Technical Requirements for Lunar Structures

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Technical Requirements for Lunar Structures

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Abstract: The moon has recently regained the interest of many of the world's space agencies. Lunar missions are the first steps in expanding manned and unmanned exploration inside our solar system. The moon represents various options; it can be used as a laboratory in low gravity, it is the closest and most accessible planetary object from the Earth, and it possesses many resources that humans could potentially exploit. This paper has two objectives: to review the current status of the knowledge of lunar environmental requirements for future lunar structures, and to attempt to classify different future lunar structures based on the current knowledge of the subject. The paper divides lunar development into three phases. The first phase is building shelters for equipment only; in the second phase, small temporary habitats will be built, and finally in the third phase, habitable lunar bases will be built with observatories, laboratories, or production plants. Initially, the main aspects of the lunar environment that will cause concerns will be lunar dust and meteoroids, and later will include effects due to the vacuum environment, lunar gravity, radiation, a rapid change of temperature, and the length of the lunar day. This paper presents a classification of technical requirements based on the current knowledge of these factors, and their importance in each of the phases of construction. It gives recommendations for future research in relation to the development of conceptual plans for lunar structures, and for the evolution of a lunar construction code to direct these structural designs. Some examples are presented along with the current status of the bibliography of the subject.

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Introduction

The moon has recently regained the interest of many of the world's national space agencies. The moon has developed a dual role in human thought. First, through pre-Apollo years (1958–1969), Apollo exploration (1969–1972), and the current post-Apollo era (1972-to present), it has been shown that the moon is a scientifically important celestial body in near proximity of the earth. Second, the moon, because of its closeness to earth, is a natural target for the first step of human exploration beyond our planet, including future utilization of its natural resources (see Jolliff et al. 2006, p. 619) and even colonization. The knowledge of the moon's environmental conditions and resultant technical requirements for lunar structures is key to their successful designs depending on the phase of construction. This paper proposes three phases of construction on the moon:

- Phase 1 (2010–2020): Designs for equipment shelters during initial unmanned robotic or manned missions;
- Phase 2 (2020–2030): Development of structures for medium length of stay (up to several months); and
- Phase 3 (2030 and beyond): Long-term construction of lunar structures for different purposes (primarily for long-term habitats, resource use, laboratories, and finally, permanent lunar bases).

First, a brief description of each phase is presented. Then, the moon's environmental conditions and technical requirements for lunar structures are discussed based on available data. They include temperature, radiation, gravity, atmosphere/pressure, the lunar day, lunar surface conditions (lunar dust), lunar seismicity, and meteoroids. The impact on materials, shapes, and location of lunar structures is also assessed. Then, a short review of recent findings of lunar missions and how they can affect future lunar structures is provided. Science objectives of selected planned missions that will be useful for lunar structure design are also described. Finally, a set of recommendations for future research is presented.

Moon: The Nearest Important Destination

The moon is the celestial body that, beyond the planet earth, has been the most systematically sampled and studied. Physical characteristics of the moon and earth are compared in Table 1. Although exploration of the moon is still incomplete, the overall effort has been extensive. The first Russian imaging missions (Luna, Zond) and American missions (Ranger) were flown between 1959 and 1965. At the same time, a systematic earth-based mapping of the moon by telescope began, and it led to determination of lunar stratigraphy. The Luna 10 mission provided the first orbital gamma-ray chemical data in 1966. Lunar Orbiter returned images in preparation for the United States manned Apollo

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Table 1. Comparison of the Physical Characteristics of the Moon and Earth (Heiken et al. 1991)

Property	Moon	Earth
Mass	73.53×10^{21} kg	5.976×10^{24} kg
Radius (spherical)	1,738 km	6,371 km
Surface area	37.9×10^{6} km^2	510.1×10^{6} km^2
Flattening[a]	0.0005	0.0034
Mean density	3.34 g/cm^3	5.517 g/cm^3
Gravity at equator	1.62 m/s^2	9.81 m/s^2
Escape velocity at equator	2.38 km/s	11.2 km/s
Sidereal rotation time	27.322 days	23.9345 h
Inclination of equator/orbit	6°41′	23°28′
Mean surface temperature	107°C (day); −153°C (night)	22°C
Temperature extremes (see, also Table 2)	−233°C (?) to 123°C	−89 to 58°C
Atmosphere	$\sim10^{4}$ molecules/cm^3 (day)	
	200×10^{3} molecules/cm^3 (night)	25×10^{18} molecules/cm^3 (STP)
Moment of inertia (I/MR^2)	0.395	0.3315
Heat flow (average)	~29 mW/m^2	63 mW/m^2
Seismic energy	20×10^{9} (or 10^{13}?)J/year[b]	10^{17}–10^{18} J/year
Magnetic field	0 (small paleofield)	24–56 A/m

[a](Equatorial-ideal)/ideal radii.

[b]These estimates account for moonquakes only and do not account for seismic activity from meteoroid impacts.

missions. Unmanned soft landings and surface operations took place between 1964 and 1976, with the first data on soil physics and chemistry sent by radio back from lunar service in 1966 and the first Soviet robotic collection of lunar samples returned by Luna 16 in 1970. However, the greatest achievements in lunar sampling were the six Apollo manned landings between 1969 and 1972 (NASA 1969, 1970, 1971a, 1971b, 1972, 1979). Fig. 1, a pair of Lick Observatory (Santa Cruz, Calif.) photographs, depicts six Apollo and three Luna sample-return sites with labels showing selected lunar features (Spudis 1999, p. 126).

Lunar research has brought attention to a rich output of information achieved from the past lunar exploration scientific data; there are several depositories of lunar samples and scientific results. The most important are listed below:

- Lunar and Planetary Institute (LPI);
- National Space Science Data Center (NSSDC);
- National Technical Information Service;
- NASA Johnson Space Center History Office; and
- NASA Johnson Space Center Lunar Sample Curatorial Facility.

These data have provided the database for various scientific aspects of the moon. Some of these data are the basis of the current knowledge on derived technical requirements for future lunar structures (Heiken et al. 1991, p. xix).

Future lunar structures will serve to achieve a permanent utilization of the moon and its resources. The moon will also serve as a place for future laboratories, astronomical observatories, testing grounds, and manufacturing plants. Finally, it will be an important stepping stone in reaching other planets from our solar system.

Three Phases of Construction

Lunar base development has previously been categorized into stages, usually by the degree of human presence on the moon (Eckart 1999, p. 225; Toklu 2000; Ruess et al. 2004). A similar approach is taken here, although the phases are defined by the uses of the different structures in each phase, rather than the human presence, thus focusing on the technical requirements for construction. The evolution of the structures that will be used on the moon can be classified into three general phases: (1) those of support and shelters for scientific equipment; (2) temporary habitats for conducting science and exploration; and (3) long-term settlements primarily for resource utilization.

Phase 1

The first phase involves the structures that are closest to realization. It is not included as a stage in the previously mentioned lunar base plans because it does not involve inhabitants; however, in lunar structure evolution, it is an important phase. Structures that will support or contain scientific equipment are the basis of

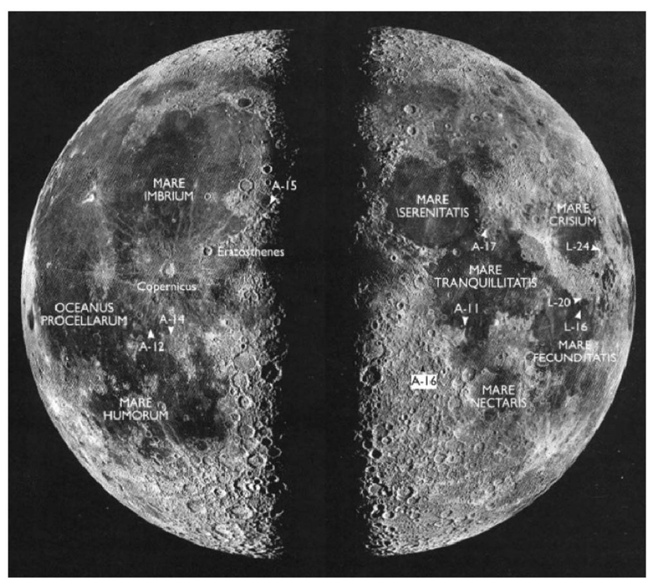

Fig. 1. Location of the Apollo (A) and Luna (L) sample-return sites (Photograph © UC Regents/Lick Observatory)

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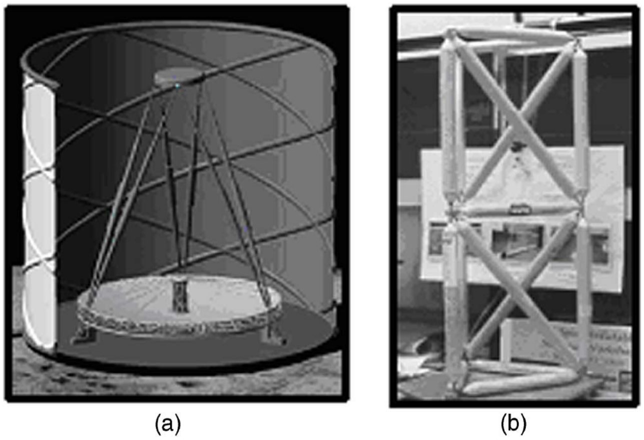

Fig. 2. Phase 1 structures: (la) LLMT (Angel 2005; drawn by Tom Conners); (b) rigidizable structure (Cadogan and Scarborough 2001, with permission from ILC Dover)

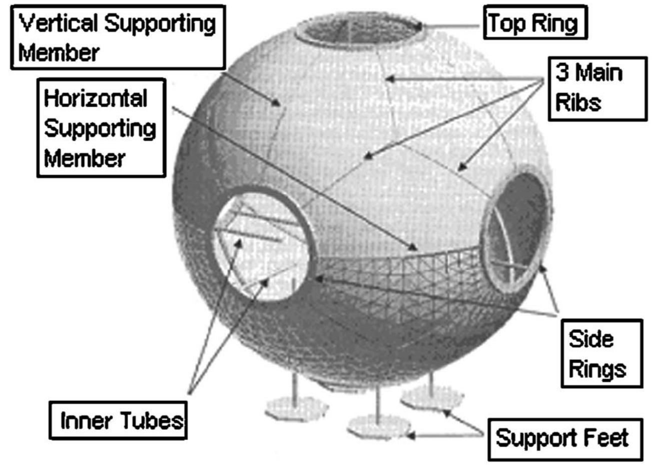

Fig. 3. Phase 2 habitat (Criswell and Carlson 2004, ASCE)

this phase. Phase 1 will begin around 2010, and extend exclusively until around 2020; after that time, it will continue, running concurrently with Phase 2 and then Phase 3. An example of a structure in this phase is an assembly that would house a lunar liquid mirror telescope (LLMT), which was recently proposed by Dr. Roger Angel and his team. A possible structure that would surround the LLMT and a rigidizable structure developed by the Jet Propulsion Laboratory (JPL) and L'Garde are shown in Fig. 2 (Cadogan and Scarborough 2001; Angel 2005). These structures will be built entirely on earth and transported to the moon, where they will be automatically deployed, or set up by robots or humans. These structures will not be inhabited by humans; if people are required to erect the structures, they will use the lunar module of their spacecraft for shelter during their short stay on the moon, which is not considered part of the phase. Any extended time spent on the moon for which a separate shelter is required is considered part of Phase 2.

