NASA/TM—2012-217213 AIAA–2012–0875

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March 2012

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Prepared for the
50th Aerospace Science Conference
sponsored by the American Institute of Aeronautics and Astronautics
Nashville, Tennessee, January 9–12, 2012

National Aeronautics and
Space Administration

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Cleveland, Ohio 44135

March 2012

Acknowledgments

The authors wish to thank D.A. Jaworske and K.W. Street, Jr., and the NASA Glenn Research Center, and B.J. O'Brien of the University of Western Australia for many helpful discussions. Financial and programmatic support for this work was provided by the Exploration Technology Development and Demonstration's Life Support and Habitation project (R.A. Stephan, NASA Johnson Space Center).

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Implications of Adhesion Studies for Dust Mitigation on Thermal Control Surfaces

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Abstract

Experiments measuring the adhesion forces under ultrahigh vacuum conditions (10^{-10} torr) between a synthetic volcanic glass and commonly used space exploration materials have recently been described. The glass has a chemistry and surface structure typical of the lunar regolith. It was found that Van der Waals forces between the glass and common spacecraft materials was negligible. Charge transfer between the materials was induced by mechanically striking the spacecraft material pin against the glass plate. No measurable adhesion occurred when striking the highly conducting materials, however, on striking insulating dielectric materials the adhesion increased dramatically. This indicates that electrostatic forces dominate over Van der Waals forces under these conditions. The presence of small amounts of surface contaminants was found to lower adhesive forces by at least two orders of magnitude, and perhaps more. Both particle and space exploration material surfaces will be cleaned by the interaction with the solar wind and other energetic processes and stay clean because of the extremely high vacuum (10^{-12} torr) so the atomically clean adhesion values are probably the relevant ones for the lunar surface environment. These results are used to interpret the results of dust mitigation technology experiments utilizing textured surfaces, work function matching surfaces and brushing. They have also been used to reinterpret the results of the Apollo 14 Thermal Degradation Samples experiment.

Nomenclature

AgFEP	0.24 mm (0.010 in.) thick fluorinated ethylene propylene (FEP) with a silver reflecting surface on the back
AlFEP	0.13 mm (0.005 in.) thick FEP with an aluminum reflecting surface on the back
AxFEP	both AgFEP and AlFEP
AZ93	a white thermal control paint formulated by AZ Technologies similar to Z93
α	absorptivity over the solar spectrum (250 to 2500 nm)
α_{rel}	α/α of pristine surface
ε	emissivity over thermal range (100 to 400 K)
ε_{rel}	ε/ε of pristine surface

Introduction

One of the surprising findings of the Apollo program was the tenacity with which the lunar dust adhered to virtually every piece of equipment with which it came into contact. This was particularly problematic for thermal control surfaces (Ref. 1). This was perhaps best illustrated by the overheating of the radiators of the Lunar Roving Vehicle (LRV). Previous simulations using lunar soil returned from Apollo 12 and a vacuum chamber seemed to indicate that the dust could be removed from the LRV radiator using a nylon bristle brush (Ref. 2), which appeared to be confirmed by the Apollo 14 Thermal

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Degradation Samples experiment (TDS) (Ref. 3). This turned out not to be the case and, as a result, LRV batteries ran at above nominal operating temperatures for a substantial fraction of their mission (Ref. 4). Fortunately, there were no battery failures, but it illustrates how little is known about the adhesion of lunar soil to surfaces in the lunar environment.

Berkebile et al. recently reported on the results of a study to quantify the adhesion force between a lunar dust surrogate (synthetic volcanic glass) and typical thermal control materials under ultrahigh vacuum (UHV) conditions (Ref. 5). It is the object of this review to explore how these data relate to recent studies of the degradation of thermal control surfaces, the mitigation of dust adhered to thermal control surfaces, and the results of the Apollo 14 TDS experiment.

UHV Adhesion Experiments

The objective of the Berkebile experiment was to quantify the adhesion force between the synthetic volcanic glass and typical spacecraft surfaces under UHV, and try to clarify the most important factors affecting it. Although this review will focus on thermal control surfaces, particularly silver backed fluoroethylenepropylene (AgFEP) and AZ93 thermal control paint, several other common spacecraft materials were included in the study and shed light on the nature of the adhesion.

It is generally acknowledged that there are three forces which combine to make up the total adhesion force. These are the electrostatic force, capillary forces, and Van der Waals forces. It has been recently suggested that Lewis acid-base forces could also be important (Ref. 6). Capillary forces will be absent in the lunar vacuum, but the relative strength of the other forces is currently under debate. The nature of the adhesion force is important because this will guide the mitigation efforts.

The actual experiment necessarily makes several compromises. A torsion balance was used to measure the pull-off force (Ref. 7), so only macroscopic samples could be used. A plate of synthetic norite volcanic glass with a lunar-like composition (Zybek Advanced Products) was used in place of the lunar dust. And the lunar vacuum was simulated in an ultrahigh vacuum chamber which was pumped to a vacuum of 10^{-10} torr or better, but still two orders of magnitude higher than lunar vacuum. Activation by the solar wind was simulated by sputtering the surface with Ar^{+} ions. A photograph of the experimental set-up is shown in Figure 1.

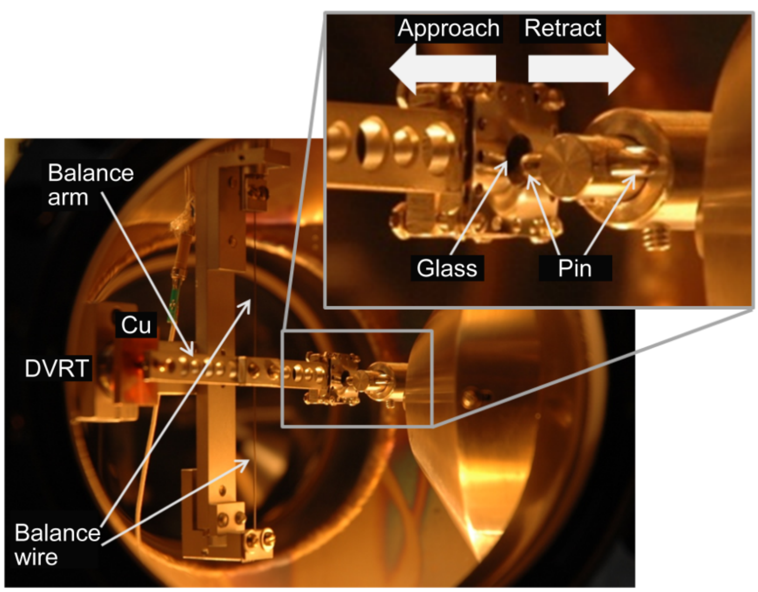

Figure 1.—View of the Adhesion Rig apparatus showing the torsion balance though a viewport in the UHV chamber, with a close up of the adhesion interface between the test material pin and the synthetic volcanic glass plate in the inset.

