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## Human Safety in the Lunar Environment

Robert H. Lewis

Any attempt to establish a continuously staffed base or permanent settlement on the Moon must safely meet the challenges posed by the Moon's surface environment. This environment is drastically different from the Earth's, and radiation and meteoroids are significant hazards to human safety. These dangers may be mitigated through the use of underground habitats, the piling up of lunar material as shielding, and the use of teleoperated devices for surface operations.

### The Lunar Environment

The Moon is less dense than the Earth and considerably smaller. Its density indicates that the Moon's bulk composition is also somewhat different from Earth's, although it is still a terrestrial (rocky) body. The Moon's surface gravity is only one-sixth the Earth's. And, with its consequently lower escape velocity, the Moon cannot maintain a significant atmosphere. Thus, the surface is directly exposed to the vacuum of space. Lacking an atmospheric buffer, the Moon has a surface temperature that varies over several hundred degrees Celsius during the course of a lunar day/night cycle. A complete lunar day, one full rotation about its axis, requires approximately 27-1/3 terrestrial days.

Compared to the Earth, the Moon is geologically inactive. Volcanism and internally generated seismic activity are almost nonexistent. Furthermore, water and atmospheric processes are unknown on the Moon. Other than igneous differentiation, which occurred early in lunar history, the main geological process that has acted on the Moon is impact cratering.

The Moon was heavily bombarded by meteoroids throughout much of its early existence. Evidence from the Apollo expeditions suggests that the bombardment decreased significantly about 3.8 billion years ago. This early bombardment and subsequent impacts during the past 3.8 billion years have pulverized the lunar surface into dust and small fragments of rock, a layer referred to as the lunar "regolith." The majority of the Moon's surface is made up of heavily cratered terrain, rich in the mineral plagioclase feldspar and known as the lunar "highlands." The uncompacted, upper portion of the highlands' regolith is 10 to 20 meters deep in most places. A smaller portion of the lunar surface, mostly on the Earth-facing side, consists of basaltic lava flows and is known as the lunar "maria." The maria are geologically younger than the highlands and thus have been cratered far less than the highlands have. The depth of uncompacted

regolith in the maria is roughly 4 to 5 meters.

The bulk density of lunar regolith increases with depth. Its upper surface is believed to have 45-percent porosity (Taylor 1982, p. 119). The porous upper 20 cm of the regolith results from repeated meteoroid impacts, which stir up the exposed surface and occasionally form large craters. These meteoroids represent potential hazards to both manned and unmanned activities. The meteoroid hazard on the lunar surface may be greater than that in free space (Mansfield 1971, p. 1-4-14). In addition to the free-space flux of meteoroids, there is also ejecta from the impacts. Some fragments of ejecta could have larger masses and slower velocities than the free-space population of meteoroids.

The Moon's surface is exposed to three types of hazardous ionizing radiation. The first two, the solar wind and solar flares, are produced by the Sun. The third type has its origin outside the solar system and is known as galactic cosmic rays.

The solar wind is an isotropically distributed, neutral plasma travelling at an average velocity of 400 km/sec. In Earth/Moon space, it has an average density of about 10 particles per cubic centimeter (Taylor 1982, p. 155). This plasma is composed of a relatively constant flux of charged particles, mainly electrons and protons, plus ions of various elements.

A solar flare is similar in composition to the solar wind, but its individual particles possess higher energies. A solar flare may be considered a transient perturbation in the solar wind. Exact timing of the occurrence of a flare is difficult to predict, but the frequency of flares may be related to the 11-year solar cycle. Most flares can be observed at the Sun's surface some time before a large increase in the solar wind's higher energy particles is detected in the vicinity of the Moon. Not all solar flares yield particles that reach the Earth/Moon vicinity, but, of those which do, this flux reaches a peak within hours and then decreases over several days to the previous solar wind level.

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Galactic cosmic rays are apparently isotropically produced outside the solar system. The average cosmic ray flux has been almost constant over the past 50 million years (Taylor 1982, p. 159). Cosmic rays are made up of very high energy particles consisting mostly of protons and electrons, plus some heavy nuclei (iron, for example), positrons, and gamma rays. Both the Earth and the Moon are exposed to these cosmic rays, but the Moon's surface receives a higher intensity of cosmic rays than does the Earth's surface.

The Earth's magnetic field and atmosphere provide significant protection, lacking on the Moon. The cosmic ray flux per square centimeter of lunar surface per year (during minimum solar activity) contains  $1.29 \times 10^8$  protons plus  $1.24 \times 10^7$  helium nuclei plus  $1.39 \times 10^6$  heavier ions for a total of  $1.4279 \times 10^8$  particles per  $\text{cm}^2$  per year.\* Fortunately, as the energy of the radiation increases from solar wind to cosmic rays, the frequency of encountering that radiation decreases.

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\*Counting only particles with a velocity greater than 10 MeV per nucleon. Information from D. Stuart Nachtwey, Medical Sciences Division, Lyndon B. Johnson Space Center, Houston.

### Lunar Public Works

The dry, barren Moon might not seem like a promising land for settlement. But, with the eyes of a chemist, a pioneer settler may see lunar conditions as advantages and lunar soil as a bountiful resource.

#### Lunar Water Works



The first concern of a lunar pioneer must be water. There may or may not be water, as trapped ice, at the lunar poles, but there certainly is an abundance of its chemical components, oxygen and hydrogen. Oxygen is the most abundant chemical element (45% by weight) in the lunar soils, from which it may be extracted by various processes. In contrast, the concentration of hydrogen in lunar soil is very low, but the total quantity available is nevertheless great. The lunar surface has been bathed for billions of years in the solar wind, a flux of ionized atoms from the exterior of the Sun. These ions embed themselves in the surface of grains of lunar topsoil. Furthermore, meteorites, unimpeded by an atmosphere, continually plow under the old solar-wind-rich grains and expose new grains. In this way, large amounts of hydrogen have become buried in the soil, enough to produce (if combined with lunar oxygen) about 1 million gallons (3.8 million liters) of water per square mile (2.6 km<sup>2</sup>) of soil to a depth of 2 yards (1.8 m). This hydrogen can be extracted by heating the soil to about 700°C. Supplying the Lunar Water Works is a matter of technology and economics, but not a matter of availability of oxygen and hydrogen on the Moon.

