ENVIRONMENTAL EFFECTS ON LUNAR ASTRONOMICAL OBSERVATORIES

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The Moon offers a stable platform with excellent seeing conditions for astronomical observations. Some troublesome aspects of the lunar environment will need to be overcome to realize the full potential of the Moon as an observatory site. Mitigation of negative effects of vacuum, thermal radiation, dust, and micrometeorite impact is feasible with careful engineering and operational planning. Shields against impact, dust, and solar radiation need to be developed. Means of restoring degraded surfaces are probably essential for optical and thermal control surfaces deployed in long-lifetime lunar facilities. Precursor missions should be planned to validate and enhance the understanding of the lunar environment (e.g., dust behavior without and with human presence) and to determine environmental effects on surfaces and components. Precursor missions should generate data useful in establishing keepout zones around observatory facilities where rocket launches and landings, mining, and vehicular traffic could be detrimental to observatory operation.

INTRODUCTION

The Moon's environment makes it an excellent place from which to make astronomical observations (*Burns and Mendell,* 1988; *Burns et al.*, 1990). Recent papers (*Johnson and Wetzel,* 1990) have considered the science, engineering, and construction associated with lunar astronomical observatories. Some of the environmental factors that make the Moon a useful platform for astronomy, however, are not benign and will require special efforts to mitigate their effects. This paper reviews the environmental factors likely to cause degradation of the components and systems of astronomical facilities on the Moon, summarizes results of studies of spacecraft exposed to the lunar environment, and presents a preliminary assessment of ways to diminish the damaging effects of the space environment.

SPACE ENVIRONMENTAL FACTORS

In this section, we summarize the features of the lunar environment that seem most troublesome to the longevity and operation of astronomical facilities on the Moon. Some environmental characteristics, such as a low magnetic field (10^{-2} to 10^{-4} Earth's field at the equator) and a seismically stable surface will not lead to degradation of equipment and will not be discussed. Details of these and other characteristics of the Moon's surface environment are given by *Taylor* (1988). Some environmental factors of the low Earth orbit (LEO) environment, which may provide additional insight into the lunar environment, are also discussed.

Atmosphere

The Moon has an extremely tenuous atmosphere. At night, it contains only 2×10^5 molecules/cm^3 (*Hoffman et al.,* (1973), giving a pressure of 10^{-12} torr. This hard vacuum will create problems with outgassing of materials and causes solar and cosmic radiation and micrometeorites to hit the lunar surface unimpeded, as discussed below. The nighttime atmosphere is composed chiefly of H and noble gases (*Hoffman et al.,* 1973). Measurements were not made during the lunar daytime by Apollo instruments, but slight enhancements of CO_2 and CH_4 just before sunrise (*Hoffman and Hodges,* 1975) suggest that these gases dominate the atmosphere during the daytime (*Hodges,* 1976).

The atmosphere in LEO is quite different from that of the Moon. The presence of atomic oxygen in LEO creates a difficult degradation problem, as was observed from the components of the Solar Maximum satellite (SMS) that were returned by the space shuttle (*Liang et al.,* 1985). Orbiting space debris (paint chips, etc.) also create problems for satellites in LEO (*Kessler,* 1985; *Barrett et al.,* 1988). Note that orbiting space debris and highly oxidizing gases, such as atomic oxygen, that are present in LEO are absent on the Moon.

Surface Temperatures

The Moon's surface undergoes a drastic thermal cycling from dawn to noon. The surface temperature is a function of the amount of incident solar radiation, the amount reflected off the lunar surface (only about 7%), and the amount radiated in the infrared. At the Apollo 17 site, for example, located about 20° north of the equator, the temperature ranged from 384 K to 102 K during the month-long lunar day (*Keihm and Langseth,* 1973). Furthermore, the temperature decreases rapidly at sunset, falling about 5 K/hr. In polar regions, the predawn temperature is about 80 K (*Mendell and Low,* 1970), and in permanently shadowed areas near the poles the temperature is even lower. The large range in temperature and rapid change at sunset could affect many structures and materials.

