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THE PARTICULATE ENVIRONMENT SURROUNDING THE SPACE STATION: ESTIMATES FROM THE PACS DATA

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Abstract. Estimates of the sources of particulates surrounding Space Station are made based on the existing orbital observations data base. Particulates surrounding the Shuttle are mostly event related or from the residual release of mass (dust) brought to orbit from the ground. The particulates surrounding the Space Station are likely to arise from additional sources such as operations, docking, erosion, and abrasion. Thus, scaling of the existing data base to long-duration missions in low-Earth orbit requires analysis, modeling, and simulation testing.

Introduction and Background

The presence of particulates in the Space Station environment could cause a variety of deleterious effects. Their settling on sensitive optical surfaces will cause decreased performance by physically obscuring or scattering emission from bright off-axis sources. Particulates above surfaces in the field-of-view of sensitive instruments will efficiently scatter and emit thermally. These near field sources could dominate remote emission levels. Sunlit particulates appear brighter than stars, entire cities, and even lightning strokes.

Additional deleterious effects will result from particle impact causing surface roughening during the lifetime of the Space Station. Drag will increase as the surface becomes rougher. Thermal balance may change as absorptivity or reflectivity of surfaces is altered. Changes in the surfaces of the solar collectors may decrease power production as aging occurs.

Ever since the first manned missions in Earth orbit, there have been visual reports of activity-induced particles surrounding the spacecraft. During the Mercury through Apollo missions many unusual particle observations were reported. The sensitivity to particle detection however strongly depends upon illumination geometry, and quantification of the observations required more controlled observations. Both video and coronagraphic investigations were undertaken on Skylab in 1973 (Schuerman and Weinberg, 1976; Schuerman et al., 1977; Giovane et al., 1977). Particles with radii as small as 5 μm were detected. Our analysis of their data has revealed that the numerous particles observed had a size distribution which followed a rough $r^{-1.5}$ dependence, i.e., on average there would be 30 times as many 5 μm radius particles as 50 μm radius particles. Moreover the particle velocities observed were in the 0.1 to 20 m s^{-1} range with the larger particles generally moving more slowly. These particles were observed after Skylab had been on-orbit for a month. Because the Shuttle orbiter was to act as an orbital observation platform carrying astronomical and aeronomical experiments into orbit for week-long observation missions, NASA realized that the local particulate environment could seriously compromise the ability to make remote observations.

From the inception of the Shuttle program, environmental optical quality goals were set by a NASA panel. The Contamination Requirement Design Group (CRDG) guidelines specified an acceptable particulate contamination level on-orbit for the normal Shuttle operational environment as an average of less than one particle per orbit entering a 1.5×10^{-5} sr field-of-view along any line within 60° of the -Z axis (out of bay), and this field-of-view should contain no discernible particles for 90% of the operational period. A discernible particle is a particle with diameter of 5 μm within a range of 10 km.

Contamination below this level was generally deemed as undetectable or as an acceptable nuisance level. Recent advances in detector technology (especially in the infrared) may require more stringent future guidelines for Space Station or may drive the most sensitive experiments off large space structures onto free-flying platforms. The particles surrounding Shuttle observed on-orbit are believed to arise primarily from ground-based processing. The orbiter processing facilities have been improved significantly with particulate counts being carefully monitored by passive techniques, such as witness arrays, at every stage of processing. The improvements have resulted in substantially less particulate loading (area coverage) on the arrays. In spite of these improvements it is still recommended that most sensitive payloads adopt protective measures against particles until safely on-orbit. Another major contamination period is during ascent when the payload bay venting could move particles around and down onto sensitive surfaces. Simultaneously, vibrations from the solid rocket boosters and when the Shuttle goes transonic will act to redistribute particles. It has long been known that activities such as water dumps generate copious ice particles, but in this paper we report that a whole range of events such as crew activities and engine firings can shake loose or produce particles detectible to sensitive astronomical instruments. While on-orbit, micrometeorites may spall off material as modeled by Barengoltz (1980). He predicted that formation of smaller particles down to 2 μm is favored. Data from the passive collection techniques and ground processing facilities are carefully reviewed in the Particulate Environment Section of ENVIRONET which has been compiled by Barengoltz (1985). A general review of this environment has also recently appeared (Green et al., 1985).

