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LUNAR DUST DEPOSITION EFFECTS ON THE SOLAR ABSORPTANCE OF THERMAL CONTROL MATERIALS

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Abstract

An experimental program was conducted to study the contamination effects of actual lunar dust when deposited on selected thermal control materials in a vacuum environment, with in situ measurement of their optical properties (spectral solar reflectance) after the materials were tapped and the dust brushed off. The test data, presented as final values of total solar absorptance as a function of soil condition (stored in vacuum or nitrogen) and test material condition (brushed with nylon- or brass-bristle brush or tapped), show a wide variation in the optical degradation effects of lunar dust and in the ease of removing the dust from the various materials.

Introduction

Accurate definition of certain lunar soil characteristics was required for the development of lunar surface equipment. Successful development and operation of such equipment will provide increased ability to obtain engineering and scientific data from future Apollo lunar missions. The lunar roving vehicle (LRV) and other equipment are currently being developed to increase capabilities on the lunar surface. Equipment development requires timely definition of the lunar soil adhesion characteristics, because lunar dust contamination could adversely affect the optical properties of thermal control surfaces or other components such as camera lenses. Experiments with lunar dust were required to define the optical degradation that external surfaces will experience and to determine if brushing would be an effective cleaning method.

After a review of data from several sources on the effects of lunar soil (or dust), real and simulated, on thermal control materials, tests were performed at the NASA Manned Spacecraft Center (MSC) to evaluate these effects under ground conditions more closely simulating the actual lunar conditions. This paper describes the tests, which consisted of (1) depositing actual lunar dust on selected thermal control materials in a vacuum environment and (2) obtaining in situ measurement of the optical properties (spectral solar reflectance) of the materials after the materials were tapped and brushed to remove the dust. Also, the data from these tests are compared with the results of additional tests involving actual lunar dust under ambient atmospheric conditions and simulated lunar dust under vacuum and atmospheric conditions.

Test Description

Test Objectives

The following were the three major test objectives:

1. To evaluate the effects of lunar dust on thermal control material in a vacuum environment
2. To evaluate the performance of two types of brushes used in removing the dust
3. To compare the effect on thermal control materials of lunar dust maintained under vacuum conditions with the effect on thermal control materials of lunar dust stored in a nitrogen environment at atmospheric pressure

The following were two minor test objectives:

1. To evaluate the performance of the vacuum-qualified portable reflectometer provided for the tests under vacuum conditions
2. To evaluate the performance of the vacuum system and operators used in performing the dust-deposition tests

Thermal Control Materials

Ten different thermal control materials (surfaces), — three white paints, two second-surface mirrors (SSM), four other surface materials used on current spacecraft, and a space-suit exterior material — were included in the test program. The surfaces that were exposed to the lunar dust and the sequence followed during the tests are listed in Table 1. Samples of these surfaces were attached to 2- by 3-inch aluminum plates by using double-backed tape.

TABLE 1. MATERIALS AND TEST SEQUENCE

Sample set	Coating sample	Coating
A — Actual lunar dust maintained under vacuum conditions; nylon brush	1	S-13g (zinc oxide/RTV602 silicone)
	2	Z-93 (zinc oxide/potassium silicate)
	3	DC 92-007 (titanium dioxide/silicone)
	4	Microsheet SSM
	5	Teflon SSM
	6	Anodized aluminum (sulphuric acid)
	7	1-mil aluminized Kapton (Kapton side exposed)
	8	Schjeldahl tape (aluminized Kapton with silicone monoxide outer coating)
	9	External suit material (Beta cloth)
	10	Modularized equipment storage area (MESA) blanket white cloth (Dacron bonded to aluminized Mylar)
B — Actual lunar dust maintained under vacuum conditions; brass brush	1	S-13g
	2	Z-93
	3	DC 92-007
	4	Microsheet SSM
	5	Teflon SSM
	6	Anodized aluminum
	7	1-mil aluminized Kapton (Kapton side exposed)
	8	Schjeldahl tape
	9	External suit material
	10	MESA blanket white cloth
C — Actual lunar dust stored in a nitrogen environment at atmospheric pressure; nylon brush	1	Z-93
	2	DC 92-007
	3	Microsheet SSM
	4	1-mil aluminized Kapton (Kapton side exposed)
D — Actual lunar dust stored in a nitrogen environment at atmospheric pressure; brass brush	1	Z-93
	2	DC 92-007
	3	Microsheet SSM
	4	1-mil aluminized Kapton (Kapton side exposed)
Standards	1	Z-93
	2	S-13g
	3	Skyspar (TiO_2/epoxy)

