LUNAR CONSTRUCTION RESEARCH

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I. INTRODUCTION

Before 1962, the requirement for a clear, decisive engineering approach to the problem of extraterrestrial construction had been recognized by few. Admittedly, the problem of merely placing man on the moon and successfully recovering him has occupied a major portion of space planning. Even so, prior to 1958, both the Air Force and the Army had engaged in preliminary investigations on moon-based facilities. These studies were general in character, covering shelter concepts, communication facilities and means of lunar mobility. The studies could have been expanded into acceptable engineering approaches to the problem, but with the establishment of NASA and its responsibility for space programs, the Army and Air Force projects died stillborn. Only recently has NASA accepted the baton and applied serious consideration to the engineering aspects of prolonged lunar habitation.

In November 1962, the Office of Manned Space Flight, NASA Headquarters, after reviewing the results of previous studies by the Corps of Engineers, asked them to undertake an analysis of the research and experimental effort required to develop a lunar construction capability and to present plans for program implementation. This study, conducted by our staff in the Office, Chief of Engineers, was completed by 30 April 1963 and a report was submitted to NASA. Subsequent to, and partially based on the Engineers' report, Marshall Space Flight Center, NASA completed an analysis of the engineering test requirements for an Apollo logistic support system. Although the objective of this analysis was Apollo support, results have direct application to any logistic system supporting the build-up and supply of a lunar base system. Overlapping this study in time is a current contract by NASA with the Boeing company, Aero-Space Division, for a study entitled "The Initial Concept for a Lunar Base". This study, commencing on 15 July, will be completed by 1 December 1963.

These three studies form the outstanding NASA studies to date on the subject of lunar basing. However, other minor and subsidiary study approaches are being made. These include, but are not limited to, a life-support investigation by the Manned Spacecraft Center, NASA, and several short-term studies assigned to OCE by OMSF. The OCE studies, currently being prepared or in progress, are subdivided into "Lunar Base Studies" and "Lunar Surface Operations Simulator Studies". The base studies are in the fields of:

(1) Lunar Energy Systems, Nuclear and Chemical
(2) Power Distribution and Conditioning Equipment
(3) Foundations and Structures
(4) Construction Procedures
(5) Construction and Materials Handling Equipment

The simulator studies involve:

(1) Solar Simulation
(2) Soil Simulants

The intent of this paper is to summarize the results of the three major studies cited and to analyze their directive influence on the character of lunar base design and construction. In doing so, it should be emphasized that this analysis and the opinions rendered represent solely the viewpoint of the writer.

II. THE OCE STUDY

A. PROCEDURE

The Corps of Engineers study was conducted in two phases. The first completed in January 1963, resulted in an interim report primarily concerned with identification of elements of the technical development program in order to facilitate early consideration of FY 64 program requirements. The second involved a much more comprehensive analysis of the technical program (particularly problem areas), refinement of schedules and fund estimates, and development of a detailed plan for executing the lunar construction training program.

In the study, current NASA planning and prior efforts by workers in this field were examined to develop the major areas of engineering application involved in attaining a lunar construction capability. Each was then analyzed in depth to determine requirements, evaluate these in terms of current state-of-the art, identify specific research and development tasks and prepare detailed statements of methodology, effort, cost and facilities needed to accomplish such tasks. Particular attention was given to the capability of existing or planned terrestrial facilities to serve program needs.

Findings concerning the individual technical areas were then synthesized into a comprehensive technical development program integrated in time with current NASA thinking regarding manned lunar operations and associated lunar facility requirements. Available resources, related programs, restraints, and past experience in comparable governmental research and development programs were related to the technical program and a plan for program implementation was drawn up representing the optimum combination of all factors involved.

B. LUNAR BASE CONCEPT

Fundamental to this study was a concept for a lunar base, to include a time-phased estimate of the types of facilities needed to support planned operations on the moon. Guidance provided by NASA Headquarters included a modular base concept, a lunar model detailing the applicable physical characteristics of the lunar environment, vehicle launch schedules and vehicle dimension and payload characteristics. As the study progressed, it was found necessary to make further assumptions within the framework of the planning data provided.

