

# OPERATIONAL CONSIDERATIONS FOR LUNAR TRANSPORTATION

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*Transportation of people and cargo between low Earth orbit and the surface of the Moon will be one of the most important elements in a lunar base program. This paper will identify some of the important lessons from the space shuttle program and discuss their application in future lunar vehicle operations. Also, some unique challenges in flight planning, training, vehicle servicing, payload integration, and flight control for lunar transportation will be outlined. This paper relies heavily on recent studies of space shuttle development and operations with the goal of applying shuttle experience in the design of a practical and efficient lunar transportation system.*

## INTRODUCTION

The two basic program components of a lunar transportation system are development and operations. The focus of this paper is operations. However, in many ways, efficient operations result from careful planning in the development phase. This planning must be applied in the vehicle design process and in the definition of program goals. Transportation operations will be a major cost factor in a lunar base program, and so the vehicles must be designed for efficiency and low life-cycle cost. The space shuttle program had similar goals at its inception, and so the lessons of shuttle operations provide a good experience base for development of operations concepts for routine lunar transportation. Several significant lessons from the shuttle program that may apply to lunar vehicle development and operations will be discussed in this paper.

There are many ways to define and subdivide operations functions. The operations functions to be discussed in this paper are flight planning, training, vehicle servicing, payload integration, and flight control. These are the major activities that contribute to operational cost in the space shuttle program (JSC, 1988a). In this paper, each operational function will be discussed, and some significant aspects related to lunar operations will be described.

As a starting point, it is necessary to define a basic scenario for the lunar transportation system. 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 will be assembled at the servicing facility to begin a flight to the Moon. The vehicle will depart from Earth orbit under the power of an orbital transfer stage. The vehicle will enter lunar orbit and a descent craft will separate from the transfer stage to land on the lunar surface. Return trips will begin with an ascent into lunar orbit where the transfer stage is waiting. The transfer stage then carries the payload, and possibly the lander craft, back to Earth orbit. It is assumed that insertion into Earth orbit will be accomplished with an aerobraking

maneuver followed by small propulsive maneuvers to circularize the orbit and rendezvous with the servicing facility.

There are many variations of the transportation scenario that must be considered. Orbital transfers and lunar descent and ascent can be accomplished with vehicles of one or many 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 reuse, 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. This paper will not resolve those issues, but it will describe some of the factors that must be considered in the solution.

## LESSONS LEARNED FROM SHUTTLE OPERATIONS

There are a number of lessons that have been learned in the initial years of operating the space shuttle that also apply to operation of a lunar transportation system.

### Define the Operational Scenario as Part of the Conceptual Design

In the conceptual design phase of the space shuttle, initial assumptions were made about the operational scenario for the vehicle. The crucial element of the scenario was the assumed flight rate of 60 flights per year. As the shuttle design evolved, changes were made due to weight restrictions, budget limitations, and the risks of new technology. The definition of the optional scenario did not remain in step with the vehicle design, and this contributed to underestimation of operations costs by over 400% (Petro, 1986).

In the conceptual design of lunar spacecraft it will be important to define the operational scenario for these vehicles. The important scenario elements are flight frequency, lifetime of vehicles, location of transportation nodes, availability of facilities and personnel for servicing, and the traffic model for cargo and people. The relationship between lunar transportation and other

space operations must also be determined. Clear definition of both vehicle designs and the operational scenario will make possible a reliable and realistic estimate of life-cycle cost for the lunar transportation system.

### **Establish a Strategy for Evolutionary Growth Including the Transition from Development to Operations**

The space shuttle can be described as a research and development vehicle with an operational mission. It is a first-generation system, and expectations for using it in a totally routine manner were probably never realistic. It might be realistic, however, to expect that the shuttle system will evolve into second- and third-generation systems that will approach and eventually attain the level of routine operations performed by commercial airlines. This evolution can be accomplished by improving vehicle systems, streamlining operations, and modifying vehicle configuration on the basis of operational experience.