#### Lunar Community Farm



The next concern of a lunar pioneer will be food. Like hydrogen, carbon and nitrogen are available in large quantities from the lunar soil, although they are present in very low concentrations, having been placed there, like hydrogen, by the solar wind. All the other nutrients necessary to life are likewise present in the soil. Pioneer settlers

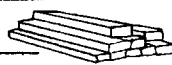
should be able to obtain these elements by heating the soil. Once people have provided them with lunar water, carbon dioxide, oxygen, and nitrogen, plants should be able to extract nutrients directly from the lunar soil.

#### Lunar Filling Station



The lunar covered wagon will be a chemical rocket, its horsepower hydrogen and oxygen. Hauling these propellants from Earth will be expensive. It may prove cheaper to provide them from the lunar soil. Forty tonnes of hydrogen, a reasonable estimate of the amount needed for all transportation from low Earth orbit for a year, could be obtained from just 0.3 km<sup>2</sup> of soil mined to a depth of 1 m. Alternatively, lunar transport vehicles might burn a metal such as iron, aluminum, or silicon, even though these are less efficient rocket fuels than hydrogen. All three are major constituents of lunar soils, in chemical combination with oxygen, from which they can be extracted. In fact, each is a byproduct of one or more processes for producing oxygen. [Several techniques for extracting oxygen from lunar soils are proposed in the Materials volume of this Space Resources report.]

#### Lunar Lumberyard



Better than burning the iron, aluminum, and silicon produced as byproducts of oxygen extraction from lunar soils might be to use them to construct lunar shelters. Iron and aluminum can be fabricated into beams. The boards of space construction may well be made of glass. Molten lunar soil can be cast into silicate sheets or spun into fiberglass. These may have greater strength than similar products on Earth because of the lack of water to interfere with their polymer bonds. Partially distilled in a solar furnace, soil residue may take on the composition of a good cement, which when combined with locally produced water and the abundance of aggregate would become

concrete. [These manufacturing processes are also discussed in the accompanying Materials volume.] The unprocessed soil itself can serve as shielding against the diurnal temperature fluctuations and, more importantly, against the hazards of radiation unscreened by an atmosphere and undeflected by a magnetic field, as discussed by Rob Lewis in this paper.

#### Lunar Light and Power



The Sun shines on the Moon plentifully and predictably, but only half the time. Storing solar energy over the 2-week-long lunar night seems difficult and may have to be done in the form of hydrogen, metals, and oxygen whose extraction was powered by energy from the Sun. Thus, initially, lunar power is likely to come from an imported nuclear power plant. But electrical power derived from the Sun is a likely lunar product and may even be the first major export to the Earth from the Moon (once the souvenir market has been satisfied). Eventually, the solar cells will probably be derived from lunar silicon, a byproduct of oxygen extraction, or from lunar ilmenite, recently shown to be photovoltaic. Conversion need not be efficient if a local material, simply obtained, is used as the photovoltaic. More futuristically, lunar helium-3 has been proposed for use as a fusion fuel superior to tritium in that it is not radioactive, does not have to be made in nuclear fission reactors, and yields a proton instead of a more destructive neutron when it fuses with deuterium.

Lunar soil contains in abundance the materials required for life support, transportation, construction, and power. With proper understanding and new ideas, lunar pioneers should be able to turn the lunar environment to their advantage.

Taken from Larry A. Haskin and Russell O. Colson, 1990, *Lunar Resources—Toward Living Off the Lunar Land*, in Proc.

1st Symp. NASA/Univ. of Arizona Space Engineering Research Center (in press), ed. Terry Triffet (Tucson).

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## The Human Factor

In order to develop permanent human settlements on the Moon, we must understand how the local environment influences the settlers' safety and health. The lack of atmosphere and the extreme temperature range mandate the use of sealed and thermally insulated enclosures. These enclosures—the colonists' first line of defense—will range from individual space suits to buildings. The next line of defense must protect the colonists from both meteoroids and radiation.

Meteoroid impacts may have effects ranging from long-term erosion of the surface materials of pressure vessels and space suits all the way to penetration and subsequent loss of pressure and injury to personnel (see fig. 9). More serious impacts could result in destruction of equipment and loss of life.

Figure 9

### **Crisis at the Lunar Base**

*A projectile has penetrated the roof of one of the lunar base modules and the air is rapidly escaping. Three workers are trying to get into an emergency safe room, which can be independently pressurized with air. Two people in an adjoining room prepare to rescue their fellow workers. The remains of the projectile can be seen on the floor of the room. This projectile is probably a lunar rock ejected by a meteorite impact several kilometers from the base. A primary meteorite would likely be completely melted or vaporized by its high-velocity impact into the module, but a secondary lunar projectile would likely be going slowly enough that some of it would remain intact after penetrating the roof. Detailed safety studies are necessary to determine whether such a meteorite strike (or hardware failure or human error) is likely to create a loss-of-pressure emergency that must be allowed for in lunar base design.*

Artist: Pamela Lee

CAPACITY 3  
SAFE ROOM

EMERGENCY

PRESS

TEMP. MAP

3/7/11 10:10 AM

In 1971, the Rockwell Lunar Base Synthesis Study investigated several strategies for dealing with the meteoroid hazard. They took a probabilistic approach to the problem of safety and examined several options. Rockwell was interested in providing portable shielding for short-term surface activities as well as more permanent fixed shielding. The shielding might be needed many times during an expedition covering large distances.

On Earth, mobile expeditions which require temporary environmental protection that is lightweight and easy to redeploy often use tents. The Rockwell study examined the use of a tent-like structure which could be erected over an inhabited pressure vessel. The tent could be constructed of a lightweight material such as aluminum foil or nylon. The Rockwell investigators anticipated that such a structure would act as an extra outer layer of protection against meteoroid impact. For their calculations, the tent had an area of 46 m<sup>2</sup> and the insulated wall of the pressure vessel had a density of approximately 8 kg/m<sup>3</sup>. A small gap between the tent and pressure wall was initially considered. This arrangement could provide a 0.9999 probability of no penetrations in 100 days if only a free-space meteoroid flux was assumed. However, assuming also the secondary ejecta hazard, they found that the tent system had only a 0.1 probability of not

being penetrated within 100 days. A logical next step would be to add more layers of material to the tent. This, of course, increases the weight of the tent and its associated transportation costs.

The next option that Rockwell considered was identical to that just described but with an additional layer of material filling the gap. In theory, the tent would serve to fragment a meteoroid and the underlying material would impede and absorb the fragments before they reached the pressure vessel. On the basis of their surface meteoroid flux model, the gap filler would need to have a density of 16 kg/m<sup>3</sup> to provide a 0.9999 probability of no penetration within 100 days. A design of this type may prove to be practical as portable meteoroid shielding for short-term surface activities.

