

AFTERWORD

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“Arriving at the lunar module [for the last time], I experience a sense of impending loss. Soon I will leave the Moon, probably forever. And, in a peculiar way, I have come to feel a strange affection for this peaceful, changeless companion of the Earth.” (*Scott, 1973*)

11.1. RETURN TO THE MOON

As the 1990s begin, the Moon is more visible as an object for discussion and planning than at any time since the Apollo program ended nearly 20 years ago. Much of this new interest is scientific. The intervening years have seen a steady stream of new discoveries that have expanded our knowledge about the Moon and have established new ties between the origin of the Moon and the origin of the Earth. But most of the current interest reflects a changed attitude toward the Moon itself. The Moon has become a nearby, familiar, convenient, and accessible world. It has been reached safely by humans, briefly explored, and partly understood. It is natural—almost unavoidable—to think about the Moon when considering the U.S.’s role in the future exploration of space.

Ideas for returning to the Moon with robotic spacecraft and human beings are being heard more often and from higher levels in the government. The goal of using a polar-orbiting spacecraft to make a global scientific survey of the Moon has been studied for nearly two decades (*Lunar Science Institute, 1972*) and has been recommended by several NASA advisory committees (e.g., *Solar System Exploration*

Committee, 1983). In 1986, a presidential commission (*National Commission on Space, 1986*) proposed an ambitious long-term space program that included robotic exploration of the Moon, establishment of a human outpost on the Moon, the use of lunar resources, and human expeditions to Mars. On July 20, 1989, President George Bush marked the 20th anniversary of the Apollo 11 landing by establishing what is now known as the Space Exploration Initiative (SEI), a long-term program of human exploration, first of the Moon and then of Mars.

Since the President’s speech, NASA, the National Space Council, the National Academy of Sciences, and many organizations in the private sector have been actively studying and planning how such exploration could be done. The Moon has suddenly become many things: an exciting focus for planetary science, a target for human occupation, and a resource base for further explorations into the solar system.

11.2. CURRENT UNDERSTANDING OF THE MOON: A BASE FOR PLANNING

11.2.1. The Post-Apollo Moon

The Apollo program’s greatest triumph was to provide enough information about the Moon to plan future exploration and development. Before Apollo,

“ . . . everything we knew about the Moon was based on low-resolution remote sensing, numerical models, and speculation, all carried out by a small number of largely-ignored

scientists. We couldn't even see half of the Moon, we couldn't tell what it was made of, and we had no idea whether it was young or old. To explain any observed lunar phenomenon, there were a variety of theories, all of them untestable, and most of them wrong." (*Briggs*, 1986, pp. iii-iv)

Because of the Apollo program, it is now clear that humans can return to the Moon, that they can live and work on it, and that they can do important scientific work while they are there. Much of the Moon is still an exciting mystery, but its nature is now known to a degree never before possible. The Moon has become an individual world with its own set of unique characteristics.

Dryness. Much to the surprise of almost everyone, the Moon seems to be a completely waterless planet. Its returned rocks contain no water, unlike almost all rocks on the Earth. Water, possibly brought in by cometary impacts, may be preserved at the lunar poles (see section 3.8), but water has apparently never played a major role in the Moon's history.

Lifelessness. The Moon turned out to be just as dead as almost everybody thought it would be. No life, living or fossil, has been found on the Moon. The Moon is even poor in the key chemical elements that are essential for life: hydrogen, carbon, nitrogen, and others. (There is more carbon brought to the Moon by the solar wind than there is in the lunar rocks themselves; see section 8.8.)

Diversity. The Moon is not a homogeneous, uniform world; its surface is made up of a wide range of rocks. The light and dark regions (highlands and maria) seen from Earth are the end result of planet-wide chemical and geological separations during a long period of ancient lunar history. The highlands are made up of ancient, light-colored, Al-rich crustal rocks. The maria are covered by younger, dark-colored, basaltic lavas. All over the Moon there are also complex breccias, fragmental rocks produced by meteoroid impact.

History. The Moon is not just a large meteoroid, primordial and unchanged since the solar system formed. Instead, it is an evolved planet with an exciting and unique history whose outlines have been established by dating the returned samples. The oldest lunar rocks stem from events dating almost to the formation of the solar system, 4.6 b.y. ago. Once formed, the Moon has been modified by a variety of geological forces: widespread primordial melting, intense meteoroid bombardment, internal heating, and the eruption of huge floods of basaltic lava. For about the last 3 b.y., the Moon appears to

have been quiet, although some basaltic volcanism may have occurred in this period. The seismometers placed on the Moon's surface by the Apollo astronauts suggest that it is relatively inactive now.

Surface weathering. Even with no water or air, the Moon is "weathered" by the small cosmic particles that continually bombard its surface. This bombardment has gradually built up the regolith, a powdery layer that covers and conceals the Moon's bedrock. This layer has also trapped and preserved cosmic particles from the sun (the solar wind) and the stars (galactic cosmic rays).

The scientific exploration of the Moon has not ended with the Apollo and Luna programs. Sample analyses, data analyses, and pure serendipity have all expanded the picture of the Moon since the last Luna mission in 1976:

- Small fragments of new lunar rocks and minerals continue to be found in soils and breccia samples, increasing the diversity of known lunar rocks and indicating that the bedrock at the Apollo and Luna sites is not representative of the entire Moon.
- Additional lunar samples have unexpectedly appeared as meteorites collected from the Antarctic ice cap (see section 2.2).
- The solar-wind N trapped in lunar soil breccias shows a significant increase in the isotopic ratio $^{15}\text{N}/^{14}\text{N}$ over geologic time, a change still unexplained by lunar scientists and solar astrophysicists alike (section 7.7).
- As more lunar samples have been analyzed, the uniform primordial "magma ocean" has been splitting into a more complex pattern of smaller "magma seas," leaving behind many unanswered questions about the formation of the lunar crust and the Moon's internal structure (section 2.4.3, especially Fig. 2.5).
- Twenty years of continuing laser ranging to the retroreflectors left by the Apollo astronauts have improved our knowledge of the Moon's motions and orbital dynamics; the Earth-Moon distance, about 400,000 km, can now be measured routinely with a precision of 2-3 cm.
- Finally, a new theory for the origin of the Moon has appeared: the "Giant Impact" of an early planetesimal with the primordial Earth, which spun off heated and vaporized material to make the Moon. This idea is supported (for the

moment at least) by both theoretical studies and the extensive chemical data obtained from returned samples (section 2.4.1).

Scientifically, the Moon has become many different worlds. It is an archive of early planetary history, which preserves for our inspection the records of ancient processes that shaped all the terrestrial planets, including the Earth. The Moon is also a space probe and time machine, for its soil has trapped and preserved the historical records of the sun and the stars. And it is a partner of the Earth, for it now seems clear that the origins of the two worlds—and our own beginnings—are somehow tied together.

The Moon is also a world we can use. Only three days away from Earth by spacecraft and already partially explored, it is a natural target for future human exploration. Geologically, the Moon is still largely unknown, waiting for humans to fill in huge blank areas on its map (see Plates 10.1 to 10.6). The unsolved geological problems of its origin and history can be attacked with the new scientific and exploration capabilities that humans can provide, just as humans have long explored the geology of the Earth. The Moon is also an excellent base for equipment; it is a stable, airless platform on which to erect instruments for many sciences: astronomy, physics, chemistry, life sciences, and a host of others.

Finally, the Moon is a good place to build and launch other things. Its low gravity provides stability for construction, but it is still easy to launch large payloads back to Earth or out to Mars. Oxygen makes up fully half the weight of the Moon's rocks, and much of the remainder consists of potentially useful metals: Fe, Ti, and Al in particular. The Moon could supply many of the materials needed for large operations in space: bulk shielding to protect against radiation, metals and melted glasses for construction, and oxygen for propellants and life support.

11.2.2. Environmental Impacts

Many unfavored and uninhabited regions of the Earth, once ignored as “worthless,” are now valued and preserved as aesthetic monuments because of their austere beauty. Astronaut Edwin (“Buzz”) Aldrin Jr. was stunned by the “magnificent desolation” of the Moon (*Armstrong et al.*, 1970, p. 325). The awe that lunar terrains have produced in their few human visitors is clearly seen in the words and lives of the astronauts who have been exposed to the Moon (*Collins*, 1974).

The lunar surface environment (see Chapters 3 and 4) has been described as dead, harsh, extreme, and hostile. Human survival and scientific operations there are difficult and challenging. Yet many present

lunar environmental features are precisely what make the Moon a desirable place to be. The lack of an atmosphere is good for astronomy, and the large-scale availability of heat and cold makes exciting chemistry and physics experiments possible. The present lunar environment is not to be wasted, and its preservation must be an important part of planning for the future use of the Moon.

The lunar surface environment will be changed greatly when humans return for long visits to do scientific research or to mine lunar resources. The lunar environment is clearly vulnerable to change, and changes have already been produced. The astronaut footprints and the equipment left at the Apollo landing sites will last for several million years (until, of course, they are disturbed by future visitors).