Radiation

Because of the lack of an absorbing atmosphere and, for charged particles, the small magnetic field, radiation from the sun and galaxy hit the lunar surface unimpeded. Sunlight provides one damaging type of radiation: ultraviolet light. The sun's spectrum peaks in the visible, at about 0.5 μm, but a significant amount of it, 7%, is between 0.28 and 0.40 μm (*Robinson,* 1966). Since the solar constant is 1393 W/m^2 at the Earth-Moon distance from the sun (*Coulson,* 1975), the total ultraviolet flux is about 95 W/m^2.

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There are three sources of charged-particle radiation with different energies and fluxes: (1) high-energy (1-10 GeV/nucleon) galactic cosmic rays, with fluxes of about 1/cm^2/sec and penetration depths up to a few meters; (2) solar flare particles with energies of 1-100 MeV/nucleon, fluxes up to 100/cm^2/sec, and penetration depths of about 1 cm; and (3) solar wind particles, which have much lower energies (1000 eV), small penetration depths, but high fluxes (10^8/cm^2/sec). These penetration depths refer to the primary particles only. Reactions between high-energy particles and lunar materials cause a cascade of radiation that penetrates deeper (*Silberberg et al.*, 1985), up to several meters for cosmic rays and solar flares. Although solar wind particles have low energies, their high flux might make them capable of damaging materials on the lunar surface. The more energetic radiations could damage electronic equipment.

Micrometeorites

The tenuous lunar atmosphere allows even the smallest micrometeorites to impact with their full cosmic velocity, which is 10 km/sec, though some arrive at >50 km/sec (*Berg and Grun*, 1973). This rain of minute projectiles poses a hazard to all surfaces exposed on the lunar surface, but it presents a serious threat to delicate materials such as telescope mirrors and coatings.

Almost all lunar rock surfaces that were exposed to space contain numerous microcraters. Studies of lunar rocks (e.g., *Fechtig et al.*, 1974) have revealed the average flux during the past several hundred million years. However, data from the Surveyor III TV camera shroud returned by the Apollo 12 mission and study of Apollo windows (*Cour-Palais*, 1974) indicate that the present flux of particles $<10^{-7}$ g, which are capable of making craters up to 10 μm across, is about 10 times greater than that measured on lunar rocks. Study of louver material from the SMS (*Barrett et al.*, 1988) confirmed that fluxes are greater now than the average of the past several hundred million years. Combining the fluxes of particles $<10^{-7}$ g measured on spacecraft with those $>10^{-7}$ measured on Apollo rocks, we arrive at the flux estimates in Table 1.

These fluxes are clearly high enough to damage telescope mirrors, but they apply to 2π geometry. A telescope shielded within a collimator would be exposed to a lower flux. For example, a telescope mirror 1 m across located at the base of a 1-m tube would be exposed to only 29% of the direct flux. A tube 3 m long would decrease the flux to 5% of the values listed in Table 1. Figure 1 demonstrates quantitatively how the direct flux is decreased by using a collimator tube for shielding. Even long tubes, however, still allow substantial numbers of micrometeorites to strike an unprotected surface, and there is an additional source of impact-derived debris due to secondary impact events caused by ejecta of primary events. These not only make craters, but also commonly cause deposition of accretionary spatter (*Zook*, 1978).

TABLE 1. Microcrater product rates on the Moon.

Crater diameter (μm)	Craters/m^2/yr
>0.1	300,000
>1	12,000
>10	3,000
>100	0.6
1000	0.001

Values are estimated from data given by *Fechtig et al.* (1974), *Cour-Palais* (1974), and *Barrett et al.* (1988).

