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Lunar Vehicle Assembly and Processing on Space Station Freedom

by

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Abstract

Space Station Freedom has been designed with the capability to evolve in functionality and size. A likely direction for Freedom evolution will be toward the establishment of a Low Earth Orbit (LEO) transportation node for solar system exploration vehicles. The Human Exploration Initiative proposed by President Bush in July of 1989 takes advantage of Freedom's evolutionary nature by utilizing Freedom's on orbit resources for the assembly, check-out and refurbishment of lunar and Mars transfer vehicles. This paper discusses a concept for accommodating lunar vehicles on Space Station Freedom. Lunar vehicle processing requirements and their associated impacts on Freedom are evaluated with respect to need for additional crew, EVA, power and thermal rejection capability. A preliminary definition of a lunar vehicle processing facility is described and an assessment is made of support equipment required in the facility to accomplish the processing tasks. Additional resource requirements coupled with the need for new structure and the lunar vehicle processing facility, induce a major change in the physical characteristics of Freedom. Mass properties, microgravity environment, flight attitude, controllability and reboost fuel requirements are all evaluated to assess the impact on Freedom of accommodating the massive lunar transportation vehicles. The results of the above analysis indicate that Freedom can evolve into a highly capable lunar transportation node with respect to accommodating the assembly of vehicles, fuel tanks and aerobrakes, the check-out and validation of the assembled vehicles and their associated subsystems, and the refurbishment of these same vehicles after a mission has been completed.

Introduction

In response to the President's call for a Human Exploration Initiative (HEI), NASA Administrator Richard H. Truly created a task force to conduct a 90 day study investigating the objectives, strategies, schedules and technologies associated with exploring the Moon and Mars. Five reference approaches were developed with the common theme centered on building and utilizing Space Station Freedom, returning man to the Moon and then proceeding to Mars. These approaches require the use of robotic probes, heavy lift launch vehicles (HLVs), space based transfer vehicles and extraterrestrial habitats and support systems. The Langley Research Center (LaRC) Space Station Freedom Office (SSFO) was tasked with assessing HEI impacts on Freedom configuration evolution with respect to HEI related research and development and with the use of Freedom as a low Earth orbit (LEO) transportation node for space transfer vehicle (STV) assembly, check-out and refurbishment. All five reference approaches studied use Freedom as an in space laboratory for testing lunar vehicle and lunar base subsystem technology. During this time, Freedom is configured to support the verification flight of the first lunar transfer vehicle (LTV) / lunar excursion vehicle (LEV) stack. Freedom is then configured to support expendable lunar vehicles, then reusable lunar vehicles and finally reusable Mars transfer vehicles (MTVs).

Space Station Accommodation of the Human Exploration Initiative

Freedom's initial and on-going research during the HEI will deal with long-term microgravity countermeasures, closed life support systems and life sciences. The baseline assembly complete Freedom configuration generates 75 kilowatts of power, contains one pressurized habitation module that houses a crew of eight, and three pressurized laboratory modules. In order to accommodate research requirements and transportation node functionality, Freedom must be designed to evolve so that pressurized volume, structure, resources and specialized facilities can be added without causing a significant disturbance to the existing configuration environment. During the 90 day study, LaRC defined four distinct space station configuration milestones beyond the initial assembly complete configuration through which Freedom would have to evolve.(Figure 1)

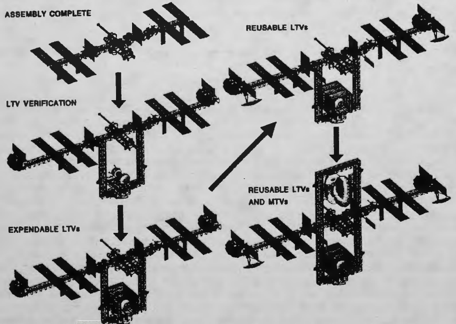


Figure 1: Space Station Configurations for HEI

The main driver growth element for the first three transportation node configurations is the facility used for assembling and processing the lunar vehicles called the Assembly/Servicing Facility (ASF). The ASF is sized to enclose an LTV, LEV and one aerobrake resulting in a large 30x20x20 meter rectangular hangar facility that must be located away from the transverse boom for clearance and symmetry reasons. Two 11 truss bay lower keels and a nine truss bay lower boom are added so that the ASF can be placed on top of the lower boom (Figure 2). This location allows proper clearance between the top of the ASF and a berthed orbiter and aligns the ASF with the configuration centerline. An argument can be made for shortening the keels by four truss bays on each side and locating the ASF on the bottom of the lower boom, but the space for Earth viewing payloads would be greatly reduced. The ASF functionality and hardware will be discussed in more detail later in this paper.