Lunar Dust

The tests were performed with lunar dust that was returned on the Apollo 12 mission and then stored under two different conditions. The main portion of the test used lunar dust which had always been maintained under vacuum conditions (sample 12001,20). These results were compared with results obtained by using lunar dust that had been stored in a nitrogen environment at atmospheric pressure (sample 12001,85). Five grams of lunar dust from each category were made available for these tests by the curator of the MSC Lunar Receiving Laboratory (LRL). The two types of dust samples were applied to separate sample sets and were maintained separately (Table 1).

Brushes

As mentioned previously, a major test objective was to compare the performance of two types of brushes used in removing the dust. As shown in Table 1, the surfaces in sample set A were tested with lunar dust maintained under vacuum conditions and were brushed with the MSC suit brush which has nylon bristles. This brush, with roughly 3-inch-long flexible nylon bristles, was included in these tests because it had been developed to remove the lunar dust from the astronauts' suits prior to their entering the lunar module and was readily available. The surfaces in sample set B were tested with the lunar dust stored in vacuum and were brushed with a brass-bristle brush supplied by the NASA Marshall Space Flight Center (MSFC). Figure 1 shows the two brushes. The brass-bristle brush was used at MSFC for studies with simulated lunar dust (discussed in a later section). The brass bristles were thin, flexible, and approximately 3/4 inch long. The surfaces in sample sets C and D, identical with those in sample sets A and B, were tested with the lunar dust stored in nitrogen at atmospheric pressure.

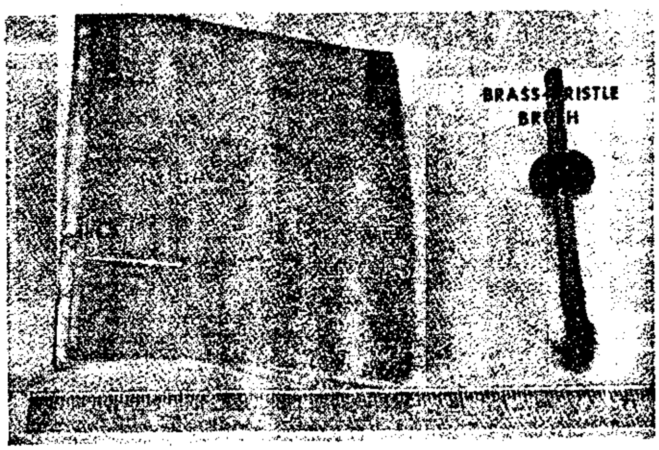


Figure 1.- Nylon- and brass-bristle brushes used in removing lunar dust from samples.

Reflectometer

The solar reflectometer used for these experiments was built by a NASA contractor and was supplied through the courtesy of MSFC. Reference 1 contains a description of the instrument. This portable instrument consists of two light sources to cover the 0.25- to 2.5-micron range, the transfer optics, and a 10-centimeter integrating sphere. A filter wheel which yields eight different spectral bandwidths is included as part of the transfer optics. One light source is a quartz-envelope mercury-arc lamp which illuminates the sample in the short ultraviolet spectral region. The other light source is a tungsten-arc lamp which illuminates the sample for the seven remaining filters.

To obtain an absolute reflectance value, the beam is first directed to the integrating sphere wall to obtain a 100-percent reading. A reading is also taken without the beam to obtain a zero reading. The beam is then directed upon the sample to measure its reflectance. A special jig was constructed which held the sample plates and the reflectometer head in a fixed relative orientation. Figure 2 shows the mounting of the thermal control material sample and the placing of the reflectometer head for a measurement.

