Lunar Base Development Issues, Technology Requirements, and Research Needs

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Abstract

The development, design, and construction of a lunar base will be an extremely complex technical task. It will be even more challenging to set up the funding scheme and the international cooperative structures that will be required to establish humankind’s first outpost on another planetary body. This paper provides a summary of development issues, technology requirements, and research needs of a lunar base program. Non-technical aspects covered include the rationale for installing a lunar base, financing, cost, management, and legal issues, as well as general development aspects. Technical aspects discussed include the impact of the lunar environment on base design and development, Earth-Moon transportation, and site selection. The specific requirements of habitat design, thermal control, power supply, life support, communications, lunar surface transportation, extra-vehicular activities, and in-situ resources utilization are discussed, as well as logistics, cost, and modeling aspects. Also, it is outlined that a lunar base may very well serve as a testbed for technologies required for human Mars missions. The contents of this paper are based on countless lunar base-related studies that have been conducted in the past four decades and *The Lunar Base Handbook* that has been published recently and is also introduced here.

Lunar Base Design Activities and Status

Current lunar base studies all build on what may be called the Apollo Legacy. The Apollo program provided a wealth of lunar data and operational experience both for Earth-Moon transfers and on the lunar surface. However, more than thirty years have passed since the first lunar landing and so many of the experiences of the Apollo era are essentially lost. Apollo also constitutes a political and psychological burden. Due to what may be called the 'been there done that'-effect, the public and space agencies have largely lost interest in the Moon. Only in Japan is lunar exploration on the space agency’s agenda. Consequently, only very few conferences on lunar or planetary base development and design have taken place in the past 30 years. Nevertheless, numerous lunar base design studies have been conducted. The focus of these studies was mainly on areas such as in-situ resource utilization (ISRU) and lunar base habitat design. A comparative lack of detailed design studies could be observed in other areas, such as thermal control, communication, and lunar surface transportation. A general problem is that the different technologies required for a lunar base have very different Technology Readiness Levels (TRLs). Studies on lunar base models have been published by H.H. Koelle, P. Eckart, and others. While Koelle's model is mainly focusing on large-scale lunar bases, the focus of Eckart's model is on initial lunar bases with few crew members, providing first order of magnitude estimates of lunar base initial / resupply masses, power requirements, and heat loads, etc. [Eckart, 1996a; Koelle, 1999]

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There was also a lack of coordination between lunar base-related activities, including space agency studies and academic efforts, as well as commercial attempts and individual activities. Two groups that are trying to provide coordination are the Subcommittee on Lunar Development (now: Moon-Mars Committee) of the International Academy of Astronautics (IAA) and the International Lunar Exploration Working Group (ILEWG). ILEWG was founded in April 1995 and its members are space agencies, research institutes, industry, and universities. However, neither of these organizations has been able to overcome the general lack of an organizational structure of the lunar base community. [IAA, 1999; ILEWG, 1999]

Lunar Base Rationale

The first order of business of any future lunar base development initiative needs to be the definition of a clear rationale. This rationale can be essentially composed of a:

- Scientific rationale (Science of / from / on the Moon)
- Economic rationale (e.g., in-situ resource utilization)
- Cultural rationale (e.g., evolution of humankind)

Scientific and economic reasons for lunar base development need to be truly justified, i.e., they should be the best or only alternative to reach a specific scientific or economical goal. With respect to ‘Science of the Moon’, the lunar community has to work on explaining to the public that the Moon is still mainly 'terra incognita', that there is still much to discover and so much we do not know. Long-term prospects of a lunar base need to be clearly defined without raising false expectations, especially with respect to the Moon's economical potential.