Freedom's first evolution milestone must accommodate and support the lunar vehicle verification flight which will deliver a small amount of cargo to the lunar surface. A substantial amount of EVA is required to build the lower keels and boom, run utilities, relocate RCS pods and assemble the ASF resulting in the need for a second airlock equipped with advanced 8 psi space suits to replace Freedom's limited shuttle type suits. The need for on station debris protection for the lunar verification vehicles was determined to be small at the start of the initiative so only the service track assembly portion of the ASF is included at the first evolution milestone. The service track assembly is the structure that supports the lunar vehicle mounting fixtures, remote manipulators and all other mechanisms and resources housed inside the ASF enclosure. Heavy

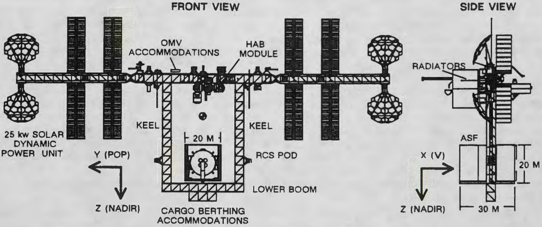


Figure 2: Reusable Lunar Vehicle Transportation Node

lift launch vehicles (HLLV) will be used to transport lunar vehicles and cargo to Freedom requiring automated docking using a station based orbital maneuver vehicle (OMV) and a cargo berthing fixture located near the service track assembly. Processing of the lunar vehicles will require two additional crew members and an associated 25 kw increase in power requirements. Two 25 kw solar dynamic power units will be mounted on six bay truss extensions on each side of the transverse boom resulting in a total of 125kw power generation capability for Freedom. Additional thermal rejection capability is also added commensurate with the power increase.

The next evolution milestone for Freedom involves additions for accommodating expendable lunar vehicles. At this phase, another habitat module is added to the port side of Freedom's module pattern to house two additional crew members required for preflight operations and to provide accommodations for future transient lunar mission crews. Two extended resource nodes (one meter longer than the baseline node) are also added so that the new habitat module will have the proper spacing from the adjacent module. The ASF enclosure is constructed to provide debris protection.

Freedom's third evolution milestone accommodates the manned reusable lunar vehicles that will be journeying to and from the Moon for the following decade. Increases in station based research and vehicle processing requirements result in overall station power consumption exceeding 125 kw. Two more 25 kw solar dynamic units will be added to Freedom resulting in a total of 175 kw of power generation capability. Corresponding thermal rejection capability is also added.

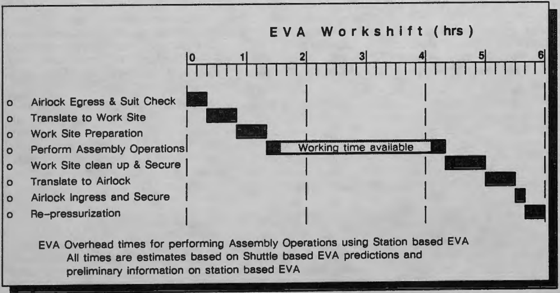
The fourth evolution milestone identified by LaRC during the 90 day study would support both lunar and Mars operations. Upper keels and an upper boom would be added to accommodate the large Mars vehicle and aerobrake with a service track assembly derived from the lunar ASF hardware. No enclosure would be provided since most of the Mars transfer vehicle's time in low Earth orbit is planned to be spent away from Freedom requiring the vehicle to have its own debris protection. A more thorough discussion of Freedom's evolution to accommodate the Mars aspect of the HEI can be found in reference [1].

Lunar Transportation Node Assembly and Checkout

The achievement of these evolution milestones will be dependent on the successful completion of the necessary station assembly operations. The operations required will include intra-vehicular activities (IVA), teleoperation of the remote manipulator systems, and extra-vehicular activity (EVA). Since the most time constrained resource needed for the assembly operations is likely to be EVA, some station assembly estimates have been made based on the necessary EVA times. The following assumptions have been used to obtain these estimates: All EVA excursions are limited to a duration of six hours per day maximum for the outer airlock hatch to be open. Current ground-rules for EVA limit duration to six hours outside, and require a rest day on the day after the EVA work day. EVA excursions must be performed by a minimum of a two man team outside, with a one man IVA support crewman. The four man assembly crew consists of; two EVA astronauts, one IVA astronaut for EVA support, and one IVA mobile servicing center (MSC) and remote manipulator system (RMS) operator. All assembly hardware and support equipment must be secured between EVA excursions to insure that Space Station Freedom is prepared for a reboost in the case that no additional EVA's can be scheduled before the next scheduled reboost. This may occur due to equipment failure or any number of other unexpected occurrences. The assembly scenario's are based on using station based EVA and the advanced eight PSI suits. The STS can not remain on orbit long enough to perform the tasks required in an efficient manner. Also, the STS suit cannot be used for these tasks since it requires very long pre-breathe cycles and can not be refurbished on-orbit. It is assumed that the materials, equipment, and supplies needed for any assembly task can be loaded onto the mobile transporter (MT) by the Space Station RMS without support of an EVA team, and that the MT can be at the work site before the EVA crew gets there. Possibility of automated assembly support by FTS is not factored into the timelines.