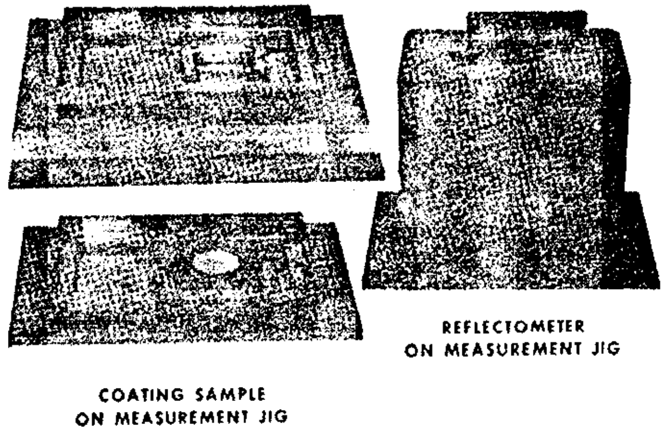


Figure 2.- Special mounting jig used to position the reflectometer head and the sample plate.

F-201 Vacuum Chamber

The dust-deposition tests used the LRL F-201 vacuum system, a vacuum chamber designed especially for use in complex vacuum operations. This chamber is a two-glove system in which glove operators perform the operations necessary to fulfill the test objectives. The test operations are described in detail in a later section of this paper. Figure 3 depicts a view, through the science observer port, showing the reflectometer head, the sample jig, the sample plates, and other supporting equipment in chamber F-201. The chamber working area measures approximately 32 inches from front to back and over 4 feet from side to side. The chamber pressure during test operations was maintained between 10^{-5} and 10^{-6} torr, which was the minimum attainable by the F-201 system. The reflectometer was outgassed under vacuum levels in the 10^{-6} torr region for several days prior to the test so that it would not introduce an unacceptable gas load into chamber F-201 during pumpdown operations.

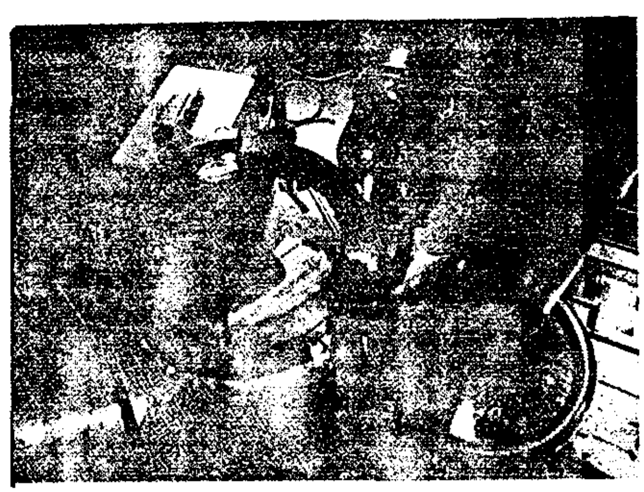


Figure 3.- View through the science observer port into LRL chamber F-201.

Test Procedure

The test procedure that was followed during the dust-deposition tests is outlined in this section. Pretest photographs were taken of each coating sample. Operations on the samples were performed in groups of four, according to the sequence shown in Table 1. Each sample was first measured with the reflectometer, with the chamber lights turned off to minimize stray light incident upon the instrument. Approximately 0.1 cc of lunar dust was deposited on each sample, in as nearly a uniform manner as possible, by scooping this amount from the appropriate lunar dust container with a 0.1-cc scoop. After four such samples were covered, photographs were taken with the F-201 elevator and overhead camera system. The samples were then returned to the chamber base, held by one end, and lightly tapped against the lunar dust collection tray two or three times to remove as much lunar dust as possible. The four samples were then remeasured and rephotographed. At this time, the samples were brushed with either the nylon- or the brass-bristle brush to remove as much of the remaining dust as possible. Measurements and photographs were taken, and the entire process was repeated on another set of four samples. Motion pictures were taken of each type of operation for a documentary record of the test procedure.

Reduction of Data

The solar reflectometer output consists of eight chart traces for each filter position. To obtain an integrated value, the reading for each filter is multiplied by the percent of the solar energy falling in this bandwidth, the eight readings are added, and this sum is divided by the total spectrum covered. This procedure gives the solar reflectance of the sample. By subtracting the solar reflectance from unity, assuming opaque specimens, the solar absorptance α_s of the material is obtained.

