

Centaur Application to Robotic and Crewed Lunar Lander Evolution

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Abstract. Human space exploration, while a clear imperative for the progression of human civilization, can be severely impeded by excessively high operational costs and perceived high risk. A cost effective method of accomplishing every phase of exploration transport is mandatory to avoid this trap. Centaur, the upper stage on the current Lockheed Martin Atlas V rocket, is an excellent candidate for modification as a robotic and possible human transport vehicle to our nearest neighbor. The Centaur is produced in Denver, Colorado. Centaur has proven to be extremely robust and reliable, with 77 consecutive successful flights. Modifications to the current design would allow the Centaur to function as an in-space propulsion system. With its present capability Centaur can directly support robotic probe landings on the moon and is directly extensible to larger landing tasks including high-mass crewed missions. Lunar descent would be accomplished in two phases: primary descent using the RL10 engine and a final horizontal terminal phase powered by pressure fed thrusters mounted along the Centaur tank. Utilizing the Centaur for human exploration would greatly reduce cost by leveraging an already designed and manufactured stage. It would increase safety by its robustness and redundancy that the Centaur has proven in many successful launches. With the Centaur concept for human exploration, NASA can have the safety and cost effectiveness needed to explore the Moon, Mars, and beyond.

Keywords: Centaur, Cryogenics, Human Lunar Lander

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INTRODUCTION

NASA plans to use a LO₂/LH₂ lander to support sending humans to the moon as early as 2018. NASA's Lunar Precursor and Robotic Program (LPRP) provides the opportunity to test and demonstrate this lander or significant elements of it as early as 2012 (Stanley, 2006). Development of a new cryogenic stage, especially a stage required to accommodate multiple burns and long mission duration capability is a technically challenging and costly endeavor.

The use of Centaur as the foundation for the LPRP and Lunar Surface Access Module (LSAM) landers would allow the lander to benefit from Centaur's unrivalled flight history. Application of flight proven hardware to the maximum extent would significantly lower technical risk and suppress lander development costs. Leveraging Centaur hardware and systems would permit NASA to field the LPRP sooner, enabling NASA to gain experience with a cryogenic lander long before the next humans revisit the moon. Flight-demonstrated safety and reliability for these vehicles would thus be established and designs matured based on real-world flight data. This philosophy provides a firm foundation for the astronauts' safety based not on presumptive analysis but on actual and extensive flight hours.

A progressive evolution of Centaur to support LPRP and crewed missions is shown in Figure 1. The Cryogenic Fluid Management (CFM), structure, RL10 interface, primary avionics, propulsion system are potentially common between Centaur and the lunar derivatives. An Atlas/NASA collaborative development of the Centaur lunar lander variants would result in a low risk development program.

