IECM Camera/Photometer, to be submitted, 1988.

Green, B. D., G. K. Yates, M. Ahmadjian, and H. Miranda, The particulate environment around the Shuttle as determined by the PACS experiment, to appear in SPIE Proceedings No. 777, 1987.

Scialdone, J. J., Particulate contamination during Shuttle ascent, to appear in SPIE Proceedings No. 777, 1987.
Simpson, J. P., and F. C. Witteborn, Effect of the Shuttle contaminant environment on a sensitive infrared telescope, Appl. Opt., 16(8), 2051-2073, 1977.