Test Results and Discussion

The results of the dust-deposition tests on samples 1 to 4 of sample set A are shown in Figures 4 to 6. These photographs show the succession of dust deposition, tapping to remove the dust, and brushing off the dust with the nylon-bristle brush. Qualitatively, it is seen that tapping the samples is not completely effective in removing the dust, while brushing appears to clean the coated surfaces insofar as can be determined visually. These visual data become more meaningful when the quantitative solar absorptance data are presented later.

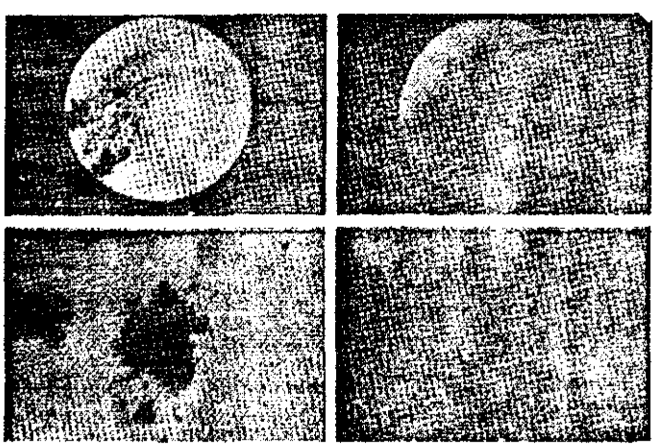


Figure 4.- Materials in sample set A after application of the lunar dust (samples 1 to 4).

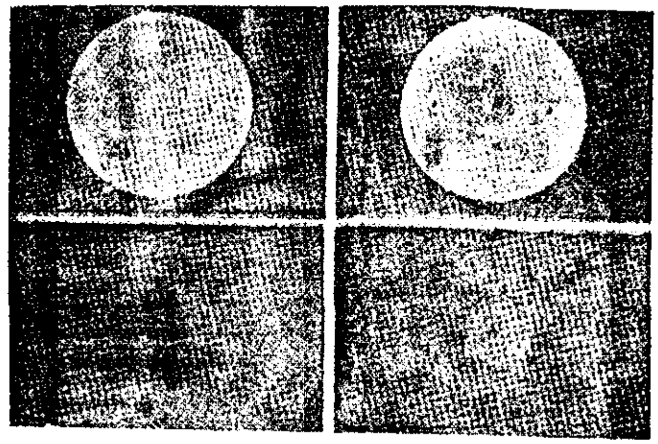


Figure 5.- Materials in sample set A after the dust was tapped off (samples 1 to 4).

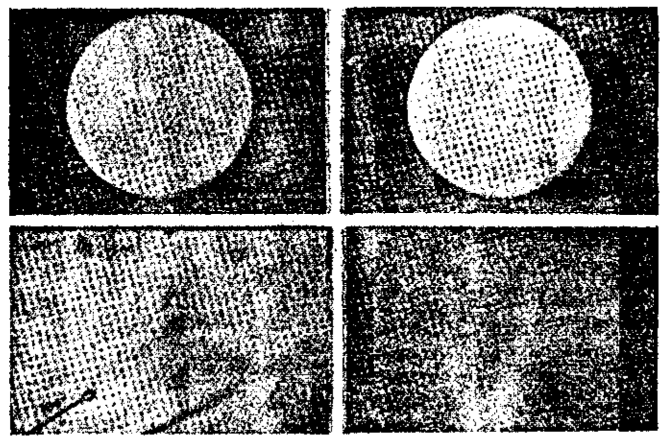


Figure 6.- Materials in sample set A after the dust was brushed off with the nylon-bristle brush (samples 1 to 4).

Test Data Presentation

The final test data are shown in Table 2. The data are presented as final values of total solar absorptance as a function of soil condition (stored in vacuum or nitrogen) and test condition (brushed with nylon- or brass-bristle brush or tapped). Initial solar absorptance data for each sample are also presented as background data. After measurement of each sample set, the standards were measured, and the uniformity of the results indicated that the reflectometer was not degraded in its performance by the vacuum exposure. The reflectometer data on equivalent samples were highly repeatable, and in most cases the two solar absorptance values were within 0.01 or 0.02 of each other.