Human effects on the near-vacuum lunar atmosphere are more impressive and potentially more worrisome. Each Apollo mission released on the Moon a mass of gas roughly equal to the existing lunar atmosphere (*Vondrak*, 1974). Measurements of the atmosphere during the Apollo 12 mission found that routine depressurizations of the Lunar Module, many meters away from the detectors, abruptly raised the local gas concentrations by an order of magnitude above the landing-induced local atmosphere of 10^{-6} N/m² (10^{-8} torr). The gas cloud surrounding an astronaut as he moved across the lunar surface was sufficient to saturate the detector (10^{-4} N/m² or 10^{-6} torr) any time the astronaut approached within a few meters (*NASA Manned Spacecraft Center*, 1970). After the Apollo 14 mission was over, continuous monitoring of the Apollo 14 landing site indicates that it will be years before the daytime atmospheric pressure at the site will drop back to the normal 10^{-10} N/m² (10^{-12} torr) (*Johnson et al.*, 1972; see Fig. 3.12). With a low mission rate, the lunar atmosphere can recover from these perturbations, but the effects of continuing missions, large-scale occupation, and lunar mining activities need to be considered in more detail (section 3.9.3).

Planning to minimize the effect of future human explorations on the lunar environment is essential. Some of the possible effects are mitigated by another factor—the growing realization that merely living on the Moon will require a rigidly controlled and largely closed ecological life support system (*MacElroy et al.*, 1985). With all wastes (especially fluids) contained in a closed system for cost and logistics reasons, the dry and airless lunar environment will remain largely unchanged. In addition, human lunar habitations will have to be located underground or beneath thick layers of regolith to provide shielding from lethal cosmic radiation and solar flares. Perhaps much lunar industry will also be carried out underground.

11.3. GOALS FOR FUTURE LUNAR EXPLORATION

The space program has always had two seemingly contradictory themes: pure adventure and pragmatic benefits. To some, these two themes cannot coexist. There is a perception that the adventure ended abruptly with the Apollo landings and that lunar exploration will now be pragmatic and a little boring, an idea equivalent to believing that all adventure in the New World ended with Columbus' fourth voyage. Adventure—perhaps sometimes unwanted—will continue to be a natural part of future lunar exploration. What has changed since the Apollo program is that these explorations and adventures can now be confidently planned. The interest in returning to the Moon has generated a large number of publications (see Appendix A11.1), in which four general goals for future lunar exploration are discussed in detail: science, transportation, resources, and benefits to future astronauts.

11.3.1. Science

Science goals for the Moon fall into two types: *planetary science*, which studies the Moon itself, and *platform science*, in which the Moon is used as a base for instruments for other kinds of scientific observations.

The Moon is an interesting planet in its own right and deserves intensive study with the other terrestrial planets. Initial theories that the Moon might be an unchanged primordial object (similar to a huge meteoroid) were quickly ended by the Apollo missions. The Moon turned out to be something far more interesting: a partly-evolved planet with its own geological history. The Moon preserves an important record of early events that occurred on all the terrestrial planets between about 4.6 and 3 b.y. ago, a record that has been largely destroyed on Earth by our planet's thick atmosphere, abundant water, and crustal movements. Furthermore, the Moon preserves records of the sun's behavior during this same period. Ancient lunar soils, developed and then buried under lava flows or layers of impact ejecta, may provide a record of ancient solar and galactic activity. The study of the Moon's geology is still in its infancy. The rocks returned from the Moon so far are only a tantalizing sample of a planetary geologic record that is different from the Earth's but just as rich.

Astronomy and astrophysics are among the most prominent of the platform sciences that would benefit from a base on the Moon. The lack of atmosphere, the stability of the ground surface on the nearly aseismic Moon, and the radio-quiet zones

present on the lunar farside would make possible many deep-space observations not possible from the Earth's surface or even from Earth orbit. These studies range from radio interferometry (*Burke, 1985; Burns, 1985*) to gamma-ray astronomy (*Haymes, 1985*). As one example of experimental physics, the possibility of neutrino detection on the Moon has been proposed (*Cherry and Lande, 1985*). Astronomers and physicists are now thinking more seriously about using the Moon (*Burns and Mendell, 1988*), and the identification of other possible experiments only awaits the application of their imaginations.

11.3.2. Transportation

Small robotic missions to the Moon and into deep space can be launched successfully from the deep gravity well of the Earth's surface. Larger missions, especially human missions headed beyond the Moon, are better launched from places where less fuel is required to overcome Earth's gravity, i.e., from orbit or from the low-gravity surface of the Moon.

The large spacecraft required for a major human mission to Mars, for example, could be assembled in space from materials brought up from the Earth in a series of small launches or supplied from the Moon. Potential lunar resources, especially oxygen and metals, could be used on platforms at the gravitationally stable Lagrange points in the Earth-Moon neighborhood (*Keaton, 1985*), in facilities in lunar orbit, or on the Moon itself (*Duke et al., 1985*). The Moon is both accessible and fairly well known, and its role as a supporting element in a general space transportation system is likely to increase in importance as flights and commerce in space increase.

11.3.3. Resources

The future use of lunar resources must be considered in terms of two different markets. The first market is in space, and the economic driver is gravity. It is gravitationally easier to transport a given mass (e.g., of oxygen) from the low-gravity lunar surface down to Earth orbit or out to Mars than it is to lift the same mass from the high-gravity surface of the Earth. As the required consumption of oxygen in space increases, a lunar source becomes more attractive, despite the complexity and expense of developing the required facilities on the Moon.

The second market for lunar resources is on Earth, and the economic driver must be terrestrial scarcity. At present, no such market exists, aside from the scientific market for returned lunar samples. Any future resource would have to be both rare and badly needed to overcome the high cost of bringing it back routinely from the Moon.

These two kinds of potential lunar resources are discussed briefly in the following subsections. Detailed discussions of specific resources are given in Appendix A11.2.

Lunar resources for use in space. The most readily available resource on the Moon is bulk lunar regolith for use in radiation shielding. This material can be used either in place or transported from the Moon for use in spacecraft being assembled in low-Earth orbit, in lunar orbit, or at a Lagrange point.

Among possible processed resources, rocket propellants are being given the most serious consideration. Such propellants currently account for the great majority of the total mass that must be lifted from Earth to orbit for current deep-space missions (e.g., 77% for the recently launched Galileo mission to Jupiter), and almost ten times as much propellant must be burned in the launch vehicle just to bring that mass to low-Earth orbit. If near-Earth space traffic becomes considerable, then the cost benefits for lunar propellant production (particularly oxygen) could be considerable (Simon, 1985). Possible methods have been proposed for producing O, H, silane (SiH₄), and even more exotic potential fuels. Other possible resources include metals, glasses, fibers, and concrete. If the recommendations of a recent presidential advisory commission (*National Commission on Space*, 1986) are realized in the next few decades, then propellant production will be the first priority for lunar industry. Thus the ties between future space transportation and the future of lunar mining are very close.

Lunar resources for use on Earth. At present the only market for returned lunar materials is for scientific research. The samples are currently so exotic that they are also potentially valuable to museums and private collectors, if they ever become available to private enterprise. However, this value is artificially inflated by their present rarity; the price of lunar samples would deflate rapidly if large amounts were returned as a consequence of lunar development.

One unique possible lunar resource has recently been identified, the isotope ³He, which originates in the sun and is collected in the lunar regolith by exposure to the solar wind (see sections 8.8.1, 8.8.2, and 8.8.4). Wittenberg *et al.* (1987) have suggested that fusion energy might be more readily and safely obtained on Earth if fusion reactors could use ³He instead of the currently-used tritium (³H). Helium-3 is too rare on Earth, where it is overshadowed by the more common ⁴He produced by radioactive decay. On the Moon, ³He might be extracted economically from the regolith, and Wittenberg *et al.* (1987) calculate that the energy gained by returning it to Earth would be about 250 times the energy used

in obtaining it from the Moon. This idea may not come to pass in the form proposed, but it provides an excellent example of the new ideas for using the Moon that may result from further serious consideration.

11.3.4. Benefits to Future Astronauts: *Terra Firma Nova*

For astronauts in space near the Moon, or even in low-Earth orbit, the Moon can provide an attractive haven from the demands of space itself. At a fundamental level, the Moon provides a massive, solid presence that no spacecraft or space station can duplicate. Everyone, astronauts included, knows the basic desire to step out onto a natural surface and walk around. Beyond psychology, there are real concerns about the physiological effects of long-term weightlessness on human beings. Even short periods of weightlessness in both U.S. and U.S.S.R. orbiting space stations have revealed cardiovascular problems, skeletal and muscular atrophy, and loss of bone calcium, as well as potential psychological problems (Nicogossian *et al.*, 1989; Lorr *et al.*, 1989; Garshnek, 1989; Spangenburg and Moser, 1987). The longer periods spent in weightlessness by U.S.S.R. cosmonauts have verified these problems and have spurred the search for countermeasures.

If humans become numerous in space, the Moon can provide a convenient and accessible remedy for their needs. The low gravity of the Moon may not provide a complete cure for the physiological problems of weightlessness, but low gravity is likely to be better than none. Furthermore, humans in a lunar base can be shielded from the harsh radiation environment of space (especially from short-term solar flares) more easily and for longer periods of time than in a spacecraft or space station. If the future occupation of space is to be prolonged and open to many individuals, the Moon provides an attractive haven for rest, recreation, recovering from weightlessness, avoiding solar flares, and even for taking long walks or otherwise exercising in a gravitational field.