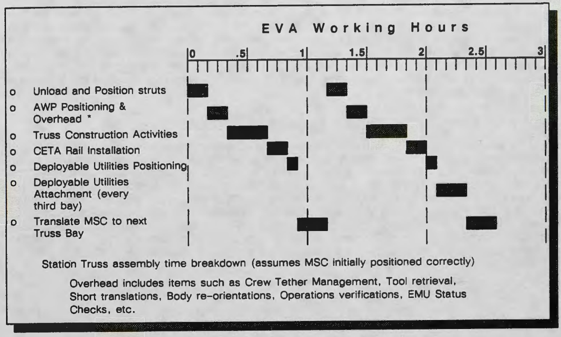
Typical EVA overhead operations will comprise a large part of the EVA processing time available for each session. These EVA overhead times, which are shown in Figure 3 are based on information found in the section titled Assembly EVA Task Menu of reference [5], and physical constraints of the Space Station such as MT translation times etc. Suit check consists of the dexterous manipulation of all suit joints while monitoring the suit sensors and indicators. Translate to work site and translate to airlock (from work site) is an average time to reach a destination anywhere on the completed Lunar Transportation Node. Translation will take less time to nearer locations, and longer to more remote locations. These times are based on a success oriented schedule, and do not include any allowance for potential problems that may arise during the EVA excursion.

As illustrated by Figure 4, and compared with the previous chart, the time required to assemble two truss bays with utilities and Crew Equipment and Translation Aids (CETA) Rail uses nearly all of the average time available to perform construction activities on one EVA excursion. This means that during the early phase of truss construction, when working near the transverse boom, three bays per day might be achieved due to short translation times to the work site, but as the translation times get longer the number of truss bays constructed per EVA will decrease to two. The overhead times shown are required times, and are conservative times. Deployable utilities positioning assumes that the utilities spool is mounted on the front of the MSC,



EVA Overhead times for performing Assembly Operations using Station based EVA
All times are estimates based on Shuttle based EVA predictions and preliminary information on station based EVA

Figure 3: Typical EVA Overhead Operations



Station Truss assembly time breakdown (assumes MSC initially positioned correctly)

Overhead includes items such as Crew Tether Management, Tool retrieval, Short translations, Body re-orientations, Operations verifications, EMU Status Checks, etc.

Figure 4: Typical Truss Assembly Operations

and reels out the utilities tray as the MSC translates to the next bay. Also, it is assumed that the next bay is inline. If the MT must turn before assembling the next truss bay, the time will be longer. Translation of the MSC to the next bay includes securing the assembly work platform (AWP), translating the MT bottom base to the truss bay just completed, and then translating the MT top base and MSC to the location of the next inline bay. If the next bay requires a turn, the time to translate to the next bay must be increased by about ten minutes.

Using the EVA timetable established above, Table 1 shows the estimated number of working days required to perform the assembly tasks. All working days may not require a full six hour EVA excursion, but tasks are arranged such that a logical stopping point can be reached by the time the 6 hour EVA limit is reached. During the construction of the lower keels and boom, it is assumed that the first six bays of each keel can be constructed at the rate of three bays per day, and that the rest will be constructed at the rate of two bays per day. RCS module relocation includes one day to dismount one RCS from the transverse boom and stow it on the MSC, then

LTV VERIFICATION CONFIGURATION

DESCRIPTION OF OPERATION	ESTIMATED TIME (DAYS FOR FOUR CREW)
ATTACH AND CHECKOUT AIRLOCK	2
MOUNT OMV & ACCOMMODATIONS	1
ASSEMBLE BOOM EXTENSIONS	4
INSTALL RADIATOR PANELS	12
BUILD LOWER KEELS AND BOOM	15
RELOCATE NADIR RCS MODULES	4
ASSEMBLE SD POWER UNITS	6
INSTALL FOUR APAEs	4
INSTALL LOWER BOOM CARGO BERTHING ACCOMMODATIONS	1
ASSEMBLE ASF SERVICE TRACK	6

EXPENDABLE LTV CONFIGURATION

DESCRIPTION OF OPERATION	ESTIMATED TIME (DAYS FOR FOUR CREW)
ATTACH EXTENDED RESOURCE NODE	1
ASSEMBLE ASF ENCLOSURE	2
ATTACH HABITATION MODULE	1
ATTACH EXTENDED RESOURCE NODE	1
ACTIVATE NEW MODULE & NODES	1

REUSABLE LTV CONFIGURATION

DESCRIPTION OF OPERATION	ESTIMATED TIME (DAYS FOR FOUR CREW)
ASSEMBLE SD POWER UNITS	6
INSTALL RADIATOR PANELS	6
INSTALL ONE APAE	1

Table 1: Construction Times for HEI Configurations

another day to install the RCS at its new location on the keel. It is assumed that the MT will be moved from the transverse boom location to the keel location during the time between the two EVA work shifts. It is assumed that the four APAE's are not to be mounted physically close to each other. If they are to be mounted on adjacent truss bays, or with one truss bay in between, it is possible that two APAE's may be mounted in one working day. The ASF enclosure is a deployable structure that will be positioned and attached at one end during one EVA work day; then it will deploy automatically before the next EVA work day which will be used to perform the remaining attachment operations.

Lunar Vehicle Processing Requirements

LTV processing on-orbit will consist of the initial assembly of the LTV aerobrake, mating of the aerobrake to the rest of the vehicle, and vehicle to aerobrake interface checkout prior to the LTV's first flight. For subsequent flights of the LTV, vehicle refurbishment operations will be performed. Processing operations for assembly and refurbishment of LTVs on-orbit will consist of the same kind of operations that must be performed on the ground at the Kennedy Space Center (KSC) to prepare current space vehicles for launch. Therefore, in performing an assessment of the on-orbit operations required to prepare a typical LTV for flight, a set of analogous ground operations were selected as a baseline for determining a preliminary set of processing requirements [4]. As an example of the operations that must be performed on-orbit, an LTV refurbishment flow is presented here.