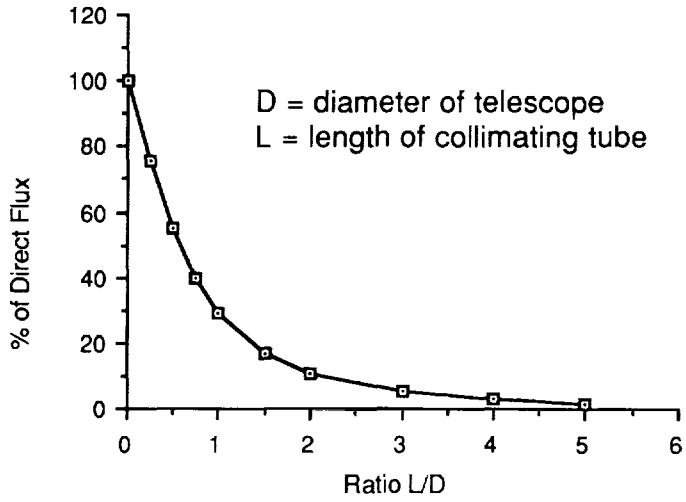

Fig. 1. Plot of the percent of direct flux of micrometeorites reaching a telescope surface of diameter D as a function of the length L of a collimating tube.

As alluded to above, micrometeorites create a degradation problem in LEO as well as on the lunar surface. The lack of atmosphere in Earth orbit allows micrometeorites to impact unrestrained, as in the case of the lunar surface environment. Measurements acquired from the study of returned components from the SMS (*Schramm et al.*, 1985; *Kessler*, 1985; *Barrett et al.*, 1988) indicate that unprotected surfaces are very susceptible to micrometeorite damage. Schramm indicates that the exterior insulation blankets returned from SMS inadvertently acted as micrometeorite capture devices. These results indicate the need for protective coatings or temporary covers for long durations in the space (orbital or lunar surface) environment.

Dust

The lunar surface is covered with a global veneer of debris generated from underlying bedrock by meteorite impacts. This material, called the lunar regolith, contains rock and mineral fragments and glasses formed by melting of soil, rock, and minerals. Its mean grain size ranges from 40 to 268 μm and varies chaotically with depths (*Heiken*, 1975). In most samples returned by Apollo and Luna missions, about 25 wt% of the rgolith is <20 μm in size and about 10 wt% is <10 μm. In short, the lunar surface is dusty, and optical equipment must be protected from contamination and subsequent damage by dust particles.

Dust could be thrown onto mirror surfaces by artificial means such as rocket launches, surface vehicles, or astronaut suits. This man-made degration problem is one that can (and should) be controlled with proper regulations and procedures, which are discussed in more detail later in this paper. An unknown amount of dust might be transported by charge differences built up by photoconductivity effects near the day-night terminator. *Criswell* (1972) described a bright glow photographed by Surveyor 7 and explained the phenomenon as levitation of dust grains about 5-10 μm in radius. The grains were lifted only 3-30 cm above the local horizon and had a column density of 5 grains/cm^2. How effective this mechanism is needs to be tested by measurements on the lunar surface.

DEGRADATION OF MATERIALS AND SYSTEMS

Investigations of Surveyor Components

Surveyor III components were studied on Earth after these parts had been exposed to the lunar environment for 31 months (roughly 32 lunar days) from April 20, 1967 until November 20, 1969. Parts studied were (1) the television camera, which included optics, electronics, cables, and support struts; (2) the scoop portion of the soil mechanics surface sampler device (which contained over 6 g of lunar soil); (3) a section of polished aluminum tube 19.7 cm long; and (4) a section of cabling and painted aluminum tube (*Nickle,* 1971; *Carroll et al.,* 1972).

These parts were analyzed for surface changes and characteristics (e.g., adherence of soil particles, sputtering, and UV-induced degradation of thermal control coatings), micrometeorite impacts, radiation damage, particle tracks, and naturally induced radioactivity.

Although the Surveyor III was on the lunar surface for 31 months, it was operated for only 2 weeks. It experienced 30½ months' exposure in a dormant or nonoperating state. Involved were 1500 resistors, capacitors, diodes, and transistors in the camera returned to Earth. Tests after recovery verified the integrity of most parts after 31 months on the Moon (*Carroll et al.,* 1972). A few components failed, apparently because of thermal cycling to very low temperatures (e.g., a tantalum capacitor) and as a result of thermal strain (e.g., glass envelopes). Some failures caused a cascade of failures. For example, a failure of the circuit that drove the shutter was caused by the failure of a transistor that had been degraded in a preflight test; this caused failure of a shutter solenoid, which in turn caused evaporation of a photoconductor in the vidicon as a result of the shutter being open (*Carroll and Blair,* 1972).

