A Commercially Based Lunar Architecture

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The present ESAS architecture for lunar exploration is dependent on a large launcher. It has been assumed that either the ARES V or something similar, such as the proposed Jupiter "Direct" lifters are mandatory for serious lunar exploration. These launch vehicles require extensive development with costs ranging into the tens of billions of dollars and with first flight likely most of a decade away. In the end they will mimic the Saturn V programmatically: a single-purpose lifter with a single user who must bear all costs. This programmatic structure has not been shown to be effective in the long term. It is characterized by low demonstrated reliability, ballooning costs and a glacial pace of improvements.

The use of smaller, commercial launchers coupled with orbital depots eliminates the need for a large launch vehicle. Much is made of the need for more launches- this is perceived as a detriment. However since 75% of all the mass lifted to low earth orbit is merely propellant with no intrinsic value it represents the optimal cargo for low-cost, strictly commercial launch operations. These commercial launch vehicles, lifting a simple payload to a repeatable location, can be operated on regular, predictable schedules. Relieved of the burden of hauling propellants, the mass of the Altair and Orion vehicles for a lunar mission is very small and can also be easily carried on existing launch vehicles. This strategy leads to high infrastructure utilization, economic production rates, high demonstrated reliability and the lowest possible costs.

This architecture encourages the exploration of the moon to be conducted not in single, disconnected missions, but in a continuous process which builds orbital and surface resources year by year. The architecture and vehicles themselves are directly applicable to Near Earth Object and Mars exploration and the establishment of a functioning depot at earth-moon L2 provides a gateway for future high-mass spacecraft venturing to the rest of the solar system.

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Acronyms

ACES	Advanced Common Evolved Stage
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
CRYOTE	Cryogenic Orbital Testbed
DTAL	Dual Thrust Axis Lander
DTAL-R	Dual Thrust Axis Lander - Robotic
DTAL-Crew	Dual Thrust Axis Lander - Crew
ECLSS	Environmental Control and Life Support Systems
EDS	Earth Departure Stage
ESAS	Exploration Systems Architecture Study
g	Earth's Gravity
GHe	Gaseous Helium
GH2	Gaseous Hydrogen
GO2	Gaseous Oxygen
IMLEO	Initial Mass to Low Earth orbit
Isp	Specific Impulse
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
LS	Lunar Surface
LSAM	Lunar Surface Access Module
L2	Earth-Moon LaGrange Point 2
MLI	Multi Layer Insulation
MMH	Monomethyl Hydrazine
MSFC	Marshall Space Flight Center
mT	Metric Tons
NASA	National Aeronautics and Space Administration
NTO	Nitrogen Tetroxide
N2O	Nitrous Oxide
PMD	Propellant Management Device
SM	Service Module
TEI	Trans Earth Injection
TPS	Thermal Protection System
ULA	United Launch Alliance

I. LUNAR ARCHITECTURES AND OPTIMIZATION

Table 1. NASA's current architecture has a plethora of unique propulsion elements adding to the development and sustainment costs while reducing mission availability.
Ares I 5 Segment Booster
Ares I Upper Stage
Ares V 5.5 Segment Booster
Ares V Core
Ares V Earth Departure Stage
Orion Service Module
Altair Descent Vehicle
Altair Ascent Vehicle

To date the debate surrounding the optimal architecture to support a lunar exploration program has centered around which heavy lift booster should be used to lift the apparently stupendous masses of material that are required for real exploration beyond the scope of Apollo. The ESAS architecture has lead to the demand for not one but two heavy lift boosters, two large upper stages, a large lunar descent vehicle, another unique Orion service module and a lunar ascent vehicle, Table 1. These machines share minimal commonality and require multiple propellant combinations and four main engine types. Each requires a separate development program with attendant costs approaching $100 billion followed by a profusion of long term support contracts to support just a couple annual flights of each element.

The ESAS architecture and other similar ones such as Lunar Direct are focused so tightly on the lift capability that they almost wholly lose sight of the overall system operation and indeed of the costly overheads and real-world problems with supporting a huge number of vehicle configurations at low utilization rate into the indefinite future. These architectures are almost wholly intolerant of the inevitable changes that occur to their proposed payloads. The demand to lift another 3 tons of material from LEO to the lunar surface poses a huge, almost insurmountable obstacle. This means that performance is effectively limited by the architecture- it is incapable of adapting to changing needs. It is simply assumed that you have to live within the highly prescribed boundaries of the architecture and its many pieces.

Architecture Support Costs

Perhaps uniquely among aerospace companies, ULA currently operates an entire stable of rocket types- ranging from low-end Delta II rockets, to the Atlas family and the Delta IV HLV. As such we have a unique perspective on the operation of many distinct vehicle types. We operate three distinct booster types and four upper stages, three upper stage engine and strap on solid types and over a dozen types of payload adapters and fairings from six launch pads. We are confronted on a daily basis with the relentless pressures of supporting these diverse product lines with a proliferation of ground support systems, design philosophies, construction methods, integration methods, analysis techniques and cargo types. While our team can call upon enormous resources to resolve problems and keep up with a demanding launch schedule it is a prime goal for our company to reduce, simplify and streamline our product lines. Indeed, ULA was formed largely as a method to consolidate the over abundance of American launch assets to reduce costs for our customers. As such ULA has consolidated management and engineering in Denver, will consolidate production to Decatur in 2010 and is in the process of defining our upper stage/payload fairing and sub-system consolidation to one or two systems.

Without a change in operational direction the Lunar Exploration efforts are progressing in a direction which will very nearly mimic this unaffordable and inefficient situation. The USG will be bound to a vastly complex suite of hardware that will make the present Space Shuttle system look streamlined by comparison.

In the Constellation exploration architecture a problem in any element tends to ground the remainder of the system since they all must be joined in LEO. Hence contractual problems with attendant unpredictable and escalating costs and protracted schedules can rapidly become the rule. The logistical impact of the moon's restricted launch windows can amplify these problems. A failure to meet performance demands in one area will inevitably propagate to affect nearly all systems- amplifying cost problems.

II. ARCHITECTING FOR SUSTAINABILITY

The big space exploration question facing NASA and the nation is: Can a viable lunar architecture be designed that avoids huge development and sustaining costs while being flexible and efficient?

Development and Sustainment Costs

We believe that through embracing commercial competition and the partnership between NASA and industry that the answer is "yes". Robust, flexible, affordable exploration is not only possible, but must be pursued to sustain the interest of the American public and their substantial funding commitment.

The guiding philosophy that we have followed in developing the proposed sustainable exploration architecture is to use the least number of distinct elements. This meant not only all-up vehicles but the least number of main engines, avionics systems, fluids systems, ECLSS systems, etc. By keeping the many elements as common as possible development is foreshortened and costs suppressed. Recognizing that each vehicle has unique functions it had to perform in addition to functions it shared with all other elements flexibility and modularity had to be built in.

Significantly the vehicles had to be useful for as many tasks as possible- not just moon missions. In this way the development and overhead costs would be shared by NASA, DoD and commercial customers. The production rate would rise due to high utility and supplier component costs would fall, while the increased launch tempo improves system reliability. A distribution of demand from multiple sources would also stabilize launch rates and smooth out disturbances from program-peculiar issues.

Of greatest importance was the ability to compete as many functions as possible in a marketplace. As much of the architecture as possible must be a commodity- something that many suppliers can provide. Without competition the suppliers to NASA would be in an eternal monopoly position- not a recipe for cost containment or innovation. This is the precise situation that is lamented today. The architecture needs to create a situation where many companies can make a business case close- a reliable, predictable demand with a calculable cash flow and good returns. If this is in place then continuing development costs will be undertaken commercially, allowing government investment to focus on the actual exploration mission rather than spending 90% of NASA's exploration budget on space transportation as is currently the case.

Public Utility

One of the anchors of sustainability is that a project must benefit many users. To date, the manned space program has been effectively pitted against a wide range of unmanned scientific activities in the yearly battle for limited resources. The present Shuttle system was never able to deliver utility for scientists sending probes to Mars or Jupiter. It is simply too expensive and risky to use for the mundane purposes of placing a weather satellite into orbit. However with the right architecture for lunar exploration all users benefit. The key here is to create the functional equivalent of a highway- a tool that everyone can use and whose cost is borne in proportion to the user's demand. With Exploration leading this transformation new opportunities in space utilization, such as manufacturing, tourism and solar power satellites may finally be realized.

Lunar Transport Basics, Safety and Reliability

It is easy to be dazzled by the drama of astronauts lifting off on a pillar of flame but most of the work of going to the moon is just about moving propellants. At least 70% of the job of launching mass to LEO, the first step on the way to the moon, is moving the liquid hydrogen and oxygen we will need for the subsequent steps. Because of its magnitude, moving propellant is far and away the most important element of any lunar architecture but it is often wholly ignored. It is crucial that the handling and moving of propellants be very efficient. The more efficiently propellants are delivered for all the various purposes the greater the overall system affordability and performance. To a lesser extent this is also true of cargo- the tools and consumables needed for lunar operations.

Conversely the movement of crew, the most visible activity from the public perspective, is nearly invisible from the transport perspective. Because of the low crew mass the efficiency of their transport can be compromised in the interests of optimizing for safety and reliability. In an effective architecture this will not materially affect the bottom line performance.

A pragmatic approach to crew safety must be taken based on hard won experience. Despite the best engineering design and analysis activities it is amply clear that even highly vetted designs such as the Space Shuttle can fail catastrophically. Probabilistic analyses are spectacularly flawed in that they make sweeping assumptions about failure modes and the means to prevent them. Nature relentlessly renders these complex analyses moot when we find another hidden failure mode via flight experience. Ground testing can assure a baseline level of confidence but only extensive flight experience can truly generate a safe vehicle with high confidence in its overall reliability. Aircraft flight testing relies implicitly on this principle.

