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EFFECTS OF METEOROIDS AND SPACE DEBRIS ON THE PARTICULATE ENVIRONMENT FOR SPACE STATION

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Abstract. A large orbiting platform such as Space Station will be subjected to numerous impacts by meteoroids and space debris fragments. These hypervelocity impacts will produce clouds of ejected structural material in the vicinity of the spacecraft. In this paper we report the development of a preliminary model for impact-generated ejecta production which combines the fluxes of meteoroids and space debris fragments with a description of the number of ejecta particles produced by hypervelocity impacts. Modeling results give mean ejecta densities from 30% to 100% of the present particulate background limitation of 1 particle 5 microns and larger per orbit per 1×10^{-5} sr field-of-view as seen by a 1-m-diameter aperture telescope in the 1990s time frame. Projected increases in the space debris flux raise this density to 300% of this limitation after 2010. The model is also applied to estimate the vulnerability of metallic claddings on composite structural members to penetration by hypervelocity projectiles, thereby exposing the substrate to atomic oxygen. The estimated annual number of penetrations is from 4 to 8 per m^2 of cross-sectional area in the mid 1990s, increasing to more than 40 penetrations per m^2 after 2010.

Introduction

The probability of penetration of the habitation volumes of prior manned spacecraft by natural meteoroids was low (Cour-Palais, 1987); it remains low for spacecraft with cross-sectional areas not exceeding tens of m^2. This probability increases somewhat for Space Station, which will have a cross-sectional area of 100-300 m^2 (depending on its orientation relative to the meteoroid flux). The current space debris environment, which is not well known, appears to pose a similar threat to spacecraft habitation volumes. The future space debris environment may increase dramatically, possibly exceeding the meteoroid environment by an order of magnitude during the lifetime of Space Station (Su and Kessler, 1985).

The potential for impacts of natural meteoroids and space debris fragments with spacecraft surfaces has generated sufficient concern over penetration of habitation volumes that structural means of distributing the impact energy have been developed. The usual mitigation measure is the construction of a thin "bumper" some distance outboard of the pressure wall. When a hypervelocity projectile (natural meteoroid or space debris fragment) penetrates a properly designed bumper, a cloud of projectile and bumper material (solid, liquid, or vapor, or a combination) strikes but does not cause severe damage to the pressure wall (Cour-Palais, 1987).

Hypervelocity projectiles that are smaller than those for which a bumper was designed and those that impact unshielded areas of the spacecraft (presumably with wall thickness sufficient to preclude penetration) will produce clouds of ejected structural material in the vicinity of the spacecraft. A significant fraction of this ejected material will be in the form of solid particles with diameters exceeding 5 microns. Gault et al. (1963) showed that the ejecta particle flux will greatly exceed (by 3-4 orders of magnitude) the flux of impacting particles of the same mass. This potentially major particulate source for large orbiting platforms such as Space Station has not been considered previously. Impacting meteoroids and space debris fragments may also increase the potential for atomic oxygen erosion of vulnerable materials by penetrating the protective metallic cladding being considered for such materials.

In this paper, we report the development of a preliminary model for impact-generated ejecta production. The model is similar to that reported by Seebaugh and Linnerud (1984) for explosively generated ejecta. The major parameters in the model are the fluxes of meteoroids and space debris fragments at the orbital altitudes of interest and the number of ejecta particles generated by a hypervelocity impact on a spacecraft surface. In the following sections we briefly describe the components of the model and results obtained for Space Station.

Fluxes of Meteoroids and Space Debris Fragments

The undisturbed meteoroid flux is given by Cour-Palais (1987)

$$\log N = -14.37 - 1.21 \log m \quad \text{for } 10^{-6}\text{ g} < m < 1\text{ g} \qquad (1)$$

$$\log N = -14.34 - 1.58 \log m - 0.06 (\log m)^2 \text{ for} \qquad (2)$$

$$10^{-9}\text{ g} < m < 10^{-6}\text{ g}$$

where N is the flux (per m^2 per sec) and m is the projectile mass in g. The lower limit of application of equation (2) is extended to 10^{-12} g in JSC 30000. Since the undisturbed meteoroid flux is omnidirectional with respect to the Earth, a correction for Earth shielding must be applied to equations (1) and (2). The Earth's gravitational field also attracts (focuses) the meteoroids. The current estimate of the meteoroid flux at an orbital altitude of 400 km is given in Fig. 1 (using shielding and focusing factors from JSC 30000). The mass density of meteoroids is 0.5 g cm^{-3} (Cour-Palais, 1987). The meteoroids impact the Space Station at a mean velocity of 20 km s^{-1}.