The function of the structures in this phase will be to protect the equipment from dust, meteoroids, and radiation, as well as to provide structural support. The temperature fluctuations and seismic activity will also be important considerations that will affect the design of the structures.

Phase 2

Phase 2 of construction begins with the first structures that are deployed on the moon and inhabited by humans, which will start around 2020 (Hawes 2005). This phase is similar to the late part of Eckart's pioneering phase and the first lunar outpost (Eckart 1999, p. 236), as well as to Toklu's prefabricated classification (Toklu 2000). The purpose of the structures in this phase will be to conduct science, allowing people to work with the equipment that has already been placed there, and to investigate and prepare possible locations for a permanent lunar base. They will be intended for only a short time on the moon, up to several months. As well, they will be designed for few people, up to approximately 10.

In this phase, the structures will be inflatable to maximize the final volume of habitable space while minimizing the initial, compacted volume and weight because these structures will also be constructed on earth before relocating them to the moon; additionally, they should be modular to allow the lunar base to be expanded, eventually leading into Phase 3. An example of an inflatable habitat, possible in Phase 2, is shown in Fig. 3 (Criswell and Carlson 2004). Although they will initially be constructed with resources from earth, Phase 2 will involve some lunar resource utilization. This will mainly be the use of regolith for shielding the habitat from radiation, thermal extremes and cycling, and meteoroids.

These requirements, unique from those of Phase 1, are impacted by additional environmental conditions, which must be considered in their design. As well as dust, meteoroids, radiation, temperature, and seismic activity, the effects of gravity, pressure, and the length of the lunar day will also become significantly more relevant because human safety is involved. As well, each of the conditions that were important in Phase 1 will affect design in Phase 2 in a different, often more significant way; for example, although temperature was a concern in Phase 1 and still is in Phase 2, the temperature must be controlled to a much greater extent in Phase 2 due to the human presence.

Phase 3

The final phase of lunar construction, as the farthest from realization, is also the least rigidly defined. It will begin with more permanent, habitable lunar bases, as in the consolidation and settlement phases of Eckart, and the in situ resource construction of Toklu (Eckart 1999, p. 236; Toklu 2000). This phase will develop through a gradual transition from Phase 2, by about 2030 (Hawes 2005). Instead of relocating the structures to the moon, Phase 2 structures will be extended and other structures will be constructed on the moon from in situ resources such as lunar concrete. They will be able to house many people comfortably, as their inhabitants will stay in them for extended periods of time; also, it should be possible to build on and expand them to increase capacity.

The purposes of this phase will be to continue science involving the moon and to increase lunar resource use. After Phase 3 begins, processing and production plants will be built to develop in situ resource utilization. Lunar resources will be used to a further extent than simply for regolith shielding; they will be used to expand the previously existing bases and reduce dependence on supplies from the earth. At this time, the lunar habitats should have little dependence on supplies from earth for survival.

The environmental conditions that are important in this phase will be the same as those that were considered in Phase 2; however, they will be dealt with differently. Specifically, radiation

Table 2. Effect of Regolith Cover on Temperature Ranges and Variations on the Moon (Adapted from Aulesa et al. 2000)

Thickness of regolith cover (m)	Monthly variation and range (°C)							
	Permanently shadowed polar craters (Average T=233°C)		Other polar areas (Average T=−53°C)		Equatorial zone (Average T=−18°C)		Midlatitudes (Average T=−35.5°C)	
	Variation	Range	Variation	Range	Variation	Range	Variation	Range
0.0	0.0	−233	±10	−63 to −43	±140	−153 to 122	±50	−85.5 to 14.5
0.5	0.0	−233	±3.9	−56.9 to −49.1	±55.8	−73.8 to −37.8	±19.6	−55.1 to −15.9
1.0	0.0	−233	±1.2	−54.2 to −51.8	±16.6	−34.6 to −1.4	±5.8	−41.3 to −29.7
1.5	0.0	−233	±0.5	−53.5 to −52.5	±7.5	−25.5 to −10.5	±2.7	−38.2 to −32.8
2.0	0.0	−233	±0.3	−53.3 to −52.7	±4.3	−22.3 to −13.7	±1.5	−37.0 to −34.0
2.5	0.0	−233	±0.2	−53.2 to −52.8	±2.8	−20.8 to −15.2	±1.0	−36.5 to −34.5

shielding will be more advanced and location will be selected to minimize the effects of radiation, temperature, and meteoroids. Also, all of the conditions must be addressed so that the inhabitants are comfortable, rather than simply surviving, because they will remain in the habitats for a longer time.

Environmental Conditions and Resultant Requirements

Unique technical requirements exist for construction on the moon, and are primarily caused by the harsh lunar environment. Between the earth and the moon, there are several important differences to consider, and while most of these are challenges to the design, some, such as seismicity, are actually less important considerations than they would be on earth, as the estimates of the released seismic energy on the moon are much smaller. The most significant factors that differentiate lunar construction from construction on earth are the following:

- Temperature;
- Radiation;
- Atmosphere and pressure;
- Meteoroids;
- Gravity;
- The length of the lunar day;
- Dust; and
- Seismicity.

Each of these must be considered to varying degrees with respect to each phase of construction, although the most important in all phases are temperature, radiation, pressure, and meteoroids (see Appendix I for importance of and requirements due to each condition). The lunar construction code should include information on these conditions and the structural requirements that they create.

Temperature

One of the most important environmental differences between construction on the moon and construction on earth is the temperature ranges of the two planets. Because of the long lunar day and thin atmosphere, the temperature on the moon varies greatly, by up to 280 K at the equator. Further, at the equator it has an average temperature of only 255 K, or −18°C (Aulesa et al. 2000). This means any structure placed on the moon must be able to sustain very cold temperatures, as well as severe thermal strain caused by the fluctuation.

Although the equator represents the largest temperature variation on the moon, the coldest temperatures occur in the permanently shadowed parts of craters at the poles. There, the temperatures are constant at 40 K, or −233°C (Aulesa et al. 2000). The most moderate temperature conditions, considering both the range and average temperature, are at the polar areas other than permanently shadowed craters, where the average is −53°C and varies by ±10°C, or the midlatitudes where the average is warmer at −35.5°C but varies by ±50°C (Aulesa et al. 2000) (see Table 2).

Also summarized in Table 2 are the results of one method of temperature shielding; that is, a regolith cover (Aulesa et al. 2000). Regolith provides thermal insulation and can be used to shield a habitat from the temperature gradient, as well as radiation and meteoroids. Two meters of regolith shield bring the ranges in all locations, except at the equator, to a small variation.

Using a regolith shield, however, is only a feasible solution for Phases 2 and 3; in Phase 1, when structures will be used as support for scientific equipment such as telescopes, covering them in regolith is not an option. Also, while a regolith shield could be used to keep the internal temperature of the structure more consistent, the structure itself still must be able to withstand the cold, at least during set up. Therefore, in all phases, the materials used in construction must maintain their properties in the temperatures of the environment without shielding, such as Kevlar, which does not become brittle until −196°C (Kennedy et al. 2001, p. 540), and therefore, could be used in all areas of the moon except the permanently shadowed craters. In Phase 1 this is required for the life of the structure, and in Phases 2 and 3, it is important while the structure is being deployed, built, or repaired.

Radiation

The hazardous radiation that reaches the moon comes primarily from two sources: galactic cosmic rays (GCR) and solar energetic particle (SEP) events (Parnell et al. 1998). This radiation is considered to be a significant threat to human life in addition to having a negative impact on equipment. To protect human life in a habitat, radiation shielding is necessary in Phases 2 and 3. It is also important in Phase 1; the degree to which it is important depends on the purpose of the structure (for radiation analysis, see Appendix II).

Phase 1

Because structures in the first phase will not be designed to shelter humans, biological radiation effects are not a concern; however, radiation also has a negative impact on equipment. The state of electronic equipment can be altered by an ion-induced charge

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from radiation particles, and radiation can create extra noise for sensors; it also breaks down materials and reduces power output from solar panels (Parnell et al. 1998). For some of these problems, radiation shielding can be used, and the vulnerable parts can be sheltered by the structure or by regolith, which would reduce the effects of the radiation, as is suggested for the LLMT (Angel 2005). Most shielding in this phase will be part of the structure, and included in the construction on earth, rather than added during setup or deployment. Few structures are likely to be buried or covered in regolith. Other approaches, where shielding is not possible, include redundant circuits for electronics and larger than required solar panels (Parnell et al. 1998). Structures in this phase must use materials that are relatively resistant to radiation, or radiation-hardened materials (Parnell et al. 1998).

Radiation Limits for Phases 2 and 3

The average radiation dose on earth is 0.0036 Sv/yr; however, on the moon, the average dose, caused almost entirely by galactic cosmic rays (GCR) and Solar Energetic Particle (SEP) events, is considerably larger at 0.25 Sv/yr (Lindsey 2003) or greater (ISU 2000). Further, individual SEP events can deliver up to 1000 Sv (Lindsey 2003). Humans on the moon must be protected from this significant increase in radiation, although how much protection is required depends on factors such as the length of stay, and a definitive limit is still undetermined. A maximum dose of 0.5 Sv/yr is recommended by the Space Studies Board in 1996 (Aulesa 2000), which is consistent with the National Council on Radiation Protection's (NCRP) recommendation in 1989 (Parnell et al. 1998). However, the career maximum for blood forming organs is 1 to 4 Sv, so even that dose can only be endured for less than two to eight years, considering other sources of radiation throughout the person's life. For very long-term bases, this will not be an acceptable limit. Also, sufficient protection must be provided from solar flares because all of the maximum radiation dose should not be received over the few hours of a solar flare. Further, for nuclear power plant workers, the International Commission of Radiological Protection recommends an annual limit of 0.05 Sv (Parnell et al. 1998). Because the nuclear power plant workers will be exposed to the radiation for years, rather than just a short mission considered by the Space Studies Board, their recommended dose is lower. This indicates that structures in phase two may not need significant shielding; however, toward the end of the second and into the third phase, more effective shielding will be required.

