

IN-SPACE OPERATIONS FOR LUNAR AND MARS SPACE TRANSFER VEHICLES

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Abstract

The objective of this paper is to discuss the in-space operations required to process the lunar and Mars mission vehicles envisioned in early studies for the Space Exploration Initiative (SEI). Recent studies, which have examined the degree to which on-orbit operations change as a function of the Earth-to-orbit (ETO) launch vehicle size, identified a common set of on-orbit vehicle processing tasks, and generated functional requirements for in-space processing nodes, are summarized in this paper.

Timelines for on-orbit processing of two different lunar transfer vehicles (LTVs) were developed to compare a "current practice", labor-intensive EVA approach to ones utilizing telerobotics and advanced automation. LTV aerobrake concepts ranging from simple deployment to considerable assembly are compared. Similar timelines for the on-orbit processing of a nuclear Mars transfer vehicle (MTV) are also presented. Aerobrakes can be processed in a timely manner, and should not be ruled out for SEI missions. The "tall pole" time interval for on-orbit vehicle initial processing is the delivery of elements to orbit, not the processing tasks.

A discussion of the low-Earth-orbit (LEO) infrastructure required to support on-orbit vehicle processing is presented. The LEO infrastructure required to support on-orbit space transfer vehicle processing operations is determined by the complexity and amount of on-orbit processing operations, which is dictated by the design of the flight vehicle. Processing support can be an integral part of each vehicle to be assembled, or it can be permanent infrastructure remaining in LEO. Use of deployed rather than assembled aerobrakes minimizes on-orbit operations. Early lunar missions with expendable vehicles will not require on-orbit processing if the ETO launcher is large enough, but later space-based reusable LTVs will. All MTVs proposed for the SEI are inherently large and will require significant on-orbit processing operations.

The paper concludes with a discussion of hardware design recommendations and specific technology needs that will minimize the required on-orbit operations. On-orbit proces-

ing time savings of up to 66% could be realized if the recommendations and technologies are incorporated into the space transfer vehicles.

Introduction

This paper discusses those on-orbit processing operations that will probably be required for some of the Space Exploration Initiative space transfer vehicle elements. Also included is discussion of some aspects of the on-orbit infrastructure that may be required to support such operations. The emphasis of this paper is the amount of time these processing operations might require and how this time duration changes as a function of how the operation is executed and how the hardware is designed. On-orbit processing operations include the assembly activity as well as operations related to inspection, protection from orbital debris, storage, checkout, fueling, crew transfer, etc.

On July 20, 1989, President Bush described the Space Exploration Initiative as consisting essentially of "... back to the Moon to stay ... and on to Mars." In the intervening years, he has endorsed the SEI objectives on many occasions by further defining the goal, providing policy guidance on architectures, identifying a possible role for international participation, establishing a timetable, and requesting budgetary support. The most recent evidence of continuing strong administration commitment is his issuance of Space Policy Directive No. 6 outlining participation of the DoD, DoE and DoC and establishing a National Program Office to be led by the NASA Associate Administrator for Exploration.¹

In addition to the ongoing NASA studies of how such an initiative might be implemented, Gen. Thomas Stafford was designated to lead a National Synthesis Group beginning in late 1990 to further define several possible approaches for mission implementation. The group's report outlined four mission architectures that define mission scope and possible implementation approaches.² Each of these mission architectures has been examined in detail (reference 3 documents the NASA analysis of one of the architectures) to further define implementation requirements and hardware system details.

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Emphasis is currently being directed at defining the details of the initial unmanned precursor lunar missions. A first manned landing could occur as early as 1999. The First Lunar Outpost (FLO) Study is a current NASA in-house, inter-center multi-team effort designed to identify approach, details, schedule, cost, technology requirements, and required new system developments. An early conclusion of the studies has been that a single large heavy-lift launch vehicle (HLLV), larger than Saturn V, would be required for each cargo and manned launch. Each mission consists of a cargo and a piloted launch that proceed independently to the Moon. Many of the study results obtained over the last few years, under the MSFC contracts cited in references 4 through 7, have provided the basis for the approaches being refined in the current FLO studies.

The use of a single launch vehicle (if available) for each element of the manned lunar mission eliminates on-orbit processing operations. This approach would seem to be appropriate in the current national economic environment and as a simplifying approach for a first manned mission, if a large HLLV is developed. Reliance on a plan to develop such a large HLLV, shown in Figure 1, for early and later lunar missions has the added value of defining the launch vehicle required for the Mars missions. Such requirements must be defined now if the NLS program is to provide such a vehicle rather than require that two new launch vehicles be developed in parallel. If, however, the required capability (mass and volume) HLLV is not available for the FLO, a smaller

launch vehicle could be utilized with the result that some degree of on-orbit processing operations will be required.

The least amount of on-orbit operations occurs with a dual-launch for each mission element and an on-orbit rendezvous/capture scenario (capture being a refinement to the Apollo-style collision docking). Figure 2 shows such a mission profile from a recent MSFC study.⁴ Figure 3 shows the launch vehicle manifesting for this type mission.⁶ Note that the second piloted launch requires an undock-and-recapture maneuver between the return capsule and lunar lander (similar to that of Apollo) prior to rendezvous/capture with the first launch payload. A significant aspect of the first launch is to minimize propellant boil-off while waiting for about a month until the second launch arrives in LEO. The rendezvous/capture scenario has been adequately demonstrated in the past, but could be automated with advanced technologies for additional development cost.

Utilizing an even smaller ETO vehicle (Shuttle, Titan IV, small NLS, etc.) would stretch the delivery/assembly period over a longer time span and result in more hardware pieces to receive, inspect, assemble, and checkout.^{8,9} It is for this scenario that on-orbit processing operations and the supporting infrastructure become significant mission elements and require an unrealistic number of ETO launches.

In later years when there are several missions to the Moon each year, and hardware recovery, refurbishment, and reuse are demonstrated to be economical, such LEO operations and infrastructure will be required. The lunar transfer ve-