In order to verify that CRDG guidelines were met a pair of cameras in a stereo viewing geometry were included as part of the Induced Environment Contamination Monitor (IECM) diagnostic pallet which was manifested on the earliest missions (STS-2,-3,-4) and on the Spacelab 1 mission (STS-9). This pallet was assembled under the guidance of Edgar Miller of NASA/Marshall Space Flight Center. The pallet and its results have been described by the previous speaker (see also Miller, 1983, 1984). There have been other observations of particles in the Shuttle environment. The low light level television cameras observed large particles during STS-3 as previously reported by Maag et al. (1983). They analyzed videotape data from the camera located in the forward part of the bay looking aft with a 4° field-of-view. With the tail blocking the Sun, any particles in the bay or near the tail were observed from their forward scattering lobe. This configuration provides the most sensitive detection of particles. Particle distances from the camera were not known, but atmospheric drag was used to size/range particles. Because of the relative insensitivity of the camera only large particles could be detected even in the forward scattering configuration. Nevertheless, a large number of particles were detected. They were estimated to be in the mm-cm radius size range. Over 60 particles larger than 5 mm were observed.

Another interesting set of observations were acquired by the Temperature Controlled Quartz Crystal Microbalances (TQCM) flown on the Spacelab 1 mission by McKeown et al. (1985). Sensors were pointed along five directions (±X, ±Y, -Z). The sensor facing out of the bay (-Z) acquired the least mass indicating that collisional backscattering of particulates does not appear to be a significant process. The sensor facing Spacelab 1 gained the most mass. Post-flight analysis of particulates found that most particles were in the 1 to 20 μm range, a size which is below the camera data threshold. This indicates that the cameras see only a small portion of the particles in the environment. The sources of the TQCM particulates were estimated via elemental analysis to be from ascent redistribution and solid rocket motor firings on-orbit. However, crew activity-generated particles must be substantial to explain the large accretion on the sensor facing Spacelab 1.

The Air Force realized that particulates could interfere with remote atmospheric observations of the chemical processes occurring in the thermosphere and mesosphere which are planned from the Shuttle. In order to assess the magnitude and time scales for this interference the Particle Analysis Cameras for Shuttle (PACS) experiment was developed. Analysis of the film images from the cameras would have permitted position and velocity determination. An error analysis of the digitization and correlation procedure performed by EKTRON indicated accurate determinations of position and velocity components at the few percent level were attainable from film data (Gold and Jumper, 1986). More importantly the particle's scattered intensity and persistence after orbital events could be accurately monitored from the film data.

The PACS cameras differed from the IECM cameras in several aspects, however. Film exposures were taken in sets of four. This exposure sequence was repeated every 120 s. In order to detect small particles, ASA2000 negative film was used and the cameras were focused at 25 m rather than infinity. This distance represents a compromise between enhanced near field sensitivity to particles and loss of the far field stars which allowed for orientiation and in-flight calibration. (For the 25 m focal distance, stars were observed as small, well-defined circles. Because the stellar irradiance was spread over several film resolution elements, only stars brighter than seventh magnitude have been observed in the PACS data.)

The objectives of the PACS experiment were to: (1) quantify the particulate sizes and trajectories so as to identify source locations; (2) determine the severity of events such as dumps, purges, maneuvers, and various operations and measure their decay (clearing) times. The experiment design and performance have been presented elsewhere (Green et al., 1987) and will be only briefly summarized here.

The PACS Experiment

The principal investigator for the PACS Experiment was M. Ahmadjian at the Air Force Geophysics Laboratory. PACS was part of the first Goddard Hitchhiker mission aboard STS-61C (Columbia). The Columbia had just undergone a substantial refurbishment taking 2 years. Unfortunately the launch was delayed for several weeks due to inclement weather including heavy rains while on the launch pad. Thus, this mission was likely to have a larger than representative contamination environment. Lift-off occurred at 6:55 a.m. (EST) on January 12, 1986. A nearly circular orbit of 290 km altitude was achieved at 28° inclination. After orbit stabilization and opening the payload bay doors, PACS was turned on at 3 hr 30 min mission elapsed time (day 0/3:30 MET).