Phase 2

Large-scale radiation shielding will be required, beginning in Phase 2, to protect humans spending time in lunar structures. The most commonly suggested type of radiation shielding is a regolith cover because it includes the advantages of in situ resource utilization, as well as providing meteoroid and thermal shielding. A regolith shield increases the amount of mass through which radiation particles must pass, and with enough shielding, it can stop the particles or slow them to an acceptable energy level. However, a sufficient layer of shielding must be provided because initial collisions create high-energy particles, or brehmsstrahlung radiation, and with just a thin layer, the inhabitants of the structure will be exposed to these high-energy particles, increasing the radiation damage that occurs rather than reducing it (Buhler and Wichmann 2005). The minimum suggested amount of shielding varies between sources, from 2 m of regolith to over 5 m; the thickness required depends on the radiation limit that is recommended, and the density of regolith. The earth's atmosphere provides 1000 g/cm^2 of shielding at sea level, so equivalent protection on the moon is ideal (Heiken et al. 1991, p. 53); however, 700 g/cm^2 is considered acceptable, as inhabitants will not be on the moon for extended periods of time (Aulesa et al. 2000). If the lowest density of regolith is approximately 1.3 g/cm^3, the regolith shield will have to be 5.4 m thick to provide 700 g/cm^2 of protection (Aulesa 2000).

Phase 3

In Phase 3 there are further methods of radiation shielding to consider. Other than only regolith, an electrostatic radiation shield used with regolith (Buhler and Wichmann 2005) is possible, or, if the habitat is constructed in a lava tube, the ceiling of the lava tube itself may be used. In this phase, radiation shielding is extremely important because an increased amount of time will be spent on the moon. The amount of radiation received should be as low as possible; ideally, it should be as low as that received on earth to avoid any increase in the inhabitants' probability of cancer.

Atmosphere and Pressure

The near-zero pressure of 3 nPa on the moon increases the severity of several of the environmental conditions that are relevant to lunar construction. The thin atmosphere of, at most, 2×10^5 molecules/cm^3, which occurs at night, provides little thermal insulation, contributing to the significant temperature range and thermal cycling that exist on the moon. A dense atmosphere would provide some radiation shielding, reducing the measures required to protect equipment and humans from it. Finally, a thicker atmosphere would burn up meteors, and fewer meteoroids would reach the surface.

The thin atmosphere also results in specific structural requirements in the second and third phases. In these phases, the internal pressure in the structure must be sufficient to sustain human life, so the structure becomes a pressure vessel. The internal pressure must be at least 26 (Aulesa 2000) to 30 kPa (Langlais and Saulnier 2000) to support human life and avoid altitude sickness, if it is composed purely of oxygen. Realistically, however, the pressure must be higher to make the living environment comfortable and avoid such effects as difficulty speaking and ineffective coughing (Eckart 1999, p. 276), and most importantly to reduce the extreme fire hazard that pure oxygen would cause.

The internal pressure of the structures in the second and third phases will create substantial tensile loads on the structure. The regolith piled on the structure for shielding in Phase 2 will somewhat counter the load on the top. However, due to the reduced gravity, the pressure caused by its weight will not be greater than the internal pressure. If the regolith shield is 5.4 m high, gravity is 1.62 m/s^2, and the density of regolith is between 1.3 (Aulesa et al. 2000) and 1.75 g/cm^3 (Sadeh et al. 2000), the pressure created by the regolith will be between 11.4 and 15.9 kPa, which is much less than the minimum required internal pressure for human life, of 26–30 kPa (Aulesa 2000; Langlais and Saulnier 2000). Also, there will be horizontal loads on the structure due to the pressure, which the regolith will not counter.

Meteoroids

Meteoroid bombardment is to be considered since the formation of the moon has resulted in the present lunar topography. Meteoroids are a threat to structures on the moon because there is almost no atmosphere on the moon to burn them up or even slow

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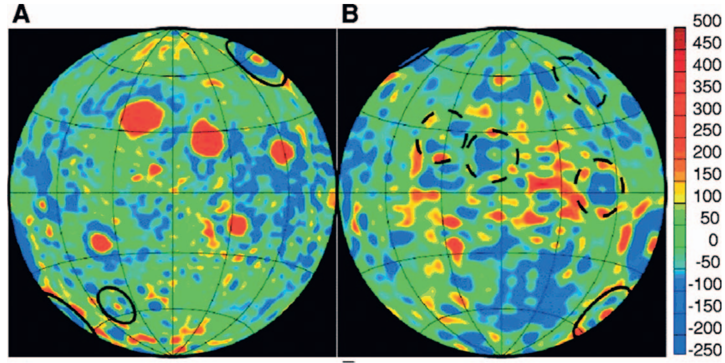

Fig. 4. (Color) Lunar gravity variations in 10^{-5} m/s^2 (Konopliv et al. 1998, reprinted with permission from the American Association for the Advancement of Science)

them down. As a result, meteoroids impact the moon with their full velocity, which can range from 10 to 72 km/s (Coronado et al. 1987, p. 12).

For some structures in Phase 1, such as a lunar telescope, the threat may simply have to be accepted because creating a shield that would protect the equipment but not interfere with its view may not be possible. Furthermore, as Gorenstein says in an analysis of a proposed lunar observatory, "disturbances would be meteoroid impacts but the probability that an impact would affect the observatory is small" (Gorenstein 2002, p. 46). Particularly for larger particles, meteoroid flux is very low (see Appendix III).

However, even small particles constitute a threat in Phases 2 and 3; meteoroid impact is a more significant concern because a leak in a structure in one of these phases could be catastrophic if not repaired quickly. Therefore, meteoroid shielding is required. One solution is a regolith covering, which would absorb the impact of meteoroids, preventing them from reaching the structure.

Using the Fish–Summers penetration equation, Lindsey analyzes the thickness of the regolith layer required to protect a structure from meteoroids of diameter 7 cm or smaller, and finds it to be 45.9 cm (Lindsey 2003). The flux of a meteoroid this large is 1.76×10^{-4} impacts/km^2/year and decreases for larger particles, making a catastrophic impact very unlikely with 45.9 cm of shielding (Lindsey 2003). Furthermore, using this equation (Hayashida and Robinson 1991), the effectiveness of a regolith shield of 5.4 m can be approximated. This is also the recommended thickness for sufficient radiation shielding, and would provide protection from meteoroids with a diameter of 52 cm or smaller, reducing the flux of a penetrating impact on the structure to between 10^{-8} and 10^{-7} impacts/km^2/year (see Appendix III) (Lindsey 2003; Eckart 1999, p. 148).

Although meteoroids are an important concern in lunar structural design, the probability of impact is very low. Because of this, meteoroid shielding is primarily a concern in the later phases of construction. A regolith shield that will provide temperature and radiation protection is also sufficient to provide meteoroid protection; however, more advanced solutions may be investigated for late in Phase 3. For additional meteoroid shielding, a layer of the structure should provide some protection, as suggested for the TransHab (Kennedy et al. 2001, p. 545).

Gravity

The effects of the reduced gravity on the moon compared to the earth significantly alter the loads that must be considered in lunar construction. Self-weight of the structures is much less of a concern, as the gravity on the moon is only approximately 1.62 m/s^2 (ISU 2000), or one-sixth of the earth's gravity, and varies very slightly due to mass concentrations. In Fig. 4, the variations on the nearside (left) and far side (right) are depicted, with variations in 10^{-5} m/s^2 (Carroll et al. 2005; Konopliv et al. 1998). In Phase 1, this will primarily be a benefit in design because the structure will simply have to support less weight. In Phases 2 and 3, however, lower gravity will not significantly counter the net vertical tensile loads caused by the internal pressure required to sustain human life.

Length of Lunar Day

One lunar day, the time from one new moon to the next, is 29.53059 earth days (ISU 2000). This causes some substantial environmental differences between the earth and moon. Primarily, the long lunar day gives the moon more time to heat up while exposed to the sun, and then more time to cool during the night, contributing, along with the lack of atmosphere, to the extreme thermal cycling. This drastic difference from earth requires some changes in the way that lunar construction must be approached; lunar structures must be able to withstand extremely cold temperatures and their sharp variation. Specifically, the materials used must retain similar properties over the range of temperatures, and also must not fail easily due to thermal fatigue.

To achieve this, insulation such as lunar regolith will be used; however, the insulated parts of the structure must still be exposed to the environment while the structure is being deployed or constructed. Here, the length of the lunar day is beneficial; it is long enough so that missions to set up structures on the moon can be timed such that the structure is set up in relatively mild temperatures, and thermal shielding can be in place before extreme temperatures occur.

Dust

Dust, while it does not create any specific technical requirements, is a feature of the lunar surface that complicates construction. The lunar sunrise and sunset create a photoelectric change in the conductivity of the dust particles, which causes them to levitate and allows them to adhere to surfaces (Eckart 1999, p. 139). This could interfere with any mechanical parts on the outside of a structure, the deployment of the structure, or the observations of scientific equipment. To counter this, abrasion resistant materials must be used, and any moving parts should not be easily deterred by dust.

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Seismic Activity

Although lunar seismicity is a consideration in the design of lunar structures, the annual seismic energy released on the moon is significantly less than that on earth; unlike earthquakes, moonquakes will have little impact on lunar structural design.

In the *Apollo 15 Preliminary Science Report*, it is estimated that the annual seismic energy release on the moon is $10^{11}-10^{15}$ ergs, whereas on earth it is approximately 5×10^{24} ergs (NASA 1971b); the seismic energy released on the moon is at least approximately $1/(5 \times 10^{9})$ of that released on earth. Further, the largest recorded moonquake in the Apollo data was 2–3 on the Richter scale, and the usual magnitudes of moonquakes were only 1–2. A further source supports 1–2 magnitude on the Richter scale as the average, but suggests the one larger quake may have been as much as 4 (Toklu 2000), although this is still significantly lower than many of those on earth.

There were five sites with special seismographs placed on the moon during the landings of Apollo 12, 14, 15, 16, and 17 (NASA 1969, 1971a, 1971b, 1972, 1973). For many millions of years, the moon has been a dynamically quiet planetary body with not known plate motions, no active volcanoes, and no ocean trench systems in place. It was very special to find out that each lunar seismograph detected 600–3,000 moonquakes every year, but most of them were very small: up to about 2 on the Richter scale. The events could be divided into three different groups: deep moonquakes (with their foci at depths of 600−900 km in the moon), shallow moonquakes (less frequent), and moonquakes artificially induced by a meteoroid impact. All of them are very interesting events. The deep moonquakes showed some periodic regularity depending on the point when the moon's orbit is closest to the earth. They occurred at these centers at opposite phases of the tidal pull, so that the most active periods are 14 days apart. Bolt suggests in his classic on earthquakes that the tidal pull of the earth on the moon triggers the occurrence of deep seismic energy releases (Bolt 1988). The pattern of the moonquakes is also sharply different from that of earthquakes. The seismic *S* waves and surface waves on lunar seismograms are not very clearly defined and distinct as those of earthquakes. Mendell presented a discussion of the lunar seismic environment on an optical interferometer placed on the moon. He concluded that some earlier studies overstated the seismic impact on the future moon observatories but these effects must be taken into account and properly mitigated (Mendell 1998).