Preferably, the lunar base should be an element of a step-by-step ‘Roadmap of Human Space Exploration’. For example, the lunar base could be a stepping stone towards the further exploration of the Solar System. In this respect it may be interesting to note that John Young, former Gemini, Apollo and Space Shuttle astronaut and now Associate Director for the NASA Johnson Space Center (JSC), pointed out at the Lunar Base Development Conference in July 1999 in Houston, TX, that from his point of view humankind will have to go back to the Moon first, before human mission to Mars can take place. Based on his personal experience there was still so much to learn before the risk of a Mars mission could be taken. Young also emphasized the Moon's potential role in global change detection, astronomy, and planetary defense, i.e., keeping a watchful eye on asteroids and comets that are potentially dangerous to the Earth. In any case, lunar base development as a goal should be back on the official agendas of the world's space agencies, at least by the time the International Space Station will be operational. Commercial missions to Moon may be conducted in parallel. [Eckart, 1999; Young, 1999]

Economical, Political, Legal, and Management Issues

The main economical issues that are related to the establishment of a lunar base are (a) how to finance it and (b) to define its economical potential. Although an increasing number of entrepreneurs are interested in commercial uses of the Moon, it appears unlikely that these efforts can lead to a private lunar base development program in a relatively near future. Due to the cost associated with a lunar base program, it is likely that public funding and agency involvement will be required. The economical potential of a lunar base should also be defined in a step-by-step approach. While or after the first step of a development program is taken (e.g., during or after a precursor phase), the economical prospects of the next phase can be defined in a much more credible fashion. Long-term projections may be useful, but should carefully try to eliminate unknowns in the development plan.

The availability of funding will strongly depend on the opinions and attitudes of public and politicians. A lunar base will not be funded unless a public majority supports this endeavor. Therefore, it will be important to first define the political dimension of lunar base development. After the government and the public motivation to support a lunar base have been evaluated, it will be possible to influence space policy and public opinion and thus ensure the required support. The main legal issue is certainly the applicability of the 'Common Heritage of Mankind'-principle that is stated in the Moon Treaty. Although this aspect may have a severe impact on the exploitation of lunar resources, legal issues are certainly not on top of the current agenda, given the state of development. It is also unclear whether we will have suitable management strategies and planning for a project as complex as a lunar base. However, it can be assumed that those tools could be developed in time or as the project progresses. [Eckart, 1999]

Site Selection

The selection of a lunar base site will be strongly influenced by the focus or rationale of the base and the power supply method. For example, if the focus of the base were on ISRU, it would have to be ensured that appropriate resources are available at the site. Also, specific science goals may call for different locations on the lunar surface. Simplifying the selection categories, the main issues will be (a) polar vs. non-polar / equatorial site and (b) far side vs. near side / limb site. Due to the energy storage requirement for the lunar night that lasts approximately 14 days at non-polar sites, the use of solar power is virtually impossible there, at least using current energy technology. This problem could be solved through the application of nuclear power supply systems. Continuous solar power supply may be provided in some permanently lighted areas that probably exist on some mountains in the lunar south polar region. Other technical site selection criteria include surface topography, site accessibility, lighting requirements, surface temperatures, as well as communication and tracking requirements. [Eckart, 1999]

Lunar Base Development Issues

At the beginning of a lunar base program, a development logic should be defined that is agreed to by all parties involved. As described in the previous section, the central issue will be the focus of the lunar base. Based on a rationale, a lunar base development program will likely be comprised of the four 'classical' phases:

- Precursor Phase
- Pioneering Phase
- Consolidation Phase
- Settlement Phase

Once such a four-phase program has been set up (of course, with a decreasing level of detail for later phases), the research needs of the first phase can be more clearly defined. Considering that we are still in the precursor phase, our current focus should be on projects that are principally feasible, given the financial and technological constraints. Hardware projects should mainly build on commercial-off-the-shelf (COTS) equipment. Studies should focus on analytically investigating the most urgent technology trades and logistics issues. [Eckart, 1999]

Lunar Base Elements & Surface Infrastructure

The definition of the required lunar base and surface infrastructure elements can be derived from the functions to be provided. During this selection process, numerous trade studies will have to be performed, for example, investigating the use of rigid modules vs. the use of inflatable modules. Once all elements are defined, lunar base layout strategies can be investigated. The definition of the layout needs to consider the relative location requirements of the different elements. Also, the required site preparation and construction tasks need to be taken into account. In a next step, lunar surface assembly strategies can be developed. Due to major problems that are to be expected because of the lunar dust environment, it may be useful to develop and apply design guidelines for lunar structures and equipment, to minimize the effects of lunar dust. [Eckart, 1999; Young, 1999]