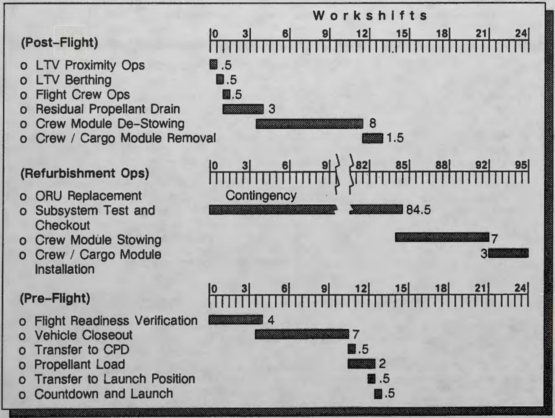


Figure 5: Lunar Refurbishment Processing Operations

Figure 5 lists the estimated times for refurbishing a typical LTV so that it can be re-used on another mission. The operations required have been divided into three main categories; Post-Flight operations, Refurbishment operations, and Pre-Flight operations. The Post-Flight operations consist of those operations that must be accomplished as soon as possible after the

LTV returns from its mission. The LTV proximity operations. and berthing comprise the steps needed to perform the rendezvous and docking of the LTV with Space Station Freedom. The flight crew operations are those activities needed to safe the vehicle and allow the crew to disembark. The residual propellant that was not needed for the mission is drained from the vehicle to insure crew and vehicle safety during the remainder of the refurbishment operations. Perishable supplies, scientific results obtained during the mission, and waste will then be removed from the crew module, and finally the Crew module will be removed for refurbishment and cargo will be off-loaded for return to earth. The Refurbishment Operations category contains those operations that must be performed on the LTV to prepare it for the next mission. These include the replacement of any Orbital Replaceable Units (ORU) that may have failed during the previous flight or been identified as marginal during the post-flight self-diagnostic health check of LTV systems. The next step is to perform test and checkout of all the vehicle subsystems. The Subsystems have been identified as: aerobrake, propulsion, power, thermal, avionics, and crew module. The crew module consumables and scientific experiments will then be stowed and the crew module and cargo will be installed on the LTV. The last category in our example, Pre-Flight Operations, is applicable to both the first flight after initial assembly, and subsequent flights after refurbishment. Pre-Flight Operations consist of those operations that must be performed as near to the launch of the LTV on its mission as feasible. The Flight Readiness Verification includes; the flight software load, the vehicle end-to-end test, the countdown demonstration test, the flight simulation test, and the cargo integration test. Vehicle Closeout consists of the operations needed to bring all of the LTV systems to flight readiness, perform final inspections, and allow crew ingress to the vehicle. If on-station cryogenic propellant loading is deemed unacceptable, the LTV would then be transferred to a co-orbiting cryogenic propellant depot (CPD) for loading of its liquid hydrogen fuel and liquid oxygen reactant. After propellant load is complete, the LTV is transferred to the launch position by an advanced OMV for the final countdown and launch to the Moon.

Assembly/Servicing Facility Hardware Description

The ASF is the core of the lunar transportation node with respect to lunar vehicle assembly, check-out, servicing and refurbishment. The lunar vehicle stack for which the ASF is sized, consists of an LEV, LTV, an associated aerobrake and fuel tanks. The ASF provides debris protection for the vehicles and EVA crew members through the use of a retractable enclosure. The lunar vehicles are supported and serviced on the ASF service track assembly (STA) that contains vehicle interface and assembly fixtures as well as storage areas and guide rails for mobile manipulators. Two mobile manipulators are included in the ASF so that all of the vehicle's orbital replaceable units (ORU) can be accessed for servicing and replacement. Figure 6 shows the ASF with vehicles and Table 2 lists the masses of ASF elements.

The ASF enclosure is a 30x20x20 meter rectangular shield that can be retracted along the service track assembly when clear access is needed for manipulator arm hand-offs or vehicle departure. The front wall is a garage-type door that opens for enclosure retraction and small cargo transfers. The enclosure has 2400 square meters of debris protection shielding made out of aluminum alloy and multi-layer insulation (MLI). The protection consists of a main wall of 1.6 mm alloy and a bumper wall of 0.4 mm alloy separated by a 3 cm gap filled with MLI. The protection provided is almost as good as that provided by the shields on the Freedom pressurized modules [2]. A trade off will have to be made between protection, thickness and mass in order to optimize launch vehicle utilization so that the best possible protection can be launched in the fewest number of flights.

The service track assembly is the backbone of the ASF in that it provides structural support and interfaces between the lunar vehicles and the space station. When fully deployed, the STA is 17 meters wide and 30 meters long. It is designed to be packaged in a 4.4 meter shroud requiring two shuttle flights to bring it up. The STA is composed of the servicing base and the vehicle interface and attach fixtures (Figure 7). The servicing base provides debris protection for the bottom of the ASF and contains the manipulator and enclosure guide rails. A strong back and utility trough run down the center of the base providing a structure/utility bus for vehicle/ASF/station interfaces. Storage lockers and support equipment are located along the top of the trough in the areas not occupied by vehicle interface and attach fixtures.