Much of the data collected in the Apollo seismic experiments were due to meteoroid impact, demonstrating that meteoroids will be a much more significant concern than moonquakes with an original source from the moon interior; this is shown in Fig. 5, with the seismic activity due to moonquake shown on the left, and the greater activity of a meteoroid impact on the right (Latham et al. 1972). Also, due to the small magnitude of lunar seismicity, the main structural loads to consider in lunar construction will be due to the self-weight of the structure and equipment in Phase 1, and the internal pressure of a habitat in Phases 2 and 3, rather than moonquakes.

Materials

The materials used in lunar structures must be resistant to the environmental conditions and retain their mechanical properties for which they were chosen. However, as the purpose of the lunar structures evolves, the type of material that will best serve the purpose will also change, so a variety of acceptable materials are required. One common factor influencing the material choice in all phases is mass and volume during transportation. The mass and volume that is transported should always be minimized due to the high cost and amount of fuel required. Although limitations for individual missions will vary and are not discussed here, minimizing these properties is expected to remain important for all phases.

Phase 1

In Phase 1, the materials used must be able to function in temperature extremes, maintain their properties while exposed to radiation, and be resistant to abrasion. The structure should also be as compact and lightweight as possible to reduce cost of transportation, and be deployed on the moon to take on its final shape. Options in the phase include solid collapsible structures, inflatable fabric, plastic, or metal film structures, and rigidizable inflatable structures (Kennedy et al. 2001; Cadogan and Scarborough 2001). The best option of these is rigidizable material because it can have the advantage of small volume and weight when stored, and can be deployed on the moon to a larger size. Further, they do not depend on maintaining internal air pressure to keep their shape, as other inflatable structures do. Rigidizable materials provide the benefits of inflatable structures, without the risk of a catastrophic failure if a small puncture occurs (Cadogan and Scarborough 2001). This is an important property in this stage because meteoroid shielding will not be provided.

Phase 2

The internal air pressure of the structure must be maintained in Phase 2 because it is necessary to sustain human life. For this reason, rigidizable inflatable structures may still be used, although not all of the advantages that they provide in Phase 1 apply. However, the structures in this phase may still be inflatable because they will be transported from the earth, and therefore, must be small and lightweight for travel, but able to expand to provide adequate space. The membranes of these structures will be multilayered, including a liner, bladder, restraint layer, insulating layer, and protective layer for meteoroids. An example of this is in the design of the TransHab, shown in Fig. 6 (Kennedy et al. 2001, pp. 535–548; Langlais and Saulnier 2000).

Testing has been performed on materials chosen for the TransHab for low earth orbit (Kennedy et al. 2001, pp. 548–552), although before a material can be used, it must be tested to ensure that it retains its properties in the lunar environment, including extreme temperatures, radiation, and abrasion. The former two conditions are most important during deployment, as regolith will later be used for radiation, temperature, and meteoroid shielding; abrasion resistance is necessary throughout the life of the structure. In this phase, lightweight, rigid, collapsible metal or alloy structures could also be used.

Phase 3

In situ resource utilization will be the main source of the materials used in Phase 3. In addition to regolith for shielding, lunar resources will be used to construct the main structure of the habitat. To build the structure, lunar materials that may be used include lunar concrete (Lin 1987; Lin et al. 1991; Eckart 1999, p. 656), sulphur-based concrete (Casanova and Aulesa 2000; Eckart 1999, p. 656), and cast basalt (Greene 2004).

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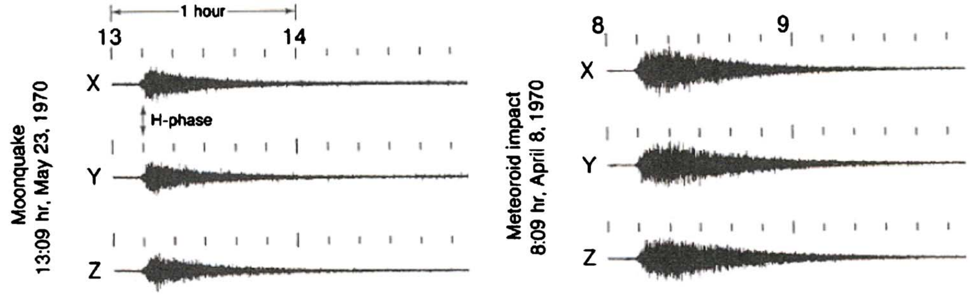

Fig. 5. Moonquake and meteoroid seismic activity (Latham et al. 1972, p. 377, Fig. 2, printable license is given with permission from Springer Science and Business Media)

Lunar concrete, although it may be possible, presents several difficulties; it would require water transported from earth or obtained from the moon, which would also evaporate more quickly in the thin atmosphere, resulting in weaker concrete. To prevent the water from evaporating from the mortar, epoxy binders could be added to the concrete, or the concrete could be preset in a pressurized environment to prevent evaporation (Eckart 1999, p. 657), such as the pressurized construction dome suggested by Langlais and Saulnier (2000). Although lunar concrete presents difficulties, they may be overcome, and lunar concrete is a viable option for Phase 3 structure (Lin et al. 1991). An alternative to lunar concrete that would eliminate these problems is sulphur concrete, which does not require water, needs less energy to manufacture, and can be produced in cold environments (Casanova and Aulesa 2000).

Finally, because basalt is widely available on the moon, cast basalt is suggested as a lunar construction material (Greene 2004; Rogers and Sture 1991). It also does not require water to cast, but uses heat, which can be obtained from concentrated sunlight (Greene 2004).

All of these materials share one major drawback. They are stronger under compression than tension; the tensile strength of concrete is only approximately 10% of its compressive strength (Casanova and Aulesa 2000). However, because of the internal pressure required in a lunar habitat, the net loads on the structure will be tensile. This means their optimum properties are not taken advantage of, which must be considered in the structural design. When Phase 3 is in development, these and other possible materials must be more closely examined with respect to the specific needs of the habitat (Thangavelu 2000).

Shape

In Phase 1, the shape will be determined primarily by the requirements of the scientific equipment that will be supported or protected by the structure. Before Phase 2, there will be little choice in possible shapes for the structure. When different shapes are options, there are two important areas to consider in deciding the shape of a lunar habitat. They are the human requirements and the structural stresses. The practicality of the space available necessarily determines what shapes are options, and the stresses that the shape would have to sustain determine the best choice of these options. Here, shapes will be considered separately for Phase 2.

In the second phase, inflatable structures will be used because they are lightweight and small when compacted, and can provide a large volume when deployed. Some of the most efficient in mass to final volume are sphere, cylinder, and toroid shells; these structures also eliminate sharp corners that would concentrate shell stresses. The stresses due to internal pressure on these shapes are shown in Fig. 7 (Kennedy et al. 2001, p. 537). Another possibility is an inflatable dome with an anchored base (Langlais and Saulnier 2000). Structures that have been proposed or built for space or planetary habitats that use these structures are the TransHab, a combination of a toroid and cylinder (Kennedy et al. 2001, p. 528), the spherical inflatable habitat proposed by Criswell and Carlson (2004) (see Fig. 3), the Astrophytum, consisting of four spheres arranged radially around a cylinder (Borin and Fiscelli 2004), and a hemispherical inflatable construction dome (Langlais and Saulnier 2000).

A sphere does not allow a very efficient use of space, although it gives the most habitable volume for the material used. The space created with the shape of a cylinder or toroid would be much more efficient, although they would both create more volume and mass when compacted.

Structures in the third phase will most likely be dome shaped or rounded because, while they will probably built from concrete or a similar material, they will still include an airtight membrane, so sharp corners should be avoided.

Location

In Phase 1, the scientific goal of the mission will be the most important factor in determining the location of the lunar structure.

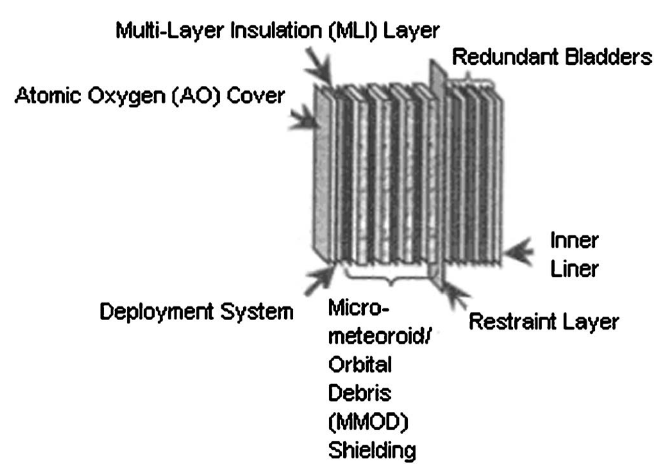

Fig. 6. Multilayered membrane structure for TransHab in LEO (Kennedy et al. 2001, p. 535, reprinted with permission from the American Institute of Aeronautics and Astronautics)

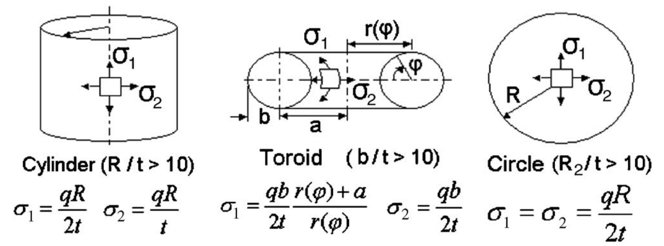

Fig. 7. Stresses in thin-walled vessels (Kennedy et al. 2001, p. 537, reprinted with permission from the American Institute of Aeronautics and Astronautics).

For example, the south pole, including the South Pole Aitken Basin, is a geologically interesting location that is the goal of a proposed NASA sample return mission (Koelle et al. 2005), and is also an important target in the National Research Council's Solar System Exploration Strategy (Smith 2002, Chap. 2); it may also become a desired location for scientific experiments requiring structures. For astronomy, a location on the far side of the moon may be ideal because it is shielded from radio noise from earth, or to investigate the existence of ice water, a polar location would be required.

Scientific areas of interest will still be important in Phase 2, and additionally, locations that have resources will be important to investigate the possibility of in situ resource utilization. These resources include ^{3}He, which is rare on earth but could be used as fuel in nuclear fusion, oxygen for rocket fuel, and materials such as concrete for lunar construction.