Lunar Base Thermal Control

The main thermal control problem on the lunar surface is the rejection of low-temperature heat around lunar noon, when the background (or sink) temperature may be higher than that of the low-temperature heat to be rejected. Relatively few studies have been conducted in this area. Especially, further studies regarding the use of heat pumps and or radiator shades need to be conducted. Heat pumps are used to increase the temperature of the heat to be rejected. The application of radiator shades leads to a reduction of the effective sink temperature. Another thermal issue that needs to be addressed is cryogenics storage on the lunar surface. Cryogenic propellants may be required to refuel lunar transfer vehicles. [Eckart, 1999]

Lunar Base Power Supply

As indicated above, the lunar night lasts approximately 14 days at non-polar locations. Consequently, it appears virtually impossible to use exclusively solar power supply systems there. Current technology could not provide mass-efficient energy storage systems for night-time power supply. Even the use of regenerative fuel cells (RFCs) could result in an energy storage system mass that may easily outweigh the mass of all other lunar base systems combined. [Eckart, 1996a] This problem could be solved through the application of nuclear power supply systems. However, it remains to be seen whether the use of nuclear power in space will be politically feasible in the future. Also, the required nuclear fission systems would still have to be developed. Continuous solar power supply may be provided in some permanently lighted areas (‘peaks of eternal light’) that probably exist on some mountains in the lunar south polar region. Although lunar base power supply is probably THE single most critical aspect of lunar base development, not too many studies have focused on this issue in the past. [Eckart, 1999]

Lunar Base Life Support

Providing a life support capability at a lunar base should not be a major problem, as far as physico-chemical life support systems are concerned. Far more complex is the inclusion of bioregenerative life support technology. The ultimate goal of advanced life support is to minimize the resupply of consumables. This may also be achieved by growing plants for food supply. Despite the extensive research in this area, mainly funded by NASA at JSC (BioPlex Project) and other locations, it will probably take several decades until fully-integrated bioregenerative life support systems for application in space will be available. Even then, these will actually be hybrid systems because numerous physico-chemical elements will still have to be included. Although the author of this paper argues that the use of plants in life support systems will probably not yield any overall mass savings [Eckart, 1996a], it needs to be stressed that plants should certainly be included in future life support systems for psychological and nutritional reasons. Human missions to Mars will also benefit from this research because reduction of transportation mass and self-sufficiency are even more critical for this type of mission. [Eckart, 1996b; Eckart, 1999]

Communication and Navigation Systems for a Lunar Base

Relatively few studies have been conducted in past years regarding the definition of a communication and navigation systems architecture for a lunar base. The main issue regarding a lunar base communications infrastructure is whether it should rather be a ground-based or a Deep Space Network (DSN)-type architecture, i.e., space-based. In either case the need for additional ground-based or space-based systems will have to be investigated. Depending on the location of the lunar base, additional relay satellites may be required in lunar orbit or at the Lagrangian point behind the Moon (L_2). Navigation requirements for lunar transfer and on the lunar surface will decide the need for a kind of global positioning system (GPS) in lunar orbit. If the requirements are not too stringent, tracking from Earth in combination with a lunar surface based system may be sufficient. [Eckart, 1999]

Lunar Extra-vehicular Activities (EVAs) & Surface Transportation Systems

The definition and development of space suits, portable life support systems (PLSS), and surface transportation systems can draw extensively from experiences gained during the Apollo missions. The major difference is that EVA equipment and surface vehicles for a lunar base will have to be reused frequently. Maintenance requirements, that will be mainly due to the impact of lunar dust, will have to be minimized. The major design trade involved concerns the selection of lunar base habitat pressure and space suit pressure. For example, operational aspects drive for a relatively low suit pressure, while safety issues drive for a relatively high habitat pressure. The larger the pressure differential, the longer will be the prebreathing requirements before an EVA can take place. Ideally, the duration of prebreathing should be reduced to zero. Technology development requirements for space suit and PLSS will also be driven by the need to minimize the mass of the equipment. The number of pressurized and unpressurized surface vehicles needed at a lunar base will strongly depend on the focus of the base, and thus the functions to be provided. [Eckart, 1999]

