Robust Lunar Exploration Using an Efficient Lunar Lander Derived from Existing Upper Stages

AIAA 2009-6566

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Future large scale lunar exploration is impeded by the high cost of accessing the lunar surface. This cost is composed of terrestrial launch costs and the cost of developing and operating efficient lunar landers capable of delivering crew and large payloads to the lunar surface. Developing lunar landers from a platform based upon an operational upper stage minimizes development and recurring costs while increasing crew safety and reliability.

The Dual Thrust Axis Lander (DTAL) lands horizontally. It uses an RL10 engine to accomplish the descent deceleration to just above the lunar surface. Final landing is accomplished using thrusters mounted along the DTAL body. This configuration places the crew and payloads safely and conveniently close to the lunar surface.

This paper describes DTAL and its benefits in supporting a robust lunar exploration program. Initial DTAL-enabled large robotic missions allow NASA to return to the moon quickly and demonstrate hardware to be used by crews that follow. This same mission design supports placement of large lunar base elements (habitats, power plants, rovers, excavation equipment, etc). As the uncrewed missions are completed, and the system matures, astronauts will then use the same, now proven system to access the lunar surface.

The reliable DTAL propulsion stage provides the flexibility to visit destinations other than the moon. DTAL's mass and thermal efficient design provides the capability to visit NEO's or possibly even Mars. By supplying the life support consumables with O2 and H2 from the large primary propellant tanks long duration missions are possible.

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Acronyms

ACES	Advanced Common Evolved Stage
ACS	Attitude Control System
ATHLETE	All-Terrain Hex-Legged Extra-Terrestrial Explorer
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
CRYOTE	Cryogenic Orbital Testbed
DASH	Descent Assisted, Split Habitat
DTAL	Dual Thrust Axis Lander
DTAL-R	Dual Thrust Axis Lander - Robotic
ECLSS	Environmental Control and Life Support Systems
EDS	Earth Departure Stage
EELV	Evolved Expendable Launch Vehicle
ESAS	Exploration Systems Architecture Study
ET	External Tank
FPR	Flight Performance Reserve
FSPS	Fission Surface Power System
GHe	Gaseous Helium
GH2	Gaseous Hydrogen
GO2	Gaseous Oxygen
IMLEO	Initial Mass to Low Earth orbit
Isp	Specific Impulse
ISRU	In-Situ Resource Utilization
IVF	Integrated Vehicle Fluids
LEM	Lunar Excursion Module
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LLO	Low Lunar Orbit
LOI	Lunar Orbit Insertion
LO2	Liquid Oxygen
LPRP	Lunar Precursor and Robotic Program
LRO	Lunar Reconnaissance Orbiter
LRU	Line Replaceable Unit
LS	Lunar Surface
LSAM	Lunar Surface Access Module
LSS	Lunar Surface Systems
MLI	Multi Layer Insulation
MMH	Monomethyl Hydrazine
MSFC	Marshall Space Flight Center
mT	Metric Tons
NASA	National Aeronautics and Space Administration
NEO	Near Earth Object
NTO	Nitrogen Tetroxide
N2O	Nitrous Oxide
N2O4	Nitrogen Tetroxide
OML	Outer Mould Line
PMD	Propellant Management Device
SM	Service Module
TEI	Trans Earth Injection
ULA	United Launch Alliance

I. INTRODUCTION

The Columbia Accident Investigation Board recommended that "The design of the system [that replaces the shuttle] should give overriding priority to crew safety, than trade safety against other performance criteria, such as low cost and reusability, or against advanced space operation capabilities other than crew transfer"[1]. This philosophy is especially applicable to the lunar lander where reduced abort options compete with performance limitations and minimal flight experience. Maximizing the use of systems with a long history minimizes risks to the astronauts. Systems that fly frequently provide substantially safer exploration through constant demonstration of reliability and continuous learning and improvement (Figure 1). Such activities also sustain an experienced technical team.

Beyond safely and reliably transporting people to the lunar surface, the lander must also be capable of supporting the mission requirements. NASA's stated lunar exploration requirements include crewed sortie and expedition missions as well as robotic and uncrewed base deployment/service missions. The deployment missions include transporting and unloading large, heavy items like habitat modules to assemble the lunar base as well as delivering smaller payloads such as rovers and supplies. The crew expedition mission transport function is similar to a 'taxi', delivering people to a lunar base, while the sortie missions require medium surface duration at remote locations, requiring the lander to function as a temporary habitat.

Apollo's Lunar Excursion Module (LEM) (Figure 2) reliably supported America's first forays to the moon with a very robust lunar lander supporting two crew members exploring the lunar surface for a few days. The storable propellants used by the LEM were contained in a cluster of multiple tanks with an embedded engine that allowed for a relatively compact propulsion system, providing the crew with practical lunar surface access.

Because of the high performance provided by LO2/LH2 propulsion, NASA has chosen to use a LO2/LH2 lander to support sending the next humans to the moon[2]. LH2 introduces numerous challenges to the stage designer. The -420° F cryogen with low surface tension challenges the storage and handling of LH2 for the long periods required to support lunar missions, especially missions requiring more than a single launch. LH2 with a density of only 4.3 lb/ft^3 is like trying to pack cotton candy; it requires huge volumes to store the required quantity of fuel to support the mission.

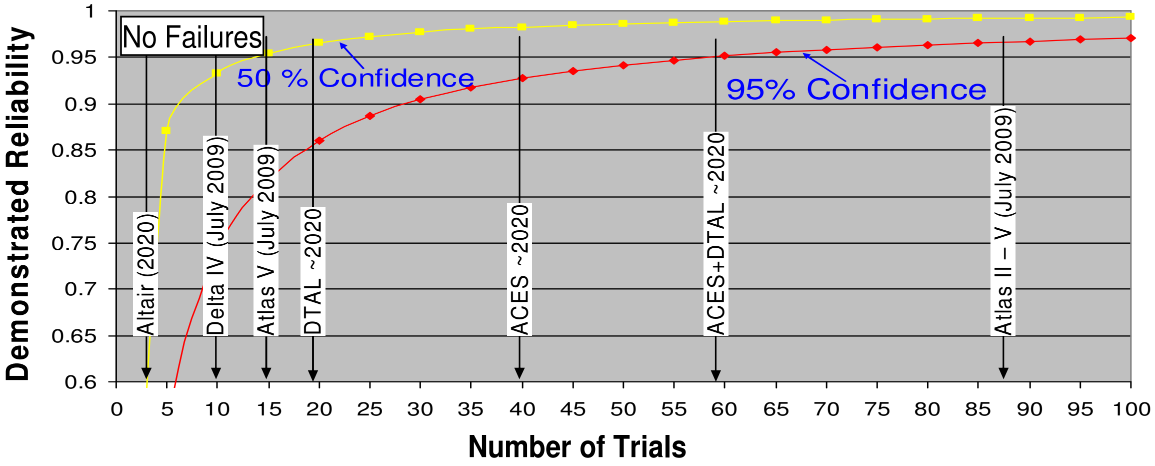

Figure 1. Flight demonstrated reliability provides the best proof of a systems ability to safely support the mission.

The unique properties of a high energy LO2/LH2 propulsion stage naturally require unique design solutions different from those successfully employed by Apollo's LEM. To enable the LH2 storage one needs to develop cryogenic propellant tanks that are not only mass efficient but also thermally efficient. All existing cryogenic propulsion systems have solved this problem by resorting to a single LH2 and a single LO2 tank linearly spaced along the stage's axis (Figure 3). This design allows for the minimum tank surface area and penetrations enabling the inevitable tank heating to be passively controlled.

Similarly, existing cryogenic systems mount the large area ratio LO2/LH2 engine(s) at the stage base, exposed to the space environment. The large, extremely hot, radiatively cooled nozzles emit enormous amounts of heat that designers need to direct primarily to space. Also, expander cycle engines, such as the RL10 must be warm prior to ignition to provide the energy required to boot-strap the pumps during the start sequence. External solar radiation provides the energy for this boot-strap process.

The challenge that lander designers face is that the combination of large high expansion ratio engines and linearly spaced tanks with the low density of LH2 result in a very tall stage, even allowing for a large diameter. Such a stage, landing vertically on the lunar surface is unstable, requiring extremely large landing legs while placing the crew and cargo dangerously high above the lunar surface.

