IV. Spacecraft Changes

PART A

LUNAR DUST AND RADIATION DARKENING OF SURVEYOR 3 SURFACES

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One of the most conspicuous features noted by the astronauts during examination of Surveyor on the Moon and later during examination of the returned hardware in the Lunar Receiving Laboratory (LRL) was the change in color. The overall tan color was in sharp contrast to the stark white paint and shiny metallic surfaces of Surveyor before launch (and to that on the model used by the astronauts during training).

Discoloration due to radiation darkening of the paint and to accumulated lunar dust had been expected. However, the expected patterns of radiation damage and conjectured patterns of dust accumulation were not evident on the returned hardware. The investigation to establish the causes of discoloration and the apparent absence of expected patterns has yielded information, primarily on the effects of lunar fines, which will be of value to future lunar operations.

The white paint used on Surveyor was known to be subject to radiation darkening. The nature and rate of discoloration had been measured in simulation tests (refs. 1 and 2), and the effect verified from temperature measurements on Surveyor 1 (ref. 3). Patterns of discoloration related to solar illumination geometry were expected because the magnitude of discoloration increases with total solar irradiation.

The abnormal landing of Surveyor 3 resulted in veiling glare and substantial loss of contrast in the pictures taken during spacecraft operation. This effect was attributed to dust on the mirror; the upper part of the mirror was significantly more affected than the lower, recessed part. It was reasonable to expect a similar coating of lunar dust on other surfaces of the camera, and with comparable variations in quantity. The astronauts observed dust contamination on the Surveyor, but detected no directional pattern associated with the Lunar Module (LM) landing (ref. 4). No effects from the LM had been expected, as there was ". . . preflight consideration that the landing occur outside of a 500-foot radius of the target to minimize contamination of the Surveyor vehicle by descent engine exhaust and any attendant dust excitation" (ref. 5).

Summary

Measured spectral reflectance, evidence obtained from photographs, scanning electron microscopy, and the work of other investigators on Surveyor hardware have been used to develop an understanding of the observed discoloration and its meaning to future space and lunar operations.

Measured reflectance data have been analyzed to separate and understand the effects of lunar dust and radiation damage and to conclude that organic contamination is not a major contributor to the discoloration.

Radiation-induced discoloration on the various surfaces has been found to be proportional to the degree of solar illumination. Photobleaching of the radiation damage was observed and is responsible for a gradual change in the color of the camera's surface during the evaluation program.

Organic contamination, although undoubtedly present, does not seem to be a significant factor in the observed discoloration of the external surfaces.

Almost all exposed external surfaces on the

camera are partially covered with a fine layer of lunar dust. The distribution of lunar material indicates significant contributions from fines disturbed by the initial Surveyor landing and by the approach and landing of the LM. The approaching LM apparently disturbed lunar surface material (which reached the Surveyor) over about the last 300 m of its ground track, in addition to the observed dust cloud immediately before touchdown. Some of the disturbed surface material contributed to the contamination; some of the dust cloud impacted the Surveyor and produced observable surface changes.

Lunar material, even in very small quantities, can have a significant effect on temperature control and optical performance of hardware on the lunar surface.

Examination Evidence

When the returned camera was examined in the LRL, the exterior was a dirty gray-to-tan color, with varying shades and tones and with considerable evidence of disturbance caused by handling during retrieval and return. There was no evidence of the expected contrast in radiation discoloration between surfaces with extensive solar exposure and those with little or no exposure. All external surfaces of the camera were discolored or contaminated in varying degrees.

The only obvious discoloration pattern was a series of shadows that did not correspond to solar illumination or other identifiable spacecraft geometry. In all cases, these sharply defined darker regions were found on the side of the camera that faced northwest, toward the LM landing site. Each shadow was associated with a protruding or raised surface located on the camera and near the dark region. These patterns have been shown by Jaffe (ref. 6) and Cour-Palais (ref. 7) to be the result of "sandblasting" of the camera surface by lunar material disturbed by the descending LM.

When the support collar was removed from the camera, a quantity of dark, particulate material was found inside the collar recess. (See fig. 1.) A bright spot on the camera body appeared to be an image of the inspection hole (fig. 1), but alined with the inspection hole (fig. 2) at a peculiar angle. The displacement of the image subsequently was shown to correspond exactly to the angle of incidence of material disturbed by the landing LM. Thus, the dark, particulate material trapped in the recess "sandblasted" the surface inside the clamp and produced the bright spot. It represents a sample of the LM-disturbed lunar material that "sandblasted" the Surveyor.