Test Data Discussion

A study of the data in Table 2 indicates the following:

1. Brushing dust from the sample surface is an effective method of removing the dust.
2. The nylon-bristle brush is far superior to the brass-bristle brush in removing dust from the

TABLE 2. CHANGE IN SOLAR ABSORPTANCE OF THERMAL CONTROL COATINGS AFTER LUNAR DUST DEPOSITION, TAPPING, AND BRUSHING OFF THE DUST

Material	Test parameter (a)	Soil condition (b)	
		D_V/V	D_N/V
S-13g	Initial	0.28 (av)	--
	NB	.31	--
	BB	.52	--
	TAP	.63	--
Z-93	Initial	.18 (av)	0.19 (av)
	NB	.28	.31
	BB	.40	.34
	TAP	[c].25	.54
DC 92-007	Initial	.28 (av)	.32 (av)
	NB	.49	.50
	BB	.58	[d].63/0.57
	TAP	.73	.75
Microsheet SSM	Initial	.09 (av)	.08 (av)
	NB	.09	.08
	BB	.10	.10
	TAP	.29	.46
Teflon SSM	Initial	.08 (av)	--
	NB	.21	--
	BB	.29	--
	TAP	.41	--
Anodized Al	Initial	.24 (av)	--
	NB	.25	--
	BB	.32	--
	TAP	.38	--
1-mil aluminized Kapton	Initial	.18 (av)	19 (av)
	NB	.20	.35
	BB	.25	.28
	TAP	.54	.48
Schjeldahl tape*	Initial	.14 (av)	--
	NB	.22	--
	BB	.20	--
	TAP	.52	--
External suit material	Initial	.26 (av)	--
	NB	.38	--
	BB	.51	--
	TAP	.69	--
MESA blanket white cloth	Initial	.29 (av)	--
	NB	.43	--
	BB	.61	--
	TAP	.70	--

[a]NB = nylon-bristle brush, BB = brass-bristle brush, TAP = tapped.

[b]D_V = actual lunar dust maintained under vacuum conditions, D_N = actual lunar dust stored in a nitrogen environment at atmospheric pressure, V = tests run in vacuum.

[c]This value is attributed to an original reflectometer measurement error.

[d]Sample was measured after brushing with the brass-bristle brush, then remeasured after brushing with the nylon-bristle brush.

sample surface. The brass-bristle brush was detrimental to some surfaces, such as the Teflon SSM, because it marred the surface with minute scratch marks. A further comparison was performed on the nylon- and brass-bristle brushes for the DC 92-007 sample. The sample surface was first brushed with the brass-bristle brush and then rebrushed with the nylon-bristle brush. As seen in Table 2, the DC 92-007 sample showed a decrease in solar absorptance after rebrushing with the nylon-bristle brush.

3. There is apparently no significant difference between the effects of lunar dust which was stored in a vacuum and that which was stored in nitrogen, when both types of dust are applied in a vacuum environment. The data also indicate that, in the case of the DC 92-007 and the microsheet (quartz) SSM samples, the solar absorptance values are comparable. In the case of the Z-93 sample, the data for brushed samples are comparable, but data for tapped samples are not. In the case of Kapton, the data for tapped and brass-bristle brushed samples appear to agree.

4. There is a wide variation in the adhesion of lunar dust to the various materials. As seen in Table 2, the original solar absorptance of the microsheet SSM sample is almost totally restored after brushing, while the Teflon SSM sample is not cleaned as easily. This deviation could be due to the nature of the Teflon SSM, which does not present as "hard" a surface as the microsheet (quartz) SSM, and also may be due in part to the ability of Teflon to hold a static charge. As noted on the returned Surveyor III scoop brought back on the Apollo 12 mission, the lunar dust adhered more diligently to a Teflon surface than to surrounding materials, and the Teflon surface was more difficult to clean. By comparing the three white paints (S-13g, Z-93, and DC 92-007), it is seen from Table 2 that the initial solar absorptance of S-13g is more easily recovered. This fact could be due to the pigment-to-volume concentration of S-13g being the highest in this group, so that the S-13g exposes less silicone binder at the surface to hold a static charge. It is seen from the data in Table 2 that "smooth and hard" surfaces such as the microsheet SSM and the anodized aluminum could be cleaned very well, while "rough" surfaces such as the cloths could be cleaned only rather poorly. Surfaces such as Kapton and Schjeldahl tape are intermediate in their ability to be cleaned; they show only a fairly small increase in solar absorptance after the brushing.