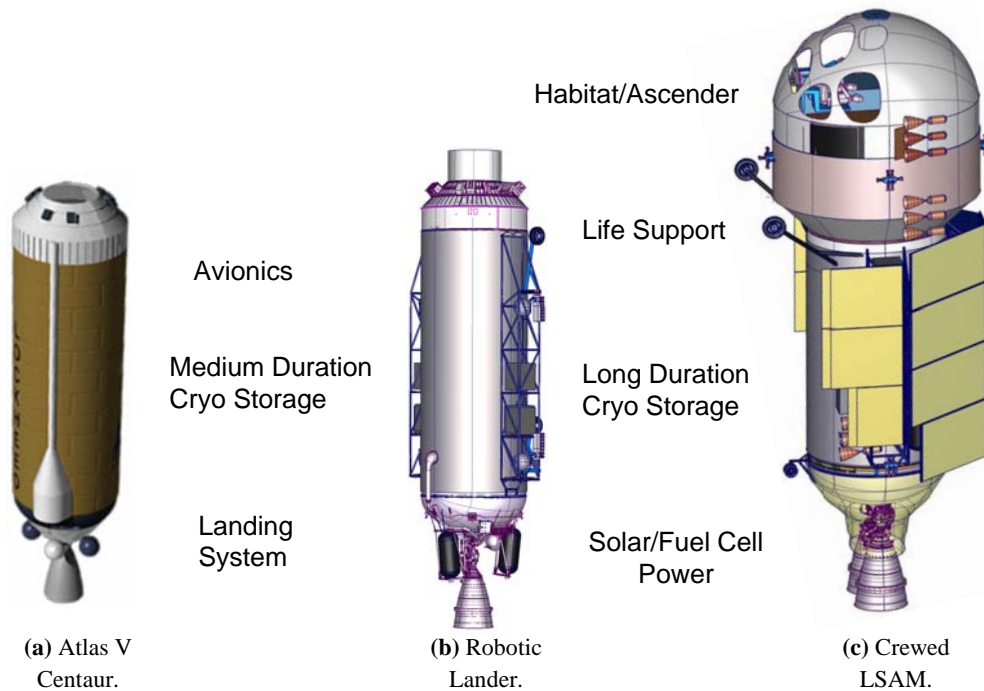


FIGURE 1. Evolution from Today's Centaur to a Robotic and Crewed Centaur Lander is straightforward.

CENTAUR HISTORY

Centaur provides an ideal foundation from which to evolve future in-space high-energy stages (Kutter, 2005). The Centaur upper stage has been the mainstay for high-energy missions for over four decades. Overall, there have been 179 successful Centaur missions—including such notable exploration missions as Mariner, Viking, Voyager, Cassini, SOHO and recently MRO and the Pluto New Horizons mission. NASA continues to voice its confidence in the Atlas/Centaur with the upcoming SDO, MSL and LRO missions scheduled to fly on Atlas/Centaur in 2008 and 2009.

The two keys to successful usage of the high-energy LO_2/LH_2 propellants for upper stages is integrated systems design and cryogenic fluid management, especially for missions requiring long-coast durations between burns, and multiple-burn missions (Kutter, 2005). Fundamental to flying these missions is a thorough understanding of the nonequilibrium cryogenic thermodynamics and low and zero-gravity fluid behavior. Centaur is the only cryogenic stage that has repeatedly demonstrated this long-coast capability, both with 10-foot and 14-foot diameter configurations. LH_2 and LO_2 both have unique behaviors in low gravity, and a detailed understanding of the complex interaction of the fluid dynamics of the propellant on the tank thermodynamics is required for system thermal management. Tank pressure control during the coast is critical to minimize vented-propellant, efficient use of the ACS propellant, and to ensure that the engine inlet conditions are met for each burn. With 179 flights, the Centaur team has accumulated more in-space LO_2/LH_2 flight experience than everyone else combined.

The Centaur has the highest propellant mass fraction yet demonstrated- roughly 91% of its total mass is useable propellant. With this high built-in performance advantage, inevitable hardware and mass additions can be accommodated to augment the present mission flight duration capability with minimal performance decrement. Its low burnout weight and high Isp engines means that missions can be extended to envelope most exploration-related propulsion tasks.

ROBOTIC PRECURSOR LUNAR PROGRAM

For robotic missions, it is envisioned that a Centaur derived lander would be placed into Low Earth Orbit (LEO) atop an Atlas Heavy Lift Vehicle (HLV) (Figure 2), the CLV, or other large performance launch vehicle. The figure shows an Atlas V HLV with an upper stage Centaur and the Centaur lunar-lander as a 3rd stage. Once in LEO, the Centaur lander would conduct its first burn to place it on a trans-lunar trajectory. The second burn injects the stage into Lunar Orbit with a third burn performing the final lunar descent.

The Atlas/Centaur team has developed a mission peculiar kit to enhance the existing Centaur to enable longer duration missions and operations at and on the moon (Figure 3) (Szatkowski, 2006). These relatively simple enhancements enable mission durations to be increased from ½ day to 7 days duration. Avionics upgrades include solar arrays, rechargeable batteries and a power control module to support long duration power needs. A star tracker, landing radars, communication uplink for long duration and surface proximity navigation are added. The thermal upgrades include enhanced multi-layer insulation, improved low-K brackets and moving of the RCS system from the Centaur aft bulkhead onto the warm lander beams.