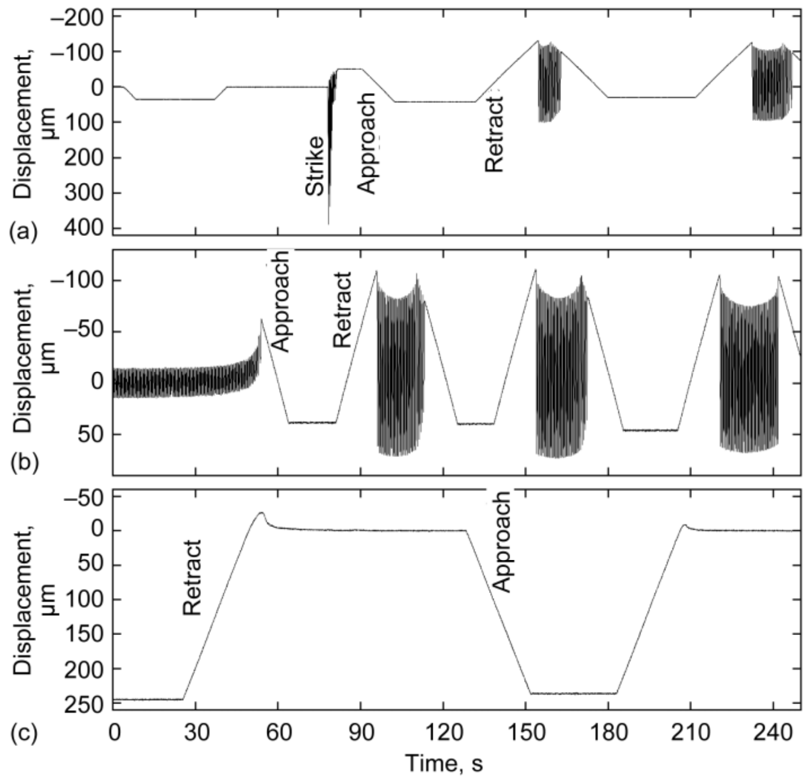

Figure 2.—Torsion balance displacement for three experimental runs: (a) a strike to impart a charge, (b) an electrostatic force dominated run as can be seen in the way displacement occurs before contact (left to right), (c) a Van der Waals force dominated run where there is no displacement before contact (right to left).

The experimental details have been described fully previously (Ref. 7), but the concept is straightforward. A polished 3 mm pin with hemispherical ends is driven towards the glass plate with a speed of 9.3 µm/s. It continues to be driven until the plate is pushed back which twists the torsion wire. This exerts a torque on the wire, $\tau = -\kappa\theta$, where θ is the displacement angle and κ is the torsional spring constant. After being displaced to a load of 0.1 to 0.5 mN, as measured by a differential variable reluctance transducer (DVRT) that measures the position of a balance arm on the opposite side of the plate, the drive motor is halted, and the pin and plate remain in contact for a specified, but variable, period of time, usually 15 to 30 sec. Then the pin is withdrawn from the plate at the same speed. After passing the torsion balance equilibrium point, the wire tends to pull the plate and pin apart. Separation occurs when the spring force equals the adhesion force. Examples of the data are shown in Figure 2. After the pin detaches from the plate, the torsion balance oscillates, as can be seen in the figure.

A variation on the procedure was used to apply an electrostatic force. The pin was placed 50 µm from the plate. It was then quickly brought into contact with the plate and retracted. Under many conditions this resulted in the deposition of charge on the pin, the plate, or both.

Two types of adhesion forces could be observed, electrostatic and Van der Waals. Discriminating between the two was simply a matter of watching the position of the balance during approach. Figure 2 shows the differences seen in the movement of the balance. When the pin approached the glass on the balance, the balance would be pulled from equilibrium over a distance of up to several µm in the case of electrostatic forces (Fig. 2(b)), whereas a movement of the balance was not observed during approach for Van der Waals attraction (Fig. 2(c)). Van der Waals attraction was likely not observed during approach due to its short range nature and the 500-nm limit of balance displacement measurement. Measurements of the adhesion force were made under different loads, typically in the range of 0.1 to 0.5 mN. The duration of the loads was 30 sec for the Van der Waals measurements whereas the loads were typically maintained 15 sec for cases of electrostatic adhesion. No dependence on the load duration or magnitude was seen for electrostatic adhesion. The adhesion force values given throughout this report are generally the average of three or more contacts with the standard deviation calculated and shown as error bars.

The surfaces of the materials were cleaned by bombardment with Ar ions accelerated to 2 keV from an ion gun (sputter cleaning). This process removed atmospheric contamination due to water and organic compounds from mineral surfaces and created a number of broken bonds, both of which leave the surface in a state similar to that which dust particles have in an airless body environment. Metals were sputtered until no improvement in the C and O surface contamination could be discerned using a built-in Auger electron spectrometer before each measurement. Plastic materials were sputtered for 30 sec to 5 min each day before measurements. No dependence on sputter duration was seen after the initial sputter cycle. The synthetic volcanic glass was cleaned through ion bombardment prior to all measurements, unless explicitly stated.

Van der Waals Forces

The adhesion force due to Van der Waals interactions was below the apparatus detection limits (–5 μN) for most of the glass and pin sample pairs. (Adhesion is an attractive force and so given a negative sign. Applied loads are positive in sign.) Forces as high as 10 mN were applied to press the pin and plate together, and were held as long as 10 min. The results were the same whether the volcanic glass was tested "dirty" or had been sputter cleaned, and whether the pin was dirty or cleaned. All four combinations were tested, and all four yielded no measurable adhesion.

There were two exceptions to this, the cases of the PTFE and 6061 aluminum pins. In the case of PTFE, the adhesion force ranged from –0.02 to –0.10 mN, and depended on the magnitude of the applied force in a roughly linear fashion for any particular contact position (Fig. 3). However, the adhesion varied widely between contact positions, even for similarly treated samples. Leaving the pin attached to the glass at a load of 1.9 mN for a period of 2 hr resulted in an increase in the adhesion force by a factor of 5 to 10 over 30-second-long loads. Sputter cleaning the glass increased the adhesion force by about a factor of 2 to 4. Cleaning both the glass and the PTFE pin increased the adhesion as much as an additional factor of 2.

The 6061 aluminum pins adhesion ranged from –0.01 to –0.08 mN and exhibited behavior that was difficult to interpret. Contrary to expectations, the adhesion force decreased at higher applied forces. Although there was a wide range of adhesion values, all values greater than –0.02 mN occurred when the applied load was less than 0.4 mN.

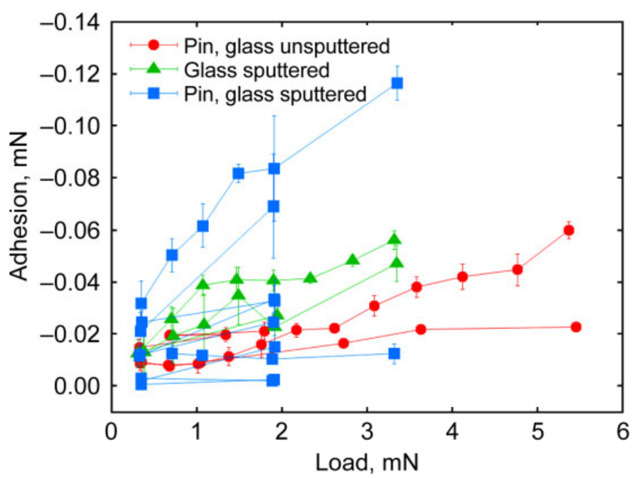

Figure 3.—Adhesion force due to Van der Waals interactions as a function of load for a PTFE pin on synthetic volcanic glass. Measurements of different loads at any particular contact position are connected by lines.