A. Altair: NASA's Baseline Lander

With Altair, NASA followed the Apollo LEM design, clustering multiple tanks around an embedded RL10 engine (Figure 4). The Altair "storable stage design" does not account for the unique requirements of a cryogenic stage and engine:

- Insufficient energy for start due to embedding the RL-10 between multiple cryogenic tanks.
- Multiple, long feedlines requiring pre-burn chilldown.
- Severe tank heating during the burn due to close engine-tank proximity.
- Engine over heating.
- Minimal pre-launch engine access for such things as electromechanical actuators, spark ignition testing, leak checks, and possible line replaceable units (LRUs).

Figure 2. Apollo's Lunar Excursion Module utilizing dense, storable propellants consisted of multiple propellant tanks clustered in a compact system. Credit: NASA.

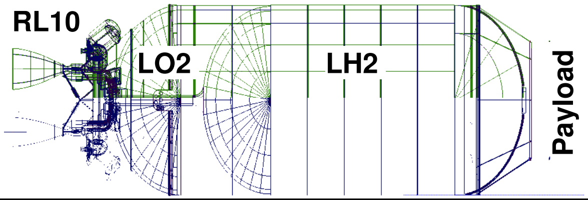

Figure 3. Current cryogenic propulsion stages contain the cryogenic LO2 and LH2 in large, sequentially spaced tanks to provide a light weight, thermally efficient system.

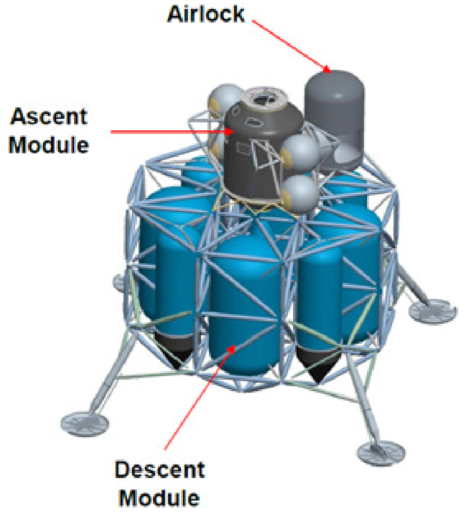

Figure 4. Vertically landing a large LO2/LH2 stage results in crew and cargo placed high above the lunar surface. Credit: NASA

- Differential tank pull-through resulting in large unusable propellant.
- Challenging tank pressure control during burns and long coast phases due to the multiplicity of tanks.
- Increased tank heating due to all of the additional penetrations.
- Severe lunar regolith entrainment in the engine plume during landing, due to placing the very large, high energy exhaust plume within a few feet of the lunar surface, resulting in severely limited visibility. The resulting high velocity debris may result in collateral impact damage to Altair or the lunar base even if separated by a significant distance.
- Extremely wide stage requiring a unique 10 m diameter payload fairing severely limiting launch options.
- The subdivided low pressure tanks that will be at minimum gauge for pump fed H2/O2 engine application with supporting truss structure, result in a much heavier stage than traditional non-subdivided, in-line stage design. The Altair mass fraction has huge impact all the way through the Exploration architecture requiring greater launch capability.

Even with the multi-tank, imbedded engine design, Altair results in the crew and cargo being over 6 m above the lunar surface (Figure 5). This configuration results in increased risks to the crew who must regularly access the lunar surface from the equivalent of a three story building. There is the potential added risk of the crew being required to work under suspended loads during cargo off-loading. For the dedicated cargo missions, the Altair design requires dedicated cranes or a building sized ATHLETE, JPL's lunar rover, to support habitat and other large cargo transfer to the lunar surface.

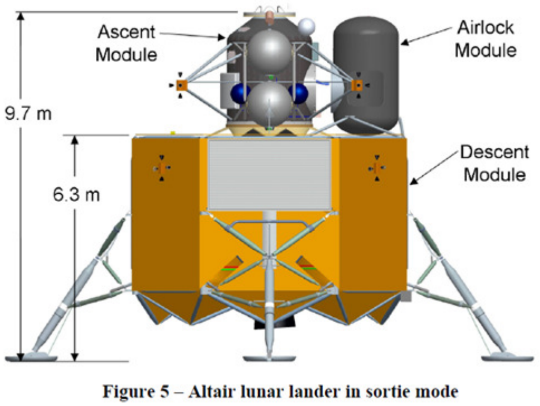

Figure 5. Even with Altair's imbedded RL10/multi-tank design crew and cargo are over 6 m above the lunar surface. Credit: NASA

B. DASH Alternative

An alternative NASA-proposed solution is to separate lunar descent and landing into two distinct functions. NASA LaRC provides such an innovative solution with their proposed DASH concept[3] (Figure 6). With DASH, the large, efficient LO2/LH2 stage is jettisoned after performing ~90% of the lunar descent, leaving the actual landing to a small, compact storable propulsion stage that might also be the ascent stage. Near surface staging provides numerous positive attributes: very compact lander, easy surface access, inherent reliability of hypergolic pressure-fed storable propellants, good surface visibility during landing, and minimal dust entrainment. The disadvantage of near surface staging is that one loses the opportunity to utilize the intact cryogenic propulsion stage hardware and its residual LO2 & LH2 to support lunar operations, and the possible lunar base damage imposed when the large propulsion stage impacts the moon.

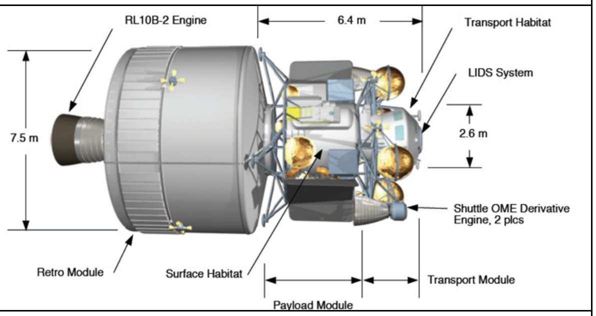

Figure 6. NASA LaRC's DASH drop stage concept solves the lander geometry dilemma by disposing of the LO2/LH2 propulsion stage prior to landing with a small storable propulsion system. Credit: NASA

C. *Dual Thrust Axis Lander*

The Dual Thrust Axis Lander (DTAL) provides another solution that addresses the conflicting requirements of descent and landing while keeping the lander intact all the way to the surface. Like the DASH concept, DTAL utilizes efficient LO2/LH2 propulsion for descent, but transitions to small engines mounted along the stage allowing horizontal landing (Figure 7)[4,5]. The use of high side-mounted thrusters for terminal descent and landing provides the pilot with a clear view of the surface, unobscured by entrained regolith, easing DTAL's ability to adjust touchdown to ground terrain (Figure 8).

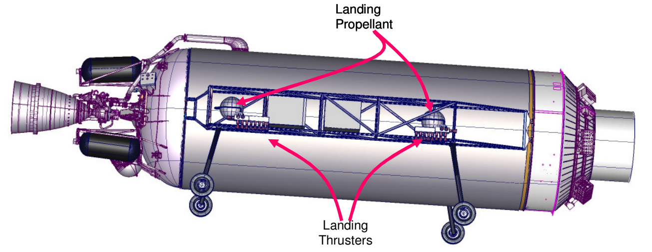

Figure 7. Horizontal landing enables an efficient LO2/LH2 propulsion system while still providing easy surface access for the crew and cargo.

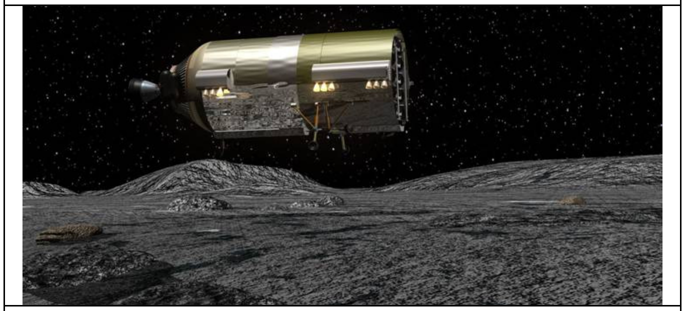

Figure 8. DTAL's provides clear surface view with minimal surface disturbance using distributed, small thrusters providing the ability for final landing location changes.