NASA's basic concept envisioned a family of modules of as few types as possible which could be combined in a variety of arrays to meet operational requirements. Both time and operational considerations dictate that only the most rudimentary construction capability be developed to support the Apollo landings. However, as stay times increase in the 1970-1972 period and lunar operations become more advanced, temporary bases with integrated life-support systems will be necessary. Depending on additional knowledge gained by Apollo operations, these temporary bases may be expandable into semipermanent bases or a new generation of facilities may be required. These semipermanent bases, needed in the period 1973-1975, could evolve into permanent bases with more sophisticated and centralized support facilities.

Present lunar construction concepts depend on limited hard data and extensive assumptions regarding the characteristics of the lunar environment and the lunar surface material, particularly the latter. Ranger and Surveyor probes will provide much valuable information on the composition of lunar surface materials but definitive data will not be available until man explores the moon. Notwithstanding this fact, most basic program requirements for developing a lunar construction capability can be foreseen now. It is entirely feasible at present to proceed with work in critical long lead-time areas and to develop a lunar construction capability in a timely manner. Such a program will clearly be subject to change in detail, but close control and built-in flexibility and responsiveness will minimize the adverse effects of such changes.

C. REQUIREMENTS

For purposes of the study, the following schedule for attainment of a lunar construction capability was provided by NASA:

Construction Capability	Time Period
Support for Apollo landings	1968 - 1969
Temporary bases, 6 man	1970 - 1971
Temporary bases, 8-12 man	1971 - 1973
Semipermanent bases, 12-18 man	1973 - 1975

To meet this schedule, two factors were considered critical. The first is a prompt start. The second is the timely acquisition of data on the characteristics of the lunar environment and lunar surface materials.

In addition to time schedules, lunar construction program requirements fall into several other general categories. These are performance requirements in terms of efficiency, simplicity, reliability and safety of systems and hardware items. The lunar environment imposes a multitude of restrictions and requirements on the development of suitable construction methods, techniques, and materials. Finally, the restraints imposed by the resources available to the program and by vehicle configurations and launch rates introduce requirements affecting program planning and execution.

This study considered requirements in those several contexts but its primary orientation, as an engineering study, was on the technical engineering development effort necessary to develop a capability to construct lunar facilities. Necessarily included in the scope of the program are tools, equipment, materials, systems, methods and techniques. Testing and demonstration of components, end items and man-systems on earth are likewise essential elements of the program, as is training of those who will perform the construction operations on the moon. In general terms, the required technical effort is as follows:

1. Identify in detail the types of engineering works that must be built on the moon in the period 1968-1975.

2. Develop design criteria and construction methods for these lunar facilities.

3. Determine performance requirements for engineering materials, methods, processes and man-systems in the lunar environment.

4. Develop and test new materials, methods and processes as required.

5. Design and test (on earth) prototype structures and man-systems to the extent required to demonstrate their adequacy, limitations, and degree of reliability.

6. Determine the need for, and develop equipment, methods and procedures to accomplish maintenance and repair of engineering works on the moon.

7. Identify training requirements, develop training procedures, and train men who will build, operate and maintain lunar bases.

As mentioned, the technical engineering development program was based on a series of studies in each of the major engineering areas involved in lunar construction. The results of these were arranged into a coherent development program, with special attention given to those specific tasks which should be started in FY 64 to achieve a lunar construction capability in an orderly and timely manner. These tasks were in the fields of selenology, construction materials, excavation and surface modification, equipment, electric power and life support.

D. PROGRAM EXECUTION

The study proposed a plan of action to implement the program requirements outlined above. The plan considered program management, research facilities required and funding. Facilities and estimated costs are discussed below:

1. Facilities

The study determined that a capability for integrated, real-time testing of man-systems in a simulated lunar environment, including the lunar surface materials, is essential to the lunar construction development program proposed. It was further determined that no facility, existing or presently planned, could achieve that capability. Performance specifications and preliminary plans for such a facility, called the Lunar Environmental Research and Test Facility (LERT), were developed during the study.

A number of ancilliary facilities, including one for low-order simulation of certain lunar phenomena under ambient earth atmospheric pressure (the Operations and Training Building), are also necessary. Preliminary criteria, plans and cost data were developed in the study for all such facilities.

2. Costs

The ultimate complete cost of developing a lunar construction capability was not estimated since the costs of suitable cargo and personnel delivery systems were beyond the scope of this study. In addition, the technical studies on which this report was based, while defining the planning, research, development and engineering effort required, did not attempt to make more than gross estimates of costs beyond FY 68. However, an order-of-magnitude estimate of total program costs, exclusive of purchase of operational hardware for use on the lunar surface, approaches $500 million.