However, these measures would be completely inadequate for any long-duration habitat (for a stay of over 100 days), so the addition of shielding material seemed desirable. If lunar regolith were used as a gap filler, significant protection could be added without increasing transport costs from Earth. Rockwell concluded that a gap of approximately 15.2 cm (6 inches), filled with lunar regolith, would reduce the penetration risk to less than one chance in 10 000 over a 2- to 5-year stay.

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Although meteoroid impacts may be a serious problem on an infrequent basis, the effect of ionizing radiation on human health is continuous and cumulative over an individual's lifetime. A brief discussion of radiation dosimetry is now in order. The fundamental unit of radiation transfer is the *rad*; 1 rad represents the deposition of 100 ergs of energy in 1 gram of mass. The characteristics of the deposition mechanisms vary and additional factors must be considered. One conversion factor is the quality factor, *Q*, which is conservatively based on the experimentally determined relative biological effectiveness, *RBE*. When *Q* is multiplied by the rad exposure, the result is a unit of dosage corrected for the type of radiation; this resulting dosage is measured in a unit known as the *rem*.

Individual responses to radiation exposure vary somewhat and there is controversy over safe limits for long-term, low-level exposures. Currently, the maximum permissible whole-body dose for radiation workers is 5 rem/year and for the general public 0.5 rem/year (CRC Handbook of Tables for Applied Engineering Science 1980, p. 753). Both of these doses are larger than the dose of background radiation at sea level that humans are normally exposed to. Just as radiation workers must accept a greater risk than do members of the general public, so astronauts are prepared to accept a greater risk than radiation workers. Table 3, provided by Stu Nachtwey, lists the doses and health risks that the Medical Sciences Division at the Johnson Space Center estimates an astronaut on a Mars or lunar base mission would be exposed to during a period of minimum solar activity.



TABLE 3. *Approximate Radiation Doses and Health Risks for an Astronaut on a Mars or Lunar Base Mission During Minimum Solar Activity*  
 [From D. Stuart Nachtwey, Johnson Space Center]

Radiation source	Representative shielding	Skin dose equivalent	Deep organ (5 cm) dose equivalent	Excess lifetime cancer incidence in a 35-year-old male*
<b>Chronic exposure</b>				
Trapped belts (one-way transit)	2 g/cm <sup>2</sup> Al	< 2 rem	< 2 rem	< 0.1%
Free space	4 g/cm <sup>2</sup> Al	75 rem/yr	53 rem/yr	~ 1.2%/yr of exposure
On lunar surface	4 g/cm <sup>2</sup> Al	38 rem/yr	27 rem/yr	~ 0.6%/yr of exposure
On martian surface	16 g/cm <sup>2</sup> CO <sub>2</sub> (atm.)	13.2 rem/yr	12 rem/yr	~ 0.3%/yr of exposure
<b>Acute exposure to large (e.g., Aug. '72) solar particle event</b>				
Free space	2 g/cm <sup>2</sup> Al	1900 rem	254 rem	~ 5.7%
On lunar surface	4 g/cm <sup>2</sup> Al	440 rem	80 rem	~ 1.8%
+ shielding	15 g/cm <sup>2</sup> Al	19 rem	9 rem	~ 0.2%
On martian surface	16 g/cm <sup>2</sup> CO <sub>2</sub> (atm.)	9 rem	4.6 rem	~ 0.1%
+ shielding	60 g/cm <sup>2</sup> Al	< 1 rem	< 1 rem	< 0.03%

\*The excess cancer incidence for a 35-year-old female is roughly twice that for a 35-year-old male.

The rate of irradiation per unit time and the age and sex of the individual at irradiation are also important. Younger people are more sensitive to the cancer-inducing effects of radiation than older people, and females are more sensitive than males because of cancer induction to the breast and thyroid. Other serious radiation effects include cataracts, genetic damage, and death. Radiation exposure is considered cumulative over an individual's lifetime.

Solar flares and cosmic rays are the most dangerous radiation events that lunar pioneers will be exposed to. The cosmic ray dosage at the lunar surface is about 30 rem/year and, over an 11-year solar cycle, solar flare particles with energies greater than 30 MeV can deliver 1000 rem (Silberberg et al. 1985). Solar flares deliver most of their energy periodically during only a few days out of an 11-year cycle; whereas, the cosmic ray flux is constant.

Although the lunar surface radiation flux is too high to spend much time in, it is definitely possible to alleviate the radiation danger with shielding. When colonists are removed from continuous exposure to surface radiation, long-term settlement becomes possible. As in the case of meteoroid protection, the simplest solution is to use locally available regolith for bulk shielding of habitats.

Silberberg et al. (1985) have suggested that a compacted layer of lunar regolith at least 2 meters thick should be placed over permanent habitats. With shielding of this thickness, the colonists' yearly exposure could be held to 5 rem per year if they spent no more than 20 percent of each Earth month on the surface. In order to provide an overall level of protection of no more than 5 rem per year even in the event of an extreme solar flare, such as occurred in February 1956, the depth of shielding would have to be doubled.

For the sake of completeness, it should be pointed out that some lunar regoliths contain a naturally radioactive component material known as KREEP. KREEP, probably a product of volcanism, contains radioactive potassium, uranium, and thorium. Material containing a high concentration of KREEP should not be used for shielding, and care should be taken to avoid concentrating it as shielding is prepared. The concentration of KREEP in most regolith material would add an amount of radioactivity no more than that in the granite used in buildings here on Earth. If the small contribution by KREEP to radiation dose is considered when exposures are calculated, it should not pose any significant health problem by itself.

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It is a well-known fact that cosmic rays produce secondary particles, such as neutrons, upon collision with matter. These byproducts can add to the radiation exposure if the shielding is not "thick" enough to absorb the secondary neutrons as well. It turns out that the 15.2-cm-thick layer of compacted regolith proposed earlier for a meteoroid shield is not optimum. Obviously, if "thin" shielding is to be used, its utility must be examined in light of its disadvantages.

It seems likely that the initial lunar base will be constructed of modified space station modules, Space Shuttle external tanks, or similar pressure vessels. These pressure vessels will be transported

to the lunar surface and placed in excavations. Once the modules are in place, they will be covered with the previously excavated regolith to provide shielding (see fig. 10). Land (1985) describes various approaches and consequences to providing support for the shielding above the pressurized enclosures. Logistically and structurally the use of bulk regolith is a convenient solution. Its use reduces the need to transport mass out of the Earth's gravity well and favors the transport of sophisticated value-added mass instead. Eventually, as the settlement begins to grow and develop industrial capability, locally available metals, glass, and bulk regolith can be fabricated into new facilities.