United Launch Alliance's (ULA's) Centaur and Delta IV upper stages provide an excellent cryogenic propulsion framework for developing a reliable, mass-efficient lunar lander (Figure 9). These stages have proven to be extremely robust and reliable, with Centaur boasting 87 consecutive successful flights and 187 total missions to date. The Delta IV upper stage has conducted 11 consecutive successful missions and 13 total missions to date. Both stages are propelled by variants of Pratt and Whitney Rocketdyne's RL10 engine. Enhanced RL10 engines are being proposed to power Altair and ULA's future Advanced Common Evolved Stage (ACES).

The use of these proven stages as the framework for cargo and crew landers promotes crew safety while significantly lowering technical risk and suppressing lunar lander development costs. Leveraging ULA's upper stages permits fielding landers sooner, enabling large robotic missions and lunar base deployment years before humans return to the moon. This philosophy provides a firm foundation for ensuring astronaut safety.

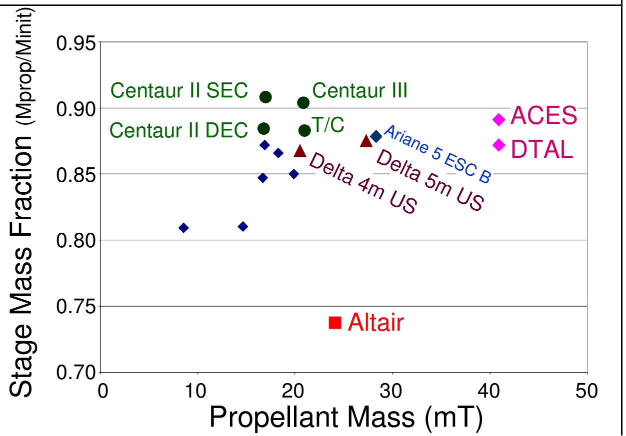

Figure 9. Lunar exploration benefits from utilizing a high mass-fraction lander derived from America's premier upper stages.

DTAL uses the RL10 to perform most of the descent burn and then rotates until its long axis is parallel to the ground. At about 6,000 feet above the lunar surface DTAL transitions to the lateral thrusters, turning off the RL10 (Figure 10). The lateral thrusters, which are aligned perpendicular from the RL10, support the final descent and terminal landing. The small, responsive lateral thrusters allow precision control of the descent and translation rates. DTAL will build on ULA's existing propellant slosh – vehicle dynamic control logic experience to ensure that induced slosh does not adversely couple with flight control system.

D. Advanced Common Evolved Stage (ACES)

ULA is in the process of defining a new upper stage that will replace Centaur and the two Delta IV upper stages. The Advanced Common Evolved Stage (ACES) is part of ULA's long-term strategy to consolidate not only upper stages but also payload fairings, facilities, processes and payload adapters. ACES is being designed primarily to provide an efficient, common platform supporting ULA's existing national security, as well as NASA science and commercial missions. Extensibility to additional transportation needs such as higher thrust, human rating and long duration missions is also being considered during this early development.

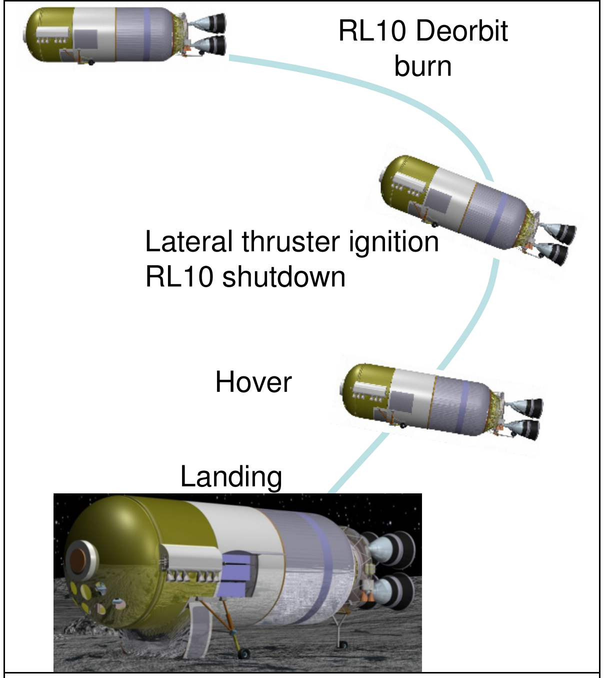

Figure 10. DTAL descent trajectory.

ACES is being designed with a larger propellant load than ULA's current three cryogenic upper stages to provide higher energy. The baseline 41 mT propellant load is contained in a 5 m diameter, common bulkhead stage that is about the same length as ULA's existing upper stages. ACES is intended to become the foundation for a modular system of stages that will meet the requirements of a wide variety of uses for space utilization from upper stages to in-space stages, propellant depots and lunar landers[6].

ACES is based on a simple modular design (Figure 11). Use of multiple barrel panels, similar to Centaur, provides a straight-forward means to building multiple-length (propellant load) stages that are otherwise common. The common equipment shelf accommodates 1, 2, or 4 RL-10 engines. ACES will take advantage of the existing Centaur and Delta subsystems such as avionics, pneumatic, and propulsion elements. The majority of these subsystems are directly transferable with little or no changes required. The ACES design is optimized with long-duration cryogenic applications in mind. A number of passive-thermal management features will be incorporated into the stage at the system level. The tank geometry is designed to minimize the exposed surface area. Through the use of a thermally isolated equipment shelf tank penetrations are being minimized. Vapor-cooling paths, where vented hydrogen is used to intercept the remaining high-load heat paths, are integrated into the tank structure.

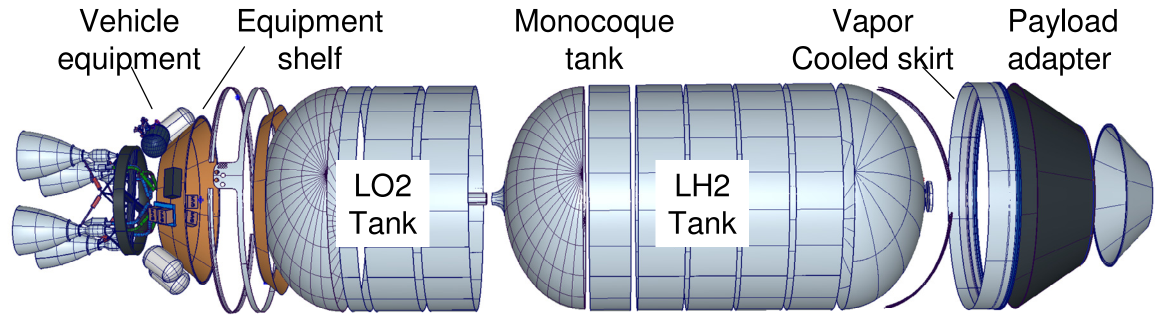

Figure 11. ULA's planned Advanced Common Evolved Stage (ACES) will fly on both the Atlas V and Delta IV boosters, enhancing mission capability while reducing costs through commonality. ACES design encompasses intended variations supporting upper stage and in-space applications such as the Earth departure stage, propellant depots, and lunar landers.

DTAL adds enhanced thermal protection, the horizontal propulsion system, landing legs and the payload module (Crew Ascender or cargo module) to the basic ACES propulsion system (Figure 12).

The lateral propulsion system provides highly responsive, multi-axis control with maximum reliability but with inherently low, throttleable thrust. This lateral propulsion system can be a pressure fed, hypergolic system derived from existing robust engines. If technology matures sufficiently, a LO2/LH2 system could be utilized for enhanced performance. The throttleable lateral landing thrusters allow precision control of the final descent and translation rates. Since nearly all the work of descent will be performed using the high-efficiency RL10 engines, the system has a low gross weight. Even substantial hover and final descent durations using the lateral thrusters do not demand onerous propellant burdens. The ability to rapidly maneuver is a clear advantage enabling selection of an optimal landing site. The distribution of lateral thrusters around the lander enables management of widely varying centroid locations which occur from mission to mission. It also permits control over residual propellant slosh behaviors as the vehicle maneuvers. The loss of a single thruster has minimal impact on system behavior, providing increasing system reliability.

