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Paper Session III-B - A Lunar Orbiting Node in Support of Missions to Mars

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A LUNAR ORBITING NODE
IN SUPPORT OF MISSIONS TO MARS

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ABSTRACT

Future Mars missions may use lunar-derived oxygen as a propellant for interplanetary transit. A man-tended platform as a Node in low lunar orbit offers a site for storage and transfer of lunar oxygen to the transport vehicles as well as rendezvous and transfer for lunar-bound cargo and crews. In addition, it could provide an emergency safe-haven for a crew awaiting rescue. A conceptual design study yielded an approximate size for the platform needed to support typical oxygen transfer rates which were based upon NASA studies of Mars missions. The Node consists of a gravity gradient stabilized lunar orbiting tank-farm with a storage capacity of 100,000 kg of lunar oxygen, 3,300 kg of lunar cargo and 9,300 kg of Earth supplied hydrogen. An emergency habitat configuration accomodates 14 persons on-board for 110 days. The Node supports an annual lunar oxygen production of 10^6 kg with 220,000 kg of oxygen delivered to Earth orbit for an expenditure of 109,000 kg of Earth supplied hydrogen.

INTRODUCTION

The NASA Office of Exploration conducted mission studies involving manned expeditions to the Moon and Mars as part of their Bold New (Space) Initiatives Strategic plan. Within the roles assigned to each of the participating field centers, the Langley Research Center received the primary responsibility for orbital Node aspects of the future lunar and interplanetary expeditions. The Nodes as supply or transfer stations, included those in orbit about the Earth, the Moon and Mars. An orbiting Node provides the mission operation flexibility required for a continuing exploration. The transit vehicles can rendezvous with the Node to exchange or store, cargo, crew or logistic materials (food, water, propellants etc.) for subsequent delivery (or retrieval) by special purpose ascent-descent vehicles. A Node becomes a critical element when mission constraints limit the frequency of transit flights to the point where transfer quantities dictate a number of ascent-descent operations (i.e., transfer trajectory windows do not allow sufficient dwell times in a remote orbit).

The use of lunar supplied oxygen as a propellant for Mars exploration missions led to the evaluation of a Lunar Node configuration which could provide the necessary storage and transfer of liquid oxygen either for return to low Earth orbit or for direct transfer to the Mars-bound spacecraft. The Node also would serve as a transfer point for lunar bound cargo and the hydrogen propellant needed to bring the lunar oxygen up to the Node. The definition of requirements for the Node identified the potential need for a safe-haven capability that could support the entire lunar base crew during a rescue mission sequence originating from the Earth.

The descriptions and evaluation of the Lunar Node begin with an assessment of transfer requirements based upon data from concurrent NASA studies. These requirements then translate into a logistics flow sequence for the Node and the transfer vehicles. Considerations for the safe-haven then lead to descriptions of two configuration options and a summary of mass assessments for each configuration. The final section identifies areas for further evaluation considered pertinent to the configuration for the Node.

The evaluation and definition study for the Node was under the direction and guidance of Dr. L. Bernard Garrett, Head, Spacecraft Analysis Branch, NASA Langley Research Center. The effort was performed by the Bionetics Corporation as Task 14 of Contract NAS1-18267. The authors wish to acknowledge the contribution of Dr. M. J. Queijo, Mr. W. F. Cuddihy, Mr. Paul Garn and Ms. Sandra Barnes of The Bionetics Corporation for their contributions in the areas of requirements definitions, and the generation of computer-aided graphics.

DEFINITION OF NODE REQUIREMENTS

The conceptual study for the Lunar Node drew upon data generated by the co-participation in concurrent NASA exploration mission studies. The principal source became the Scenario Requirements Document (SRD) (Reference 1) which was subject to periodic updates that reflected the progress of the mission study. The final form of the lunar mission scenario selected multiple or sequential rendezvous between the transit vehicle and a number of ascent-descent vehicles and recognized that safe-haven requirements could be satisfied without an orbiting platform. However, a Lunar Node appears as a practical mission element at the time lunar base operations begin to produce propellant oxygen for other than lunar surface-lunar orbit transfer. The current scenarios indicate an initial need sometime between the years 2007 and 2010. The concept presented in the sections which follow describes a Lunar Node which could support mission scenarios for Mars exploration that use lunar derived oxygen as a propellant and included an active lunar outpost.

The specific requirements and related assumptions applied to the Lunar Node for the evolutionary expansion missions of Reference 1 appear summarized in Table 1. The development of the propellant logistics schedule required a combination of related data from the SRD draft and some assumptions, since the portion of the reference that included the lunar propellant logistics schedule had not been completed in time to support this study.

In the baseline concept, the Node supplies lunar produced liquid oxygen for Mars expeditions and assumes: (1) The transfer and ascent-descent vehicles use cryogenic chemical propulsion for all velocity changes except for aerobraking at Earth and Mars, and (2) Assembly and propellent loading of the Mars-bound vehicles are performed in Low-Earth Orbit (LEO). The transfer of lunar liquid oxygen to Mars-bound vehicles directly from the Lunar Node or from an Earth-Moon libration point would revise the propellant logistics manifest described below. The use of a Mars Node together with the use of Mars generated propellant would also impact the transfer logistics at the Lunar Node.

TABLE 1. SUMMARY OF DOCUMENTED REQUIREMENTS AND INTERPRETATIONS

Node Operation:

- Low Lunar Orbit, 100 km altitude, Polar. On-board station-keeping and communication.
- Support two person crew during transfers, 12 person crew on lunar surface, 6 months stay time.
- Safe-haven provides Manned Access, Life support, Rendezvous capabilities for rescue spacecraft.

Propellant and Cargo Transfer at the Lunar Node:

- Lunar oxygen is transferred for delivery to low Earth orbit.
- Lunar oxygen transfers at the rate of 600 metric tons annually.
- Lunar bound cargo transferred at the rate of 20 metric tons annually.

Propellant Corollaries:

- All propulsion is by H_2-O_2
- Hydrogen transfer supports Lunar Ascent/Descent Flights.
- Cryo retention recognized but not a specific item for the initial configuration.