As the purpose of lunar structures in Phase 3 evolves toward establishing a human colony on the moon, locations that make design and construction easiest and increase the lifetime of the structure will be used. Some of these locations include the inside of a lava tube, which would provide excellent environmental protection, or the poles, where peaks of eternal light might be located. While these locations may not be options in earlier phases due to the purpose of the mission, the needs of an inhabited, semipermanent base, such as reliable shielding and power production, will be more important in Phase 3. The choice of location of lunar structures will be greatly influenced by the results of future lunar missions.

Lava Tubes

The idea of locating a lunar base inside a lava tube is decades old. It was revisited in 1988 by Coombs and Hawke, who stated that lava tubes would be a good location for a base if their existence and exact location could be confirmed before the mission was sent (Coombs and Hawke 1988). Still, as late as 1999, Eckart says in his lunar base handbook that lava tubes would be a good location if they were found (Eckart 1999, p. 118). Although lava tubes offer relief from several of the severe environmental conditions present on the moon, further research into their exact location and properties is required; however, because they would not be used until Phase 2 or 3, this investigation only could be done in Phases 1 and 2.

Locating the lunar base in a lava tube would fulfill several of the previously determined technical requirements that are unique to the moon. The ceiling of the tube would provide natural meteoroid and radiation shielding significantly more than the 5.4 m required. The inside of the lava tubes may also have less dust, minimizing the complications that dust can cause (Billings et al. 2000), and what dust there is will not be exposed to the outside environment, reducing the levitation due to photoelectric change. As well, the temperature inside a lava tube is almost constant at approximately −20°C (Billings et al. 2000), which would possibly relieve the need for much insulation, as well as diminish the possibility of failure due to thermal fatigue. Further, construction and maintenance on the lunar base also would be shielded.

Peaks of Eternal Light

Some points on the lunar north pole may receive almost constant low-angle sunlight due to their elevation and the small tilt of the moon's axis. Previously, locations such as Malapert Mountain near the south pole were considered, which may also receive sunlight for more than half of the lunar day (Kruijff 2000; Sharpe and Schrunk 2002). More recently, locations on the rim of Peary Crater near the north pole were suggested, which receive constant sunlight during the summer, although the percent of time during which sunlight is received in the winter is unknown (Bussey et al. 2005). Peaks of eternal light would be useful locations for a lunar base because temperature is relatively constant at about −50°C, ±10°C (Bussey et al. 2005). Also, solar power would be available for most of the time, and finally, peaks of eternal light are probably located near permanently shadowed craters, which may contain ice water. Also, after further investigation, peaks of eternal light might provide excellent lunar base sites.

Recent Findings

A general description of the recent missions from 1976 until now is presented, and further detailed in Appendix IV, including the launch date, mission date, sponsoring (funding) agency/institution/company, general mission objectives, mission events, and some descriptive notes. There were only five missions, one of which was not initially dedicated to the moon. Hiten was the first Japanese orbital lunar mission with a controlled crash on the moon's surface in 1990. There were two American missions, Clementine (1994; http://nssdc.gsfc.nasa.gov/planetary/elementine.html) and Lunar Prospector (1998; http://nssdc.gsfc.nasa.gov/planetary/lunatprosp.html), and one ESA sponsored mission, SMART 1 (2003; http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=2003-043C), which is still in its operational phase in lunar orbit. Finally, there was one unexpected flyby mission when the faulty communication satellite AsiaSat 3/HGS 1 was directed to do two flybys to place it in geosynchronous orbit (Bell 2005). They all contributed at various levels to the current knowledge of the lunar environmental conditions. Hiten was more focused on a series of technology demonstrations for future lunar missions. Three other dedicated lunar missions (two American and one European) concentrated on two major aspects of lunar studies: remote sensing of the lunar environment, including optical imaging of the lunar surface, and lunar mapping activities. Both are of utmost importance to the future missions and also related to the derivation of specific technical requirements of lunar structures.

Clementine was launched in 1994 and achieved the mapping of the lunar surface in the same year. It brought attention to a large variation of topography of the lunar poles, especially of the moon's south pole and its South Pole–Aitken basin, and revealed the presence of this extensive depression caused by the impact of an asteroid or comet. There is also a permanent dark area around the pole, which is sufficiently cold to trap water of cometary

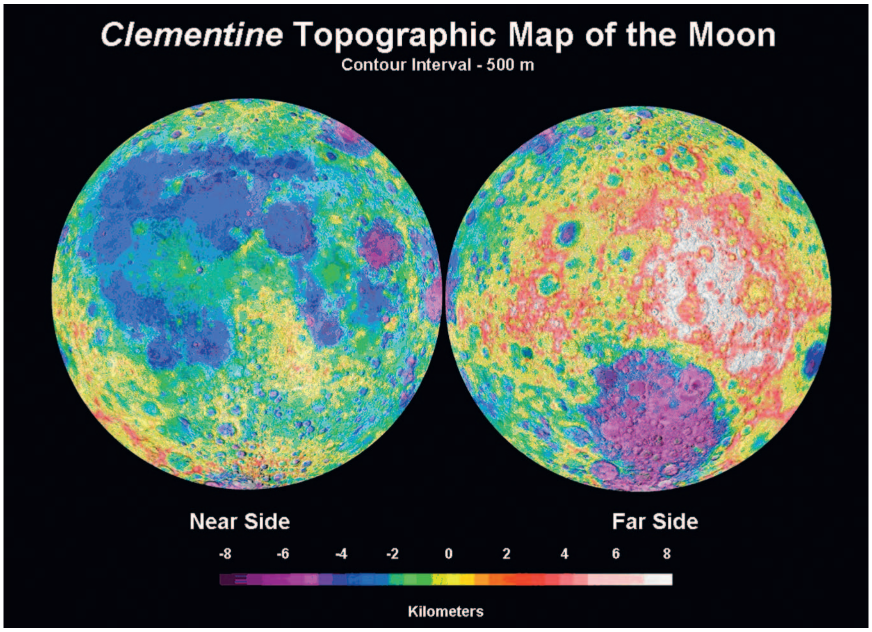

Fig. 8. (Color) Lunar topographic elevation as determined by Clementine (Spudis 1999, p. 135, reprinted with permission from Cambridge University Press)

origin in the form of ice. The laser altimeter on Clementine gave, for the first time, comprehensive images of the lunar topography, shown in the left of Fig. 8 (Clementine Project, http://nssdc.gsfc.nasa.gov/planetary/clementine.html; Clementine, http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc =1994-004A; Spudis 1999, p. 135). The near side is relatively smooth in comparison to the far side, which has extreme topographic variation. The large circular feature centred on the southern far side is the South Pole–Aitken basin, which is 2,600 km in diameter and over 12 km in depth (Clementine Project, http://nssdc.gsfc.nasa.gov/planetary/clementine.html; Clementine, http://nssdc.gsfc.nasa.gov/database/MasterCatalog? sc=1994-004A). In general, there is a similar range of elevation on the moon's surface as the range exhibited by the earth. Gravity mapping obtained from Clementine also revealed the crustal thickness, which has an average of 70 km, and varies from a few tens of kilometers on the mare basins to over 100 km in the highland areas (Clementine Project, http://nssdc.gsfc.nasa. gov/planetary/clementine.html; Clementine, http://nssdc.gsfc. nasa.gov/database/MasterCatalog?sc=1994-004A). The orbiting spacecraft also experienced a slight change in the velocity passing over mass concentrations called mascons and confirmed earlier findings of the local irregularities in the moon's gravity field. All of these findings are related to the environmental conditions on the moon, such as the distribution of the temperature due to topographic variation of the moon's surface and some aspects of the change in gravity field, but also place high importance on the impact of the location on the structural technical requirements (Clementine Project, http://nssdc.gsfc.nasa.gov/planetary/ clementine.html; Clementine, http://nssdc.gsfc.nasa.gov/database/ MasterCatalog?sc=1994-004A)

Lunar Prospector continued mapping of the lunar surface including low polar orbit investigation, and made studies associated with potential lunar resources: minerals, water ice, and certain gases. It mapped the moon's gravitational field anomalies (first encountered during the Apollo era). However, the controlled crash of the Lunar Prospector spacecraft into a crater near the south pole of the moon on July 31, 1999 did not produce any observable signature of water based on the astronomical observations made with telescopes (Lunar Prospector, http://nssdc.gsfc.nasa.gov/ planetary/lunarprosp.html).

SMART 1 (small missions for advanced research in technology) continues efforts of previous missions including the search for water ice at the south pole using near-infrared (NIR) spectrometry (ISU 2003). It also made further advances in the geology, morphology, topography, mineralogy, and geochemistry of the lunar surface. It measured minerals and chemical elements using visible light, near-infrared, and x-ray spectroscopy. The original mission of a six-month lifetime was extended until August 2006 (SMART 1, http://nssdc.gsfc.nasa.gov/database/ MasterCatalog?sc=2003-043C).

In summary, achievements of the above-listed missions have contributed substantially to the knowledge of the moon, although they do not bring much to the current knowledge with respect to technical requirements for future lunar structures. However, they have proven that the major impact of the individual technical requirements depends on the choice of location for the specific structure, regardless of the construction phase. Further advancements in the assessment of the technical requirements will be achieved through robotic missions with landing potential on the lunar surface and establishment of permanent stations to further quantify all parameters for the future lunar design code.

Planned Missions

The series of planned lunar missions shows some aspects of competition between various space-faring nations and poses some questions to streamline different efforts into a unified effort for future moon utilization and eventual colonization. Some missions will contribute to extending the knowledge of the lunar environment and its impact on the future structural requirements. The leading efforts with respect to the planned lunar missions repre-

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Table 3. NCRP Recommended Ionizing Radiation Exposure Limits for Flight Crews[a] (Parnell et al. 1998, ASCE)

Blood-forming organs	Eye	Skin
5 [depth (cm)]	0.3	0.01
0.25 [30 days (Sv)[b]]	1	1.5
0.5 [annual (Sv)]	2	3
1.0–4.0 [career (Sv)]	4	6

[a]The career depth dose equivalent is based upon a maximum 3% lifetime risk of cancer mortality. The dose equivalent yielding this risk depends on the sex and age at the start of exposure. The career dose equivalent is nearly equal to 2.0+0.075 (age 30) Sv for males and 2.0+0.075 (age 38) Sv for females, up to 4.0 Sv. Limits for 10 years exposure duration: "No specific limits are recommended for personnel involved in exploratory space missions, for example, Mars."

[b]Sievert equivalent dose determined by multiplying the absorbed dose at each energy deposition value (linear energy transfer) by the corresponding quality factor for each ion and energy.