The mission specific payload modules allow the highly reliable common propulsion system to dependably support both crew and cargo missions. Commonality between ACES, DTAL-Robotic (DTAL-R) and DTAL-Crew (Figure 13) ensures a high flight tempo of the basic propulsion system independent of Explorations flight rate, providing enhanced mission reliability and safety.

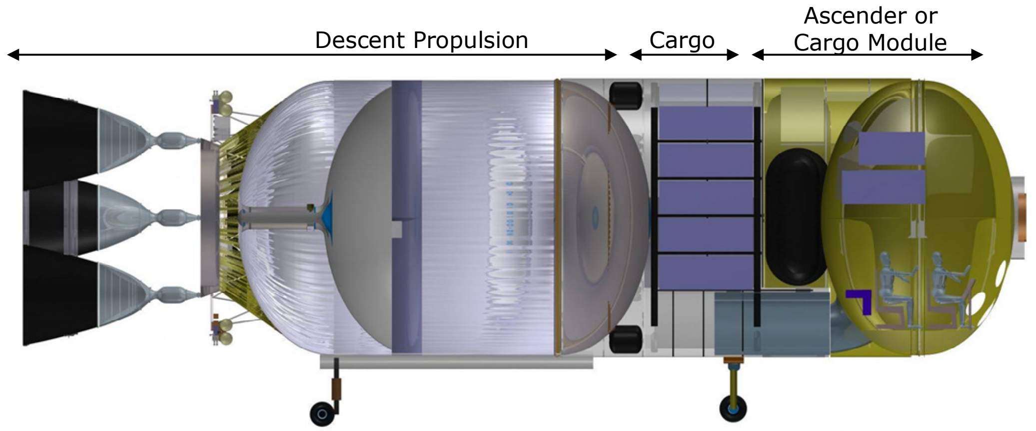

Figure 12. DTAL satisfies the competing objectives of locating crew and cargo close to the lunar surface with the requirement of a large LH2 tank and a long, high expansion area nozzle.

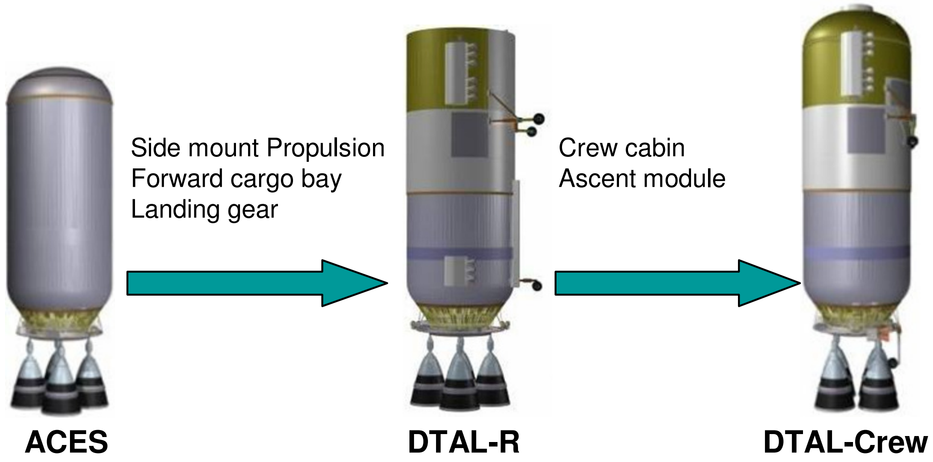

Figure 13. Commonality between DTAL-Crew, DTAL-R and ACES provide a large number of flights prior to the first crew mission will ensuring that the propulsion system design is sound.

II. LUNAR ROBOTIC AND CARGO MISSIONS

Exploration of the moon benefits from combining robotic and crewed missions. Exploratory robotic science missions provide the early, initial inspection of new locations, and enable investigation of a greater number of locations than would otherwise be possible. Subsequent larger robotic missions enable much deeper understanding and prepare for larger cargo missions deploying habitats, rovers, power systems and other elements required to support human life beyond Earth. Once people are habitually living and working on the moon, robotic cargo missions will provide the supply chain to support their daily needs.

A. Payload Accommodations and Surface Access

The proposed DTAL-R lander is ideal for these larger missions, capable of landing over 15 mT of payload depending on exploration architecture[7]. DTAL-R provides easy lunar surface access for large, oversized payloads (Figure 14). Widely spaced landing gear provides DTAL with stability even on rough or uneven terrain. This horizontal configuration results in the cargo-hold resting just 1 m above the lunar surface, providing surface obstacle clearance for all proposed landing sites.

In Figure 13, multiple 3 m long rovers are shown disembarking from DTAL-Rs cavernous 5m diameter cargo hold. DTAL-R's 5 m cargo hold and lunar performance are capable of supporting all of NASA's planned lunar surface systems, including hard shell and inflatable habitats, crewed rovers, ATHLETE, in-situ resource plants, lunar telescopes, or large drilling rigs (Figures 15). Egress is a simple matter of descending a shallow ramp to the surface.

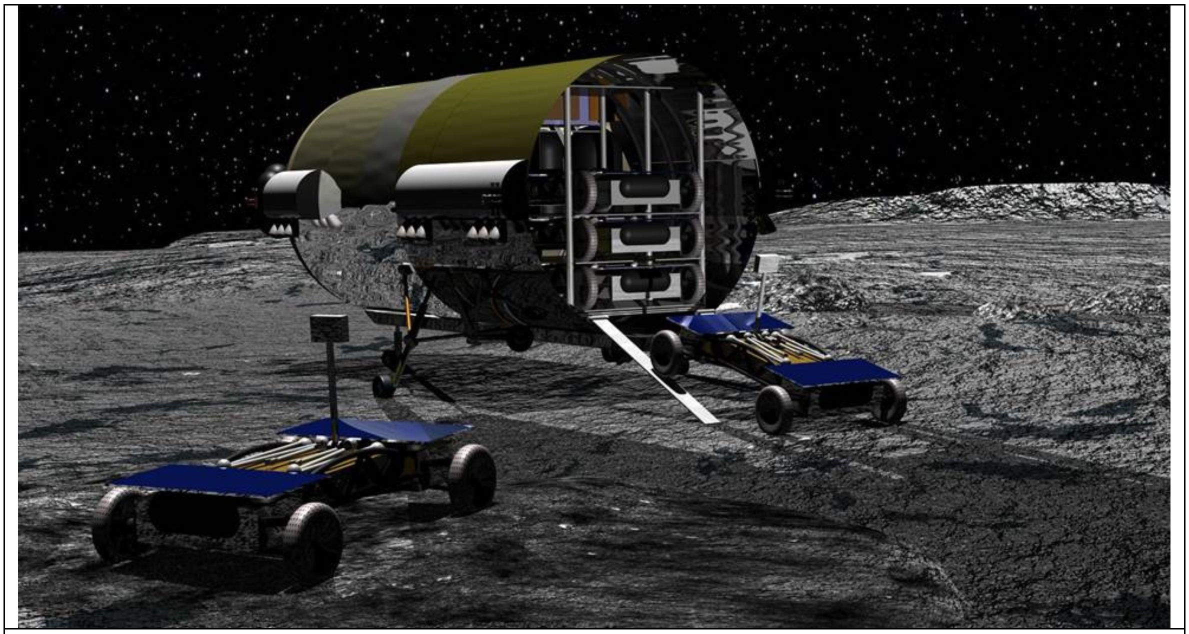

Figure 14. An optional innovative payload elevator allows multiple large robotic rovers to disembark by simply rolling down DTAL-R's ramp.

