Particle Adhesion to Surfaces Under Vacuum

Jack B. Barengoltz*
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

The objective of this work is to provide a reliable basis for the estimation of contaminant particle release during the launch of a spacecraft. The release of glass beads and "standard" dust from aluminum and glass substrates under centrifugation is measured. The experimental plan includes three ambient conditions: atmospheric pressure, low vacuum (10 Torr), and high vacuum (10^{-5} Torr), in order to investigate the dependence of release on ambient pressure. The data are expressed in removal fraction (number removed/original number) as a function of applied acceleration for discrete particle size ranges. The data are fitted by an empirical model with two parameters. The model permits estimates for particle sizes and small accelerations not tested. For particles in the size range of interest, 10–100 μm, dust adheres more strongly than glass beads for all pressure conditions and for both substrates. With one exception, both dust and glass beads adhere more strongly to glass than to aluminum at all pressures. The adhesion force for dust on glass at 10 Torr is as small as the value for dust on aluminum. This result is the only ambient pressure effect observed.

Nomenclature

a_o = characteristic acceleration for the removal of particles of a given size, corresponding to the removal of 0.5 of a collection of such particles
a^* = applied acceleration that may cause particle removal
d = particle diameter (or size)
F = adhesion force of a single particle of a specific size
F_o = characteristic adhesion force for the removal of particles of a given size, corresponding to the removal of 0.5 of a collection of such particles
F^* = applied force that may cause particle removal
k = proportionality constant in F proportional to d
k_n = proportionality constant in F_o proportional to d^n $(n \geq 2)$
k_o = proportionality constant in F_o proportional to d
k^* = proportionality constant in F^* proportional to d
k_n^* = proportionality constant in F^* proportional to d^n $(n \geq 2)$
m = mean value of log k; see Eq. (3)
ρ = particle density
σ = standard deviation of log k; see Eq. (3)

Introduction

THE strength of the adhesion of contaminant particles to surfaces is an important factor in contamination control. In general, the strength may be characterized either as the force applied to a particle or as the resulting particle acceleration required to remove the particle from a surface. The most common interest is in surface cleaning, where the adhesion is a crucial parameter in the success or failure of the cleaning method used.

For spacecraft contamination control, particle removal during launch and flight resulting from forces completely unrelated to cleaning attempts is central to the analysis of the redistribution of particle contamination. Such analyses are performed to estimate the contamination of relatively clean flight hardware by less clean systems, e.g., the Viking lander by the orbiter[1] or an ultraclean payload by the Shuttle Orbiter.[2] The release of particles is also pertinent to estimates of particles in the field of view of instruments such as IRAS,[3] SIRTF,[4] or a Shuttle-based instrument in general.[5]

The objective of the work described in this paper was to extend the available data on contaminant particle adhesion for use in spacecraft contamination analysis. The important factor was the introduction of a modest vacuum to simulate launch conditions. Also, some more realistic materials than found in the literature were investigated.

The experimental design and the materials used were not intended to support any theoretical treatment of the forces of adhesion. A list of such forces includes contact potential, electrostatic, Van der Waal's, and water capillary forces. The only theoretical note may be that the capillary effect should be absent in a vacuum. Similarly, the particle and surface materials and their surface properties were not ideal, but it is hoped they are representative of typical spacecraft surfaces and their contaminants.

The results of previous work by this author in this area[1] have been used in spacecraft contamination analyses.[2-5] These data were for glass beads on stainless steel under vacuum conditions, 0.27 to 9×10^{-3} Pa (2×10^{-3} to 6.8×10^{-5} Torr). However, the release mechanism studied was appropriate for impact-generated release simulation only. This approach renders the data inapplicable (without verification) to vibrational or constant release mechanisms and precludes valid comparisons with the usual constant acceleration results in the literature.

Zimon has written a comprehensive review on particle adhesion, which ranges from theory to experiment to applied topics.[6] The first three chapters on the fundamentals of particle adhesion, experimental methods, and adhesion in ambient air, respectively, are pertinent to this investigation. In particular, Zimon presents in chapter 3 a clear discussion of the various mechanisms of adhesion and the influence of physical parameters, with data from the literature. Corn also has published an excellent review article.[7]

In the present work, data were obtained on the release under constant acceleration of glass beads on a glass substrate, dust on glass, glass beads on aluminum, and dust on aluminum. The vacuum conditions tested included ambient pressure, 1330 Pa (10 Torr) and 1.33×10^{-3} Pa (10^{-5} Torr). The data were in the form of removal fraction, the ratio of the change in particle count to the original particle count. The experimental results were fitted into an engineering (empirical) model.[1] Where comparisons are possible, the data obtained are in reasonable agreement with the literature. These experiments are difficult to control. Order of magnitude conformity in the applied force for 50% removal is all that may be expected. The

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*Member, Technical Staff, Mechanical and Chemical Systems. Member AIAA.

results (data and model) are considered adequate for the intended purpose of estimating particle release during spaceflight.