One of the fundamental requirements for a lunar base program will be the need to periodically transport crews to and from the base and to deliver supplies. The scenario being used in the Johnson Space Center (JSC) Lunar Base Systems Study calls for 5 to 10 missions per year in the initial phase of base development. In later phases, the need for supplies from Earth may diminish, but scientific and resource objectives imply an ongoing and even increasing need for routine transportation between the lunar surface and other points in space (JSC, 1988b).

Because of the relatively high flight rate, even in the early phase, it will be very important that the lunar transportation system be operated efficiently; otherwise, transportation costs will absorb program resources to the extent that expanding the base will become difficult or impossible. Since the only previous experience with lunar transportation is from the Apollo Program in the 1960s, the lunar spacecraft being considered here are essentially first-generation vehicles. It will be a major challenge to design these vehicles with the foresight needed to ensure efficient operations in the uncertain environment of the first lunar base development program.

The development program for lunar vehicles should follow a carefully planned strategy, leading from spacecraft that will support the first landings to routine crew rotation and supply flights. As the base grows, the flight rate and the complexity of cargo operations will gradually increase. Most importantly, as the base operations mature, there will be increasing pressure to reduce the level of resources devoted to transportation activity. This means that a plan should be in place to transition smoothly from experimental-type vehicle operations to more routine operations.

The transition from transportation system development to transportation operations creates several requirements that should be addressed in vehicle design. One requirement is that vehicle designs be flexible. It should be possible for vehicle configurations to evolve over time to accept larger cargo loads, larger numbers of passengers, and more demanding performance requirements. Consideration should be given to the fact that vehicle servicing may originally occur in Earth orbit and later in lunar orbit or on the lunar surface. Also, if vehicle servicing is initially performed by human crews, those functions may be later taken over by robots. Designs should also account for the need to periodically upgrade vehicle systems such as avionics, power, or propulsion.

Another means to effectively transition to operations is to specify the long-term requirements for routine operations. Operations requirements include, for example, specifications for

software tools for automated flight planning and real-time flight control. Another requirement is the vehicle performance and environmental data needed to validate and implement the planning and flight control tools. Specification of operational requirements provides the rationale needed to support an effective flight test program. A flight test program should not only prove that a vehicle functions acceptably, but it should define the overall performance envelope and provide all the data needed to support streamlined operations. This performance definition will help to eliminate the need for continuing engineering analysis in an era of routine operations (JSC, 1988a).

### **Invest in Technology Development Programs**

Early investment in technology development was very beneficial in reducing overall space shuttle development costs (Petro, 1986). Areas where advanced technology might be beneficial in lunar vehicle development are (1) thermal protection systems; (2) aerodynamic analysis of atmospheric braking; (3) adaptive flight software for guidance and control; (4) reusable, low maintenance engines; and (4) propellant storage techniques. Any technology area that will increase the degree to which lunar vehicles can operate autonomously should also be pursued. These technology needs are common to most advanced space transportation systems.

### **Balance Maintainability Against Performance in Design Decisions**

Maintenance of high-performance systems is the primary schedule and cost driver in space shuttle orbiter processing, and it is likely to be the same for lunar vehicles (Petro, 1986). Lunar vehicles, as currently envisioned, will have high-performance engines using liquid oxygen and liquid hydrogen propellants. These engines will have to be restartable and in some cases must have a wide throttle range. Shuttle experience would indicate that the engines would require a great deal of refurbishment between uses and have a short operational lifetime. A high-performance propulsion system reduces the mass of propellant that must be launched into Earth orbit to support a lunar mission. The advantages of high performance must be weighed, however, against the potential cost of system maintenance. The cost of supporting maintenance facilities in space could be enormous, especially if human crews are required. Emphasis has to be placed on maintainability, even at the expense of performance. Maintenance requirements must be minimized and refurbishment, when required, should be automated as much as possible.

Simplicity is always a good design goal. For routine lunar transportation, it is essential. The interfaces between vehicle elements, such as an orbital transfer vehicle and a lunar lander, should be standardized. The same is true for interfaces between vehicles and payloads. Every effort should be made to keep vehicle configurations simple. Complex shapes for aerobraking vehicles should be avoided, as should configurations in which there can be a wide variation in the center of gravity location.