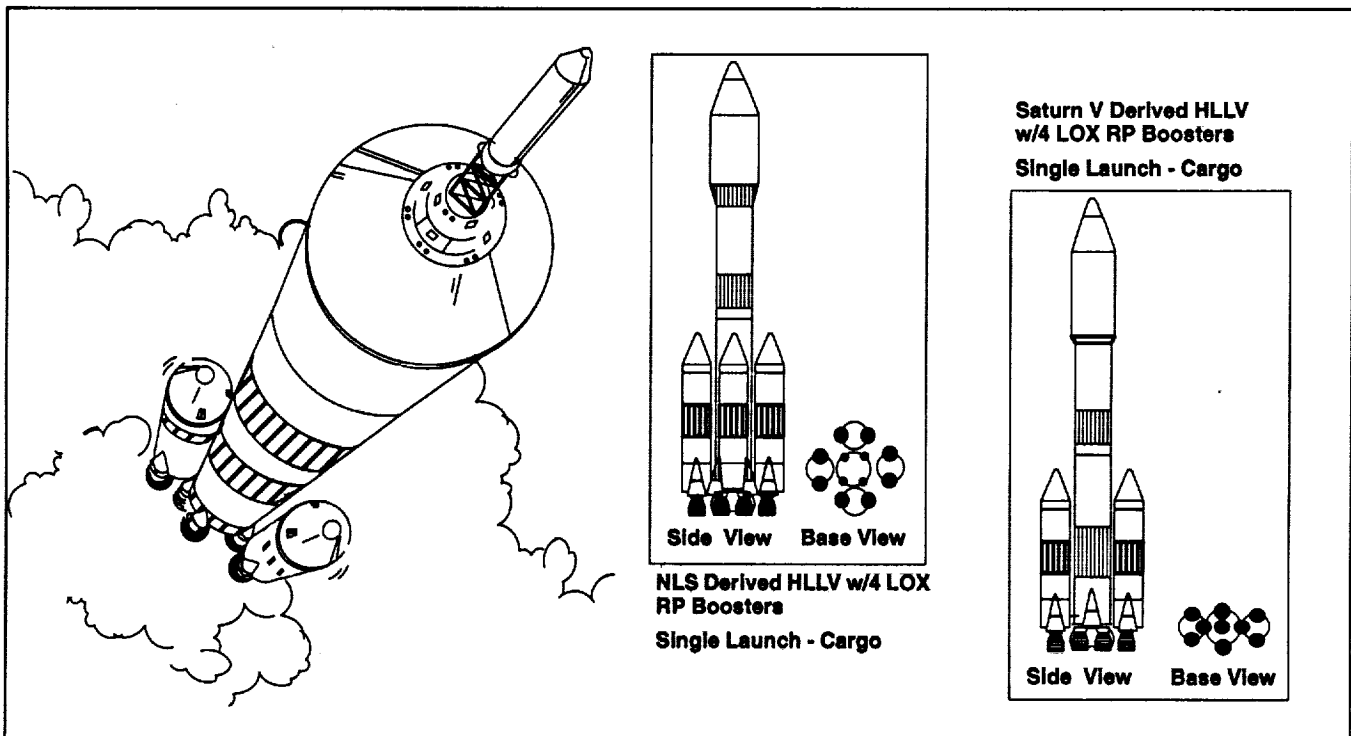


Figure 1 HLLV Concepts for Single Launch to Moon

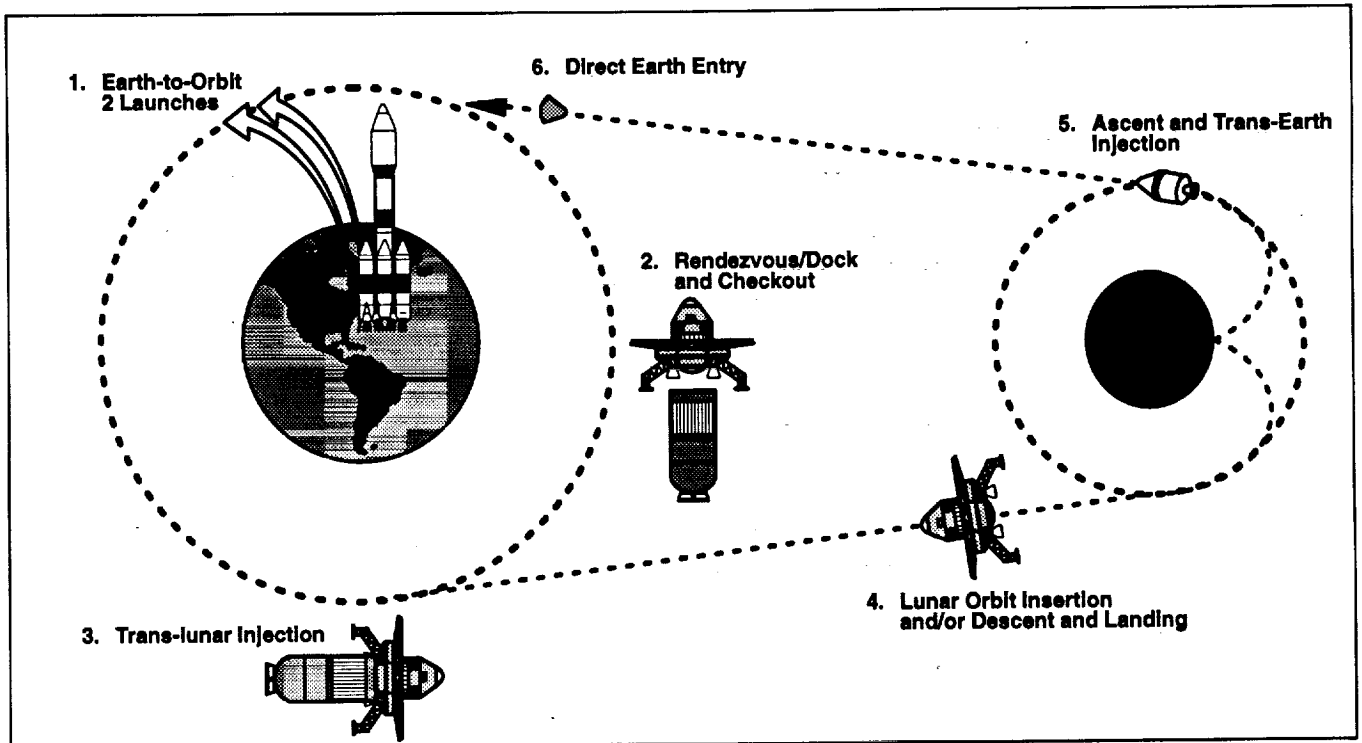


Figure 2 Recent Rendezvous/Dock Lunar Mission Profile

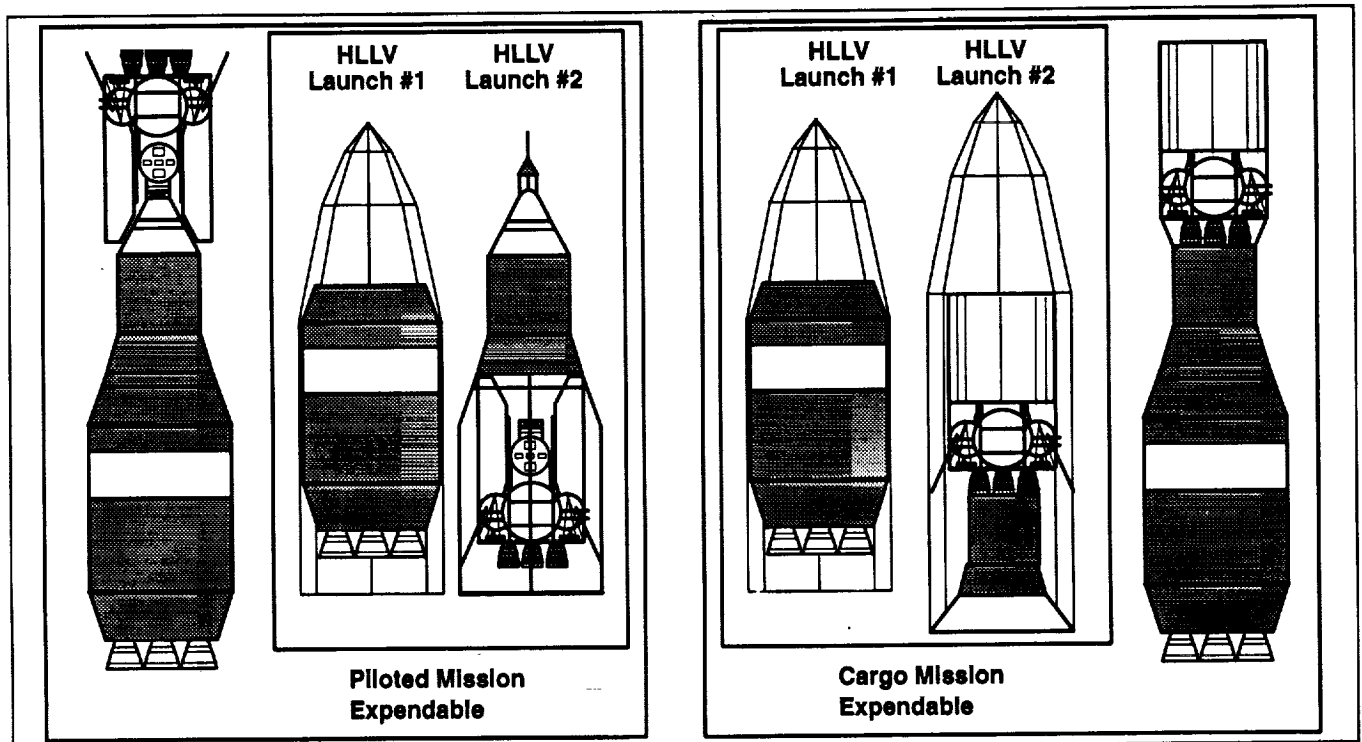


Figure 3 Launch Manifest for Rendezvous/Dock Lunar Mission

hicle would be based and fueled at a LEO node, and a shuttle or its SSTO successor vehicle would be used to ferry fresh crews and cargo between Earth and the LEO node. The need for very large lunar HLLV is then eliminated.

However, the very large HLLV (150 to 250mt) will be required for all Mars missions in order to minimize the number of launches and delivery time for the Mars transfer vehicle elements. Figure 4 indicates that 7 launches to LEO, with a 150mt launch vehicle, is required.^{5,10} The reference 11 study indicates a similar number of launches and examines several approaches for implementing on-orbit operations. One approach involves a self-contained robotic assembly, capability in the payload to capture and assemble the hardware pieces into a space transfer vehicle. A second approach involves the same self-contained robotic assembly, but adds a depot node for storing hardware awaiting assembly, and for storing special assembly hardware and elements, such as an orbital debris shields until required for the next mission. Of these two assembly scenarios, the later approach minimizes the mass penalty on the departing Mars vehicle.

A third approach is the Space Station, or other free-flying LEO node, to support the on-orbit processing operations. Of the three approaches, this scenario imposes least mass penalty associated with on-orbit processing on the departing Mars vehicle. However, this scenario requires the most effort to establish the LEO supporting infrastructure.

Reference 12 has examined those tasks that must be performed in orbit to inspect, assemble, store and test a Mars (or lunar) transfer vehicle. Table 1 presents these functions for scenarios where more than two launches per piloted or cargo

mission are required. Table 2 presents those on-orbit supporting systems required to enable these functions. A significant finding of this study was that the same in-space operations are required for each expendable space transfer vehicle regardless of launch vehicle size, and are repeated for each ETO launch. A recent MSFC trade study on ETO launch vehicle size, summarized in Figure 5, utilized these findings.¹³ Consequently, the capabilities and systems required in a supporting role in orbit do not vary depending upon the size of

Table 1 Functions Involved in On-Orbit Operations

- Deploy and erect structures
- Attach and assemble/disassemble components
- Inspect structures and components
- Calibrate systems and components
- Rendezvous and dock hardware
- Receive, berth and store components
- Maneuver components into position
- Manipulate structures and components
- Test and verify assemblies, systems, and components
- Make utility connections
- Provide effective lighting
- Communicate
- Generate and store power
- Control large space structures
- Provide thermal, radiation and debris protection
- Manage cyro fuel transfer and storage
- Manage mission data
- Provide support for contingency operations

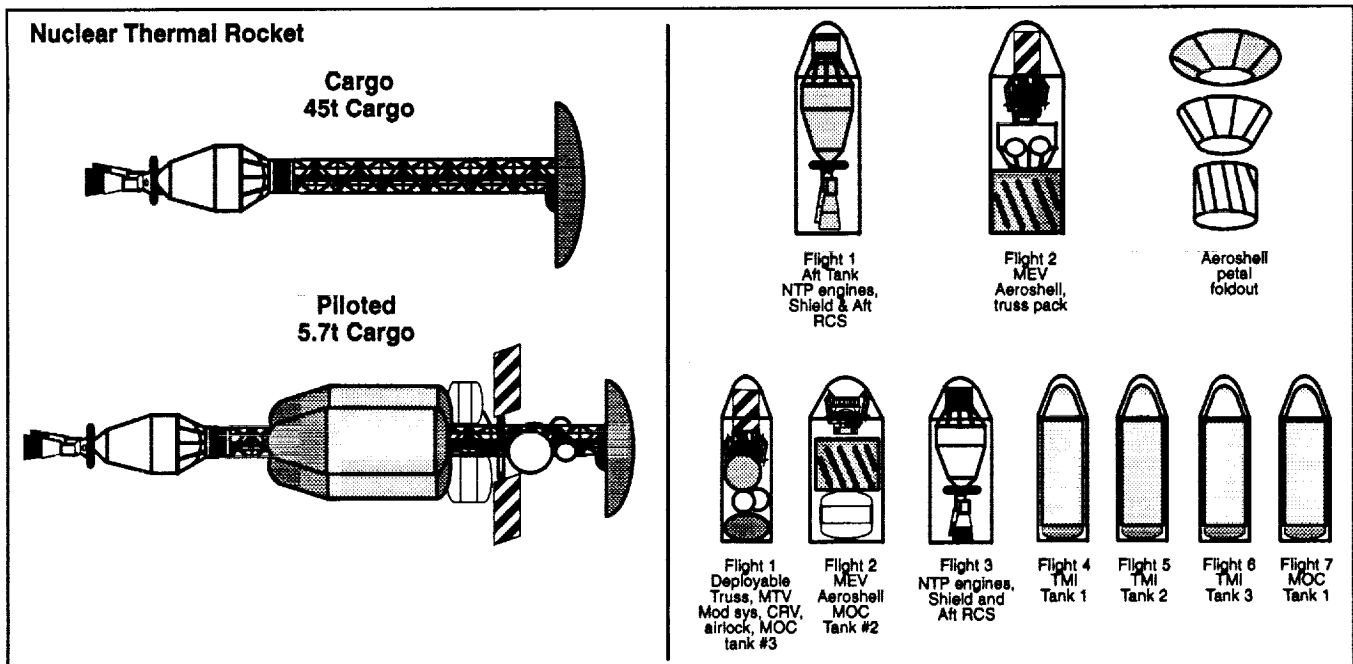


Figure 4 Launch Manifest for Mars Mission with 150mt Vehicle

Table 2 Supporting Systems Required for On-Orbit Operations

- Structural
- Robotic manipulators
- Data management computers and software
- Power generation and storage
- Communications hardware and software
- Remote sensors
- Visual Inspection hardware and software
- Cryogenic fuel control
- Docking and berthing mechanisms
- Lighting units (fixed and moveable)
- Guidance, navigation and control
- Storage
- Shielding

the ETO launch vehicle. The design of the system, and the degree of astronaut involvement, is a function of which on-orbit infrastructure scenario is selected. This selection is strongly influenced by the technologies employed, which are discussed in the later section on Design Recommendations and Technologies.

Lunar Mission Hardware Assembly Operations

The on-orbit assembly and refurbishment of two different lunar transfer vehicles (LTVs) has been examined using ap-

proaches with varying degrees of automation in order to bracket the best and worst case scenarios. Additionally, two aerobrake concepts were studied, which vary from a self-deploying design to one that requires the assembly of 19 large panels. Previously developed methodologies and databases were used for these analyses.¹⁴ Timelines refer to work shifts that are 8 hours in duration, and are for a dedicated on-orbit vehicle processing crew of four.

Lunar Transfer Vehicle Assembly and Turnaround

Quantifiable Space Shuttle ground processing tasks at Kennedy Space Center (KSC), as well as actual Shuttle EVA and remote manipulator experience in space, were used as analogies for LTV on-orbit assembly, refurbishment, and checkout tasks.¹⁴ An Assembly/Service Facility located at Space Station Freedom (SSF) was used for LTV processing, and is further described in a following section on LEO Assembly Node Infrastructure.

The Option 5 LTV shown in Figure 6 was defined by the 90-Day Study on the Human Exploration of the Moon and Mars.¹⁵ It has a core stage consisting of a crew module, core propellant tanks, and four RL-10 main engines. Liquid hydrogen and oxygen propellants are carried in four drop-tanks which are mated on orbit. An aerobrake requiring assembly