11.4. UNANSWERED QUESTIONS ABOUT THE MOON

Although our current knowledge about the Moon's nature, materials, and surface environment are adequate for detailed planning of future human activities, much important information is still missing from our current knowledge. These gaps are discussed below. The relevant research questions are listed, with emphasis on the scientific details, in Appendix A11.3.

11.4.1. The Lunar Environment

Information on the radiation and thermal environments of the lunar surface (Chapter 3) is critical because both humans and their equipment will require protection from such harsh conditions. Knowledge of radiation exposure conditions at the lunar surface is very good, but detailed biomedical studies of long-term radiation exposure hazards are still needed. For example, we need to know such basic facts as the amount of surface radiation exposure time that can be endured by astronauts on long lunar excursions.

The data on heat flow from the lunar surface are scanty and somewhat uncertain (section 3.6), leaving questions about whether the lunar heat flow is really as high as the Apollo measurements indicate. The available heat-flow data indicate that living quarters, which must be buried to provide protection from radiation, will also need extensive heat-rejection equipment.

Finally, the most unknown lunar regions are the polar areas. There is no information about whether any permanently shadowed (and therefore permanently supercooled) areas exist there, or whether frozen water and other volatiles are present.

11.4.2. Lunar Surface Processes and Evolution

Many problems about early planetary history (sections 2.4 and 8.2) are little better understood for the Moon than for the Earth. Some outstanding questions, like “How old is the oldest volcanism?” or “Are there remnants of the original magma ocean?” stand a better chance of being answered for the Moon than for the Earth. The fact that (in contrast to the Earth) dynamic geological activity ceased on the Moon a long time ago generates other questions like “How young is the youngest lunar volcanism?”

The background to most of these questions is given in the earlier chapters of this book and in Appendix A11.3. Some of these questions deal with speculations that have only been touched on in the earlier chapters, either because of a lack of data or a lack of space. As one example, there is the question (item 13 in Appendix A11.3) of “What causes the lunar transient events?” These “transient events” include enigmatic brightenings or obscurations observed by Earth astronomers, mostly from the Aristarchus Plateau but also associated with a large number of widely scattered impact craters (Tycho, Gassendi, Grimaldi, Humboldt, and many others; see *Middlehurst*, 1977). These events are mentioned briefly in section 9.2.3, where electrostatic charging of lunar surface dust is suggested as one possible cause of the optical effects. It is also

possible that these events are related to gas emissions from the lunar interior, perhaps enhanced in areas of high KREEP content (where gases may form over long timespans by radioactive decay of nongaseous elements), at sites where relatively large but young impact craters have fractured the outer lunar crust, and at sites associated with the extensive fracturing and rille formation along mare-basin rims (see Fig. 4.29c). There is some support for this hypothesis from the Apollo 15 and 16 orbital alpha-particle measurements, which detected areas of enhanced ^{222}Rn (from ^{238}U decay) as well as ^{210}Po (from decay of the Rn daughter ^{210}Pb , accumulated on the lunar surface after several years of Rn diffusion from the lunar interior; see *Gorenstein et al.*, 1974). These areas of enhanced radioactive daughter gases correlate roughly with the sites where optical transient events are concentrated. This explanation of lunar transient events is far different from that of electrostatic charging. A detailed investigation of the transient events may not only resolve the question of their origin, but may also provide one answer to the search for useful concentrations of volatile elements on the Moon.

The Moon will also serve as a field laboratory for studying processes that cannot be studied on Earth. The well-preserved impact craters of the Moon will provide data about the rare and violent changes that accompany impact events, thus leading to a better understanding of how such events affect the surfaces of all the planets and moons in the solar system. Dating the impact melts in the younger craters will help to “calibrate” the impact sizes and frequencies over the last few hundred million years, a calibration that might help to explain the major extinction events in Earth history (*Hörz*, 1985b). There has been much speculation about the cratering process, and the “ground truth” provided by studying the lunar craters is needed to obtain definite answers.

Beyond these problems remain the still-unanswered questions of the origin of the Moon and its relationship to the origin of the Earth itself.

11.4.3. Lunar Minerals, Rocks, and Soils

The extensive datasets provided on lunar minerals (Chapter 5), rocks (Chapter 6), and soils (Chapter 7) still represent a small set of intensely-studied samples rather than the results of a systematic and global sampling of the Moon. It is clear that a large fraction of existing lunar rock types were never sampled by the Apollo or Luna missions. For example, *BVSP* (1981) indicates that about two-thirds of the mare basalts on the lunar surface are unlike any yet sampled; the fraction of unknown pristine highland rocks may well be even higher.

Similarly, there are almost certainly some minerals that occur on the Moon that have not yet been collected (Vaniman and Bish, 1990). There are still questions about the existence of (1) economic mineral deposits, (2) primitive lavas that rose directly to the surface from the lunar mantle without losing crystals or becoming contaminated during their ascent, (3) actual fragments of the lunar mantle brought to the surface in volcanic lavas, and (4) large bodies of lunar granitic rock.

Exploration, either by humans or by sophisticated robots, is also needed to determine (1) how thick and widespread are the sheets of impact melt associated with large lunar craters; (2) whether ancient regolith has been preserved under old lava flows; (3) what the highland megaregolith is like, how thick it is, and what underlies it; and (4) how much of the Moon's original and present chemical constituents have been introduced by impacting meteoroids.

11.4.4. Lunar Chemistry

The systematics of lunar chemistry and its variations (Chapter 8) provide a similar variety of unanswered questions, many of which are related to the probable existence of unknown and unsampled lunar rock types. Many current inferences about chemical components (in particular, the ever-present KREEP), depend on ideal assumptions that may be changed or destroyed as more data become available. Even with the current data, it is hard to establish which chemical trends reflect internal lunar processes and which are due solely to the results of impact mixing, melting, and vaporization. Finally, a determination of the true bulk composition of the Moon is still lacking.

11.4.5. Lunar Physical Properties

The gaps in our knowledge of the physical properties of lunar materials (Chapter 9) are due to the same limitations as our knowledge of the lunar surface itself (Chapter 3). Both sets of data rely heavily on the limited studies actually made on the Moon. The lunar conditions of high vacuum and extreme dryness are difficult—often impossible—to duplicate in a terrestrial laboratory on the scale necessary for measurement of many key physical properties.

Nevertheless, the known physical properties indicate several areas where more research is needed to provide the basis for a viable lunar outpost. The foundation material for all structures will almost certainly be lunar regolith; true bedrock may be unavailable at reasonable depths (<5–10 m), except where young lava flows or impact melt sheets are present, on steep slopes within the walls of rilles (see Fig. 3.5), or in crater walls and central peaks (see

Fig. 4.12b and Plate 10.9). It is therefore essential to learn (1) what design limitations are imposed by the fundamental strength of the regolith and its stability in excavations; (2) what deeper excavations (>10 m) into the highland megaregolith might encounter; (3) whether the fine (dust) component of the regolith, which was a constant problem during the Apollo missions, will overcome and destroy our best vacuum- and dust-sealed bearings and other mechanical components; and (4) whether lunar dust will create respiratory problems for humans during long stays on the Moon.

11.4.6. Global Lunar Data and Future Mapping

The Moon is still poorly covered by remote observations, as the existing global maps clearly indicate (Chapter 10). In fact, current maps of the Moon are not nearly as complete as maps of Mars. The orbital information collected by the last Apollo missions is confined to a limited near-equatorial zone (Plates 10.1–10.6), and telescopic multispectral imaging from Earth is limited to the lunar nearside (Plate 10.9).

This incomplete coverage can be filled out by the proposed Lunar Observer mission, probably in time to provide essential data for planning the human return to the Moon. The Lunar Observer spacecraft could carry a wide range of remote-sensing instruments: gamma-ray and X-ray spectrometers, a microwave radiometer, visible- and near-infrared scanning spectrometers, a thermal-infrared spectrometer, camera systems, magnetometers, a variety of spectrometers to measure the lunar atmosphere, and a subsatellite for accurate radio tracking. From a polar orbit, this assemblage could produce complete global maps of the Moon's surface chemistry, surface mineral composition, surface thermal properties, landforms and geological features, magnetic and gravitational fields, and the lunar atmosphere.

These orbital measurements will have a major advantage—they can be calibrated by observing Apollo and Luna sites and using the actual data obtained from samples collected at those points. The increase in knowledge about the Moon as a result of the Lunar Observer mission will be comparable to the increase in knowledge produced by the Apollo program itself. With the new database, planning for the human return to the Moon—in particular the selection of landing sites—can move confidently and rapidly ahead.

11.5. THE NEXT STEPS

The Moon and its future role in space exploration are now being actively debated, and the results of this debate are not yet clear. But if the Moon is to

be explored in any way—for science, for human habitations, for resources, by robotic spacecraft, or with human beings—some specific steps are needed now.

The Lunar Observer mission (section 11.4.6) is generally regarded by both scientists and planners alike as the obvious next step in exploring and understanding the Moon. The data it can provide will raise lunar science to a new level of activity and understanding, for the mission will provide a scientific inventory of the entire Moon and will also place the tremendous amount of Apollo data into a global lunar perspective. Much of this data (e.g., chemical and geological maps, surface imagery, and an accurate lunar gravitational field) will also be important to those who are now planning how humans should return to the Moon, where they should land and establish a base, and what they should do there.