Our approach to crew safety is to combine rigorous design and test processes with machines that have the highest possible utilization and repeated prior exposure to more intense environments. The vehicle systems must have transitioned beyond the early phases of flight experience and generated a repeatable performance database. Designs must have been used, even abused and remained intact in the face of adversity before being entrusted with human lives. This is really the only way to maximize real-world reliability.

III. ARCHITECTURE CONCEPT

The lunar architecture proposed is summarized in Figure 1 and is based on three fundamental tenets:

I. Use of a common in-space propulsion stage
II. Optimal separation of logistical and crew transport activities
III. Use of propellant depots and equipment/cargo caches

The architecture is illustrated using ULA vehicle concepts for convenience. In reality, no single industrial entity can entirely support this architecture. The production and launch rates are simply not sustainable by a single team. It must be a concerted effort of several launch providers, perhaps a consortium linking industry and NASA.

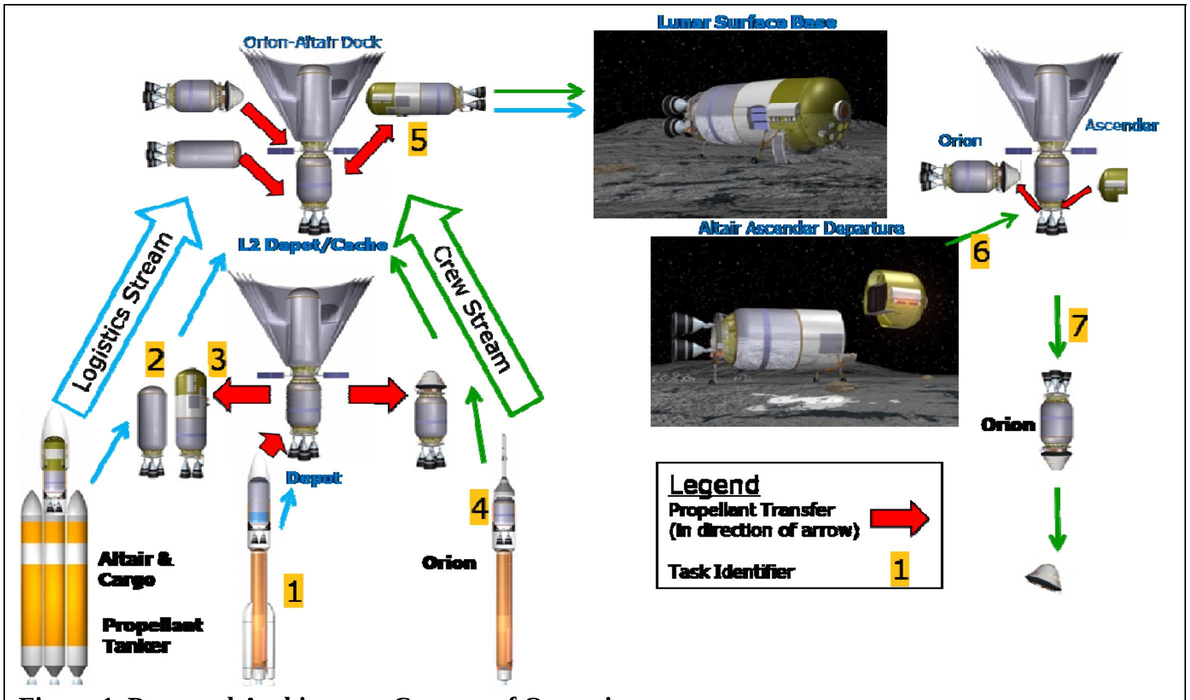

Figure 1. Proposed Architecture Concept of Operations

Common In-Space Propulsion Stage Concept

The proposed lunar architecture is based around a common propulsion stage derived from an upper stage being developed by ULA. Shown in Figure 2, it is called ACES (Advanced Common Evolved Stage) and is expected to replace the three existing cryogenic upper stages presently being used at ULA. Containing 41 mT of liquid hydrogen and liquid oxygen it is powered by four RL10 class engines. ACES builds on over 200 flights of Centaur and Delta, fusing technologies from both programs: sharing the Delta IV 200" tank diameter but with a common/nested intermediate bulkhead. ACES uses tank geometry, low conductivity tank structures, passive thermal protection and vapor cooling to suppress cryogenic propellant loss to boil-off. Since it is wholly protected from aeroloads during launch a thick MLI blanket surrounds every exposed surface.- drastically reducing external heating. ACES has no helium or hydrazine systems- all pressurization, attitude control and power is generated by consuming its two main propellants. Most importantly ACES is designed to be refilled with propellants once in space.

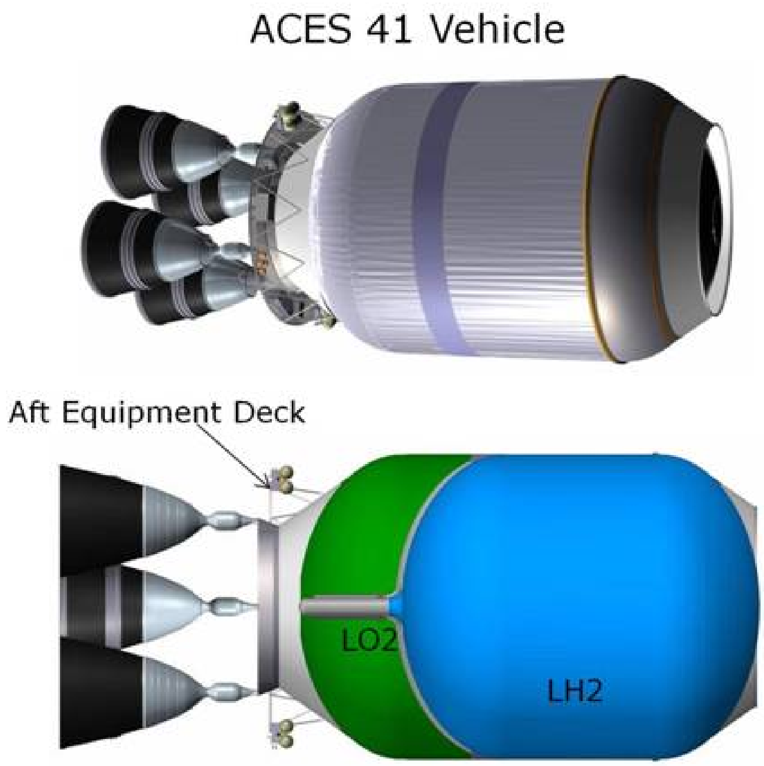

Figure 2. ACES provides a light weight, thermally efficient propulsion system that can provide the foundation for all of explorations in-space transportation needs.

The 41 mT ACES propellant capacity is sized for usage with DoD, NASA science and commercial payloads. Because ACES sub-systems are concentrated on an aft mounted equipment deck the propellant capacity can be readily modified through changes in tank side wall length. However, thanks to the use of propellant depots lunar exploration can efficiently be accommodated with as few as two tank volumes, the basic 41 mT ACES and a stretched 71 mT variant.

It is proposed that ACES provide the basic propulsion system backbone for all of Explorations in-space transport needs. While ULA may provide this basic propulsion foundation, it is envisioned that NASA and its support contractors will add all of the mission unique elements enabling the four primary in-space propulsion functions:

1) As the Service Module propulsion system for Orion- ACES/Orion
2) As the Descent Propulsion system for Altair- ACES/Altair
3) In a stretched configuration as a Propellant Tanker (71 t total capacity)
4) In a stretched configuration as a Propellant Depot (14.6 t LH2 capacity)

ACES/Orion Service Module

In the Orion Service Module configuration, (Figure 3) an ACES 41 is mated to an ECLSS module and the Orion Command Module. ACES provides its own power and that for Orion by consuming its ullage gases. Solar arrays and dedicated radiators are unneeded- ACES provides these services. Attitude control is provided by ACES working in concert with the Orion RCS. The Orion-peculiar services such as N2 replenish , CO2 scrubbing and voice communications are provided by the ECLSS module.

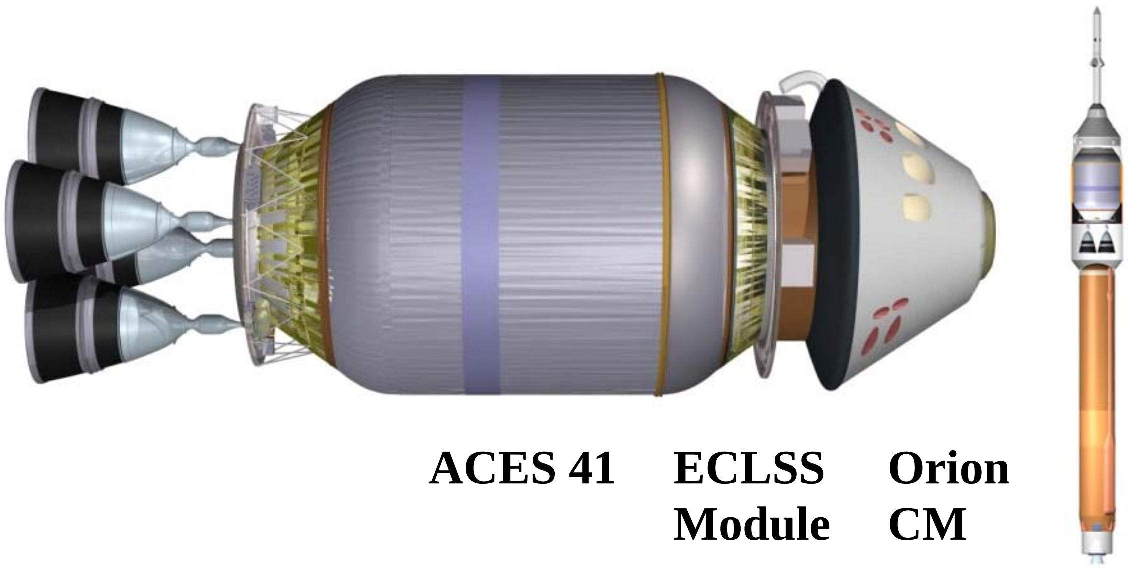

Figure 3. ACES/Orion Vehicle Assembly.