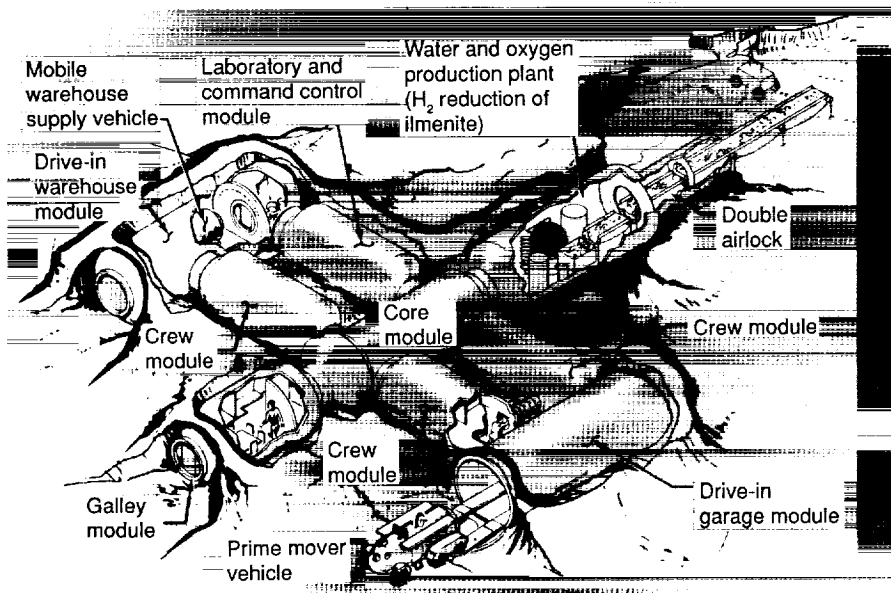


Figure 10

**Lunar Base Modular Configuration**

*Initial base components could be made up of modified space station modules. The frontispiece shows how such modules might look in the panorama of a lunar base.*

*The advantage of using modified space station modules is that they will already have been designed, tested, and fabricated for use in space. The disadvantage is that a module designed for zero gravity and free space exposure might require major changes to fit the lunar environment with 1/6 g, ubiquitous dust, and the weight of piled-on regolith shielding.*

Because of the nature of the lunar environment, much of the pioneers' time will be spent underground within their habitat modules. For safety and convenience, these modules will be linked together with tunnels (see fig. 11). While this underground environment will be different from Earth's standard, it need not be unpleasant or confining. By the time the base is under construction, manned

operations on the space station will have provided a lot of useful experience in human factors engineering. Laboratories, factories, farms, and entertainment facilities will all be integrated into the underground installations on the Moon (see fig. 12). Some types of storage will also be underground, but a number of facilities will remain above ground.

Figure 11

**Shielded Tunnels**

*The modules of a lunar base would be connected by tunnels, naturally shielded from surface hazards. The tunnels could be made airtight for use but would likely also be provided with airlocks for safety in case of depressurization.*

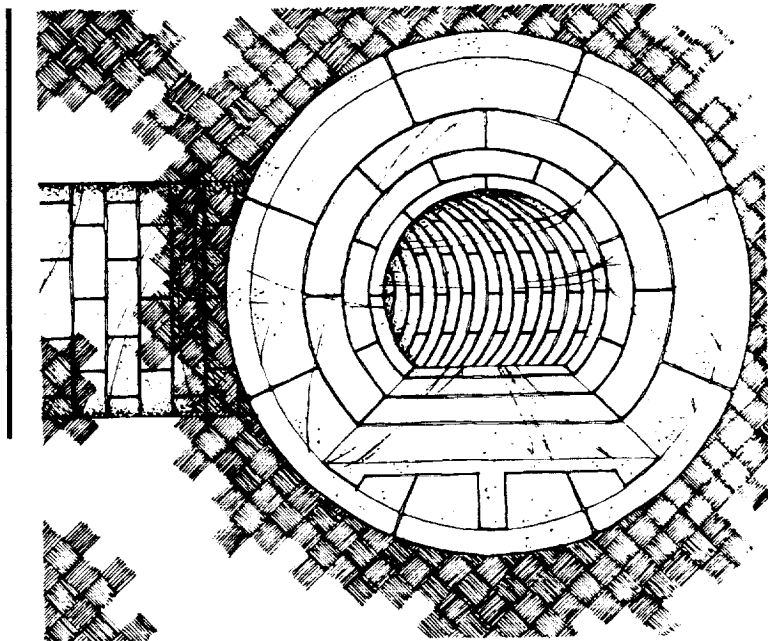
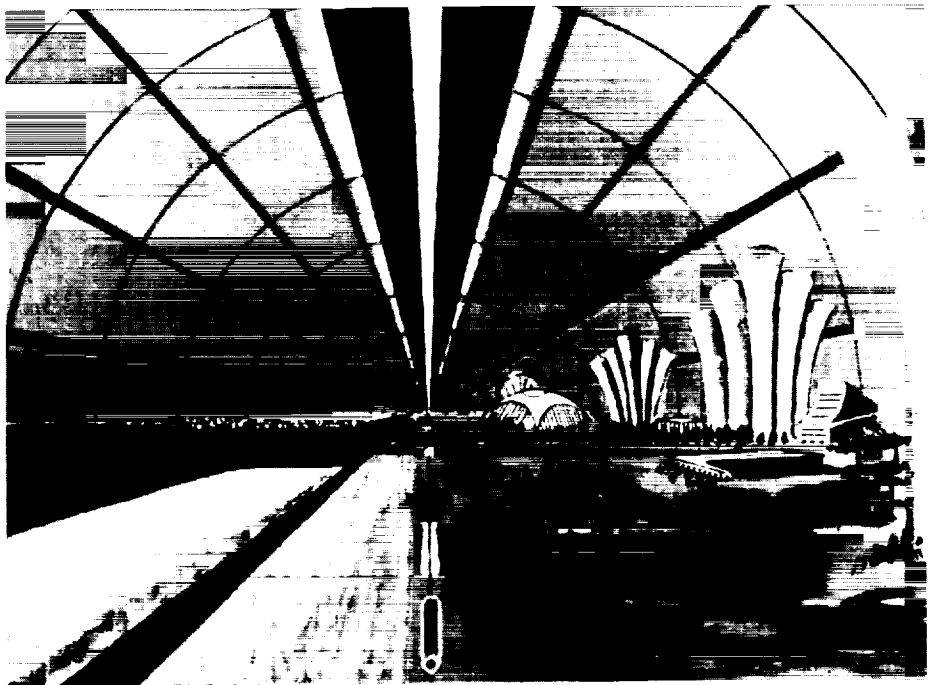


Figure 12

**An Agricultural Zone in Krafft  
Ehricke's Selenopolis**

*Although the initial lunar outpost would no doubt be quite spartan, the expanding lunar base could be modified to make life under the lunar surface quite Earthlike and pleasant.*



Transportation facilities such as hangars, landing pads, and refueling stations will be located on the lunar surface (see fig. 13). Power plants and communications superstructure will be surface installations as well. Some storage will be in surface warehouses (see fig. 14).