Comparison with Similar Tests

Several similar quantitative tests on similar coatings have been conducted at MSC under varying conditions. These included tests with actual lunar dust which had been stored in nitrogen at atmospheric pressure and tests with simulated lunar dust at atmospheric pressure. Table 3 gives a summary and comparison of the results of these tests for which quantitative data exist. These tests indicated that optical degradation of surfaces with the simulated lunar dust was less than that with the actual lunar dust because of the greater adhesion of the actual lunar material. This statement was particularly true on smooth surfaces such as second-surface mirrors and metals. Generally, the results of tests with actual lunar dust under atmospheric pressure compared favorably with the tests conducted under vacuum conditions. Also, extensive qualitative tests with simulated lunar soil in an atmospheric-pressure environment have been performed under NASA contract (ref. 2).

Qualitative dust-removal tests with simulated lunar soil in a vacuum system have been performed at MSFC. Information concerning these tests was obtained through personal correspondence and has not been published. The basic objective of these tests was to make an engineering evaluation of the relative effectiveness of various brushes in removing dust from different materials, mostly conductors and insulators, with different surface finishes. This experiment was performed at a pressure of 2×10^{-5} torr with two types of simulated lunar material. In general, the conclusion was that a brass-bristle brush appeared to be more efficient than a nylon-bristle brush in removing simulated lunar material from glass and aluminum surfaces. Figure 7 shows the apparatus used in these tests.

TABLE 3. SUMMARY AND COMPARISON OF SOLAR ABSORPTANCE FROM LUNAR DUST (ACTUAL AND SIMULATED) DEPOSITION TESTS

Material	Test parameter (a)	Soil condition (b)						
		D_V/V	D_N/V	D_N/A (c)	D_S/A (d)		D_S/A (e)	
					Sample 1	Sample 2	Sample 1	Sample 2
S-13g	Initial	0.28	--	0.19	0.10	0.10	0.26	0.25
	NB	.31	--	.23	.41	--	.26	--
	BB	.52	--	--	--	--	--	.30
	TAP	.63	--	.49	--	.31	.27	.25
Z-93	Initial	.18	0.19	.16	.09	.10	.21	.26
	NB	.28	.31	.20	.28	--	.22	--
	BB	.40	.34	--	--	--	--	.45
	TAP	[f].25	.54	.46	--	.36	.24	.43
DC 92-007	Initial	.28	.32	.21	.11	.10	.23	.22
	NB	.49	.50	.39	.58	--	.27	--
	BB	.58	[g].63/0.57	--	--	--	--	.31
	TAP	.73	.78	.76	--	.45	.56	.37
Microsheet SSM	Initial	.09	.08	.08	.04	.04	.07	.10
	NB	.09	.08	.09	.04	--	.11	--
	BB	.10	.10	--	--	--	--	.10
	TAP	.29	.46	.19	--	.05	.10	.16
Teflon SSM	Initial	.08	--	.09	.04	.05	.05	.08
	NB	.21	--	.21	.04	--	.10	--
	BB	.29	--	--	--	--	--	.18
	TAP	.41	--	.29	--	.11	.13	.28
Anodized Al	Initial	.24	--	.33	.28	.32	--	--
	NB	.25	--	.37	.29	--	--	--
	BB	.32	--	--	--	--	--	--
	TAP	.38	--	--	--	.33	--	--
	Initial			.29				
	NB			--				
	BB			--				
	TAP			.33				
1-mil aluminized Kapton	Initial	.18	.19	.36	.25	.25	.21	.21
	NB	.20	.35	.40	.27	--	.23	--
	BB	.25	.28	--	--	--	--	.24
	TAP	.54	.48	.44	--	.28	.25	.29
Schjeldahl tape	Initial	.14	--	.17	.14	.16	--	--
	NB	.22	--	.18	.14	--	--	--
	BB	.20	--	--	--	--	--	--
	TAP	.52	--	.19	--	.16	--	--
External suit material	Initial	.26	--	--	--	--	--	--
	NB	.38	--	--	--	--	--	--
	BB	.51	--	--	--	--	--	--
	TAP	.69	--	--	--	--	--	--
MESA blanket white cloth	Initial	.29	--	--	--	--	--	--
	NB	.43	--	--	--	--	--	--
	BB	.61	--	--	--	--	--	--
	TAP	.70	--	--	--	--	--	--

[a]NB = nylon-bristle brush, BB = brass-bristle brush, TAP = tapped.