There are three vehicle interface and attach fixtures envisioned for the ASF concept. These fixtures act as vehicle gantries in that once the vehicle is ready to leave the ASF, the

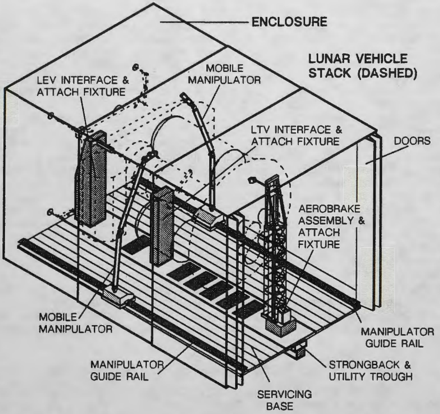


Figure 6: ASF Configuration and Components

fixtures disconnect and swing to one side allowing the vehicle clear passage out of the ASF. While the vehicle is in the ASF, the fixtures provide it with power, data, fluids and heat rejection utilities as well as structural support. Two of the vehicle interface and attach fixtures are dedicated to the LEV and LTV vehicle components. They are similar in functionality but may differ in configuration depending on vehicle design. The third fixture is used for aerobrake assembly and attachment (Figure 6). This fixture is similar to an assembly line robot in that it is pre-programmed to do specific tasks involved with assembling an aerobrake. The center section of the aerobrake is brought up in a single piece and attached to an aerobrake rotation mechanism. An ASF manipulator then places an aerobrake petal section on the center section where the construction and inspection robot seals and inspects the bond between the two pieces. The aerobrake is then rotated and another petal section is attached. The process is repeated until the entire aerobrake has been assembled. The fixture then translates the aerobrake to the LTV where the aerobrake is secured. At this point the fixture acts as an additional support for the LTV. If the lunar vehicle were all propulsive, a more simple fixture similar to the other two would be substituted.

The ASF has two duplicate mobile manipulators that run on parallel tracks on each side of the lunar vehicle enabling all external orbital replacement units (ORUs) to be accessed. A mobile base with an associated work station rides along each rail on the STA. Attached to each mobile base is a three segment arm modified from Freedom hardware to handle a greater degree of autonomy and precision. Various end effectors associated with specific processing tasks and ORUs will be stored in the servicing base in order to be accessible by the manipulators. Two stationary EVA work stations will also be available to assist in vehicle processing.

Certain technologies will have to be developed in order to produce the hardware previously described. The enclosure and servicing base will require advanced technologies involving large

SERVICE BAY ENCLOSURE			18,700
MULTI LAYER INSULATION (MLI)		3,350	
ATTACH HDWR, MOTORS		700	
STRUCTURE (INCLUDES DEBRIS PROTECTION)		14,650	
SERVICE TRACK ASSEMBLY			16,700
SERVICING BASE		5,530	
STORAGE LOCKERS		700	
UTILITIES		1,360	
EVA WORK STATIONS (2)		270	
MOBILE WORK STATIONS (2)		270	
SERVICE BAY MANIPULATORS (2)		1,130	
3 SEGMENT ARMS (2)	630		
MOBILE BASES (2)	270		
END EFFECTORS (10)	230		
LEV ATTACH UTILITY INTERFACE		1,270	
LTV ATTACH UTILITY INTERFACE		1,270	
AEROBRAKE ASSEMBLY & ATTACH FIXTURE		2,540	
STRUCTURE/MECHANISMS	2,400		
WORKSTATION	140		
HOLDING FIXTURE		230	
EVA POSITIONING AIDS		770	
FLUID STORAGE AND TRANSFER		590	
SUPPORT EQUIPMENT		770	
		TOTAL =	35,400

Table 2:
ASF Component Masses in Kilograms

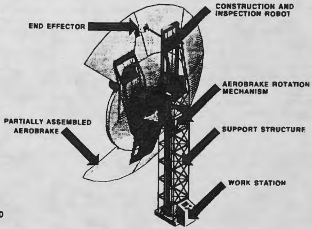


Figure 7:
Aerobrake Assembly and Attach Fixture

scale deployable/erectable space structures with an emphasis on automated assembly. Advances in automation, diagnostic software, video/lighting techniques and large scale robotic motion coupled with control/dynamic effects will be needed for the ASF manipulators. Throughout the ASF, advanced technology involving non-destructive evaluation (NDE), sensors and measurement will be needed for processing and servicing the lunar vehicles.

Configuration Impacts on Freedom Orbital Characteristics

Analysis was performed on each lunar transportation node configuration to assess the impact of physical changes instituted to support the assembly, verification and refurbishment of the lunar vehicles as well as changes made to support other aspects of the lunar mission. The computer aided engineering software package IDEAS**2 was used to perform analysis to characterize changes in mass properties, reboost fuel requirements, microgravity environment and controllability.