Preliminary trades suggest that for a high performance LH₂/LO₂ vehicle, horizontal landing (Figure 3) is preferable to vertical landing (Birckenstaedt, 2006). The key to horizontal landing is the recognition that the primary descent propulsion requirements and the hover/terminal landing propulsion requirements are diametrically opposed. The primary descent system demands high thermal efficiency, high thrust, low dry mass and high Isp to maximize landed payload. The landing phase requires a highly responsive multi-axis propulsion system with maximum reliability and inherently low thrust. The terminal landing propulsion system can tolerate lower Isp with minimal system impact but demands precision throttling. The horizontal landing methodology utilizes the RL10 and high energy LH₂/LO₂ propellants for the majority of the descent then switches to hypergolic lateral thrusters for the final descent and touchdown.

Since nearly all the work of descent was performed using the high efficiency RL10 engine and the high Isp associated with non-throttled operation, the system has a low dry weight. Even substantial hover and final descent times using the lateral thrusters do not require onerous propellant usage.

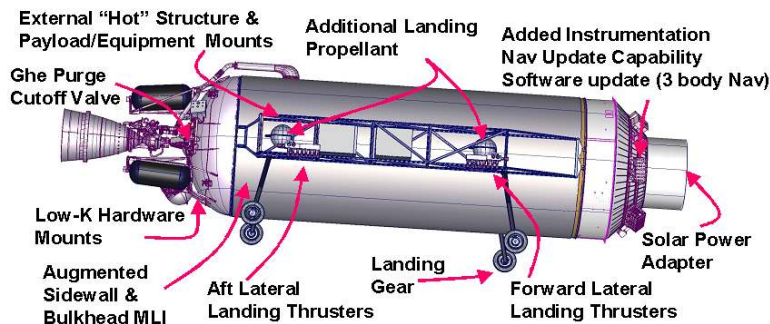


FIGURE 3. Conceptual Horizontal-Landing Centaur-Based Robotic Lunar Lander with Required Modifications.

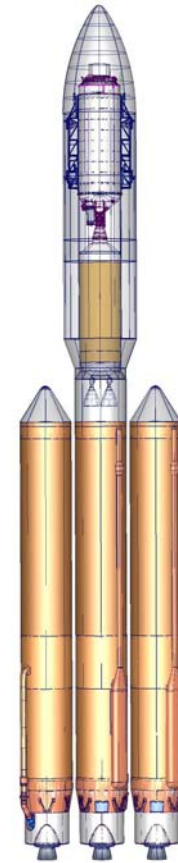


FIGURE 2. HLV with Robotic Lunar Lander as Payload.

TABLE 1. Robotic Lander Nominal Weights.

Weights in (mT)	
All-up Vehicle	28.8
Vehicle Systems	4.3
Centaur Core tank, Main propulsion	2.5
Extended Duration Mission Kit	0.8
Lunar Landing Kit	1.0
Lunar Cargo	2
Consumables	22.5
Centaur Main Propellants	21
Lander Propellants	1.5

The ability to rapidly maneuver is a clear advantage enabling the selection of an optimal landing site. The distribution of lateral thrusters circumferentially around the Centaur lander enables the management of widely varying centroid locations which are inevitable from mission to mission. It also permits control over residual propellant slosh behaviors as the vehicle maneuvers. The use of multiple lateral thrusters and their location increases system reliability. The loss of a single or even multiple thrusters has minimal impact on system behavior.

Performance and associated masses of the Centaur lander assuming an HLV launch to LEO are shown in Table 1. Elements of the extended mission kit were analyzed in detail to support Lockheed Martin's LRO secondary proposal.

CREWED LUNAR MISSION & EVOLUTIONARY DEVELOPEMENT

Can the proposed Centaur-derived robotic lunar landing system be adapted or scaled to efficiently and reliability support a crewed landing? Based on our preliminary analysis the answer is clearly yes (Patton, 2006). In fact we believe the the horizontal landing philosophy has major advantages over the traditional vertical landing designs. Figure 4 shows the basic concept.