Several significant events occurred during the 6-day mission. A 12,000 lb RCA TV satellite was launched at 0/9:32 MET (the first day of the mission at 9 hr 32 min). There were five water dumps, and a variety of attitudes were used including passive thermal control and several different inertial attitudes for comet Halley and astronomical missions. The measurement period of greatest interest to PACS occurred on the third day of the mission. Columbia traveled an entire orbit with the bay facing deep space with all activities suppressed (including thruster firings) then traveled another orbit in the gravity gradient attitude (nose to Earth) with the bay facing the wake direction again with all activities suppressed. These periods should be representative of the best observational conditions achievable in the bay of the orbiter.

While we were at Hitchhiker Control Center during the mission we gathered a great amount of available data on Shuttle attitude, Sun angles, velocity vector, Earth coordinates, and the mission timeline. The staff at the Control Center (NASA and its associated contractors) were extremely helpful, providing a wealth of information and assistance. We made extensive use of the Shuttle ground system attitude display which provided Shuttle position and orientation updates several times a minute. This data permitted us to begin understanding the PACS data as soon as the film reached PSI. The detailed orbiter ancilliary data tape became available approximately 6 months later and proved useful in verifying the preliminary analysis.

Access to the film canisters was provided 10 days after landing. Inspection revealed that the film in camera 1 had jammed from the start. Camera 2 recorded data during the entire mission exposuring over 400 ft of film. The film was developed by the Aerospace Corporation. Several copies were made and analysis began 16 days after touchdown. In total 14,788 frames of film data were acquired, covering parts of 83 orbits during every day of the mission.

Terminator crossings (sunrises, sunsets) provide optimal detection conditions for particulates. The fraction of film frames at terminator crossings in which particles were detected is plotted in Figure 1. Although particles were observed very often during the first day on-orbit, there appears to be a marked decrease in their occurrence with time on-orbit. By the end of the 6 day mission less than 25% of the terminator crossings have any detectable particles in any frame. The anomalously large value on day three may be due in part to the orbit attitude. The Shuttle spent most of day three in passive thermal control (rotisserie) attitude which sequentially exposes most surfaces to the Sun. We believe this generates particles due to local thermal expansions and flexing. This phenomenon will be discussed more fully below.

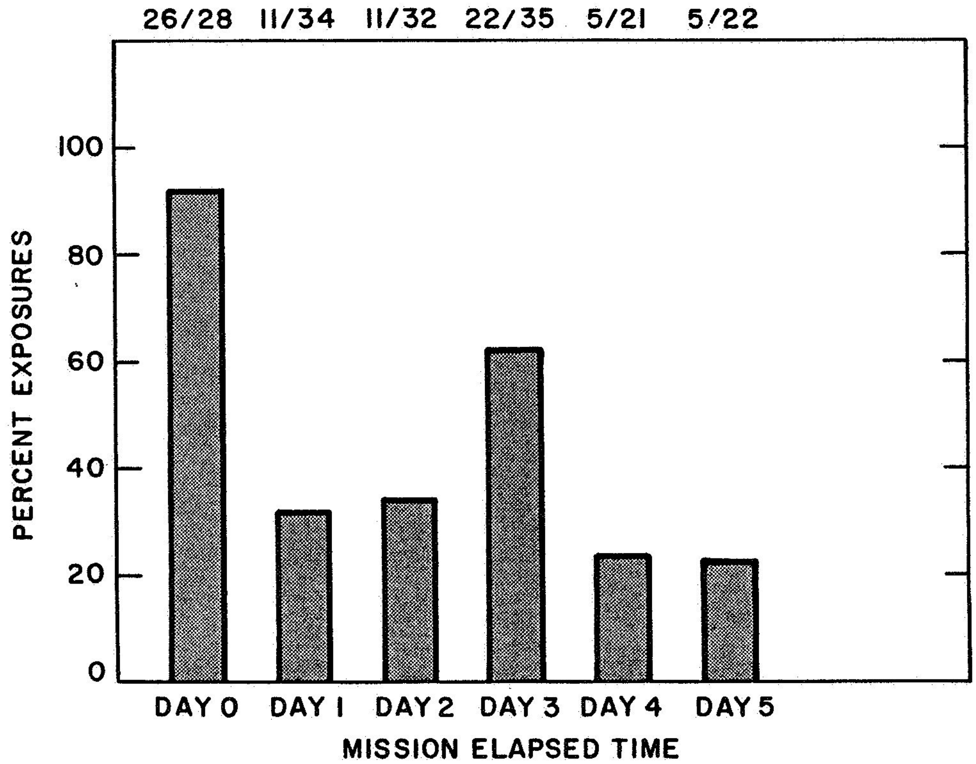

Fig. 1. Fraction of film exposures having particles at sunrise/sunset.

