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Paper Session II-C - Infrastructure for a Lunar Base

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INFRASTRUCTURE FOR A LUNAR BASE

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ABSTRACT

Exploration of the Moon is the most crucial and decisive step for human expansion into the vast reaches of space. The Moon is the natural and ideal testbed for determining human capability to survive, function, expand and settle into the space environment. Scientific studies, astronomic observations, and exploitation and utilization of space resources culminating in the establishment of a self-sufficient permanently human-tended lunar base are the goals of lunar exploration. Four development stages in the evolutionary exploration of the Moon are suggested: (1) exploratory; (2) pioneering; (3) outpost; and (4) base. Overall goals and specific objectives, functional requirements, construction conditions, and life support systems requirements needed in each stage are identified.

INTRODUCTION

The return of humans to the Moon early in the next century is inevitable. Exploration and settlement of the Moon are the most crucial and decisive steps toward human expansion into the vast reaches of space. The Moon is the natural and ideal testbed for determining the human capability to explore, function, exploit and settle the endless Space Frontier to the benefit of Earth. The primary goal is the establishment of a self-sufficient permanently human-tended lunar base. This base may include the construction of a lunar spaceport for the launching of spaceships to Mars and beyond. All these activities requires the construction and operation of structures housing a Lunar Engineered Closed/Controlled EcoSystem (L-ECCES). An L-ECCES includes initially a human module, next a plant module, and in a much later stage an animal module, along with continuously growing scientific, manufacturing and mining modules.

Human fascination with Moon exploration and its settlement dates back to the Greek mythology and the Roman culture, and continued throughout the development of astronomy. A unique synergism of science and imagination can be found in the inspiring book *From Earth to the Moon* by Jules Verne published in the second half of the last century. The Moon has long been viewed as the Earth's seventh continent waiting and pleading for millennia to be explored and utilized to the benefit of humanity.

The establishment of a lunar base has been widely studied and recommended since the Apollo era of the 1960's. Papers addressing many aspects of a lunar base can be found in the proceedings of the 1st and 2nd symposium on lunar bases held in 1984 and 1988 [1,2], respectively. Numerous papers by Duke, Mendell and Roberts since 1985 offer unique insights into the issues associated with the lunar exploration and the establishment of a lunar base

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[3,4,5,6,7,8]. A human-tended base on the Moon was recommended by the 1986 National Commission on Space Report [9], the 1987 Sally Ride Report [10], the 1988 studies of the former NASA Office of Exploration [11], the 1989 NASA 90-Day Report [12], the 1990 Augustine Report [13], and the 1991 Synthesis Group Report [14].

A lunar base involves a totally different mix of technical and scientific challenges from those faced by the short "camping" trips of the Apollo Program and the current Shuttle flights. The difficult technical problems of transportation dominated these programs. Short-term support of astronauts with several days supplies "backpacked in" is a much simpler task than support for long-duration missions. A permanently human-tended base on the Moon requires long-term support for human settlement. Although both space transportation and life support systems are important, the latter becomes the dominant factor for a lunar base.

DEVELOPMENT STAGE RATIONALE

The primary parameter determining the development stage of a lunar base is its functional maturity with particular emphasis on the level of human operations. This maturity affects: (1) the base functions and physical size; (2) the number and duty tour of the human occupants; (3) the available technological, material and human resources; and (4) the degree of base self-sufficiency. The same structural solution cannot always be optimal for all these conditions as the optimum changes according to the maturity level.

Development stages must be defined to facilitate: (1) the grouping, sorting out and comparison of various concepts for lunar structures; (2) assessing the interrelationships between base size and functions; (3) matching the base maturity with the optimum structural system considering available technologies, indigenous and imported materials, construction methods, and time; and (4) determining the base design criteria considering base maturity and performance requirements.

The functional requirements driving the design of a lunar base depend upon four basic requirements which a lunar ecosystem must provide: (1) shelter and support for human life; (2) support for plant growth and, later, animal life; (3) housing for support equipment and controls for the base life support system, communications, scientific operations, working environment and other functions; and (4) support for general and mission-specific base operations such as resources utilization, manufacturing, material processing, mining, power generation, spaceport and other activities. Many of these functional design conditions change with time. This growth requires a flexible design and an easily expandable modular base which can be reconfigured as the base evolves and expands.