## **OPERATIONAL FUNCTIONS FOR LUNAR TRANSPORTATION**

Transportation operations can be divided into five functional areas: (1) flight planning; (2) training; (3) vehicle servicing; (4) payload integration; and (5) flight control. Considerations related specifically to each function in lunar transportation operations are described in the paragraphs that follow.

## Flight Planning

There are a number of complicating factors involved in lunar flight planning due to the periodic variation of orbital planes and the resulting variation in performance requirements. With a particular vehicle, payload, and destination, there will be an optimum time of departure and flight duration (Woodcock, 1985). There may be some flexibility in timing, however, if there is enough excess vehicle performance to support some amount of orbital plane change. Flight planners will have to consider, and in some cases specify, the mass of the payload, length of the departure window, flight duration, stay-time in lunar orbit, stay-time on the lunar surface, and the amount of propellant loaded. In addition, mission abort trajectories will have to be planned.

All the complicating factors mentioned are interrelated. It will require extensive trade studies to fully explore all the lunar trajectory options. However, it should be a goal, by the time lunar base construction begins, to automate the flight planning process. The flight test program must verify the automated flight planning system for the entire range of possible trajectories and flight conditions. Ideally, the flight planning software should be part of an onboard adaptive guidance and control system. Onboard flight planning would make the transportation system less sensitive to uncertainties about the payload and to delays in vehicle servicing and departure. If problems develop during a flight, the onboard system could modify the flight profile or even plan an abort trajectory without assistance from an extensive mission support facility.

Experience from the space shuttle program might lead to the conclusion that an attempt should be made to standardize flight profiles. Such an approach might apply to flights from Earth to a space station, but the same is not true for lunar missions. The variables for lunar flight planning are so numerous and subject to frequent change that development of an automatic system would be a wise investment.

The concern about rapid-response flight planning applies in particular to potential aerobraking maneuvers. There are a number of factors that would affect aerobraking flight design that are subject to change during the course of a mission. These factors include the mass of the returned payload, the amount of remaining propellant, and the vehicle center of gravity. One goal of the development and test programs for specific aerobraking vehicles must be to build a sufficient database to support automated flight planning for the entire range of possible trajectories. Flight planning could become an operational burden if detailed engineering analysis had to be performed each time there was a vehicle, payload, or flight schedule change.

## Training

The training of crews for lunar vehicles will present some new challenges. The most significant involves the potentially long mission durations combined with the need to assign multiple tasks to crewmembers. A flight to and from the Moon is not in itself a long mission. The round trip can be completed in less than one week. Training crews to perform their flight functions for early lunar missions with short surface stay-times will be similar to training space shuttle crews. Later, transportation operations for a mature base will probably be performed by specialist pilots or be automated.

Between the earliest lunar missions and the mature operations era there is likely to be a transition period lasting many years. In this transition period, crews who operate the vehicles may also

have to remain on the lunar surface for extended periods before piloting the vehicles back to Earth. These astronauts will require extensive training in engineering and scientific functions related to surface base operations, in addition to vehicle operations.

The response to the training challenge can take at least two forms. One approach is to provide facilities for pilot proficiency training as part of the lunar base. This could be done by building a training simulator capability into operational vehicles. This would be an efficient use of existing equipment, and the technique might be applied in other space activities, especially a Mars mission.

A different approach is to design vehicles that are essentially automatic. If common vehicles are used for both manned and unmanned missions, lunar spacecraft that carry people should already be capable of operating without human intervention. However, it would take a significant change in philosophy to no longer train crews to manually control spacecraft. The approach taken in lunar transportation is likely to be a combination of enhanced automatic capabilities along with continuation of flight training during stays at a lunar base.

There are many things that can and will be done to make lunar spacecraft operations less demanding than during the Apollo program. The most crucial step is to emphasize operational simplicity as a vehicle design goal. Advanced computer technology should help reduce crew work load with features such as automatic failure detection and recovery. Programs to enhance the space shuttle and develop other space systems should provide an experience base to support this area of lunar vehicle design.