The scattered intensity of each particle is an extremely sensitive function of scattering angle and also depends on particle shape, particle composition, and particle size (Rawlins and Green, 1987). Quantitative understanding of particulate concentrations is hampered by the constantly varying illumination angles and attitudes. During the first orbital sleep period the orbiter was placed in a Sun inertial attitude with the starboard (+Y axis) wing pointed at the Sun. In this attitude when the space above the cameras is illuminated, particles are observed at constant solar-scattering angles of $90° \pm 10°$. Each orbit the Shuttle crosses the terminator and is illuminated for a few minutes before the Earth below is lit overexposing the film. The sunlit Earth is observed for 1/4 orbit. Then the sunlit Shuttle observes deep space for ~20 min before crossing the night terminator. The average number of particles observed during the two periods ("sunrise" and "afternoon") are displayed for each orbit during the Sun inertial period. Again there appears to be a decrease in particles with time on-orbit. In addition there are clearly more particles per frame at sunrise than later in the orbital day. Again we feel this is a result of thermal stresses generated at sunrise.

One of the goals of PACS was to determine the time required to return to a clean optical environment after a water dump. Although several dumps occurred during the mission and particles associated with those dumps were observed, only one happened under proper illumination conditions so that a temporal decay could be observed. Particles were observed promptly in the first frame taken about 1 min after the start of the dump. The optical environment is severely degraded during the dump. Several hundred particles are observed in the 0.13 sr field-of-view. Because this dump occurred at the end of the first sleep period the Shuttle was still in Sun inertial attitude. For fixed solar angle the observed temporal decay of the particles reflects a real drop in concentration, since detection sensitivity is a constant. The number of visual particles in each 2.7 s exposure is plotted in Figure 2 from the end of the dump until orbital sunset 19 min later. There is a rapid (nearly 2 orders of magnitude) decrease in the first 6 min followed by a much slower decay. The water ejection occurs from a jet on the opposite (port) side of the Shuttle well below the opened bay doors. Ice particles

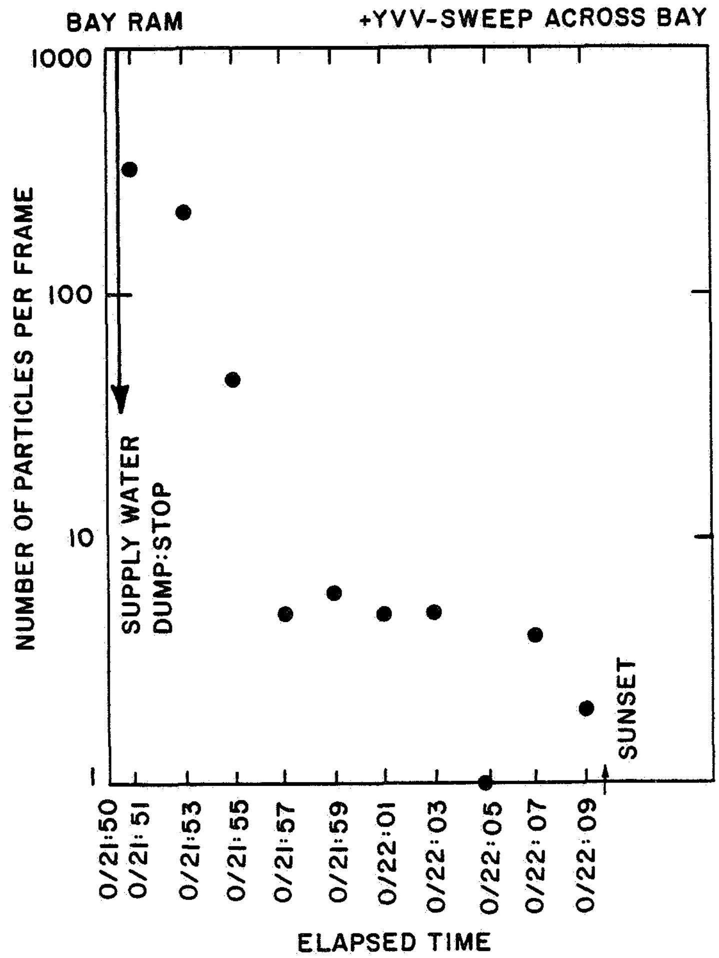

Fig. 2. Particle decay after supply water dump (visual particle count)