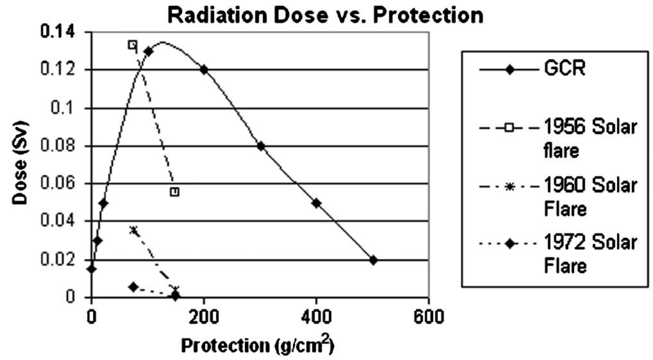

Fig. 9. Radiation dose as thickness of regolith increases (adapted from Aulesa 2000; Lindsey, 2003).

sent the United States' new exploration strategy of planned return to the moon by 2020 with aggressive planning from the technology side (Berger 2005), partially known Chinese efforts associated with their human flight program, and Indian and European ambitious plans concentrating on the scientific investigations of the moon's environmental features (see Appendix V). All of these efforts will contribute to further developing better technical requirements for all three phases of lunar construction. Some aspects are discussed below based on the available description of the current missions and their objectives.

The planned and approved missions include two American, one private (Trailblazer) and one by NASA [Lunar Reconnaissance Orbiter (LRO)] based on the new adopted strategy for planetary exploration, two Japanese (as per their preplanned effort by JAXA–Lunar-A and SELENE), one Chinese named Chang'e 1, one Indian named Chandrayaan-1 (by ISRO) and one small university-based German mission called Baden-Württemberg 1 (BW1) after the provincial program from this state of Germany and led by the Technical University of Stuttgart (Lunar Exploration Timeline, http://nssdc.gsfc.nasa.gov/planetary/lunar/lunartimeline.html; Laufer and Roeser 2005).

Major contributions will be possible through the larger missions and those sponsored or funded by the national agencies, although the new interest from private or university sectors also might be important based on initial success from the Trailblazer or BW1 missions.

The first planned mission is the Japanese one named Lunar-A in 2006. It is directed more to investigate the interior and the evolution of the moon. This mission will dispatch two penetrators into the moon's surface, with seismographs and heat-flow probes; the planned life is about one year (ISU 2003) (Lunar-A, http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=LUNAR-A). Thus, this mission will directly upgrade the current knowledge based on the Apollo era. However, based on the earlier findings, the overall impact on the technical requirements for the lunar structure is unlikely to be substantial.

The second Japanese mission is also planned for 2006 and is named SELENE. It will bring more instruments into lunar orbit and will be equipped with two additional small satellites of 50 kg each. Thus, the mission will consist of a main orbiter (150 kg), a small relay satellite (for communications), and a small very long baseline interferometry (VLBI) satellite (Planetary and Lunar Missions under Consideration, http://nssdc.gsfc.nasa.gov/planetary/prop_missions.html, and http://nssdc.gsfc.nasa.gov/planetary/prop_missions.html#change1). The latter will conduct careful investigation on the position and precession of the moon's orbit. The orbiter will perform a suite of experiments, some of which are similar to other scientific experiments performed by earlier American missions, as well as some that will supplement other planned efforts (Planetary and Lunar Missions under Consideration, http://nssdc.gsfc.nasa.gov/planetary/prop_missions.html, and http://nssdc.gsfc.nasa.gov/planetary/prop_missions.html#change1). The overall impact of all of these studies from orbit will be substantial but not with respect to technical requirements for future lunar structures, except some aspects associated with determining prime areas of future in situ investigation of the lunar surface.

The first Chinese mission to the moon, Chang'e 1, is devoted to testing several technologies for future missions, and it can be treated as the Chinese reconnaissance mission. It is intended to study the lunar environment through a similar suite of instruments as the Japanese missions, with one addition of a microwave radiometer to study the thickness of the lunar regolith. There will also be instrumentation to study the solar wind and near-lunar region, the area just above the lunar surface (Planetary and Lunar Missions under Consideration, http://nssdc.gsfc.nasa.gov/planetary/prop_missions.html, and http://nssdc.gsfc.nasa.gov/planetary/prop_missions.html#change1).

The first Indian lunar mission Chandrayaan-1, sponsored by ISRO, will have an extensive suite of instrumentation, solicited partially through announcements of opportunities. It will focus on studying 3D topography of the moon and distribution of the minerals and elemental chemical species. However, the concentrated effort will be directed to high-resolution mineralogical and chemi-

Table 4. Allowable Career Dose (in Sieverts) by Age at the Start of Radiation, and by Gender (Adapted from Parnell et al. 1998)

Age at start of career dose	Male	Female
20	1.3	0.7
30	2.0	1.4
40	2.8	2.2
50	3.5	2.9
60	4.3	3.7
70	5.0	4.4
80	5.8	5.2
90	6.5	5.9

Note: Table derived from Eq. (1), given by NCRP (Parnell et al. 1998).

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Table 5. Summary of Technical Requirements for Lunar Structures

Condition	Quantification	Importance and technical requirements		
		Phase 1	Phase 2	Phase 3
Temperature	Temperature range=280 K	High: Material must not be brittle above • −233°C in permanently shadowed craters • −150°C at the equator • −85.5°C at midlatitudes • −63°C around the poles	High: • Conditions from Phase 1 • Additionally, insulation or shielding required (2.5 m or more of regolith)	High: • Conditions from Phases 1 and 2
Radiation	Average dose=0.25 Sv/year	Medium: • Electronics and solar panels should be redundant in case of radiation damage	High: • Conditions from Phase 1 • Additionally, minimum 700 g/cm^2 shielding must be provided (approximately 5 m of regolith)	High: • Conditions from Phase 1 • 1,000 g/cm^2 shielding should be provided, or equivalent electromagnetic shielding
Atmosphere/pressure	3 nPa[a]	Medium: • Instrumentation must be vacuum tested	High: • Conditions from Phase 1 • Structure must be pressure vessel with minimum 26 kPa internal pressure, causing high tensile stresses on the structure	High: • Conditions from Phase 1 • Concrete must be manufactured in a pressure vessel to prevent water evaporation and resultant weakening
Meteoroids	Micrometeoroids (ν=10–72 km/s)	Low: • Little, if any, defense is possible	High: • Meteoroid shielding must be provided (minimum 0.5 m regolith)	High: • Meteoroid shielding must be provided separately from radiation shielding if electromagnetic radiation is used
Dust	More than 50% of particles between 20 and 100 μm[b]	Medium: • Material must be abrasion resistant • Mechanical parts must be sturdy and able to operate in dusty conditions	Medium: • Conditions from Phase 1	Medium: • Conditions from Phase 1
Length of lunar day	Lunar day=29.53059 earth days	Low: • Effect depends on mission objectives	Medium: • Missions should arrive at the beginning of the lunar day and make use of light and warm temperatures	Low
Gravity	g=1.62 m/s^2	Self-weight of structure is less	Low: • Tensile stresses are not countered by gravity	Low: • Conditions from Phase 2
Seismicity	Maximum quake recorded 4 on the Richter scale (average 1–2)	Lower risk than on earth	• Conditions from Phase 1	• Conditions from Phase 1

[a]ISU (2000), p. 15.
[b]Toklu (2000).

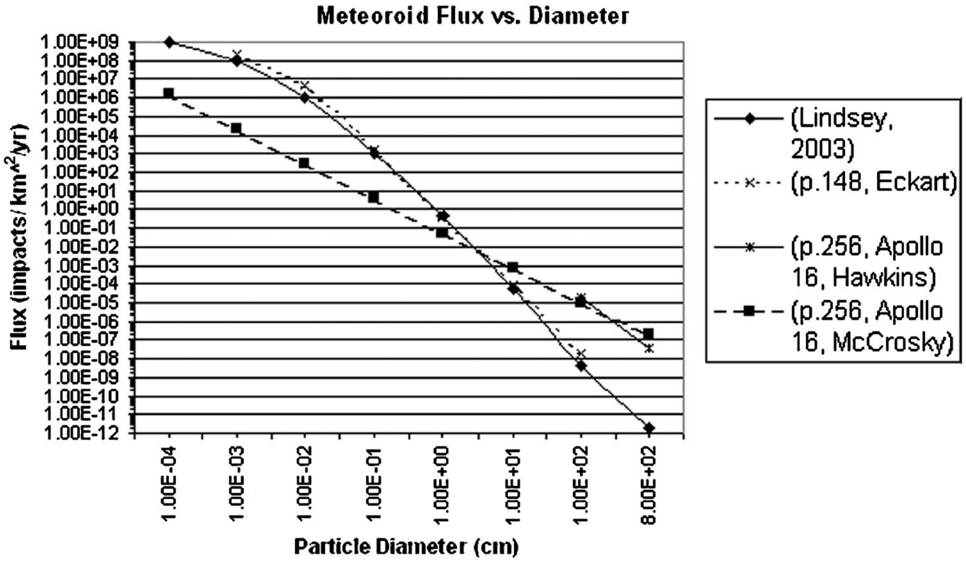

Fig. 10. Meteoroid flux versus particle diameter (adapted from Lindsey, 2003; Eckart 1999; NASA 1972).

cal imaging of the lunar poles and chemical stratigraphy of the lunar crust. A unique effort will be devoted to map the height variation of the lunar surface features (ISRO 2004; Chandrayaan-1 Lunar Orbiter, http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=CHANDRYN1). This will result in better choices of future landing sites. However, it will carry some value in the future mapping efforts of various lunar features, as they might affect the construction efforts, especially in Phases 2 and 3.

The NASA LRO mission is mainly devoted to identify landing sites for future robotic and human explorers. However, it will also bring a suite of important instruments (some for the first time) to relatively low 30–50 km polar circular orbit. A large effort will be placed on studies of the moon's radiation environment, lunar topography, and scanning of the resources in the polar regions. Mapping of the composition of the lunar surface will continue (Lunar Reconnaissance Orbiter) (http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=LUNARRO). The impact on the technical requirements for lunar structures from these studies can be foreseen, especially with respect to future radiation shielding or other arrangements for both human and structural protection during all construction phases.

Conclusion and Recommendations

This paper introduces a new classification of lunar structures into three phases. It includes most of the known important lunar environmental conditions and shows their quantitative representations as well as their impact on different technical requirements associated with each construction phase. These phases are mainly associated with the lunar structure use, and somewhat with their designed service duration. This paper is not a fully comprehensive one as the current new wave of lunar research, in the direction of the utilization of the moon or future colonization of the moon, has just started. The major portion of the overall knowledge on lunar environmental conditions used for derivation of the technical requirements for lunar structures is based equally on in situ investigations from the Apollo era and from the post-Apollo era of recent orbital missions.

The overall recommendations can be divided into three distinct groups. The first group is strategic recommendations; it outlines how to develop the construction code, which encompasses all proposed construction phases, and lists the data important to lunar construction that should be obtained through future lunar missions. The second group includes specific recommendations for baseline requirements for individual phases; however, it must be noted that all technical requirements from the previous phases should also be included (see the Table 5 in Appendix I with importance factors included for each phase). Finally, additional recommendations are made for areas that require further research in relation to lunar structures.