Experimental Method

Materials

Since particle adhesion or removal depends on size, sets of glass beads of reasonably narrow size distributions with nominal diameters of 8, 22, 48, and 68 μm were used. The Cataphote Corporation, Microbeads Division, Jackson, Mississippi, supplied these soda-lime-silica glass beads along with size distribution certifications. The specific gravity of "type A spacer graded uni-spheres" was stated by the supplier to be 2.42. The dust employed in this experiment was supplied by General Motors Corporation, AC Spark Plug Division, Flint, Michigan. Their "coarse grade standardized test dust" has a fairly flat (known) size distribution in a range of up to 800 μm. The supplier also provided a chemical analysis. The principal constituents are silica (68.5%) and alumina (16%), with the balance being oxides of iron, magnesium, calcium, and sodium.

Sample Preparation

The sample substrates were cleaned prior to particle seeding by an isopropanol rinse and blown dry with clean nitrogen gas. During seeding, the aluminum substrates were electrically grounded. The particles were dropped onto the substrate with a flattened hypodermic needle. The samples were inspected for an appropriate number of particles (about 100 for each size range), photographed, and counted under a microscope. Because of a concern for the loss of the larger particles, especially during handling, handling controls were placed in the sample rack (Fig. 1), removed, and recounted. Such losses were found to be no more than 2%. The dust particle counting included sizing with the aid of an optical scale. Dust particles were counted in ranges of nominal sizes of 7.5, 12.5, 20, 30, 40, 50, 60, 75, 80, and 100 μm.

The general centrifuge arrangement is shown in Fig. 1. Each sample was placed in a sample rack in an orientation for acceleration normal to the substrate. The apparatus permitted other orientations, but only the simplest case was investigated in this work. The sample rack was then inserted into a centrifuge tube. Multiple sample positions provided several accelerations during the same centrifuge run. The acceleration values were calculated from the rotor frequency and the samples' distances from the rotor axis. The influence of any starting and stopping transients should be negligible, compared to the effect of the applied acceleration, except at small values of the latter where some anomalous removal may be expected.

The preparation of evacuated samples included the following additional procedure. The tube was clamped onto a special device that comprised the tube clamp, a vacuum flange, a rubber stopper, and a manual linear actuator sealed in a bellows. This assembly was mounted by its flange to a small vacuum chamber (4 in. "tee"), with the tube inside. When the desired vacuum was obtained, the manual actuator was employed to push the stopper into the tube and to seal it. Then the chamber was let up to ambient pressure, and the stoppered tube was ready for the centrifuge. The vacuum system was a standard mechanical roughing/forepump, oil diffusion pump system with a liquid nitrogen trap. The intermediate pressure was obtained by roughing only. The chamber pressure was measured by thermocouple gage or ionization gage, as appropriate to the pressure. The centrifuge tube for evacuated samples is shown in Fig. 1.

Each sample was photographed and counted under a microscope after the centrifuge run was completed. The evacuated tubes first went through a reverse procedure of their preparation, with the final let-up of the vacuum system a dry nitrogen backfill.

Analytical Method

The data were analyzed in terms of the same model as previous work by this author.[1] In this model the characteristic force of adhesion F_o, corresponding to a removal fraction of 0.5, is given by

$$F_o = k_o d \tag{1}$$

or the characteristic acceleration is given by

$$a_o = 6k_o/\pi\rho d^2 \tag{2}$$

The actual adhesion force F of a given particle of diameter d is assumed to be distributed according to a log-normal distribution in k. The parameters of the model are the mean value of log k (equal to log k_o) noted as m, and the standard deviation σ. The removal fraction for a group of particles of size d is then the probability that the applied force F^* (or the applied acceleration a^*) exceeds the adhesion force F (or the acceleration a), where the latter is distributed as discussed. This probability is written:

$$P(F^* > F) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{(\log k^* - m)}{\sigma}} dt \exp\left(\frac{-t^2}{2}\right) \tag{3}$$

where

$$k^* = F^*/d = \pi\rho a^* d^2/6 \tag{4}$$

An obvious generalization of Eq. (1) to the form

$$F_o = k_n d^n \tag{5}$$

was also employed. Now one must note that

$$a_o = 6k_n/\pi\rho d^{3-n} \tag{6}$$

and that in Eq. (3)

$$k_n^* = F^*/d^n = \pi\rho a^* d^{3-n}/6 \tag{7}$$

These equations reduce to the previous form for $n = 1$.