Until the Lunar Observer flies, there is much that can (and should) be done on the ground. The scientific potential of ground-based lunar studies remains high, particularly for such activities as new lunar sample studies, telescopic multispectral scanning of the lunar nearside, ground-based radar probing of the Moon, and the application of modern methods to reanalyze the data from old lunar missions. If lunar resources are to be used, then practical demonstrations of resource production must be made before processing systems are sent to the Moon. These activities, along with other ground-based space-science research, have been delayed or cut back during the last few years as a result of the generally constrained NASA research budgets (*NASA Advisory Council*, 1986). The immediate rebuilding of a healthy and active scientific effort to study the Moon from the ground is an important, relatively inexpensive, and independently valuable step in any rational plan to return to the Moon.

The immediate steps in the return to the Moon are clear, and they are worth taking even if the remainder of the path is still uncertain. It is hard to imagine that humans will choose never to return to the Moon. The Moon is too close, too easy to get

to, too scientifically exciting, and too potentially valuable as a science outpost and a resource base to be ignored indefinitely. Human beings have never yet put their footprints on a new land and then turned back, never to return.

11.6. A PERMANENT PRESENCE

The establishment of a permanent lunar base is not a new idea. Even before the exploration of the Moon by spacecraft, concepts of lunar habitation were being carefully evaluated. Figure 11.1 shows a lunar base concept developed two decades before Apollo 11 reached the lunar surface (see *Clarke*, 1951). The base shown in this figure incorporates many of the features important in current concepts of lunar base construction: It has pressurized buildings, both solar and nuclear power sources, hydroponic farms, and even an electromagnetic launcher under construction for the delivery of lunar resources to assembly areas in space. This base is also designed around the key research element of astronomy, a scientific goal for the use of the lunar base that has only recently been revived.

It is interesting to compare Fig. 11.1 with a current model of the lunar base (Fig. 11.2). This model is much more modest, because it reflects the initial “seed” components of a permanently manned base, but it has much in common with the previous figure that predates it by some 40 years. The single greatest difference between these two figures is one not seen—the accumulated knowledge of lunar surface properties, the space environment, and space travel technology that was still the stuff of science fiction when Fig. 11.1 was made.

The lunar base shown in Fig. 11.2 is possible using slight modifications of current technology. The realization of such a base requires commitment more than research, and awaits only the time when a permanent presence in space is seen to be an advantage. The style of the base that is ultimately built may look much like that shown in Fig. 11.2, but the substance of this base will be a tremendous increase in knowledge and in technological capabilities that cannot presently be visualized.

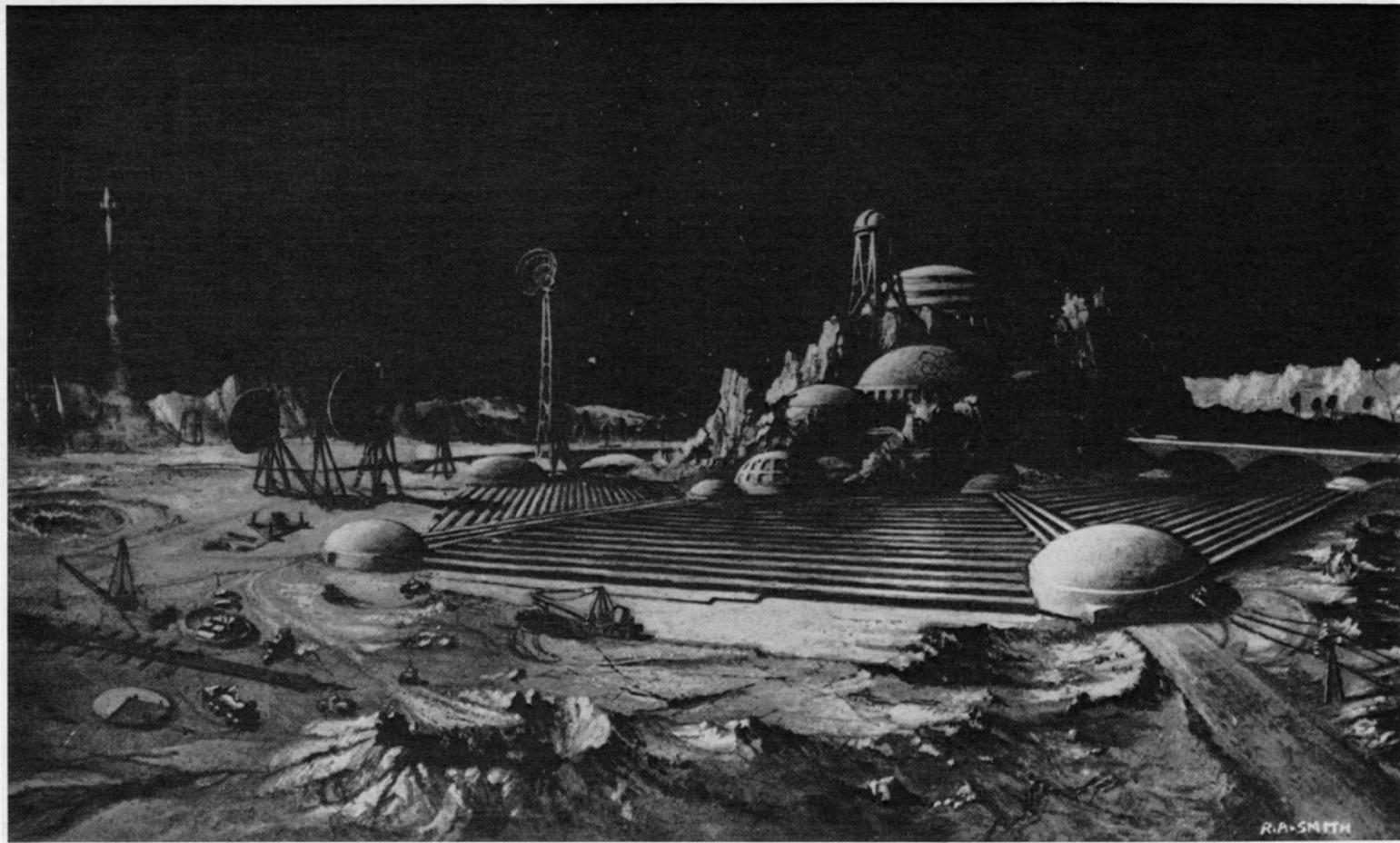
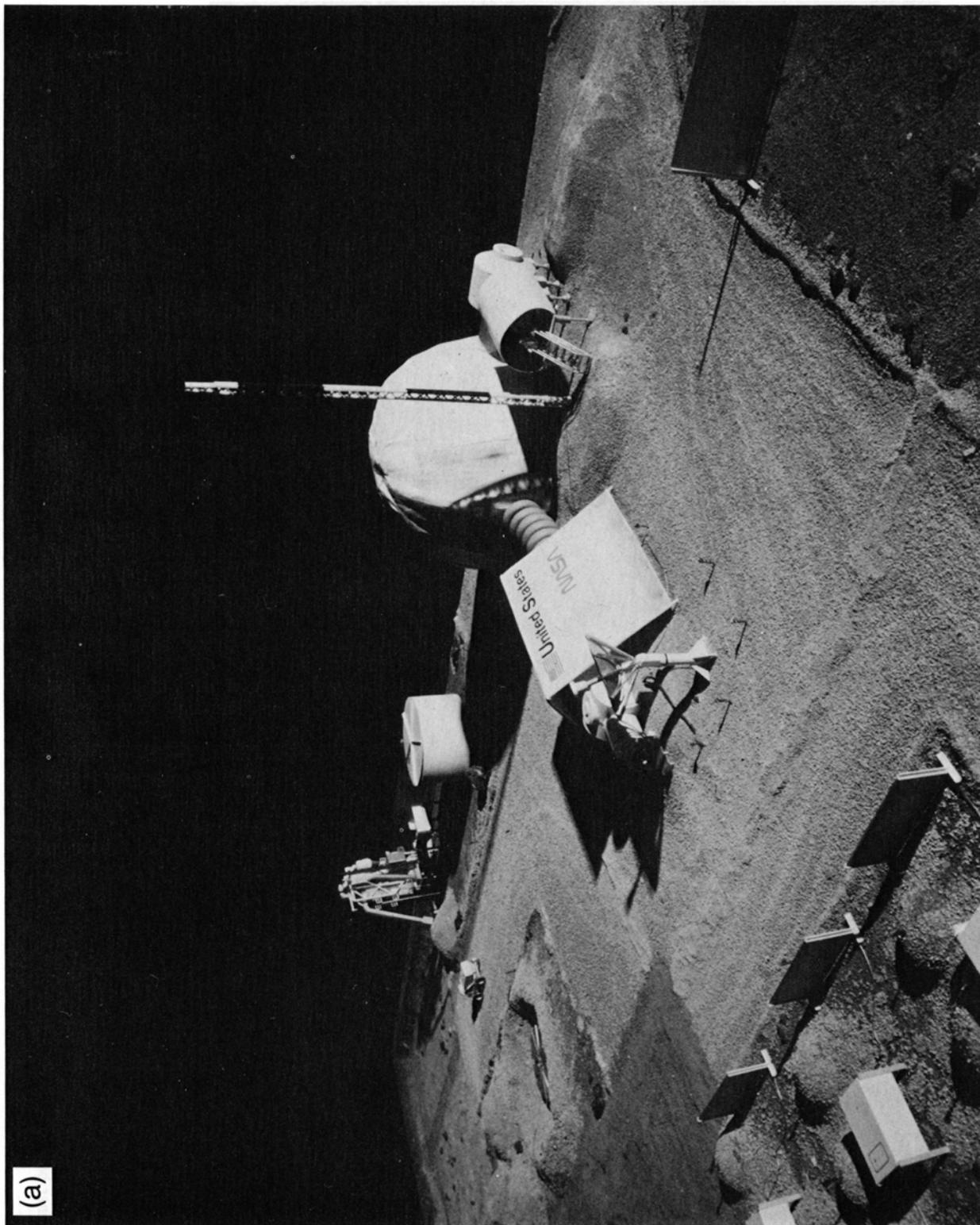