formed in the expansion will undergo complex trajectories due to plume collision effects and atmospheric drag. Although particles were observed with many different trajectories, the usual direction observed was across the bay - the direction from the water dump jet outlet to the PACS field-of-view. During the period after the dump, the Shuttle orientation with respect to the velocity vector changed. During the dump the bay was in the ram direction (+ZVV) so that atmospheric drag would tend to force the particles behind the Shuttle. By the end of the dump, a component of the atmospheric drag was across the bay so that some of the particles would be forced across the bay. This component changed with time so that just before sunset (22:07) the velocity vector had rotated so that the water jet side of the Shuttle squarely faced the ram direction (-YVV). During the decay after the dump there was no obvious change in particle direction or brightness (size/distance). However, this change in attitude may have affected the temporal decay of the particles. For comparison, the decay in particles was observed after a dump by the NASA IECM cameras agrees in magnitude with the particle counts observed by PACS. The decay in that data seems to more closely follow a single exponential decay with an e-fold time of less than 5 min. The PACS data show a more rapid early time decay. However, we feel the details of the decay are dependent on the atmospheric drag velocity vector. There were eleven fuel cell purges during PACS observational periods. We detected no obvious particulates associated with these events.

The other mission event that dramatically increased the detectible particles was the TV satellite deployment at 0/9:32 MET. This satellite was located in the rear of the bay in a retractable clamshell container. Starting with the opening of the container, particles were observed moving across the camera field-of-view away from the rear of the bay. As the satellite was spun up to its 50 rpm rotation period, copious particles were continuously observed. They first moved rapidly, then more slowly as if the particles were released early in the spin-up but with a distribution of velocities. Thus, the fast moving particles reached the field-of-view first, followed by the slower moving portion of the distribution. For all particles the direction of motion was mainly away from the rear of the bay. During the 15 min prior to satellite launch, the optical environment was the worst for the entire mission.

At several times during the mission, groups of particles were observed within the field-of-view for several sets of exposures. Groups of ~75 particles were observed to be in the same relative positions in frames taken 2 min apart. One particle took 8 min to traverse the field-of-view. These nearly immobile particles were observed in several different attitudes including the velocity vector across the bay (so that the entire column in the field-of-view was subjected to atmospheric drag) and even when the bay was in ram. Because several of these particles had clear disks they were not on the camera lens but rather quite remote, >10 m. Based on drag calculations they must have been quite large (larger than cm diameters) in order to persist with negligible motion in the field-of-view. We can offer no better explanation at this time.

Particles were often observed with rapidly oscillating radiance levels as if they were presenting different geometric aspects to the camera. We believe they were non-spherical particles rotating. One particle exhibited 47 periodic oscillations during a 2.5 s exposure. We are unable to postulate a source mechanism which would give rise to such rapidly rotating particles. Drag would tend to damp these rotations.

Besides the events which obviously degrade the optical environment around the Shuttle, there were two key observational periods during which all activities were suppressed. On mission day two, after 50 hr on-orbit, the Shuttle maneuvered into a deep space viewing attitude (nose into the velocity vector, Earth below the port wing). No further thruster firings were used to maintain this attitude. Data were acquired for 105 min in this mode, then the Shuttle maneuvered into gravity gradient attitude (nose to Earth, bay facing wake). Again thrusters were disabled. The Shuttle attitude varied only slightly

(<5°) during this orbit. The numbers of particles observed within the field-of-view during the two sequences are shown in Figures 3 and 4.