Table 3 shows the mass properties for the lunar transportation node as it evolves from the assembly complete baseline. For reference purposes, the origin of the geometrical coordinate system is located in the middle of the center truss bay of the transverse boom. The coordinate system used has the station X axis parallel to the velocity vector, the station Y axis aligned perpendicular to the orbit plane and the station Z axis directed toward the center of the earth (see Figure 2). Notable characteristics of the baseline configuration include a center of mass that is within 1.1 meters of the center of the module pattern (conducive to a good microgravity environment), an inertia relationship (IZZ > IXX > IYY) that provides no gravity gradient stability and a -3.3 degree pitch (about the Y axis) principal to body axis rotation that contributes to a non-LVLH flight attitude. The lunar vehicle verification node configuration has a large mass increase due to the fully fueled lunar vehicle stack (156,000 kg), the STA portion of the ASF, the solar dynamic power units and the lower boom and keels.. The addition of the ASF and the lunar vehicle stack on the lower boom cause the station center of mass to migrate to a point 22.1 meters below the transverse boom. The additional mass also changes the inertia properties such that the configuration is gravity gradient stable in pitch (IXX > IZZ) and changes IYY and IZZ to nearly equal values. The expendable lunar vehicle node configuration has an additional mass increase due to an additional habitation module, two resource nodes and the ASF enclosure. The reusable lunar vehicle node configuration has another small increase in its total mass due to the addition of a second set of solar dynamic power units but it has a large change in IXX and IZZ since the units are located far from the configuration center of mass. The last column of Table 3 shows the impact of removing the lunar vehicle stack from the ASF. The large decrease in mass moves the configuration center of mass to a point just 9 meters below the transverse boom. A large decrease in IXX and IYY also occurs when the lunar vehicle stack is removed.

STATION CONFIGURATION	BASELINE ASSEMBLY COMPLETE	LUNAR VEHICLE VERIFICATION NODE	EXPENDABLE LUNAR VEHICLE NODE	REUSABLE LUNAR VEHICLE NODE	REUSABLE LUNAR VEHICLE NODE (NO VEHICLES)
MASS (KILOGRAMS)	223,000	434,000	486,000	500,000	344,000
CENTER OF MASS (METERS)					
X	-1.5	-1.5	-1.0	-0.9	-0.9
Y	0.5	0.04	-0.2	-0.3	-0.5
Z	3.9	22.1	21.4	20.9	9.3
INERTIAS (KG*M*M)					
IXX	1.1 E8	4.5 E8	4.8 E8	6.0 E8	4.5 E8
IYY	2.2 E7	2.3 E8	2.6 E8	2.7 E8	1.2 E8
IZZ	1.2 E8	2.7 E8	2.8 E8	4.0 E8	3.9 E8
IXY	7.8 E5	6.4 E5	-4.8 E5	-1.0 E6	-1.0 E6
IXZ	1.0 E6	2.0 E6	-1.0 E6	-3.0 E6	-3.0 E6
IYZ	-1.6 E5	-8.0 E5	5.6 E5	1.9 E6	1.6 E5
PRINCIPAL AXIS (DEGREES)					
Z	0.5	0.1	-0.1	-0.2	-0.2
Y	-3.3	-1.1	0.1	0.8	2.6
X	0.1	1.3	-1.7	-0.9	-0.1
BALLISTIC COEFFICIENT (KG/M**2)	48.0	63.0	65.4	58.2	40.0

Table 3: Physical Characteristics of Lunar Transportation Node Configurations

A reboost fuel analysis was performed on an example lunar transportation node evolution schedule. The baseline assembly complete configuration was assumed to be completed in 1999, the lunar vehicle verification node completed in 2002, the expendable lunar vehicle node configuration completed in 2003 and the reusable lunar transportation node completed in 2004 with continuing operations till 2015 at which time the station would be configured to handle both Mars and lunar vehicles. Calculations were based on eight STS rendezvous/reboosts per year at an orbital altitude of 407 kilometers assuming fueled lunar vehicles on the station during each reboost. A MSFC/J70 two sigma atmosphere model with solar cycle peaks in 2001 and 2012 was used along with the ballistic coefficients listed in Table 3. Fuel requirements were derived for the baseline hydrazine propulsion system (ISP=230), and a hydrogen oxygen (H2O2), propulsion system (ISP=350). Assuming that 450 Kg of water could be scavenged from the orbiter fuel cells per rendezvous and converted to gaseous hydrogen and oxygen for station propulsion, the orbiter could provide nearly 3600 Kg of "free" fuel per year for station reboost using H2O2 propulsion. Figure 8 shows the yearly earth to orbit (ETO) fuel requirements for both propulsion systems with 3600 Kg of ETO fuel per year subtracted from the H2O2 numbers. Based on specific impulse alone, hydrazine propulsion will always require 50 percent more fuel for a given operation than H2O2 propulsion. During the low density period of the 11 year solar cycle, (from 2006 to 2009), all reboost operations could be performed using only scavenged orbiter water if H2O2 propulsion were used. Based on the conservative assumptions used in this reboost analysis, the fuel transported to low earth orbit for station reboost during the first 16 years of the HEI would be 165,000 Kg for a hydrazine propulsion system vs. 56,700 Kg for a H2O2 propulsion system (excluding water scavenged from the orbiter). The above numbers indicate that the growth station should switch from the baseline hydrazine propulsion to H2O2 propulsion as soon as technology permits in order to reduce the large station reboost fuel requirements associated with accommodating the HEI.