Fig. 11.1. Drawing of a lunar base (ca. 1950) by R. A. Smith (used with permission of the British Interplanetary Society). The base shown is described by *Clarke* (1951). This lunar base concept incorporates solar power (brightly illuminated area in the far distance) and nuclear power systems. The main buildings are set into the central peak of a crater, and surmounted by an astronomical observatory. The space-port is well removed from the living and working areas, a layout that would help to reduce exhaust-driven dust contamination. An electromagnetic launching system for shipment of processed resources is under construction in the left foreground: *Clarke* (1951) suggests the extraction of oxygen from lunar rocks and the production of rocket propellant as key lunar industries. There are some features of this base that would not be considered reasonable given our current knowledge (e.g., the transparent greenhouses arranged in rows around the base's main buildings would probably subject plants and astronauts to unacceptable radiation levels), but the basic features are common to many modern lunar-base concepts.



(b)

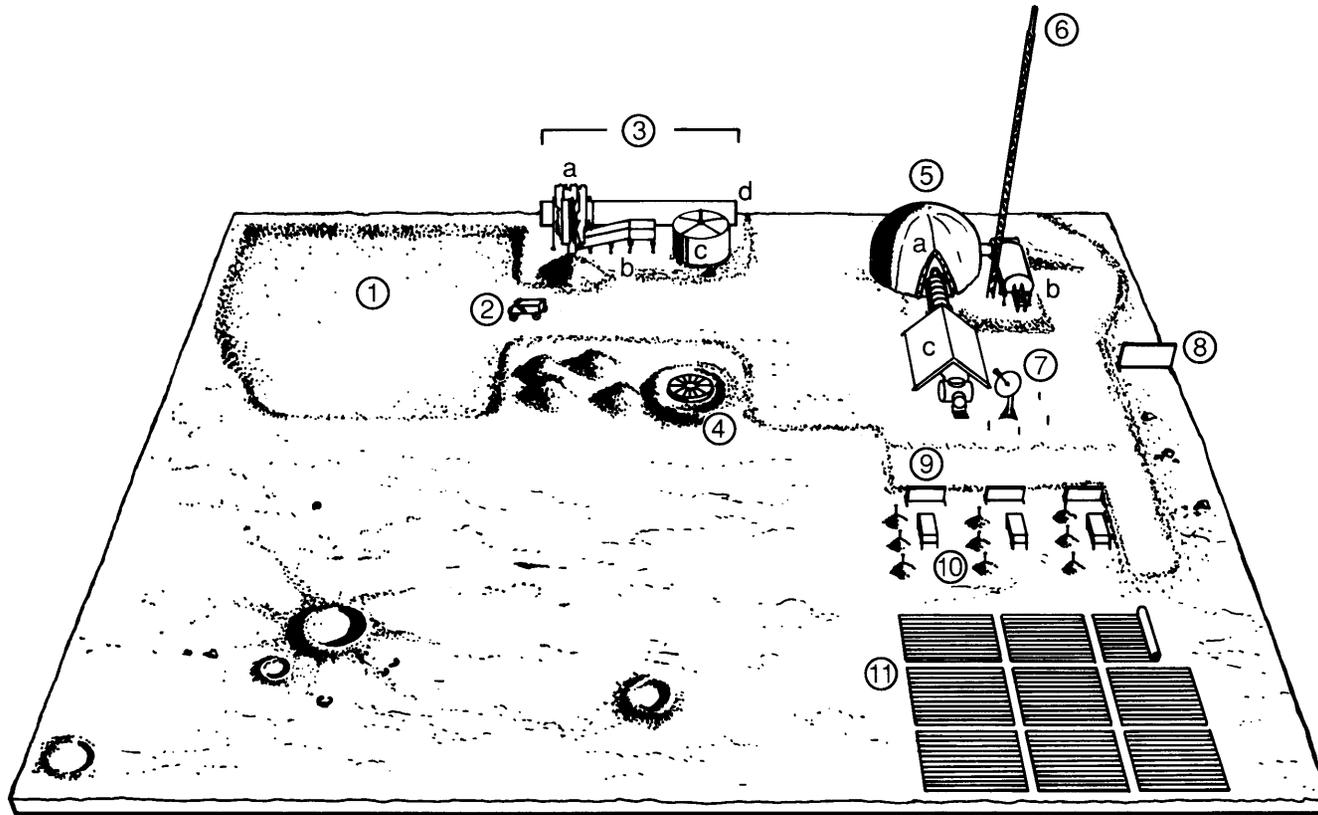


Fig. 11.2. A current NASA model of an initial lunar base (model by Mike Stovall of Eagle Aerospace, Inc.). **(a)** Photograph showing an oblique view of the major structures at the base. **(b)** Diagram showing the main components of the base: (1) A mining pit, excavated by front-end load/haulers (2) to supply a liquified- O_2 propellant production plant (3a). The plant includes tailings storage (3b), 24 t of liquid O_2 storage (3c), and a large radiator for thermal control (3d). The plant is scaled to produce 100 t of liquid O_2 per year by ilmenite reduction. Power for the O_2 plant comes from an SP-100 nuclear reactor (4), buried for radiation protection, that produces 300 kWe. The habitat (5a) is a 16-m dome that houses 12 people and the base operations in five levels, shielded by regolith-filled bags and covered by cloth. The habitat has an airlock (5b) with dust removal systems; remains of the initial base construction shack with a second airlock are shielded by a thermal-protection blanket (5c). The large radio tower (6) provides communications with a pressurized four-man rover (not shown) that may explore areas up to 100 km away; the dish antenna (7) provides high-gain video and data downlinks to Earth. Additional radiators (8 and 9) provide thermal control for the habitat and for fuel cells, respectively. The fuel cells (10) collect energy from Ga-As photovoltaic arrays (11) during the lunar day; each of the three fuel cells provides 25 kWe over the lunar night. Small dirt mounds next to the fuel cells provide thermal shielding for the hydrogen, oxygen, and water that cycle through them.

APPENDIX A 11.1: STUDIES IN LUNAR UTILIZATION

Numerous studies on lunar utilization have been carried out in the last two decades. In considering them, it is first necessary to recognize that the use of the Moon can be considered in several ways. First, there are some things that can be done on the Moon that cannot be done at all on Earth. Getting to the lunar farside to avoid Earth's radio noise and developing processes to take advantage of the extreme lunar daytime vacuum of 10^{-10} N/m² (10^{-12} torr) are two examples. Second, there are lower fuel and energy costs for exporting materials off the Moon (rather than the Earth) for use in space. Schemes for mining the lunar surface for a wide range of materials, from thermal and radiation shielding mass to oxygen-based propellants, make use of this advantage. With the exception of ³He there has been little consideration of lunar exports to Earth (see section 11.3.3), but the development of solar-power satellites using lunar materials is one form of energy export to Earth. Finally, the Moon can be considered useful in its own right as a place worthy of permanent occupation for international scientific and political cooperation. Parallels to the international use of Antarctica have already been made in this regard (Smith, 1985).

This appendix is a brief, annotated historical listing of reports and other publications that represent a wide range of studies on various aspects of lunar utilization. These works are diverse in content, although most view the Moon as "useful" in the second sense defined above, where lunar materials are to be obtained for use elsewhere in space. This listing is not intended to be exhaustive, and many additional individual papers and NASA-sponsored studies are not included. However, the documents cited here provide an excellent entry to the current literature.

1972: Dalton C. and Hohman E., eds., *Conceptual Design of a Lunar Colony*. NASA/ASEE Systems Design Institute. Publication of results from NASA grant NGT-005-114. 506 pp.

Results of an 11-week intensive study by the University of Houston, Rice University, and the NASA Manned Spacecraft Center (now the Johnson Space Center). Sections cover (1) the transition from a base to a colony, with design and function details; (2) a design analysis that includes subsystems and environmental engineering; (3) analysis of physiological, psychological, and safety requirements for the occupants; (4) site selection criteria; (5) oxygen

production schemes; (6) details of a life support system; (7) mining and excavation; (8) a brief discussion of manufacturing; (9) shelter; (10) electric and thermal power generation; and (11) conclusions and recommendations for further study. Written when the Apollo program was at its peak, this is an interesting historical document and one that discusses many details common to later studies of lunar bases and the utilization of the Moon.

from 1974 on: *Acta Astronautica*. Journal of the International Academy of Astronautics. Pergamon, New York.