The projected space debris flux from JSC 30000 is also given in Figure 1 (lower solid line, here extrapolated from a fragment diameter of 100 microns down to 5 microns). As argued in JSC 30000, this baseline is probably the minimum flux. Higher fluxes suggested in JSC 30000 are given by the dashed line (current flux) and by the dotted line (projected for 1990s). The mean mass density of space debris fragments is that of alumimum, 2.7 g cm^{-3} (Cour-Palais, 1987). The impact velocity ranges from about 2 to 16 km s^{-1}; a mean impact velocity of 10 km s^{-1} is assumed in this paper.

Ejecta Particle Generation

Seebaugh and Linnerud (1984) developed a phenomenological model for the ejecta environment created by high-explosive detonations near the Earth's surface. Oberbeck (1977) and others have shown that the crater produced by a hypervelocity impact is similar to that produced by a slightly buried high-explosive charge. It is reasonable, therefore, to expect that the ejecta environments are also similar. With this in mind, we have begun development of a model for the ejecta environment created by the hypervelocity impact of a

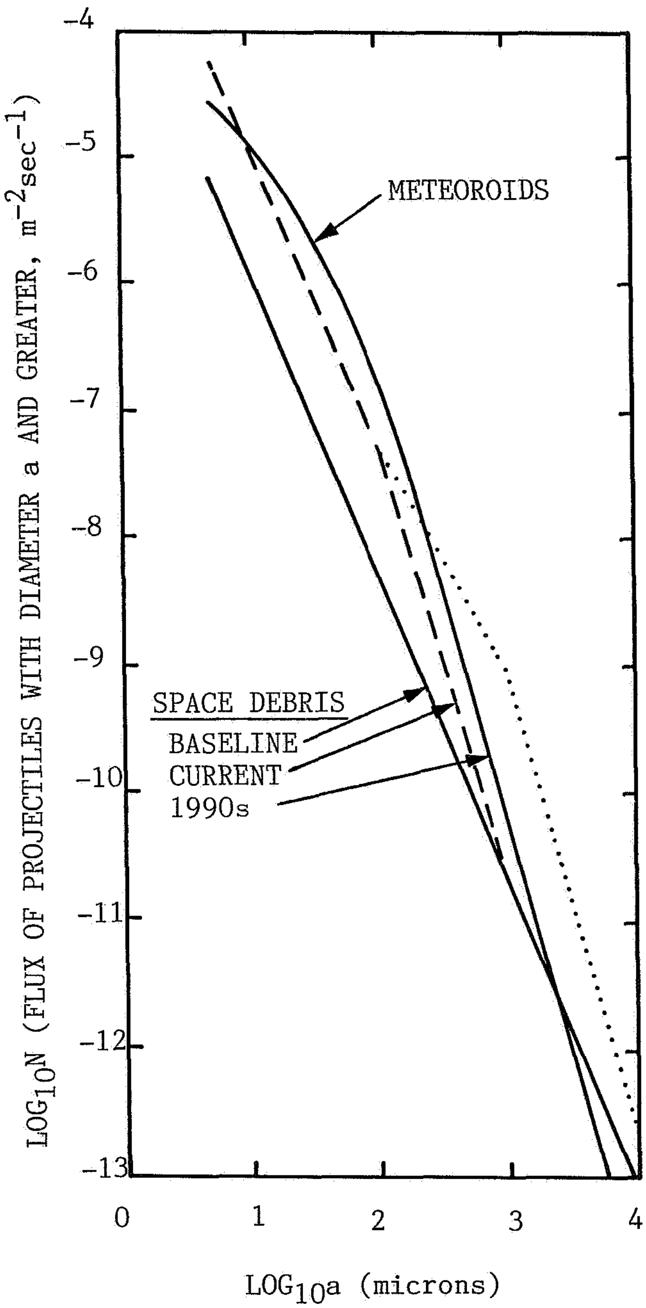

Fig. 1. Flux levels for meteoroids and space debris fragments at an altitude of 400 km.

small projectile (meteoroid or orbital debris fragment) on a spacecraft surface. For the cases modeled, the impact energy is insufficient to cause spallation of surface material; that is, the target can be considered to be semi-infinite (Cour-Palais, 1987).