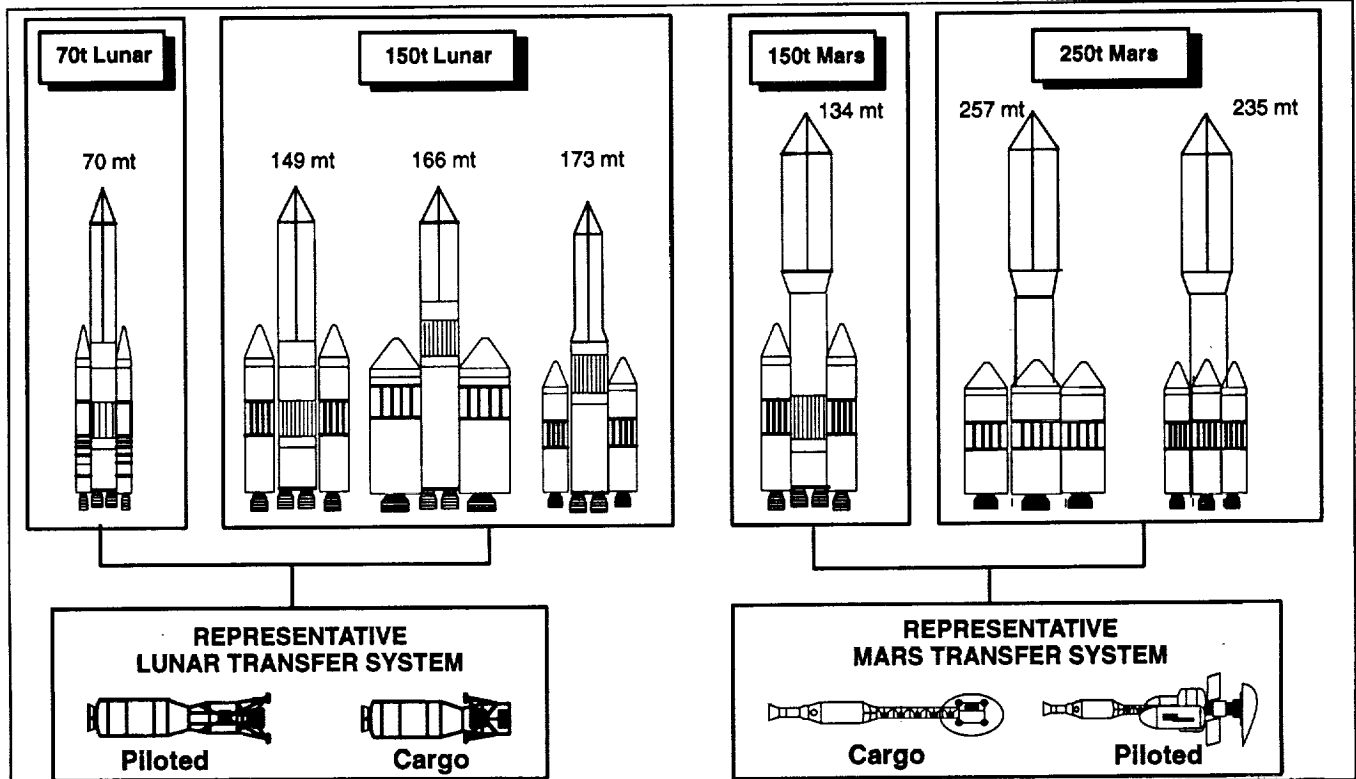


Figure 5 Summary of Trade Study to Assess Impact of Launch Vehicle Size on Complexity of On-Orbit Operations

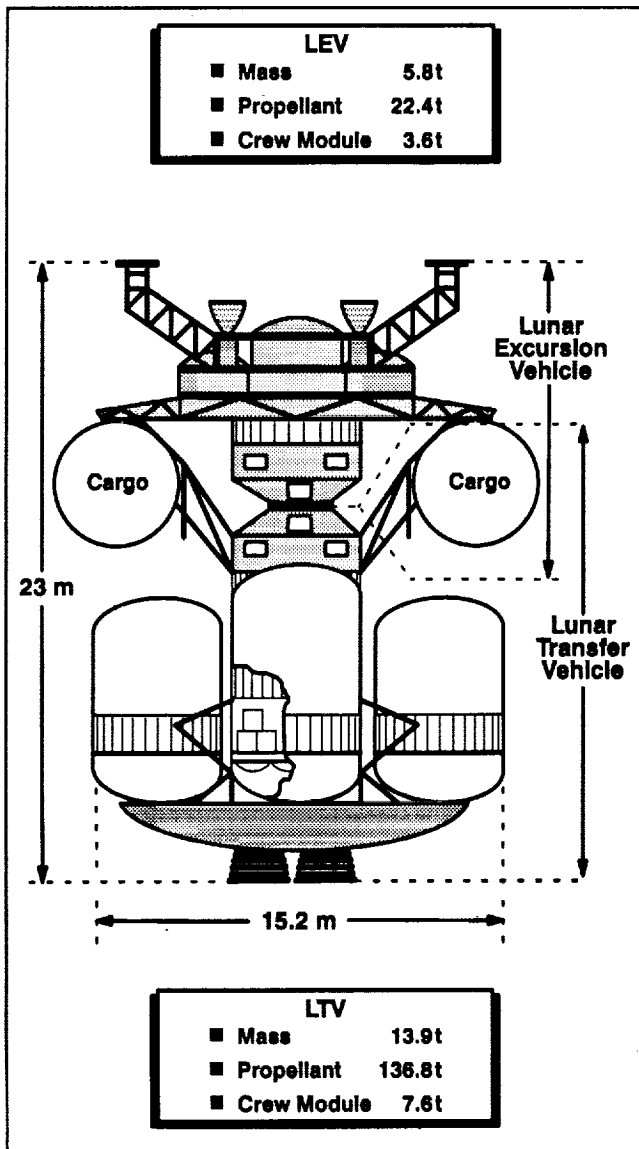


Figure 6 Option 5 Lunar Transfer Vehicle Configuration

of eight petals attached to a circular core is used for Earth-orbit capture at the end of the mission. Two cargo pods are carried by the LTV for transfer to a separate lunar excursion vehicle (LEV), which is based in lunar orbit. Three 71-ton Shuttle-C HLLVs and one Shuttle flight are required to deliver the LTV components to LEO. The processing scenario used for this Option 5 LTV is heavily dependent on use of EVA astronauts to accomplish manual tasks. Initial assembly of this LTV was estimated to take 69.5 work shifts (including 27 shifts of EVA), and is shown in Figure 7. Refurbishment and turnaround between missions will take 182.5 work shifts (including 53 EVA shifts), and is shown in Figure 8. Use of advanced telerobotics reduced the required EVA hours by 79%. If operation of the telerobots is performed from the ground, a 49% savings of IVA astronaut time can also be achieved. However, in order to achieve these savings in EVA and IVA astronaut hours, the total elapsed processing time may increase by 50% for initial assembly and 62% for turnaround.¹⁴

The second LTV selected for analysis, shown in Figure 9, was the Lunar 1-B Piloted Case LTV defined for the Marshall Space Flight Center's (MSFC) ETO Size Trade Study.¹³ This LTV is based on Martin Marietta Corporation's (MMC) 4E-5B configuration⁶, modified by substituting a Boeing crew module⁷, and consists of a single propulsion/avionics/crew module core vehicle with five RL-10 main engines and six propellant drop-tanks. An improved deployable aerobrake (discussed further in the next section on Aerobrakes for Earth Return) is left in lunar orbit while the rest of the vehicle descends to the lunar surface. Following launch of the LTV from the lunar surface, the LTV rendezvous with and captures the aerobrake, and returns to SSF in Earth orbit via an aerocapture maneuver. Five 70-ton HLLVs are required to loft these LTV components to LEO,