A journal of 13 issues per year with broad international participation. Papers published are generally aimed at the scientific exploration of space, space utilization, and space development concepts. These papers cover a wide range of topics, some of which are related to lunar utilization. The broad international participation in the production of this journal provides a more global view of space development than obtained from most other publications.

1976: Criswell D. R., ed., *Lunar Utilization*. The Lunar Science Institute, Houston. 188 pp.

A collection of abstracts from a conference held in 1976. Sections include (1) economics; (2) material resources; (3) lunar and space utilization (ideas on processing lunar materials); (4) future exploration of the Moon, asteroids, and comets for utilization purposes; and (5) transportation (getting materials off the Moon).

1977: *Space Manufacturing Facilities—Space Colonies*.

1977: *Space Manufacturing Facilities 2*.

1979: *Space Manufacturing 3*.

1981: *Space Manufacturing 4*.

1985: *Space Manufacturing 5: Engineering with Lunar and Asteroidal Materials*.

1987: *Space Manufacturing 6*.

1989: *Space Manufacturing 7: Space Resources to Improve Life on Earth*.

American Institute of Aeronautics and Astronautics, New York.

These seven books are a collection of papers from nine conferences held at Princeton University. Topics covered include manufacturing in orbit, solar power satellites, space transportation, mass drivers, medical and social topics, international relations, and economics. The papers on lunar materials are mostly concerned with chemical processing or with the electromagnetic ejection of lunar materials from the Moon for use as feedstocks in near-Earth space. Lunar base topics and acquisition of space power for use on Earth receive more emphasis in the later volumes. Future conferences in this series are planned, and more volumes will be added to the series.

1977: O'Neil G. K., ed., *Space-Based Manufacturing from Nonterrestrial Materials*. Progress in Astronautics and Aeronautics, Vol. 57, American Institute of Aeronautics and Astronautics, New York. 177 pp.

Chapters are on (1) transportation (emphasis on mass drivers), (2) materials on the Moon and how to get them off, and (3) systems analysis for space manufacturing in orbit.

1979: Billingham J., Gilbreath W., and O'Leary B., eds., *Space Resources and Space Settlements*. NASA SP-428. 288 pp.

Sections describe (1) regenerative life-support systems, (2) habitats, (3) electromagnetic mass drivers, (4) asteroids as resources, and (5) processing of nonterrestrial materials. The last section includes discussions of a lunar supply base, fiberglass from lunar materials, lunar building materials made with inorganic polymers, assessment of possible lunar ores, chemical extraction of metals and oxygen from lunar materials, and mining and beneficiation of lunar ores.

1980: Williams R. J. and Jadwick J. J., *Handbook of Lunar Materials*. NASA RP-1057, NASA Scientific and Technical Information Office. 120 pp.

This handbook contains sections on (1) general information about the Moon and lunar exploration; (2) physical properties of lunar minerals, with data from their terrestrial analogs where data on lunar samples are lacking; (3) lunar regolith and rock properties; and (4) a summary of the physical properties of SiO₂, Si, Al, Ti, Fe, Ca, Mg, O, and lunar volatiles.

1980-1985: *Space Solar Power Review*. Pergamon, New York.
from 1986 on: *Space Power*. Carfax, Abingdon, England.

A quarterly journal initially dedicated to studies of a particular space technology (solar power satellites) for acquiring energy for use on Earth. After 1985, the scope of the journal was broadened to include all aspects of space resource utilization, space manufacturing, and space colonization. Throughout the journal's publication history, papers on the use of lunar materials for solar-power-satellite manufacture and other purposes have been periodically included.

1982: O'Leary, B., ed., *Space Industrialization*. CRC Press, Boca Raton, Florida. Volume I (167 pp.), Volume II (226 pp.).

Volume I includes an overview, a discussion of near-term products and services, a section on solar power satellites, and a review of possible asteroid resources. Lunar materials are specifically discussed in sections on space manufacturing from nonterrestrial materials (including scaling of processes and research recommendations) and materials processing in space (chemical plant design and chemical processing of lunar materials).

Volume II begins with a section on lunar utilization (including a summary of lunar material properties and possible uses of the Moon as a platform in space, a source of bulk materials, and a source of chemical products). This is followed by sections on large space structures, space transportation, systems analysis and economics, human factors, and the interaction between space industrialization and social science.

1985: Mendell W. W., ed., *Lunar Bases and Space Activities of the 21st Century*. Lunar and Planetary Institute, Houston. 865 pp.

This book is a good introduction to the concepts of establishing a lunar base and using lunar resources. The collected papers are directly relevant to the construction and occupation of a lunar base, with sections on (1) lunar base concepts, (2) transportation to/from the Moon, (3) lunar science from a lunar base, (4) space science from a lunar base, (5) construction on the Moon, (6) materials process-

ing on the Moon, (7) oxygen and hydrogen production on the Moon, (8) life support and health maintenance, (9) social and political implications, and (10) relation to future Mars missions.

(Note: a second volume in this series is based on more recent work and should be released soon by Univelt, San Diego.)

1987: Andrus G. M., ed., *Symposium '86: The First Lunar Development Symposium*. The Lunar Development Council, Pitman, New Jersey. 513 pp.

A collection of 49 papers presented at a 1986 conference that combined interests in lunar development with industrial interests in magnetic-levitation transportation. About 14% of the papers deal exclusively with magnetic levitation, but the remainder either explore the connection between this technology and lunar development or deal specifically with lunar resources, products, architecture, energy systems, and life support.

1988: Johnson S. W. and Wetzel J. P., eds., *Engineering, Construction, and Operations in Space (Proceedings of Space '88)*. American Society of Civil Engineers, New York. 1349 pp.

1990: Johnson S. W. and Wetzel J. P., eds., *Engineering, Construction, and Operations in Space II (Proceedings of Space '90)*. American Society of Civil Engineers, New York. 1598 pp. (two volumes).

These books consist of papers from two conferences with strong representation by civil engineers. Sections directly relevant to lunar utilization include (1) lunar surface properties, (2) processing lunar soils, (3) lunar cement and concrete, (4) lunar construction and surface operations, (5) lunar habitats and mining, (6) lunar base design, and (7) lunar oxygen production. Many other papers deal with orbital operations, robotics, life support, astronomy (especially astronomical observatories based on the Moon), power supplies, and other issues that are common to lunar and other space operations.

The organizers intend to continue holding this conference every two years, with publication of a volume of papers for each conference.

APPENDIX A11.2: LUNAR RESOURCES

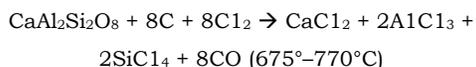
Volumes have been written on the full spectrum of potential lunar resources; Appendix A11.1 is a guide to this literature. In the text below, several major lunar resources are summarized in alphabetical order. Selection of resources for inclusion was based on either (1) abundance on the Moon or (2) a special value attached to the resource. The concepts of lunar resources are constantly changing, and new ideas (such as ^3He , section A11.2.2 below) will probably have to be added to this summary on an almost yearly basis to keep it up-to-date. However, certain resources (e.g., see *oxygen*, section A11.2.5) have already been studied extensively for more than a decade, and they are likely to remain attractive for advanced space exploitation.

A11.2.1. Aluminum

Uses. Aluminum has many potential uses as a light-weight structural metal, as a reflective or coating metal, and perhaps even as a rocket fuel, but Al metal production will probably not be practical until lunar development reaches a scale large enough to support the complex processing required.

Availability. The only practical source of Al on the Moon is the feldspar mineral plagioclase. This mineral is abundant in highland areas, both as single mineral fragments and in anorthositic rocks.

Processing. Concentration of plagioclase from highland regolith is not a well-tested process, but combined sizing and magnetic/electrostatic separation concepts have been considered (see below under *regolith*, section A11.2.6). Concentrations of plagioclase as rich as 90% should be attainable (McKay and Williams, 1979). Plagioclase has been used in terrestrial laboratory and pilot-plant operations for Al production by soda-lime sintering, but this process requires large amounts of Na and Ca carbonate. Several alternative processes are possible; of these, Bhogeswara Rao *et al.* (1979) recommend carbochlorination followed by electrolysis of the chlorides. The initial reaction is



Following this step, the AlCl_3 gas is condensed and mixed with alkali and alkaline earth chlorides for Al extraction by electrolysis. The electrolytic process has been proved by Alcoa (Bhogeswara Rao *et al.*, 1979). To carry out this process on the Moon, carbon, chlorine, and the alkali and alkaline earth chlorides must originally be supplied from Earth, but they can be recycled.

A11.2.2. Helium-3

Uses. A very specific use has been proposed for ^3He in the development of nuclear fusion energy (Wittenberg *et al.*, 1987). The advantages of ^3He fusion over the more studied ^3H fusion method are summarized in section 8.8.4.

Availability. Helium on the Moon is a product of solar wind implantation onto regolith particles. This is a very small amount of He (average of only 10 to 20 $\mu\text{g/g}$ He, concentrated in the most mature regoliths), with ^3He constituting only about 4 to 8 ng/g (about one part in 2500 of total implanted He). Nevertheless, this small amount of ^3He is so much more than found on Earth that it is a potential resource. Helium-3 is presently the only known potential resource from the Moon and cannot be obtained practically on Earth.