ACES/Altair

In the Altair configuration, (Figure 4) ACES 41 is mated to a Lunar Cargo Module or the Crew Ascender as well as multiple 1,000 pound thrust lateral-facing engines and landing gear for the final hover and landing phases[1].

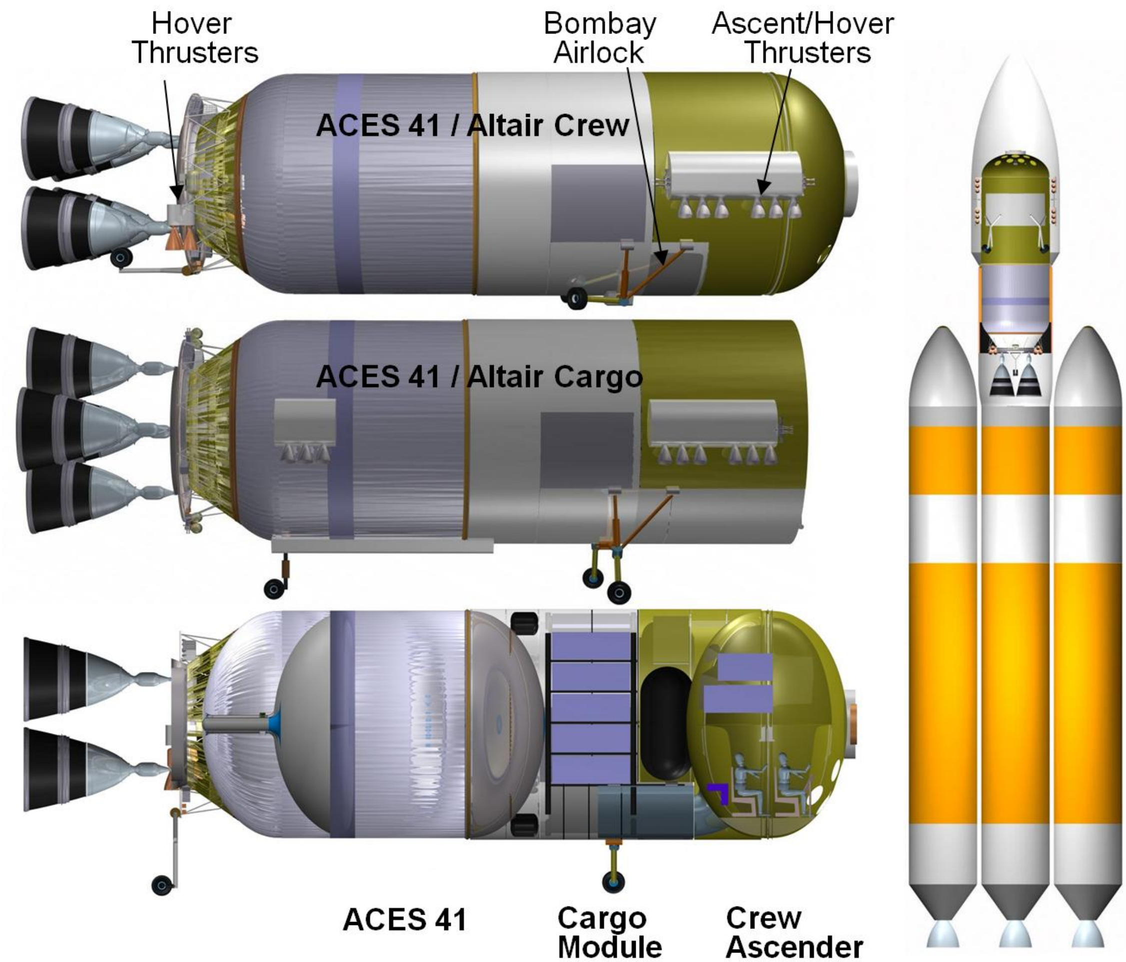

Figure 4. ACES/Altair Vehicle Assembly.

ACES Tanker

In its simplest and most common configuration the ACES tanks are stretched so that they contain 71 tons of propellants. Shown in Figure 5, this ACES 71 vehicle has no payload attached and uses the very simplest of payload fairings. Its principle purpose is to deposit or remove propellants from a depot. The ACES tanker is capable of supporting propellants that are subcooled. Subcooling of the LH2 and LO2 allows propellants to absorb heat while stored in LEO without saturation pressures rising excessively. This permits extended storage times in high heating conditions without suffering excessive mass losses.

Figure 5. ACES / Tanker Vehicle Assembly.

ACES Depot

The ACES depot shown in Figure 6 is an ACES 41 mated to a modified ACES 71 Tanker. The tanker has a shifted intermediate bulkhead to maximize LH2 storage. The main engines have been removed and a high performance deployable sunshield installed. The LH2 storage element is launched empty as a payload on an Atlas 554 or Delta IV HLV. Because it is not filled with cryogenic propellants on the ground it can dispense with external conductive insulation such as foam. Its thermal protection is strictly optimized for vacuum operations. The depot provides the multiple interfaces for transferring propellants to and from the docked vehicles and can supply power and support services to those vehicles for extended periods. As shown in Figure 7 multiple Orion, Altair and tanker vehicles can be simultaneously docked. The proposed architecture relies on two depots - one in LEO and the other at L2.

Being an empty shell the depot is extremely light, weighing approximately 12 mT. Launched on a Delta HLV results in nearly 20t of residual propellant remaining in the ACES 41 upper stage. Once in LEO, the ACES-41 residual LH2 is transferred into the LH2 depot tank. The ACES-41 LO2 residuals are then transferred to the now empty ACES-41 LH2 tank, after the tank has been evacuated of any residual H2.

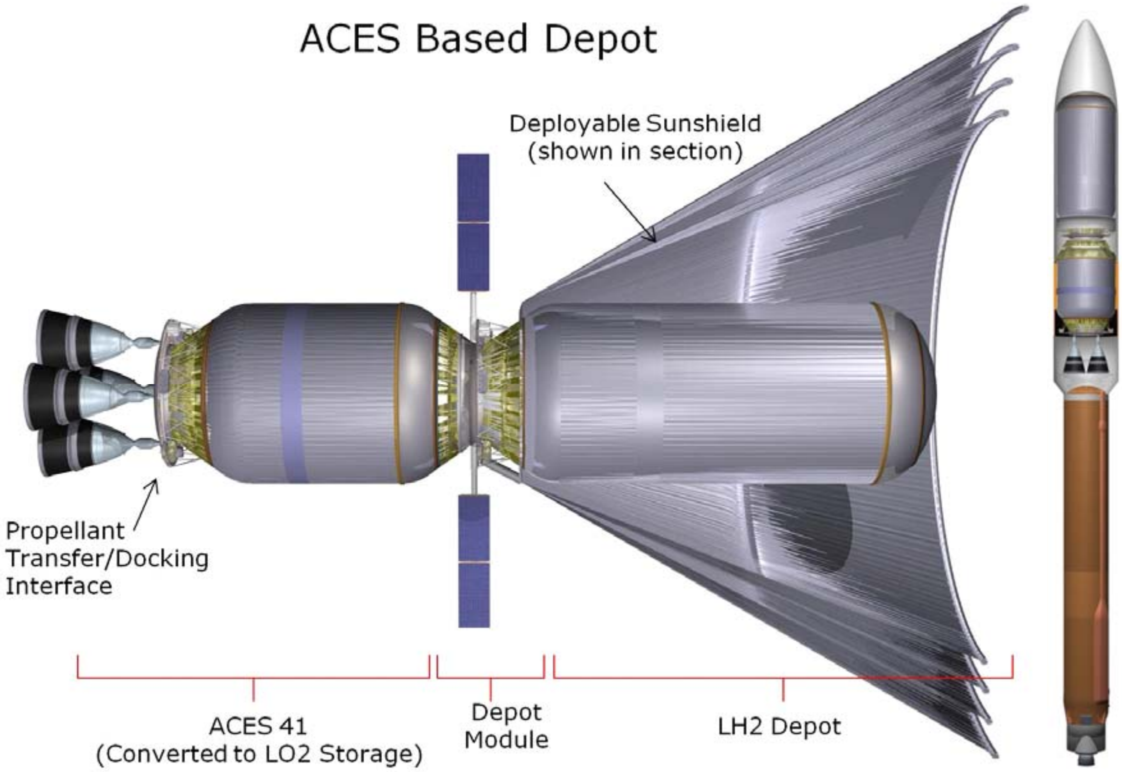

Figure 6. ACES/Depot Assembly.

The ACES depot that is moved to L2 begins its journey just the same as the LEO depot. It and its linked ACES 41 upper stage are topped to the maximum extent at the LEO depot and then the ACES 41 four RL10's execute the burns to transport the depot to L2. Subsequent tanker flights top the depot. Each LEO to L2 tanker transit delivers 29 mT of propellant to L2 where the propellant is consolidated into a single depot. The spent stages perform a small disposal maneuver leaving L2.