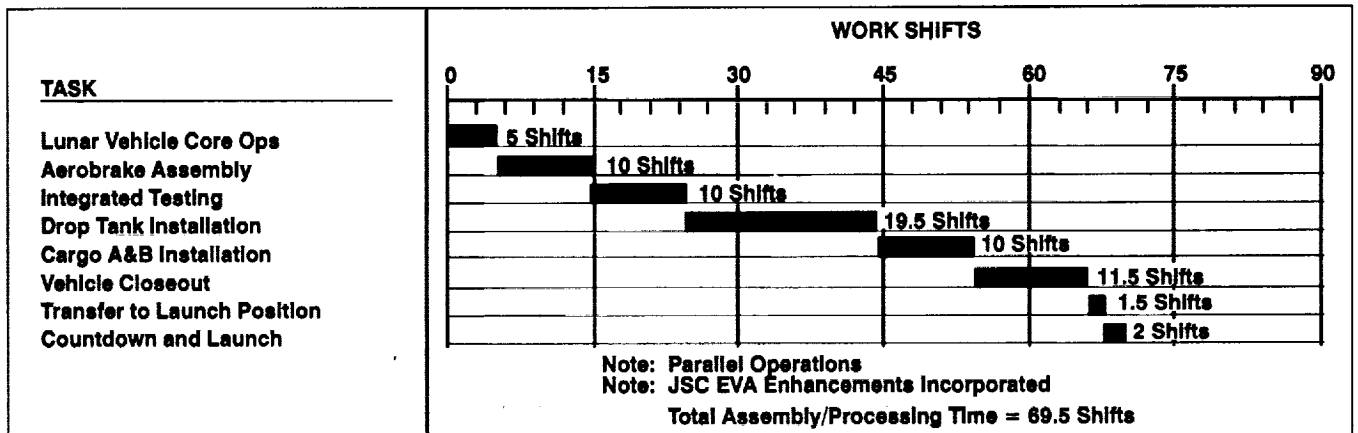


Figure 7 Assembly Timeline for Option 5 Lunar Transfer Vehicle

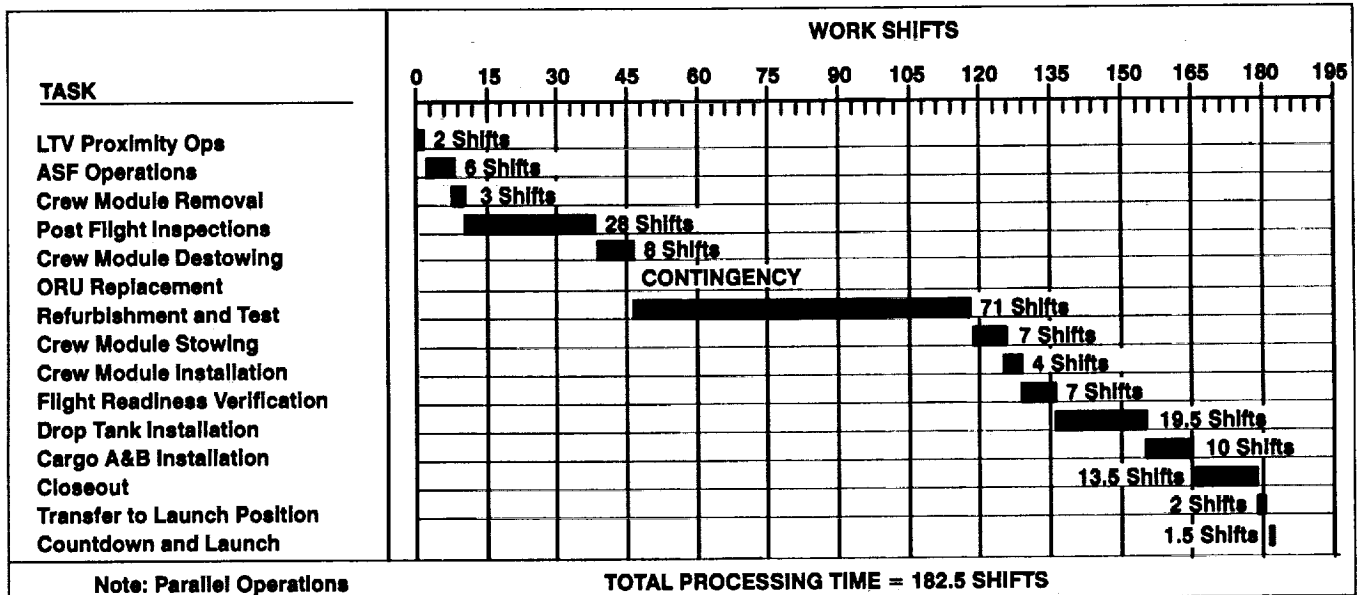


Figure 8 Refurbishment Timeline for Option 5 Lunar Transfer Vehicle

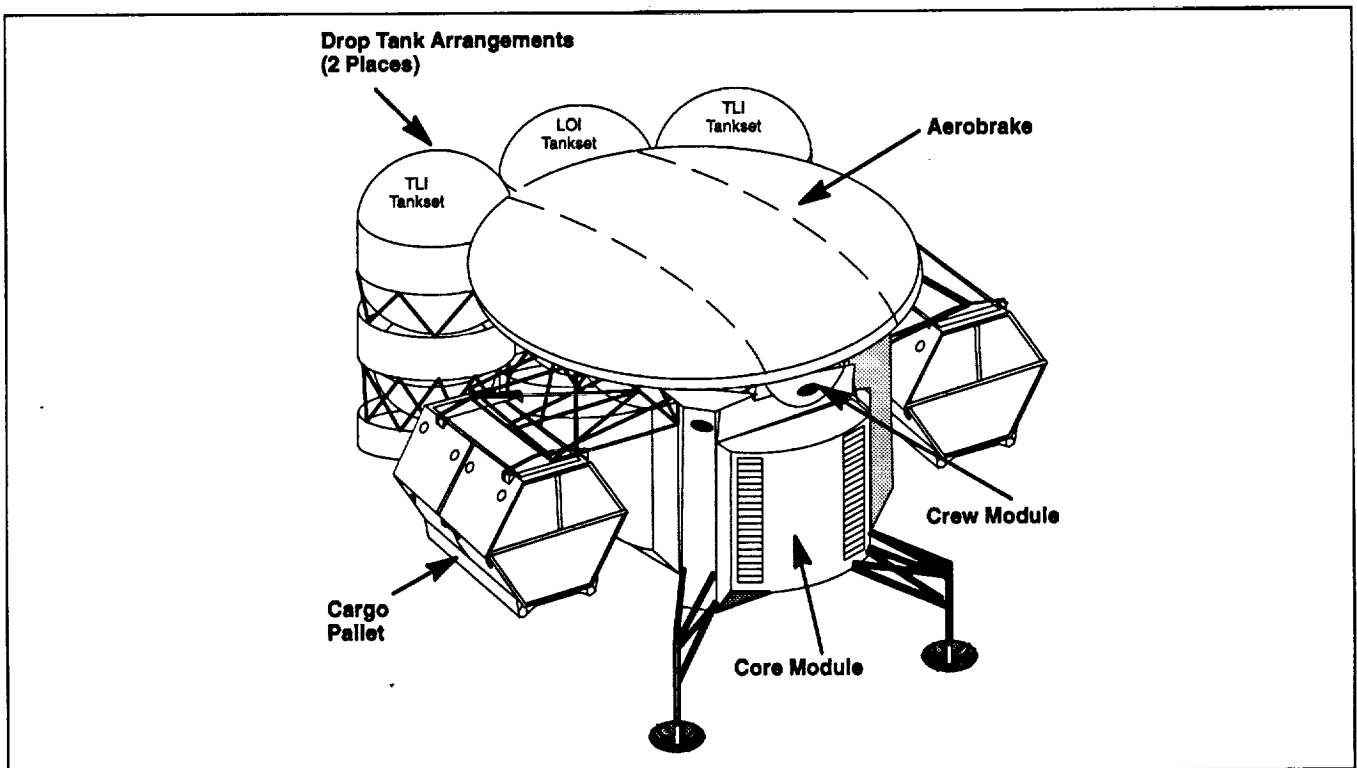


Figure 9 MMC Lunar Transfer Vehicle Configuration

as shown in Figure 10. A processing philosophy that minimizes on-orbit operations by forcing the LTV to be as robust and autonomous as possible was implemented at the direction of NASA Headquarters' Office of Exploration. Using this philosophy, initial assembly of the modified MMC LTV

was estimated to take only 33 shifts (Figure 11), while turnaround between missions would take only 61.5 shifts (Figure 12). This represents a savings of 52% for assembly and 66% for turnaround as compared to the Option 5 LTV, while completely eliminating required EVA. These savings are made

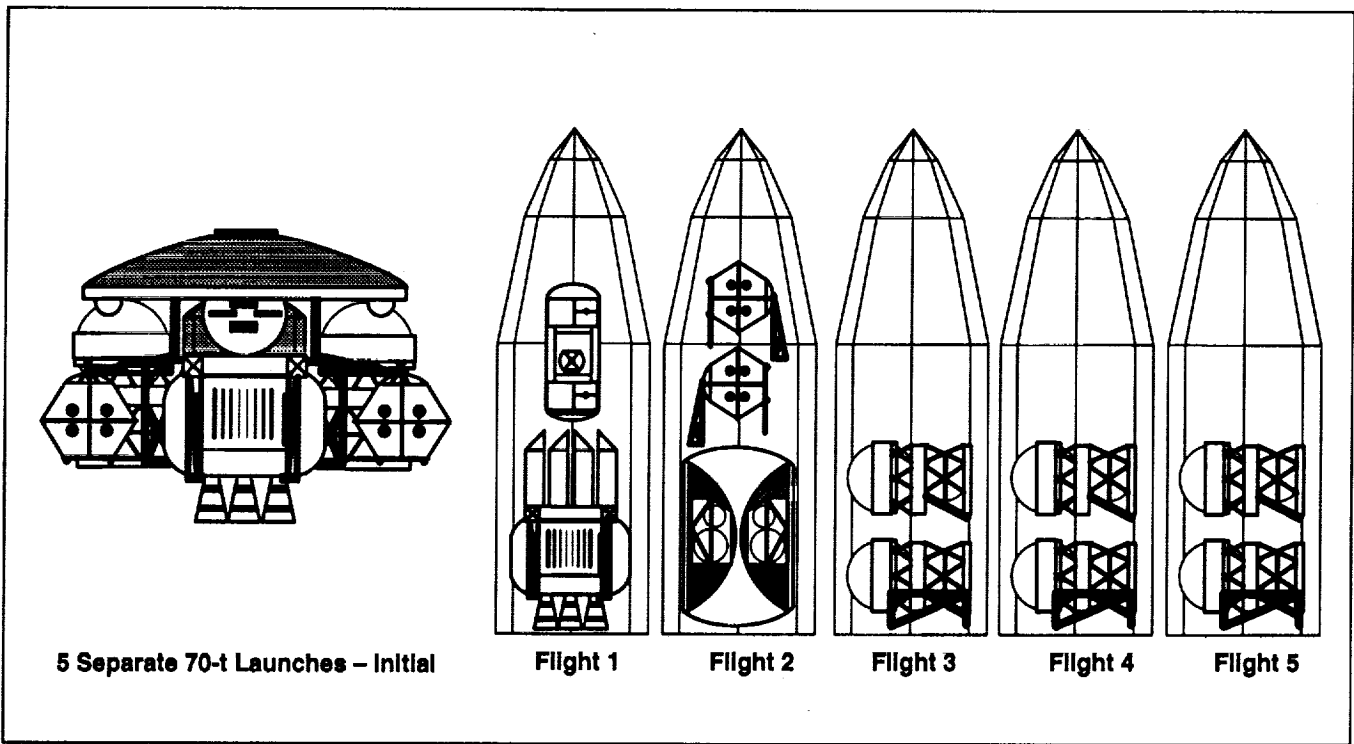


Figure 10 Launch Vehicle (70 mt) Manifest for MMC Lunar Transfer Vehicle

possible by incorporating the design recommendations and advanced technologies which were identified to reduce the labor intensive tasks based on vehicle processing analogies at KSC. These are discussed in detail in a following section on Design Recommendations and Technologies.

For either the EVA-intensive Option 5 LTV assembly or the

modified MMC LTV telerobotic assembly, the time interval between the HLLV ETO launches is longer than the time required to assemble and test the components. Therefore, ETO launch frequency is the limiting factor that determines the on-orbit processing time for initial LTV assembly.

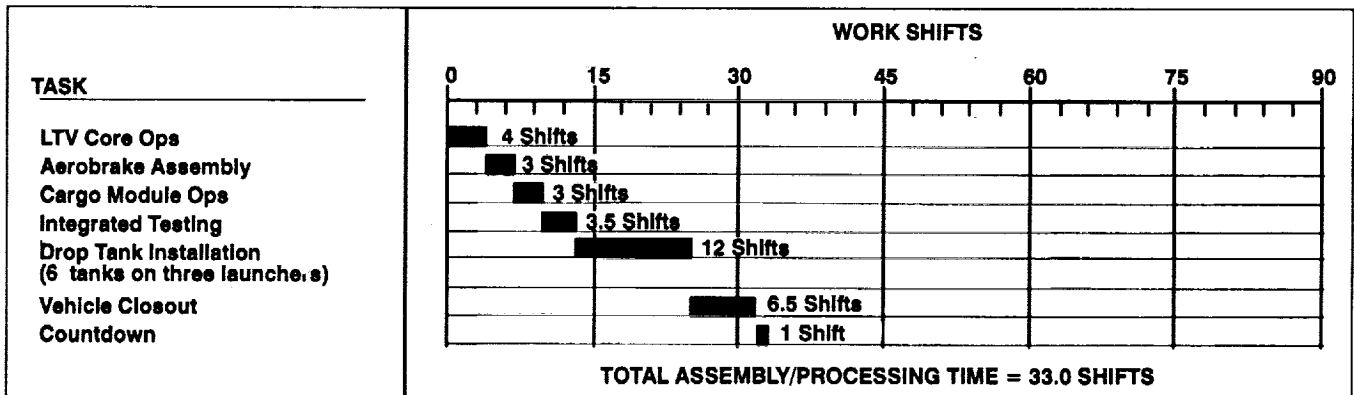


Figure 11 Assembly Timeline for MMC Lunar Transfer Vehicle

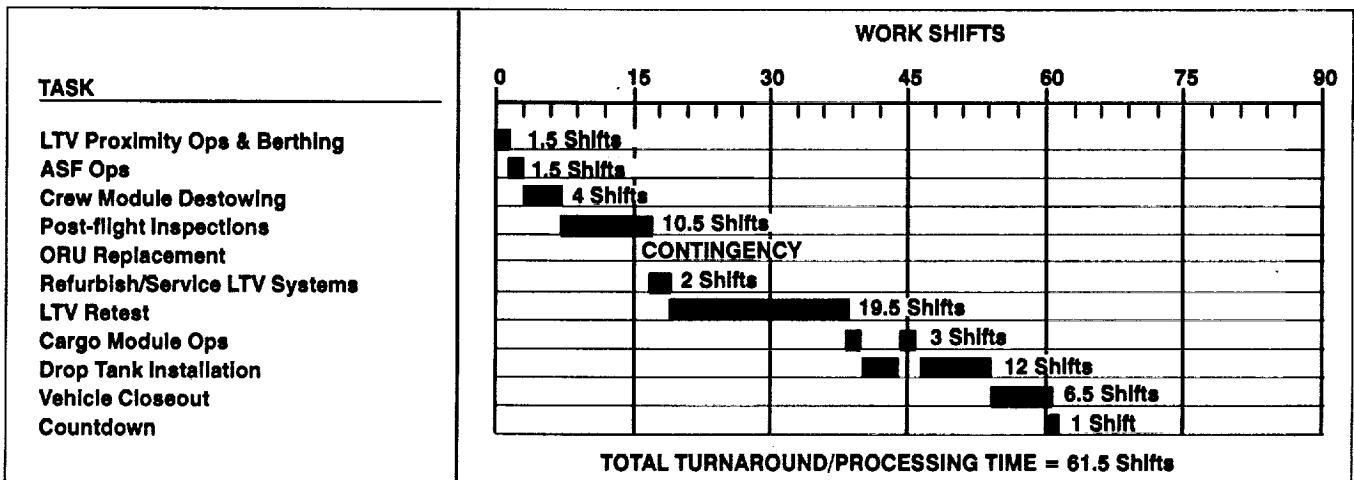


Figure 12 Refurbishment Timeline for MMC Lunar Transfer Vehicle

Aerobrakes for Earth Return

The aerobrake concept generated by Langley Research Center's Space Exploration Initiative Office is shown in Figure 13. It is 50 feet in diameter, has a lift-to-drag (L/D) ratio of 0.15, and consists of 19 hexagonal panels with pre-attached thermal protection tiles.¹⁶ This concept purposely included

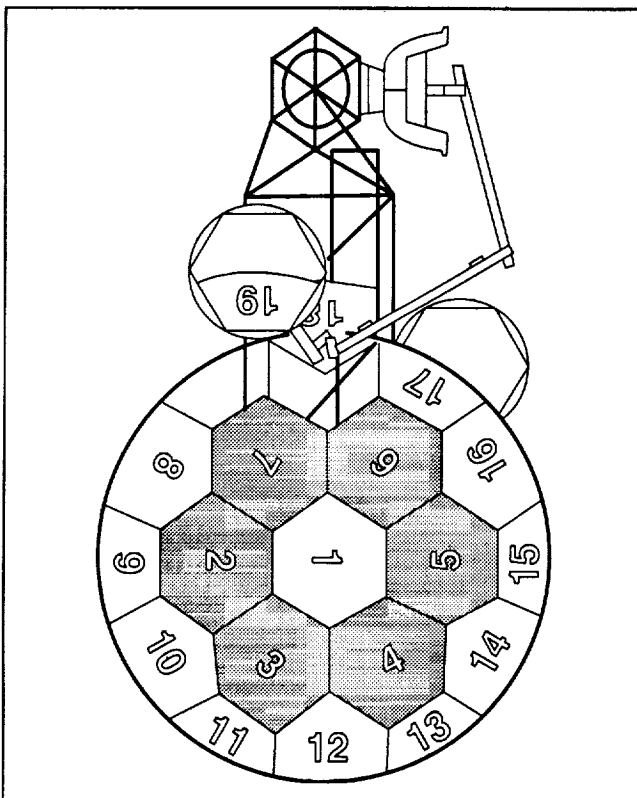


Figure 13 Robotic Assembly of Hex-Panel Aerobrake Configuration

assembly and was selected to evaluate packaging a large aerobrake in a small volume. Such a concept could also be valuable where a higher packaging density is required in a large volume HLLV to minimize the number of ETO launches. Joint design is such that a total of 305 captive bolts (spaced at one foot intervals along the joints) require torquing. However, no thermal protection closeout is required along the panel joints. Upon completion of aerobrake structural assembly, the docking ring, attitude control thruster assemblies, hydrogen boil-off storage tank, and avionics package must be installed and verified. In accordance with the NASA Headquarters' Office of Exploration philosophy to make on-orbit operations as autonomous as possible, a scenario using telerobotic assembly was developed. Assumptions included the addition of a turntable to Space Station Freedom, and use of the station's telerobots for this assembly scenario. The resulting 80.7 hour (10 shift) processing flow is shown in Figure 14.