Processing. Helium can be extracted from the lunar regolith by heating. Other gases obtained this way are predominantly SO_2 , CO , CO_2 , H_2S , $\text{H}_2\text{O-H}_2$, and N_2 (Gibson, 1973). The gases in the regolith, although rare, could generate pressures up to 10 atm when heated in a sealed collection chamber (see section 8.8.4). All of these co-generated gases also have potential uses (see below under *hydrogen*, section A11.2.3), and fractionation systems to collect all gases would insure the maximum profit from the thermal-extraction process.

The small quantities of He trapped in regolith particles would require thermal processing of large amounts of lunar regolith to obtain useful amounts of the small fraction that is ^3He . Assuming that the average regolith contains 3-4 ng/g collectable ^3He and that only the upper 10 cm of regolith is processed, an area of about 2000 km^2 of unsieved regolith would have to be mined and processed to obtain 1 t of ^3He . This is by far the largest-scale lunar resource processing scheme yet envisioned.

A11.2.3. Hydrogen

Uses. The uses proposed for lunar H_2 fall into three major categories: (1) liquid H_2 and other H-based propellants to fuel rockets (Rosenberg 1985); (2) a reductant for winning oxygen from ilmenite (Gibson and Knudsen, 1985); (3) water production for a wide range of uses.

Availability. Hydrogen is a major constituent of the solar wind, and it is implanted in small amounts in the lunar surface regolith. Although rare, H and other rare regolith gases can be extracted simply by heating. The major constraint on the availability of H_2 is the need to handle large amounts of regolith in order to collect small amounts of gas.

Processing. In addition to conventional furnace heating, other methods of H₂ extraction have been proposed, ranging from microwave heating (Tucker *et al.*, 1985) to microbial extraction (White and Hirsch, 1985). In order to extract useful amounts of H, processing must be on a large scale. Carter (1985) estimates an average H₂ recovery of about one unit mass for slightly more than 2×10^4 unit masses of <20 μm regolith processed. This would correspond to about 9×10^4 unit masses of unsieved regolith. Assuming processing of only the upper 10 cm of the regolith (as with ³He, see section A11.2.2 above), an area of about 0.7 km² of unsieved regolith would have to be sieved and heated to obtain 1 t of H₂. Although this area is large, it is less than 10⁻³ of the area required to extract a comparable mass of ³He. It is evident that large amounts of H₂ would be co-generated if an ambitious scheme of ³He mining were adopted. The production of ~1 t ³He by heating bulk regolith would release $\sim 5 \times 10^3$ t of H₂.

A11.2.4. Iron

Uses. Iron metal has potential structural uses. Its weight, however, makes it less attractive than aluminum for use off the Moon. Glass, which in vacuum can have great tensile and compressive strength, may also be a competing material for structural uses both on and off the Moon (Blacic, 1985). However, Fe could be extracted and used as a byproduct before aluminum and glass plants are in operation, if large-scale O₂ production from ilmenite becomes the first priority in lunar resource uses.

Availability. Iron is common in many lunar minerals and even occurs as small metal beads and fragments in the regolith. Magnetic separation of iron metal from the regolith, however, is complicated by the common occurrence of Fe metal as small inclusions within agglutinates, which are a kind of "slag" produced by micrometeoroid impacts. As with O₂, the energetically most favorable source of Fe is the mineral ilmenite, which is abundant in high-Ti basalts and in the regolith formed over such basalts.

Processing. Extraction of Fe metal beads from the regolith is discussed in section 5.4.3. These beads are extremely fine-grained and are largely enclosed within agglutinates; thus they are unlikely to be a convenient large-scale source of Fe on the Moon. Iron, however, is an almost unavoidable byproduct if O₂ is extracted from lunar ilmenite (FeTiO₃) for life support and propellant uses (see below under *oxygen*, section A11.2.5). For each molecule of O₂ produced, approximately two atoms of Fe are liberated (depending on the ilmenite Fe-Mg composition and the actual processes used). One might also

expect Ti as a byproduct, but substantial additional processing would be necessary to reduce the Ti as well as the Fe to metal.

A11.2.5. Oxygen

Uses. The major use proposed for lunar O₂ is as an oxidizer in rocket propellants. Liquid O₂-liquid H₂ rockets are generally considered most likely, although other liquid propellant mixtures involving oxygen (for example, SiH₄-O₂, CH₃N₂H₃-O₂, S- O₂; Rosenberg, 1985; Vaniman *et al.*, 1990) have been considered. Oxygen is also essential for life support functions, and such consumption could become a major factor if the human presence on the Moon becomes substantial.

Availability. Oxygen is almost nonexistent as a free gas on the Moon; lunar rocks are generally reduced (e.g., all Fe is metallic or ferrous, never ferric) and will not readily release O₂. Oxygen production must be based on extraction from silicate or oxide minerals. If oxygen production is based on reduction of ilmenite, a favorable source, then mineral concentrations from high-Ti mare rocks or soils will probably be necessary (see section A11.2.6).

Processing. The importance of O₂ in life support and in space-based propulsion systems has led to several proposed methods for extracting it from lunar rocks. Ilmenite is often specified as the target mineral for oxygen production, because the energy required to reduce the FeO in ilmenite to Fe + 1/2O₂ is relatively low (ΔH for the reaction is about +9.7 kcal/g-mol at 900°C; Williams and Erstfeld, 1979). Purity of the ilmenite-enriched feedstock needs to be controlled; in particular, S may be a potential process-poisoning contaminant (Williams, 1985). Two basic ilmenite reduction processes are:

1. Using H₂ as a reductant: $\text{FeTiO}_3 + \text{H}_2 \rightarrow \text{Fe} + \text{TiO}_2 + \text{H}_2\text{O}$; followed by splitting of H₂O to produce O₂. The H₂ is recycled (Gibson and Knudsen, 1985).
2. Using C as a reductant (carbothermal reduction), a process involving several sequential steps: (a) $\text{FeTiO}_3 + (1 + x)\text{C} \rightarrow \text{FeC}_x + \text{CO} + \text{TiO}_2$; (b) $\text{FeC}_x + x/2\text{O}_2 \rightarrow \text{Fe} + x\text{CO}$; (c) $y\text{CO} + (2y + 1)\text{H}_2 \rightarrow y\text{H}_2\text{O} + \text{C}_y\text{H}_{2y+2}$; (d) $\text{C}_y\text{H}_{2y+2} \rightarrow \text{C}_y + (y + 1)\text{H}_2$; (e) splitting of H₂O to produce O₂. The H₂ and C are recycled (Cutler and Krag 1985).

Oxygen may also be separated from the gases used in other processing schemes, for example, reduction of the CO used in metal production by H₂ to produce H₂O, which may then be split to produce O₂ (e.g., some schemes for Fe and Ni extraction; see Bhogeswara Rao *et al.*, 1979). Finally, O₂ might be obtained

by other methods less dependent on a concentrated mineral feedstock. Among these relatively feedstock-insensitive methods are electrolysis of bulk regolith (the "magma electrolysis" method described by *Colson and Haskin*, 1990), or by a variety of other chemical and electrochemical schemes (for a summary see *Waldron*, 1990).

A11.2.6. Regolith

Uses. Regolith uses fall into three broad categories: (1) use of unprocessed bulk regolith for purposes such as shielding from cosmic rays and solar flares, (2) processing of bulk regolith to make glasses or ceramics, and (3) use of minerals separated from regolith as a beneficiated feedstock for other processing schemes.

Availability. Regolith is ubiquitous on the Moon; it is the most readily available of lunar materials. It has a broad range in chemical and mineralogic composition. It also varies in the degree to which its mineralogic constituents are agglomerated into impact-fused soil particles and therefore difficult to separate (see discussion of agglutinates, section 7.1.3). If mineral separates are needed (see preceding sections on *oxygen*, A11.2.5, and *aluminum*, A11.2.1), site selection can be used to optimize the extractability of certain minerals such as ilmenite or feldspar. A special type of regolith, formed on lunar pyroclastic deposits, contains much glass and is enriched in certain volatile elements (see Tables A6.5 and A6.6, as well as section 8.7.5).

Processing. Unprocessed bulk regolith intended for shielding may be scooped, shoveled, or bagged and then put into position. Containerization or

casting into blocks may be necessary, particularly if the regolith shielding is to be transported and used elsewhere, either on the Moon or in space.

Processing of bulk regolith by grain-size separation can enhance certain constituents. Collection of the finest fraction can enrich plagioclase and the KREEP-like mesostasis (section 7.5.3), although the enrichment factors are poor (Fig. 7.30) and the energy and equipment devoted to fine sieving (probably to <20 μm separation) may not be cost-effective. Collection of the coarse fraction, however, can result in significant enrichments of certain minerals. In highland soils such as those at the Apollo 16 site, plagioclase can be expected to make up most of the regolith fragments coarser than 1 cm, perhaps as much as 90% if anorthositic soils can be targeted. In high-Ti mare soils the >1-cm fragments would be dominated by basalts with 10-18% ilmenite. More thorough size-separation systems that remove both the fine (<20 μm) and coarse (>200 μm) splits before magnetic/electrostatic processing may be able to produce concentrates of ~90% plagioclase from some highland soils, or a still-undetermined percentage of ilmenite from high-Ti mare soils (*McKay and Williams*, 1979; *Williams et al.*, 1979; *Agosto*, 1985).