Results

Representative data (average of four replicates) for most particle sizes and for each particle/substrate sample combination and vacuum condition tested are shown in Figs. 2–11. A two-parameter (m and σ) least-squares data fit was conducted for each case on all particle sizes per the model of Eqs. (1–4). The results of this procedure are given in Table 1. Plots of that model are also shown in these figures. A three-parameter

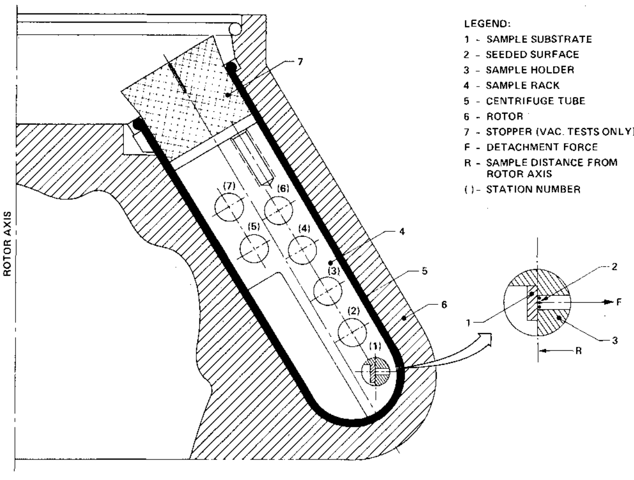

Fig. 1 Arrangement for centrifugation of samples.

search with the model of Eqs. (3) and (5-7), with n constrained on the interval 0.5-1.5, did not improve the fit. The unity value of the parameter n was best, as expected from the work of others.[6,8]

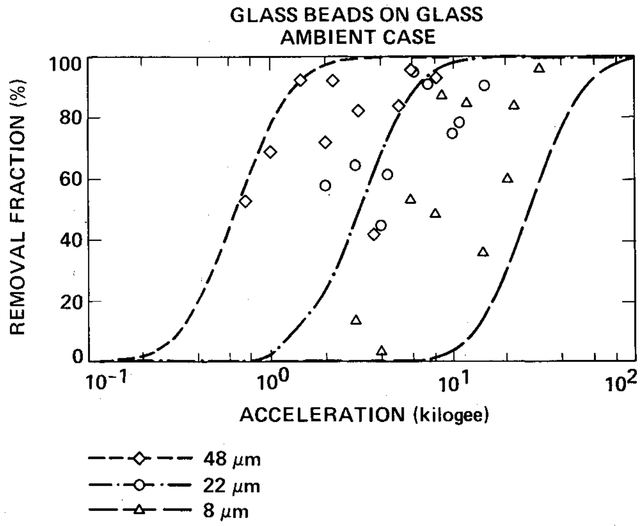

Fig. 2 Removal fraction as a function of applied acceleration for glass beads on a glass substrate under atmospheric pressure (ambient). Data for particle sizes as indicated. Model per Eq. (3) (n = 1) with parameters $m = -1.73$, $\sigma = 0.230$.

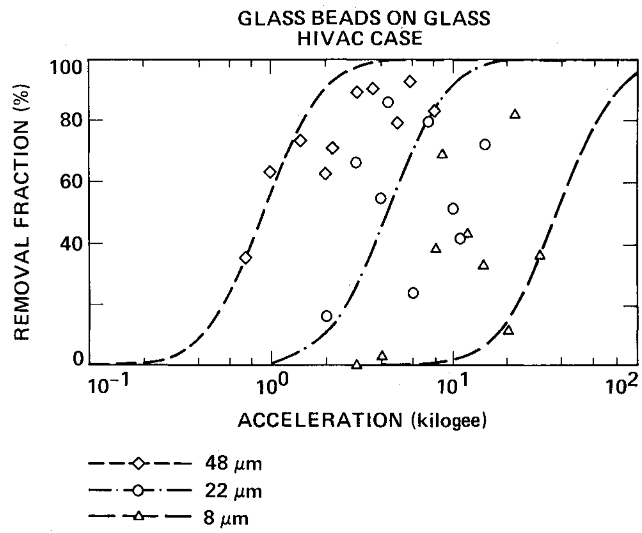

Fig. 3 Removal fraction as a function of applied acceleration for glass beads on a glass substrate under 10^{-5} Torr pressure (hivac). Data for particle sizes as indicated. Model per Eq. (3) (n = 1) with parameters $m = -1.59$, $\sigma = 0.262$.

Table 1 Particle adhesion results, derived values for m and σ[a]

Adhesion case	At ambient pressure		At 10 Torr		At 10^{-5} Torr	
	m	σ	m	σ	m	σ
Glass/ glass	−1.73	0.230	—		−1.59	0.262
Glass/Al	−2.10	0.065	—		−2.12	0.065
Dust/ glass	−1.15	0.250	−1.51	0.322	−1.19	0.220
Dust/Al	−1.44	0.265	−1.36	0.270	−1.40	0.245

[a]Units of m, σ such that 10^m and 10^σ are in N/m.