To bracket the opposite end of the on-orbit operations spectrum (i.e., no assembly and no supporting infrastructure required), the Martin Marietta rigid deployable aerobrake shown in Figure 15 was analyzed. It is 45 feet in diameter, and has an L/D of 0.14. This aerobrake is the one used for the assembly analysis of the previously described modified MMC LTV.¹⁷ All docking mechanisms, attitude control thrusters, propellant tanks, and avionics are pre-integrated into the aerobrake prior to launch. Following electro-mechanical self-deployment of its side wings, a pressure decay leak check between joint seals is performed to verify joint integrity. The deployment and checkout flow of 23 hours (3 shifts) for this aerobrake is shown in Figure 16.

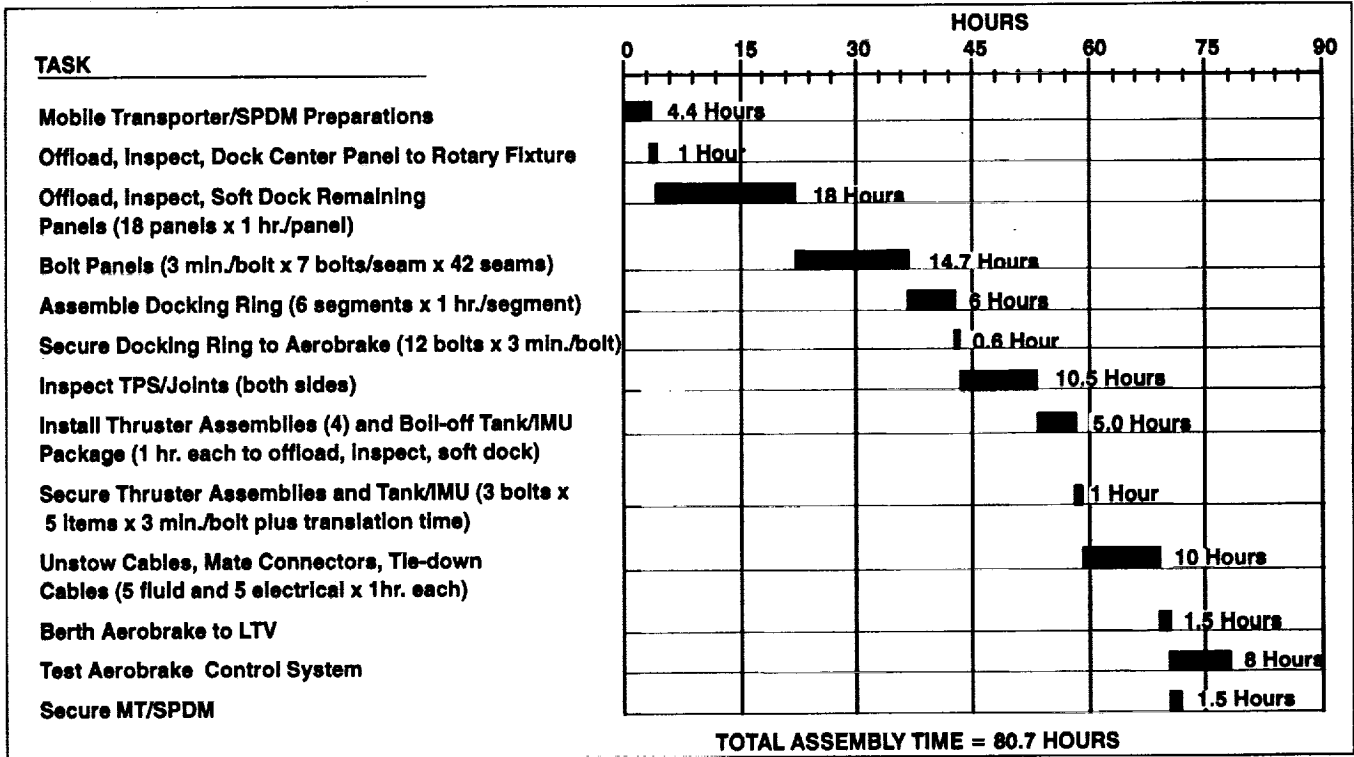


Figure 14 Assembly Timeline for Hex-Panel Aerobrake

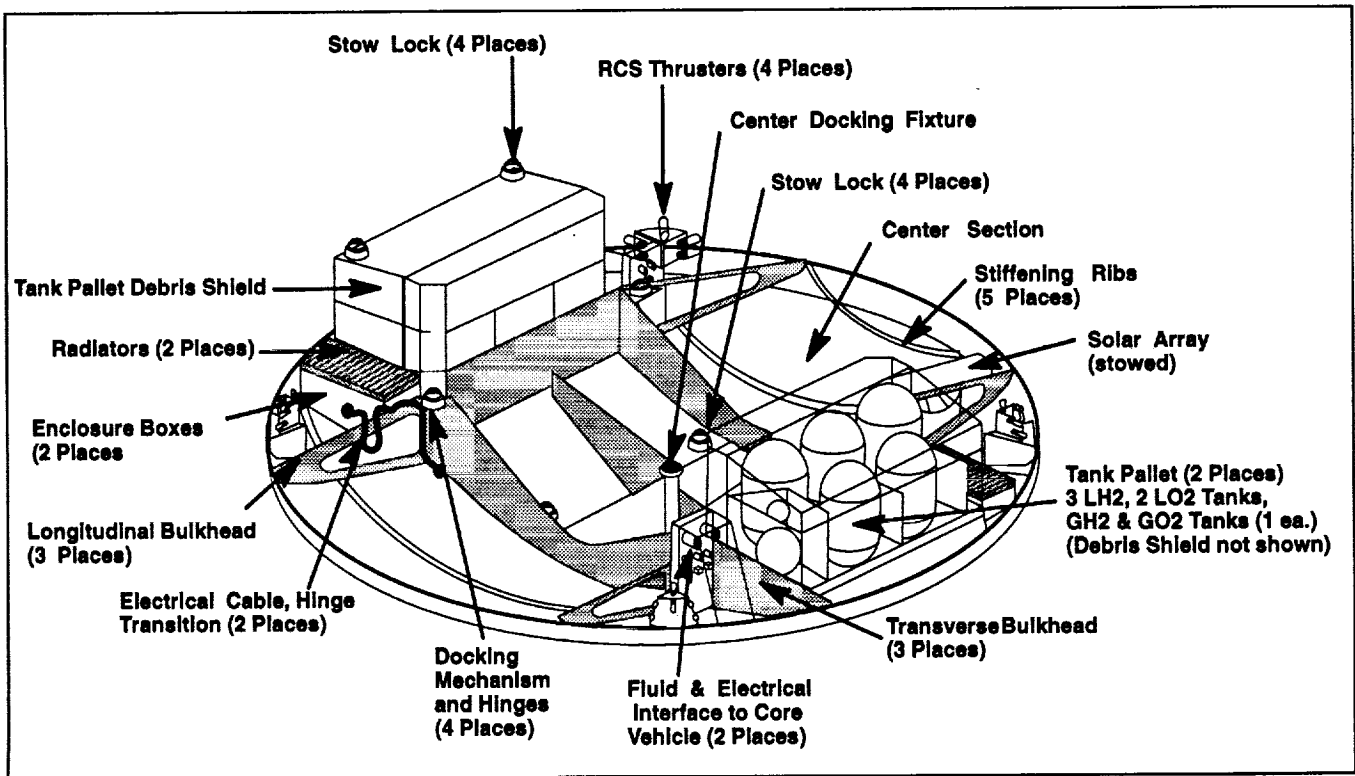


Figure 15 MMC 3-panel Aerobrake Configuration

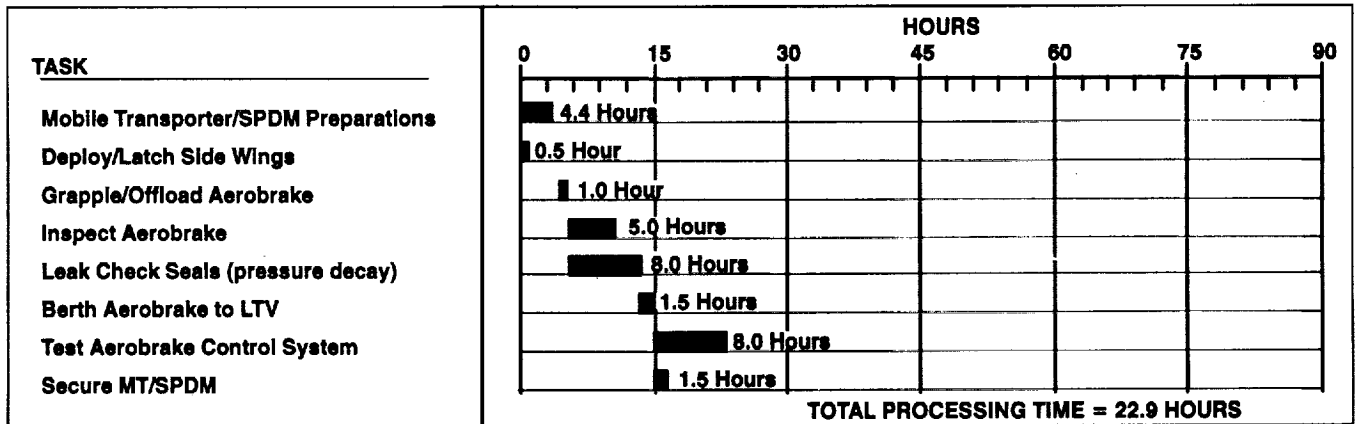


Figure 16 Processing Timeline for 3-piece Aerobrake

These two examples of aerobrake LEO processing, along with the EVA/telebotanic co-operative assembly of the Option 5 LTV eight petal aerobrake demonstrated with a neutral buoyancy simulation,¹⁸ indicate that on-orbit assembly of aerobrakes can be accomplished in a timely manner, and should be considered as an option for the Space Exploration Initiative. Large diameter ETO launch vehicle shrouds currently being considered for SEI will permit lunar aerobrakes in the 50 foot diameter class to be launched fully ready for flight.

Mars Mission Hardware Assembly Operations

On-orbit assembly analyses were performed for nuclear thermal propulsion (NTP) Mars transfer vehicles (MTVs) manifested on both 200-ton and 150-ton HLLVs. The application of aerobraking at Mars orbit aerocapture, Mars entry, and Earth return are also addressed.

Mars Transfer Vehicle Assembly

The MSFC/Boeing NTP Mars transfer vehicle, shown in Figure 17, was analyzed for on-orbit assembly.¹⁹ The forward core vehicle consists of the crew habitat module, along

with attitude control, power (solar arrays), thermal control, communications, and avionics systems. Attached to the habitat module is the crew return vehicle (CRV) used for direct entry upon Earth return. Connecting the forward core vehicle to the aft core propellant tank and twin nuclear engines is a strongback structure consisting of three conical trusses, which are nested together for ETO launch, and then separated, flipped, and mated together on orbit. Three additional drop-tanks filled with liquid hydrogen are mated to the truss structure and twin 12-inch propellant feedlines are connected between the drop tank manifold and the aft nuclear propulsion system. Remotely mated umbilicals on carrier plates were substituted for the Boeing baselined Marmon clamps (which would be difficult for a robot to install). A high L/D Mars excursion vehicle (HMEV) is docked directly to the crew habitat module, and contains the pre-integrated Mars surface habitat and science payloads. These MTV components are manifested on five 200-ton HLLVs. The HMEV is manifested to be launched on the side of an HLLV as shown in Figure 18. The MTV is 101 meters in length and total mass prior to Earth departure is 817 tons.