Electrostatic Forces

Electrostatic adhesion forces increased with the amount of charge transferred upon striking the pin to the plate. As is shown in Figure 4, this charge transfer was roughly linear over the range of the strike kinetic energy, 1 to 15 μJ. Comparisons of adhesion data are more clearly illustrated in Table 1, which shows the average adhesion per unit strike energy. This value was determined by dividing the adhesion measured in a particular experiment by the kinetic strike energy applied. Thus, materials with higher values converted more of the kinetic energy into charge separation, which resulted in greater electrostatic adhesion.

Table 1 lists the materials in order of their triboelectric affinity. A positive value tends to give up electrons and become positively charged, and a negative value tends to gain electrons and take on a negative charge. The synthetic volcanic glass probably has a triboelectric affinity near that of soda lime glass. Electrons are so mobile in metals that they do not retain charge, yet that can be attracted through image charge forces. Note that the adhesion forces, particularly for the cleaned materials, are well correlated to the triboelectric affinity.

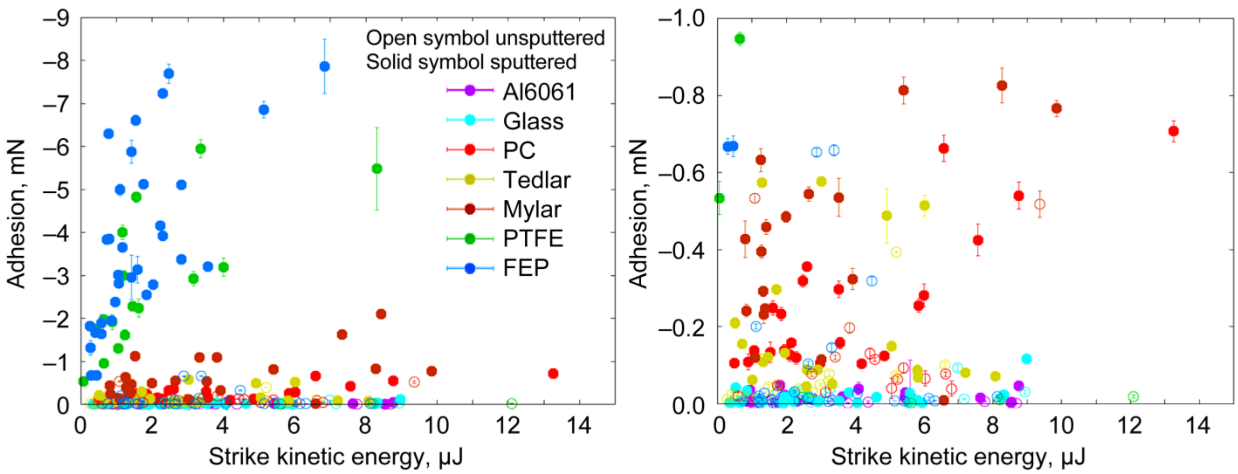

Figure 4.—Measured electrostatic adhesion force as a function of the kinetic energy of striking the pin against synthetic volcanic glass.

TABLE 1.—MEASURED AVERAGE ELECTROSTATIC ADHESION FORCE PER KINETIC ENERGY OF THE STRIKING OF THE PIN AGAINST SYNTHETIC VOLCANIC GLASS

Material	Triboelectric affinity (nC/J)[b]	Average adhesion force per strike energy (as is) (N/J)	Average adhesion force per strike energy (sputter cleaned) (N/J)
Ti-6-4	---	a	a
Al 6061	---	–1.76	–7.41
Glass (soda lime)	+25	–7.16	–10.1
AZ-93	---	a	a
Polycarbonate	–5	–16.5	–84.4
Tedlar (DuPont)	---	–30.9	–105
Mylar (DuPont)	–40	–116	–240
PTFE	–190	–0.946	–2410
FEP	–190	–37.6	–3020

[a]Indicates non-detectable adhesion below –0.005 mN, i.e., about –0.3 N/J.
[b]From Triboelectric Table (Bill Lee, Alpha Lab Inc., 2009).

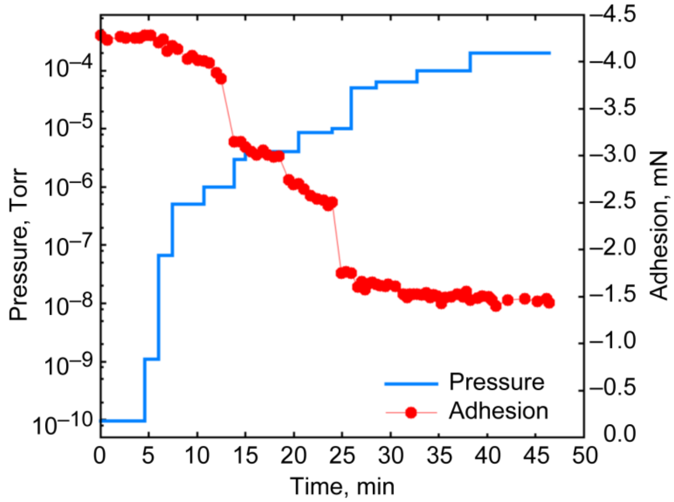

Figure 5.—FEP adhesion as a function of time during an increase of air pressure.

Surface cleanliness has been shown to be an important factor for the triboelectric charge transfer. After the initial Ar^+ ion sputter cleaning of the surfaces used in this study, the cleanliness will depend on the quality of the vacuum environment. Likewise, once the charge transfer has taken place, the persistence of the charge on the surface and, hence, the electrostatic adhesion depends on the quality of the vacuum environment. Strong electrostatic adhesion was observed here to persist for a period of at least several days with no significant degradation in a vacuum of 10^{-10} torr. Once the charged pin has been exposed to air at pressures around 10^{-6} torr, a drastic drop in the adhesion force occurs (Fig. 5). Considering that the surfaces of airless bodies are in a UHV environment under conditions which result in atomically clean materials, high fidelity tests of dust adhesion should be made with the best pressure possible, but at least $<10^{-6}$ torr, and should also include a cleaning step of any exposed surfaces.

Textured Thermal Control Surfaces

Although a wide variety of technologies have been suggested to mitigate the effects of dust, there are three principal approaches. The dust-sensitive surface can be made more dust tolerant, technology can be developed to decrease the chances of dust attaching to the surface, or technology can be developed to remove the dust from the surface. The technology development has generally followed one of two philosophies, active removal of the dust or prevention of its accumulation, and passive surfaces that keep the dust from adhering to the surfaces.

Passive dust mitigation surfaces have the distinct advantage of not requiring the input of energy. This is desirable both because spacecraft and surface systems are often energy limited, and because there is the possibility of electrical or mechanical failure in an active system. Passive dust mitigation technologies try to decrease the adhesion forces between the surface and the dust either by changing that surface’s chemistry or texture.

The simplest method to decrease the dust adhesion is by adding texture without changing the surface chemistry. By keeping the surface chemistry of the pristine surface, it is expected that the thermal optical properties of α and ε will be similar to that of the pristine surface as well. The texture that is desired is that of closely spaced cones, in essence a bed of microscopic nails. The thought is that each dust particle will be supported by only a few of these cones, drastically reducing its contact area. The cone size and spacing are critically important. If they are too widely spaced the dust particles can be trapped between the cones which may in fact lead to an increase in the contact area, and so an increase in adhesion. If the cones are too narrowly spaced, then the contact area will not differ much from the pristine surface, and there will be little advantage to the texture. Dust particles are generally described by the lunar dust community as those being smaller than 20 μm. Recent studies have shown that a significant number of lunar regolith particles are as small as 0.05 μm (Refs. 8 and 9). So dust particles on the Moon range in size over a factor of 400. It would be difficult to design a textured surface that would work for all. But the JSC-1AF test dust had few sub-micron particles and so the size ranged over only about a factor of 20.

