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Paper Session III-B - 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.

PHASES OF LUNAR BASE DEVELOPMENT

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

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.

REFERENCES


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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