Budget estimates through FY 68 were prepared during the study for major elements of the proposed program. These elements were:

a. Further study to refine and extend lunar base planning concepts.

b. The technical engineering development program. This program was broken down and costed by specific tasks, with particular attention to those which should be started in FY 64 as a base for later effort.

c. Facilities and Government furnished equipment (GFE) therefor.

d. Personnel and operating costs.

Program costs are summarized in the following tabulation:

	Years ($ millions)				
	1st	2nd	3rd	4th	5th
Lunar Base Study	0.5	-	-	-	-
Engineering Development	4.7	24.0	57.3	102.4	59.7
Facilities and GFE	3.9	29.5	3.0	2.5	.5
Personnel and Operations	1.3	1.8	4.0	8.0	12.0
TOTAL	10.4	55.3	64.3	112.9	72.2

III. STUDY BY MARSHALL SPACE FLIGHT CENTER

The MSFC study stems partially from their review of the prior OCE study, specifically that part dealing with recommended test facilities. Their suggested program attempts to define the test requirements of the Apollo Logistics Support Systems (LEM-Truck and LLV) and recognizes a future lunar base logistics follow-on. In this sense their report has meaningful application to lunar base concept studies. It should be emphasized that the testing concepts reported here are taken from a preliminary report. Elements may have been and probably are changed from that reported herein. In summary, then, the following:

The test program can be classified into the following types of testing: Parts testing, component testing, subsystem testing, thermal testing, system testing with and without astronauts, flight acceptance testing, simulated mission testing, qualification testing, and checkout. The environmental test program will follow this philosophy of thoroughly testing components, subsystems and major systems where deemed necessary.

All subsystems must be completely qualified and have undergone complete environmental testing prior to testing them in a major system. Major systems environmental tests will be performed to the greatest extent possible, considering the relative yield of information from the test with respect to the practicability of the test, its cost, and the cost of the required test facility. Actual operation by astronauts of major systems under simulated lunar environmental conditions should be done to the greatest extent possible. A major training program for astronauts should be performed under simulated environmental and mission operational conditions which come as close to reality as is technically and economically feasible. Facilities for meteoroid and particle radiation effects will not be an integral part of any major lunar environmental facility. These tests should be performed on scale models, prototypes, or test specimens at other existing or planned facilities.

The basic test philosophy and test programs for the two categories or payloads (LEM-truck and LLV payloads) will essentially be the same but the test duration for system and major subsystem testing required for the LLV payload will be longer and larger test facilities will be required as compared to those with for the LEM-truck payloads. Hence the facility planning for new facilities must take consideration the heavier test requirements for LLV payloads.

Consideration for major facilities for this testing program are essentially as follows:

1. Develop major systems for the LEM-truck payloads in existing large chambers, such as the Mark I and the GE Space Simulator. These facilities would require major modification.

2. Build a large lunar Environmental Mission Chamber with a working area of approximately 80 to 100 ft. dia. to be used primarily for mission testing. Mission testing for LEM-truck payloads including the initial payloads would be done in this chamber.

3. Build at a later date, which will depend on the scheduling of lunar base construction, a smaller Lunar Environmental Research Chamber with a working area of approximately 35 to 50 ft. dia. to be used primarily for research and development testing of major systems. This facility would be used for development testing of LLV payloads.

4. The sequence of building the above two chambers is predicated on the fact that no large chamber for research and development could be ready in

time for testing LEM-truck payloads and that these payloads would have to be developed in existing chambers which will have to have considerable modifications for this purpose.

5. Existing other types of test facilities, both industry and government-owned, should be used to the greatest extent. The availability of such facilities, including those at MSFC, is being reviewed and studied.

IV. THE BOEING STUDY

The Boeing study constitutes another step toward developing a lunar base concept. It conceives of the actuality of the lunar logistics system. It is concerned immediately and directly with lunar base design. As Boeing states in their second interim report, "the basic objective of the study is to provide a conceptual design of the modular lunar base system within the criteria set forth by NASA". To meet this objective in the four-month study, Boeing plans to accomplish the following:

1. Define and analyze parametrically each major subsystem from the minimum function for the specified 90-day stay, two-man operation and limited transportation, to the two year system with an 18-man population.