One aspect of lunar transportation that should become less demanding is descent and landing on the lunar surface. Since the vehicles will be flown repeatedly to the same site, the terrain will be well known, radio and visual navigation aids can be provided, and landing areas can be prepared. On the other hand, one of the consequences of reusable vehicles may be a larger range of mission abort options, including the option of aborting an ascent from the Moon. More abort options could significantly complicate the crew training task.

## Vehicle Servicing

The vehicle servicing requirements for lunar spacecraft may include the following functions: refurbishment of engines, refueling or replacement of propellant tanks, resupply of consumables, repair or replacement of failed components, inspection of aerobrakes, and testing of propellant tanks. Of these activities, engine maintenance is likely to be the most time consuming. The most efficient method of handling engine maintenance will probably be to design engines for easy removal and replacement as a single unit. Engines can then be serviced in a large pressurized volume in space or returned to Earth.

In general, every effort must be made to design systems for easy servicing, either with robots or from within pressurized volumes. Maintenance by crews in pressure suits should be a last resort.

## Payload Integration

The most important payload for the lunar transportation system will be people, but, if space shuttle experience is an indication, readiness of human crews will not be the most critical item in a lunar transportation system schedule. Readiness of cargo is likely to be a major concern at a transportation node because of the need to coordinate the delivery and preparation of a vehicle, its propellant, and the payload within very tight launch window

constraints. Schedules for delivery of payloads will be subject to all the factors that can delay a launch from Earth.

One way to reduce sensitivity to delivery schedule problems is to make the payload integration process as simple as possible. That can be done by minimizing the interfaces between the payload and vehicle. This will be especially important in later phases of lunar operations when payloads may have to be moved from an orbital transfer vehicle to a lunar landing craft after arrival in the lunar vicinity. Payloads on unmanned missions should require only a simple mechanical connection with the vehicle. Crew modules will require some data connections and possibly electrical connections, but these should be minimized. One option for data connections is to use radio frequency or optical links to avoid a physical connection. The complicated interface engineering and compatibility analysis that is performed in the space shuttle payload integration process must be avoided by design.

Unloading cargo and people on the lunar surface is also an important part of payload integration. Trade studies must be done to determine which unloading devices should be part of the landing craft and which should be provided at the surface base.

### Flight Control

The goals for flight control are closely related to those for flight planning. Ideally, there should be no ground facilities for real-time control of lunar spacecraft. Reliance on ground control creates an enormous institutional requirement for development and maintenance of facilities for tracking, communication, data reduction, computation, training, and management. A better allocation of resources would be to develop and verify onboard adaptive guidance, navigation, and flight control systems. Along with this, automated systems could be developed to monitor spacecraft systems with little or no additional workload placed on a human crew. In addition to the direct benefits, automated systems are going to be mandatory for planetary spaceflight and the lunar transportation system would provide a good test bed for their development.

### CONCLUSIONS

Studies of space shuttle development and operations provide several major lessons that could benefit the effort to design an efficient lunar transportation system. The program goals and the transportation scenario must be defined as part of the conceptual

design process. There must be a strategy for evolutionary growth of the system, including a plan for the transition from development to operations. An important part of the transition plan is the definition of what is required to operate the system without an ongoing vehicle and flight analysis effort. Vehicle maintainability has to be weighed against flight performance in design trade studies, and early investments should be made in technology development.

There are two major challenges in the development of an operational lunar transportation system. One is the development of high-performance vehicle systems, such as engines, which do not require extensive and frequent maintenance. The other challenge is to develop and validate highly adaptive onboard guidance, control, and flight planning systems. Onboard autonomy will require a large initial investment, but it will help to control operational costs, and its development will be mandatory for future interplanetary spaceflight. The long-range goal for transportation development should be to design systems that operate themselves.

Transportation system design will continue as part of ongoing lunar base studies. The effort to understand the lessons of past and current space vehicle programs will also continue with the goals of avoiding pitfalls and building on success.

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