Plagioclase is of interest as a feedstock for Al or ceramic/glass manufacture; ilmenite is of interest as a source of O₂ and Fe. Practical concentration of other phases is more difficult. Deposits of volcanic glass might be considered as a feedstock for surface-deposited volatile elements, but it is uncertain whether their thin volatile-element coatings are sufficient to be considered as a resource (section 8.7.9).

APPENDIX A11.3: SUMMARY OF UNANSWERED QUESTIONS ABOUT THE MOON(modified from *Lunar Geoscience Working Group*, 1986)

Problem	Present Status	Unanswered Questions Requiring Further Research/Exploration
1. Surface history and cratering rate	— Gradual decline in impact rate from 4.6 b.y. ago, with possible spikes	<ul style="list-style-type: none"> — Was there a terminal “cataclysm” ~3.9 b.y. ago? — What is the crater saturation diameter in the highlands? — Has cratering flux varied during the last 3 b.y.? — What were the characteristics of transition from primordial accretion (4.6 b.y. ago) to later heavy bombardment(s)?
2. Cratering mechanisms	<ul style="list-style-type: none"> — Comparison with terrestrial craters, explosions, and experiments to determine processes — Interplanetary comparisons 	<ul style="list-style-type: none"> — What are the variations in cratering flow field with impactor velocity, composition, and target conditions? — Is the proportional-growth model valid for basin-forming events? — How do crater central peaks and rings form? — How are large impact basins formed?
3. Crater and basin ejecta	<ul style="list-style-type: none"> — Basin secondaries abundant — Variable amounts of local rock and original target rock in ejecta — Large melt fraction 	<ul style="list-style-type: none"> — What fraction of primary vs. local ejecta is present in continuous crater/basin deposits? — Is there a consistent pattern of radial and concentric zoning of target stratigraphy in crater ejecta? — What are the shock-level distributions within, outside, and beneath craters? — Are impact melts chemically homogeneous? At what scale does homogenization cease? — What is the provenance of clasts in impact melts? — How are meteoroid siderophile elements added to impact melts? — What are the origins of LKFM and VHA impact melts?

Problem	Present Status	Unanswered Questions Requiring Further Research/Exploration
4. Lunar regolith and the sun's history	<ul style="list-style-type: none"> — Depositional models for regolith maturity indices developed — Evidence for variable solar activity 	<ul style="list-style-type: none"> — What is the nature of the regolith-bedrock interface? — What is the ratio of exotic to local material in the regolith and how did it get there? — What changes have occurred in lateral mixing of ejecta with time and crater size? — What is the nature of regolith stratification? — What are the relative and absolute ages of crater rays? — What has been the flux of micrometeoroids with time? — Determine the history of solar and galactic particles with time: Search for datable soils sandwiched between lava flows
5. Megaregolith	<ul style="list-style-type: none"> — Variable thickness, perhaps as much as 10 km 	<ul style="list-style-type: none"> — What is the exact thickness of the megaregolith? How does it vary across the Moon? — What are the geophysical signatures of the megaregolith? — Is the megaregolith chemically homogeneous?
6. Volcanism		
— Maria basalt thicknesses	<ul style="list-style-type: none"> — Both thin (<1 km) and thick (>4 km) basin fills are possible 	<ul style="list-style-type: none"> — What is the relationship between mare fill and mass concentrations (mascons)? — How many cooling units (and eruption sequences) are present in a single basin? — What are the thicknesses of individual lava flows? — Has there been ponding of lavas and subsequent differentiation?
— Duration of mare volcanism	<ul style="list-style-type: none"> — 4.2 to ~1.0 b.y. 	<ul style="list-style-type: none"> — How widespread are ancient highland basalts? How old are they? What are their compositions? <ul style="list-style-type: none"> — Where are ancient basalts exposed? — What are the ages of the youngest mare basalts?
— Highland volcanism	<ul style="list-style-type: none"> — Some possible 	<ul style="list-style-type: none"> — Is there molten rock inside the Moon today? <ul style="list-style-type: none"> — Which are of impact origin and which are of impact origin? — When did highland volcanism cease? — Not enough is known about highland volcanism to formulate key questions

Problem	Present Status	Unanswered Questions Requiring Further Research/Exploration
7. Tectonism	— Modeled and compared with images, photos, and geophysical anomalies	<ul style="list-style-type: none"> — What is the global lunar stress history? — What are the origins of lunar wrinkle ridges? — What is the history of lithospheric growth and how did it vary spatially? — Is tectonism around basins associated with the impact event, with the subsequent loading by mare basalts, or both? — What are the ages of young highland scarps? — How do floor-fractured craters form?
8. The lunar crust and “magma ocean”	— Global magma ocean, followed by serial volcanism	<ul style="list-style-type: none"> — How did the lunar crust form? — Did mare basalt source regions form at the same time as ferroan anorthosites? — What is the age range for ferroan anorthosites? — What is the time scale of early lunar differentiation? — Did early heavy impact bombardment interact with early differentiation? — Was there a single moonwide magma ocean, a series of magma seas, or other early magma forms?
— Primary highland rock types	— Represented by pristine clasts	<ul style="list-style-type: none"> — How many magmas contributed to development of the lunar crust? — How and when were these rock types mixed into polymict breccias? — How many of these rock types have been sampled so far? — How and when were intrusions emplaced into the highland crust? — Which rock types were formed in the original magma ocean?
— KREEP (Rocks with high potassium, rare earth elements, and phosphorus)	— Probably global	<ul style="list-style-type: none"> — What is the origin of KREEP? — How does the concentration of KREEP vary spatially within the lunar crust? — Was KREEP absent from the lunar surface 4 b.y. ago? — Are varieties of KREEP associated with granites and rhyolites? — Is KREEP added to the surface by impact or volcanic processes?

Problem	Present Status	Unanswered Questions Requiring Further Research/Exploration
— Crustal structure and composition		— What are the global variations in crustal thickness? — Which isostatic compensation mechanism predominates? — Is the crust layered? — What is the cause of the varied crust thickness and offset between the Moon's center of mass and center of figure? — Have basin-forming impacts excavated complete crustal sections, which can be reconstructed through the study of ejecta?
Compositional	Anorthositic "layer" above noritic "layer"?	
Seismic data:	20–25 km of crust in highlands	
Gravity data:	Unsure about models	
9. The lunar mantle		— What is the composition of the lunar mantle and how does it vary laterally?
— Seismic profile	— Density probably increases with depth	— What is the origin of mantle cumulate rocks?
— Source regions for basaltic lavas	— Heterogeneous	— What is the origin of sublimates from volatile phases present in pyroclastic deposits? What is the composition of these phases?
— Volatiles	— Characterized in pyroclastic ejecta	— What is the structure and location of the volcanic plumbing that served as conduits for mare lavas? What were the eruption mechanisms for lunar pyroclastic deposits? How did they ascend from their source regions?
10. The lunar core	<500 km radius	— Does the Moon have a metal-rich core? If so, is it iron, nickel-iron, or iron sulfide? — What is the nature of the core-mantle boundary? — What are the implications of a lunar core for models of lunar origin?
11. Global properties		— What is the precise moment of inertia?
— Moment of inertia	— 0.3905 ± 0.0023	— What is the global average lunar heat flow? How and why does it vary laterally?
— Heat flow	— About 2 times that of Earth?	— Is there any molten material left in the Moon? — What are the bulk lunar U and Th abundances?

Problem	Present Status	Unanswered Questions Requiring Further Research/Exploration
— Paleomagnetism	<ul style="list-style-type: none"> — Rocks: “fossil magnetism” not understood — Orbital: Bright swirls on the surface are highly magnetic 	<ul style="list-style-type: none"> — What is the origin of lunar paleomagnetism? — Was there once a core magnetic dynamo; if so, when did it start and stop? — What is the origin of Reiner-Gamma-type swirls? — Is the generation of transient magnetic fields an important lunar process? How are they generated? — Is there evidence for polar wandering?
12. Lunar atmosphere	<ul style="list-style-type: none"> — Tenuous; derived from solar-wind gases and radioactive decay of ^{40}K to ^{40}Ar 	<ul style="list-style-type: none"> — What are the daytime and nighttime concentrations and compositions? — What are the dynamics of the ionosphere? — What is the electron density at the surface? — How will human activities affect the lunar atmosphere?
13. Lunar transient events	<ul style="list-style-type: none"> — Controversial Earth-based observations of clouds or flashes on the Moon — Impact events 	<ul style="list-style-type: none"> — A permanent monitoring system is needed on the lunar surface — Are there gas releases from the lunar interior? — What is the relation between transient events and surface radon emission?
14. Bulk composition of the Moon	<ul style="list-style-type: none"> — Estimates based on a very restricted sample suite 	<ul style="list-style-type: none"> — What is the lunar bulk composition? — What are the implications of the bulk composition for determining the original source of lunar material and its relation to the Earth?
15. Origin of the Moon	<ul style="list-style-type: none"> — Currently favored theory: giant impact on Earth, followed by accretion in orbit around the Earth 	<ul style="list-style-type: none"> — What is the origin of the Moon? — If the collision-ejection hypothesis is valid, are there geochemical signatures in lunar rocks for both projectile and target? — What has been the evolution of the Moon’s orbit through time?