The crewed lander builds upon the robotic Centaur lander design. The developed robotic lander flight-proved the basic ability for the Centaur to perform missions to the moon with a horizontal landing. The crewed lander extends this basic propulsion capability to longer durations and heavier payloads. The crewed lander also introduces the habitation/ascent module. The same basic Centaur acts as the armature around which a highly capable lunar descent/ascent vehicle can be built. The vehicle shown can readily deliver 4 crew, all their gear and consumables including 2.7 mT of scientific cargo to the moon and sustain them for periods greater than 14 days. Table 2 provides a detailed mass breakdown. As shown, TLI and LOI burns are performed by another in-space stage.

For these extended crewed missions, long duration cryogenic storage would be achieved by extending the techniques developed for the robotic lander. The basic vehicle design separates hot and cryogenic structures and maintains a clean, readily insulated main tank design. A jettisonable, high performance sun shield is critical while in LEO or LLO. 80 layer variable-density external MLI, extensive internal insulation, vapor cooled structures and efficient heat pump/rejection systems would provide the required low heating rates while on the lunar surface.

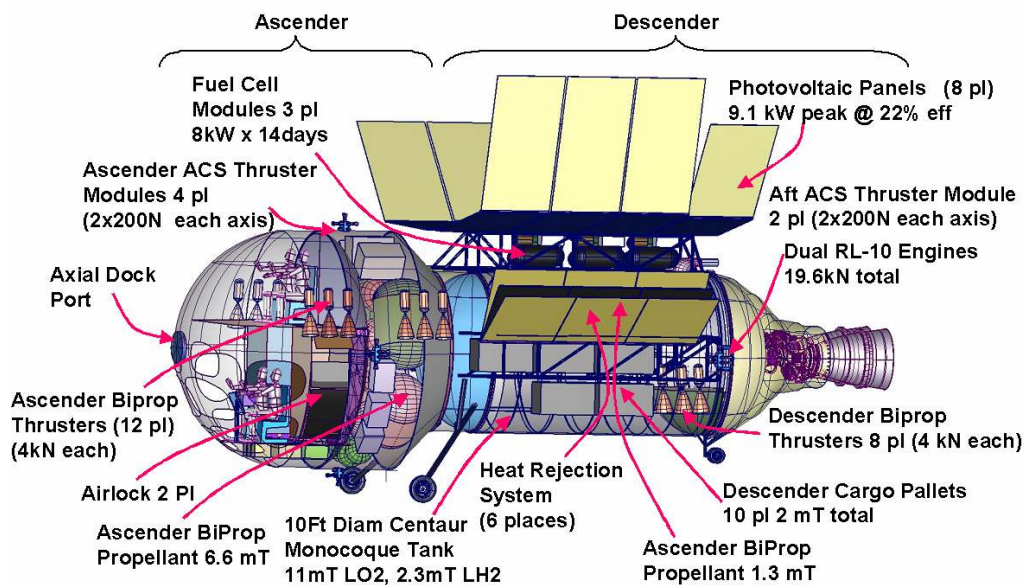


FIGURE 4. Conceptual Centaur-Based Lunar Lander.

TABLE 2. Crewed Lander Mass History (Weights).

Weights in (mT)			LLO		Lunar Surface	
	IMLEO	LEO+30 Days	Departure to Surface	Lunar Surface Arrival	Departure (14 days)	LLO Arrival
All-up Vehicle	32.2	31.8	31.6	18.3	13.6	
Descender	20.6	20.2	19.8	7.7	4.0	
Vehicle Systems	3.8	3.8	3.5	3.5	3.5	
Lunar Cargo	2.0	2.0	2.0	2.0	0.0	
Main Propulsion Consumables	13.3	12.9	12.8	1.9	0.2	
Secondary Propulsion Consumables	1.3	1.3	1.2	0.1	0.1	
Misc Consumables	0.2	0.2	0.2	0.2	0.2	
Ascender	11.6	11.6	11.8	10.6	9.2	4.4
Vehicle Systems	3.1	3.1	3.1	3.1	3.1	3.1
Crew, crew systems & payload	1.2	1.2	1.6	1.6	0.7	0.7
Main Propulsion Consumables	6.6	6.6	6.5	5.2	5.2	0.4
Crew Consumables	0.5	0.5	0.5	0.5	0.1	0.1
Pressurants & Coolants	0.16	0.16	0.16	0.16	0.11	0.11