A preliminary proof-of-concept study was undertaken to determine whether the strategy of texturing the thermal control surfaces is a promising technology to pursue. The details of this work have been previously published, so only the results will be summarized here (Ref. 10). Three thermal control surfaces, a white paint (AZ-93) and two second surface mirrors (AgFEP and AlFEP) were textured at two to four levels using an oxygen ion beam to etch away part of the surfaces leaving a cone structure. The size and spacing of the cones depended upon the time exposed to the ion beam. Since this is a passive technique and the dust was gently sifted onto the samples from above, relative dust adhesion was determined by exposing each dusted sample to a standard puff of nitrogen gas. The intent was not to demonstrate that the standard puff would totally clean the surfaces, but to compare the extent of dust removal to an untreated surface.

The test equipment and procedures have been described in previous reports, and so will not be detailed here (Refs. 11 and 12). In summary, the pristine samples were heated *in vacuo* with a solar simulator and then cooled in a 30 K cold box. The α was determined from the heating curve, and the ε from the cooling curve using Thermal Desktop (Cullimore and Ring Technologies, Inc.) modeling software. Next, samples were sprinkled with activated lunar simulant *in vacuo*. Once again the samples were heated with a solar simulator and then cooled in a 30 K cold box.

Since the samples were not uniformly covered with dust at the start of the tests, the total dust remaining after the test is not indicative of coating performance. Probably the best measure of effectiveness of a cleaning technique compares α/ε of the surface after it has been blown off $(\alpha/\varepsilon)_b$ to the α/ε of the dusted surface $(\alpha/\varepsilon)_d$ in terms of the pristine surface $(\alpha/\varepsilon)_p$. Equation (1) defines a new term, the dust removal efficiency, ξ, as:

$$\xi \equiv \frac{(\alpha/\varepsilon)_d - (\alpha/\varepsilon)_b}{(\alpha/\varepsilon)_d - (\alpha/\varepsilon)_p} \tag{1}$$

Inspection of this term reveals that if no dust is removed, that is $(\alpha/\varepsilon)_b = (\alpha/\varepsilon)_d$ then $\xi = 0$. If all of the dust has been removed, $(\alpha/\varepsilon)_b = (\alpha/\varepsilon)_p$ then $\xi = 1$.

Field emission scanning electron microscopy enables the imaging of the surfaces at high magnification. It is apparent from the photomicrographs that the pristine AxFEP surfaces were much smoother than those of the AZ93. After 16 hr of exposure the AgFEP developed surface features around 1 μm in size, whereas the AZ93 surface initially had structures near that size. It is difficult to tell from these photographs whether in fact there was any change in the surface roughness of AZ-93 due to the ion beam treatment (Ref. 10).

The optical spectra of the samples from 250 to 2500 nm before and after texturing were virtually identical. Even the spectra of the AgFEP and AlFEP that were textured for 8 or 16 hr, which changed them from specular to diffuse reflectors, were indistinguishable from their pristine counterparts. This indicates that there were no major changes to the samples that would affect their α. This was further borne out by the thermal measurements which indicated that the texturing had no significant effect on the α/ε, as seen in Table 2.

TABLE 2.—THE α/ε OF THE THERMAL CONTROL SURFACES BEFORE AND AFTER TEXTURING

α/ε	AZ93	AlFEP	AgFEP
Pristine	0.166±0.007	0.22±0.08	[a]0.09
Textured	0.165±0.008	0.19±0.02	0.096±0.002

[a]Literature value—no pristine AgFEP samples were used.

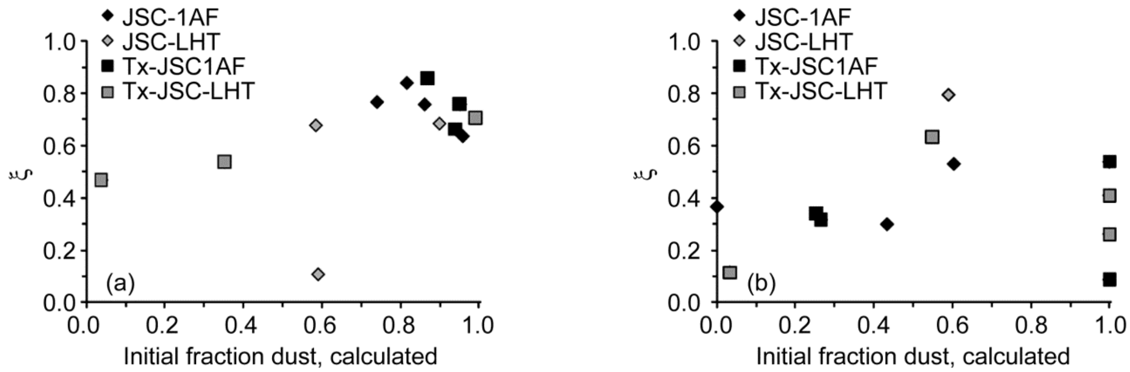

Figure 6.—Dust removal efficiency, ξ, calculated for pristine and textured (Tx) samples of (a) AZ93 and (b) AxFEP.

The dust removal effectiveness as a function of calculated initial dust coverage for pristine and textured samples is shown in Figure 6. Since ξ increases with dust coverage, it appears from these plots that it is easier to remove dust from a heavily covered surface than a lightly covered one. This is probably an indication that the adhesive forces of the dust to the surface is greater than the cohesive forces among dust particles, since heavily covered surfaces have dust piles several layers deep. It also appears the the JSC-1AF may be easier to remove than the JSC-LHT mixture, which implies that the JSC-1AF is easier to remove than the NU-LHT-1D. This may be due to particle shape and size distributions. The NU-LHT-1D is somewhat smaller, and appears to have somewhat sharper particles.

Oxygen ion beam texturing appears to have no substantial affect on the ξ of AZ93. In retrospect, this is not particularly surprising given that the paint initially has texture on the same order as that generated by the ion beam. The ion beam texturing also did not appear to reduce the adhesion of either the JSC-1AF or the JSC-LHT to AxFEP. It is noted that four of the textured samples had particularly heavy dust layers applied to them as the calculated initial dust fraction was greater than 1.0. Perhaps much of the dust was removed but after the blow off a considerable amount of dust still remained, so the ξ value was still low. But even if those data are ignored, the textured samples had no higher ξ than the pristine samples. Oxygen beam texturing was not an effective strategy to lower the adhesion for either thermal control surface.

Since surface texturing is meant to reduce the contact area between the dust particle and the surface, it acts primarily to reduce Van der Waals forces (since there are no capillary forces at work). The adhesion study results indicate that these forces are negligible. So even if texturing is successful at substantially reducing the Van der Waals forces, it would have little effect on particle adhesion, which is dominated by electrostatic forces.