Figure 13

#### **Lunar Hangars**

Mobile surface equipment will need to be stored in protective hangars. Such hangars would provide shade against the Sun's heat during the 2-week-long lunar day and lighting for work during the equally long lunar night.

Artist: Pat Rawlings

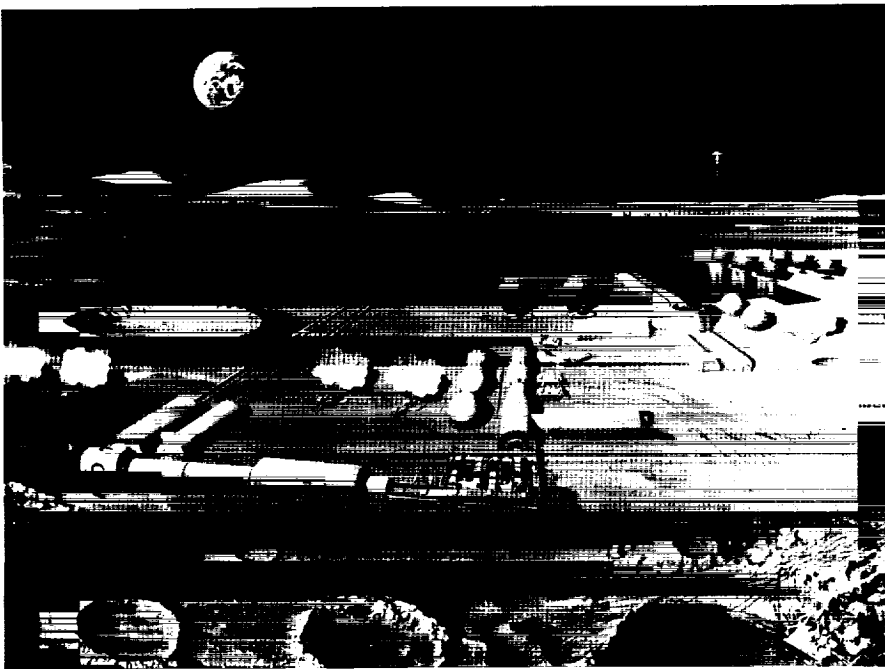


Figure 14

#### **Lunar Surface Activities**

Activities such as mining, transport, and processing will almost by necessity be conducted on the surface. While automation and teleoperation will be used extensively, some minimum amount of human tending will always be required. In this particular concept (from NASDA, the Japanese space agency), a processing plant produces oxygen and metals and an electromagnetic mass driver shoots these products into lunar orbit, where they can be used to support Earth-Moon space activities.

## Strategies for Surface Operations

Although space suits appropriate to the lunar environment were successfully used during the Apollo missions, they are not the only means of conducting surface activities. Moon suits have several disadvantages, one problem being their limited duty cycle. Consumables, recycling systems, and operator fatigue are the most obvious limitations to how long a "moon walk" can last. The Apollo 14 astronauts walked everywhere and averaged about

4-1/2 hours per moon walk. By contrast, the Apollo 17 astronauts' surface activities, augmented by their use of the lunar roving vehicle (see fig. 15), averaged about 8 hours. Another constraint due to moon suit use is the time it takes to dress and undress (see fig. 16) and repair and refurbish the suits. Plenty of spare parts will probably be required. However, these difficulties are minor annoyances. The most serious problem with exclusive use of moon suits for surface activities is their insufficient meteoroid and radiation protection.

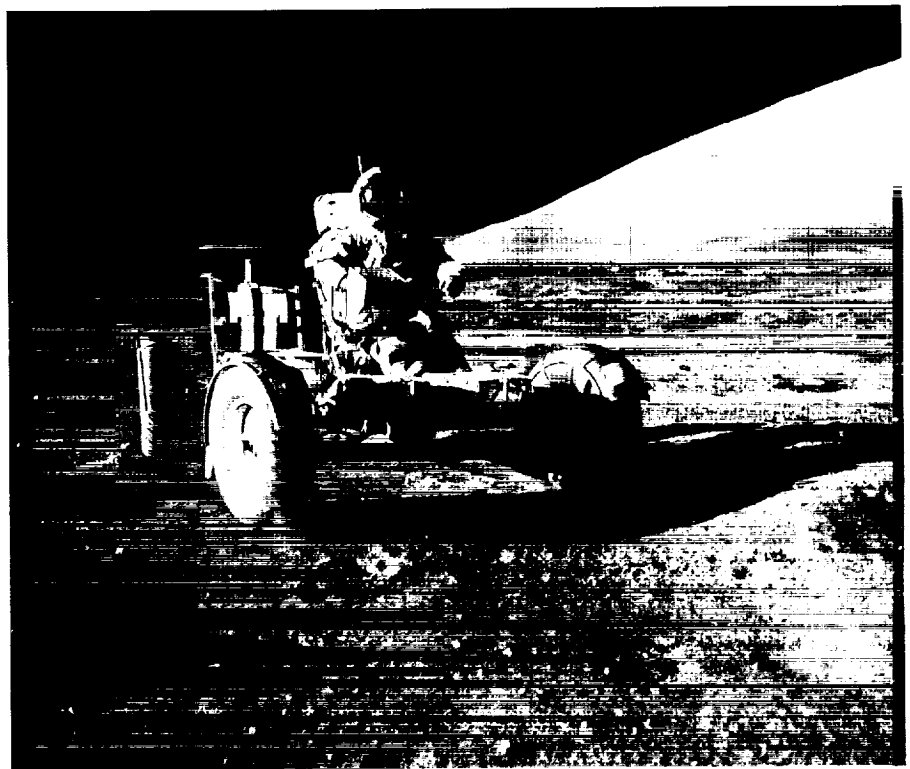


Figure 15

### Lunar Rover

*The use of the Apollo lunar Rover greatly increased the lunar explorers' effectiveness. Mobility will also be very desirable in lunar base operations and will be especially important for scientific exploration.*