The model development parallels that of Seebaugh and Linnerud (1984), substituting empirical relationships more appropriate to hypervelocity impacts for those developed for explosively generated ejecta. The mass of ejecta created by each projectile impact on a spacecraft surface is given by (Su and Kessler, 1985)

$$M_e = V^2 m \tag{3}$$

where M_e is the mass of ejecta, V is the impact velocity in km s^{-1}, and m is the mass of the projectile. The mass of the largest ejecta particle created by a hypervelocity impact is given by (Gault et al., 1963)

$$M_m = 0.1\ M_e. \tag{4}$$

The cumulative mass of ejecta particles with mass greater than M is given by (Seebaugh, 1977)

$$M_c = M_e\ [1 - (M/M_m)^{1/6}] \tag{5}$$

where M is the mass of the particle under consideration. This corresponds to the cumulative number of ejecta particles N_e with mass M or greater

$$N_e = 0.2936\ (M/M_e)^{-0.8333}\ -2 \tag{6}$$

which is in the form of equation (5) of Su and Kessler (1985). Equation (6) above has the advantage (relative to the distribution of Su and Kessler, 1985) that it gives no particles with mass greater than M_m, which is not the case with Su and Kessler's distribution.

The explosive model of Seebaugh and Linnerud combines relationships equivalent to equations (3)-(6) above with a theoretical description of the ejecta mass as a function of ejection velocity to provide initial conditions for calculation of trajectories of ejecta particles. This approach may also have merit for hypervelocity impacts on spacecraft surfaces; however, insufficient theoretical cratering calculations have been performed for the projectile energies of interest here. Some qualitative conclusions regarding ejecta velocities are advanced herein following the presentation of the results obtained for the particulate environment for Space Station.

Particulate Environment for Space Station

An orbiting platform such as Space Station presents a varying surface area to the highly directional meteoroid flux at varying positions in its orbit. The projected areas of the module cluster of Space Station are approximately 100 m^2 in the direction of the velocity vector, 200 m^2 in the direction normal to the velocity vector and the orbital plane, and 300 m^2 from above or below. For convenience, a representative area of 150 m^2 was used to represent the mean area exposed to the meteoroid flux. The space debris flux is less directional, and it is unlikely that the 300 m^2 upper and lower surfaces would be subjected to this flux. For this reason, the same area, 150 m^2, was used for space debris impact calculations.

Impacts of meteoroids and space debris fragments will occur with spacecraft surfaces at all angles from normal to essentially parallel to the surfaces. The individual impact angles will be highly dependent on the relative directions of travel of the projectiles and the target, and on the local orientation of the target surface. The number of ejecta particles produced by a given impact will vary with impact angle; however, there is a dearth of data on this effect. Only normal impacts are considered in the present analysis.

The model outlined above was applied to determine the number of ejecta particles generated by meteoroids impacting a 150-m^2 aluminum surface representing Space Station. The impacting meteoroid flux was partitioned into six size classes: 5-10 microns, 10-50 microns, 50-100 microns, 100-500 microns, 500-1000 microns, and 1000-5000 microns. The number of projectiles per orbit for each size class was determined using Figure 1. The ejecta mass for each size class was determined from equation (3) using the mean projectile mass for the size class. The number of ejecta particles generated per orbit was calculated (using the same size classes for these particles) for each representative projectile. Ejecta particles were considered to be released into the hemisphere above the target (2π sr solid angle).

Figures 2 and 3 summarize the number of projectiles with diameter greater than "a" impacting per orbit and the mean number of ejecta particles with diameter greater than "a" created per orbit per sr for the entire array of projectiles, respectively. The solid curves represent the sum of the meteoroid and the baseline space debris fragment environments (corresponding to solid lines of Figure 1). The dashed curves sum the meteorite and current space debris contributions (corresponding to the dashed space debris line of Figure 1). Similarly, the dotted curves represent the sum of the meteoroids and the curve for space debris for the 1990s (see dotted line on Figure 1).