Work Function Matching Coatings

Of the adhesion forces present at the lunar surface, only electrostatic forces have the capability of attracting dust particles to spacecraft surfaces from a distance. Electrostatic forces have been shown to be important in cohesion and adhesion of lunar dust particles (Ref. 13). Although there are multiple charging mechanisms at work in the lunar environment (Ref. 14), triboelectric-charging will probably be the most important anthropogenic charging mechanism. During triboelectric-charging electrons are transferred from a material that easily loses electrons (i.e., has a low work function) to a material that holds tightly onto its electron (i.e., has a high work function). So triboelectric-charging is minimized if the work function of the two surfaces is similar. The approach to a dust resistant coating evaluated here is to apply a coating to the thermal control surface that has a work function that matches the dust as closely as possible.

Although there have been studies that estimate the work function of the lunar dust stimulants (Ref. 15) perhaps the best match would be a coating made from the dust itself. So a sputter target was made from a slurry of the lunar stimulant NU-LHT-1D. This was used to coat AZ-93, AgFEP, and AlFEP samples with a coating a few tens of nm thick using a dual ion beam sputter deposition system (Ref. 16).

TABLE 3.—THE α/ε OF THE THERMAL CONTROL SURFACES BEFORE AND AFTER APPLYING THE WORK FUNCTION MATCHING COATING

α/ε	AZ93	AlFEP	AgFEP
Pristine	0.199±0.004	0.20±0.01	[a]0.08
Coated	0.193±0.005	0.22±0.06	[b]0.10

[a]One sample
[b]Two samples

A proof-of-concept study was undertaken to determine whether the strategy of matching the work function of thermal control surfaces to the dust is a promising technology to pursue. Three thermal control surfaces, a white paint (AZ-93) and two second surface mirrors (AgFEP and AlFEP) were coated at two levels with the work function matching coating. The same standard puff of nitrogen test that was used with the textured surfaces was also used to determine the effectiveness of these surfaces.

Workfunction matching coatings with a thickness of about 100 nm were sputter deposited onto AZ93 and AxFEP thermal control surfaces. The sputter targets were made of aluminum that had been roughened to allow a slurry of NASA/USGS Lunar Highlands Type (NU-LHT-1D) lunar simulant to be painted on. The slurry-coated targets were oven baked to make an adherent coating on the aluminum substrates for sputter deposition. The coatings were deposited by ion beam sputter deposition using an argon ion beam source to sputter the lunar simulant targets. The resulting coating had a composition similar to the lunar dust simulant, and thus also would have a similar workfunction.

Although only one type of lunar simulant was used to generate the coating, three types of simulant were used to test the adhesion to the three types of surface treatments. JSC-1AF lunar simulant was used with all three surface treatments. In addition, a 1:1 mixture of JSC-1AF and NU-LHT-1D was used on some of the textured samples, and chromite, an especially dark mineral that has been identified as being on the Moon, was used on some of the workfunction matching coatings.

The optical spectra of the samples before and after applying the work function matching coating were virtually identical. There was no visual evidence of the coating, and Table 3 shows there was no substantial difference in the integrated α/ε of the AZ93, but there may have been as much as a 10 percent increase in the AxFEP samples. As would be expected from the similar spectra, the α, ε, and α/ε of the thermal control coatings did not change appreciably upon the addition of the work function matching coating at either thickness.

These samples were also dusted with a variety of fractional dust coverages in an attempt to determine whether the effectiveness of the texturing was dependant on the amount of dust initially on the surface. As before the fractional dust coverage before the blow-off tests was calculated from the α/ε determined from previous experiments. The relationship between the dust coverage and the α/ε depends upon the lunar simulant and the thermal control surface used. Further, considerable variation from the least square line is observed. The dust removal effectiveness as a function of calculated initial dust coverage is shown in Figure 7. The ξ for the workfunction matching coating (WFM) on AZ93 appeared to be unchanged from the uncoated surfaces (Fig. 7(a)) over a wide span of dust coverage. It is noted that the JSC-1AF appears to be easier to remove from the AZ93 surfaces than the chromite. Figure 7(b) shows that workfunction matching coatings did have a large effect on the ability to clean the dust off using a nitrogen puff. Under these test conditions less than 10 percent of the dust was removed from the uncoated surfaces, but 20 to 40 percent of chromite was removed from the coated surfaces, and 50 to 80 percent of the JSC-1AF. These results suggest that the workfunction matching coatings, combined with a puff of gas, could be an effective way to remove dust from metal-backed FEP thermal control surfaces on the lunar surface.

The adhesion study asserts that electrostatic forces are most important in the adhesion of dust to spacecraft surfaces. Work function matching coatings attack the problem of lowering adhesion directly by minimizing triboelectric charge transfer. It is therefore not surprising that the coating was more effective at lowering the adhesion of JSC-1AF than chromite to thermal control surfaces. The work function of the

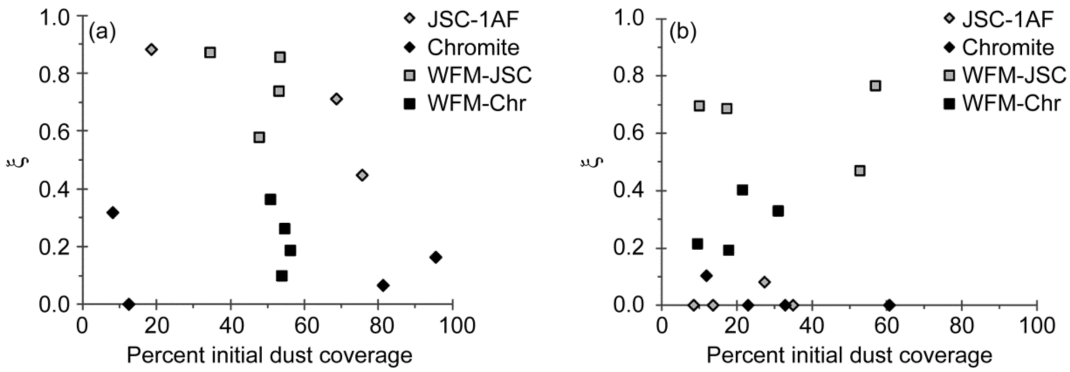

Figure 7.—Dust removal efficiency, ξ, calculated for pristine and workfunction matching coated (WFM) samples of (a) AZ93 and (b) AxFEP.

coating was matched to the aluminosilicate minerals that dominate the JSC-1AF composition, and chromite is a metal oxide. Figure 7 suggests that the differences in electrostatic adhesion to the tuned and untuned surfaces might even be utilized for beneficiation of regolith, separating out valuable oxides such as the oxygen ore ilmenite ($FeTiO_3$) from the plagioclase-rich regolith.

Brushing Experiments

Concern was raised during the Apollo program about the effect that lunar dust would have on thermal control surfaces, particularly with regard to the radiators on the LRVs which were used on the last three missions. A study was published that evaluated the effectiveness of different types of brushes in removing lunar soil and dust. Using soil returned from Apollo 12, they concluded that a nylon bristle brush would be effective to remove dust from the LRV radiator, and return it to nominal function. But when the brushing was used on the LRV radiators on the lunar surface during Apollo 15, 16, and 17, it was found to be almost wholly ineffective (Ref. 4). Exactly why there was a discrepancy between the brushing effectiveness during the ground tests and the lunar surface was never explained. It is presumed that the lunar environment simulation conditions during the tests were not of sufficient fidelity.