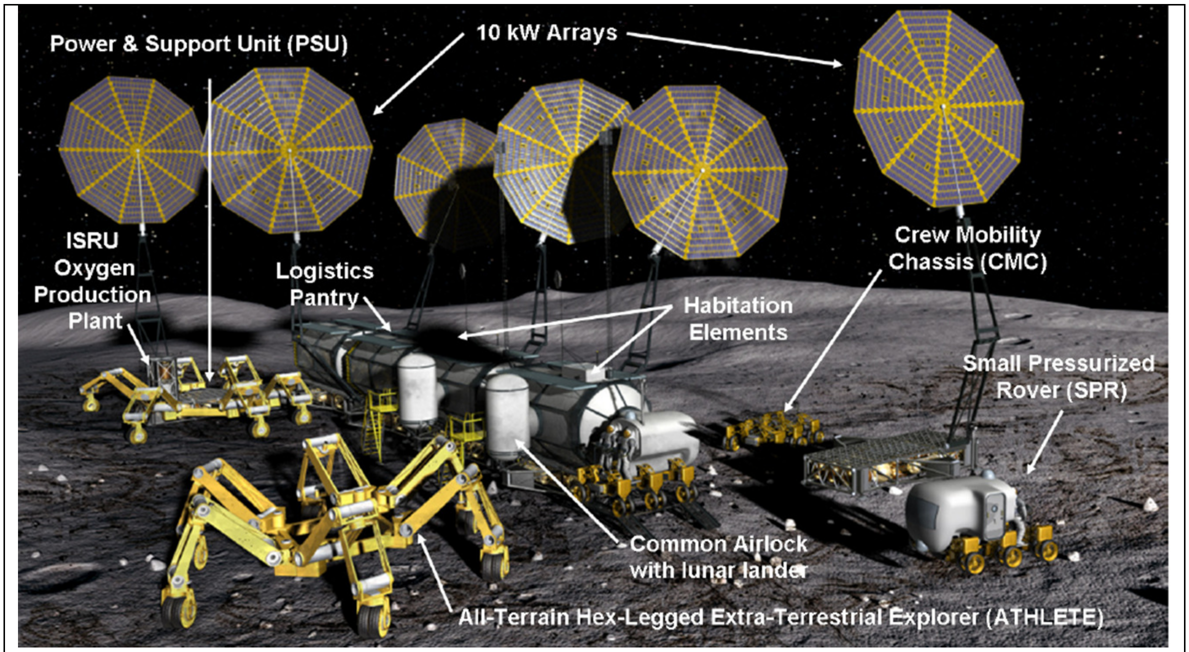

Figure 15. DTAL-R's large payload capacity supports a wide range of lunar surface systems (LSS).

DTAL-R can support NASA's most massive current lunar surface system (LSS) elements including the 9.6 mT Fission Surface Power System (FSPS).

NASA's current plan calls for the surface elements to be launched horizontally on Altair's large diameter deck inside a 10 m shroud. With DTAL-R, most of these elements would be launched axially and land horizontally on the lunar surface for easy egress. DTAL's slim 5 m diameter design is compatible with existing EELV payload fairings as well as side-mounted and in-line shuttle derived launch vehicles. At this early stage in the surface element designs, potential design modifications for vertical launch are not anticipated to be challenging.

The Lunar Electric Rover (formerly the Small Pressurized Rover) (Figure 16) with its 5m length is an example of a system that would have to be packaged vertically on DTAL-R, similar to the rovers in Figure 9.

JPL's ATHLETE (Figure 17) can be folded for flight and stowed in whatever orientation is most convenient for packaging with other LSS elements.

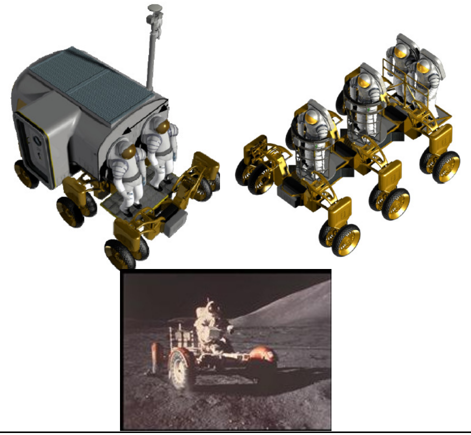

Figure 16. Lunar electric rover (pressurized or unpressurized) can be stowed vertically for launch and roll down a short ramp to the lunar surface. Credit: NASA

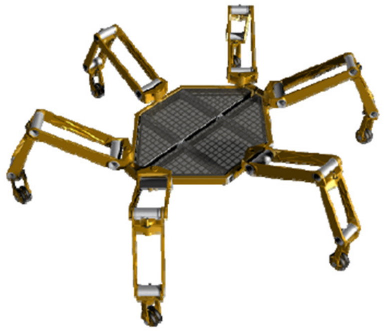

Figure 17. ATHLETE. Credit: NASA

The horizontal hard shell pressurized habitats are ~3 m in diameter and 8.4 m long, also requiring vertical integration. This geometry lends itself to packaging within DTAL-R's cargo hold. The vertical habitat modules (tuna cans) that NASA is investigating, with their 5 m diameter outer mould line (OML) would be mounted directly to the DTAL-R's front end, replacing the shown cargo module cylinder. On the lunar surface these "cans" would be rotated 90 deg to the lunar surface.

The inflatable habitats that NASA is considering (Figures 19 and 20), include a solid back bone, supplying all of the habitat services, integrated directly with the flexible habitat shell. This back-bone can either be under the habitat as in Figure 19, or take the form of rigid cylinders as in ILC-Dover's concept (Figure 20). Depending on specific habitat design these inflatable habitat's can be mounted either in the horizontal or vertical orientation.

The heaviest pressurized habitat module is currently estimated to be just under 8 mT. DTAL-R's performance capability allows NASA to grow the habitats capability, or co-manifest habitats with other LSS elements.

For human presence beyond Earth to be sustainable, we must eventually learn to "live off the land". In-Situ-Resource-Utilization (ISRU) takes advantage of local material to derive useful products. Oxygen production from lunar regolith may well be one of the first ISRU steps toward a sustainable human presence (Figure 21).

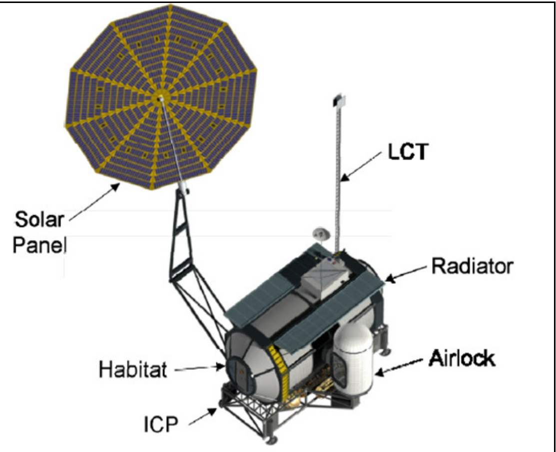

Figure 18. Hard Shell Habitat. Credit: NASA

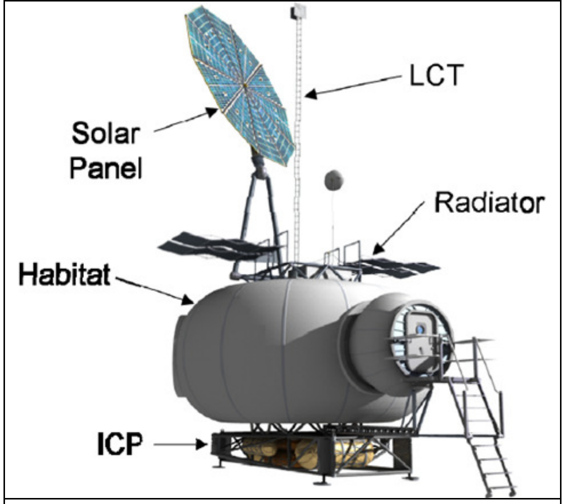

Figure 19. Inflatable Habitat. Credit : NASA

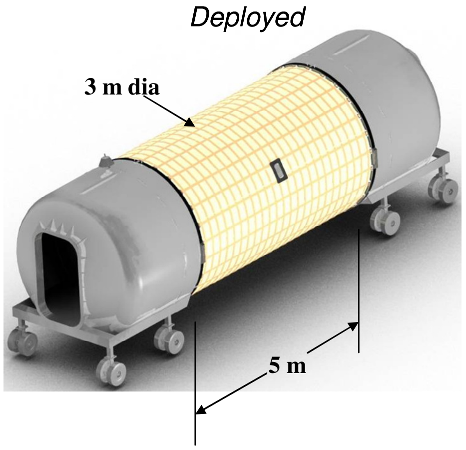

Figure 20. Inflatable lunar hab. Credit: ILC Dover

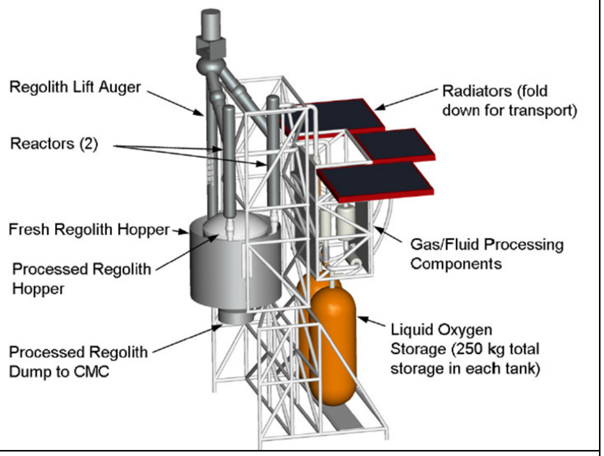

Figure 21. Oxygen production system. Credit: NASA

III. CREW MISSIONS

The principle objective of the design of DTAL is to maximize its reliability. The four RL10 engine configuration ensures that the vehicle will survive and continue the mission even with multiple engine failures (Figure 22).