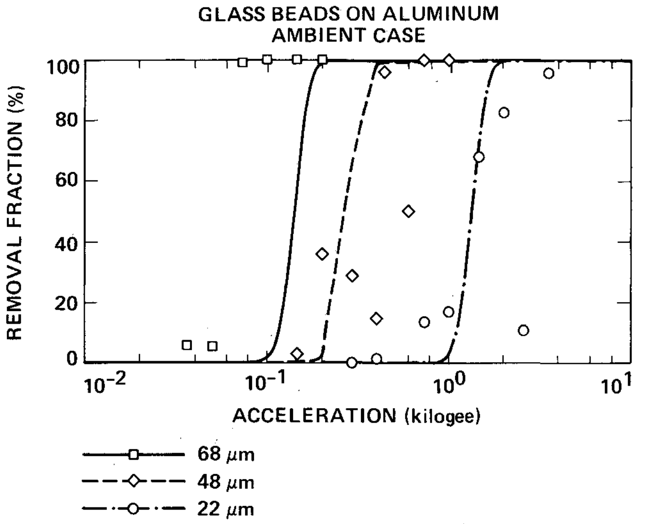

Fig. 4 Removal fraction as a function of applied acceleration for glass beads on an aluminum substrate under atmospheric pressure (ambient). Data for particle sizes as indicated. Model per Eq. (3) (n = 1) with parameters $m = -2.10$, $\sigma = 0.065$.

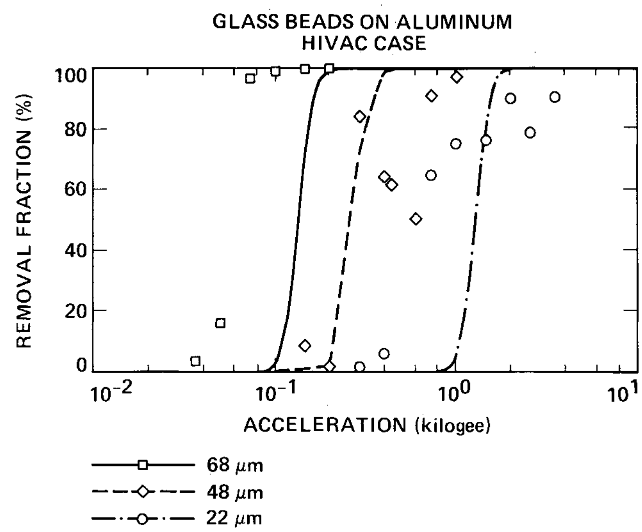

Fig. 5 Removal fraction as a function of applied acceleration for glass beads on an aluminum substrate under 10^{-5} Torr pressure (hivac). Data for particle sizes as indicated. Model per Eq. (3) (n = 1) with parameters $m = -2.12$, $\sigma = 0.065$.

The fits to the glass bead data on both glass and aluminum substrates at all three vacuum conditions were acceptable (Figs. 2-5). Better fits for each particle size independently may be found. However, this approach violates the spirit of a model for adhesion as a function of particle size.

Glass beads adhered more strongly to a glass substrate than to aluminum both at ambient and high vacuum conditions. Note that a larger (algebraic) value of m corresponds to a larger value of k_o and therefore a larger adhesion force. No statistically significant ambient pressure dependence was observed (Table 1).

The fits to the dust data were not satisfactory, however (Figs. 6-11). The discrepancy was obvious for the largest and smallest particles. Another least-squares fit with the parameter n constrained on the interval 1.5-2.5 yielded a much improved best fit for $n = 2$. The results of this fit compared to the dust adhesion data are shown in Figs. 12 and 13 for dust on glass and dust on aluminum, respectively. The size dependence and the applied acceleration have been taken into the parameter k_2^* [(Eq. (7)] so that the data for all particle sizes could be plotted together. For dust on glass, the model parameters are

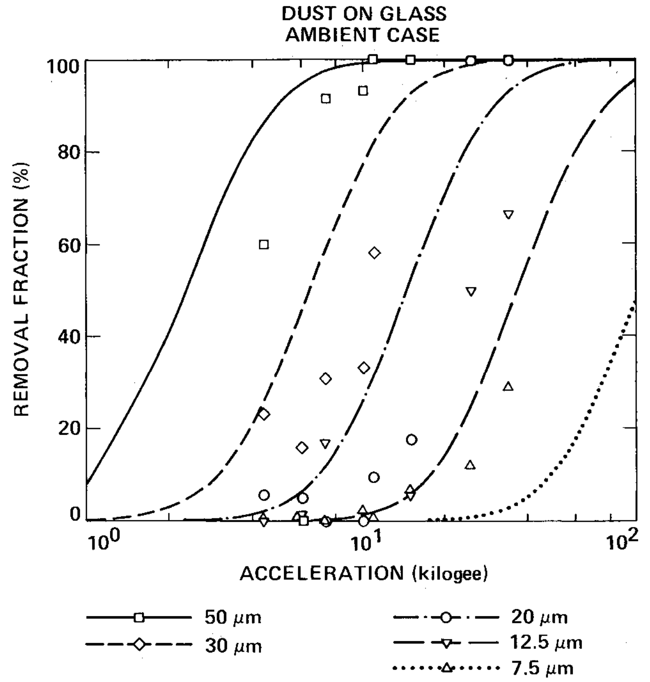

Fig. 6 Removal fraction as a function of applied acceleration for dust on a glass substrate under atmospheric pressure (ambient). Data for particle sizes as indicated. Model per Eq. (3) (n = 1) with parameters $m = -1.15$, $\sigma = 0.250$.