Steady state attitude flight mode characterization and control system sizing were performed using Attitude Predict (ATTPRED) of IDEAS**2. The ATTPRED software module can simulate the use of control momentum gyroscopes (CMGs) for attitude control. Both a CMG control law/momentum management algorithm and a steering law are modeled. The control law/momentum management algorithm is based on work done by NASA's Johnson Space Center

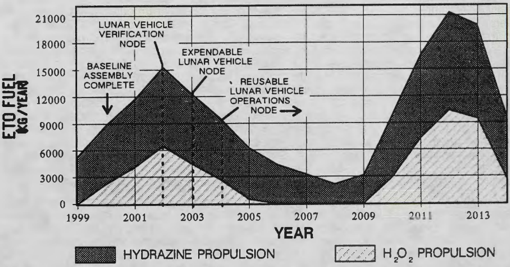


Figure 8: Yearly Reboost Fuel Requirements for Hydrazine and H_2O_2 Systems

(JSC) and the University of Texas. This controller generates a torque command which provides continuous closed-loop control of both the spacecraft attitude and CMG angular momentum via state feedback and disturbance rejection. The CMG steering law for parallel mounted CMGs is based on work done by NASA's Marshall Space Flight Center (MSFC). Given a torque command, the steering law generates appropriate gimbal rate commands, which distribute the CMG momentum vectors such that all inner gimbal angles are equal and all outer gimbals are equally spread out. The double-gimbaled CMGs are modeled as error-free actuators, which deliver the gimbal rate command subject to user defined gimbal freedom limits and gimbal rate limits [3]. The CMG controls analysis performed assumes only steady state environmental disturbances such as aerodynamic and gravity gradient torques. Large dynamic disturbances such as orbiter berthing or lunar vehicle deployment and the corresponding interactions between the CMGs, reaction control system (RCS) and station attitude will be evaluated in future studies.

Table 4 summarizes the micrgravity, flight mode and CMG control characteristics of the lunar transportation node as it evolves from the Freedom assembly complete baseline assuming a worst case (year 2001) two sigma atmosphere at an orbital altitude of 407 kilometers for all

STATION CONFIGURATION	BASELINE ASSEMBLY COMPLETE	LUNAR VEHICLE VERIFICATION NODE	EXPENDABLE LUNAR VEHICLE NODE	REUSABLE LUNAR VEHICLE NODE
STEADY STATE MICRO-G IN LAB	1.1	7.2	6.6	6.1
AVERAGE FLIGHT ATTITUDE (DEG) Z (YAW) Y (PITCH) X (ROLL)	 1.0 -7.1 -0.1	 0.1 1.9 1.3	 -0.1 2.6 -1.7	 -0.2 3.0 -0.9
ATTITUDE DEVIATIONS PER ORBIT (DEG) Z (YAW) Y (PITCH) X (ROLL)	 0.1 0.4 0.1	 0.1 0.3 0.5	 0.1 0.2 0.4	 0.1 0.3 0.1
PEAK MOMENTUM REQUIREMENT (N-M-S)	4,200	17,500	17,000	15,500

Table 4: Control Characteristics Under Worst Case Conditions

configurations. The baseline assembly complete configuration has an excellent steady state microgravity environment of 1.1 micro-G which is well below the program established 10 micro-G requirement. The baseline has a large pitch attitude of -7.1 degrees that can be attributed to two factors. First, a four meter center of pressure / center of mass offset along the Z axis results in a positive aerodynamic torque about the station pitch axis. Second, since IZZ is slightly larger than IXX for the baseline Freedom configuration, a weak gravity gradient pitch torque tends to rotate the station away from the desired LVLH flight mode. The positive aerodynamic torque coupled with the weak gravity gradient torque results in a large negative pitch rotation as the control system seeks an attitude to balance out the aerodynamic and gravity gradient torques. The ± 0.4 degrees variation in pitch attitude over the course of one orbit is due to the interaction of the articulating solar arrays and the atmospheric diurnal variation that results in an oscillating aerodynamic torque in pitch. The gains chosen for the CMG controller were optimized to provide minimal deviations in pitch attitude. The CMG peak momentum control requirement for maintaining attitude is 4,200 Newton-Meter-Seconds (N-M-S) which is well within the capability available from the six 4750 N-M-S CMGs on the baseline assembly complete configuration.

The change in mass properties associated with adding the lunar mission accommodation components impacts flight characteristics. The large shift in the Z location of the center of mass to over 20 meters below the transverse boom causes an associated shift in the optimum microgravity environment such that the sensed steady state accelerations in the laboratory modules are no better than six micro-Gs. The shift in center of mass also drastically increases the center of pressure / center of mass offset leading to even larger aerodynamic torques in the pitch channel. Fortunately, the change in inertia properties yields a counter acting gravity gradient torque resulting in near LVLH flight attitudes. For the lunar vehicle verification node configuration and the expendable lunar vehicle node configuration, the closeness of the Y and Z inertias reduces the amount of gravity gradient torque about the roll axis requiring large roll deviations of plus or minus a half of a degree for proper momentum management. This point in the station evolution requires special emphasis on managing configuration inertia properties so that the Y and Z inertias have some separation in order to avoid large roll maneuvers. The addition of two more solar dynamic units on the reusable lunar vehicle node configuration separates the Y and Z inertias resulting in smaller roll deviations for momentum management. All of the lunar node configurations have large peak momentum requirements of over 15,000 N-M-S in the pitch channel that again is linked to the large center of pressure / center of mass offset and the articulating solar arrays that give rise to an oscillating aerodynamic pitch torque. The average aerodynamic torque is equal in magnitude to the average gravity gradient torque for an orbital period but half the time the aerodynamic torque is much larger than the gravity gradient torque and half the time the aerodynamic torque is much smaller causing the CMGs to supply the difference in torque and thus yielding large cyclic momentum peaks. Although 15,000 N-M-S is within the available CMG capability, a change in assumptions and control parameters can yield results closer to what can be expected under less severe operational conditions.