PROPELLANT LOGISTICS

The long term plan for Mars exploration includes an initial ten to twelve year period with total dependence upon Earth supplied liquid oxygen and liquid hydrogen for propulsion. This era also covers the assembly of the infrastructure which includes the Lunar Node, the lunar outpost, and the lunar oxygen production facility. Once these facilities are in full operation the Lunar Node assumes its role as a propellant transfer facility and this period defines the logistic transfer requirements at the Lunar Node. Here the propellant logistics must consider both the liquid hydrogen supplied from Earth as transported from LEO and the lunar derived oxygen returned to LEO. Each step, or stage, of the transport consumes some of each propellant.

The annual transfer of 600 Metric Tons (MT) of lunar derived liquid oxygen becomes the initial parameter in the definition of the Node and its associated vehicles. A sequence that transfers 100 MT of liquid oxygen during each of six annual trips defines an effective Space Transport Vehicle (STV) that operates between LEO and the low lunar orbit of the Node. An ascent-descent sequence that transports 100 MT in three flights appears appropriate. Figure 1 shows the features of such an STV flight and Figure 2 shows the features of the LADV flights; the details are outlined below.

These flight assumptions permit an initial estimate of the masses for the STV and the Lunar Ascent-Descent Vehicle (LADV), here the results from other studies (Reference 2) lead to the selection of a transfer vehicle mass at or near 20 percent of the transferred oxygen mass. The estimates of masses for the liquid hydrogen propellant utilized the study defined value of 4707 N-sec/kg for the specific impulse coupled with a mass mixture ratio of 7 to establish the propulsion capability. The propellant masses derived reflect solutions to the impulse equation for the velocity increments associated with each segment of the flights. For the STV, the escape from Earth orbit used 3150 m/sec as established for the Apollo mission (References 3, and 4). The velocity changes associated with the lunar orbit were made the same for entering and leaving. The value selected included a small margin relative to the Apollo values of 915 m/sec, and recognized that the actual values would be somewhat less. The margin accounted for mid-course corrections and final orbit trim. The STV assumes an aerobraked deceleration equal to the velocity requirement for Earth orbit escape. The propulsion requirements for lunar ascent and descent utilized the same velocity increments at 1800 m/sec in both directions and were considered attainable. The LADV would not have all the constraints associated with the Apollo landings and would use a minimum energy trajectory. These assumptions together with the logistic transfers defined an initial estimate of the propellants needed for LADV operations. In summary, 18 LADV flights would transfer 600 MT of lunar produced oxygen to the Node in exchange for 20 MT of cargo bound for the lunar surface plus the hydrogen propellant needed for LADV operations. These parameters together define a mass of 9.3 MT for the hydrogen transferred during each flight from the STV to the Node.

The 100 MT of oxygen plus the mass of the STV combine with the velocity change requirement to define the mass of on-board hydrogen necessary for the return at 2.8 MT. The STV at LEO has a final payload consisting of the 100 MT of oxygen diminished by the amount used for a propellant during the return such that the STV arrives with 80 MT of lunar oxygen.

The active STV payload at rendezvous with the Node consist of the lunar bound cargo, 3.3 MT, the hydrogen propellant for the LADV, 9.3 MT, and the hydrogen propellant for return, 2.8 MT. These masses plus that of the STV combine with the velocity change to define the propellant mass requirements of 6.2 MT hydrogen and 43.1 MT oxygen. The oxygen available at LEO is then the difference between the 100 MT transferred in lunar orbit and the propellant consumed during a round trip STV flight and yields 37 MT for each flight. The mass of the STV, the cargo transferred, the mass of the LADV and the velocity increments all interact in the determination of propellants which in turn define the eventual oxygen yield at LEO.

The definition of mass requirements for each element of STV and LADV flight sequences, permits a further definition of the logistic technique for handling the cryogenic liquids. A review of the masses and corresponding volumes during each element of the flight led to the selection of spherical tanks of 11 m^3 volume as the transport containers and items for transfer. The tanks would hold the cryogens at nominal one atmosphere conditions which are ~90 K for oxygen at a density of 1140 kg/m^3 and ~20 K for hydrogen at a density of 70 kg/m^3. Such tanks have a diameter of 2.75 m and are of aluminum alloy construction. The mass estimate suggest that a full H_2 tank on Earth represents a handling weight of about 1.1 MT, while the same tank filled with O_2 on the lunar surface represents a handling weight of about 2.1 MT. Both values appear reasonable for local handling, storage and transport. The robotic transfer of tanks offers flexibility in handing and avoids large cryogenic fluid transfers in microgravity. The tanks will need connections to cryo maintenance systems during storage, orbital dwells and STV flights but not during the short LADV flights. It is recognized that some of the tanks will need connection to the propulsion systems during flight. These interconnections can be accomplished within the sequence of the transfers.

The above considerations define the actual flight and transfer operations; Figure 1 presents the sequence for an STV round trip. At departure from LEO, the STV carries an allotment of cargo, three tanks of oxygen propellant needed for transit to the Node, and 23 tanks of hydrogen which will supply the Earth round trip propellant and perform the LADV flights. When the STV docks to the Node, the oxygen has been expended along with the contents of seven hydrogen tanks. The transfer at the Node exchanges twelve filled hydrogen tanks and cargo for nine filled oxygen tanks plus three empty tanks. Tanks exchange one-for-one. At departure from the Node, the STV carries nine full tanks of oxygen, three tanks of hydrogen and 14 empties. The transit to LEO consumes the hydrogen and nearly three tanks of oxygen such that at LEO docking, three tanks of oxygen become available for other use and three tanks remain on-board for the next departure. Operations at LEO exchange empties for hydrogen filled tanks and cargo to repeat the sequence. The tanks are compatible with the payload bay of the shuttle such that a minimum of six could return as part of a manned flight. Delivery to orbit would utilize some form of cargo vehicle such as a Shuttle "C" configuration (Reference 5). In summary, each round trip flight for the STV delivers 3.3 MT of cargo to the lunar surface and returns a net 37 MT of liquid oxygen to LEO for an expenditure of 18.2 MT of hydrogen.