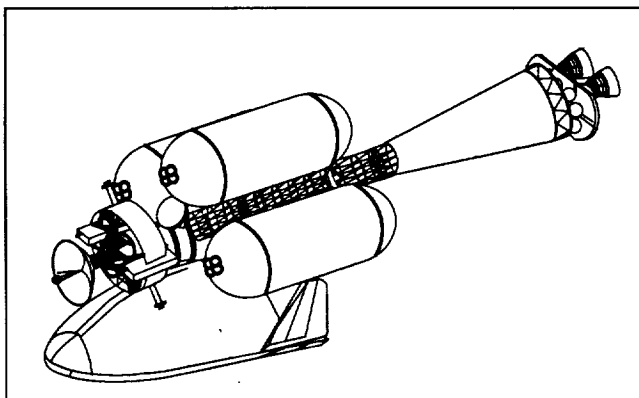


Figure 17 Boeing Mars Transfer Vehicle Configuration

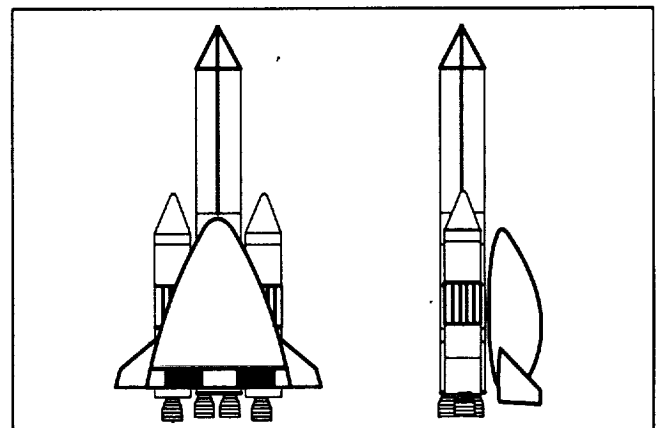


Figure 18 Boeing Concept for Launching Assembled Mars Entry Vehicle

The telerobotic on-orbit processing flow of 43 shifts for assembly of this MTV is shown in Figure 19. As with the LTV assembly flows previously discussed, the interval between ETO launches is longer than the time required to assemble the MTV components being brought up by each HLLV. A minimum assembly node, which can provide attitude control and electrical power, and serve as a platform for a manipulator arm (with a dextrous end effector) and debris shield stor-

age, is baselined for this analysis. Possible node concepts that could accommodate MTV assembly are discussed in a following section on LEO Node Infrastructure. If the "self-build" or "free-flyer" concept is selected, additional tasks and time must be added to the processing flow for top-off of expended MTV consumables. Mandating that the propulsion system nuclear reactors be launched cold (no prior run

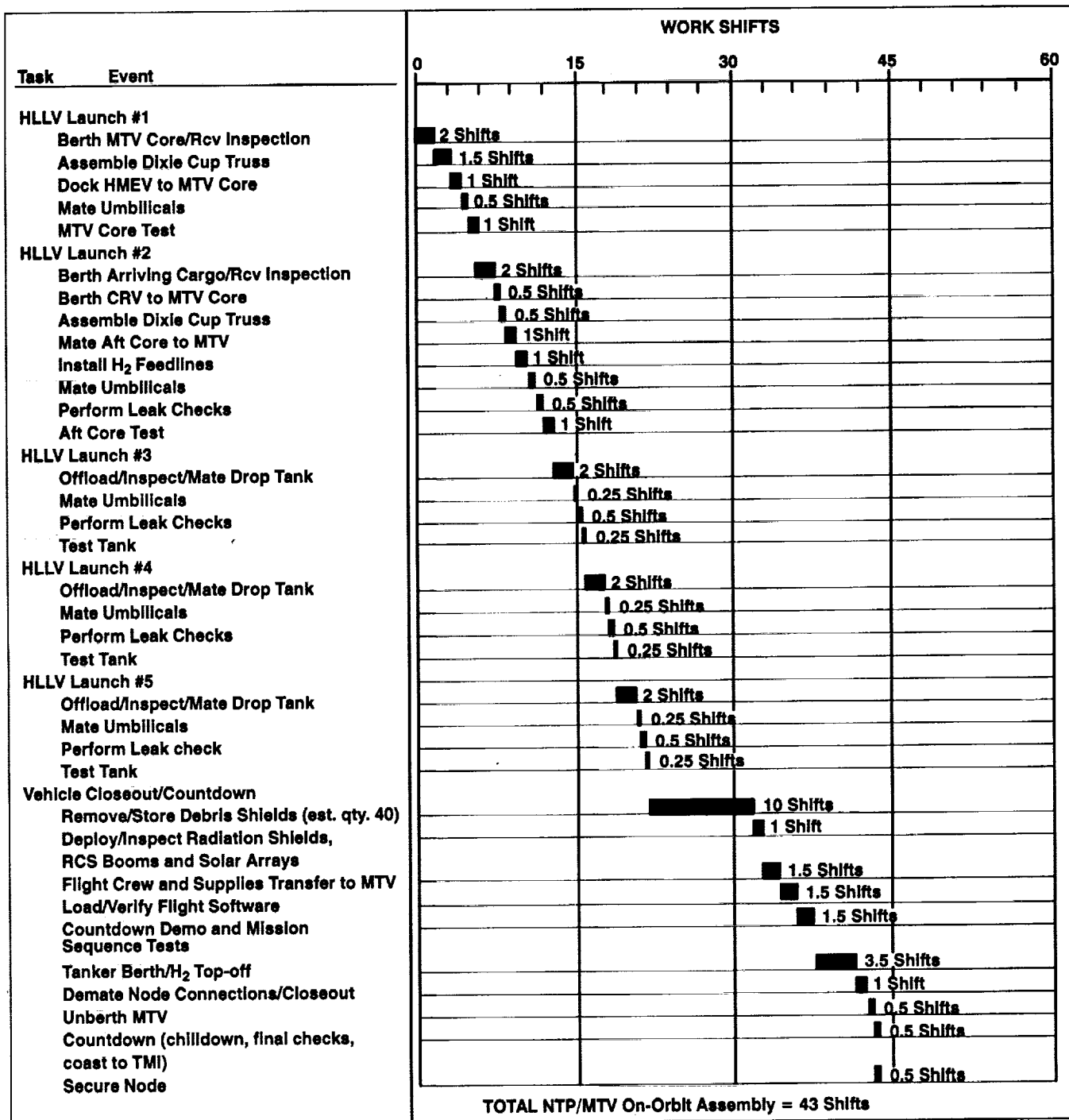


Figure 19 Assembly Timeline for Mars Transfer Vehicle

time) eliminates build-up of fission products and associated radiation hazards.

Manifesting a similar piloted MTV, shown earlier in Figure 4, on a smaller 150 ton HLLV would require seven ETO launches.¹³ Additional propellant tanks, debris shields, and aerobrake deployment and checkout operations would add 18 shifts to the on-orbit processing flow for the 200-ton HLLV-manifested MTV.

Mars Mission Aerobrake Applications

The utilization of aerobrakes (any vehicle element which uses aerodynamic forces for velocity reduction) for several phases of the Mars mission can result in significant vehicle LEO mass reductions. These phases are capture into Mars orbit after transit from Earth, entry to the Mars surface from Mars orbit, and capture into Earth orbit or direct Earth entry after transit from Mars. Preliminary studies indicate that aerobrake diameters of about 100 feet will be required for Mars orbit aerocapture and about 50 feet for Mars entry and Earth aerocapture return. Delivery of such large, fully assembled aerobrakes to Earth orbit could require an approach such as that illustrated in Figure 18 or a very large HLLV shroud. Alternatively, an assembly approach as illustrated in Figure 13, or a deployable approach, as illustrated in Figures 15 and 20, would be required. Figure 21 is a recent MSFC folding concept for the Mars entry aerobrake where heating rates and loads are relatively lower than for Mars/Earth aerocapture or Earth entry. The assembly approach of Figure 13 would obviously require the most on-orbit supporting infrastructure. The deployable approach for Figure 20 essentially eliminates assembly, but would require many

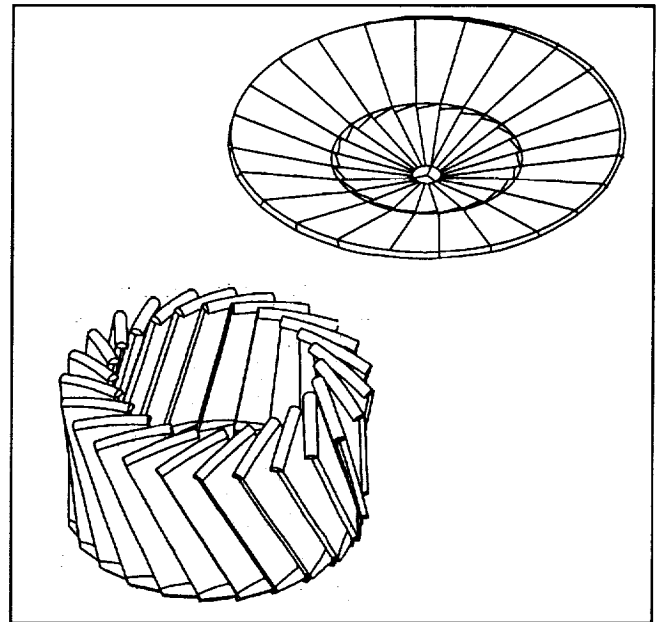


Figure 21 Boeing Umbrella Aerobrake Configuration

of the typical on-orbit functions i.e., inspection etc. Likewise, the umbrella approach of Figure 21 also essentially eliminates assembly but would require other on-orbit functions.

No one aerobrake size or structural concept will suffice for all potential lunar and Mars mission applications. Viable aerobrake concepts have been developed for each potential application. A significant consideration for each concept is to optimize, within practical limits, the combination of aerobrake packaging for delivery to Earth orbit and the required on-orbit operations.

LEO Assembly Node Infrastructure

Recent studies have begun to indicate those mission scenarios which will likely need an orbital supporting infrastructure. Whether any supporting infrastructure for any mission is required depends heavily on the size and design of the space transfer vehicle and the number of launches from the Earth required to deliver the vehicle elements to low earth orbit. Based on current SEI architecture concepts and today's launch vehicles, either a lunar or a Mars transfer vehicle would require multiple launches to LEO and would require some degree of on-orbit support to assemble and checkout the vehicles. While HLLVs possessing the required lifting and volume capabilities may become available to permit single launch lunar missions, HLLVs with similar capabilities for a Mars mission are extremely unlikely. Thus, it can be stated with assurance that Mars vehicle assembly will require a degree of on-orbit support. This eventual need for a Mars mission LEO infrastructure should be considered when selecting lunar mission approaches.

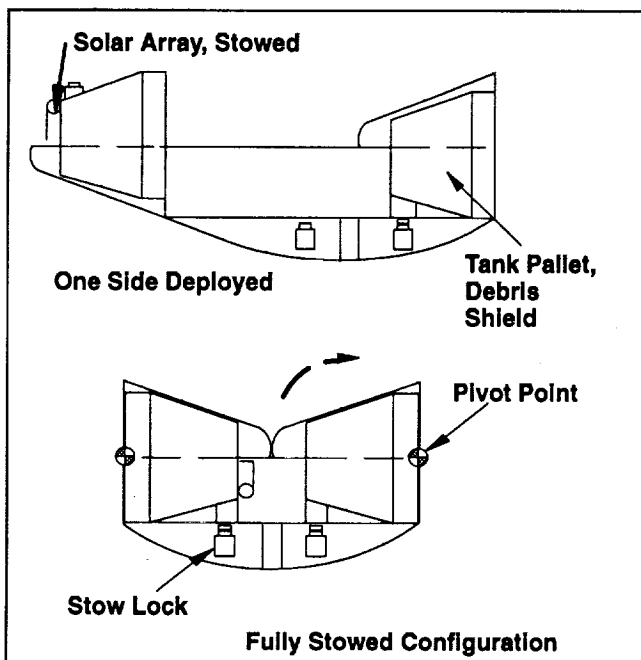


Figure 20 Three-piece Aerobrake Folding Geometry

Studies such as this have been undertaken and require further effort before an appropriate approach for a particular mission or a class of missions is identified. The high costs associated with on-orbit supporting infrastructure will force careful justification of such a mission element. The on-orbit supporting elements will likely be selected only if they are an enabling element that has no practical substitute in space transfer vehicle design or launch vehicle capability.