The particulate background limitation (quiescent period) is given in JSC 30426 as one particle 5 microns or larger per orbit per 1 x 10^{-5} sr field-of-view as seen by a 1-meter-diameter aperture telescope. This criterion is represented by the ordinates of the curves in Figure 3 at 5 microns diameter. These particulate backgrounds approach or slightly exceed the JSC 30426 limitation; however, it must be stressed that these results are averages for many orbits. Any given projectile impact will create many more particles than shown in Figure 3 for a short time. For example, an 860-micron space debris fragment (mean diameter for 500-1000 micron size class) creates 6 ejecta particles in the 5 to 10 micron size class per 1 x 10^{-5} sr. The number of small particles generated by a single impact increases as the diameter of the projectile increases. This effect many be limited by phase change phenomena as the impact energy increases. Analysis of this effect is beyond the scope of the present study.

The relatively high ejecta particle density immediately following an impact is mitigated by the relatively low number of impacts occurring during a given time period. For the example given in the preceding paragraph, there are only 0.02 impacts per orbit (on the average) for the 1990s space debris environment. For this scenario, there is an average of just over one impact per orbit of sufficient particle generating capacity to approach the one particle per 1 x 10^{-5} sr limitation.

The ejecta environment caused by meteoroid and space debris fragment impacts on Space Station surfaces may best be described as a moderate density background caused by small (5-50 microns) projectile impacts with occasional spikes caused by larger (50-500 microns) projectile impacts. The spikes will exceed the above criterion for time intervals that depend on the ejection velocities of the particles. As discussed in the Introduction, the model does not currently address this issue. The ejecta particles will leave the target surface with velocities from tens of m s^{-1} to several times the impact velocity relative to the target (Gault et al., 1963), The larger particles will tend to have the lower velocities (Seebaugh, 1977). For order-of-