LUNAR DESIGN CONDITIONS

The Moon is simultaneously a benign and a very harsh location for structures. Limiting design constraints in the lunar environment are very different from those on Earth, and they require a return to basic principles rather than routine application of Earth-bound design practices. The lunar design conditions require the exploration of unconventional and novel approached in the design of efficient and economical structures. They can be divided into three general classes: (1) environmental; (2) remoteness; and (3) pristine nature preservation conditions.

Lunar Environmental Conditions--The lunar environmental conditions can be hostile, bening or of mixed effect with respect to structural design. Hostile design conditions arise from the lack of a lunar atmosphere and an external atmospheric pressure. The structural deleterious implications include: (1) the internal pressure of the artificial atmosphere is the dominant load due to the lack of an atmosphere and, consequently, a structure becomes effectively a pressure vessel; (2) the extremely large lunar surface temperature changes (diurnal temperature change from 127 deg C (261 deg F) during daytime to -173 deg C (-279 deg F) during night time, i.e., a diurnal temperature change of 300 deg C (540 deg F)) can produce large thermal stresses and strains leading to thermal damage of materials and requiring significant insulation for acceptable thermal stability and adequate heat rejection systems; (3) for adequate protection from harmful radiation and micrometeoroid impacts, a layer of regolith is needed to cover the structure; (4) offgasing from exposed materials can result because of the external vacuum; and (5) workers must be suited for EVA construction activities.

Conditions beneficial for structural design include: (1) very low seismic activity, with few moonquakes above 1 to 2 on the Richter scale; and (2) no terrestrial-like weather loadings, such as those induced by wind, rain, ice or snow. Lunar environmental conditions of mixed structural impact are: (1) a hypogravity of about 1/6 Earth gravity which greatly reduces the gravity loads, including this from the shielding regolith cover, to at most 10% of the internal pressure loading, but which reduces vehicle surface traction and the capacity of soil anchors and foundations, and affects fluid flow; (2) the anhydrous condition that precludes outer surface corrosion and increases the strength of materials such as glass; (3) the long day-night cycle, 28-Earth days, reduces the rate and frequency of the thermal change cycle, but adversely affects power and lighting demands and limits construction schedules.

Moon Remoteness Conditions--Although the Moon is the largest celestial body closest to Earth, it is very remote in terms of terrestrial distances. The mean Moon to Earth distance is about 386,000 km (240,000 miles) and the round trip communication delay is about 2.6 s. This remoteness leads to the following critical conditions: (1) The transportation cost for material shipped from Earth, which presently is estimated to amount to about $66,000/kg ($30,000/lb), is very high. This cost encourages the development of cheaper modes of transportation, efficient new materials, lunar manufacturing of materials using indigenous resources, and light construction/manufacturing equipment; (2) The number of astronauts on duty tour is limited because of the extensive life support resources (food, air, water, temperature control, etc.) required to support humans on the Moon. As a result, this promotes the development and use of automation and robotics; (3) A must for first time success exists. There is little latitude for and great risks from on-site modifications. This promotes thorough planning, proof testing, and use of advanced controls.

Moon Pristine Conditions--The construction and operation of a lunar base must not excessively impact the inherently stable and pristine lunar environment. Concerns include both a philosophical sense of responsibility to preserve the unique conditions of the Moon and pragmatic desires to maintain these conditions for their scientific merit, including to facilitate astronomical observatories. To ensure this preservation, base construction and operations must minimize dust production and atmospheric contamination through a self-contained and self-regulated ecosystem that fully controls and recycles all wastes and pollutants. Appropriate space treaties and lunar environmental laws must be formulated to guide and regulate the development of a human-tended base and associated utilization of lunar resources.