The first surface mirror of the camera has a diffuse appearance and light tan color. Visual examination with correct lighting, infrared photography (see fig. 3), and subsequent reflectance measurements by Rennilson (see ch. IV, pt. E) showed retention of partial mirror quality. The diffuse appearance is the result of light scattering from a partial layer of lunar fines. The mirror's surface appeared brighter in the area wiped by the astronauts as part of their examination. A small region near the top of the mirror, apparently rubbed by the plastic bag some time before release from quarantine, appeared brighter and cleaner than the region wiped by the astronauts. After the mirror was removed from the camera housing, the gradation in coverage by lunar fines from top to bottom was clearly evident. The upper protruding end had substantially more lunar material on the surface.

During subsequent examination, acetate replication peels were taken by other investigators from selected areas of the mirror to remove the adhering lunar material for study. The peeled areas showed a distinct improvement in specularity, verifying that the major source of light scattering was a readily removable layer of lunar fines. However, the protruding part of the mirror retained a slight, but distinct, diffuse character while the lower, recessed end of the mirror appeared more nearly restored to its original condition.

A geometrically sharp, curved line was identified near the bottom of the mirror. This line was a perfect projection image of the front opening of the mirror assembly from a direction in front of and below the camera. Following replication peels, a part of a second, less distinct, but geometrically sharp, similar image line was identified. Low-power, optical microscopic examination showed the upper line to be a demarcation in population of small-scale, light-scattering sites, either small pits or adhering particulate material.

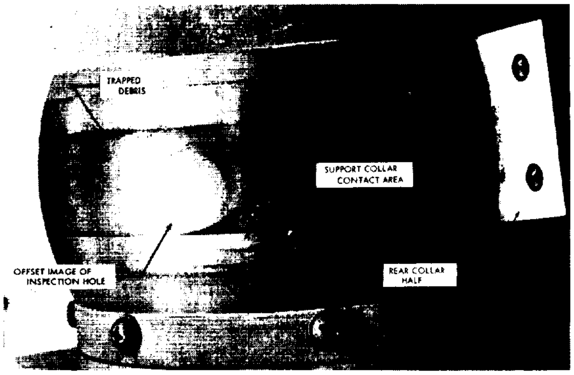

FIGURE 1.—Surveyor 3 television camera with front half of support collar removed. Back half has been displaced toward the right and upward from its original position.

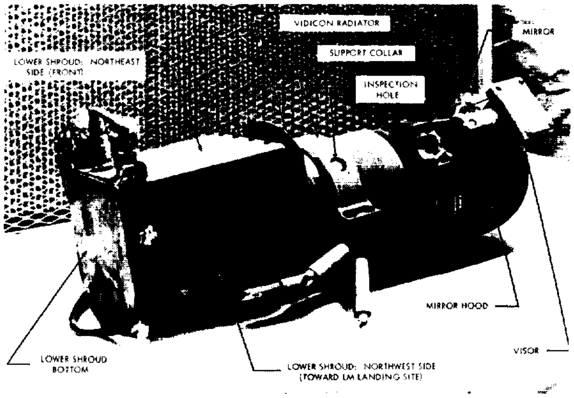

FIGURE 2.—Returned Surveyor 3 television camera.

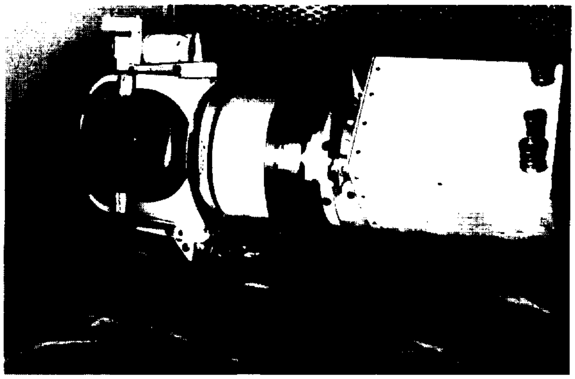

FIGURE 3.—Returned Surveyor 3 television camera photographed with infrared film. Note the clarity of the mirror compared with figure 2 (ch. I) and figure 26, (ch. IV, pt. E) of this document.