One of the priority projects of the NASA's Exploration Technology Development Program has been to develop dust mitigation technologies to remove dust from thermal control surfaces. A logical starting place is with the technology used on Apollo, the nylon bristle brush, but using the highest fidelity lunar simulation chamber available, the Lunar Dust Adhesion Belljar (LDAB). The goal of this study was to quantify the effectiveness of the nylon bristle brush to remove dust from thermal control surfaces in the LDAB as a baseline. Five different nylon bristle brushes were tested that varied in bristle diameter, bristle length, brush configuration, and bristle packing density. In addition, four other bristle materials, PTFE Teflon (DuPont), Thunderon (Nihon Sanmo Dyeing Company Ltd.), fiberglass, and carbon fiber were tested for comparison. These also varied in bristle diameter, bristle length, brush configuration, and bristle packing density. Preliminary brushing effectiveness tests were run under bench-top conditions, and the most promising candidates were tested in the LDAB. Details of this study have been published previously (Ref. 17), so only the results will be recalled here.

A four stage investigation into the effectiveness of brushing of thermal control surfaces was undertaken. In Stage 1, strip brushes of three bristle types were used to remove NU-LHT-1D lunar simulant from AZ93 and AgFEP thermal control surfaces under ambient laboratory conditions. The nylon bristle removed more than 90 percent of the dust and PTFE bristle removed nearly 80 percent of the dust from AZ93, as determined by particle counting. The Thunderon bristle brush was ineffective. On the AlFEP surface, the Thunderon bristle brush removed more than 90 percent of the dust, and the nylon bristle removed two-thirds of the dust, and the PTFE bristle brush was ineffective. In Stage 2, none of the brushes proved to be effective under simulated lunar conditions. A nylon bristle brush was not very effective in restoring the α of thermal control surface on the Apollo LRV, so perhaps it is a validation of the fidelity of our lunar simulation facility and protocol that the brushing was not effective, as opposed to the study of Jacobs (Ref. 2) that indicated otherwise.

In Stage 3 of the investigation seven additional brushes made up of three materials, two brush designs, and seven bristle lengths were tested for their effectiveness to remove dust from thermal control surfaces under ambient laboratory conditions. The carbon bristle brush was found to be ineffective, but fiberglass and nylon brushes were found to be equally effective. Both the fan brush and round brush designs proved to be more effective than the strip brushes tested in the first stage. Longer bristles were found to be more effective at removing dust than shorter bristles, though the effect seems less important than brush material. Two brushes, the nylon Escoda fan brush and the round fiberglass Zephyr brush removed more than 90 percent of the dust from AlFEP surfaces under ambient conditions, with as few as 40 strokes. Both brushes were also able to remove more than 99.5 percent of the dust from AZ-93 thermal control paint with as few as 120 strokes.

In Stage 4 the Zephyr and Escoda brushes were tested for their effectiveness at removing lunar simulant dust from thermal control surface materials under simulated lunar conditions. Both proved effective, restoring more than 80 percent of the pristine α/ε for both thermal control surfaces after 20 strokes, and more than 90 percent after 200 strokes (Figs. 8 and 9). The Escoda brush performed slightly better than the Zephyr on AgFEP, though perhaps within the error of the experiment. Although the brushes removed more dust from the AZ93 surfaces than from the AgFEP surfaces, the dusted-then-brushed AgFEP surfaces still out performed the dusted-then-brushed AZ93 surfaces, when judged by α/ε. Both brushes were judged effective at removing dust and restoring optical properties.

The effect of environment on the brushing effectiveness is summarized in Table 4, where

$$\Xi = \frac{(\%\text{dustcoverage})_{\text{before}} - (\%\text{dustcoverage})_{\text{average}}}{(\%\text{dustcoverage})_{\text{before}}} \tag{2}$$

It is noted that the brushing was consistently more effective in the bench top environment than in the simulated lunar environment of the LDAB. This can be explained by noting that in Figure 5 that the adhesion between the dust and the surface drops as the pressure increases from 10^{-10} to 10^{-4} torr. The LDAB tests were run in the 10^{-8} to 10^{-7} torr range, and the bench top at atmospheric pressure. In addition, the LDAB samples were cleaned in two RF plasmas (air and H-He) and so the surfaces had a much lower level of surface contamination of water and organic contaminants than did the bench top tests. Figures 8 and 9 show that this also has a large impact on the adhesion. So the adhesion tests identify specifically why testing brushing effectiveness under standard laboratory conditions only gives a lower bound. That is, brushing effectiveness under these conditions is necessary, but not sufficient to demonstrate effectiveness under lunar conditions.

TABLE 4.—COMPARISON OF BRUSHING EFFECTIVENESS (Ξ FOR BENCH TOP AND ξ FOR LDAB) ON BENCH-TOP AND IN A SIMULATED LUNAR ENVIRONMENT IN THE LDAB

Brush	AZ93 bench	AZ93 LDAB	AgFEP bench	AgFEP LDAB
Nylon strip	0.9	0.5	0.7	0.5
PTFE strip	0.8	0.25	---	---
Thunderon strip	---	---	0.9	0.4
Fiberglass round	---	0.9	0.9	0.9
Nylon fan	---	0.9	0.9	0.9

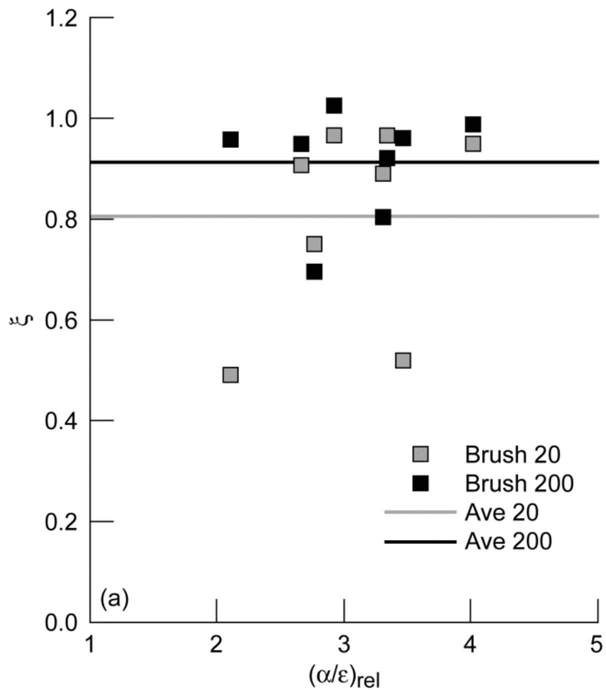

Figure 8.—The values of dust removal efficiency, ξ, as a function of relative α/ε for the (a) Zephyr and (b) Escoda brushes for JSC-1AF simulant on AZ93.