Propellant loss rates in LEO are suppressed using passive TPS. The depot is designed to primarily boil-off and vent GH2 due to its factor of 10 higher thermal capacitance than GO2. This vent GH2 is used in LEO to satisfy the substantial station keeping requirements. Indeed with a well designed TPS the boil-off and station keeping needs are nearly balanced resulting in minimal loss.

With its far lower heating rate the depot at L2 can establish near-zero boiloff losses- amounting to a few pounds per day which also nearly matches the minimal station keeping requirements at the quasi stable L2.

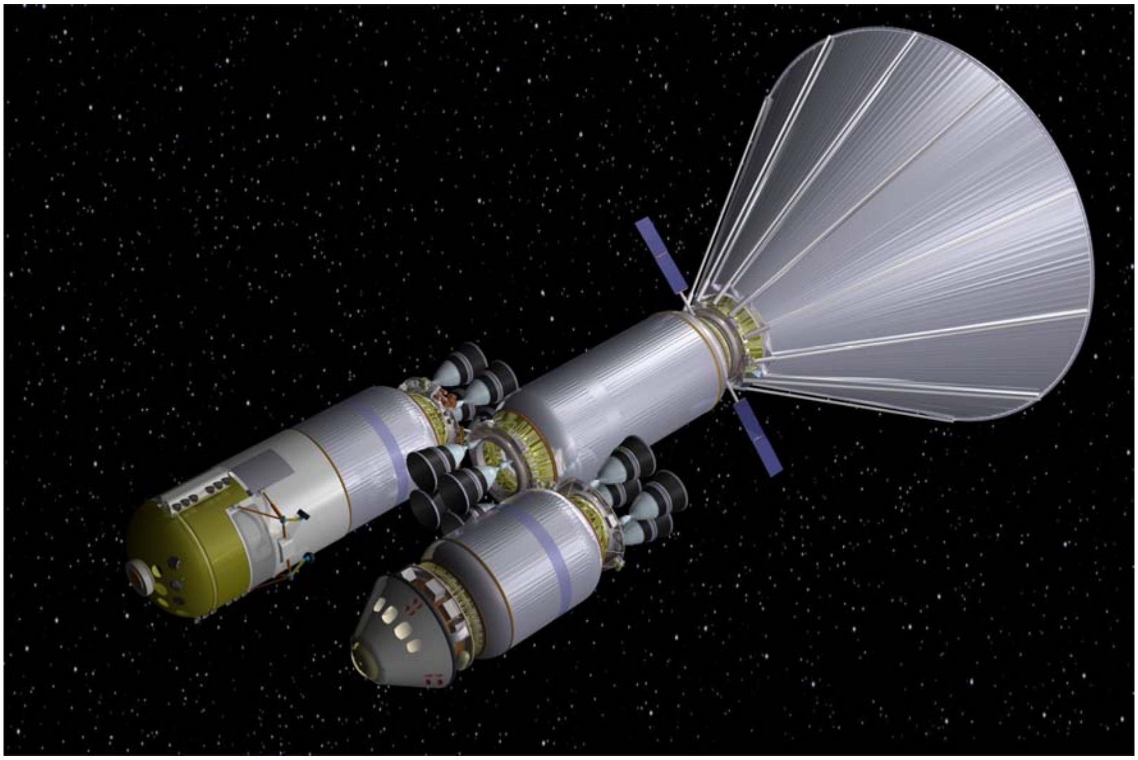

Figure 7. L2 Depot with Orion and Altair Docked

Mass and Performance Summary

The various nominal masses of vehicles and their various cargos and modules are summarized in Table 1. Table 2 summarizes the various vehicle assemblies and their basic performance capability.

Table 1. Basic Element Mass Summary.

Vehicle Element/ Assembly	Dry Mass, tons	Propellant Capacity, tons
Basic ACES 41	5	40.8 @ 5.25
Basic ACES 71/ Tanker	5.5	70.7 @ 5.0
Orion Command Module	6.0	
Orion ECLSS Module	2.0	
Orion Crew & Associated Cargo	1.0	
Altair Cargo/Descent Module	2.0	
Altair Ascender	3.0	4.0 @ 6.0
Altair Light Cargo	3.5	
Altair Heavy Cargo	20.0	
Depot Systems Module	3.0	
ACES Depot (2 docked ACES)	12.5	121

Table 2. Vehicle Assembly Mass & Performance Summary.				
Vehicle Assembly	**Total Mass**	**Delta V Capability m/sec**	**Nominal Delta V Demand, m/sec**	**Nominal Residual Propellant**
ACES/Orion @ LEO Departure	54.8	5600	4400	5
ACES/Orion @ L2 Departure	17.0	1400	800	1.4
ACES /Altair @ LEO Departure	58.3	6300	3500	13
ACES/Altair @ L2 Departure	59.0	5000	2900	16
ACES/Altair Cargo @ LEO Departure	74.8	3900	3500	3.0
ACES/Altair Cargo @ L2 Departure	66.5	Variable	2900	4.0
ACES/Tanker @ LEO Departure	76.2	11350	3500	29.0
Ascender @ Lunar Departure	7.5	2900	2650	.4

IV. LUNAR TRANSPORT OPERATIONS- TWO PATHS

There are seven primary transport tasks in this architecture highlighted in Figure 1. The first three constitute the logistics stream and are executed in a fundamentally commercial nature. The final four are the crew transport stream conducted by NASA with support from industry partners. An anchor concept of this architecture is that the logistical and crew transport activities can be substantially decoupled from one another and conducted asynchronously. Of course depot activities must be scheduled and spacecraft movements choreographed but the schedule for the delivery of 10 tons of LO2 to the LEO depot is effectively independent of what is happening with Orion or on the lunar surface. The logistical stream drives to maintain full depots and the consistent movement of tools, consumables and propellants out of Earth's gravity well and up to locations of increasing utility including the lunar surface.

The Logistics Stream

There is an underlying principle to this architecture that distinguishes this method of transportation from other approaches: the maximum performance of each vehicle is always extracted. In a typical non-refueled architecture stages such as the EDS must be designed to pump in the desired delta V for the maximum payload mass under worst case conditions. If the payload is lighter or there is a favorable launch window, or the stage performs better than worst case many tons of propellant are thrown away at staging. The unburned propellants are lost to us and provide no utility. With the proposed system a lighter cargo means that we deliver more propellant to the depots. A high performing stage has a direct and measurable benefit and a particular cargo that is lighter than maximum is not wasting the vehicle capability. The excess performance at each step of the way makes propellant a kind of currency that can be applied to downstream needs.

Task 1: Move Propellant to Low Earth Orbit Depot

This is the dominant commercial task and is expected to be done by the widest possible range of launchers and providers (Figure 8). Whichever launcher delivers propellants for the lowest cost becomes the dominant player, though it is prudent to retain a number of launch providers to ensure propellant delivery in the event of delays. The cost of this activity is a significant proportion of the lunar exploration yearly bill constituting ~75% of the Earth to orbit launch mass. NASA can use competitive pressures to control and even reduce the bulk of its Exploration expenditures. With competitive propellant launch one can expect launch prices to drop over time.

This is an area ripe for startup space launch companies since the value of the cargo is effectively nil. A failure of a low maturity booster does not result in loss of high value, irreplaceable payload and with multiple launch providers such a delay has no impact on the pace of the overall Exploration mission. It also suggests a debut function for single-stage to orbit, reusable vehicles which initially will likely have low lift capability. The ability to deliver even 1000 lbs of LO2 to a depot once a day with reusable equipment would likely be superior to a single expendable launch every month. In rough terms a total propellant delivery of 30 tons/month is baselined for this architecture as described in Section VII.

It can be argued that the dispersion of launches beyond the use of ACES based vehicles undermines the common stage tenet of the architecture. However with the launch pace inherent in this architecture the benefits to reliability and cost will be accrued even if a large number of LEO tanker launches are conducted on non-ACES vehicles. For the purposes of this study we have assumed that propellant is delivered using either an Atlas booster with 5 solids and an ACES 71 tanker or a Delta or Atlas HLV with the same tanker. These vehicles are able to deliver 26 or 34 tons of propellant to LEO, respectively.

Task 2: Move Propellants from LEO to L2

The higher heating rate in LEO motivates us to move propellants onward as rapidly as possible to the better thermal storage conditions at L2. It is a very basic "use it or lose it" proposition. The capacity of the LEO depot drives us to execute a propellant transfer to L2 roughly once every other month. This transfer can be done either with a dedicated ACES Tanker or by simply supporting the onward movement of Altair or Orion vehicles. Because of the excess performance of the ACES 41 stage for the Orion and Altair LEO to L2 segments effectively every flight to L2 and the moon is a tanker mission to a lesser or greater degree.

For dedicated propellant transfer operations, roughly every third tanker launch continues on to L2 (Figure 8). Instead of depositing propellants at LEO the ACES Tanker takes on 30- 50 tons from the LEO depot (depending on the launcher capability) and then burns to L2 in a low delta V, longer flight time trajectory. This LEO to L2 trip consumes 41 mT of propellant, enabling the gradual accumulation of propellants at L2 at the rate of roughly 29 mT per trip.