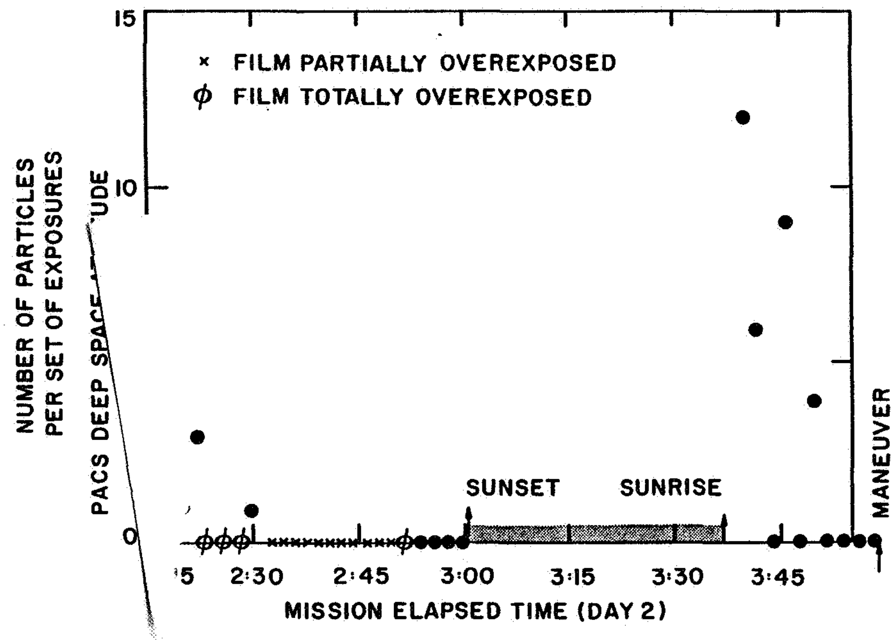

Fig. 3. Particles in field-of-view during PACS prime measurement sequence (deep space viewing - all disabled).

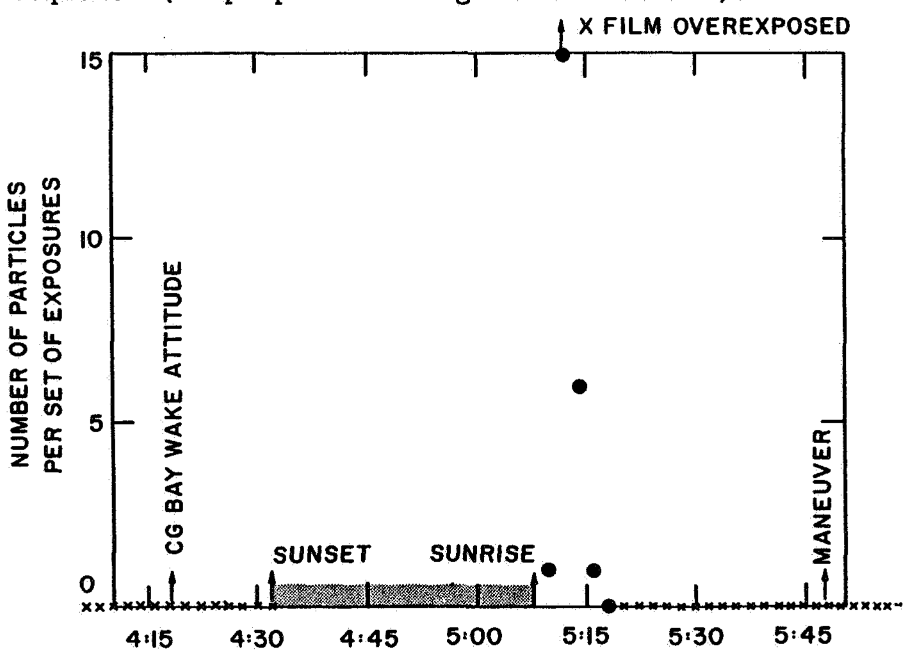

Fig. 4. Particles in field-of-view when gravity gradient attitude bay in wake (all disabled).

The frames taken in deep space viewing attitude have near optimum viewing geometry; the Sun is nearly perpendicular to the bay so that even near field particles are solar illuminated and observed at a 90° scattering angle. In Figure 3 there are two clear periods when particles were observed: just after the maneuvering was completed and just after orbital sunrise. Note there is no corresponding feature at sunset. The illumination conditions are quite constant so that the fluctuations in the particle counts after sunrise should be real. Several very different trajectories were observed. (A nose-to-tail direction of motion should have been favored due to drag.) Because the bay was not illuminated during this period (shadowed by cabin), the observed particles may have arisen from very different parts of the orbiter.