Solar radiation and effects. The maximum time of exposure to solar radiation during the time the retrieved parts were on the lunar surface is theoretically 10,686 hours. Shadowing effects limited actual exposure times to considerably less than the theoretical maximum. It was estimated, for example, that the clear optical filter on the camera had a total exposure of only 4180 hours, but that the scoop arm, which had been left fully extended at maximum elevation in 1967 at the Surveyor mission termination, had a total exposure of 9078 hours.

As the evaluation of Surveyor III parts was in progress, the tan color of the originally white paint faded due to photobleaching. Photobleaching of induced optical damage can also occur. Therefore, hardware must be sampled and returned carefully to avoid or account for subsequent alteration in the terrestrial laboratory environment (*Carroll and Blair,* 1972). Although some environment-induced failures occurred, it is clear from the superb results obtained by most Apollo Lunar Surface Experiments Packages (ALSEP) experiments that it will be possible to produce systems that will function through many lunations.

Degradation of thermal control coatings. Coatings exposed to the space environment exhibit radiation-induced darkening that increases with time. After 31 months on the Moon, inorganic coatings originally white were tan in appearance. This discoloration was observed to be in a pattern consistent with the amount of irradiation received (*Carroll and Blair,* 1972). Overall discoloration patterns were the result of several effects attributable to solar radiation (e.g., in the ultraviolet), lunar dust, and products of organic outgassing from spacecraft parts (*Carroll and Blair,* 1972). Dust and irradiation played the key roles in altering the appearance (and usefulness) of the surface coatings.

The blue color of the scoop faded to a whitish blue. The surfaces painted with inorganic white degraded from a solar absorptance of 0.2 to 0.38 up to 0.74, depending on orientation. Polished aluminum tubes rose in absorptance from 0.15 to 0.26 (on a "clean" or relatively dust-free surface) to 0.75 where dust was present (*Anderson et al.,* 1971).

The greatest changes in reflectance were for shorter (0.6 to 1.0 μm) as opposed to longer wavelengths (up through 2.0 or 2.4 μm). Both solar radiation and dust were instrumental in decreasing reflectance.

Dust presence. It was estimated that the upper portion of the clear filter, which was positioned over the Surveyor camera lens by remote command at the close of the Surveyor III mission, had 25% of its surface area covered by particulate material. This fine-grained lunar soil had a median grain size of 0.8 μm and ranged up to 15 μm in size (*Nickle,* 1971). Dust on the Surveyor mirror was thought to have caused a marked loss of contrast in relayed pictures during the performance of the Surveyor mission (*Carroll and Blair,* 1972). "Lunar material, even in small quantities, can have a significant effect on temperature control and optical performance of hardware on the lunar surface" (*Carroll and Blair,* 1972). Even 10^{-5} to 10^{-4} g of lunar fines per square centimeter can increase absorbed solar thermal energy for a reflective thermal-control surface by a factor as large as 2 or 3 (*Carroll and Blair,* 1972). On the other hand, there are no reports of degradation of the laser reflectors left by three Apollo missions.

Sources of dust. There was dust on the returned Surveyor III television camera attributable to one or more of five sources (*Carroll and Blair,* 1972): (1) The disturbance of the soil during the Surveyor III landing, accentuated by the vernier descent engines continued thrusting during two rebounds from the lunar surface; (2) disturbance mechanisms operating on the Moon (e.g., meteroid impact and electrostatic charging); (3) Apollo 12 lunar module approach and landing; (4) operation of the scoop on the Moon; and (5) retrieval and return to Earth by Apollo 12 astronauts.

The Surveyor III and lunar module (LM) landings were probably the most significant sources of the dust found on the camera. The descent engine, which disturbed the dusty surface over the last 1000 ft of its ground track before landing 155 m away, was probably the most significant dust source. Dust was accelerated by the LM rocket plume to velocities in excess of 100 m/sec. This accelerated dust literally sandblasted the Surveyor III and removed much discolored paint (*Cour-Palais et al.,* 1972).