The LADV makes three identical flights that exchange oxygen for cargo and hydrogen at the Node, Figure 2 illustrates the sequence and logistics. The LADV carries seven tanks of which six can be exchanged at the Node. At lift-off from the lunar surface, the LADV carries three full oxygen tanks for transfer, one filled oxygen tank for propellant and three hydrogen tanks that also supply propellant. At rendezvous with the Node the LADV has three full oxygen tanks for transfer, one partially filled oxygen tank and three empty tanks, The three full oxygen tanks and one of the empties exchange for four hydrogen filled tanks and 1.1 MT of the cargo. At departure from the Node the LADV carries the cargo, four full tanks of hydrogen and a partial tank of oxygen. Upon landing, the LADV tankage consists of three full of hydrogen, three empties for refill with lunar oxygen and an empty on-board oxygen tank. Three such flights prepare the Node for the next exchange rendezvous with the STV. In summary, three LADV flights deliver 3.3 MT of cargo to the lunar surface and 100 MT of lunar oxygen to the Node. The deliveries require the expenditure of 9.3 MT of Earth supplied hydrogen plus 64.3 MT of lunar provided oxygen.

The summary of propellant transfer logistics indicated by Figures 1 and 2, suggest that about 37 percent of the O_2 delivered to lunar orbit will become available at LEO and about 60 percent of the lunar surface O_2 production can be delivered to lunar orbit. The combined result is to deliver approximately 22 percent of the lunar oxygen production to LEO. An annual production rate of 986 MT for lunar oxygen yields 222 MT to LEO for other use, and consumes 109 MT of Earth supplied hydrogen.

CREW HABITAT OPTION

The Scenario Requirements Document (Reference 1) identifies the need to provide a safe-haven for crews stranded either from the lunar base or the transportation vehicles until rescue can be effected from LEO. The Lunar Node offers a site for such a safe-haven at an intermediate location between the lunar surface and LEO. The contingency events which could require such an emergency shelter include a lunar habitat that became inoperative or a malfunctioning space transfer vehicle with exchange crews aboard and therefore was unable to return to LEO. In such a context, a safe-haven provides a habitat with air, food, water and minimal creature comforts sufficient to sustain the crew until rescue. Safe-haven does not include protection from solar flares. The safe-haven crew capacity and duration of stay are not specified in the SRD, however, for the purpose of sizing, the Node considered two bounding conditions. The minimum safe-haven capability is provided by the equivalent of one Space Station Freedom resource node and one scaled-down logistics module. This volume permits Space Suit Operations, multiple vehicle docking capability, and life support for a two-person crew during man-tended periods of up to five days. This is considered the "Tended" configuration. The need to evacuate the lunar base could generate an emergency condition for a crew of 14 that had to stay for 110 days (capacity to abort one visit from the STV). This "Habitat" Configuration, includes a Space Station Freedom habitat module in addition to the resource node and provides a capacity for 1500 man-days of emergency occupancy. The option incorporates a pressurized volume that provides some additional amenities such as exercise equipment, showers, separate sleeping areas, a galley, and other features associated with long duration, large crew missions. The survival resources of oxygen, food, water, and personal items considered only open cycle systems. Carbon-dioxide is absorbed from the air but not recycled. Water is not recycled but stored as liquid waste. Clothing, bedding, and food service utensils are used once and then stored as trash. The masses and volumes of supplies required for life support in orbit are well established; the data compiled for Space Station Freedom (Reference 6) provided the basis for deriving a 1500-man day support requirement totalling 32.9 MT and a volume of 66 m^3. The electrical power capacity for the "Tended" option was set at the 20 kW level. This level would sustain the crew and meet operations requirements. For the safe-haven "Habitat" the electrical power demand was selected to be 35 kW, largely due to the life support power requirement. Further evaluation of energy use and energy storage for dark periods is required to arrive at a confident estimate.

LUNAR NODE DESCRIPTION

The two conditions for on-board crew accommodations within the Lunar Node result in two baseline configurations which share a number of common features. Table 2 summarizes the principal features and requirements for the Nodes. The concepts for the Lunar Nodes are shown in Figures 3, 4 and 5. Figures 3 and 4 show the "Habitat" configuration docked with the STV and LADV, respectively; Figure 5 shows the "Tended" configuration docked with the LADV. All three figures show the concepts for transferring propellant in tanks and cargo in packages. The Mars missions include the options for a transfer of the oxygen propellant directly to the Mars-bound vehicles during a lunar orbit rendezvous. The Nodes have the capacity for such transfers, the tanks and masses associated with such transfers are shown in Figures 4 and 5. The principal design features for the Lunar Nodes are described below, and first address the mutual items and then the unique features.

A. Docking Capability The docking adapter is universal to the STV, LADV, and the Lunar Node; it permits the simultaneous docking of both vehicles to the Node. Figure 6 shows such a concept. A resource node from Space Station Freedom has been adapted to provide the multiple docking functions in addition to environmental control and life support for the crew.

B. Robotic Transfer Unit The transfer unit moves the tanks and cargo between the LADV, Node and STV. The unit compares to the Remote Manipulator System on the shuttle and would need to position a filled O_2 tank, (mass ~ 13 MT), at distances up to 15 meters.

C. Communication and Tracking The links for the Node communication system assume a relay satellite in higher orbit. The links would include voice, video, and housekeeping data telemetry. The tracking system operates line-of-sight to the horizon for operation with the LADV, and line-of-sight as available for the STV. Both the communication and tracking functions require controls for antenna positioning.

D. Cryo-Maintenance The attachment mechanism for securing the tanks includes a collection manifold linked to the tank vent-and-fill lines. The STV flight schedule in effect determines the maximum on-board storage time for any tank. A nominal reliquification capability is included to preserve the O_2 and H_2. The option remains to retain the boil-off, using the gases for attitude stabilization or potentially in fuel cells for energy during dark periods.

E. Power System The power system has been estimated on the basis of 15 kW to operate the node plus 2.5 kW for each person aboard. The photovoltaic power system has been sized for either 20 kW or 35 kW, depending upon the safe-haven capacity. Re-generative fuel cells are the preferred power storage option.