Table 5 lists the results of flight mode characterization of the reusable lunar vehicle transportation node under more benign assumptions. The first column represents a control simulation where the natural gravity gradient pitch stability is taken advantage of to reduce the cyclic pitch momentum peaks. Instead of holding the station to within a fraction of a degree of the average pitch flight attitude, the station is allowed to oscillate with the aerodynamic torque using the CMGs only as dampers to keep the station within five degrees of LVLH. Using this "relaxed" pitch control, the gains are chosen to minimize pitch angular momentum (at the expense of pitch attitude maintenance). The resulting peak momentum control requirement of 3,000 N-M-S demonstrates the effectiveness of this method although attitude deviations of 3 degrees in pitch over one orbit might not be acceptable for certain station operations. This method of relaxing the pitch control would be less effective for the baseline assembly complete configuration since it has no gravity gradient stability. Another assumption made earlier was the use of a worst year two sigma atmosphere which represents an atmospheric density that might occur once every 11 years during a period of intense solar flare activity. The second column in Table 5 lists the control characteristics of the reusable vehicle transportation node assuming a *nominal* atmosphere at the peak of the 11 year solar cycle in 2001. Control momentum requirements drop by over 5,000 N-M-S as compared to the same configuration (and control gains) using the two sigma atmosphere. Relaxing the pitch control and using a nominal atmosphere reduces peak momentum requirements to 2,000 N-M-S. Columns four and five show the impact on the flight characteristics when the lunar vehicle stack is removed from the

CONTROL ASSUMPTIONS	WORST YEAR 2 SIGMA ATMOSPHERE, RELAXED PITCH CONTROL	WORST YEAR NOMINAL ATMOSPHERE	WORST YEAR NOMINAL ATMOSPHERE, RELAXED PITCH CONTROL	WORST YEAR 2 SIGMA ATMOSPHERE, NO VEHICLES	WORST YEAR NOMINAL ATMOSPHERE, NO VEHICLES
STEADY STATE MICRO-G IN LAB	6.2	6.0	6.1	2.1	1.9
AVERAGE FLIGHT ATTITUDE (DEG)					
Z (YAW)	-0.2	-0.2	-0.2	-0.2	-0.2
Y (PITCH)	3.0	1.7	1.7	3.7	3.1
X (ROLL)	-0.9	-0.9	-0.9	-0.1	-0.1
ATTITUDE DEVIATIONS PER ORBIT (DEG)					
Z (YAW)	0.1	0.1	0.1	0.1	0.1
Y (PITCH)	+2,-3	0.2	+1.5,-2.5	0.4	0.2
X (ROLL)	0.1	0.1	0.1	0.1	0.1
PEAK MOMENTUM REQUIREMENT (N-M-S)	3,000	10,000	2,000	8,500	5,500

Table 5: Control Characteristics of the Reusable Lunar Vehicle Transportation Node

station. Since the center of mass moves 10 meters closer to the module pattern, the steady state microgravity level sensed in the lab improves to around two micro-Gs. The ASF is located in a position on the lower boom that minimizes the X axis center of mass migrations for different vehicle configurations. This reduces pitch principal axis shifts enabling the station to maintain a near LVLH flight attitude independent of what is in the ASF. Peak momentum requirements also drop substantially due to the reductions in pitch aerodynamic torque associated with the reduced center of pressure / center of mass offset.

Conclusion

This paper described the impact of evolving the baseline assembly complete Freedom configuration to a transportation node for lunar vehicles. Three evolution milestones beyond the baseline configuration were analyzed. Almost three months of EVA time is required to construct the truss and facilities required to support reusable lunar vehicle operations on Freedom. Lunar vehicle processing will require up to four months per vehicle for post-flight, refurbishment and pre-flight operations. A concept for accommodating lunar vehicle processing, the ASF, was described with respect to hardware configuration and functionality. The impact of additional resources, structure and facilities in support of the Human Exploration Initiative with respect to the orbital characteristics of Freedom was also assessed. Reboost analysis indicated that a hydrogen oxygen propulsion system can offer significant savings in fuel logistics as compared to the baseline hydrazine propulsion system. For all lunar transportation node configurations studied, flight attitudes were within ± five degrees of LVLH, sensed *steady state* accelerations in the module cluster were below 10 micro-Gs and *steady state* control momentum requirements were within the baseline capability. The results of the above analysis indicate that Freedom is capable of evolving into a lunar transportation node in support of the Human Exploration Initiative.

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