Erosion surfaces in the lunar environment. Three processes may be considered in evaluating erosional effects on parts exposed to the lunar environment: (1) sputtering of individual atoms by the solar wind (mainly hydrogen); (2) damage from solar flare heavy nuclei (e.g., Fe); and (3) micrometeorite impact (*Baber et al.,* 1971).

Estimated erosion rates per year from these effects are very small (e.g., 0.4 Å for sputtering, 0.1 to 0.4 Å for heavy nuclei, and 1-2 Å for micrometeorite impacts). Micrometeorite impact is probably the most significant mechanism of the three for degradation of telescope optical surfaces, although the effects of sputtering on optical coatings over several years requires a restorative capability or replacement.

Results of examinations for micrometeroid impacts. The television camera shroud, the camera's optical filters, and a piece

of aluminum tube were scanned for possible craters resulting from micrometeorite impacts. Magnifications in the range of 25× to 40× and greater were used over substantial portions of the surfaces of these objects as the search for impact craters proceeded (*Cour-Palais et al.,* 1971; *Brownlee et al.,* 1971).

No hypervelocity impact craters were identified in the original studies on the 0.2 sq m of the shroud or on the optical filters. Five craters ranging in diameter from 130 to 300 μm were noted as having a possible hypervelocity impact origin. The many other craters found were thought to have originated as a result of impact of low-velocity debris accelerated by the LM descent engine plume. However, continued study of the Surveyor materials and of impact pits on lunar rocks led to a reevaluation of the original Surveyor data (*Cour-Palais,* 1974), which indicated that most of the craters on the returned material were hypervelocity impact pits. Nevertheless, damage from low-velocity impact was still substantial.

Buvinger (1971) performed an investigation by electron replication microscopy of two sections of the unpainted aluminum tubing. Erosion damage apparently resulted from impact of soil particles during landing maneuvers. Some pits in the approximately 1-mm range had some characteristics of hypervelocity impacts. Solar-wind sputtering apparently had little effect on the tube, and damage by particle impact was apparently by lower-velocity particles and limited to a depth no greater than 2 mm.

Investigations of LEO Satellites

Degradation studies of satellite components returned from LEO have been conducted. The space shuttle, or space transportation system (STS), with its reusable capability to be launched into orbit and return, has created the potential to go into space and repair satellites, and return components or even entire satellites. The STS has been used to perform a repair mission on the SMS (*SMRM,* 1985) and to retrieve two Hughes communication satellites, Palapa and Westar. The Long Duration Exposure Facility (LDEF) was placed into orbit by the shuttle for planned retrieval 12 months later. Many of the experiments on LDEF incorporated studies on space degradation. This section summarizes some of the degradation studies that have been conducted on LEO satellite components and relates their possible implications to the lunar environment.

Investigations of SMS components. The SMS was launched in February, 1980, into a 310 n.m. (674 km) circular orbit, with solar flare research as its primary objective. Between 6 and 10 months after launch, the satellite suffered a series of failures with the attitude-control system, rendering several of the instruments inoperable and some others at limited capability. The Solar Maximum Recovery Mission (SMRM) was performed in April, 1984. The Modular Attitude Control System (MACS) module, the Main Electronics Box (MEB), and their associated thermal blankets were replaced with new units, and the old units were returned to Earth for investigation following more than four years in LEO (*SMRM,* 1985). The flight electronics parts showed no adverse effects from the LEO radiation environment. In general, the components returned from the SMS were in good condition.

Analyses were performed on the materials retrieved from the SMS thermal control system. The presence of atomic oxygen caused most of the degradation of the materials. Fortunately, atomic oxygen, a major problem in LEO, is absent in the lunar environment, and will not be discussed in detail here.

Analysis of the multilayer insulation (MLI) blankets indicated that micrometeorite and debris impacts had caused hundreds of impact craters. Seventy-micrometer craters formed complete holes through the 50-μm-thick initial layer of thermal blanket. Roughly 160 of these craters penetrated the surfaces, which encompassed an area of 0.153 sq m (*Kessler,* 1985). This high micrometeorite flux demonstrates the importance of protecting components and systems exposed to the space environment. *Schramm et al.* (1985) indicated that the MLI blankets acted inadvertently as a micrometeorite capture device. This indicates the potential benefits gained by using protective coatings and covers.