In-situ Resource Utilization (ISRU) at a Lunar Base

Numerous studies on the use of in-situ resources on the lunar surface have been conducted in past decades, and a large number of reports and papers have been published. Research on various ISRU concepts is ongoing, especially regarding the extraction of oxygen from lunar soil. The main task of the upcoming years will be to define short lists of the most promising processes for the extraction of the most important resources, including not only oxygen, but also hydrogen, aluminum, and others. Then, the aim should be to increase the Technology Readiness Levels (TRLs) of the most promising concepts. Currently, most concepts have only reached a TRL of 2 or 3 (conceptual design formulated and possibly tested). Long-term logistics studies should investigate whether lunar ISRU may support Mars missions in an economical fashion. [Eckart, 1999; Lewis, 1993]

Lunar Base Logistics and Cost

Apart from the development of technology, the investigation of lunar base transportation and logistics issues will also be extremely important. For example, suitable launch systems, the most important prerequisite for lunar base development, are not available at the moment. Currently, the investigation of single-stage-to-orbit (SSTO) launch systems with relatively low payload masses into Earth orbit is in fashion. However, a serious lunar base development program will definitely require heavy-lift launch capability, most likely ‘big dumb boosters’, possibly two-stage-to-orbit (TSTO) or SSTO. Another important issue will be the definition of suitable logistics nodes and Earth-Moon transportation scenarios. In this respect the scheduling of missions may become rather sophisticated. For example, the return of a transfer vehicle from the lunar surface to a space station in low Earth orbit (LEO) is subject to severe timing constraints. On the other hand, logistics scenarios including the export of lunar resources, e.g., in support of Mars missions, may even provide a rationale for lunar base development. Credible cost estimates will be required for every stage of lunar development. The lack of an appropriate experience base makes cost estimations for a lunar base program extremely difficult. The only solution to this problem can be the continuous improvement and refinement of existing cost models. [Eckart, 1999]

The Lunar Base Handbook

The issues that could only be very briefly addressed in the previous sections are extensively dealt with in *The Lunar Base Handbook* that has recently been published by the author of this paper. The book is an introduction on lunar base design, development, and operations and provides an overview about:

- The Moon and its environment
- The current status of lunar base design
- Tools we need to design a lunar base
- Checklists and flowcharts that outline the design process
- Technological requirements of a lunar base

It includes 24 chapters on about 880 pages covering engineering and technology aspects, as well as development, legal, economical, transportation, and cost aspects. The book provides historical background and an outlook into the future, beyond a lunar base. More than 50 leading space experts have supported the book as reviewers and / or by providing an introductory essay for one of the chapters. This group includes Apollo astronauts Buzz Aldrin, Harrison H. Schmitt, and John Young, as well as Arthur C. Clarke, Jeffrey Hoffman, John Logsdon, David McKay, Wendell W. Mendell, Carl Pilcher, and many others. [Eckart, 1999]

Conclusions

This paper has outlined a number of steps that need to be taken in order to define and implement a lunar base development plan. Specifically, it is suggested that the community justifies the lunar base case by defining:

- A lunar base within the frame of a roadmap of human space exploration
- A lunar base development plan based on a stepwise approach
- Lunar base functions and requirements
- Technology and science research issues

In order to obtain sufficient public and political support, the lunar base community also needs to conduct an extensive lobbying campaign. A convincing rationale and business plan for lunar base development has to be provided. Care should be taken not to raise false expectations by prematurely overselling the Moon's prospective benefits - whether as a power-generating station for beaming energy throughout space or as a site for mining Helium-3. To achieve all this, an infrastructure should be set up that integrates most, if not all, of the current lunar base activities, including the IAA's, ILEWG's, and others. The lunar base community can probably learn a lot from the Mars Society in this respect. The goal of this effort should be to be ready when the time has come for the start of a lunar base development program.

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NOTE: This paper is implicitely based on countless references. They are too numerous to be listed here. Detailed lists of references can be found in most of the publications and web sites indicated above.