LUNAR DESCENT, ASCENT AND ABORT

Like the robotic lander the crewed Centaur Lander executes the primary lunar descent with a 250 second burn of the RL10 engines. Twenty 4 kN throttleable biprop thrusters are distributed into fore (Ascender mounted) and aft (Descender mounted) areas to provide the terminal descent propulsion. Two hundred seconds of descent/hover propellants are available to the crew with the abort to orbit option available. An additional 40 seconds are available once committed to landing. The circumferential distribution of down-thrust enables the vehicle to fly with a widely varying longitudinal and lateral centroid. The separation of thrusters enables large pitch and roll authority via differential thrust of the primary hover thrusters. Rolling or pitching the vehicle provides a large yaw or direct lateral/longitudinal translation force capability.

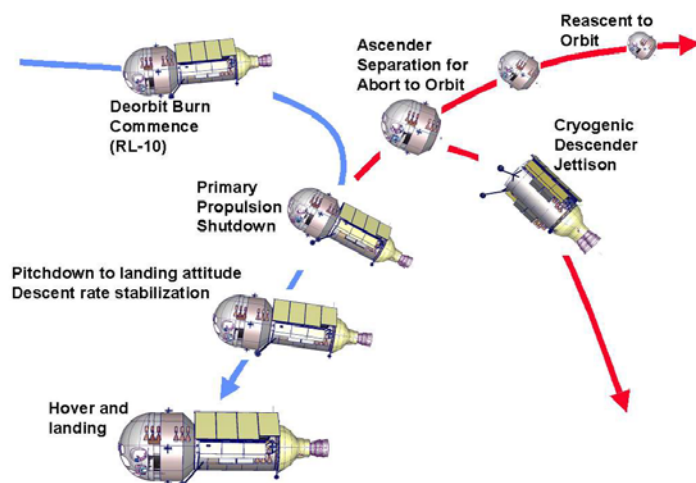


FIGURE 5. Descent, Landing and Abort Concept.

The flight crew is placed as low as possible in the vehicle with the largest practical down-facing window size to provide the pilot with an enhanced view of the lunar surface and landing site. This maximizes the pilot's ability to perform a safe landing on the unprepared lunar surface. Widely spaced, wheeled gear allow touchdown with nonzero forward velocity. The overall geometry places the crew cabin 1 m above the ground and the vehicle centroid less than 2.7 m high- a clear advantage over vertical landing systems. The descent propulsion thrusters are 3 m above the surface so as to minimize exhaust interaction with surface features and eliminate the potential for damage. Because of the distribution of mass in the vehicle over 45% of the landing thrust is provided by the aft thrusters- moving much of the dust-raising down thrust over 7 m away from the crew's windows. In short, the vehicle closely approximates a modern helicopter in physical design- a design refined by decades of usage for landing on unprepared surfaces with minimal prior knowledge.

Abort to orbit is built-in to the design. As shown in Figure 5, the Descender and Ascender elements can be separated cleanly since there is no interdependence of the Ascender and Descender propulsion, fluids or avionics systems. The Ascender system is designed with sufficient propellant and other consumables to return to LLO using

its 12 biprop thrusters. The bulk of the heavy scientific cargo, fuel cells, solar panels, heat rejection apparatus, landing gear and cryogenic storage provisions remain on the discarded Centaur Descender.

LUNAR SURFACE ACCESS

Once on the lunar surface the crew can access the surface without ladders or other impediments. In similar fashion the scientific cargo is immediately accessible for deployment (Figure 6). Much of it is at chest level and each of the ten 200 kg pallets on the Descender can be lowered directly to the surface via simple mechanisms and without the crew engaging in elaborate deployment procedures. Concerns for work beneath suspended loads are minimized.