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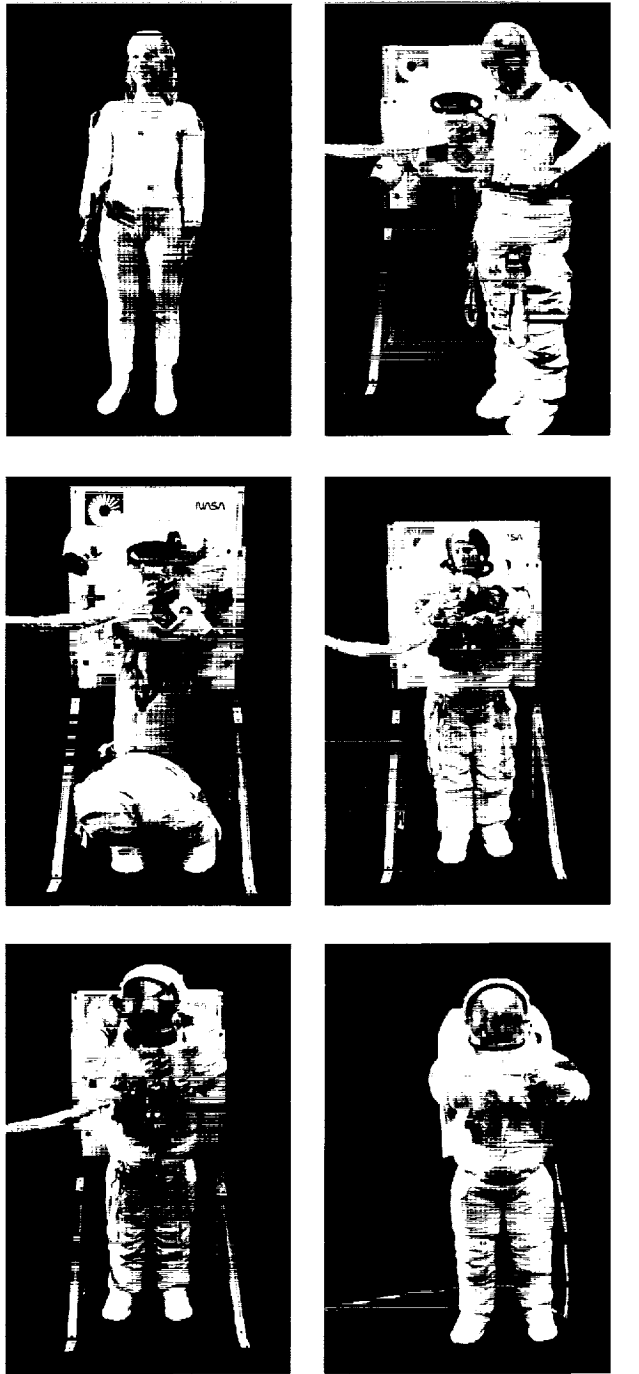


Figure 16

**Suiting Up**

*Much time is consumed donning or doffing a space suit.*



Therefore, the development of pressurized surface vehicles equipped with external tools and manipulators is desirable (see fig. 17). These vehicles would be analogous to the specialized

submarines used for exploration, research, and repair in the Earth's oceans. Such devices provide their operators with a safe environment and permit access to a more hazardous one.

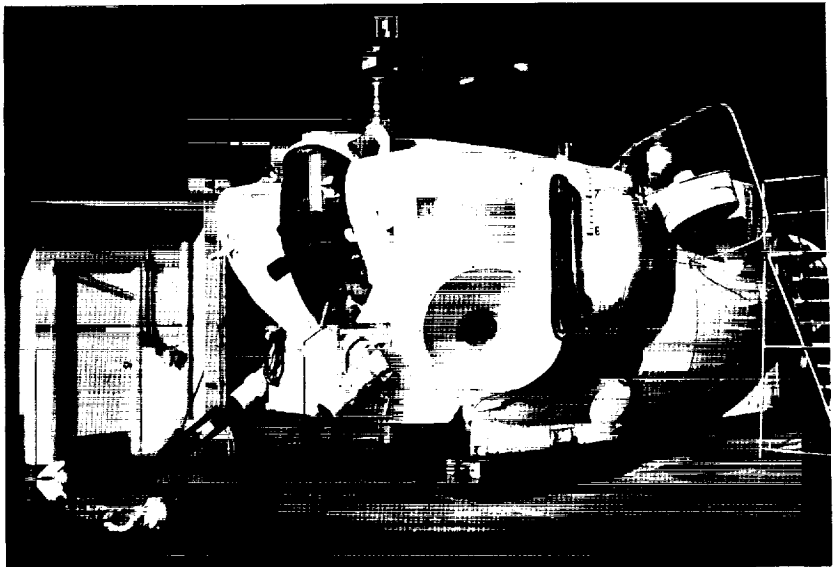
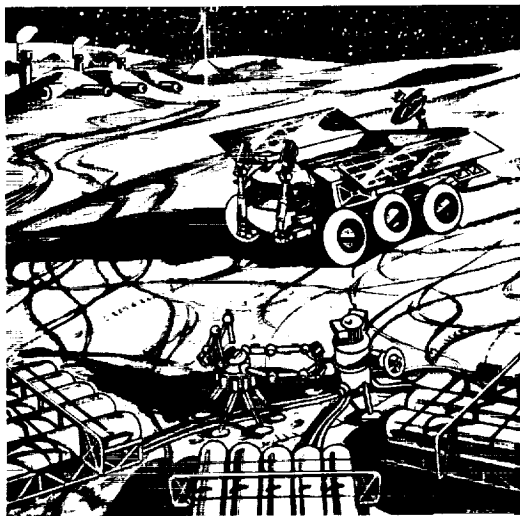


Figure 17

#### **Vehicles for Operations in Hostile Environments**

*"Alvin" deep-diving research submarines protect their crews from the hostile ocean environment while permitting mobility and interaction within it. Cameras, floodlights, and portholes enhance the crew's visual access to their surroundings, and specialized manipulators and end effectors allow physical interaction. Inside the submarine, the crew is maintained in a shirt-sleeve environment. It seems highly likely that pressurized surface vehicles equipped with external tools will be developed to meet similar needs on the lunar surface.*



If vehicles of this type were developed for use on the Moon, they would definitely have to provide meteoroid protection and the radiation protection necessary to keep the occupants' exposure well within the 50 rem/year limit [to the blood-forming organs (NCRP Report No. 98, July 31, 1989, p. 164)]. A thick layer of compacted regolith built into the hull may serve this purpose.