DTAL-Crew's ascent module is placed far forward with a clean, unencumbered separation plane allowing for full flight abort capability (Figure 23). The clean separation plane and gimbaled lateral thrusters ensure that the ascent module can separate from the descent vehicle even under severe spin conditions and through all phases of descent.

The ACES propulsion system incorporates a robust vehicle health monitoring system. Performance of the ACES systems will be well characterized thanks to the high flight rate enabled by using ACES as an upper stage as well as supporting robotic and crew lunar landings. This vehicle characterization is critical to deciding if an abort is required. Such characterization in the actual flight environment is not possible if the stage only flies once or twice a year.

The pilots sit at the front of the DTAL-Crew cabin with downward facing, panoramic windows providing a clear view of the landing terrain. The high mounted distributed lateral thrusters minimize surface dust entrainment (Figure 24) maximizing pilot visibility throughout the descent and landing. The lateral thrusters, which are 90° rotated from the RL10, support the final descent and terminal landing. The small, responsive lateral thrusters allow precision control of the descent and translation rates.

Once on the lunar surface (Figure 25) the crew accesses the surface without ladders or other impediments through an under-belly airlock (Figure 26). The airlock deploys down and out once DTAL is on the lunar surface, similar to opening bomb bay doors on an aircraft. The airlock is very large and has two exterior doors. Being below the main cabin it acts as "dust room" where the crew can take off, clean and stow their suits prior to entering the main cabin.

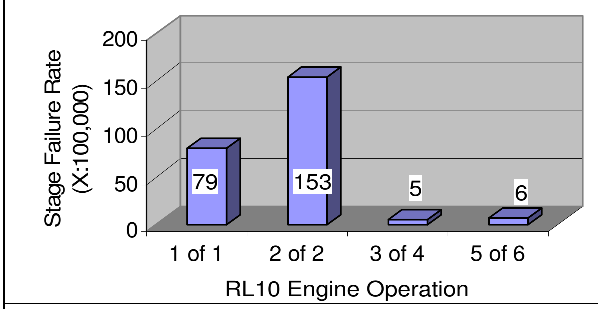

Figure 22. By incorporating engine out accommodation DTAL significantly improves mission reliability.

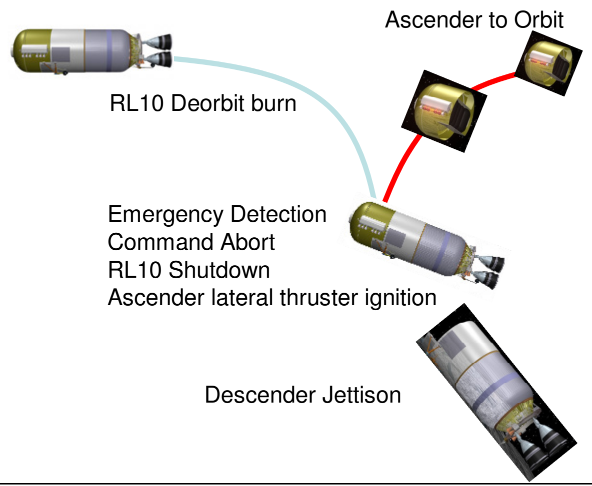

Figure 23. DTAL-Crew's clean separation plane supports full abort.

Figure 24. DTAL-Crew's forward, downward facing windows provide the pilots unimpeded view of the lunar surface during descent supporting the pilot's ability to assess the landing area for obstacles.

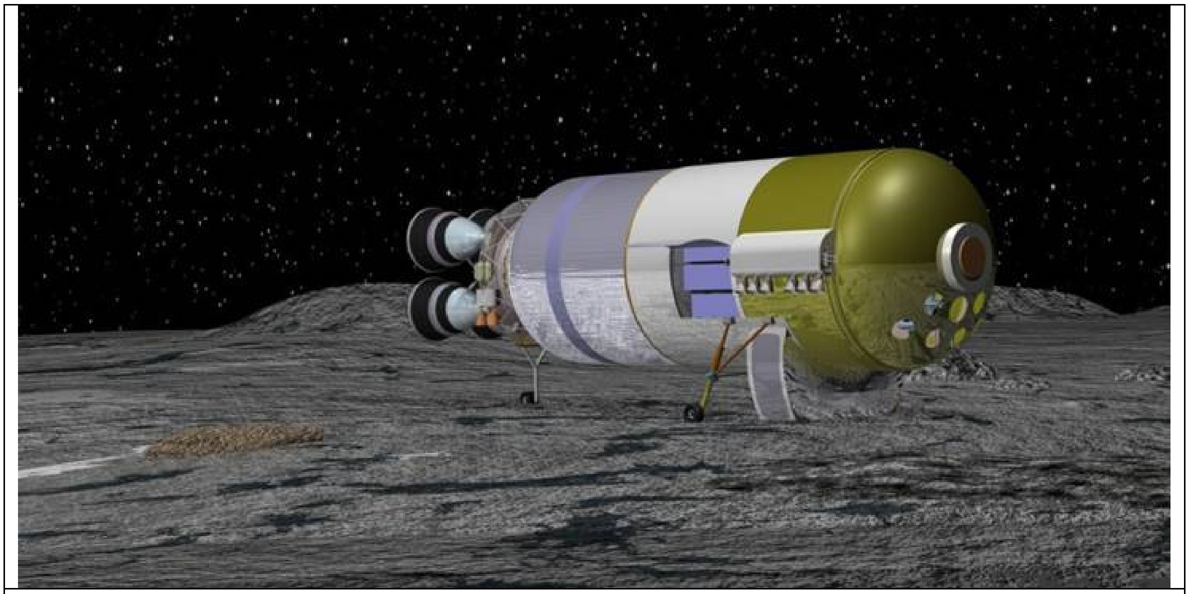

Figure 25. DTAL-Crew provides the crew easy access to the lunar surface and stowed cargo.

DTAL-Crew's unpressurized mission cargo is stored on an internally mounted moveable rack system maximizing use of DTAL-Crew's large internal vacuum cargo capacity (Figure 26). This access hatch performs the final lowering of cargo containers to the surface. This provides the crew with simple surface access to all cargo without having to engage in elaborate deployment procedures. Concerns for work beneath suspended loads are minimized.

Lander mobility will also be valuable once a lunar base has been established. When the lander touches down it will kick up high-velocity dust and rocky debris. In order to protect the base, landings will happen remotely from the base itself. Unloading and transporting the crew and cargo over this 'last mile' is a significant challenge. Alternatively, driving or towing DTAL directly to the 'front door' of the lunar base greatly simplifies surface operations. The base will require dozens of robotic cargo and crew lander missions during its lifetime. If each of these landers is left where it touches down the base will soon be surrounded by discarded descent stages, each of which must be avoided by future landers. The ability to move these spent stages to the lunar base facilitates their integration into the lunar base, the scavenging of parts, and getting the stages out of the way for subsequent missions. With proper up-front design, key elements of the DTAL, such as batteries, valves, and computers, can be specifically designed to ease their removal and reintegration with other lunar assets.