In Figure 4 the gravity gradient data are presented. The film is most often overexposed in this attitude. The Earth is in the field-of-view so that the sunlit Earth overexposes the film. The best viewing conditions are when the Shuttle bottom is illuminated and the Earth is still dark as occurred from 2/05:10 to 05:18. Here again a flurry of particles is observed just after orbital sunrise. They are observed with a solar illumination angle of ~160°. This is a very sensitive configuration (Rawlins and Green, 1987). The bay is shadowed, but the field-of-view begins to be illuminated about 3.5 m from the cameras. The particle trajectories seem to be mainly rear to forward. The bay is in wake and not solar illuminated; thus, any particles observed most probably are swept into the field-of-view by drag.

Scialdone (1986) has recently suggested that several thermal processes could drive particles off surfaces. We feel that the current data show clear evidence that sunrise-related thermal stresses induce particle generation.

Summary of PACS Data and Particle Model

The PACS camera successfully gathered data on the orbital particulate contamination environment during mission STS-61C. The film data clearly indicate that the solar illumination angle is the key parameter. We suspect particles were often present but we were able to observe them only under proper illumination conditions. At terminator crossings (when illumination conditions were reasonably good) particles were observed about one-third of the time within the 17° x 24° field-of-view of the PACS cameras. Particles were observed: when all activity was suppressed, after maneuvering, after payload bay door operations, during the preparations for a satellite launch, during and after water dumps, and after sunrise. During active events such as dumps and the satellite launch, the particle trajectories observed extrapolated back to the vicinity of the source. Atmospheric drag accelerations only slightly perturb the trajectories of detected particles during these events. Only a few particles were detected by the strobe-illumination. This indicates that the particles were nearly always beyond 2 m from the cameras. It also appears that particles are often very asymmetric offering different geometrical areas to the cameras at an angular rate of up to 20 per second. Particles with trajectories from every direction were observed.

We can attempt to compare the PACS observations with the CRDG guideline standards. Roughly particle occurrence is on average 1/3 particle per 0.3 s exposure (~1 particle per second) late in the mission within the 0.126 sr field-of-view of PACS. This corresponds to approximately 2/3 particle per orbit within a 1.5 x 10^{-5} sr field-of-view. The PACS observations would satisfy the CRDG guidelines except that PACS is unable to sense particles down to 5 μm diameters and certainly is not sensitive enough to see one at 5 km. However, the PACS results are encouraging in that there may be quiescent times when the optical environment is quite clean. Unfortunately there are many times when it is not.

The PACS data in conjunction with other orbital data bases have been used to create the framework model of the Shuttle environment. Excluding orbiter activities (dumps, thruster firings) the clearing time for the environment appears to have characteristic clearing times (e-fold) of 5 hr in a solar inertial attitude, and of 11 days for a variable attitude mission. The solar-induced particle cloud produces 100 particles sr^{-1} during a 10-min period. The clearing time (e-fold) following a water dump is 2 to 10 min depending on attitude. On average there were 8 particles sr^{-1} s^{-1} larger than 40 μm surrounding the Shuttle during the middle of mission.

In order to compare the various observations of particulates on-orbit, a $r^{-1.5}$ scaling was applied to achieve a 5 μm detection threshold for all measurements. Additionally, fields-of-view were adjusted to 1.5 x 10^{-5} sr. The scaled observations from PACS (STS-61C), STS-4 star cameras, Infrared Telescope (Spacelab 2), and Skylab are all presented in Figure 5 as a function of time on-orbit. Considerable variation is observed. The temporal decay of particulates (which are dominantly residual particles from ground accumulation) is shown as observed (solid line) and extrapolated (dashed line). From the figure it is seen that based on this extrapolation, CRDG design goals would be met after 20 to 40 days on-orbit. Based on surface area alone, the initial particulate generation rate surrounding the Space Station would be about 1000 particles per 10^{-5} sr per orbit.