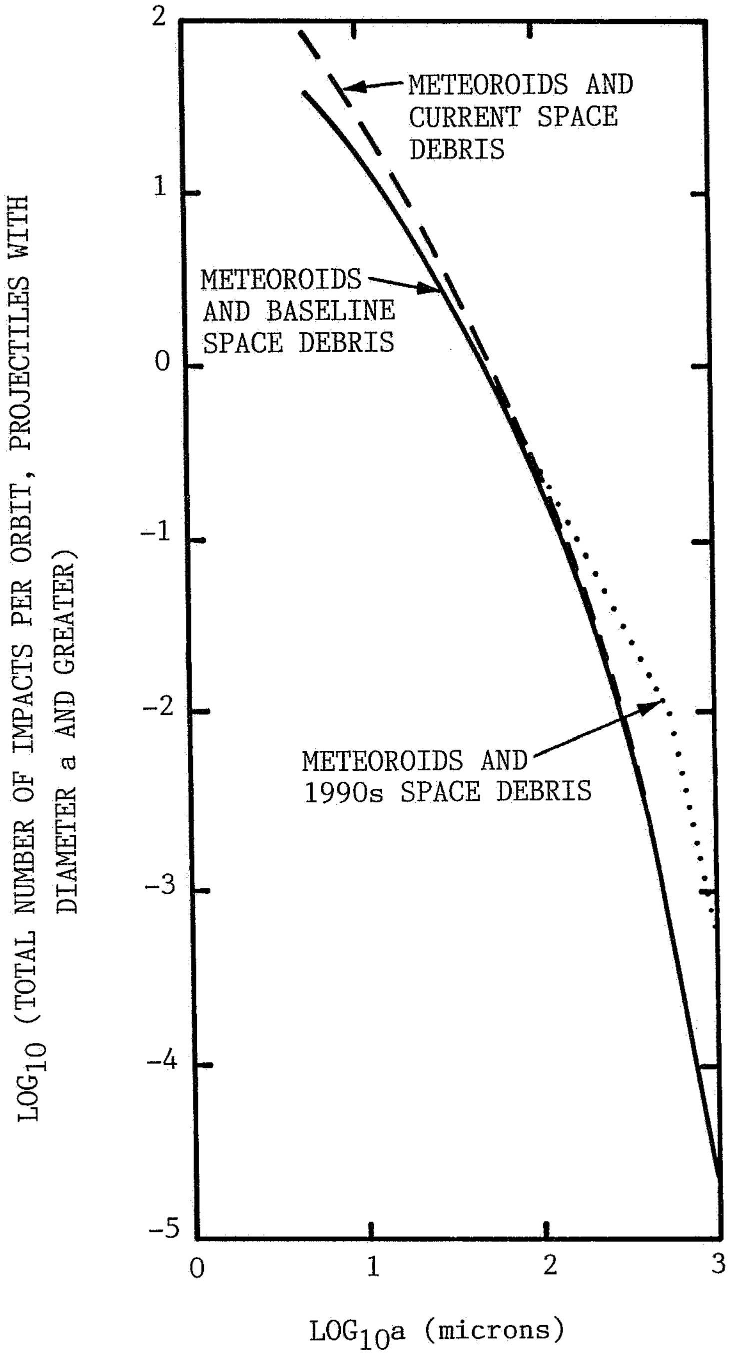

Fig. 2. Number of impacts of meteoroids and space debris fragments with 150-m^2 module cluster at an altitude of 400 km.

magnitude analyses, a particle velocity equal to the critical impact velocity (70 m s^{-1} for aluminum targets) may be used (Sewell and Kinney, 1968). If a particular instrument is sensitive to particles to a range of 1 km, then the above limitation would be exceeded for an interval of approximately 15 s following these occasional impact events.

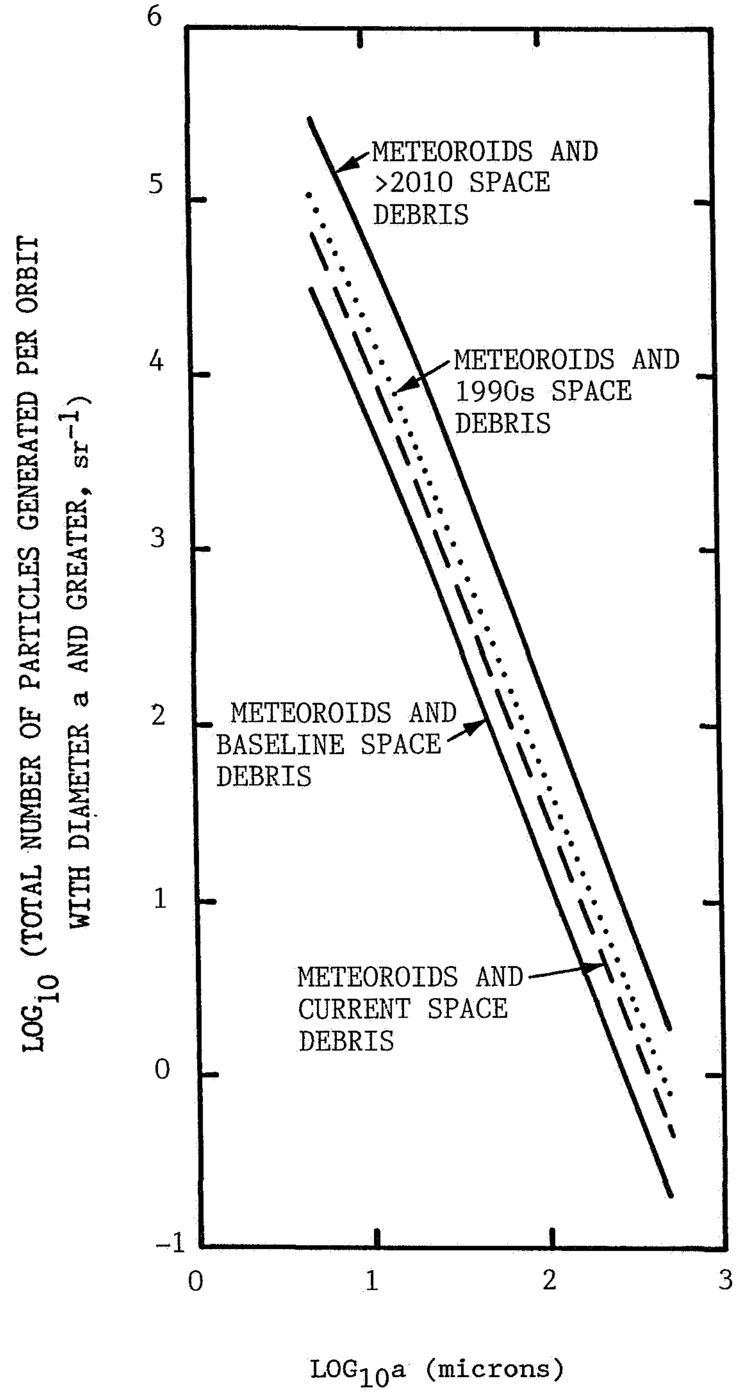

Fig. 3. Total number of ejecta particles generated per orbit per steradian for 150-m^2 module cluster at an altitude of 400 km.