DEVELOPMENT STAGES

The size, characteristics, and development schedule for a lunar base depend on the specific mission objectives, national priorities and financial resources. A prime goal is to provide the type of structure and the associated infrastructure required to efficiently house the ecosystem to support humans and to carry out the planned base objectives. These requirements and associated level of maturity affect the general base layout and size, type of structures, construction features and facilities needed. Four evolutionary development stages spanning from a simple encampment to a mature base, likely extending over 50 to 100 years, are proposed. These four stage are: *(1) exploratary; (2) pioneering; (3) outpost; and (4) a self-sufficient permanently human-tended base.*

The characteristics of each development stage can be described in only a general manner since the details can change according to the mission objectives, priorities, and available enabling technologies. Although many types of structures can be considered, it is apparent that a most desirable candidate type is a modular inflatable structure that can evolve from a single module in an early stage to an expanding full base. The proposed inflatable structure shown in Fig. 1 is formed with modules consisting of (1) membranes forming the roof, subfloor and side walls, and (2) a framing system composed of four tension columns and four upper and four lower compression arches [15]. Using Kevlar 49 as membrane material, an internal pressure of 69 kPa (10 psi), and a single inflated module of 6.1x6.1x3 m (20x20x10 ft), baseline required membrane thicknesses range from 0.3 to 0.46 mm (0.012 to 0.018 in). Tubular pressurized framing components may be made of a similar membrane material. The total baseline (prior to introducing a safety factor) mass of such a single inflatable module amounts to only 195 kg (429 lb). Moreover, such a module can be stowed in a volume many times smaller than its deployed shape.

<u>Exploratory Stage</u>--The exploratory stage consists of unmanned probes, robotic surveys, and short-term manned missions building on previous lunar missions, including the six Apollo human landings from Apollo 11 on July 20, 1969 through Apollo 17 in December 1972. Much vital information can be obtained from upgrades probes and robotic missions through utilization of technological advancements since the 1960's.

In this stage, crews of 2 to 4 astronauts with duty tours ranging from 3 to 13 Earth days during the lunar daylight period are envisioned. The landing module must provide the structure required to house the crew and the mission functions, similarly to the Apollo Lunar Excursion Module (LEM). Thus, it must be completely assembled and tested as a human-rated habitation module capable of withstanding both the internal pressure and the forces induced by the flight dynamics. Energy is expected to be supplied by deployable photovoltaic solar panels. No radiation shielding and micrometeoroid protection can be provided in this stage beyond that of the landing module and the EVA suit. All life support is supplied by physical/chemical systems with all supplies imported from Earth and all waste products recovered and returned to Earth.

Objectives of the exploratory stage include site selection and exploration for the establishment of a base, sampling and testing of regolith and subsurface materials, geochemical assessment, gathering of site topographical data, measurement of radiation, micrometeoroid impact, seismic and gravity data, testing of remote sensing systems, and testing and evaluation of a lunar rover. Testing of inflatable components must be undertaken as a precursor for the later use of inflatable structural modules.

Pioneering Stage--This stage involves crews of 4 to 12 astronauts staying for up to one month, thus experiencing both the sizzling hot lunar daylight time and the frigid lunar night. Two structures are envisioned for a base in this stage, the landing module serving as the initial human shelter and a two-module inflatable structure preoutfitted to allow immediate deployment and utilization. One module serves as living and exercise quarters, with a second module housing a working area and airlock for input/output access.

A prime task of this stage is to test the deployment, construction and operation of an inflatable structure. No radiation shielding and protection from micrometeoroid impacts can be provided within the resources and time sehedule available in this stage. All life support is supplied by physical/chemical systems with all supplies imported from Earth and all waste products stored and returned to Earth. Energy is to be supplied hy deployable photovoltaic solar panels.

Objectives of the pioneering stage missions also include development and testing of regolith handling and moving operations, robotic construction and mining equipment, use of batteries for energy storage, introduction of a nuclear reactor for power supply during the lunar night, testing of heat rejection systems, initial trials of hydroponic plant growth, intensive assessment of lunar resources, initial testing for extraction of lunar resources such as oxygen and helium 3, and exploration trips with a lunar rover.

Outpost Stage--The outpost stage marks the transition from an encampment to the establishment of a permanent infrastructure geared toward achieving a self-sufficient base. Rotating crews of 10 to 20 astronauts for duty tours from 1 to 6 months are envisioned. To accommodate the outpost activities, an inflatable structure consisting of two clusters, each of about 10 identical modules connected by a passageway containing an airlock for access to the lunar surface, is needed. Such an inflatable structure is portrayed in Fig. 1. One cluster is for living, exercise and leisure use, with the second being the work area. All modules must be preoutfitted to allow their immediate deployment, occupancy and operation.