Examination of peels using the scanning electron microscope showed a difference in small-scale ($\sim 1\ \mu m$) surface features across both of these lines. Although other explanations are possible (i.e., highly directional contamination during pre-launch vacuum testing), these lines most likely represent the effects of debris from two points on the lunar surface near the camera. The geometry associated with these images and location of the probable points on the lunar surface are described by Nickle. (See ch. IV, pt. D.)

During the evaluation program, the discolored white paint on the camera's exterior surface seemed to be fading, which was first attributed to gradual loss of lunar fines from the surface. It has been demonstrated since that the effect was due to photobleaching of radiation damage in the paint and that no loss of lunar material had occurred. The photobleaching of this paint had not been identified previously because of its slow rate; however, the effect is not surprising, as this bleaching of induced optical damage is well known (ref. 8).

Reflectance Measurements and Analysis

During the evaluation, spectral reflectance was measured in the 0.4- to 2.5-μm wavelength range on samples from representative areas of the camera surfaces. Description of the method and complete data are contained in reference 9. It has been possible to analyze these data, correlate the results with other investigations, and reach conclusions regarding the contributions of dust, organic contaminants, and radiation damage to the total discoloration.

The white surfaces showed a decrease in reflectance at all wavelengths in the range measured. Laboratory tests (refs. 1, 2, and 10) have shown that neither ultraviolet radiation nor low-energy protons cause optical damage of this paint in the near infrared (wavelength $>1.0\ \mu m$). Thus, the observed reduction in reflectance at wavelengths greater than 1 μm is attributed to the presence of lunar dust; the magnitude of the reduction is proportional to the quantity of lunar dust present.

The expression developed to analyze the effects of dust and radiation is shown by

$$\rho_{m_\lambda} = \rho_{D_\lambda} K_\lambda A_D + \rho_{P_\lambda}(1 - a_\lambda A_D)^2$$

where

ρ_{m_λ} = measured sample reflectance at wavelength λ
$\rho_{D_\lambda} K_\lambda A_D$ = first surface back reflection from dust particles (negligible quantity for the white paints)
ρ_{P_λ} = reflectance of paint surface at wavelength λ ($\rho_{P_\lambda} = \rho_{0_\lambda}$ if no radiation damage has occurred; ρ_{0_λ} is original paint reflectance).
a_λ = proportionality constant related to absorptance and scattering of dust at wavelength λ
A_D = fraction of surface area covered by lunar dust

This expression shows that the reduction in reflectance is proportional to the fractional area covered by lunar fines and the spectral absorption and scattering of the lunar fines. (The incident and reflected energies pass through the dust "filter," thus the squared term.)

This expression, with the knowledge that radiation does not produce near-infrared damage and with information on the spectral properties provided by Nash[1] permits separation of the effects for all wavelengths. The radiation degradation then can be compared to laboratory simulation results, both in spectral character and total magnitude.

Similarly, the calculation permits comparison of the relative quantities of lunar material on various areas of the camera. The relative quantities so determined are shown in table 1.

Transmission measurements were made by Rennilson (see ch. IV, pt. E) before and after removing the layer of lunar fines from the clear filter of the camera. For this measurement, the detector senses only that energy in a small, solid angle in the forward direction; the energy that encounters lunar particles is either absorbed or scattered out of the forward direction of the beam. Thus, the measurement becomes a good estimate of the fractional area of the filter covered by lunar fines. The fraction 0.25, thus calculated, has been verified by Nickle (see ch. IV, pt. D) from data given by Robertson et al. (See ch. IV, pt. B.) Comparable, but somewhat different, measurements of the clean and dusty areas of the filter were made as part of this investigation. For these measurements, the filter was mounted at the entrance port of an integrating sphere so that both the forward scattered and direct transmitted energy were detected. Comparison of data from these two measurements makes it possible to estimate the value of spectral absorptance of the lunar fines on the clear filter. The accuracies of these measurements warrant only an estimate of the magnitude of the absorptance; however, such an estimate permits a reasonable assumption of the quantity of lunar material on the painted surfaces from reflectance data and the equation presented.

Other Evidence

Examination of metal surfaces (screws and washers) from the camera, using the scanning electron microscope (SEM), provided the first direct indication that lunar dust was responsible for a major part of the discoloration observed. Similar examinations permitted determinations of the quantity and particle size distribution of the lunar material on metallic camera surfaces.