While the proposed architecture uses the direct approach of moving propellants via traditional chemical propulsive means, the door is left open to more efficient techniques such as solar thermal or solar electric propulsion. With a thermally efficient propellant storage system such a vehicle could readily move even larger propellant stores to L2 and accomplish it with less expendable hardware. The cost of transit to L2 can be thus addressed by competitive means. With a well-defined, stable mission task these presently exotic propulsion systems can justify greater investment to mature their designs. Their promise of lower transport costs could finally be realized. Once again a significant part of the Exploration task is addressable with competitive pressures and technological leverage to bound operational costs.

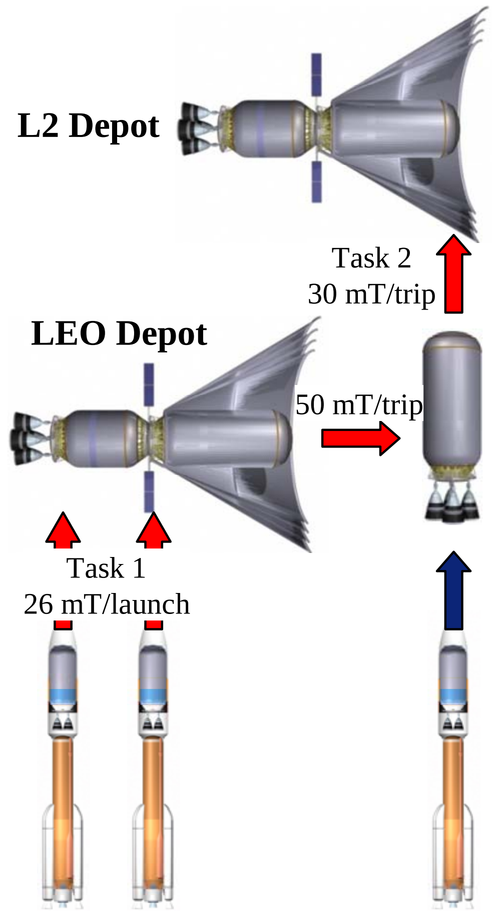

Figure 8. A constant flow of propellant through the LEO depot to the L2 depot supplies the L2 depot and lunar operations.

Task 3: Move Altair and Cargo to Lunar Surface

The most complex commercial activity is the delivery of Altair vehicles and their cargo to the moon. Long before a crew arrives many tons of hardware is prepositioned for their use on the lunar surface. This includes rovers, radiators, solar power systems, gas handling and compressor systems, excavating equipment and other bulky cargo and consumables. Figure 9 shows a landed Altair cargo vehicle dispensing multiple robotic rovers.

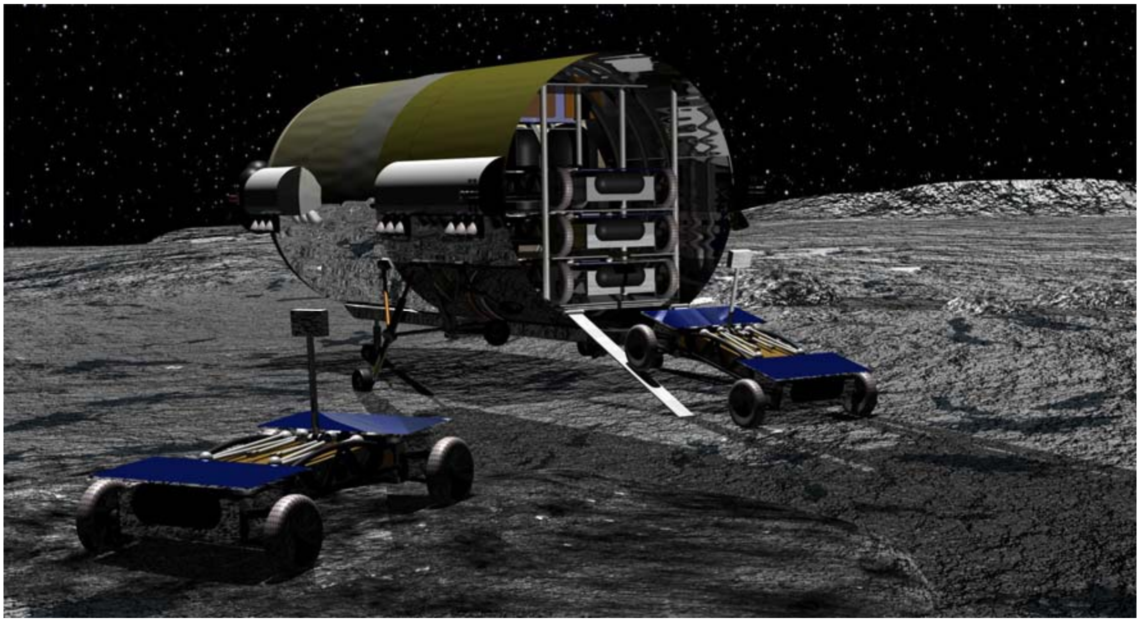

Figure 9 Altair-Cargo Vehicle Discharging Cargo

ACES/Altair is launched on a Delta IV HLV booster with ACES/Altair replacing the Delta IV upper stage providing a total LEO lift mass of 36t. Refueled from the LEO depot the ACES/Altair can deliver in excess of 30 tons of combined cargo and vehicle mass to L2. Generally however it arrives at L2 with substantial propellant residual. If the Altair is intended to be cached at L2 for future crew use it deposits its propellants into the depot for efficient long term storage.

The ACES/Altair is loaded or topped from the L2 depot just prior to lunar descent. This includes the loading of the Ascender propellant tanks which are used during the terminal hover/landing phase. Fully loaded, it can deliver a combined mass of vehicles (such as the ascender), cargo and unused propellants greater than 40t to the lunar surface.

The ACES tanks on the landed descenders are used for cryogenic propellant storage on the lunar surface and just as at L2 they gradually build their stores. The cycle of power generation would be established with fuel cells active during the lunar night and solar systems during the day. The conversion of water to the reactants and back in rhythm with the lunar day would be established. The support of a substantial crew on the lunar surface requires the storage, handling and transport of industrial quantities of reactants, water, sewage, nitrogen, scrubbed CO_2, etc. The landed descenders each have substantial capacity to support the storage and processing of these materials and with each landing the ACES tanks are added to this lunar base tank farm. The ability to close the local ecosystem would gradually increase with a subsequent reduction in lost mass. Transfer of fluids between tanks is enabled by the ability to move the ACES/Altair after landing. It can be driven or towed to be adjacent to other landed vehicles so their systems can be joined.

From a safety and reliability standpoint the entire Altair function will have been demonstrated multiple times before a crew flies on one. Confidence in the Altair will be the best that can be attained. Predictable heating rates and boiloff losses are essential to long term surface stays and these can be highly variable depending on vehicle attitude, illumination and the site itself. The thermodynamic performance of Altair systems will be well known and understood long before a crew arrives. The proper function of environmental control, power and all other systems will be demonstrated on the actual hardware prior to the crew relying on it.

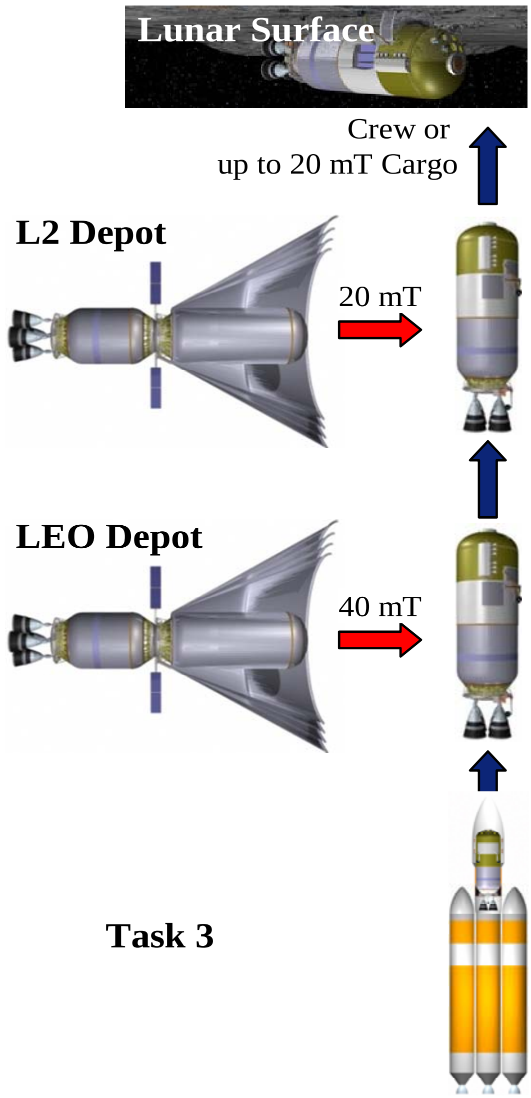

Figure 10. Through refueling in LEO and L2 the DTAL can safely land 4 crew or up to 20 mT cargo on the lunar surface.

The Crew Transport Stream

Task: 4 Move Crew to L2

The departure of the crew from Earth to the moon is the highest visibility activity and is accomplished under the direct control of NASA but using the same propulsion hardware as for Tasks 1 and 2, maximizing the demonstrated reliability and cost benefits. The ACES/Orion is launched on the simplest, most reliable Atlas vehicle, one without solids and with engine out capability on the ACES upper stage. The performance of this stack is such that approximately 11 mT of mass can be delivered to LEO, sufficient for the Orion capsule with the ACES stage supporting the service module function.

Once refueled at the LEO depot the ACES/Orion can execute a high delta-V rapid transfer to L2 and arrive within four days. All residual ACES/Orion propellants are transferred into the L2 depot for long term storage. This allows the ACES/Orion to be kept in cislunar space for extended periods without suffering intolerable propellant losses associated with a cryogenic service module. While ACES/Orion is docked to the L2 depot, all station keeping, power and other systems maintenance services are provided by the depot.