References 12 and 20 are two of the recent studies about the on-orbit support functions to be provided by the on-orbit infrastructure. Reference 21 is a preliminary look at the technologies requiring advancement if these functions are to be provided. Not all these functions or technologies would be required in a first mission, but are thought to be needed by the time repetitive Mars missions and a permanent lunar base are being implemented. Early lunar missions may be single-launch, or at least dual-launch rendezvous/capture missions, and will probably each be self-sufficient and independent of any on-orbit support.

The break point for requiring on-orbit support and infrastructure appears to occur when the space transfer vehicle requires more than two launches, requires fueling operations, requires robotic or EVA assembly, or involves refurbishment operations prior to a next mission. Several on-orbit support-

ing infrastructure concepts have been studied, ranging from an evolved Space Station Freedom to a smaller free-flying assembly node to self-contained robotic arms on the vehicle being assembled.

Figure 22 is an early concept of how Space Station Freedom might evolve to accommodate assembly, checkout, and refurbishment of lunar and Mars vehicles. Recent studies seem to indicate that the large size of the current Mars vehicle concepts are not compatible with the current Space Station Freedom resources available. Figure 23 is a concept for an assembly/servicing facility for processing lunar transfer vehicles, and would be located on a lower keel truss of the evolved station.²² Reference 23 indicates that many Space Station Freedom elements may be usable as SEI vehicle elements.

Figure 24 shows a man-tended orbital node for Mars vehicle assembly. Depending upon launch vehicle size, as many as five (250mt) to seven (150mt) HLLV launches could be required to deliver all vehicle elements to Earth orbit. Besides assembling and checking out the vehicle, its elements must be protected from orbital debris for the assembly duration. A minimum of 30 days between launches is expected. Man-tended implies that the crew is sheltered elsewhere, perhaps at Space Station Freedom, during the assembly and check-

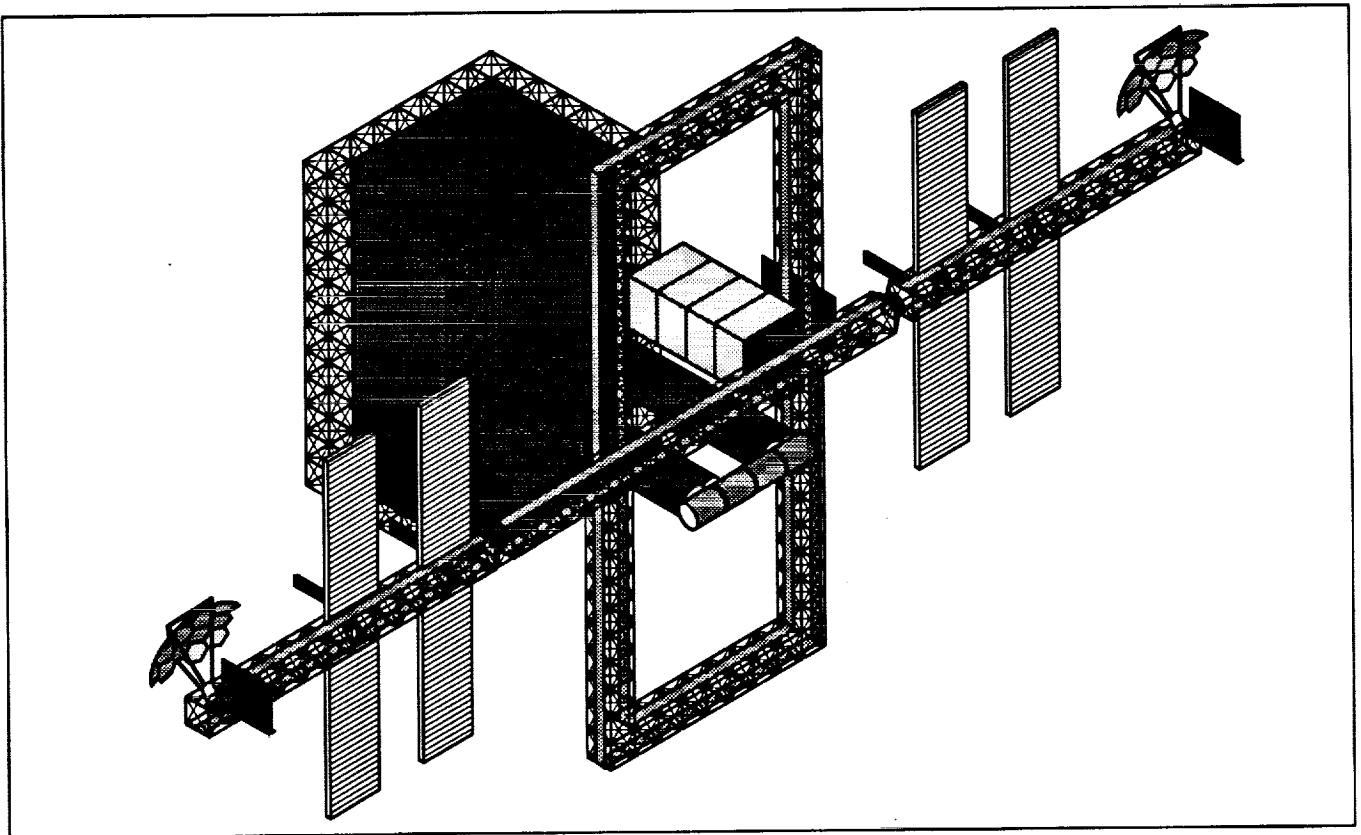


Figure 22 Space Station Evolution Concept for Mars Mission Accommodation

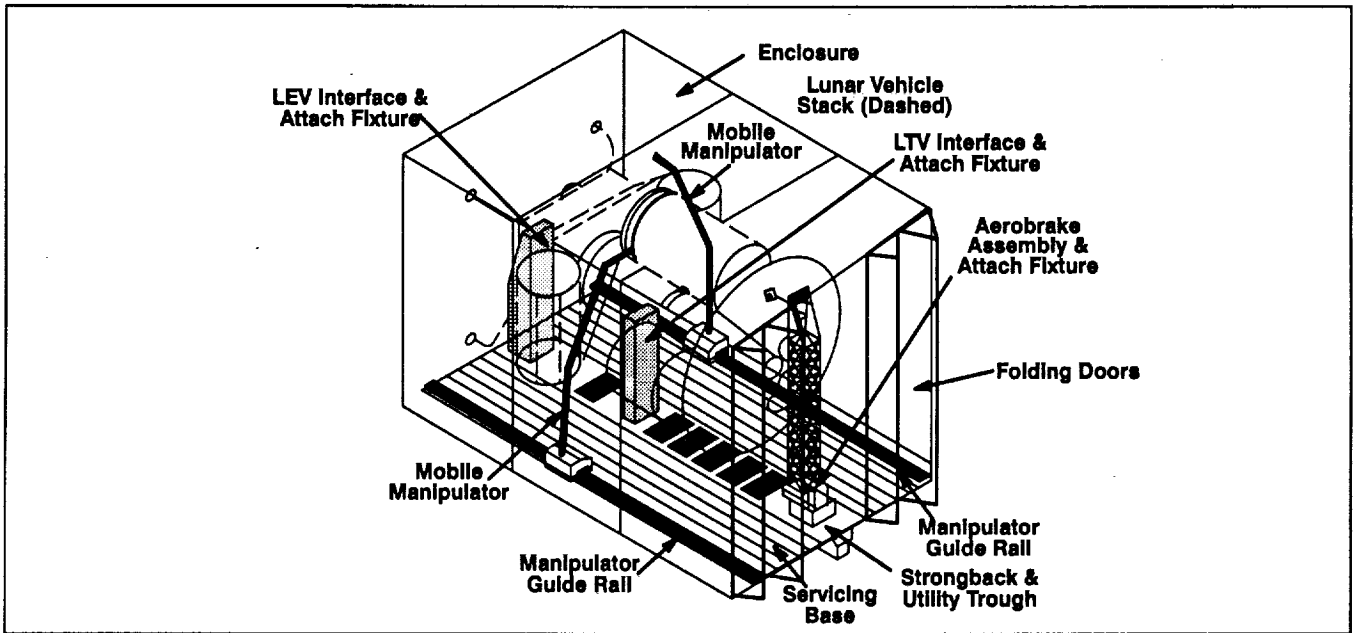


Figure 23 Space Station Hangar Concept for Lunar Vehicle Processing

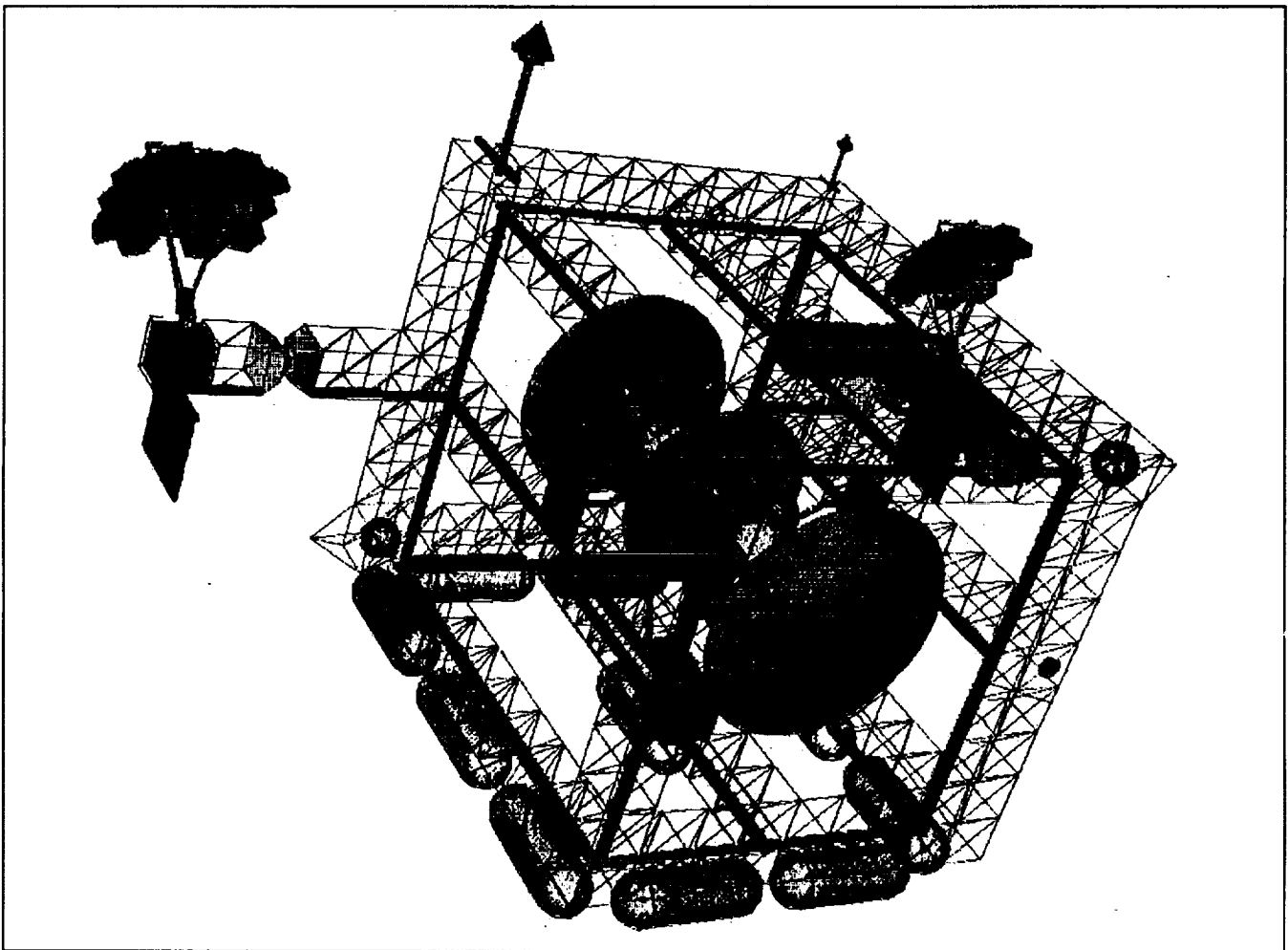


Figure 24 Concept of LEO Node for Vehicle Assembly

out period. While the man-tended approach may be intended to reduce cost, it will require a crew transportation vehicle to move between nodes. Such a man-tended node may or may not contain fueling tanks, depending upon safety demands. Figure 25 is an early concept for a fueling depot node. Safety considerations and vehicle design will determine if such an independent node is appropriate. If so, crew transport is again required. Figure 26 is a more recent Boeing concept for Mars vehicle assembly. It would be man-tended and specific to the processing scenario for a Mars transfer vehicle.