Twin airlocks with hatches near the bottom of the Ascender vehicle enable efficient and redundant access to the lunar surface. Placement of the external hatches enables the deployment of inflatable habitat structures directly on to the lunar surface while retaining connection to the Ascender ECLSS systems. Even with a habitat attached one airlock remains clear. A vertical landing system is nearly incompatible with this effective method of expanding workspace and hence will hinder extended duration operations.

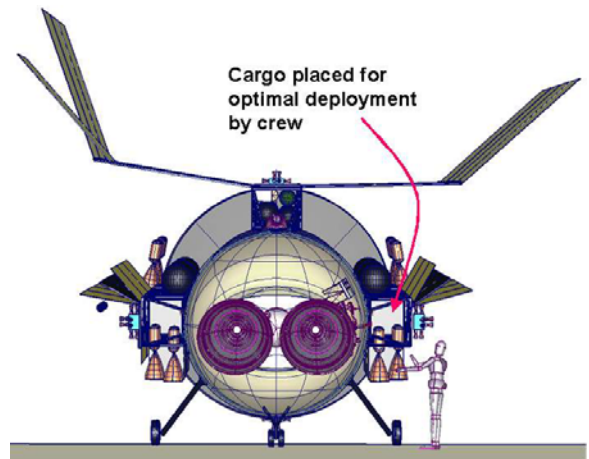


FIGURE 6. Aft View Showing Descender Cargo.

INTEGRATED POWER SYSTEM

Power generated by integrated solar and fuel cell systems provide in excess of 17 kW of power under peak solar illumination. Fuel cell power of 8 kW continuous is available for 14 days. This suggests that a lunar mission could be readily extended beyond the lunar daytime to nearly encompass a complete lunar day. An integrated thermal rejection system can reject these high power levels even at solar noon and can be modulated to precisely match the actual power consumption and local environment.

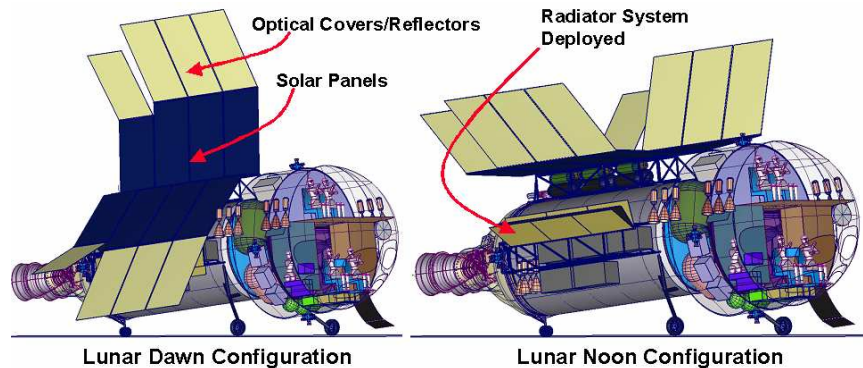


FIGURE 7. Solar Power and Waste Heat Radiation System Deployment.

The horizontal vehicle configuration is optimal for the simple deployment and subsequent orientation of the solar panels. As shown in Figure 1 (right side image) the solar panels are covered with low-emissivity optical covers so as to minimize heating during orbital phases of flight and to guard the panels from landing generated dust. Once on the ground the optical covers swing back and the entire solar panel/optical cover assembly can be pivoted to face the sun (Figure 7). Each of the eight panels is independently movable. The panel/cover angles can be optimized to increase power generation by increasing incident light or to reduce vehicle heating as required. In similar fashion, six independently controlled radiators can be deployed. The radiator panels, sandwiched between low-emissivity optical panels allow efficient rejection of heat regardless of the local illumination.