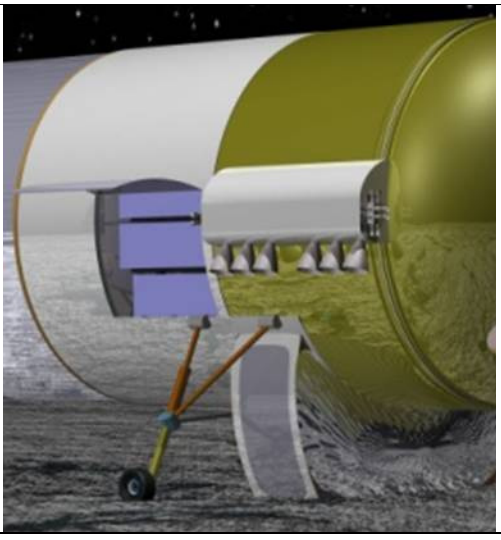

Figure 26. The airlock deploys from the bottom of DTAL-Crew providing the crew easy surface access. The cargo elevator allows the crew to access all of the cargo at chest height.

To return to lunar orbit after the surface mission the Ascender propellant tanks are brought to pressure. With the Descender stage systems stowed and umbilicals retracted the Ascender thrusters are brought to 30% power to achieve positive upload at the Descender/Ascender separation interface. Commanding separation, the Ascender then ramps up thrust, departing the lunar surface and descent vehicle at a steep angle (Figure 27). With this benign separation orientation the

Ascender does not directly blast the spent descent stage with its engine plume allowing the descent stage to be preserved without damage for potential future use.

The arrangement of propellants and distributed multiple thrusters on the Ascender minimizes center of gravity movement and accommodates widely varying amounts of residuals, up-cargo or variations in crew complement.

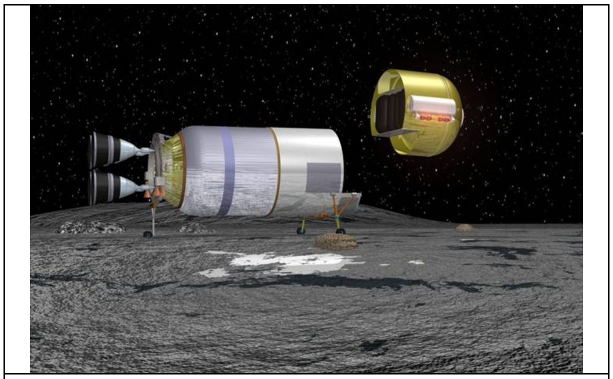

Figure 27. DTAL-Crew's ascent module interface provides a clean separation plane. The lateral thruster placement minimizes impingement of remaining hardware during departure, minimizing damage and allowing the remaining hardware to be used for surface needs.

B. Ascender Crew Cabin and Ascent Vehicle

The Ascender (Figures 28 and 29) provides the capability for extended crew operations on the lunar surface. The cabin is 4.5 m (15 ft) in diameter with nearly 28 m^3 (1,000 ft^3) habitable volume divided between the 7.5 m^2 (80 ft^2) lower flight deck area and the 8.5 m^2 (92 ft^2) upper flight deck area. The primary pressurized structure is composed of efficient axis-symmetric elements that benefit from internal pressure stabilization. Behind the pressure compartment is a simple equipment cylinder for supporting main terminal descent and ascent propellants, pressurants, avionics, and ECLSS hardware. The main ascent thrust loads, distributed by the multiple thrusters, are efficiently reacted into the Ascender cylindrical elements tangent to the structure. The Ascender interfaces to the Descender propulsion stage via a simple cylinder optimized for low thermal conductivity and weight.

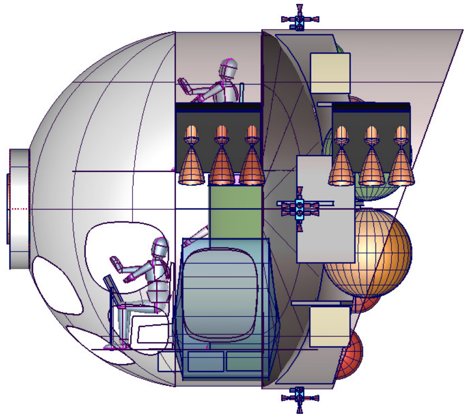

Figure 28. The Ascender integrates the crew cabin and ascent propulsion into a compact, efficient structure.

To the extent practical, systems not required for ascent are mounted on the Descender stage. Until the ascent to lunar orbit, the Ascender receives all of its power from the Descender as well as breathing-oxygen, water and cooling capacity. With the copious power available it is practical to pump down the airlock instead of simply venting the gas during each airlock cycle, supporting a demanding lunar surface schedule. To replace atmospheric nitrogen, redundant nitrous oxide (N2O) tanks provides N2O fluid, which is catalytically reacted to form supplemental breathing air (oxygen and nitrogen) and also nitrogen to pressurize the N2O4 propellant tanks. Dozens of airlock cycles can be accommodated with onboard stores of O2 and N2O supporting robust surface operations for sortie missions.

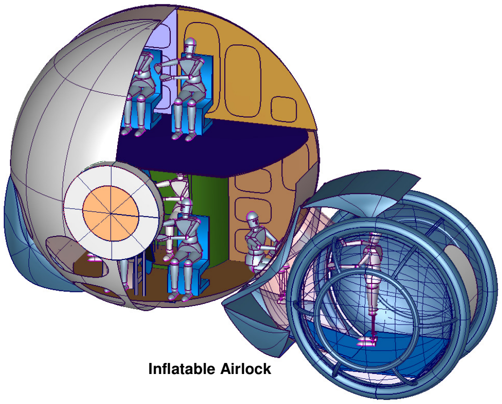

Figure 29. The crew cabin accommodates four astronauts on the lunar surface and includes a large soft-shell airlock at ground level.

This basic crew cabin can be enhanced to support extended deep space missions to NEO's or potentially even Mars.

IV. EXTENSIBILITY

A. *O2 and H2 Residuals*

The most obvious and easiest DTAL resource to use on the lunar surface is residual propellant, O2 and H2. O2 and H2 store vast amounts of energy that can readily be tapped using fuel cells. Fuel cells can provide power for rovers through the day or even the crew during the extended lunar night. One kilogram of H2 + O2 provides 2 kilowatt hours of power. The water effluent from the fuel cells provides potable water for the crew and is stored for future electrolysis to support mission power requirements. The oxygen gas is also useful as breathing air.

	O2	H2	
Unusable gas	300	100	Kg
Trapped liquid	60	30	Kg
Flight performance reserve	1,000		Kg
Launch development margin	>1,000		Kg
Payload development margin	>1,000		Kg
Dedicated cryogen delivery	As required		

Table 1. Expected DTAL O2 and H2 available for use on the lunar surface.

Cryogenic stages invariably retain large quantities of unusable O2 and H2 at the end of a mission consisting of ullage gases and trapped liquids. Beyond unusable propellant all missions retain mission margins to accommodate off-nominal dispersions, flight performance reserve (FPR) and development margins (Table 1). Missions may allocate additional reserves to accommodate mission unique requirements. Any remaining payload development margin will translate into performance excess that will now be available in the form of excess O2 and H2 for lunar surface use.

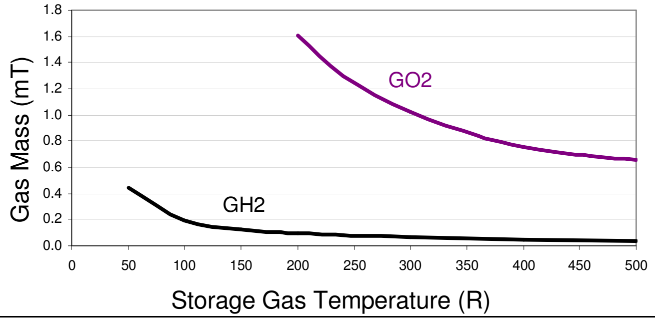

Figure 30. Shallow cooling will allow storage of substantial quantities of O2 and H2 in DTAL's tanks. Figure assumes either H2 or O2 fills both propellant tanks for lunar storage.

The helium typically used to pressurize propellant tanks is a contaminant that complicates use of residual O2 and H2 in a fuel cell. ULA is currently developing the integrated vehicle fluids (IVF) system that will allow ACES and DTAL to replace this helium with autogenous pressurization improving mission performance while easing DTAL's surface use of the residuals. IVF utilizes the O2 and H2, efficiently stored in the propellant tanks, to support all propulsion, attitude control, pressurization and power requirements efficiently supporting numerous burns and long duration missions.