2. The subsystems requirements will then be applied to an analysis of modules that might be designed to meet the requirements. Logical modules will be derived to fulfill the needs of varying base sizes and deployment up to 18-man base complexes. The function of each will be defined and the limits of its desired functional capability will be established.

3. A conceptual design of each module will be prepared. Dimensions, configuration and weight estimates, as well as operating characteristics and limits will be provided.

4. The interfaces between modules and subsystems will be defined. The effect of these interfaces on base design, weight, operating man hours, and performance will be investigated to determine the impact on selected base complexes. This will include an estimate of the flow of communications, materials, energy, and personnel to uncover interface problem areas.

5. Concepts for installation, operation, and maintenance of several base systems of various degrees of complexity and lifetime will be delineated.

6. A parametric analysis will be made to determine quantities of materials (other than modules) required for installation, operation, and maintenance. The analysis will consider base sizes, lifetime, degree of logistics independence, and activity level. The resulting data will be summarized in the form of logistics plans for the several typical base systems.

The basic modular concept, together with the stated ground rules and implied mission objectives have been the starting point for systems analyses aimed at guiding the subsystems investigations and contributing to the overall concept definition. Subsystems guidance is in the form of requirements definition, functional at first, but becoming more quantitative as the concept is developed. Additionally, as the subsystem aspects of the base concept are developed, meaningful concepts for base installation, operation, maintenance, and logistics support can be developed and described.

Boeing finds the following major trends developing thus far in the study:

1. Design of a basic lunar shelter with integrated meteoroid and radiation shielding adequate for a 1-year storage and subsequent 3-month occupancy appears feasible. This shelter requires no lunar soil cover for this period of operation but is structurally capable of withstanding a 2-foot thick cover of soil for protection in extended operations.

2. For longer operations beyond 3-months, these shelters should be emplaced on the lunar surface with a protective cover of lunar soil. A 2-foot thick layer of soil should provide the necessary shielding (with safety factor of 2) for up to two years operations. Underground emplacement does not appear necessary for the range of assumptions considered in this study. Burying the shelter increases the difficulties, and reduces the flexibility inherent in the modular concept.

3. All support elements for a three-man, 90 day lunar base operation may be carried in one Saturn V logistics payload of 25,000 pounds. These elements include the shelter with its integral life support, power, communications and fuel modules, and a lunar roving vehicle with its fuel.

4. This basic shelter module provides the flexibility of (a) accommodating up to six men in normal operations (or twelve in special situations), and (b) of operating without emplacement for about 3 months, or (c) emplaced on the lunar surface under a 2-foot thick soil cover for up to two years.

5. Plans for the larger bases would use this 6-man basic shelter module to accommodate 12 and 18 man crews with two and three interconnected shelter modules respectively. Each shelter-module payload would carry expandable supplies to fit the 25,000 pound Saturn V capability. Other essential base components, like vehicles, power plants, supplies, and unusual instruments would ride in the flexible cargo-payload modules.

6. The basic six-man shelter module has multiple utility: to be clustered into larger bases of whatever size, to serve as an optimum outpost, and to grow without waste from the simplest base to the most complex.

7. Nuclear power supply appears desirable to support lunar base operations extending to six months and beyond.

8. Hydrogen storage on the Moon for one year before use is a major problem and requires special design of tankage including:

Improved insulation
Delivery of hydrogen to the lunar base as a solid in tanks.

V. ANALYSIS

Lunar construction research, literally and figuratively, is barely off the ground. Studies in progress or concluded do little more than point the way. However, they do constitute the necessary first steps of deciding where you are going to go, with what equipment and training and how soon.

The OCE study took a sharp look at the technical effort requisite to obtaining an engineering capability for lunar design and construction. Marshall Space Flight Center has been and is engaged in a conceptual approach to the problem of how does one prepare a capability for an Earth-lunar logistics system. These two studies are complementary. Boeing is going a step further. Their study constitutes the first NASA effort to develop a lunar base concept. Now the following steps seem obvious, i.e., the establishment of new facilities the primary aim of which is to obtain a lunar construction capability in fact.

REFERENCES

Boeing - "Initial Concept for a Lunar Base", First and Second Monthly Progress Reports, 15 August 1963, and 15 September 1963.

MSFC - "Preliminary Test Program for Apollo Logistic Support Systems Payloads", August 1963.

OCE - "Special Study of the Research and Development Effort Required to Provide a U.S. Lunar Construction Capability," April 1963.