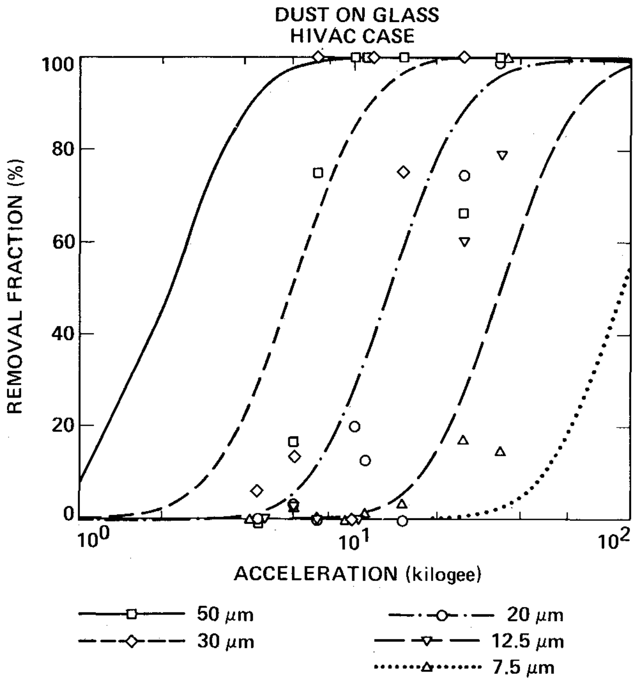

Fig. 8 Removal fraction as a function of applied acceleration for dust on a glass substrate under 10^{-5} Torr pressure (hivac). Data for particle sizes as indicated. Model per Eq. (3) (n = 1) with parameters $m = -1.19$, $\sigma = 0.220$.

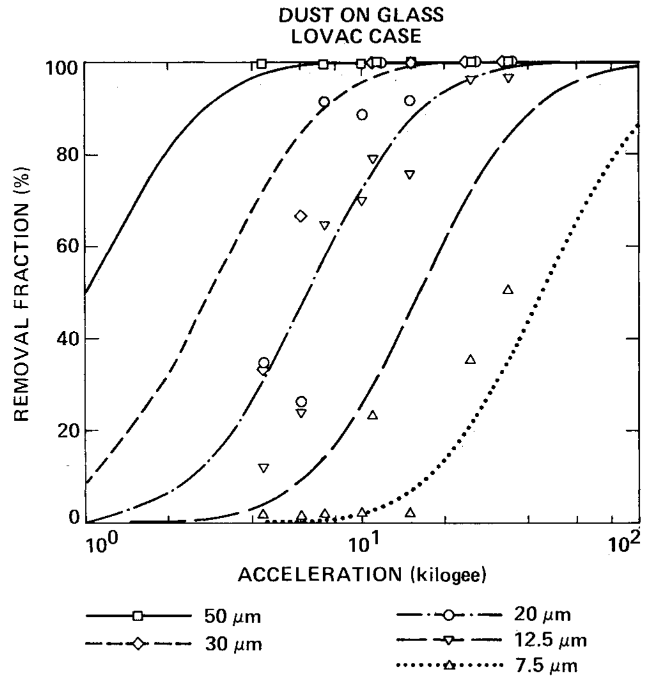

Fig. 7 Removal fraction as a function of applied acceleration for dust on a glass substrate under 10 Torr pressure (lovac). Data for particle sizes as indicated. Model per Eq. (3) (n = 1) with parameters $m = -1.51$, $\sigma = 0.322$.

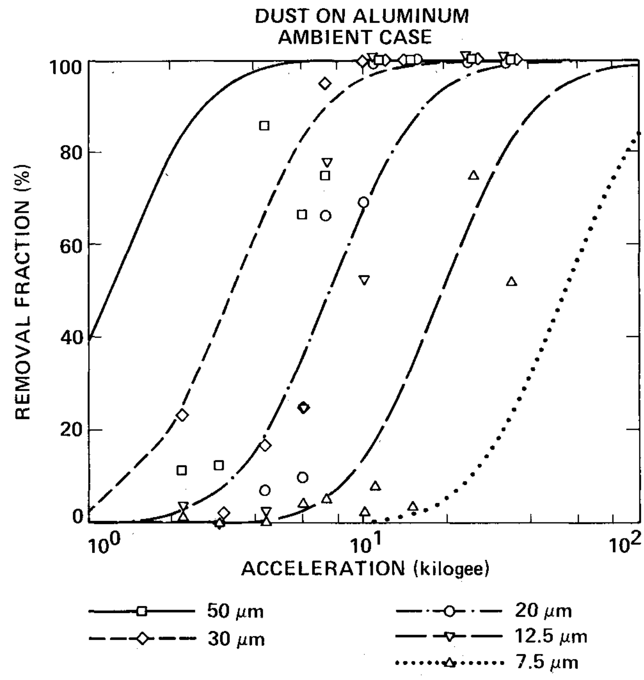

Fig. 9 Removal fraction as a function of applied acceleration for dust on an aluminum substrate under atmospheric pressure (ambient). Data for particle sizes as indicated. Model per Eq. (3) (n = 1) with parameters $m = -1.44$, $\sigma = 0.265$.