A final recent concept for supporting on-orbit operations has been developed by Boeing and involves a robotic crawler with arms able to effect self-assembly through berthing and other robotic operations. While astronaut involvement on-orbit is minimized, there would be mass inefficiencies in the vehicle required to support the robotic hardware. Additional time, logistics, and cost to replenish vehicle consumables will be required if the vehicle must serve as its own assembly node. Also, provision for orbital debris shielding offers another complexity and inefficiency, unless the shields are left in Earth orbit. If such hardware is left in LEO and not used for subsequent missions, disposal in a safe manner is required.

Requirements for the LEO supporting infrastructure can only be generalized at present, and is not required for some mission concepts. More mature launch and space transfer vehicle concepts will permit further definition of these re-

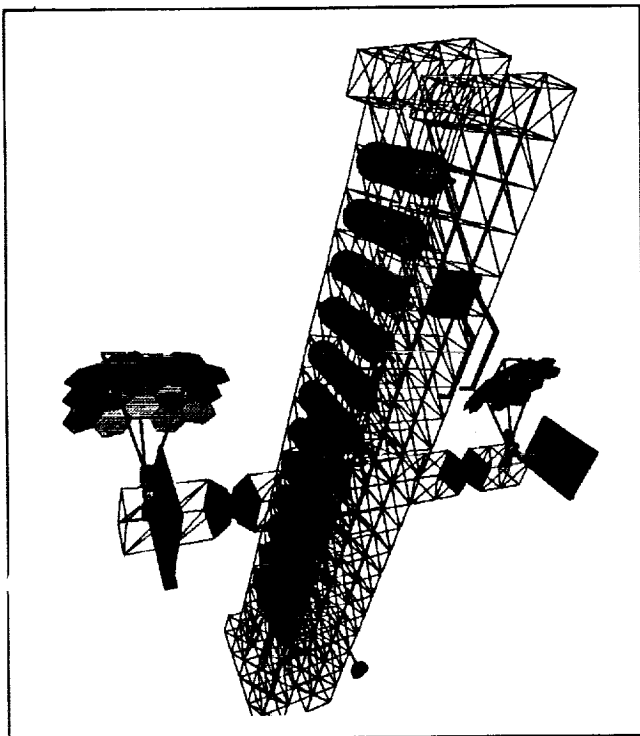


Figure 25 Concept of LEO Fuel Depot

quirements. Mars vehicle assembly and the reusable-hardware mission scenarios will require a supporting on-orbit infrastructure.

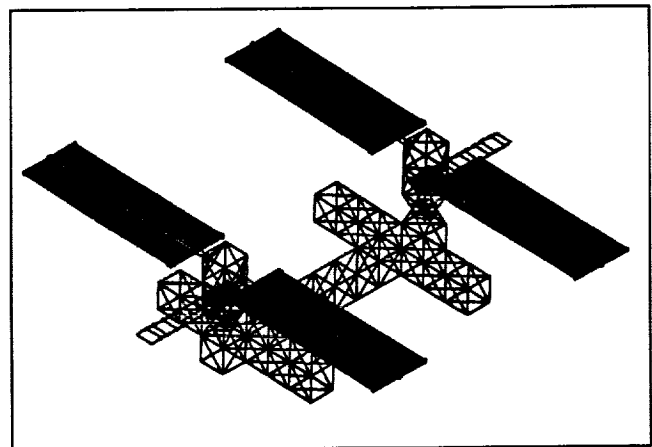


Figure 26 Concept of Minimal LEO Node for Mars Vehicle Assembly

Design Recommendations and Technologies

The design recommendations and technology needs listed in Tables 3 and 4 are applicable to any manned or unmanned space vehicle which utilizes on-orbit processing operations. They have been selected for the high leverage they will provide in reducing the the most labor intensive tasks identified from vehicle processing analogies at KSC.

A prime example of these savings is the elimination of 16 shifts of EVA required to intrusively inspect LTV main engine turbopumps with borescopes, by incorporating built-in engine plume analysis sensors for detection of turbopump blade and bearing-wear long before failure. Other propulsion recommendations include using electromechanical actuators for engine gimbaling, thus eliminating the need for complex, service-intensive hydraulic systems. To minimize the risk of on-orbit propellant leaks, which may be difficult to isolate and repair, propellant systems should be integrated on the ground as complete stages whenever possible. Use of expendable propellant drop tanks for reusable vehicles presents a significant risk to mission reliability due to the repeated disturbances of critical cryogenic connections. Propellant resupply using fluid transfer from tankers or a propellant depot will reduce opportunities for leaks, thus increasing mission reliability.²⁴ The need for redundant seals on all fluid system components is evidenced by the hydrogen leaks that grounded the Space Shuttle fleet in 1990 due to single seals on valve shafts.

Attachment recommendations include autonomous electrical and fluid umbilical connections (using a structurally mated carrier plate), which would eliminate many EVA hours for this recurring task. Orbital replacement units (ORUs) need to be of a "snap-in" modular design with self-

Table 3 Vehicle Design Recommendations

<p>GENERIC</p> <ul style="list-style-type: none"> ■ Design serviceable hardware for ease of EVA/ telerobotic access, including sufficient spacing between parts ■ Design for automation with self-aligning mating components, partial-turn connectors, and pre-defined visual cues ■ Include integrated grapple fixtures on all manipulated elements ■ Design to allow on-orbit disassembly to facilitate repair or recovery for assembly problems ■ Provide EVA backup capability for all telerobotic tasks ■ Minimize number of parts to be handled/assembled 	<p>PROPULSION</p> <ul style="list-style-type: none"> ■ Integrate propellant tanks, engines, and manifolds on ground whenever possible ■ Develop engines not requiring intrusive inspection and servicing ■ Utilize electromechanical actuators for engine gimbaling ■ Utilize propellant transfer from tanker/depot for reusable vehicles ■ Utilize redundant seals on all fluid joints
<p>ATTACHMENT</p> <ul style="list-style-type: none"> ■ Provide automated umbilical mate/demate with auto-verification of interface ■ Provide "snap-in" mounting of ORUs ■ Avoid threaded fasteners 	<p>CREW MODULE</p> <ul style="list-style-type: none"> ■ Skylab type waste management unit ■ Berth transfer vehicle directly to pressurized node for servicing

mating connections. Threaded fasteners for on-orbit use should be avoided since galled threads on fasteners have been a very common problem on flight hardware at KSC. Captive, partial-turn fasteners will facilitate both EVA and telerobotic connection tasks.

Crew module refurbishment recommendations begin with a "Skylab" type of commode (utilizing fecal bags) to eliminate the lengthy refurbishment required for a "Shuttle" type waste management facility. The labor intensive refurbish-

ment of the crew module between missions requires IVA access from pressurized modules in order to eliminate what would otherwise be excessive EVA transfers. Coupled to this is the desire to leave the crew module attached to the LTV core vehicle to eliminate the reconnection and verification tasks. It is therefore recommended that a returning transfer vehicle be berthed directly to a pressurized node. Use of a pressurized transfer tunnel (similar to an airport jetway) is an alternative if the vehicle must be berthed in a remote facility (such as a hanger on the SSF lower keel).

Table 4 Needed Technologies for On-Orbit Vehicle Processing

<ul style="list-style-type: none"> ■ Robotics <ul style="list-style-type: none"> □ Dexterous end effectors □ Automated umbilicals ■ Artificial Intelligence/Expert Systems <ul style="list-style-type: none"> □ Inspection □ Diagnostic checkout ■ Vehicle Health Management <ul style="list-style-type: none"> □ BIT capable of fault detection/isolation to ORU level ■ Zero-Gravity Cryogenic Fluid Management <ul style="list-style-type: none"> □ Transfer □ Long term storage □ Leak detection/isolation ■ Advanced Power Components <ul style="list-style-type: none"> □ Fuel cells □ Batteries
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Generic design guidelines will enable and enhance both EVA and telerobotic accomplishment of tasks and ensure that recovery from problems is possible. Access to hardware requiring servicing or change-out, without having to first remove other hardware, has been a major design problem on current flight vehicles. Whenever telerobotics and automation are used to replace EVA for accomplishment of manual tasks, EVA back-up capability must be maintained for contingencies.

The advanced technologies needed to implement these vehicle design recommendations are listed in Table 4. Robotic technologies, such as dexterous end effectors and automated umbilicals, will eliminate much of the needed EVA. Expert systems using artificial intelligence for inspection and diagnostic testing will permit significant reduction in astronaut IVA hours for vehicle processing. Inspection is a repetitive task which can be automated with "before and after" image comparison techniques to detect anomalous conditions. Vehicle health management (VHM) with "built-in test" (BIT)

equipment (sensors and software) could provide fault isolation capability to the ORU level and greatly reduce the amount of orbital support equipment needed. VHM should also provide automated verification of continuity across all pins when umbilicals are mated. Finally, VHM could perform system and component trend analysis, thus eliminating unnecessary retest of healthy components.

Zero-gravity transfer and long term storage of cryogenic fluids is required, along with leak detection and isolation techniques. Advanced fuel cells and batteries could greatly reduce the extensive conditioning and monitoring that current components require.

Current programs such as Space Shuttle and Space Station Freedom started out down the path of reduced operations and life cycle costs. As budget realities set in, development and application of advanced technologies were cut, with the resulting impact of increased operations and costs downstream. If advanced technologies are not mandated for SEI flight vehicles, on-orbit processing can still be accomplished using EVA and SSF-era telerobotics. However, the magnitude and complexity of labor-intensive tasks will greatly increase, with resulting negative impacts to on-orbit infrastructure requirements and costs. It should also be noted that incorporation of these advanced technologies into vehicle designs not only facilitates on-orbit processing operations, but should also reduce the complexity and time required for ground checkout at the launch site. Additional rationale, along with readiness levels for these and other technologies applicable to on-orbit vehicle processing operations, are discussed in Reference 21.

Concluding Remarks

All studies to date indicate that Mars transfer vehicle assembly will require some degree of on-orbit support. On-orbit support for lunar vehicles may be needed, depending on the mission scenario and ETO launcher selected. Any scenario involving more than two ETO launches per transfer vehicle, fueling operations, robotic or EVA assembly, or refurbishment operations prior to a next mission, will likely require a LEO supporting infrastructure.

Any on-orbit supporting infrastructure required for LEO vehicle processing operations is determined by the complexity and amount of on-orbit assembly and servicing operations, which in turn is dictated by the design of the flight vehicle hardware elements.

On-orbit supporting infrastructure elements will be used only if they are enabling elements that have no practical substitutes in space transfer vehicle design or launch vehicle capability.

The on-orbit processing operations required to prepare any large space transfer vehicle for its initial mission are the

same regardless of ETO launcher size. However, the number of repetitions of those tasks is a function of the ETO launch vehicle size. Refurbishment of reusable manned vehicles increases the quantity and complexity of tasks.

The time interval between HLLV ETO launches is longer than the time required to initially process (either manually or telerobotically) the vehicle components being brought up by each HLLV.

On-orbit assembly of aerobrakes can be accomplished in a timely manner and should be considered as an option for the Space Exploration Initiative. Deployable aerobrakes eliminate assembly, therefore reducing on-orbit operations and supporting LEO infrastructure requirements.

Space transfer vehicles must allow simple and adequate access to all serviceable hardware without having to remove and replace (and retest) other hardware in the way.

On-orbit vehicle processing can be accomplished with current technologies and practices, but incorporation of advanced technologies into space transfer vehicle designs will greatly reduce the complexity and magnitude of labor-intensive tasks.

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