Another way to reduce radiation exposure problems might be to permit only older personnel (volunteers over 35 and people who have already had children) to spend much time on the surface and keep the younger personnel underground. This idea is based on the premise that delayed reactions to irradiation, like cancer, take long enough to develop that older people who are exposed may die of natural causes before the reaction occurs. However, this seems to be a solution of minimal merit. Every colonist will require an individual radiation dosimetry record and a "weather" forecast concerning the solar flare hazard whenever he or she leaves the habitat.

A truly satisfactory solution appears possible. Taking the manned vehicle concept one step further reveals another type of device, the teleoperated robot, which is well suited to the lunar environment. A teleoperated

robot is a remotely controlled device which may be used to provide a human presence in a hazardous environment. Typically, the human operator directly controls the activities of the robot and receives feedback from it, so it is an electronic and mechanical extension of the person, essentially a surrogate body. Teleoperated robots have been used in the nuclear industry for years; they are finding applications in underwater work at great depths; and they have seen limited application in space.

Lunar teleoperators, like the ones shown in figure 18, could be operated in one of two modes: directly from the lunar habitat, as in figure 19, or indirectly from a space station or a facility on Earth. Each mode has its unique characteristics. Operation from Earth would be slower because of the several-second, round-trip radio signal delay. In this case, the teleoperated device may require built-in reflexes to protect itself, if the most recent command from Earth is in conflict with current local conditions. An example of this would be having the teleoperated device stop before walking or driving over the edge of a cliff which has just appeared on the operator's TV screen on Earth. In the early 1970s, the Russians successfully demonstrated the usefulness of their Lunokhod teleoperated roving vehicles on the Moon (see fig. 20).

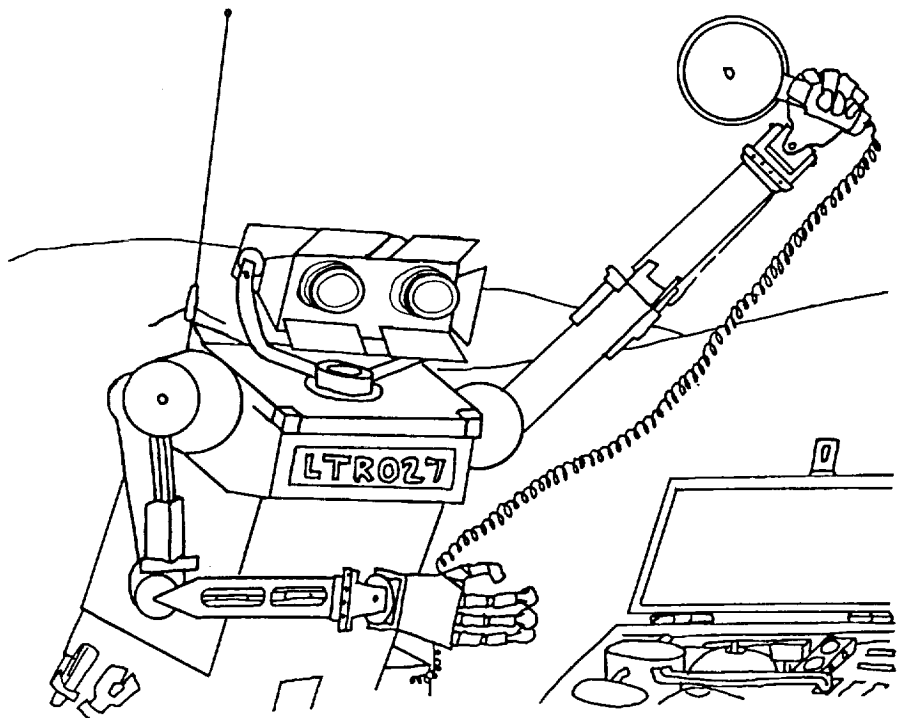
It has been commonly thought that the main problem faced by Earth-based operators who "commute" to work on the Moon by radio would be severe fatigue and frustration due to the timelag. To evaluate this possibility, I conducted a series of lunar-time-delay manipulation and mobility experiments using a mobile robot equipped with a 4-degree-of-

freedom manipulator arm (see fig. 21). My results (1989) indicate that the 3-sec delay inherent in round-trip communication between the Earth and the Moon is not a significant barrier to teleoperated manipulation and mobility. With proper system design, this mode of operation will, at worst, require patient people and predictive positioning aids.

Figure 18

### Teleoperated Robot

Teleoperated robots will be designed to provide a human presence on the lunar surface. This robot's arms have the same freedom of movement as human arms: three degrees at the shoulder, one at the elbow, and three at the wrist. Its hands are modeled on human hands but require only three fingers and a thumb. The robot's head can turn up and down, right and left. It has two TV cameras for stereo vision (with glare shades, which are movable on hinges).