It was not possible to obtain direct images of the lunar fines on the painted surfaces by using the SEM. Anderson (see ch. IV, pt. F) measured relative quantities of lunar material on the painted surfaces using a microprobe attachment for a SEM. These results show similar agreement with determinations made from reflectance data (calculated in a way similar to that described).

The relative quantities of lunar material in various surfaces were determined by Schaeffer[2] and Satkiewicz (see ch. IV, pt. H) and are given for comparison in reference 9. Schaeffer measured the quantity of trapped solar wind helium on samples from selected areas on the camera. The helium content, dominated by that trapped in the lunar fines, provides a measure of the relative quantity of lunar material. Satkiewicz, using an ion microprobe, traced the composition of sputtered materials with depth. Tracing the change in content of materials unique to the

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[1] D. Nash, JPL, personal communication.

[2] O. A. Schaeffer, State University of New York, personal communication.

TABLE 1.—*Comparison*[a] *of amount of lunar dust on various painted surfaces of the camera*

Sample or measurement	*Location*	*Relative quantity*[a] *of lunar dust*
906	Top of visor	[a] (1.0)
907	Mirror hood: south[b] side (away from LM)	.5
908	Mirror hood: north side (toward LM)	1.0
898	Lower shroud: northwest side (toward LM)	.9
900	Lower shroud: southeast side (away from LM)	.4
T–3	Lower shroud: southeast side (small area adjacent to camera power cable)	<<.1
893	Lower shroud: front (facing northeast)	.7
T–7	Lower shroud: rear (facing west)	1.1
T–8	Lower shroud: rear (facing south)	.8

[a] Normalized to visor top (906).

[b] Lunar direction; for spacecraft orientation on the Moon, see ch. I.

lunar fines and to the paint permits an estimate of area coverage and effective thickness of the lunar material.

Discussion and Conclusions

Radiation Damage

Discoloration caused by radiation damage has been shown to be proportional to the solar illumination, as expected. The spectral character of the damage matches that obtained from simulation tests conducted in the laboratory. The magnitude of the damage is in reasonable agreement with laboratory simulations.

The observed photobleaching was not surprising, although it had not been observed previously on this paint. The observation emphasizes the need to return and subsequently handle hardware under controlled conditions.

The major value of the successful confirmation of expected radiation damage lies in the resulting conclusions regarding dust effects and organic contamination. The observed damage also emphasizes the need to consider degradation of thermal-control surfaces and the corresponding uncertainty in the thermal design of space and lunar vehicles.

Organic Contaminants

From analyses of reflectance data, it was concluded that organic contaminants, although most likely present, were not significant contributors to the observed discoloration. This conclusion is substantiated by the work of Simoneit. (See ch. V.) Effects of organic contaminants, although not significant to the discoloration of the thermal surfaces, may be a factor in the condition of the optics.

Lunar Dust

Adhering lunar dust radically changed the optical properties of the thermal-control surfaces and degraded the performance of the optics on the Surveyor camera. Veiling glare and contrast attenuation experienced during the Surveyor 3 lunar operations was due to lunar fines adhering to the mirror.

The distribution of lunar material on the various parts of the camera is summarized in table 1. These values are relative and normalized to the fractional area on top of the visor. The samples measured on the north and northwest side facing the LM landing site (samples 908 and 898), exposed to the "sandblast" effect, indicate a substantially higher coverage by lunar material than the opposite side. Because the sandblasting produced a lighter color by removing material, the earlier coverage was even higher. Although deposition of the heavy coating on the north and northwest surfaces may have occurred during the Surveyor landing, such an explanation is inconsistent with the amount found on the northeast (front) side.

Almost as much lunar material appeared on the front (sample 893, facing northeast) as on the side toward the LM landing site (northwest). During the Surveyor landing, deposition on the front was unlikely; deposition without some shadowing and light/dark contrast caused by protruding cable connectors would have been impossible. Deposition during final stages of the LM landing (when detected by the astronauts) also would have produced contrasts that were not evident.

The camera surface showed considerable evidence of scuffing and disturbance as the result of unavoidable handling during retrieval and return. This handling undoubtedly resulted in some redistribution of dust from one area to another. However, because the "sandblast" patterns remained so evident, redistribution was not sufficient to cancel the contrasts discussed above.