Task 5: Move Crew from L2 to Lunar Surface

The ACES/Altair is loaded just prior to departure from L2 depot. The high propellant capacity of the ACES vehicle allows either an accelerated transit from L2 to the lunar surface or the delivery of large amounts of propellant to the lunar surface for usage there. Cargo is minimized since much will have been prepositioned by prior Altair landings thus giving the crewed Altair the highest possible performance margins.

With a deliberately low cargo burden on a crewed Altair the amount of propellants delivered to the surface and available for consumption there is in excess of 10 mT. The total amount of landed propellant dictates the surface stay duration since it bounds the amount of breathing air, power and water that is available to the crew. Figure 11 shows the ACES/Altair landed with cargo hatches open and its unique bomb-bay style airlock deployed.

Figure 11. Landed ACES/Altair Vehicle.

Task 6: Move Crew from Lunar Surface to L2

The Altair ascender proposed by this architecture uses a propulsion system burning the same LH2 and LO2 propellants as the ACES descent stage. The propellants are loaded just prior to their usage. They are stored for the duration of the surface stay inside the highly insulated and thermodynamically efficient ACES descent tanks. A tanking just prior to departure to L2 mimics what is done on Earth for launches to LEO where the rockets are fueled hours prior to departure. This greatly simplifies the thermal control systems on the ascender at the cost of a few pounds of propellants for tank chilldown.

Instead of the bulky single engine concepts traditionally proposed the ascender will use 12 smaller chambers each with a 1000 lb thrust capability with throttling to approximately 30% power. The chambers are fed from twin pumps driven by a hybrid gas-generator cycle. Their location permits the ascender center of gravity to vary substantially – a significant challenge for single engine designs. The rocket exhausts are peripheral to the ascender and do not impinge on the descender – hence the descender systems remain intact and ready for use at the lunar base. Figure 12 shows the ascender departing the lunar surface.

The ascender burns to L2 where it docks and dumps its residual propellants into the depot. The ascender is kept at L2 depot for future reuse when mated to an arriving Altair stage. In this way the delivery of a new Ascender for each crew is avoided- saving substantial cost.

Task 7: Move crew From L2 to Earth

When a crew is ready to return to earth the ACES/Orion tank is filled from the L2 depot to approximately 10% of capacity. A short duration burn initiates the transfer to Earth. It is entirely possible to execute this with the onboard RCS system rather than the RL10 engines if desired.

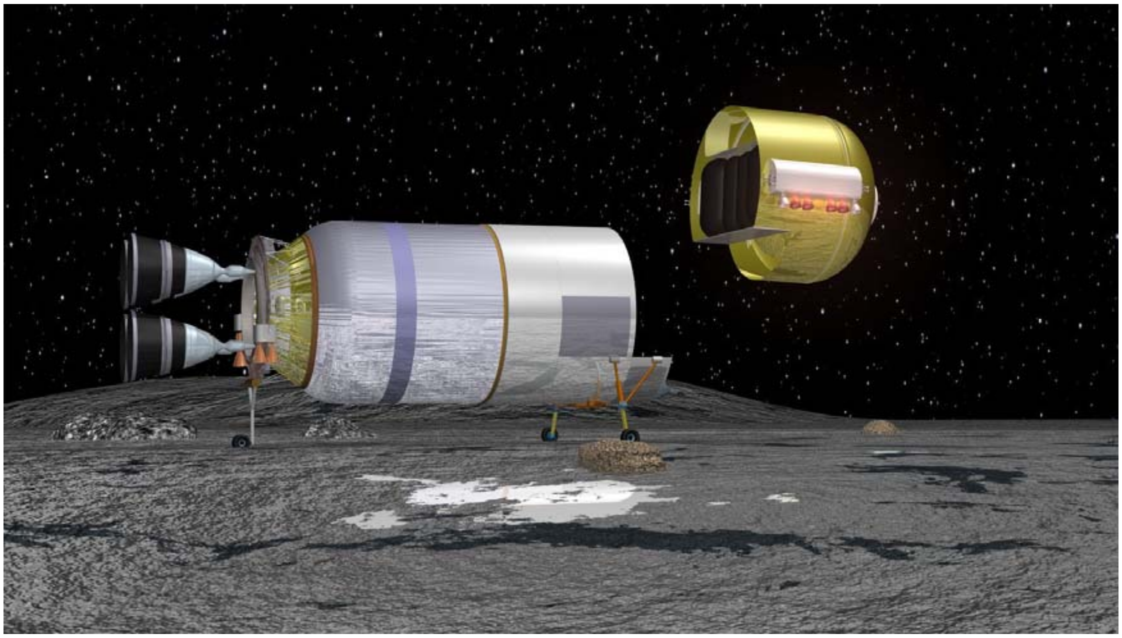

Figure 12 Departing Ascender Vehicle

V. PROPELLANT DEPOTS AND EQUIPMENT CACHES

The proposed use of propellant depots for lunar transport is hardly new. What is new is the perspective that depots can be simple and cost effective. Prior efforts tend to focus on the necessity for zero boiloff thermal stasis under highly adverse LEO heating conditions and on the challenges of storing propellants for years without usage. Unproven zero-G fluid handling, high capacity cryocoolers and measurement systems are assumed mandatory with the implication of substantial risks and large development costs and drawn out schedules. This vision for the depot itself is one of an orbital behemoth with complexity and cost similar to a space station. This daunting challenge tends to neutralize the benefits of the depot and foreshorten discussions of what the real requirements are and how a depot might be used.

This architecture proposes a depot system that effectively sidesteps these difficulties[2]. The ACES depot shown in Figure 6 is composed in its initial form of simply a slightly modified ACES 71 tank and the mated ACES 41 vehicle that placed it into position. This configuration, requiring no orbital assembly, constitutes a depot capable of efficiently storing 121 mT of propellant. It permits the segregation of LH2 and LO2 propellants, provides the radiation and conductive barriers needed for optimal thermal management and the docking and fluid interfaces for its primary function.

The ACES depot has no need for anything close to zero boiloff- especially in LEO. The thermal systems use vaporized hydrogen to completely suppress LO2 boiloff – the enormous heat capacity of hydrogen is fully taken advantage of, yet still on the order of 60 lbm of hydrogen will be vaporized per day. Over the course of a year nearly 10 tons of hydrogen will be consumed- a daunting number. However over 300 tons of propellant will have been transferred through the LEO depot in a year- the heating loss is less than 4% of the throughput. Furthermore the gasified hydrogen, warmed by solar radiation constitutes a simple solar-thermal propulsion system with a high Isp of 390 seconds. It is used as a monopropellant to provide the bulk of reboost, stationkeeping and maneuver control. With the assumed boiloff losses this amounts to 2-3 m/sec of delta V per day. Given the demands on the depot this is probably low and would have to be supplemented. So in reality there is no loss- just the cost of doing business in LEO. Striving to suppress heating to the lowest possible level with exotic technology is pointless. Amplifying throughput is the best way to make the depot more efficient.

ACES depot also has minimal need for exotic zero G cryogenic fluids handling. All propellant transfer operations are conducted with both the depot and the donor/receiver vehicles in a fully settled milli-G environment. Based on decades of Centaur operations this low acceleration will produce precise liquid/gas interfaces that allow accurate mass gauging, straightforward propellant transfer and predictable thermodynamics. The expenditure of a few pounds of hydrogen collapses the technical risk to a minimum[3]. ULA is working with NASA and industry partners to develop CRYOTE (CRYogenic Orbital TEstbed) that will provide a near term, cost effective demonstration of cryogenic transfer and long duration storage in space[4].

Since the L2 depot is in a deep space environment without the challenge of Earths radiation, the boiloff rate can be suppressed to very low levels- matching its lower stationkeeping demands as well. The L2 depot is critical since it enables the use of LH2/LO2 on both the Orion and Altair Ascenders- thus permitting a single propellant combination to be used throughout the architecture. The ability to sequester propellants in a depot means that surface stays are not limited by the losses of Orion propellants from stationkeeping in low lunar orbit- only by the consumables on the Lunar Surface.

VI. ARCHITECTURE DISCUSSION

The proposed architecture departs from historical efforts in two significant ways: it makes no attempt to attain the absolute minimum delta V for the mission and it does not demand that minimal vehicle masses be imposed. Those goals have been the focus of nearly every lunar exploration trade study to date, but such approaches do not necessarily yield a practical and sustainable system. They can lead to point-design, highly constrained systems with brittle interactions wherein a weight or Isp problem in one area can rapidly propagate to the functional collapse of the entire system. This generates costs which are effectively unbounded, the motivation being that we must spend what it takes to keep the system alive.

It is well understood that there is a delta V penalty for transiting through L2 to the lunar surface but this perceived hurdle is overcome by the ability to simply gradually muster propellants, vehicles and cargo at a staging area where they can be managed for indefinite periods with minimal station keeping losses. The presence of the depots means that any particular transport task is never starved for performance. The masses of any particular vehicle can grow without any substantial impact on the mission and without demanding redesign to the propulsion systems. Depots enable the reuse of the in-space stages by simple refueling allowing the stages to remain small and have low burnout masses. Their modest size allows substantial commonality with ongoing DoD and commercial missions.

Having depots with ample supplies of propellant means that less efficient but more expeditious trajectories can be used. For the first time we can trade mass/cost for shorter transit times. The reverse is also true- we can trade long transit times for much lower costs. By breaking up the transit job into smaller elements with decoupled schedules we take advantage of the limited launch windows from LEO, and by having substantial excess performance we can depart at less than perfect orbital conditions. These properties increase the robustness of the architecture and blunt the need for costly hardware redesigns.