TABLE 2. SUMMARY OF LUNAR NODE REQUIREMENTS AND FEATURES

	REQUIREMENTS	FEATURES
1.	Lunar Orbit Storage of Cryogenic Liquids. • LH_2 9.3 MT total, 3.1 MT for 55 days max • LO_2 100 MT total, 33.3 MT for 55 days max	Remotely actuated tank attachments for 12 spherical tanks 11 m^3 capacity each. Attachments include provisions for maintaining both O_2 and H_2 as cryogenic liquids.
2.	Lunar Orbit Storage of Cargo Pallets. 3.33 MT max	Remotely actuated package attachments for three packages of 1.1 MT each.
3.	Docking Capability for STV and LADV Individually and Simultaneously	Universal docking unit based upon Space Station Freedom resource node accommodates up to 3 spacecraft at one time.
4.	Tank and Cargo Transfer. Node to STV: 12 tanks exchanged and 3.3 MT cargo transferred Node to LADV: 4 tanks exchanged and and 1.1 MT cargo transferred	Teleoperated boom and end effectors with capabilities that include: • Reach up to 15 m. • Mass up to 15 MT. • Position within 20 cm during transition with provisions for fine motion within a 1 cm diameter during engagement.
5.	Communication and Rendezvous. Tracking Links for both manned and teleoperated docking	RF links via communication satellite relay include: Command, control, telemetry data, video and relay of docking support data from radars and lasers to show ranging and positioning.
6.	Spacecraft Functions as Emergency Haven for Lunar Crew (1500 man-days support capacity, 110 day operation) with power, ECLSS, GN&C, and expendables included on-board.	Node structure is a pressurized cabin based upon the Space Station Freedom habitat module. Exterior modified for tanks and cargo attachment.
7.	Spacecraft Functions as Man-Tended (Two man crew 5 days) with power ECLSS, GN&C and limited expendables.	Node structure is open truss gridwork with attachment points for tanks and and cargo. Resource node plus an enclosure (scaled down logistics module) houses all operating subsystems.

F. Habitat Module Full Crew Safe-Haven (Figures 3 and 4) This option has the capability to sustain the expanded crew for a period of 110 days. The structure and accommodations are based upon the Space Station Freedom habitat module.

G. Minimum Crew Accommodation (Figures 5 and 6) The minimum crew option utilizes the resource node as the principal manned operations area, with the necessary ancillaries attached. An open beam structure supports and provides the retention mechanism for the tankage and cargo. The structural concept resembles that used for the NASA Long Duration Exposure Facility.

LUNAR NODE MASSES

The estimates for masses of the Lunar Node configuration used Space Station Freedom aluminum technology as the base and added assessments of consumables. The mass estimates addressed a total of four cases, as the "Tended" and "Habitat" configurations with either a full complement of on-board oxygen or with hydrogen and cargo. These loading conditions represent the maximum and minimum loading conditions. Table 3 summarizes these masses and show that the transferred oxygen represents the largest single mass element for the system.

TABLE 3. SUMMARY OF LUNAR NODE MASSES

MASS ELEMENT	NODE MASSES WITH O_2 (MT)		NODE MASSES WITH H_2 (MT)	
	Habitat	Tended	Habitat	Tended
Propellant and Tanks Transferred	102.3	102.3	11.3	11.3
Cargo (per trip)			3.3	3.3
Resource Node and Docking Adapter	5.2	5.2	5.2	5.2
Robotics and Transfer	7.5	7.5	7.5	7.5
Communications, Tracking, GNandC	3.5	3.5	3.5	3.5
Cryo Maintenance	2.5	2.5	2.5	2.5
Space Habitat	34.0		34.0	
On-Board Supplies and Consumables	33.0	3.0	33.0	3.0
Man-Tended Truss and Structure		12.0		12.0
Power Supply	3.3	2.4	3.3	2.4
Total Node	191.3	138.4	103.6	50.7

CONCLUSIONS AND CONTINUING STUDIES

This initial single-point evaluation shows that a Lunar Node can expand the flexibility of a lunar base. A Lunar Node provides a focal point and buffer storage for cargo, propellants and crews. The present study identifies three areas that justify further evaluation. The safe-haven requirements need a trade study to refine crew compliments and dwell times compatible with the majority of contingencies. This single point evaluation underscores the need for sensitivity studies that cover a range of propellant mixtures, specific impulses and velocity change requirements. Lunar base missions will not have to use the conservative trajectories required for Apollo. The refinement of the Node operating subsystems definitions would benefit from an analysis of orbital properties that included the time in sunlight, and the dynamics associated with rendezvous. These parameters would support the definitions of the solar collection field, energy storage capacities, communication links and rendezvous opportunities.

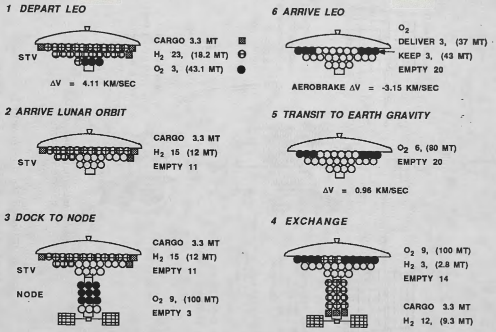
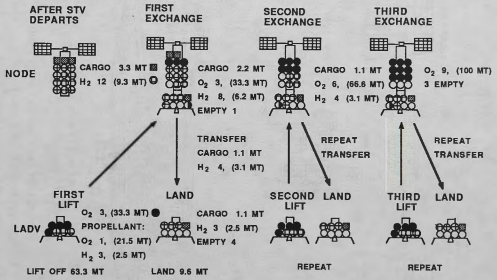


Figure 1. Flight Sequence for the STV Showing Propellant Usage and Transfer Logistics



LUNAR BASE O_2 REQUIRED FOR EACH STV FLIGHT 164.3 MT (986 MT PER YEAR)

Figure 2. Flight Sequence for the LADV Showing Propellant Usage and Exchange Logistics