Strategic Recommendations

A concentrated international and multidisciplinary effort is proposed to evolve, based on the current and newly acquired knowledge, the lunar construction code [as some efforts in this direction have already been attempted in the literature, *The Lunar Sourcebook* (Heiken et al. 1991) and *The Lunar Base Handbook* (Eckart 1999)]. The lunar construction code will include a description of the lunar environmental conditions from an engineering point of view, with their quantification and available mapping. It will also include guidelines for the development of lunar structures as proposed in the three construction phases for future moon utilization and colonization. This code will be upgraded on an annual basis, taking into account all available findings from the current missions.

Data in the following areas should be gathered in future lunar missions to include in the lunar construction code:
- Local lunar soil conditions;
- Additional information about temperatures;
- More accurate and precise meteoroid flux data;
- Radiation fluctuation, depending on location and time;
- Gravity field irregularities; and
- Mapping development for seismic activity of meteoroids and moonquakes, topography, and stratigraphy.

These mission objectives should be internationally coordinated for proper accumulation of all data.

Table 6. Summary of Recent Missions (1976 to Present)

Mission name	Agency	Mission objectives	Mission events
Hiten	ISAS	• Test trajectory control utilizing gravity assist double lunar swingbys	• Launched in 1990, entered lunar orbit the same year
• Launch date: January 24, 1990		• Insert a subsatellite into lunar orbit	• Intentionally crashed into the lunar surface on April 10, 1993
• On-orbit dry mass: 143 kg		• Conduct optical navigation experiments on a spin-stabilized spacecraft	
		• Test fault tolerant onboard computer and packet telemetry	
		• Conduct cis-lunar aerobreaking experiments	
		• Detect and measure mass and velocity of micrometeorite particles	
Notes:			
• Complicated but successful mission profile was achieved, which included nine swingbys, two areobreaking maneuvers, a release of the small Hagomoro spacecraft, and a planned crash of the main spacecraft into lunar surface (closest approach in the lunar orbit 422 km).			
• Hiten (originally called MUSES-A) was an ISAS earth orbiting satellite designed to test and verify technologies for future lunar and planetary missions. The spacecraft carried a small satellite named Hagoromo, which was released in the vicinity of the moon but it never reached lunar orbit and was lost. Hiten itself was put into highly elliptical earth orbit which passed by the moon ten times during the mission, which ended when Hiten was intentionally crashed into the moon (in 1993). Three follow-up objectives were also added later in the mission: excursion to the L4 and L5 Langrangian points of the earth–moon system, orbit of the Hiten around the moon, and hard landing on the lunar surface. This mission included Japan's first lunar flyby, lunar orbiter, and lunar surface impact, making Japan only the third nation (after former the Soviet Union and the United states) to achieve each of these goals.			
Clementine	SDIO/NASA	• Test sensors and spacecraft components under extended exposure to the space environment	• Launched 1994 (after two flybys lunar insertion was achieved
• Launch date: January 25, 1994			• Mapping of the lunar surface achieved the same year
• On-orbit dry mass: 227 kg		• Make scientific observations of the moon and near-earth Asteroid 1620 (Geographos)	• Malfunction of one of the OBCs caused the thrusters to fire until it used up all of its fuel, then it spun up without any control until the end of the mission
Notes:			
• Near successful mission profile was achieved with two earth flybys, lunar insertion, and successful operation on the elliptical polar lunar orbit.			
• Clementine performed two series of lunar mappings during the first three months. It left the lunar orbits in May, but continued to test the spacecraft components.			
• The flyby of the near-earth Asteroid Geographos was impossible.			
Lunar Prospector	NASA	• Low polar orbit investigation of the moon	• Launched in 1998; had a 105-h cruise to the moon
• Launch date: January 7, 1998		• Mapping of the surface composition and possible polar ice deposits	• It was inserted into the lunar orbit; at the end of the year it was lowered from 100 to 40 km
• On-orbit dry mass: 158 kg		• Measurements of magnetic and gravity fields	
		• Studies of lunar outgassing fields	• It was lowered to 30 km and was subsequently crushed in a controlled way into the moon on July 31, 1999
		• Learn more about the size and content of the moon's core	
Notes:			
• Complicated mission profile successfully achieved with a 105-h cruise to the moon.			
• Lunar Prospector was devoted to "prospect" the lunar crust and atmosphere for potential resources, including minerals, water ice, and certain gases via investigation using four scientific instruments. It mapped the moon's gravitational and magnetic fields, confirming gravitational field anomalies first encountered during the Apollo era. Lunar Prospector's crash produced no observable signature of water.			
SMART 1	ESA	• Test solar electric propulsion, miniaturization technology	• Launched 2003 (secondary payload on the Ariane-5 Cyclade rocket)
• Launch date: September 27, 2003		• RS: search for ice at the South Pole using NIR spectrometry	
• On-orbit dry mass: 305 kg		• Map minerals and chemical elements using visible light, near-IR, and x-rays	• Entered lunar orbit in 2004
			• Scheduled to be used until August 2006

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Table 6. (*Continued.*)

Mission name	Agency	Mission objectives	Mission events

Notes:

• A solar-electric propulsion system (ion drive) was used. A complicated mission profile was achieved. First the spacecraft was put into geostationary transfer orbit, 742–36,016 km, inclined at 7° to the equator. Three lunar resonance maneuvers were used in 2004 to minimize propellant use. Lunar orbit capture on November 14 at a distance of 60,000 km from the lunar surface. Then, after a series of maneuvers, SMART 1 was lowered into 300–3,000 km polar lunar orbit. The original mission of a 6-month lifetime was extended by a year (until August 2006).

• Testing: solar-powered ion.drive and experimental deep-space telecommunications system.

• Science: study geology, morphology, topography, mineralogy, geochemistry, exospheric environment to learn about planetary formation, formation of earth–moon system, near/far side dichotomy, volcanic/tectonic activity, thermal and dynamical processes involved in lunar evolution, and water ice and external processes on the lunar surface.

Specific Recommendations for Technical Requirements

The specific recommendations present the technical requirements derived from the lunar environmental conditions. These requirements, which should be included in the lunar construction code, are listed in more detail in Appendix I and summarized below (see Appendix I).

Phase 1

The materials used in Phase 1 must be able to sustain very low temperatures, in some cases as low as −233°C. Also, the materials must be abrasion resistant against the lunar dust. Redundancy is required in electronics and solar panels to minimize the damage caused by radiation.

Phase 2

In addition to the requirements of Phase 1, further shielding is needed to protect the inhabitants of the structures; at least 700 g/cm^2 of regolith is required for radiation shielding. This regolith is also enough to lower the internal temperature range in most areas to 2°C or less, and it will provide sufficient meteoroid shielding to lower the risk of penetration to 9×10^{-8} impacts/km^2/year. The requirements due to the thin lunar atmosphere are also important in this phase. A minimum of 26 kPa of pure oxygen is required to sustain human life, although the pressure inside the structures will be greater with a mixed gas atmosphere to reduce the risk of fire. Because of this, the structures in this and the next phase will be pressure vessels; combined with the low gravity, these conditions result in large tensile stresses on the structure. Therefore, the shapes of the structures in this phase will be spherical, cylindrical, or toroidal shells to eliminate corners and avoid stress concentrations.

The inflatable structures in this phase will be multilayered, distributing some of the requirements such as temperature control, additional meteoroid shielding, and pressure containment over several different layers. These layers must include a bladder, restraint layer, and inner liner, and may also include a deploying mechanism and thermal insulation.

Phase 3

Most of the conditions from Phase 2 carry over to Phase 3, with a few more options. More shapes are possible because the structure will be constructed from in situ resources. Materials produced in situ, such as lunar concrete, must be tested before use to determine their properties; lunar concrete should also be manufactured in a pressure vessel (such as the construction dome) to prevent the water from evaporating and weakening the concrete. Radiation shielding in this phase should provide a minimum of 1,000 g/cm^2, as the earth's atmosphere does, due to the longer duration stays on the moon in this phase. This may be provided through electromagnetic shielding; if it is, alternate meteoroid shielding must then be used.

Additional Recommendations

In this category of recommendations, areas of suggested research associated with future lunar structures are indicated. Advances have already been made in some of these areas.

- Develop rigidizable pneumatic structures that are highly resistant to radiation, temperature and abrasion;
- Research vacuum multilayered pressure vessels (with external vacuum conditions);
- Develop new materials that are highly temperature and radiation resistant;
- Develop a suite of initial in situ structural experiments with regolith shielding, to be performed during the first robotic lunar missions;
- Develop a suite of initial in situ investigations of lunar soil for lunar civil engineering applications, to be performed during the first robotic and later manned lunar missions;
- Develop radiation shielding for lunar structures; and
- Develop a suite of ground-based experiments including simulations of lunar conditions.

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Appendix I. Technical Requirements

A summary of the technical requirements for lunar structures is given in Table 5.

Notes

The location of the lunar base, specific to the mission objectives and phase, will alter the importance of the environmental conditions, changing the technical requirements of the structure. Particularly in Phase 2, it must be considered in conjunction with the environmental conditions to determine the technical requirements of the structure. Some locations that will have a significant impact include the following;

1. Lavatubes provide natural temperature, radiation, and meteoroid shielding, shifting the focus of environmental conditions to the near vacuum conditions, dust, and gravity