$m = 3.58$ and $\sigma = 0.25$ for the ambient and high vacuum cases, but $m = 3.35$ and $\sigma = 0.25$ for the low vacuum case (Fig. 12). For dust on aluminum (Fig. 13), the model parameters are $m = 3.30$ and $\sigma = 0.25$ for all vacuum conditions. The units of these parameters are such that their antilogarithms (base 10) are expressed in N/m^2.

Considerable scatter in the data was observed, caused in part by sizing errors, as well as the typical variations expected[6,7] (Figs. 12 and 13). The adhesion of dust to a glass substrate was larger than to an aluminum substrate under ambient and high vacuum conditions. Dust adhered to glass more weakly at the low vacuum condition (Fig. 12). In fact, the adhesion was essentially the same as for dust on aluminum at all conditions. This result was the only ambient pressure dependence observed. These tendencies are also indicated in Table 1, despite the poor quality of the $n = 1$ model fit for dust particles.

A comparison of the adhesion of glass beads to the adhesion of dust is difficult because the best models obtained preclude a comparison of k values ($n = 1$ and $n = 2$, respectively).

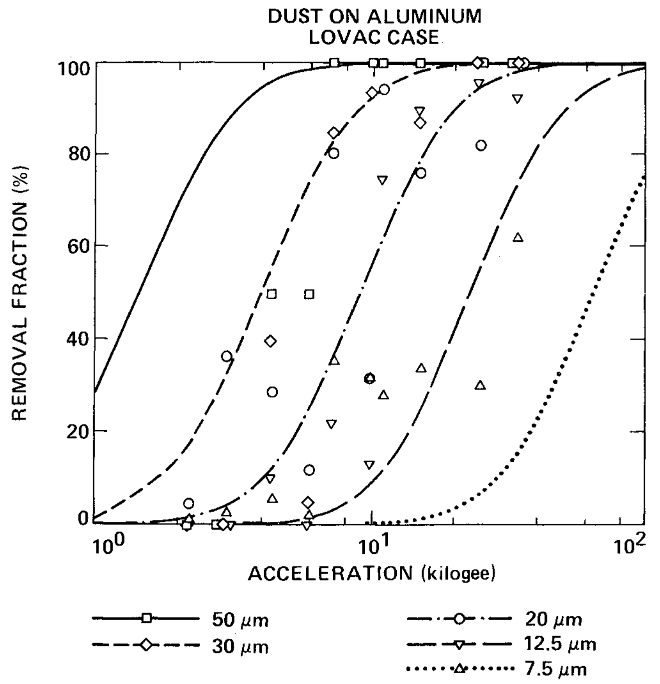

Fig. 10 Removal fraction as a function of applied acceleration for dust on an aluminum substrate under 10 Torr pressure (lovac). Data for particle sizes as indicated. Model per Eq. (3) (n = 1) with parameters $m = -1.36$, $\sigma = 0.270$.

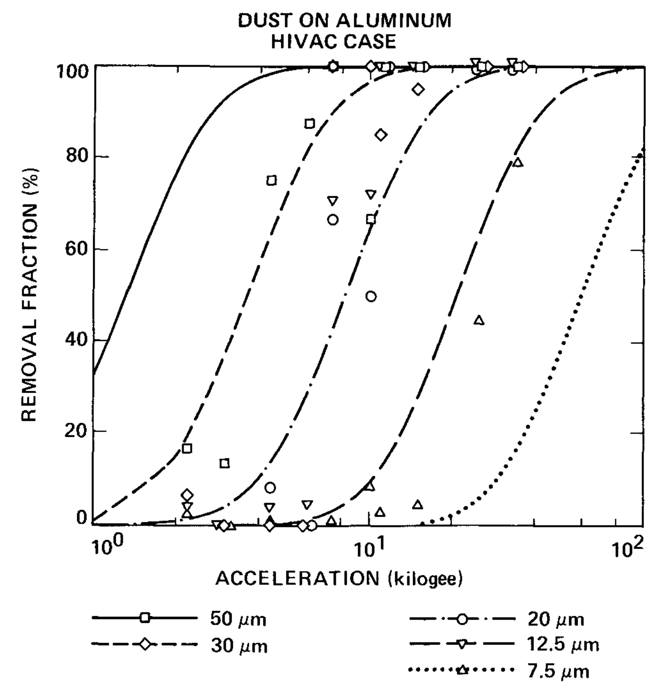

Fig. 11 Removal fraction as a function of applied acceleration for dust on an aluminum substrate under 10^{-5} Torr pressure (hivac). Data for particle sizes as indicated. Model per Eq. (3) (n = 1) with parameters $m = -1.40$, $\alpha = 0.245$.