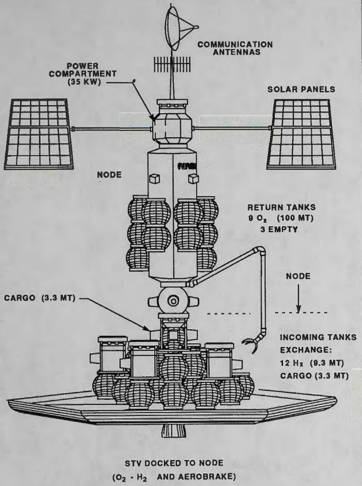


Figure 3. Concept for the Habitat Lunar Node Docked to the STV for Transfer of Propellants and Cargo

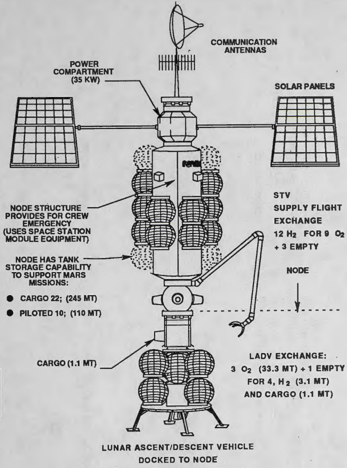


Figure 4. Concept for the Habitat Lunar Node Docked to the LADV for Exchange of Propellants and Cargo

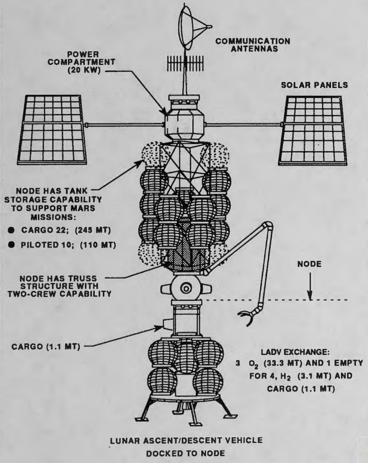


Figure 5. Concept for the Tended Lunar Node Docked to the LADV for Exchange of Propellants and Cargo

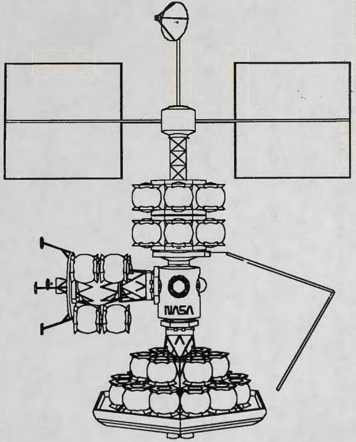


Figure 6. Alternate Concept for the Tended Lunar Node Docked to the STV and LADV

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A Transportation System for a Lunar Base

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A Transportation System for a Lunar Base

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ABSTRACT

This paper will discuss the conceptual design of a transportation system for supporting a permanent base on the surface of the Moon, early in the Twenty-first Century. There is a brief description of a particular lunar base development scenario from which the requirements for the transportation system were derived. The lunar base concept was developed as part of the Lunar Base Systems Study at the Johnson Space Center.

The transportation system consists of a node in low Earth orbit, an orbital transfer vehicle (OTV), and a landing craft. The OTV provides transportation between Earth orbit and lunar orbit. The landing craft transports payloads between lunar orbit and the lunar surface. Each of the vehicles can be operated in an expendable mode or a reusable mode. If the OTV is to be re-used, its return to Earth orbit is accomplished with an aerobraking maneuver. If the landing craft is to be re-used, it is stored on the lunar surface between missions and refueled in lunar orbit by an OTV. Both vehicles use liquid oxygen and liquid hydrogen as propellants.

The lunar vehicles are intended to be operated either as automated cargo vehicles or for transport of personnel. The payload capacity ranges from 6,000 kilograms for a round-trip mission with a crew, to 25,000 kilograms for a one-way cargo delivery mission. The techniques used in developing the conceptual design will be discussed as will other transportation options, which were considered in system selection.

LUNAR BASE CONCEPT

The lunar base, which the transportation system is intended to support, is a permanent human outpost on the surface of the Moon with a rotating crew of 12 people. The people live in an inflated, spherical habitat with several interior levels. The habitat sits in a depression on the surface and is covered by a layer of lunar soil, which provides radiation shielding. The base concept is illustrated in Figure 1. Electrical power will be supplied by photo-voltaic collectors and regenerative fuel cells.

Activities at the lunar base will include a wide range of physical science research, life science research, and demonstration projects leading to the use of lunar resources. The base will support geological exploration in the vicinity of the base and in more remote regions, as well. The lunar base will also provide an opportunity to test systems for future planetary exploration and settlement.

The primary site being considered for the base is Lacus Veris, a region in one of the outer rings of the Orientale Basin at 13 degrees south latitude. The site is relatively close to the west limb of the Moon which is convenient for access to far side locations where a radio-astronomy observatory could be established.(1)

PHASES OF LUNAR BASE DEVELOPMENT

The Lunar Base System Study team adapted a previously defined four-phase lunar development scenario for planning purposes.(2)

Phase 1 is a precursor phase in which the Moon is explored with automated probes. This phase may also include some human exploration. It is assumed that by the end of Phase 1, a site for a lunar base would be selected and enough information would be known about the site to permit construction to begin on the first mission of Phase 2.

Phase 2 is the construction phase for the initial permanent base. This phase requires a series of human missions to the lunar surface and deliveries of large cargo. Concurrent with the base construction, there will be scientific and engineering activity leading to projects to demonstrate the use of lunar resources. By the end of Phase 2, the base will be continuously occupied but will still be completely dependent on supplies from Earth.

Phase 3 is characterized by production and use of lunar resources. Based on current speculation, oxygen derived from lunar regolith is the most likely resource to be exploited in an early period of lunar development. Lunar oxygen could be used in life support systems and in propulsion and power generation systems when combined with fuel from Earth. Lunar-derived oxygen might be transported to lunar orbit and even exported to Earth orbit for use as propellant. Throughout Phase 3, the base will grow steadily and possibly expand into multiple bases and outposts. There may also be a gradual decrease in dependence on Earth for some types of supplies.