Rennilson reports evidence of more dust on the returned mirror than during Surveyor operations in 1967. (See ch. IV, pt. E.) In order to reach the mirror, dust disturbed directly by the LM exhaust must have occurred while the LM was about 300 m or more from its landing site (assuming line-of-sight trajectories for particles and assuming negligible effect from secondary material disturbed by surface impact of particles blown by the LM exhaust).

Thus, a major fraction of the lunar material on the northeast (front) and northwest sides must have arrived from a diffuse (multi-directional) source, disturbed by the approaching LM somewhat uniformly over most of the last 300 m or more of its ground track.

Some areas of the camera not in "sight" of the approaching LM also have a covering of lunar dust; this probably is due to the abnormal Surveyor 3 landing, which is known to have affected the camera mirror. The lunar material on the returned polished tube was oriented in such a way that it must have been deposited during the Surveyor landing.

Long-term deposition, such as lunar surface debris disturbed by meteorite impact, probably would produce uniformity on all sides; this was not observed. If the lines observed on the mirror are a result of secondaries produced by meteoroid impacts on the lunar surface in the vicinity of the Surveyor, such secondaries would be expected to contribute to the dust discoloration of the camera, but to an insignificant degree (<10 percent of the total lunar material).

The observed dust, therefore, originated from both the Surveyor and LM landings, with each contributing a significant amount to various surfaces. "Lunar transport" seems to be relatively insignificant, if evident at all.

From reflectance data and filter transmission measurements described, it is possible to show that the dust contaminant on the camera is in the range of 10^{-5} to 10^{-4} g of lunar fines per square centimeter of surface area. This small quantity radically alters the reflectance of the critical reflective thermal-control surfaces, increasing the absorbed solar thermal energy by a factor of 2 or 3. The quantity is small compared to the approximately 10^{-3} g/cm^2, which arrived at the Surveyor from the LM landing 155 m away. Because of the size and velocity of arriving particles, the primary effect of this final "blast" was to clean, rather than to contaminate, the surface. However, fines disturbed earlier in the LM approach contributed to the contamination of the Surveyor camera surfaces.

Clearly, lunar material disturbed by ascent or descent rockets can have a major effect on equipment on the lunar surface, even at a substantial distance from the flight path.

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PART B

CHARACTERIZATION OF DUST ON CLEAR FILTER FROM RETURNED SURVEYOR 3 TELEVISION CAMERA

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Surveyor 3 landed on the Moon in April 1967. Part of the spacecraft was returned to Earth in November 1969 by the Apollo 12 astronauts.

A stripping film containing dust removed from the camera light filter was received for study by Battelle-Northwest (BNW) from the Jet Propulsion Laboratory (JPL). The study conducted involved the characterization of the dust; the results of the study are presented here.

Individual particles of dust from the Surveyor 3 camera light filter were examined. The dust particles (from 2 to 40 μm) were released from a (stripping) cellulose film, isolated, and analyzed by optical microscopy, electron microprobe, and X-ray diffraction. The analytical results indicate that the dust is of lunar origin. While the average composition and characteristics are in agreement with other lunar fine analyses (see ref. 1), this study clearly shows significant composition variation from particle to particle in the micrometer-size range.

Handling of Primary Samples

The samples, three cellulose films, were taken consecutively from one-half of the clear filter. The sample package was opened in the front section of a laminar air flow clean bench; the samples were immediately transferred into the bench work area. (See fig. 1.) The films were taped to clean microscope slides with the particle-containing surface facing up. (See fig. 2.) The samples remained in the bench until packaged for return to JPL.

Analytical Processing

Examination of "As Received" Cellulose Films

Figure 3 shows the particle content of the three films and a blank. This blank may not be the same lot of film used to strip the particles.

It is apparent from the photomicrographs that the first strip (ND–1) removed much more dust than succeeding strips (ND–2 and ND–3). Film ND–1 was used to obtain the particles for study. No additional work was performed on ND–2 and ND–3.

General Procedure for Individual Particles

The general procedure for analysis of an individual particle involves the steps described below. Particle 5 was photographed at various steps to help visualize the procedure. (See fig. 4.)

Step 1: Locate or select a particle in the cellulose film for analysis. (See fig. 4(a).)

Step 2: Cut a square of film (about 100 by 100 μm) containing the particle and remove the square to a clean microscope