[b]D_V = actual lunar dust maintained under vacuum conditions, D_N = actual lunar dust stored in a nitrogen environment at atmospheric pressure, D_S = simulated lunar dust, A = tests run at atmospheric pressure, V = tests run in vacuum.

[c]Measurements made with Beckman DK2A.

[d]Measurements made with Gier-Dunkle MS 251. Simulated soil consists of red-crushed volcanic scoria and a sand/kaolinite mixture, with carbon black added to obtain proper albedo characteristics.

[e]Measurements made by portable reflectometer. Simulated soil as in item d but with carbon black removed.

[f]This value is attributed to an original reflectometer measurement error.

[g]Sample was measured after brushing with the brass-bristle brush, then remeasured after brushing with the nylon-bristle brush.

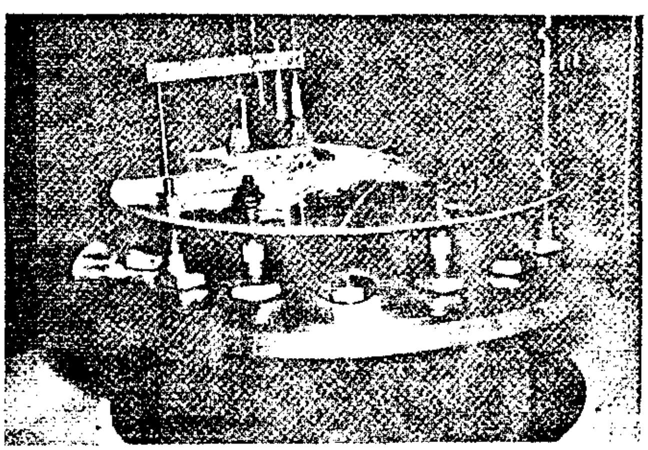
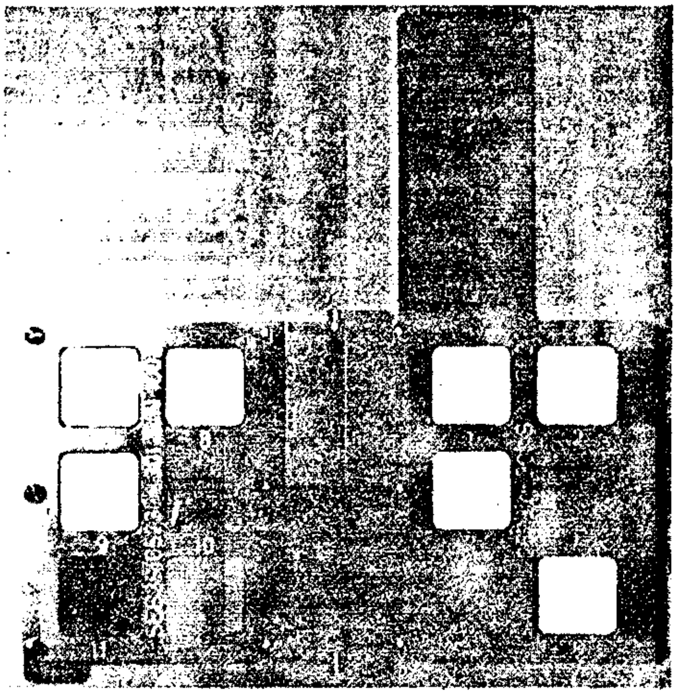


Figure 7.- Experiment setup for the MSFC dust-removal test using simulated lunar soil.

The Apollo 14 astronauts performed a lunar-dust-deposition test for the first time on the lunar surface to obtain optical-degradation values for materials in the actual lunar environment. Two sets of samples were carried for this purpose on Apollo 14. Figure 8 is a photograph of the samples. Both sets had lunar material deposited on them, but on one set the dust was only tapped off, while the other set was brushed with the nylon-bristle brush. On the lunar surface, the samples were then placed in a closed but not vacuum-sealed container. The two sets of samples were returned to the LRL, where they were placed in quarantine. (Radiative property measurements are expected to be performed after quarantine release.) The results of this test should indicate the ability of the nylon-bristle brush to clean thermal control surfaces and provide further verification of the degradation results obtained in laboratory tests.