In Phase 4, the base or bases will evolve into a nearly self-sufficient lunar colony.

TRANSPORTATION SYSTEM REQUIREMENTS

The primary focus of current lunar base conceptual design activity is Phase 2; the base construction phase. The duration of Phase 2 is expected to be 3 to 6 years. In the simplest terms, the requirement for the system is to provide a transportation link between low Earth orbit and the lunar base, from the site selection phase through base construction and initial operations. This basic requirement can be detailed as follows:

1) Transport exploration teams of 4 people, to potential base sites in a crew module.

2) Deliver elements of the base and construction equipment.

3) Transport personnel to and from the base and deliver supplies on a regular basis. Ten crew rotation missions per year are required when the base population reaches 12 people, assuming that the crew modules carry six people per mission and the average tour of duty is 70 days.

As part of the lunar base definition, two standard container sizes were established for all payloads. The cargo containers have a diameter of 4.5 meters and lengths of 4.5 or 9 meters. Most of the crew supplies and much of the other equipment will be delivered in pressurized containers but the standard sizes also apply to unpressurized payloads. The maximum payload mass is 25 metric tons (25,000 kilograms), but the majority of cargo elements will be significantly smaller than this maximum limit.

People will be transported in a crew module which is a cylindrical pressure vessel with a diameter of 4.5 meters, a length of 4.5 meters, and a mass of 6 metric tons. The module has a bulkhead separating it into two equal, cylindrical chambers. Each chamber is intended to provide independent life support in an emergency. Generally, the upper chamber serves as a flight deck and habitation area and the lower chamber serves as an airlock and storage area. The crew module will normally carry four to six people.

Basic Transportation Scenario

In the first few years, a typical mission will carry 4 people to the lunar base site. In order to extend surface stay time without increasing the size and mass of the crew module, a "construction shack" will be delivered as cargo on a separate landing craft. The construction shack is a self-contained habitat that will support the crew during the early missions while the main habitat is being constructed. The shack is the heaviest single payload that has been identified for Phase 2, with a diameter of 4.5 meters, a length of 9 meters and a mass of 25 metric tons.

Other large payloads to be delivered on automated cargo missions are the main habitat and supporting equipment, the power generation system, construction equipment, and a pressurized surface rover. Supplies for the crew must also be delivered but it may be possible to carry the majority of these supplies on the crew transport missions.

It is assumed that all missions in support of lunar base construction and operations will originate at a servicing facility in low Earth orbit. This facility could be similar to the currently planned Space Station or it could be a derivative with very different characteristics. Vehicle elements, payloads, propellant, and people are assembled at the servicing facility to begin a flight to the Moon. The vehicle departs from Earth orbit under the power of an orbital transfer stage. The vehicle enters lunar orbit and a descent craft separates from the transfer vehicle to land on the lunar surface. Return trips begin with an ascent into lunar orbit where the orbital transfer vehicle is waiting. A transfer stage then carries the payload and possibly the landing craft, back to Earth orbit. It is assumed that insertion into Earth orbit is accomplished with an aerobraking maneuver followed by small propulsive maneuvers to circularize the orbit and rendezvous with the transportation node. The series of major maneuvers in a lunar mission are illustrated in Figure 2.

There are many variations of the transportation scenario which must be considered. Orbital transfers and lunar descent and ascent can be accomplished with vehicles of one or several stages. A libration point could be used as the staging point in the lunar vicinity rather than lunar orbit. The lunar landing craft could be returned to Earth orbit for servicing, left in lunar orbit for later re-use, stationed on the lunar surface, or expended after each use. These options and others must be studied in depth to gain an understanding of their implications for system performance and operational efficiency.

Trade studies and preliminary sizing of proposed lunar vehicles were accomplished using a lunar vehicle sizing program which was an in-house development.(3) Performance requirements based on Project Apollo lunar missions were used in the vehicle sizing program. Using the results of the preliminary sizing activity, a conceptual design of a complete lunar transportation system was developed.

The general conclusions of the trade studies were that the lunar vehicle should consist of a single-stage OTV and a single-stage landing craft. The maneuvers performed by the OTV are trans-lunar injection, lunar orbit insertion, trans-Earth injection, and Earth orbit insertion. The maneuvers performed by the landing craft are lunar de-orbit, landing, and ascent. Aerobraking should be used for the return to Earth orbit and liquid oxygen and hydrogen should be used as the propellants. Other parametric studies were done to determine reasonable payload masses for one-way and round trip missions using a common set of vehicles. This work resulted in the adoption of six metric tons as the maximum round trip payload, 15 metric tons as the standard one-way payload, and 25 metric tons as the maximum payload, if the vehicles are expended.

VEHICLE CONFIGURATIONS

A large number of potential vehicle configurations were developed in the course of the study. Two of the earlier configurations are described in the following sections., The third configuration is the selected vehicle design for this phase of the study and will be described in more detail. The three configurations that are described were developed in an evolutionary sequence.

Proposed Configuration 1: Earth orbit-based Landing Craft, Single Aerobrake

The first proposed configuration, shown in Figure 3, consists of an integrated OTV and landing craft. The OTV has an aerobrake which is large enough to protect the landing craft when returning to Earth orbit at the end of a mission. Returning the landing craft to Earth orbit allows for the use of totally reusable vehicles from the beginning of a lunar program without the need for a servicing facility in lunar orbit. The landing craft design is a concept developed by the Lunar Base Systems Study contractor (4). The OTV concept was developed by the author.(5)

The access tunnel is the key feature of the landing craft design. It is a pressurized volume and also a major structural element. When the landing craft is carrying people, the tunnel serves as an airlock for the crew to enter and leave the vehicle, both on the lunar surface and when docked to an orbital facility.

This proposed configuration offers a number of advantageous features. The pressurized access tunnel provides a common interface between the landing craft and the transportation node regardless of the type of payload being carried. The common interface exists even when there is no payload. The heat shield surface of the aerobrake has no engine doors, attachment fittings, or other penetrations. This reduces the potential for damage to the heat shield and eliminates some mechanical systems. A malfunction in a door mechanism on an aerobrake could be a catastrophic failure.