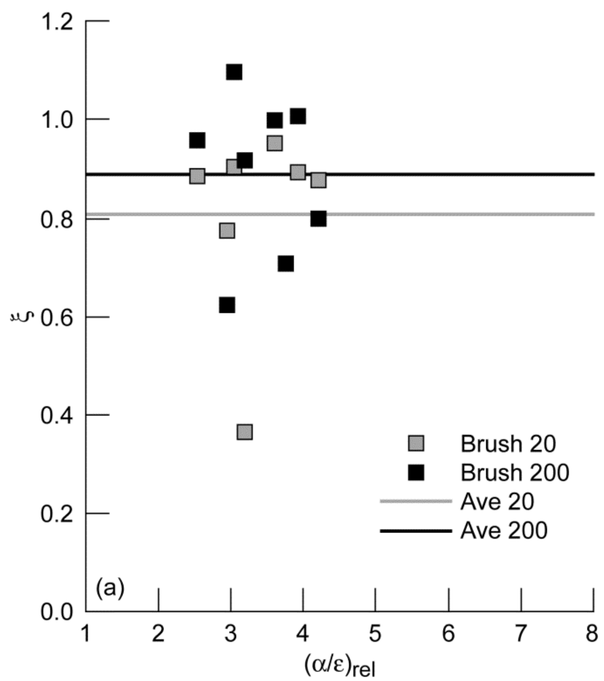

Figure 9.—The values of dust removal efficiency, ξ, as a function of relative α/ε for the (a) Zephyr and (b) Escoda brushes for JSC-1AF simulant on AgFEP.

Apollo 14 TDS Experiments

On February 5, 1971 the Apollo 14 Lunar Module, *Antares*, landed on the Fra Mauro formation of the Moon, and astronauts Alan Shepard and Edgar Mitchell became the third pair of humans to walk the lunar surface. They would remain on the Moon for 33 hr before returning to their colleague Stuart Roosa in the Command Module *Kitty Hawk* and returning to Earth. During their brief stay they ventured onto the surface for two extravehicular activities (EVAs) for a total of 9 hr and 22 min. During the second EVA, at the first geological site visited, 8 min of the Commander, Alan Shepard’s, time was scheduled for an activity designated the Thermal Degradation Sample (TDS) experiment (Ref. 18).

The TDS experiment was a simple test “To evaluate the effect of lunar dust on the optical properties (absorptivity and emissivity) of 12 candidate thermal coatings. Two duplicate arrays each containing 12 coatings were taken to the Moon. After covering them with dust, one was tapped to remove the dust and the other was cleaned with a nylon bristle brush (Ref. 19).” Photographs of the samples were taken with the Apollo Lunar Closeup stereographic Camera (ALCC) in their pristine state, after they were dusted and tapped, and after the one was brushed (Ref. 20). Three of the photographs, shown in Figure 10, demonstrate the results. The TDS samples were then returned to the Earth so that their solar absorptance and thermal emittance could be measured. The experiment was “expected to yield material data to aid in the selection of radiator surfaces on the Lunar Roving Vehicle (LRV) and other advanced lunar operational equipment (Ref. 19).” The twelve samples were candidate thermal control materials in 1971, and are listed in Table 5 (Ref. 4).

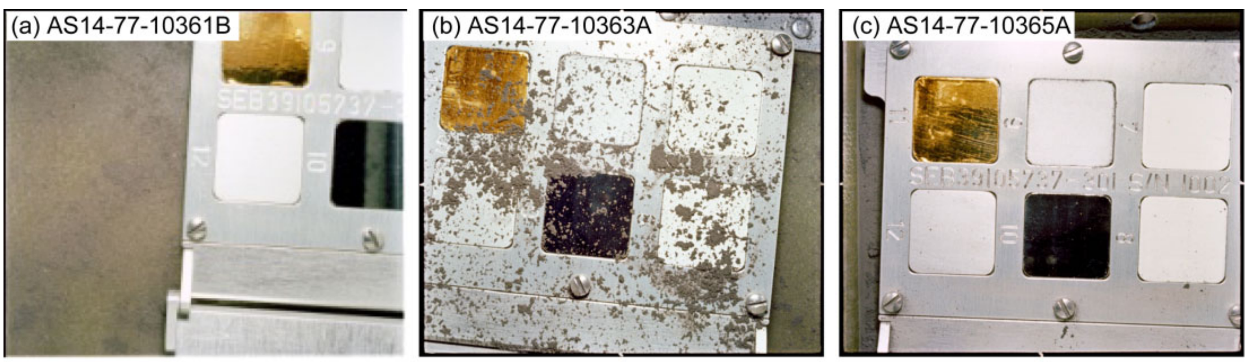

Figure 10.—Photographs showing the condition of the 1002 TDS plate before dust exposure (a), after scooping dust onto it and shaking it off (b), after brushing with the MESA brush (c).

TABLE 5.—CANDIDATE THERMAL CONTROL MATERIALS TESTED IN THE TDS EXPERIMENT (AFTER GOLD, 1971)

Sample	Thermal control material
1	S-13G (white paint)
2	Z-93 (ZnO/potassium silicate white paint)
3	Goddard MS-74 (white paint)
4	Ag-FEP (Inconel back film, FEP side exposed)
5	Ag-Quartz (quartz side exposed)
6	Dow Corning 92-007 (TiO_2/silicone white paint)
7	Cat-a-lac White (TiO_2/epoxy)
8	3M White Velvet (400 series TiO_2/epoxy polyester)
9	Dacron on Al-Mylar fabric laminate
10	Oxidized SiO-Al-Kapton with SiO side exposed
11	Al-Kapton with Kapton side exposed
12	Anodized 6061 Al MIL-A-8625, type II, class I

After completing the experiment there was a well choreographed plan to load the TDS into the EVA-2 Equipment Transfer Bag which was loaded onto the LM Ascent Stage at the end of the EVA. Here it was stowed in the interim stowage assembly over the ascent stage engine cover. It was then transferred to the Command Module in the ISA Decontamination Bag and stowed on top of CM Vol (A1). Presumably this occurred as planned because there is no mention otherwise in the mission records and Jacobs, Durkee, and Harris report that at the time of writing their manuscript it was in quarantine (Ref. 2).

But there is no further mention of the TDS in the record. Jacobs, Durkee, and Harris never published a follow-on paper describing the results of the TDS. No NASA reports of the results have been found. A search through the archives at the NASA Johnson Space Center finds no reports, no data, no TDS hardware. The Smithsonian Institution likewise has no record of it being transferred to them. The principals and their managers are either deceased or have no memory of the TDS or any post-flight tests. Except for the photos, the Apollo 14 TDS is lost to history.

But the Apollo 14 TDS experiment yielded results that appear to conflict with the rest of the Apollo experience with lunar dust. First, the adhesion of the lunar dust to the experiment seemed anomalously low. Although the exact motion used to remove the dust might be either shaking or tapping, the result was cohesive clumps of dust that did not appear to stick well to the samples or sample holder. The appearance of a lot of dust in Figure 10(b) must be tempered by Shepard's remark in the technical debriefing that he was "surprised that there was little adherence of the surface dust. I expected a little bit more. It didn't adhere very much (Ref. 21)." Second, it appears that the nylon bristle brush removed most of the dust from the surfaces, though it scratched the soft polymer surfaces. But again this must be tempered with the poor performance of the LRV radiators in Apollo 15, 16, and 17 and the failure of the nylon bristle brush to clean them (Ref. 4). And last, what is to be made of the very strong soil cohesion compared to the adhesion to the thermal control materials?

The events surrounding the TDS experiment have been reconstructed through the nominal mission plan, corrected by the recorded transcripts and a detailed analysis has been described elsewhere (Ref. 22). The key feature is that the TDS samples were protected from the lunar solar wind environment during the entire mission except when the experiment was actually being carried out, less than 1 min for each sample.

Recall that adhesion was enhanced by one or two orders of magnitude when the surfaces were cleaned by sputtering with argon ions for 5 min or more. Under the conditions in the vacuum chamber this corresponds to a fluence of about 4×10^{15} Ar^+/cm. FEP showed enhanced adhesion when sputtered only 15 s, corresponding to a fluence of 8×10^{14} Ar^+/cm.