Although the $n = 1$ model is questionable for dust, some conclusions may be reached by inspection of the fit parameters of Table 1 (where this comparison is possible). One must note that the $n = 1$ model always underestimated the adhesion for the larger dust particles, fit the intermediate sizes, and overestimated the adhesion of the smaller particles (Figs. 6–11). Therefore, dust adhered more strongly than glass beads to the same substrate under ambient and vacuum conditions, at least for particles no smaller than 20 μm. This effect was even greater than the parameters in Table 1 would indicate. The

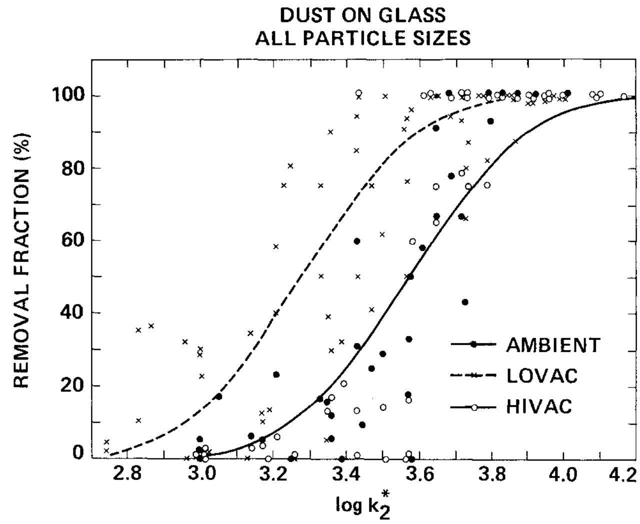

Fig. 12 Removal fraction as a function of log k_2^* [Eq. (7), n = 2] for dust on a glass substrate for all particle sizes and under pressure conditions indicated. Model per Eq. (3) with parameters $m = -3.58$ for ambient and hivac (10^{-5} Torr), and $m = -3.35$ for lovac (10 Torr); $\sigma = 0.25$.

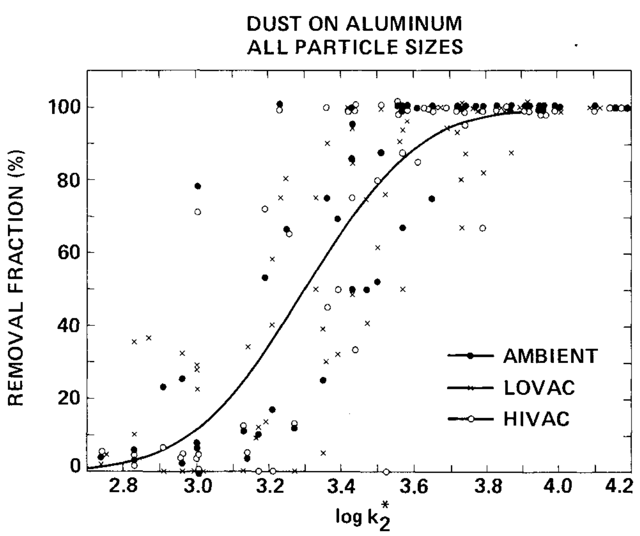

Fig. 13 Removal fraction as a function of log k_2^* [Eq. (7), n = 2] for dust on an aluminum substrate for all particle sizes and under pressure conditions indicated. Model per Eq. (3) with parameters $m = -3.30$, for ambient, lovac (10 Torr) and hivac (10^{-5} Torr); $\sigma = 0.25$.

best models obtained permit a direct comparison of the values of F_o for glass beads [(Eq. 1)] and for dust [Eq. (5), with $n = 2$] of a specific size. This approach, with the best k_o and k_2 values found, shows that the adhesion force of a dust particle approached the adhesion force of a glass bead, c.p., for particles smaller than 7 μm.

Discussion

The results of this experiment lead to comparisons with published work, some conjectures, and a conclusion in regard to utility for spacecraft contamination analysis. Comparison with data in the literature is difficult, both because of the variability of results (presumably due to uncontrolled parameters) and because materials and conditions examined are rarely identical. Corn[8] studied the adhesion of various glasses and expressed his results in the same form as Eq. (1). With the interpretation that his values represent the mean, he finds the following values for k_o: 0.17 N/m for Pyrex particles on Pyrex optical flats, 0.12 N/m for quartz particles on Pyrex optical flats, and 0.075 N/m for quartz particles on glass slides. These data are at ambient pressure and 95% relative humidity. The comparable value of k_o in the present work was 0.019 N/m (glass beads on glass at ambient pressure in Table 1). In the log-normal distribution, the result was -1.73 ± 0.46 (where 0.46 is the quality of the fit). Thus, the adhesion found was significantly smaller in this experiment. This apparent discrepancy was presumably due to a much lower relative humidity (50% nominal) and possibly due to particle material differences. Using a factor of 2.5 taken from Corn's work[8] to estimate what the present result would have been at 95% relative humidity, one obtains $k_o = 0.048$ N/m. Factors of 5 or more are readily available in the literature.[6,7] Thus the present result is consistent with Corn's value for quartz particles on glass slides, which does match for substrate material and roughness.