Estimates of future space debris populations (Su and Kessler, 1985) indicate that this population may exceed the meteoroid flux by a substantial amount, perhaps as much as a factor of 10 for years beyond 2010. If this high flux level occurs, the number of ejecta particles generated will increase to the level of the line labeled ">2010" in Figure 3. This particulate environment exceeds the 1×10^{-5} sr criterion by a factor of 3.

The planned truss structure for Space Station is an assembly of aluminum-clad composite tubes. Impacts of meteoroids and space debris fragments on the truss structure will produce craters in the cladding. If the craters penetrate through the full depth of the cladding, the composite substrate will be exposed to erosion by atomic oxygen. The projectile diameter required to penetrate 0.018-cm-thick aluminum cladding (LAR-13562) was calculated as a function of projectile velocity and impact angle for meteoroids and space debris fragments (Seebaugh, unpublished). The expected number of impacts resulting in complete penetration of the specified cladding for a truss structure with 17-m^2 cross-sectional area (cross boom configuration for Space Station) are given below for an impact angle of 45° (Cour-Palais, 1987):

Scenario	No. Penetrations Per Year
Meteoroids only	65
Meteoroids with baseline space debris flux	70
Meteoroids with 1990s space debris flux	140
Meteoroids with ">2010" space debris flux	

The lowest value in the above table represents approximately one penetration in each truss member per year. The highest value exceeds 10 penetrations in each truss member per year, or about two penetrations in each meter of truss member length. These values will increase with decreasing thickness of the cladding.

Conclusions

Modeling results show that the mean ejecta density produced by impacts of meteoroids and space debris fragments with Space Station surfaces is from 30% to 100% of the particulate background limitation of 1 particle 5 microns or larger in diameter per orbit per 1×10^{-5} sr. No other particulate sources are included in this estimate, which applies to the 1990s time frame. The uncertainty, which is primarily a result of the lack of information on the space debris flux at Space Station altitude, may be larger than a factor of 3. New knowledge is more likely to increase the estimate of particulate production by impact processes. As a result of future orbital activity, these particulate densities will probably increase by an additional factor of 3 after 2010.

The particulate densities given in the preceding paragraph are mean values over many orbits. Ejecta densities will exceed these mean values following impacts of larger projectiles for a few tens of seconds.

Meteoroids and space debris fragments in the diameter range of 100 to 500 microns produce 80% of the impact generated ejecta. Further work on defining the space debris environment, which is required for many reasons, should provide firmer estimates for the projectile flux in this size range.

Experimental results for hypervelocity impacts of particles in the 5 to 1000 micron range into potential Space Station surface materials are required to increase confidence in the ejecta generation model. This includes determination of ejecta particle sizes and ejection velocities for impact angles from normal to about 75°. The model should be extended to incorporate these data and develop a predictive capability for the attenuation of the particulate environment following an impact. Monte Carlo calculations, similar to those performed by Su and Kessler (1985), would be useful in determining how the variations in projectile flux with time, relative velocities between spacecraft and projectiles, and spacecraft surface orientation affect the particulate environment.

Composite structural members with thin metallic cladding will be vulnerable to atomic oxygen erosion at the locations of impact craters which completely penetrate the cladding. Impacts of larger projectiles will produce both metallic and non-metallic ejecta (the latter from the substrate). The estimated number of penetrations for 0.018-cm-thick aluminum cladding is from about 60 to 140 per year during the 1990s, increasing to about 740 per year after 2010.

Co-orbiting platforms with smaller cross sections than Space Station will have proportionally less severe particulate environments associated with impact ejecta. If these platforms use cladded composite structural members, they will be vulnerable to atomic oxygen erosion to the same degree as Space Station.

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