With this L2 transit architecture the entire surface of the moon is directly accessible at virtually any time- an enormous logistical simplification. By the same token a retreat from the lunar surface can be undertaken at any time and very quickly if an emergency demands it. The standard Task 6+7 pathway through L2 can be used or an ACES/Orion at L2 can be tanked at L2 to high propellant levels for a fast transit to LLO and a rendezvous with an Ascender for a direct trip back to Earth. Very rapid return trajectories are possible from the moon if ample propellants are available. Nearly all thinking to date has assumed vehicles that are starved for performance, often running on the dregs of their propellant stores. The improved safety of copious depot stores cannot be overestimated.

VII. ARCHITECTURE EXECUTION

Several scenarios were modeled to explore how the proposed architecture could function- varying the pace of launch, boiloff rates etc. The following serves to illustrate a concept of how a lunar exploration process might begin. The bottom line is that highly aggressive lunar exploration programs can be effectively addressed with depots coupled to launchers that are in the 11-36 tons to LEO class.

The presence of a launcher in the 50-80 tons to LEO class reduces the launch rate and reduces the dependency on depots. Combining depots with these larger launchers hugely amplifies the architecture performance.

Lunar Operations - Year 1

The first year of the project is consumed with the establishment of infrastructure and the proving out of all critical systems and operations. The timeline shown in Figure 13 shows the pace of activities and Table 3 summarizes the total activities at year end. All powered operations will have been demonstrated end to end and all the equipment required for extended stays on the lunar surface will be in place and awaiting the arrival of crews. The launch rate is high but distributed over multiple launcher types. As previously noted the majority of flights are repetitive propellant tanker flights which could be executed by multiple launch providers.

The production rates required for this effort place all the industrial providers on a high production rate with large overhead dilutions. It is highly likely that for components such as the engines, new manufacturing and test facilities and perhaps licensed production may be required. In any event the entire space launch industry would be placed on a production footing not seen since the 1960's. Solid motor propellant consumption would be approximately equivalent to six of today's Shuttle SRMs.

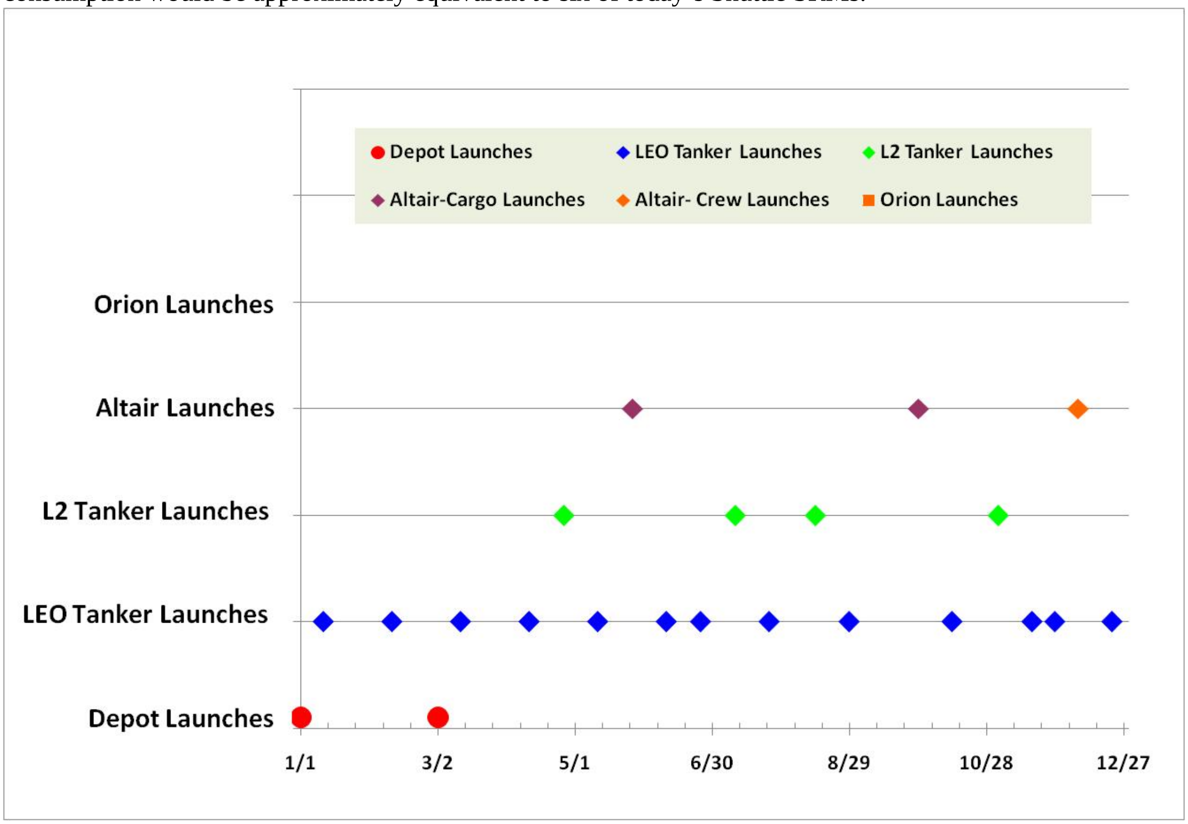

Figure 13. Year 1 Launch Timeline.

Table 3. Year 1 Summary of Operations Lunar Operations.			
Depot Launches	2	Propellant Flux thru LEO Depot	355t
LEO Tanker Launches	13	Propellant Flux thru L2 Depot	170t
L2 Tanker Launches	4	Cargo Mass on Lunar Surface	40t
Altair Cargo Launches	2	Propellant Mass to Lunar Surface	3.5t
Altair- Crew Launches	1	All-Up Altairs at L2	1
		Spare Altair Ascenders at L2	1
Total ACES stages	22	Total Mass to LEO	738t
Total SRM's	65	Total Propellant to LEO	549t
Total RS68	27	Lunar Touchdowns	2
Total RL10	88	Ascender Launches to L2	1
Total RD180	13	Storage days on Surface	>12
		Solar Power on Surface	30kW

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Lunar Operations - Year 2

With the way to the moon paved with propellants, cargo and vehicles, Year 2 commences crewed operations on the lunar surface. Figure 14 shows the timeline and Table 4 summarizes the system state at years end. The scenario modeled had an aggressive pace to attempt to stress the transport architecture. By spreading the tasks across multiple launcher types and launch complexes this ambitious approach was readily supported.

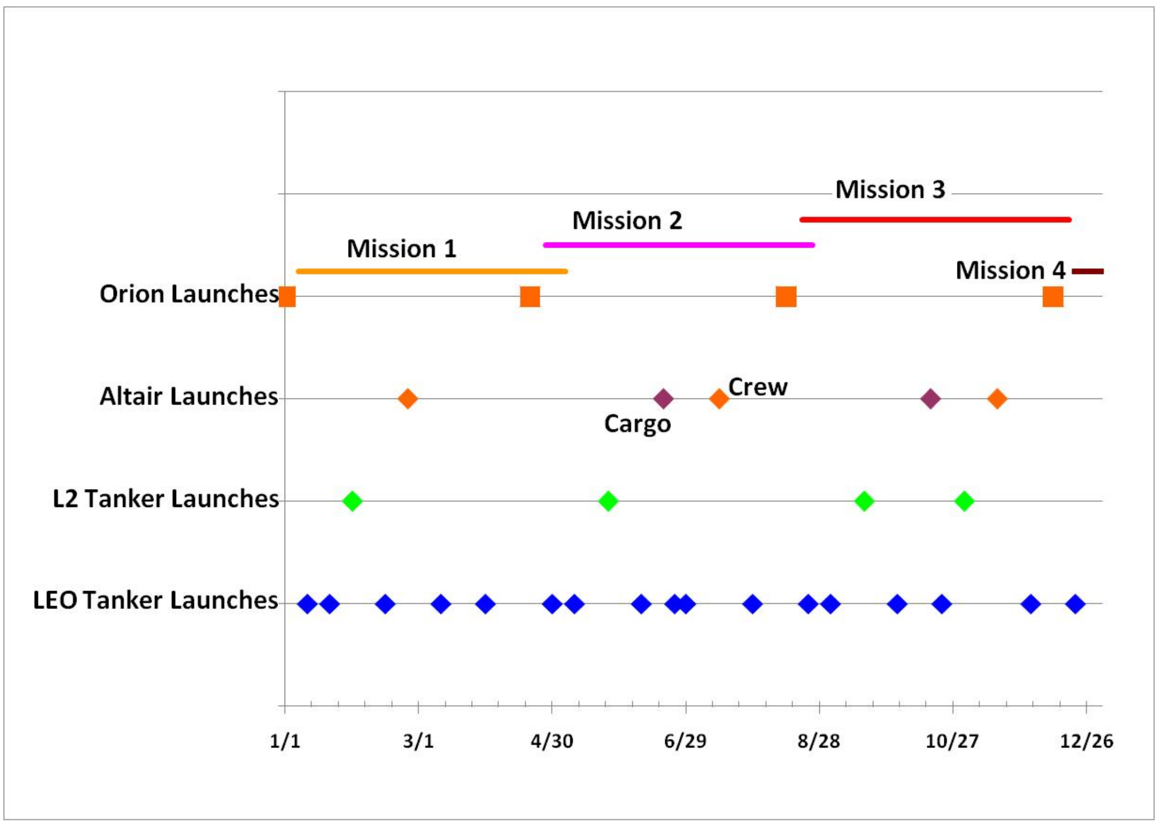

Figure 14. Year 2 Launch and Activity Timeline.