Kordecki and Orr[9] (also cited in Refs. 6 and 7) find a detachment force by centrifugation for 98% removal of 50 μm glass particles from glass at 50% relative humidity of 0.37 dyne. With Eq. (3) and the present values of m and σ, this force may be estimated at 0.27 dyne, in reasonable agreement. On the other hand, their analogous value for glass on aluminum is 1.35 dyne, while the prediction of this work would be only 0.054 dyne. This discrepancy is due in large measure to the anomalously small σ of the present results (0.065 in Table 1). A more representative value might be 0.23. Then the prediction of this work, c.p., would be 0.12 dyne. Kordecki and Orr's results are also hard to understand in that they find that the adhesion of glass particles to aluminum increases with decreasing relative humidity. Their value at 90% relative humidity is 0.50 dyne.

Zimon quotes a 90% removal of glass particles from steel at 0.2 dyne (relative humidity not given).[6] The prediction of this work, with the neglect of the steel and aluminum substrate difference, would be 0.11 dyne.

In the area of conjecture, the observed low adhesion of dust to glass at a pressure of 1330 Pa (10 Torr) may reflect either the loss of static charge in the discharge regime or else the partial loss of water. The first hypothesis is interesting because the effect did not occur for the aluminum substrate, which was grounded during seeding. Then the current data could be interpreted as anomalously high for dust on glass at ambient and high vacuum due to static charge, and otherwise the same for either glass or aluminum substrates. However, the results for dust on glass at high vacuum cannot be explained this way. Water loss may explain the data by a gradual reduction in capillary force to zero, followed by a stage where the water remaining screens the Van de Waal's force, and a final stage where the water is absent. This hypothesis also requires more water on the glass substrate than the aluminum. However, Zimon states that water effects are nil below 65% relative humidity.[6]

The observed greater adhesion of dust than glass beads and the form of the size dependence found were indicative of an enhanced contact area for the larger dust particles. This may be a result of composite particles with flat surfaces.

A comparison of the release of glass particles in a vacuum caused by a constant acceleration with the results of previous work by this author,[1] where the acceleration simulated impact, is desirable. If the effect of slightly different vacuum conditions and possible differences between a stainless steel and an aluminum substrate are ignored, a comparison may be attempted. The adhesion strength parameter k_o under constant acceleration was found to be about 0.008 N/m. The corresponding value in an impact simulation is much larger, 0.13 N/m.[1] Apparently the continuously applied acceleration was more efficient at particle removal than a short duration impulse. Presumably, particles can move laterally to new positions on the surface and then be released from more favorable situations. This conjecture could have important implications for particle release caused by a launch environment or by a repetitive shock environment.

Conclusion

The data and model for the removal of dust particles from an aluminum substrate by centrifugation may be a reliable, conservative basis for the estimation of contaminant particle release during the launch of spacecraft. The total number of particles vs size (i.e., a contamination estimate) and an estimate of the maximum vibrational acceleration for each surface of interest are all else required. The dust employed in this experiment should be a better simulation than other materials used in published work. Collected fallout particles would be best, of course, but are not a readily available standardized test specimen (because of interfacility variation). The data for aluminum provide an upper bound for the release of dust from glass substrates as well. Centrifugation data are expected to estimate adequately the release of tightly bound particles (overestimate release caused by vibration).[6] This approach may underestimate the release of weakly held particles, but for spacecraft launch, this should not be important. The utility of this data and model may be established only by a flight verification comprising a representative surface intentionally contaminated with well-characterized particles to a known degree and instrumented to measure the surface's acceleration.

Acknowledgments

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References

[1]Barengoltz, J. and Edgars, D., "The Relocation of Particulate Contamination During Spaceflight," Jet Propulsion Lab., California Inst. of Technology, Pasadena, CA, TM 33-737, 1975.

[2]Scialdone, J. J., "Particulate Contaminant Relocation During Shuttle Ascent," NASA GSFC TM 87794, 1986.

[3]Andreozzi, L. C., Irace, W. R., and Maag, C. R., "Contamination Control of the Infrared Astronomical Satellite," *Optics in Adverse Environments, Proceedings of SPIE Seminar,* Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1980.

[4]Simpson, J. P. and Witteborn, F. C., "Effect of the Shuttle Contaminant Environment on a Sensitive Infrared Telescope," *Applied Optics,* Vol. 16, No. 3, Aug. 1977.

[5]Barengoltz, J., "Particulate Release Rate from Shuttle Orbiter Surfaces Due to Meteoroid Impact," *Journal of Spacecraft and Rockets,* Vol. 17, Jan.-Feb. 1980.

[6]Zimon, A. D., *Adhesion of Dust and Powder,* translated by M. Corn, Plenum Press, New York, 1969.

[7]Corn, M., "The Adhesion of Solid Particles to Solid Surfaces I," *Journal of the Air Pollution Control Association,* Vol. 11, Nov. 1961.

[8]Corn, M., "The Adhesion of Solid Particles to Solid Surfaces II," *Journal of the Air Pollution Control Association,* Vol. 11, Dec. 1961.

[9]Kordecki, M. C. and Orr, C., "Adhesion of Solid Particles to Solid Surfaces," *Archives of Environmental Health,* Vol. 1, No. 1, July 1960.