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Table 7. Future Missions

Planned launch date	Mission name	Agency	Mission objectives
End of 2005	Trailblazer	Transorbital (U.S.)	• To gather high-resolution images of the moon, earth, and of the mission itself
	• On-orbit dry mass: 100 kg (plus TLI kick motor)		• To carry certain inert cargo to the moon surface at the conclusion of the mission
	• Planned as an orbiter on an elliptical orbit. Pericenter: 50 km, later 10 km		• To perform some unspecified scientific investigations
Notes:			
Private industry sponsored mission. The objectives are not very well specified. However, the mission profile depicted on their web site is relatively complex. It includes the following: a 4-day cruise to the moon, an insert to an elliptical orbit, then lowering to the first nominal altitude of 50 km over the lunar surface, then further lowering to 10 km to make images of the abandoned hardware from Apollo and Luna missions, and the final descent during a controlled impact landing on the moon. It will also carry a specially hardened capsule with the specific undisclosed cargo.			
Not earlier than 2006	Lunar-A	JAXA (Japan)	• To gather information about the interior of the moon
	• On-orbit dry mass: 520 kg 2×13 kg penetrators		• To study the evolution of the moon
	• 200–300 km near circular orbit (lowered to 40 km to deploy two penetrators)		
Notes:			
LUNAR-A is an unmanned probe to study the interior and the evolution of the moon. The probe will land on the moon surface and the observation devices will separate from it to investigate the internal structure of the moon. There will be two penetrators in a spear-shaped case, 80 cm long. They will penetrate the depth to about 2 m. The penetrators will be equipped with seismometers and heat-flow probes, and their life span is designed for about a year. The LUNAR-A mother ship will gather information from the penetrators, while also photographing the lunar surface with its camera. There will also be some navigation experiments performed during this mission.			
2006	SELENE	JAXA (Japan)	• To study the origin, evolution and tectonics of the moon from orbit for nominally one year
	• On-orbit dry mass: 150 kg for orbiter (plus two subsatellites, each of 50 kg)		
	• 100 km, polar, circular orbit		
Notes:			
SELENE will carry 13 instruments including imagers, a radar sounder, laser altimeter, x-ray fluorescence spectrometer, and gamma-ray spectrometer. It will consist of three separate units: the main orbiter, a small relay satellite, and a small VLBI satellite. The relay satellite will be used to transmit communications from the orbiter to the earth. The VLBI satellite will be used to conduct investigations on the position and precession of the moon. SELENE will take 5 days to reach the moon. Initially, it will be put to a $120 \times 13{,}000$ km polar orbit. Then, the relay satellite will be released into a $100 \times 2{,}400$ km orbit and the VLBI will be released into a 100×800 km orbit. The orbiter will be then lowered to a nominal 100 km circular orbit. SELENE was launched in September 2007.			
Late 2007	Chang'e 1	CNSA (People's ROC)	• To test future space technologies for future missions
	• On-orbit dry mass: 130–150 kg for orbiter		• To study the lunar environment
	• 200 km, polar, circular orbit		• To study surface regolith
Notes:			
The orbiter will be the first of a series of Chinese missions to the moon. First, the orbiter will be placed in lunar orbit for about one year to test various technologies for future missions. The orbiter will carry out a series of scientific investigations; a stereo-camera will map the lunar surface, an altimeter will measure the distance to the surface, a gamma/x-ray spectrometer will study the composition and radioactive components of the moon surface, a microwave radiometer will study the thickness of the lunar regolith, and there will also be instrumentation to study solar wind and the near lunar region.			
2007–2008	Chandrayaan-1	ISRO (India)	• To map topographic features in 3D; distribution of various minerals and elemental chemical species
	• On-orbit dry mass: 55 kg		
	• 100 km, polar, circular orbit		• To test future space technologies for future missions
			• To test space technologies for future missions
			Specific areas of studies include:
			• High-resolution mineralogical and chemical imaging of lunar poles
			• Search for surface or subsurface water ice on the moon, especially at lunar poles
			• Chemical stratigraphy of lunar crust
			• Mapping of the height variation of the lunar surface features

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Table 7. (*Continued.*)

Planned launch date	Mission name	Agency	Mission objectives
			• Observation of x-ray spectrum greater than 10 keV and stereographic coverage of the moon's surface with 5-m resolution
Notes: The CHANDRAYAAN-1 mission will be the first Indian mission to the moon, with the scientific objectives to upgrade knowledge about the planet. Several scientific payloads are planned to achieve them via AO solicitation process for a total of 10 kg payload mass and 10 W power. The mission will be a lunar polar orbiter at an altitude of about 100 km using indigenous spacecraft and launch vehicle of ISRO.			
End of 2008	LRO • On-orbit dry mass: 500–600kg • 100 kg lander? 30–50 km, polar, circular orbit	NASA (U.S.)	• To identify landing sites for future robotic and human explorers • To study the moon's radiation environment • To map the lunar topography in high resolution • To scan for resources in the polar regions To map further the composition of the lunar surface
Notes: The LRO mission is the first mission to the moon based on the NASA vision plans. It is planned to be launched in 2008 and has a complex mission profile including a 4-day cruise to the moon and an initial lunar orbit with the periselene altitude of 100 km; then the spacecraft will be lowered. The mission will last ~1 year in a 30–50 km altitude lunar polar orbit. The platform will be three-axis stabilized and power of about 400 W will be provided by solar arrays and batteries. A communication system will secure uplink and downlink. The final scientific payload will have a suite of instruments (a high-resolution camera to document a small-scale landing hazards and lighting conditions at the lunar poles; a laser altimeter to measure landing sites slopes and search for polar ices; a neutron detector for water ice and space radiation detection, a radiometer to map temperature and possible ice deposits, a Lyman-alpha mapper to observe the lunar surface in ultraviolet; a cosmic ray telescope to investigate background space radiation.) There is also the possibility of installing a miniature synthetic aperture radar sensor to map the moon's surface.			
After 2008/2009	Lunar Mission BW1 • On-orbit dry mass: not yet specified • Launch mass <200 kg	University of Stuttgart (Germany)	• To perform technology demonstration for a small satellite (electric propulsion systems for complex attitude control and orbit transfer maneuvers using autonomous guidance and navigation; visible/near-infrared and thermal infrared imaging combined with target pointing observations; radio frequency and microwave technology for broadband communication, relay functions and radar sounding; new advanced OBC architectures; evaluation of degradation of satellite subsystems) • To identify scientific targets in cislunar space (gravitational and magnetic field and radiation observations) • Observations of earth influences and earth-moon interactions, and observations of near-earth objects and the Kordylewski clouds • Identification of other lunar scientific targets (lunar surface observation, selection of future landing sites, and other measurements)
Notes: University sponsored mission being used as a platform for master's and Ph.D. student research based on the former successful small satellites known as the "Stuttgart Small Satellite Programme." This will be launched by a piggyback launch opportunity to the GTO. This small satellite of approximate size of 1 m×1 m×1 m will use an electric propulsion system. Mission profile details have not been specified.			

Note: SELENE=selenological and engineering explorer; VBLI=very long baseline interferometry; LRO=lunar reconnaissance orbiter; GTO =geostationary-transfer orbit; and BW1=Baden-Württemberg 1.

2. Peaks of eternal light provide relatively constant temperatures, as well as other benefits. For this location, radiation, pressure, and meteoroids become more significant considerations.

Appendix II. Radiation Analysis

The significant biological risk caused by radiation on the moon demands substantial structural shielding beginning in Phase 2, when humans begin to spend time in lunar structures. Currently, there are no specific radiation limits, and suggested doses depend on factors such as length of exposure, area exposed, and age at the start of exposure. Table 3 gives suggested limits from the National Council on Radiation Protection for blood forming organs, eyes, and skin, over 30 days, a year, and a career (see Table 3).

For missions early in the second phase, these limits can be used; however, as individuals spend more time on the moon, more specific annual limits are required.

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The NCRP also gives an equation for the maximum radiation that should be received, depending on the age at which the dose starts [see Eq. (1)], (Parnell et al. 1998). From this equation, maximum career doses are calculated (see Table 4)

$$\beta = 2.0 + 0.075 \times (\alpha - T_0), \tag{1}$$

where $T_0=30$ for males, 38 for females; α=age at start of dose; and β=career dose maximum.

Beginning in Phase 2, regolith will be the primary method of radiation shielding, and in Phase 3, it may be complemented with other methods such as electromagnetic shielding. By increasing the mass through which the radiation particles must pass, regolith decreases the energy of the particles, eventually stopping them and reducing the dose (Parnell et al. 1998). However, a thin layer of shielding breaks down some particles and creates high-energy particles, or brehmsstrahlung radiation, which is more harmful than the initial radiation (Buhler and Wichmann 2005; Aulesa 2000). For this reason, if any shielding is used, it must be sufficiently thick. Fig. 9 shows the changes in dose of GCR and SEP events caused by different thickness of shield. While the dose of GCR with no shielding is slightly lower than that with 500 g/cm^2, shielding is required to reduce the dose caused by SEP events; therefore, more than 500 g/cm^2 of shielding should be used. Further, the atmosphere on earth provides 1,000 g/cm^2 of shielding, so this level of protection is desired on the moon as well to reduce the radiation to earth levels. For shorter stays on the moon, particularly in Phase 2, 700 g/cm^2 is considered adequate (Aulesa et al. 2000). If the density if the regolith is between 1.3 and 1.5 g/cm^3, the regolith shield will have to be between 4.7 and 5.4 m thick.

Presently, there are no set radiation limits for lunar missions; the NCRP suggestions should be adhered to, although radiation doses should also be kept as low as possible. To achieve this, a minimum of 5.4 m of regolith is suggested for Phase 2, and in Phase 3, the shielding should provide protection equal to that of the earth's atmosphere, at 1,000 g/cm^2 (see, also, Table 5).

Appendix III. Meteoroid Analysis

Although the effectiveness of a regolith shield in preventing meteoroid damage is unknown and experimental testing must be done before such a shield can be assumed to be effective, the Fish–Summers penetration equation is used here to determine the approximate protection that will be provided with a layer of regolith 5.4 m thick. This thickness is used because it is the recommended amount for radiation protection, beginning in phase two.

The Fish–Summers equation is given below [see Eq. (2)] (Hayashida and Robinson 1991).

$$t_t = k_t \times m_m^{0.352} \times v_m^{0.875} \times \rho_m^{1/6} \tag{2}$$

where t=thickness of target material (cm); v=velocity (km/s); k=constant for target material; m=mass (g); ρ=density (g/cm^3).

The subscript Al stands for aluminum; m for meteoroid; re for regolith; and t for target: $k_{Al}=0.57$; $k_{re}=1.18$ [using $t_{Al} \times \rho_{Al}/\rho_{re} = t_{re}$ (Lindsey 2003)]; $v_m=18$ km/s (close to average velocity of meteoroids (Coronado et al. 1987, p. 12)); $\rho_{Al}=2.7$ g/cm^3; $\rho_m=0.5$ g/cm^3; and $\rho_{re}=1.3$ g/cm^3 [minimum value (Aulesa 2000) used to increase safety].

Assuming a regolith thickness of 5.4 m, the equation shows that a meteoroid of maximum mass of 37 kg, or diameter of 52 cm, could impact the shield and not penetrate through spallation (Hayashida and Robinson 1991). This lowers the flux of penetrating meteoroids to between 10^{-8} and 10^{-7} impacts/km^2/year; meteoroid flux as a function of particle diameter is shown in Fig. 10 (Lindsey 2003; Eckart 1999, p. 148). Therefore, 5.4 m of regolith should be more than sufficient shielding. However, this calculation can only be used as guide, as the equation is not intended for evaluating regolith as a shield.

Appendix IV. Recent Lunar Missions (1976–Present)

A summary of recent lunar missions since 1976 is given in Table 6.

Table 6 is derived from the following sources: ISU 2003 and Koelle et al. 2005, this is the LBQ2-05 article. Table 6 does not include Russian Luna missions from the 1970's but information about their findings is included in the literature.

Appendix V. Planned Lunar Missions (Approved)

Table 7 outlines lunar missions that are planned for the future.

Table 7 derived from the following sources: ISU 2003 and Koelle et al. 2005, this is the LBQ2-05 article.

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