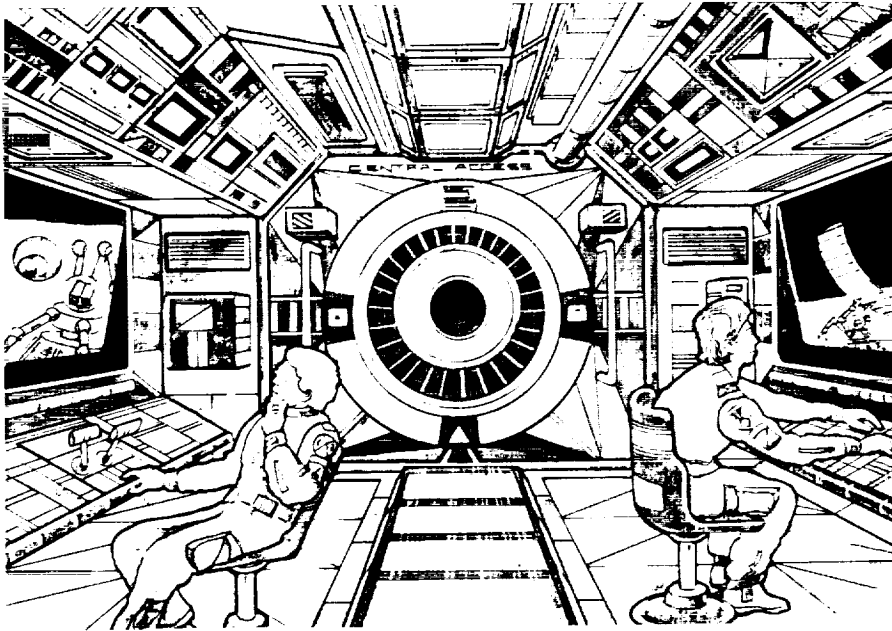


Figure 19

**Teleoperations Control Center  
Underground at the Lunar Base**

Surface activities could easily be directed from comfortable underground facilities. Such control centers would provide safe environments for lunar workers who would otherwise be required to do routine jobs in a hazardous environment. Each operator could supervise the activities of many semi-autonomous robots or directly control one telerobot to apply more specialized skills to the task at hand. Although the two human operators shown are controlling and monitoring telerobotic equipment at two different locations, they could just as easily be coordinating their teleoperations. Such a team effort could even be assisted by additional controllers located at other sites on the Moon or elsewhere, as long as there were enough telerobots at the work site and sufficient communications channels. Keep in mind that the controllers would always have the option to shut down their telerobots temporarily so that they could take a personal break or attend immediately to another matter within the base without losing travel or space suit removal time or wasting limited excursion supplies like oxygen.

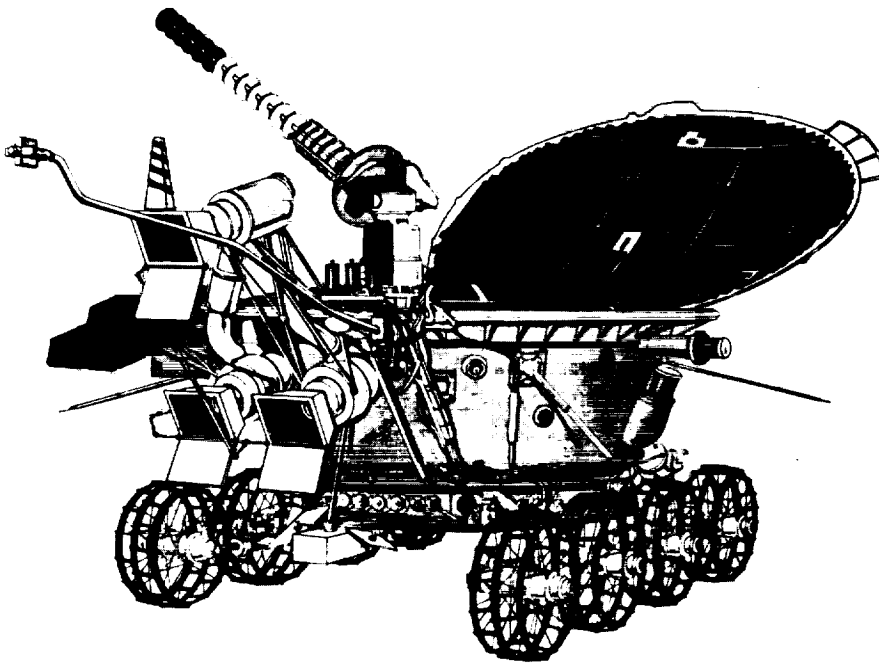


Figure 20

**Lunokhod**

Automated vehicles roving over another planetary body were first used in the early 1970s by the Soviets on their Lunokhod missions. These lunokhods were capable of traveling tens of kilometers at speeds up to 2 km/hr. They were run from a Soviet control center by a crew of five—commander, driver, navigator, operator, and onboard-systems engineer. The crew used slow-scan television images and systems readouts to drive and operate the vehicles.

ORIGINAL PAGE  
BLACK AND WHITE PHOTOGRAPH

Figure 21

**SSI Teleoperations Simulation Chamber**

The Space Studies Institute in Princeton, NJ, has been involved in a continuing experiment to evaluate the usefulness of time-delayed teleoperation under lunar conditions. Here the designers, Rob Lewis and David Brody, demonstrate a telerobotics facility to Jean-Loup Chrétien, who has been a guest cosmonaut. The facility consists of an operator control console and a simulated lunar environment chamber (with its side cover removed to reveal the interior). On the far right, a mobile robot equipped with a 4-degree-of-freedom manipulator can be seen interacting with a workstation while under the time-delayed control of the operator. Although the operator receives video from inside the chamber, direct visual access into it is not possible during experiment runs. The chamber has been optimized to visually replicate lunar conditions when viewed with video cameras.

Photo: Barbara Faughnan



Local use of teleoperated devices would not be hampered by time delays, but it would require additional relay stations, such as comsats or mountaintop repeaters, to overcome the obstacles to line-of-sight radio propagation on the lunar surface. It seems likely that teleoperated robots will be controlled from Earth, from the Moon, and from points in between.

Teleoperated robots will not replace people; rather they will enhance a person's capabilities. As mentioned earlier, the teleoperated robot may be controlled in a master-slave mode, given sufficient feedback to allow the human operator to sense and react to the robot's environment

as if the person were there. Another control approach uses "supervised autonomy." Supervised autonomy involves a working partnership between a human, who sets goals and supervises their implementation, and a more fully automated robot, which is responsible for carrying out specific tasks. Much less feedback would be necessary using this strategy.

Sending a number of teleoperated machines to the Moon to prepare the way for later colonists may be warranted. This would have the twin advantages of maximizing safety and limiting the cost of the initial missions, as local materials could be used to prepare a base

and supplies before the people moved in. Once the settlement was occupied, teleoperators controlled from Earth would act as "force multipliers." They could be run by several shifts of operators on Earth each day (including weekends). Thus, each machine could do the work of three or more lunar colonists, without the costs of bringing those colonists to the Moon and providing life support for them. In addition, teleoperated devices could potentially permit experts from Earth to provide timely services otherwise unavailable locally.

Teleoperated machines used in conjunction with a manned base could be regularly repaired and rebuilt by the lunar staff as required by changing needs. We should remember that teleoperated machines are far less sensitive to radiation than people and can be optimized for their environment and tasks. If a teleoperator is hit by a meteoroid, it may possibly be repaired or salvaged. If not, it certainly is more expendable than a person. Thus, the development of teleoperators for lunar surface use is definitely worth further investigation.

The Moon is an ideal "large" space station and offers many advantages

over other near-Earth locations, such as natural gravity and useful resources. Extensive human activities on the Moon will be constrained initially by the lunar environment because it is so different from the Earth's. Means to ease these constraints are possible and should be pursued. There is much to be gained from a permanent human presence on the Moon.

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