The deployment and construction of this multi-module structure requires a high level of automation and robotics not yet available. Development of enabling automation and robotics for lunar construction is thus a must prior to the outpost stage. Radiation shielding and micrometeoroid protection is provided by covering the inflatable structure with a layer of regolith about 3 m (10 ft) thick. Hence, development of methods and automated equipment to move large masses of regolith are another objectives. Nuclear power of about 5 MW must be supplied in addition to photovoltaic power to meet the power requirements of the outpost.

Other objectives of the outpost stage include the testing and operation of advanced life support system and to further lay down the foundations for a flexible, expandable and permanent lunar base infrastructure. Physical/chemical systems imported from Earth must still be used, but at the same time the building of a bioregenerative life support system must be initiated. Hydroponic plant growth must be expanded and experiments to weather regolith into a plant growth medium have to be undertaken.

Mining and extraction of lunar resources (oxygen, helium 3, minerals) are to become permanent ongoing activities. Manufacturing in the lunar hypogravity environment is to be initiated. Construction of a photovoltaic solar farm with its energy to be beamed to Earth is another task. Lunar rover exploration of the Moon's far side and planning of an astronomic observatory are to be undertaken in this stage.

Base Stage--The base stage is the most advanced step before multiple base development and eventual lunar human settlements. A mature single base, with a permanent population of 20 to 50 astronauts with duty tours from 6 months to one year is foreseen. To accommodate such a large crew, the outpost inflatable structure needs to be expanded through the addition of similar clusters of about 10 modules each. In addition, an entire cluster should be dedicated for the bioregenerative life support system, i.e., a plant module. Power requirements up to about 100 MW are to be met from nuclear and photovoltaic sources.

The goal of the base stage is to establish a permanent lunar infrastructure capable of reaching an acceptable level of self-sufficiency, i.e., capable of sustaining a Lunar Engineered Closed/Controlled EcoSystem (L-ECCES). Life support systems should include both physical/chemical and bioregenerative systems, with the later in the dominant role and the former in a backup and support role. Objectives of the base are to bring the tasks outlined for the outpost to the level of a continuous activity. Additional tasks include the construction of an astronomic observatory on the far side of the Moon and of a lunar spaceport for launching of spaceships to Mars, the inner and outer solar systems and beyond.

As the base becomes more mature, manufacturing of products using lunar indigenous resources for export to Earth and continuous expansion of the photovoltaic solar farm are envisioned. The ultimate goal is to establish a base that becomes economically viable and which can lead to the construction of additional lunar bases and possibly similar infrastructure on Mars.

CONCLUDING REMARKS

Establishment of a self-sufficient permanently human-tended lunar base is the major goal and challenge of space exploration and human expansion into space in the next century. A rationale for an evolutionary development of a lunar base and the governing functional design considerations are briefly outlined. Four evolutionary development stages are suggested. The first two encampment stages are the exploratory and pioneering stages. Initial exploration and establishment of the elements required to develop a lunar infrastructure are the basic objectives of these two stages. In the following outpost stage, the enabling technologies for the build up of a lunar infrastructure are demonstrated and refined. Finally, the last stage involves the development of a permanently human-tended lunar base with an acceptable level of self-sufficiency to support a permanent crew of 20 to 50 astronauts for tours from 6 months to one year.

The future of humanity will undoubtedly be affected by the human expansion into space. *Any civilization that does not challenge the impossible is doomed to fail. And, the impossible for our civilization is the conquest of the endless Space Frontier.. The first step in this immense enterprise is a human-tended lunar base.*

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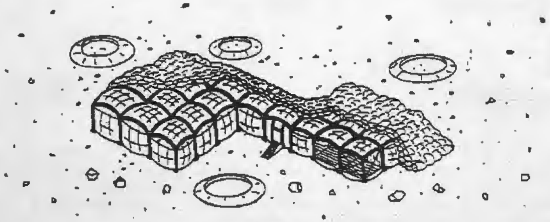

Fig. 1 An overall view of a lunar inflatable structure consisting of two clusters of identical modules.