In the lunar environment, any astronomical observatory, especially the delicate optical equipment and sensors, will need to be protected from the micrometeorite environment. Much can be gained from the study of the micrometeorite environment in LEO. Information gathered can be used to examine better ways to protect systems on the lunar surface.

Other LEO investigations. As we noted above, the STS retrieved two Hughes Communication satellites, Palapa B-2 and Westar VI, and returned them to Earth in 1984. The two spacecraft were only in orbit for eight months and there were no detailed degradation investigations conducted on the satellites (M. West, personal communication, 1987).

The LDEF was launched from the STS in 1984 with a planned retrieval 12 months later. This retrieval effort was delayed until 1990. LDEF was designed to accommodate a large number of science and technology experiments, many of which were designed to study space degradation (*Clark et al.,* 1984). There will be a vast amount to be learned about degradation in space from the study of the experiments.

Impact and debris studies have been conducted on the shuttle and Apollo/Skylab where impact craters have been found. However, these experiments and studies had either short exposure times or no conclusive technique to differentiate orbital debris from micrometeorites (*Kessler,* 1985). The detection of orbital debris is receiving an increasing amount of attention, and in the next few years both specially designed radars and experiments carried on the shuttle will produce new data on both orbital debris and the micrometeoroid flux.

MITIGATION OF DEGRADATION

As *Carroll et al.* (1972) note, "The need to protect optical elements from dust contamination was obvious during Surveyor III lunar operations in 1967 and was confirmed during analysis of returned hardware. All other optical performance information gained from post-mortem analysis is secondary to this conclusion."

Observatory design and operation can mitigate and compensate for the potentially detrimental effects of solar radiation, dust accumulation, surface erosion, changes in thermal control coatings, and micrometeorite impacts. We outline below some ideas for blunting the hazardous effects of the lunar environment.

Dust Mitigation

Rocket landing and ascent operations can be performed at locations sufficiently far removed from observatory sites to prevent dust erosion and accumulation on optics, antennae, and thermal control surfaces. Shielding against dust driven by rocket plumes may be useful. How great the required keep-out distances or shielding heights against accelerated dust must be depends on the rocket engine and plumes. Keep-out distances may be in excess of 1000 ft based on the extent of LM descent engine sand blasting effects, dust disturbance, and deposition on Surveyor III components.

H. Schmitt (personal communication, 1988) suggested that optics be provided with lens caps that could be remotely controlled to cover and protect optical surfaces before permitting construction and repair teams to approach observatories on the Moon. He notes that the lunar dust is difficult to avoid in astronaut and vehicular traffic on the Moon.

Preserving Thermal Control Surfaces

Some telescope components and other base facilities will be dependent for temperature control on the use of thermal control coatings designed to have appropriate values of absorptance and reflectance. If these coatings degrade—as was noted in the case of Surveyor III coatings—temperatures of critical components will deviate from specified values and diminish or negate observatory performance. Protecting coatings by use of layers that intercept UV radiation may help. More stable coatings applied under conditions avoiding contamination may also help.

Use of Shields

Shields against micrometeorite impact, dust particles, and solar radiation can be devised to reduce the probability of impact, contamination, or interference by stray light rays. Shields can reduce the probability of impact on optics by reducing the portion of the sky from which impacting particles can originate. Appropriate baffles can prevent the shield from directing stray or scattered light on mirrors or other optics.

Restoration

According to *Watson et al.* (1988), equipment for restoring coatings on telescope mirrors and thermal control surfaces has been developed and tested on orbit by the USSR. These metal coating operations were performed in space after extensive experimentation in ground-based laboratories to overcome technical difficulties associated with heating, vaporization, and deposition of aluminum. In 1975, cosmonauts Gubarev and Grecho were reported to have recoated the mirror of a solar telescope on the Salyut spacecraft. More coating restoration experiments on orbit were performed in subsequent spacecraft in 1979, 1980, and 1984. Details have not been made available, but results were reported as excellent. These coating-technology experiments suggest that the capability to restore optical and thermal control surfaces degraded by exposure to the space environment may be available for astronomical observatories on the Moon.