B. *DTAL Tanks to Store H2 and O2*

The large, well insulated DTAL cryogenic propellant tanks are excellent vessels in which to store the prodigious quantities of regenerative O2 and H2 gas converted from water electrolysis. The waste product from fuel cells is water, readily collected and stored. During the lunar day this water can be electrolyzed back into the constituent gases, O2 and H2. Storage of useful quantities of gas is a challenge, requiring heavy high pressure bottles, liquefying the gases, or vast volumes. Use of high pressure bottles requires dedicated delivery of these heavy elements to the lunar surface. Liquefying and storing the gases is very energy intensive, especially during the hot lunar day when solar power is available.

The DTAL propellant tanks conveniently provide very large volumes within which to store the gases. Even with these large tanks, gas cooling will be required to store useful quantities of gas. Through the use of sun shields and shallow refrigeration one can efficiently store these gases (Figure 30).

C. *Use of the Large LH2 Tank on the Lunar Surface to Increase Habitat Volume*

The ISS demonstrates the weight penalty of habitat volume to support crew (Table 2). NASA's Constellation program is planning numerous dedicated lunar missions to deploy this habitable volume. From the beginning of the Space Shuttle program people have discussed fully orbiting the Space Shuttle's External Tanks (ET) and using the tanks for habitat volume. DTAL's large monolithic H2 tank may be effectively converted for use as habitable volume. Common convention suggests that converting large cryogenic tanks into habitable space requires significant effort in the form of human labor, not readily available in space. This is one of the reasons why the ET conversion concepts were never realized. However, if the H2 tank is already connected to a "node" prior to launch it may be possible to simplify the conversion process. With proper planning, complex wiring, plumbing or carpentry will not be required to convert the DTAL-R LH2 tank into productive space. The conversion could be as simple as opening the access hatch and adding lighting and ventilation, connected to pre-launch installed pass-throughs and internal tank mounted hooks allowing the tank to support productive crew use. Addition of modular dividers, shelves, beds and other simple fixtures will enhance the benefit of such use.

	Habitable Volume	Mass
ISS habitat (Harmony[8])	75 m^3	14 mT
Altair[9]	17.5 m^3	-
Orion[10]	20 m^3	14 mT
Lunar habitat (Hard Shell[2])	78 m^3	8 mT
Lunar base (Outpost[2])	234 m^3	8 mT
DASH[2]	14 m^3	y mT
BA 330[11]	330 m^3	23 mT
DTAL Ascender cabin	28 m^3	-
DTAL LH2 tank	100 m^3	0 mT

Table 2. Converting DTAL-R's LH2 tank into habitable volume can be enabled with proper planning to provide large crewed space compared to alternative solutions.

Figure 31 shows what LH2 tank conversion might look like. The forward, "payload" habitat node includes the entire infrastructure to support people, environmental control and life support system (ECLSS), bathrooms, showers, galley, etc. fully integrated on Earth. A tunnel leading aft to the DTAL LH2 tank would open up a lot of extra habitable volume once on the lunar surface. Prior to opening the node-tank connecting tunnel, the H2 tank would be vented to evacuate any residual H2 and allowed to warm up to room temperature and filled with air.

Converting DTAL's tank for living space once on the lunar surface offers a mass "free" habitat. This very large volume compares very favorably to habitable volumes provided by ISS, Altair, Orion, proposed lunar habitat volumes, LaRC's proposed DASH lander or even Bigelow's planned Sun Dancer module (Table 2). The conversion of the LH2 tank support crew quarters provides an attractive option for the start or addition to a lunar base.

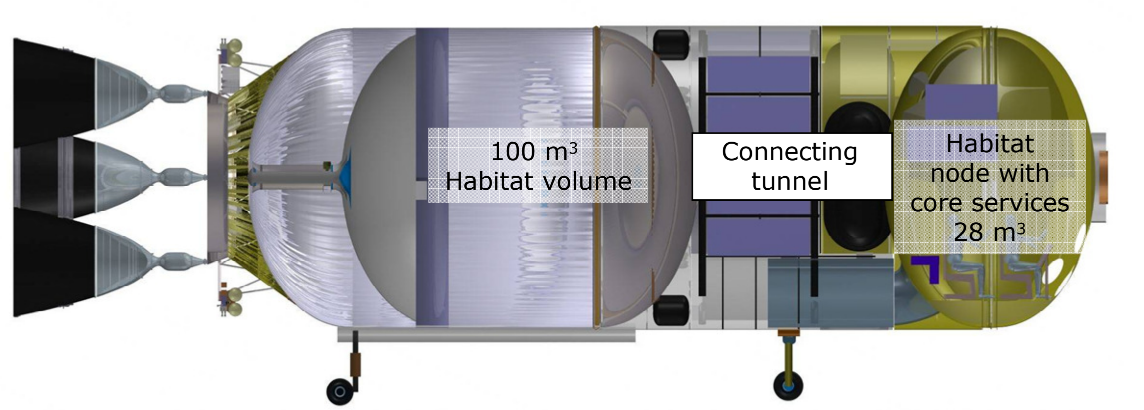

Figure 31. DTAL-R out fitted for LH2 conversion to habitat volume.

V. SUMMARY

The establishment of robust human presence on the moon before 2020 is a completely attainable goal and it can be achieved at costs that are consistent with NASA's existing budget[7]. This affordable, exciting future is enabled through the use of an open transportation architecture and by building on America's existing cryogenic upper stages to develop the lunar lander.

DTAL's cryogenic propulsion system builds on over four decades and 200 cryogenic in-space flights to provide a robust, mass and thermally efficient stage supporting reliable lunar surface access for crew and cargo. Through the use of mission-specific payload modules, ACES, DTAL-R and DTAL-Crew share a highly reliable common propulsion system. This commonality ensures a high flight tempo independent of Exploration's flight rate or destination, demonstrating the propulsion system a dozen or more times annually. This robust flight tempo supports a well utilized, highly seasoned launch team while enabling active learning of the stage supporting continuous improvement. The large number of flights provides a vast data base of nominal operating conditions enabling the health monitoring system to provide accurate determination of pending problems and command crew abort if required.

The in-line tank-engine design caters to the unique characteristics of LO2/LH2 tankage and the large high area ratio engines. By minimizing tank surface area and penetrations combined with a simple geometry easing implementation of MLI and vapor cooling DTAL provides a cryogenic system that can passively support very long duration cryogenic storage. The single LH2 and LO2 tank system simplifies the pneumatic system increasing mission reliability. The in-line structural design provides a superior mass fraction stage that improves the robustness of the entire Exploration architecture. The slim, 5-m diameter design is compatible with existing EELV's as well as side-mount and in-line shuttle derived launch vehicles.

Preliminary analysis indicates that DTAL-R is compatible with all of NASA's planned lunar elements including large habitats, rovers, power systems and ISRU plants. The horizontal landing enabled by DTAL's dual propulsion system provides easy surface access for even the largest payloads, eliminating the need for unique surface handling equipment such as cranes and completely avoids crew risk associated with working under suspended loads. Early DTAL-R missions can support large robotic exploratory missions and emplace major lunar base elements prior to the first crew missions. This enables a robust lunar infrastructure enabling long duration crew stays from the beginning of America's return to the moon.

Crew safety was of utmost importance in the development of the DTAL concept. Commonality with ACES and DTAL-R ensures that the crew's first mission to the moon will be on a lander with a large proven successful track record. Placement of the pilots forward with panoramic, downward facing windows ensures that the pilots have complete situational awareness as they descend and touch down on the lunar surface. The small, high mounted lateral thrusters minimize dust entrainment and associated loss of visibility during the critical terminal descent and landing. These small lateral thrusters provide the crew with unparalleled maneuverability enabling late course changes to avoid surface obstacles. The clean interface between the Ascender and descent modules enable anytime abort, right down to the lunar surface.

The reliable DTAL propulsion stage provides the flexibility to visit destinations other than the moon. DTAL's mass and thermal efficient design provides the capability to visit NEO's or possibly even Mars. By supplying the life support commodities from the large primary propellant tanks long duration missions are possible.

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