The regolith on the lunar surface has also been cleaned for literally millions of years by the action of the solar wind. But the same could not be said of the TDS sample plates. They were exposed for a long period of time to the Earth's atmosphere, and then the spacecraft atmosphere. As is well known in the surface science community, all materials so exposed are covered by a film of adsorbed water, and organic compounds. Because the equipment transfer bag in which the TDS were stored was not sealed, the TDS was exposed to vacuum for about 45 min before the experiment was started (Ref. 23). Because of the physical constraints of its container, the pressure the TDS experienced was probably considerably higher than the nominal 10^{-12} torr lunar atmospheric pressure. The temperature as measured on the Lunar Portable Magnetometer was reported by Mitchell to be 125 °F (52 °C) at the start of the EVA (Ref. 22). If this is indicative of the temperature of the TDS, it might have helped to remove volatile gases and perhaps even much of the water vapor from the surface, but would not have removed the organic contamination. This could only be removed by sputtering from the solar wind.

Although details of the solar wind at the time and place of the Apollo 14 TDS experiment are not available, typical solar wind proton flux ranges 10^9 to 10^{12} particles/cm^2-sec with energy ranging from 0.2 to 3 keV (Ref. 24). This means that the fluence of protons striking the 1002 sample probably ranged from 10^{10} to 10^{13} protons/cm^2-sec. The proton energy would have been similar to that of the Ar^+ used to sputter clean Berkebile's samples (2 keV). It depends on the material being sputtered, but Ar^+ sputters roughly 1000 times more efficiently than protons (Ref. 25). Proton sputtering is so inefficient that sputtering by He^{2+} actually is more important, even though He^{2+} only comprises about 4 percent of the solar wind (Ref. 26), it sputters about 35 times more efficiently than protons and so accounts for about

60 percent of the sputtering. So the total fluence of the solar wind ranged from 10^{11} to 10^{14} ions/cm^2. But in terms of sputtering efficiency, it is the equivalent of 10^9 to 10^{12} Ar^+ sputtering. So, assuming the shortest cleaning time in the Berkebile experiment, in order to clean the TDS samples they would have had to have been exposed to the solar wind for at least 11 min, and perhaps as long as several days.

The tenacity with which the dust stuck to other Apollo surfaces leads to the conclusion that this cleaning occurs in minutes or hours rather than days. But it seems unlikely that the nominal 49 s exposure was long enough. Although the record of how long the 1001 sample was exposed to the solar wind is less certain, since the entire second experiment was completed in 2.5 min, the fluence range for this sample was probably similar, and not sufficient to clean the samples. Thus, the conditions under which the TDS experiments were conducted were not comparable to the conditions under which general problems with the dust were noted. Except for the first minute of exposure of space suits, experiments, and the Lunar Roving Vehicle to the external lunar environment, all of these components were better cleaned by the solar wind. It is therefore not surprising that the dust adhesion to the TDS was low by comparison.

O'Brien has suggested that the adhesion of the dust to the TDS was also affected by the fact that the experiment was hand held, and so happened entirely with the aura of gas that diffused into the environment from Alan Shepard's space suit (Ref. 27). The aura is not well characterized, but Cold Cathode Gage (CCG) measurements on Apollo 12 saturated when an astronaut passed within several meters of it (Ref. 28). O'Brien suggests that the pressure might have been as high as 10^{-8} torr or more. Although this is plausible, the adhesion measurements of Berkebile suggest that there is not a large drop in the adhesion forces due to adsorbed gases on the surfaces until the pressure exceeds about 10^{-6} torr. However, if the space suit aura contained organic contaminants, and it likely did, the aura could have replenished the contamination layer that the solar wind was sputtering off.

Conclusions

The results of the adhesion measurements between synthetic volcanic glass and common spacecraft materials in UHV provide a framework in which the results of dust mitigation studies can be understood. Electrostatic forces were found to dominate over Van der Waals forces. Thus, dust mitigation strategies which attack neutral adhesion such as textures surfaces and lotus coatings are doomed to failure. Even if they can completely eliminate the effects of Van der Waals forces, the decrease in the adhesion will be minimal, perhaps not even measurable. Effective dust mitigation must attack electrostatic forces. This can be done either passively by limiting triboelectric charging, as with work function matching coatings, or actively by manipulating the charging of the dust and spacecraft surface.

The role of molecular level surface contamination as an important factor for dust adhesion in UHV has been underappreciated. Linked to this is the realization that spacecraft surfaces are scoured by the solar wind with a fluence that atomically cleans surfaces within minutes to hours. Space suit off-gassing can re-contaminate surfaces near it and may also influence dust adhesion. Contamination from terrestrial atmospheric gases lowers the adhesion markedly, so tests done without removing the contamination layer (by sputtering, etc.) and keeping it from reforming (by maintaining pressures lower than 10^{-6} torr during the test) will have little relevance to adhesion during space operations. It is proposed that the protection of the Apollo 14 TDS experiment from the solar wind lead to the anomalously low dust adhesion that was reported by Alan Shepard.

Armed with this knowledge, dust mitigation technology development can move forward with rational constraints. The mitigation technology must acknowledge that electrostatic interactions dominate adhesion, and attack the problem from that basis. Further, validation of any dust mitigation technology that is intended to work in an airless environment must proceed only in high vacuum or ultrahigh vacuum environmental chambers with atomically clean surfaces.

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01-03-2012	Technical Memorandum	

4. TITLE AND SUBTITLE Implications of Adhesion Studies for Dust Mitigation on Thermal Control Surfaces	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Gaier, James, R.; Berkebile, Stephen, P.	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER WBS 780896.04.06.02.03
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191	**8. PERFORMING ORGANIZATION REPORT NUMBER** E-18114
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001	**10. SPONSORING/MONITOR'S ACRONYM(S)** NASA
	11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2012-217213

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 91
Available electronically at http://www.sti.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES
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14. ABSTRACT
Experiments measuring the adhesion forces under ultrahigh vacuum conditions (10^{-10} torr) between a synthetic volcanic glass and commonly used space exploration materials have recently been described. The glass has a chemistry and surface structure typical of the lunar regolith. It was found that Van der Waals forces between the glass and common spacecraft materials was negligible. Charge transfer between the materials was induced by mechanically striking the spacecraft material pin against the glass plate. No measurable adhesion occurred when striking the highly conducting materials, however, on striking insulating dielectric materials the adhesion increased dramatically. This indicates that electrostatic forces dominate over Van der Waals forces under these conditions. The presence of small amounts of surface contaminants was found to lower adhesive forces by at least two orders of magnitude, and perhaps more. Both particle and space exploration material surfaces will be cleaned by the interaction with the solar wind and other energetic processes and stay clean because of the extremely high vacuum (10^{-12} torr) so the atomically clean adhesion values are probably the relevant ones for the lunar surface environment. These results are used to interpret the results of dust mitigation technology experiments utilizing textured surfaces, work function matching surfaces and brushing. They have also been used to reinterpret the results of the Apollo 14 Thermal Degradation Samples experiment.

15. SUBJECT TERMS
Lunar soil; Lunar dust; Thermal control

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** STI Help Desk (email:help@sti.nasa.gov)
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	23	**19b. TELEPHONE NUMBER** *(include area code)* 443-757-5802