It has also been suggested that large mirrors for space use be composed of numerous replaceable segments so that if impact or abrasion causes damage, only the degraded portion need be replaced. Also, mirror surface coatings should be selected that are compatible with cleaning processes and reduce electric charge effects (*Bouquet et al.*, 1988).

Laboratory Investigations

Laboratory studies have played and continue to play an important role in estimating the degradation likely when components of space systems are exposed to the space environment. The thermal-vacuum test (*Flanagan*, 1986) will be an essential step in the development and preflight preparations for any observatory components to be deployed on the lunar surface. The systems will be subjected to vacuum and thermal cycling comparable to that found on the Moon to assure that they are capable of operating under very cold and very hot conditions and can accommodate large temperature gradients.

Vacuum chambers with thermal cycling can also include solar simulation that provides an approximation of the solar spectrum. Micrometeorite protection systems can be designed based on available laboratory data (e.g., from light gas guns and Van de Graff generators) and data gathered from recovered components (e.g., LDEF, SMS).

Precursor Missions

Plans to return to the Moon should include visits to at least one Apollo landing site to ascertain the degradation and changes in selected Apollo materials and components. Six Apollo landings were made between 1969 and 1972, and a wide range of equipment was left on the surface, including the descent stages of the LM, lunar roving vehicles (LRV), and the ALSEP. Items to be studied include thermal blankets, optics, retroreflectors (for laser ranging), batteries and motors (e.g., on the LRV), communications equipment such as parabolic dishes, various pieces of tankage, and test equipment.

These parts can be studied to ascertain the degradation caused by long-term exposure to micrometeorite bombardment, solar and cosmic radiation, thermal cycling, and vacuum. Areas for study are suggested by the previous experience with Surveyor hardware (*Scott and Zuckerman*, 1971; *Nickle and Carroll*, 1972). To be determined are dust and radiation darkening of surfaces, particle impact effects (both primary and secondary), and the effects of long-term thermal cycling in vacuum.

The goals of the visit and study will be to improve the technology for design, fabrication, and test of future lunar astronomical observatories (*Johnson*, 1988), enhance our understanding of processes that occur on the Moon and of the rates at which they operate, and to check the validity of accepted design approaches. Figure 2 demonstrates a generic representation of our need to better understand lunar environmental degradation (*Johnson and Wetzel*, 1988). As shown in this figure, we possess a very limited amount of experience with lunar surface degradation. We must gather additional information about degradation and its effects

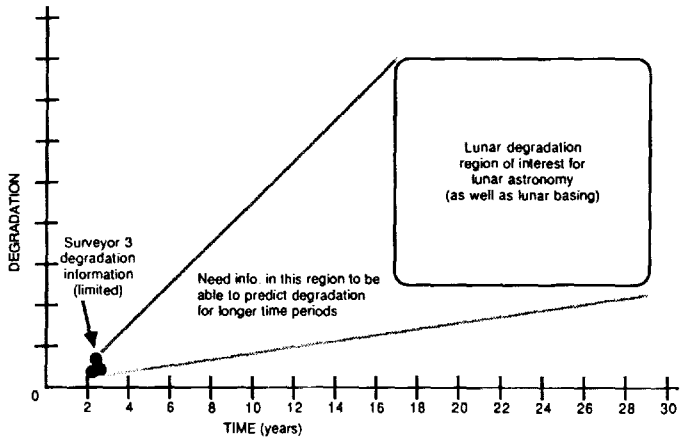

Fig. 2. Schematic representation of the information needed to investigate degradation on the lunar surface over a long period of time.

over a long period of time. For example, revisiting and studying the materials and equipment from the Apollo sites will allow us to acquire information about lunar degradation in the 30-year time range.

Examination of Apollo materials will be extremely valuable, but will leave many questions unanswered. Additional experiments will be required to fully understand micrometeorite impacts (both primary and secondary), dust levitation, and assorted operational disturbances.