There are several drawbacks to this design. The volume for payloads is limited to a cylindrical volume which is about 4.5 meters long and 4.5 meters in diameter. The OTV design is specialized for carrying the lunar landing craft and is not very adaptable to other missions. Because of its small diameter and right angle bend, the tunnel in the landing craft is probably too cramped for use as an airlock. Making the tunnel larger would add a significant weight penalty to the vehicle when it is serving as an unmanned cargo carrier.

Proposed Configuration 2: Earth orbit-based Landing Craft, Twin Aerobrakes

In the second proposed configuration, shown in Figure 4, the OTV and landing craft are more independent vehicles.(6) Both are returned to low Earth orbit for servicing, but each has its own aerobrake.

A unique feature of this concept is the rotating aerobrake structures. Fitting spacecraft behind aerobrakes and providing clearance for engine plumes is one of the challenges in designing aerobraking spacecraft. In many designs, engines must be movable or engine doors must be provided in the heat shield. Attitude control thrusters must be retractable. Also, aligning the engine thrust vector through the combined center of mass of the vehicle and payload can be difficult. In this concept, it is the aerobrake which moves, while the engines and other complex hardware are stationary. If desired, the aerobrakes can be removed without modifying the other vehicle elements.

Selected Configuration: Lunar-based Landing Craft, Single Aerobrake

The configuration selected in this study is similar to Configuration 2 except that the requirement for returning the landing craft to Earth orbit is eliminated. There is only one aerobrake which is carried by the OTV. The landing craft is expended in early missions. Later, the OTV will carry extra propellant to refuel the landing craft so that the landing craft can return to the surface base and ascend again to meet a future OTV. This approach takes advantage of the permanent lunar base as a transportation node. Also, some of the problems associated with plane changes for landing craft or OTVs waiting in lunar orbit are eliminated. A detailed description of the vehicle is contained in Reference 7.

The basic OTV and aerobrake are shown in Figure 5. The OTV can also be used in this expendable configuration, without an aerobrake, to carry payloads to the moon, or other destinations. The OTV has four engines, and four cylindrical propellant tanks, two for the liquid hydrogen and two for the liquid oxygen propellant.

The landing craft is similar to the OTV, with four engines and four propellant tanks. The propellant tanks are smaller and the hydrogen tanks are spherical rather than cylindrical. Although they are not shown in the illustrations, the OTV and landing craft would be covered with blankets for thermal insulation and protection from debris.

The landing craft could carry a wide range of payloads including a crew module as shown in Figure 6. On the lunar surface, the crew would exit from the module through the bottom hatch, onto the egress platform between the propellant tanks. A ladder extends from the platform to the surface. The egress platform has an open grid floor so that lunar dust can be shaken off suits before returning to the module. The egress platform also provides storage area for equipment to be used on the surface.

After the base is established, a flexible tunnel at the landing site would connect the side hatch to a pressurized rover. The crew could exit from the landing craft and travel to the base without wearing pressure suits.

The landing craft can operate as an independent spacecraft. In some cases the landing craft, without a payload or operator, will ascend to meet an arriving OTV or descend to the surface to await its next mission. The landing craft, in an emergency, could carry people between the surface and lunar orbit without a crew module. The people, in pressure suits, could ride in harnesses on the landing craft egress platform.

An illustration of the OTV and a crew module docked to a landing craft and a crew module is shown in Figure 7. This configuration would occur in lunar orbit during a typical crew rotation mission.

VEHICLE SIZE AND MASS

The Lunar Vehicle Sizing Program was used to determine the mass of propellant needed to accomplish the required missions. Based on this propellant mass, tank diameters were calculated. Historical data was used to estimate the mass of vehicle components. The aerobrake diameter was determined by applying geometric relationships which define the protected zone behind the heat shield. Using total vehicle mass at the critical points in all of the required missions, an appropriate engine thrust level was calculated. The mass estimates for major vehicle elements are provided in Table 1.

VEHICLE SYSTEMS DESCRIPTION

Aerobrake

The aerobrake is intended to be a very simple and relatively lightweight vehicle component. The frame and skin are made of aluminum or some composite material. The outside surface is covered with a reusable heat shield material, such as the silica-based tiles used on the Space Shuttle orbiter. These tiles do not require a weather-proof surface, like that on the Shuttle tiles, since the aerobrake is based in space and never descends below the upper atmosphere.

The OTV is attached to the aerobrake at four points, two at the forward end and two at the aft end. The forward end of the OTV is either attached to the forward section of the OTV frame or to extended struts. The aft attachments permit the OTV to pivot between these two positions.

If the OTV is attached to the extended struts, there will be clearance for the attachment of a landing craft or other large payload to the front of the OTV. Large payloads, including the landing craft, cannot be contained within the protected zone behind the aerobrake and so these payloads are never returned to Earth orbit. After separation from large payloads, a mechanical actuator rotates the OTV down to its forward attachment points. Small payloads, such as the crew module, would fit within the protected zone of the aerobrake when the OTV is in its lowered position.

OTV and Landing Craft Structure

The OTV and landing craft have a simple rectangular truss structure made of aluminum or some composite material. These vehicles are very large and so they are designed for assembly and repair in space. The landing gear on the landing craft cannot be folded. The main struts and two support struts on each leg have pneumatic or mechanical shock absorbers. Since the landing craft is intended for multiple uses, the landing gear must be able to withstand many landing impacts.

Propellant Tanks

The propellant tanks in the OTV and landing craft are aluminum shells with external reinforcing structure. Each tank has some surface insulation, however, additional insulation of the tanks will be provided by blankets covering the outside of each vehicle. Some form of active refrigeration may be needed as part of the tank system in order to minimize boil-off of the cryogenic propellants.

Engines and Thrust Vector Control

The OTV and landing craft each have four engines. The thrust level for each engine is 36,000 Newtons (8,100 lbf). The engines on the lander require throttling capability to 50 percent of the full thrust level. Each engine has a redundant set of electro-mechanical actuators for thrust vector control. The maximum gimbal angle requirement will be set by the operation of the landing craft with one engine.