Station Particulate Environment

Somewhat at odds with these Shuttle observations is the Skylab coronagraphic data. Taken after 25 days on-orbit, substantial particulate contamination was observed. This brings into doubt the ability to extrapolate a decay of the particulate cloud density. Observational data from later during the 9-month mission would provide critical insight into this behavior. Skylab data represent the only practical existing data base beside any Soviet observations.

At some level, particulates generated by orbital processes will establish a quasi-steady state level. A careful engineering approach may permit scaling of Shuttle observations to a Space Station scenario. The effects of thrusters (used for orbit and attitude maintenance), docking activities, crew activities (internal and EVA), dumps, and residual particles from ground accumulation may all be estimated roughly based on Shuttle observations. A detailed model of size distribution, spatial transport, and temporal behavior of each source must be developed and applied to the Space Station configuration. The effects of particle redistribution may be simpler due to small geometric obstruction factors. Unfortunately, additional processes are likely to generate particles, whose magnitudes are much more difficult to assess. The variety of mechanical operations to be undertaken on Space Station are likely to generate unusual distributions of particles. Modeling these sources will be most difficult. Additionally, erosion will result in particle generation. Oxygen atoms will

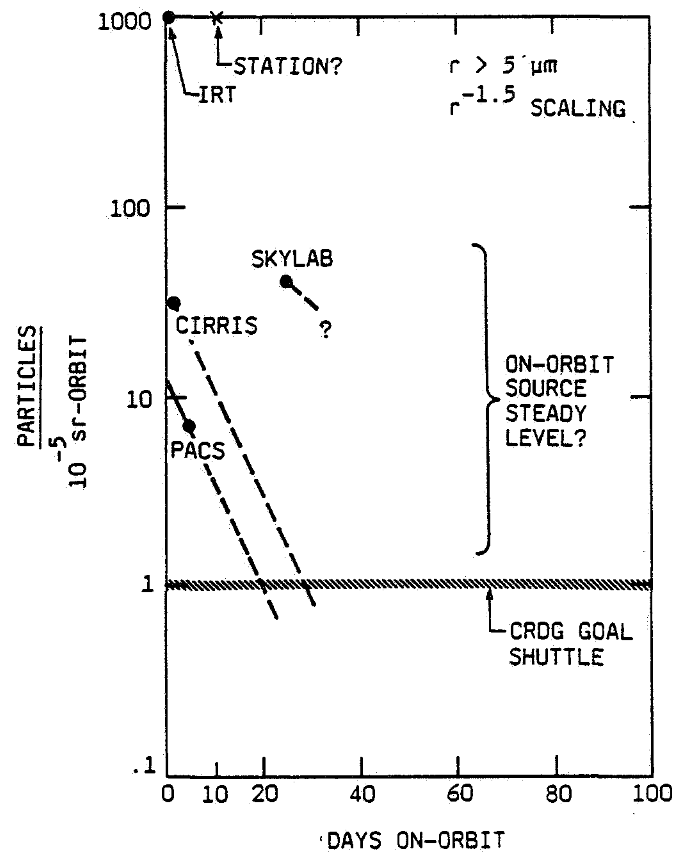

Fig. 5. Residual particulate environment surrounding spacecraft.

penetrate protective coatings at pinholes or fractures leading to undercutting and eventual particle/flake formation. Accelerated laboratory tests have clearly demonstrated this effect and its potentially serious impact. In order to achieve a similar goal for Space Station as was set by the CRDG for Shuttle from any source, less than 1 particle ($r > 5$ μm) may be generated per 10 m^2 of surface area per orbit.

The key unknowns which must be addressed to more accurately predict the particulate environment surrounding the Space Station are: the details of the particle dynamics, the generation rates for each process and size distributions; and a predictive two-dimensional model. The velocities and angular distributions of particles leaving surfaces must be determined as input to the model. Drag and effects of particle charging must be included in the model. The goal of this model should be to guide development of guidelines for Space Station users: to minimize their impact on observational capabilities yet permit a range of activities to be undertaken. Thus, the magnitude of particle generation and its spatial and temporal extent for each source or activity can guide location on Space Station and observational time period selection.

The coupled activities of: (1) further analysis of existing data from on-orbit, (2) ground-based and orbital tests of particle production upon abrasion or erosion, and (3) modeling to permit scaling relationships for the

Space Station configuration will provide an improved insight into the environment to be encountered by Space Station.

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