Apollo materials will shed light on the present flux of micrometeorites and shrewd collection of surfaces shielded from direct impact will provide crucial information about the flux of and damage done by secondary projectiles. Nevertheless, an array of micrometeorite detectors, either passive or active, ought to be deployed on the lunar surface to obtain information on fluxes, masses, velocities, and directions of impacting particles. A device of this sort was emplaced during the Apollo 17 mission (*Berg et al.*, 1973). Furthermore, instruments like this will be developed for use on the space station. In addition to supplementing data that will be obtained from study of surfaces of the Apollo spacecraft and instruments, the new generation of lunar surface micrometeorite detectors will provide up-to-date data and a basis for comparison with detectors in LEO. This will help establish the natural flux in LEO, a critical parameter to know if we are to accurately monitor the growth of man-made debris in LEO.

As noted earlier, *Criswell* (1972) suggested that a brightening at the horizon in Surveyor photographs taken shortly after sunset was caused by electostatic effects. The idea is that electrons are removed by the photoelectric effect when sunlight strikes the surface. This results in a charge inbalance with the uncharged surroundings, causing small grains to be lifted off the ground. It seems prudent to determine the extent to which this process operates and assess whether it will interfere with lunar surface operations. It might, for example, cause micrometer-sized dust grains to be deposited on telescope mirrors, thereby degrading astronomical observations. An active detector designed to measure the flux and size distribution of low-velocity dust grains could provide the necessary information.

It will also be necessary to monitor disturbance caused by lunar base operations. This includes dust raised by rockets landing and taking off, vehicles moving, and astronauts walking. For example, if astronauts are needed to service telescopes, one must know how much dust could be transferred from their spacesuits onto a mirror. Perhaps this could be measured by having astronauts approach a low-velocity dust detector. If significant dust were measured, other means of servicing telescopes would have to be devised. Disturbance by the transportation system could also be monitored by an array of dust detectors. Effects of the lunar base operations on the present lunar atmosphere should also be monitered (*Fernini et al.*, 1990).

SUMMARY AND CONCLUSIONS

Although the Moon is an excellent place for astronomy, special efforts will be required to mitigate or compensate for detrimental effects of the lunar environment on observatory components. The most troublesome characteristics of the lunar environment are the vacuum (which leads to outgassing), solar and cosmic radiation, micrometeorite impacts, the surface temperature regime, and the ubiquitous dust particles.

Valuable information on degradation of parts and systems in the lunar environment was obtained by retrieval to Earth and careful analysis of Surveyor III components. These components had been on the Moon nearly 32 lunar days from April, 1967, to November, 1969. Most parts retained their integrity, but a few failed (e.g., because of thermal cycling). Degradation of coatings also occurred, primarily because of ultraviolet radiation and the static and dynamic effects of dust particles on optical and thermal-control surfaces. The dust can cause scattering of light and loss of contrast in optical trains.

Several approaches can be taken to mitigate the negative effects of the lunar environment on astronomical observatory components. First, an effort is needed to better understand and model the degradation mechanisms. This effort should be addressed early in precursor missions to the Moon. Second, operational rules will be necessary to confine activities that generate dust and rocket plumes to zones outside those where astronomical observatories are being used. When it is necessary to approach the observatory sites with vehicles and construction or maintenance teams, precautionary shielding should be activated to protect optics and reduce deposition on thermal-control surfaces. Processes will eventually be needed to clean and restore dusty and impact-damaged surfaces. Fortunately, the lunar environment, although dusty, lacks the hazards in LEO associated with atomic oxygen and orbiting debris, such as chips of paint, from previous missions.

Although the lunar thermal regime offers a severe test of observatory components, careful engineering can control degradation, and the number of cycles to be endured (about one per month) is much fewer than cycles encountered in LEO (about 480 per month). The environment on the lunar surface is conducive to the use of shields and baffles against micrometeorite impact, dust particles, and solar radiation. Experiments in terrestrial laboratories and precursor missions to the Moon are needed to assist in predicting degradation and in reducing its ravaging effects on future lunar astronomical observatories. Restoration processes should be developed to enhance the longevity of observatory components on the Moon. The technology of degradation mitigation that will be developed will apply not only to astronomical observatories, but also to a wide range of lunar base elements. It is prudent to initiate studies of lunar environmental effects early so that beneficial results can be implemented early in the planning of all lunar base facilities.

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