Electrical Power

Electrical power for the OTV and landing craft is provided by a fuel cell system which will use hydrogen and oxygen reactants from the propellant tanks. The fuel cells are located in the central area between the propellant tanks on the OTV and below the egress platform on the landing craft. In general, the OTV and landing craft will not provide services to payloads, but some electrical power might be provided to the crew module and similar payloads.

Avionics

The avionics system on the OTV and landing craft consists of four redundant sets of equipment, located in two boxes attached to the structure of each vehicle. The rectangular avionics boxes are one meter square and two meters long. Each box contains two complete sets of guidance, navigation, and flight control equipment including a computer, inertial navigation unit, rate and acceleration sensors, and a communications system. The avionics boxes have independent cooling systems with radiators mounted on the outside of the box. The four avionics systems on each vehicle operate as a redundant set and only one system needs to remain functional for safe operation.

Attitude Control

The OTV and landing craft have attitude control thruster assemblies on each of the eight corners of the vehicle structure. Each assembly has three thrusters. The thrusters will use hydrogen and oxygen propellant from the main propellant tanks. Thrusters will receive commands from the vehicle computers, based on programmed mission plans or inputs from an attached crew module or remote control facility. There will also be four control thruster assemblies on the rim of the aerobrake.

Thermal Control

Heaters and heat rejection equipment will be built into individual subsystem modules, whenever possible. Payloads, including the crew module, will have their own heat rejection capability. The overall vehicle requirements for thermal control are handled by insulation blankets, electrical heaters, and possibly a refrigeration system. The primary purpose of a refrigeration system would be to keep the cryogenic propellants cold. This system might require radiators which are not shown in any of the vehicle drawings.

External Protection

Most of the exterior of the OTV and landing craft will be covered by blankets of flexible material which will thermally insulate the vehicles, especially propellant tanks. These blankets will be easily removed for inspection and maintenance activities.

CONCLUSION

The lunar transportation system concept presented here has the potential to meet the requirements of lunar base operations and to satisfy the design objectives of flexibility, simplicity, and evolutionary growth. Current efforts have concentrated on conventional propulsion but there are many other alternatives which need to be studied. However, conventional systems have provided a good starting point in building engineering experience and in developing tools and techniques for design and analysis.

By no means has the study attempted to conclusively settle all of the trade study issues in lunar transportation nor has it attempted to produce the final design of a vehicle to be used in the next century. The point of the study was to define a reasonable transportation system concept that can be used in further definition of lunar base operations, transportation node design, and launch vehicle requirements. This study is a point of departure for future work.

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TABLE 1: Vehicle Element Mass Estimates

Inert OTV	6,500 kg
OTV propellant tanks	2,500
OTV propellant (maximum)	100,000
Total OTV (maximum)	109,000
Aerobrake	6,000
Inert landing craft	7,000
Landing craft propellant tanks	1,000
Landing craft propellant	20,000
Total Landing craft	28,000
Crew Module	6,000
Propellant tanker structure	2,000
Propellant tanks	2,000
Propellant	40,000
Total Propellant Tanker	44,000

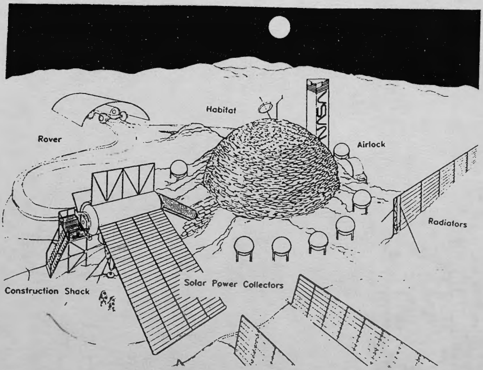

Figure 1: Lunar Base Concept

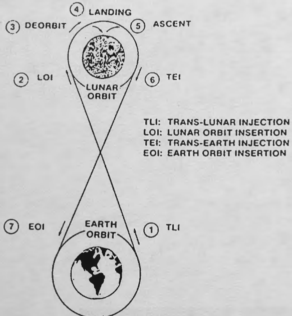

Figure 2: Major Earth-to-Moon Maneuvers

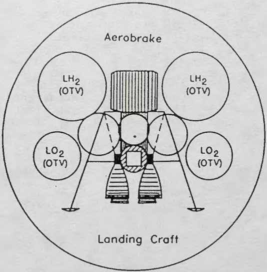

Figure 3: Configuration 1

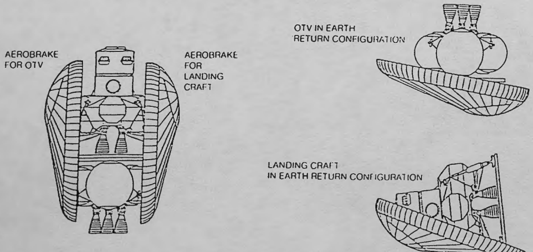

Figure 4: Configuration 2 - Orbital Transfer Vehicle and Landing Craft

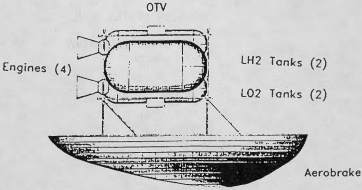

Figure 5: Selected Configuration - Orbital Transfer Vehicle and Aerobrake

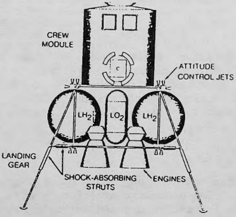

Figure 6: Selected Configuration - Landing Craft and Crew Module

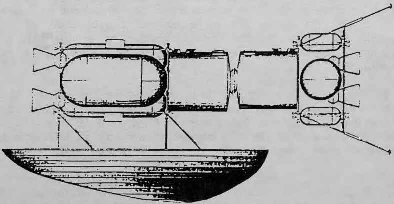

Figure 7: Orbital Transfer Vehicle, Landing Craft, and Crew Modules