CREW HABITAT AND ASCENT VEHICLE

The Ascender, with its 4.6 m exterior diameter provides a basic capability for extended crew operations on the lunar surface. More important than its nearly 29 m³ habitable volume is the nearly 7.5 m² flight deck area and the 8.5 m² upper deck area. Nearly 10 m³ in storage volume is available to the crew for consumable, gear and cargo storage. The primary pressurized structure is composed of efficient axisymmetric elements that benefit from internal pressure stabilization. Behind the pressure compartment is a simple cylinder for supporting Ascender propellants, pressurants, avionics and ECLSS hardware. The main thrust loads, distributed by the multiple thrusters, are reacted into the Ascender cylindrical elements tangent to the structure. The Ascender interfaces to the Descender Centaur via a simple cone optimized for low thermal conductivity and weight.

The ascender receives all of its surface power from the Descender as well as breathing air and cooling capacity. With the copious power available it is practical to pump down the airlock instead of simply wasting the gas at each airlock cycle. However with extended stays there is inevitable loss of nitrogen as GO₂ is replenished via the Centaur main tanks. Triply redundant Nitrous Oxide tanks provide up to 135 kg of fluid which is catalytically reacted to form supplemental breathing air and also to pressurize the NTO tanks. Hundreds of airlock cycles can be accommodated with airlock pump-down depressurization combined with the large onboard stores of O₂ and N₂O.

To return to LLO after the surface mission the Ascender tanks are brought to pressure by the onboard GH₂ and N₂O pressurization systems. If desired, residual Descender propellants can be moved to the ascender to increase system margins. With Descender systems stowed and umbilicals retracted the Ascender thrusters can be brought to 35% power to achieve a small positive upload at the separation interface. Commanding separation the Ascender can then come to hover without violent separation dynamics and translate slowly away from the Descender. Once clear, application of full power on the Ascender provides up to .35 g for initial ascent rising to 1 g at the end of ascent. In this way the Descender can be preserved without damage for potential future use. The arrangement of propellants and thrusters on the Ascender minimize CG movement and permit widely varying amounts of residuals or up-cargo.

CONCLUSION

Using Centaur to get to the moon provides a low-cost, long term solution for a return to the moon. Only minor upgrades would be needed on an already proven design for a robotic mission, and then further upgrades would be needed for a human mission. Thus, the goal can be accomplished as an evolutionary approach in two simple steps, starting with an already solid foundation. Trade studies and testing have been done since the 1970's making Centaur worthy for long duration missions with an efficient and flight proven CFM system. Starting with an already good foundation minimizes cost and risk and maximizes efficiency, redundancy, and safety.

NOMENCLATURE

ACS	= Attitude Control System
Atlas HLV	= Atlas Heavy Lift Vehicle
CaLV	= Cargo launch vehicle (>100 mT class)
CEV	= Crew Exploration Vehicle
CFM	= Cryogenic Fluid Management
CLV	= Crew Launch Vehicle
ECLSS	= Environmental Control and Life Support Systems
EDS	= Earth Departure Stage
ESAS	= Exploration Systems Architecture Study
g	= Earth's Gravity
GHe	= Gaseous Helium
GH ₂	= Gaseous Hydrogen

GO ₂	= Gaseous Oxygen
IMLEO	= Initial Mass to Low Earth orbit
Isp	= Specific Impulse
LEO	= Low Earth Orbit
LH ₂	= Liquid Hydrogen
LLO	= Low Lunar Orbit
LOI	= Lunar Orbit Insertion
LO ₂	= Liquid Oxygen
LPRP	= Lunar Precursor and Robotic Program
LRO	= Lunar Reconnaissance Orbiter
LS	= Lunar Surface
LSAM	= Lunar Surface Access Module
MLI	= Multi Layer Insulation
MMH	= Monomethyl Hydrazine
MSFC	= Marshall Space Flight Center
mT	= Metric Tons
NASA	= National Aeronautics and Space Administration
NTO	= Nitrogen Tetroxide
N ₂ O	= Nitrous Oxide
PMD	= Propellant Management Device
SM	= Service Module
TEI	= Trans Earth Injection

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