Coating material	Position
S-13g	1
Z-93	2
MS-74 (3 pigments ZnO, Al_2O_3, and TiO_2 and a K_2SiO_3 binder)	3
Teflon SSM	4
Microsheet SSM	5
DC 92-007	6
Cat-a-lac white (TiO_2/epoxy)	7
3M white (TiO_2/epoxy/polyester)	8
MESA blanket white cloth	9
GT 1015 tape (aluminized Kapton with SiO outer coating (Al side exposed)	10
1-mil aluminized Kapton	11
Anodized aluminum	12

Figure 8.- Photograph of the Apollo 14 samples.

Recommendations for Future Tests

A literature study yielded the following two categories which are worthy of future studies:

1. Effect of static charge on adhesion of lunar dust
2. Effect of ultrahigh vacuum levels on adhesion of lunar dust

A discussion of each category is presented.

Effect of Static Charge

Reference 3 indicates that the force of adhesion and the charge value are proportional, as evidenced in the detachment of small spherical glass particles from painted surfaces. Also, the electrical charges increase as the particle size diminishes so that the electrical component of the adhesive forces also becomes greater. Although these data were obtained for small solid particles, further research into this phenomenon with lunar dust would be useful since it appears that electrostatic forces may play a major part in adhesion of dust to a painted surface.

The force of adhesion may be varied by eliminating or reducing the electrostatic component (reducing the charge density). This reduction may be accomplished by modification of the surface, namely, replacing certain surface molecular groups with others. This approach was not feasible, in the study described, since thermal control coatings are involved.

Theoretical indications are that conducting particles will be discharged when they fall on a grounded surface; however, insulating or semiconducting particles tend to retain their charge. Furthermore, if the surface is nonconducting and nongrounded and if other means of charge leakage such as ionization of the air are impossible, then Coulomb forces may produce adhesion of the particles for a considerable time.

It is hoped that further tests can determine whether adhesion of lunar soil is a strong or a weak function of electrostatic charge. A proposed experiment setup will involve the sample coming into contact with a grounded metal plate and being brushed with a grounded brass-bristle brush. These data will be compared to data in which the sample or the brass-bristle brush has not been grounded.

Effect of Ultrahigh Vacuum

There are indications (ref. 4) that particles of a silicate material in an ultrahigh-vacuum environment (6.3×10^{-10} to 1.3×10^{-9} torr), with a particle size distribution nearly equivalent to that of lunar soil, exhibit adhesion to a substrate to a greater degree than at somewhat higher pressure levels (10^{-6} torr). Therefore, it is appropriate to perform additional tests with lunar soil at ultrahigh-vacuum levels to compare with those tests previously performed at vacuum levels in the 10^{-6} torr range.

Concluding Remarks

Test conclusions are summarized as follows:

1. Brushing dust from the sample surface is an effective method of removing dust.
2. The nylon-bristle brush is far superior to the brass-bristle brush for removing the lunar dust from the sample surface.
3. There is apparently no significant difference between the effect of lunar dust which was stored in a vacuum and that which was stored in nitrogen when both types of dust are applied in a vacuum environment.
4. There is a wide variation in adhesion of lunar dust to various materials.

As a result of these lunar-dust-deposition tests in a vacuum environment, the following additional comments are made:

1. The nylon-bristle brush is quite efficient and should be considered for use in removing lunar dust from thermal control materials.
2. In future ground tests of this type, lunar dust which is stored in a nitrogen environment at atmospheric pressure can be used in vacuum tests without significant loss in efficiency.
3. Of the possible thermal control materials for use in lunar surface operations, quartz second-surface mirrors, which are highly efficient thermally, can apparently be cleaned easily without

showing a degradation in solar absorptance. Improvements in metallized polymers (of which silvered Teflon is a representative and highly thermally efficient coating) must be forthcoming to enable a more efficient cleaning of lunar dust from its surface.

References

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