Initial crewed missions have 120 day stay durations and overlap by approximately 10 days with the newly arrived crew. The intent was to have continuous human occupation of the lunar base once it was established. This allows maintenance to be done on the increasingly complex life support and scientific equipment on the lunar surface. It is never left unattended. This leverages one of the most powerful attributes of a human crew- the ability to rapidly address contingencies with minimal preplanning.

Surface operations at this stage are assumed to be substantially open-loop. Waste products like CO2 and water are recovered and stored but only minimally reused. Because the Altair ascender does not damage the Altair descender when it departs, those tanks are gradually converted over to store the tons of water, sewage, gaseous H2, O2 and methane that are generated by the lunar base. This industrial scale chemical processing infrastructure will be required to eventually close the life support ecosystem.

Table 4. Year 2 Summary of Operations			
Depot Launches	0	Propellant Flux thru LEO Depot	447t
LEO Tanker Launches	17	Propellant Flux thru L2 Depot	189t
L2 Tanker Launches	4		
Altair Cargo Launches	2	Useful Mass on Lunar Surface	143t
Altair- Crew Launches	3	Cum Useful mass on Lunar Surface	194t
Orion Launches	4	Crew Days on Lunar Surface	1496
Total ACES stages	30	Total Mass to LEO	933t
Total SRM's	80	Total Propellant to LEO	670t
Total RS68	30	Lunar Touchdowns	6
Total RL10	120	Ascender Launches	5
Total RD180	19	Operating days on Surface	358
		Solar Power on Surface	100kW

Lunar Operations- Year 3

Year 3 is an extension of crewed operations, but with the increasing amount of fluids recycling on the lunar surface, the surface stays can be extended to 5 months with substantial overlap of crews so that teams of 8 are present for weeks at a time (Figure 15). Table 5 summarizes the status at the end of Year 3. Figure 16 shows the cumulative state for the system, illustrating the relative masses being moved through various locations.

Since more ascenders are present than are required to fly the crew home they can be used for transport from the lunar base to more distant science sites. The ability to refuel this vehicle turns it into a rocket powered helicopter with all the utility that that implies. Robotic systems can be quickly delivered to remote locations without long overland journeys. Crews can be dispersed but also rapidly returned to the base in the event of adverse space weather. The ability to efficiently deliver large cargos and especially propellants to the lunar surface is hugely enabling for the exploration of remote sites.

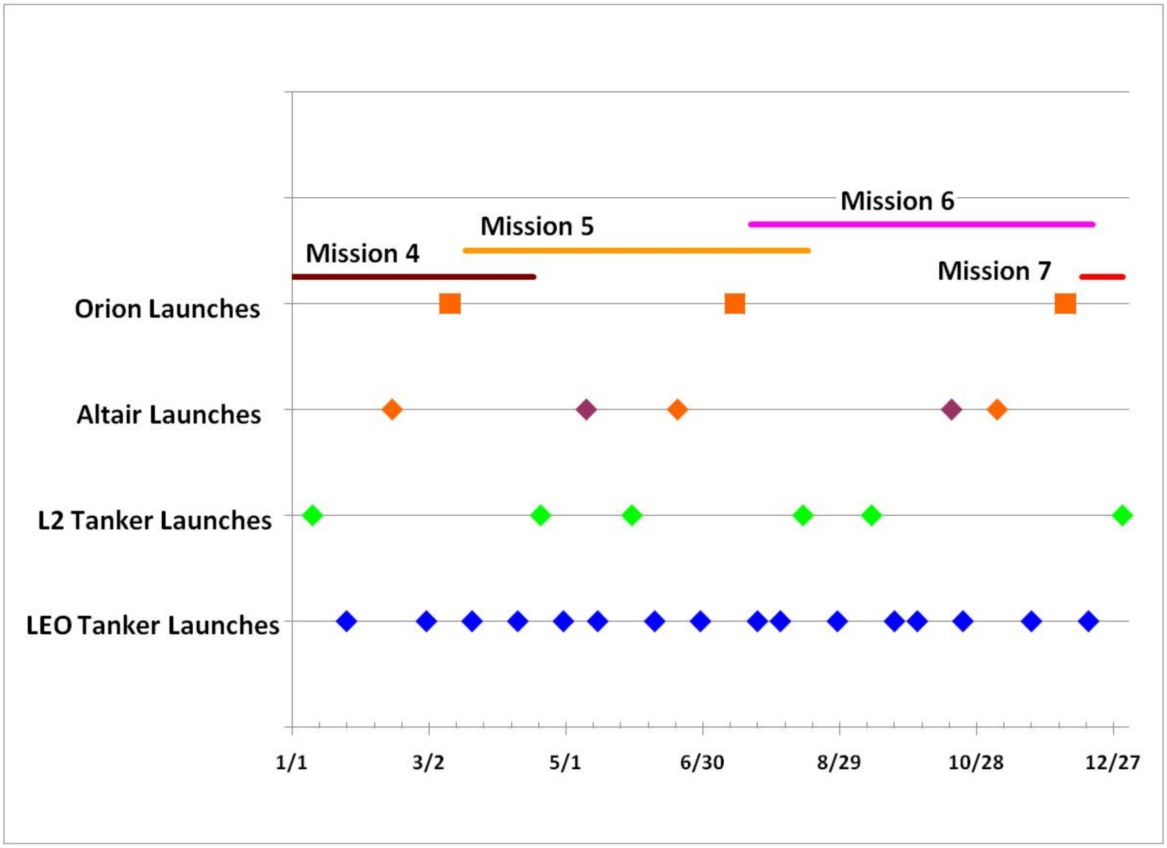

Figure 15. Year 3 Launch and Activity Timeline.

Table 5. Year 3 Summary of Operations.			
Depot Launches	0	Propellant Flux thru LEO Depot	485t
LEO Tanker Launches	16	Propellant Flux thru L2 Depot	243t
L2 Tanker Launches	6		
Altair Cargo Launches	2	Useful Mass on Lunar Surface	119t
Altair- Crew Launches	3	Cum Useful mass on Lunar Surface	313t
Orion Launches	4	Crew Days on Lunar Surface	1700
Total ACES stages	31	Total Mass to LEO	1011t
Total SRM's	45	Total Propellant to LEO	728t
Total RS68	27	Lunar Touchdowns	5
Total RL10	124	Ascender Launches	4
Total RD180	39	Operating days on Surface	365
		Solar Power on Surface	150kW

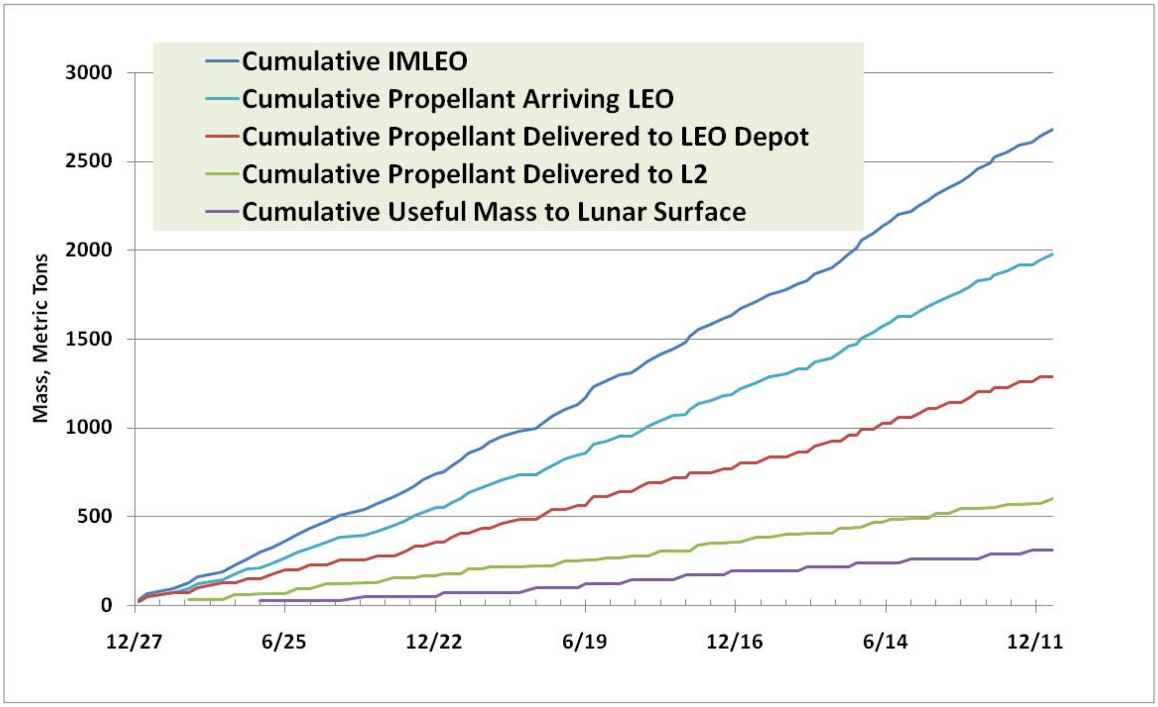

Figure 16 – Three Year Summary of Activities

While this scenario illustrates how moderate capability launch vehicles can support a highly ambitious lunar exploration effort, more affordable options can also be effectively executed. Figure 17 illustrates the overall development plan for the proposed architecture with respect to anticipated budgets. By foregoing large booster development efforts costing tens of billions of dollars and using a common ACES stage for in-space propulsion needs the lunar exploration element designs can be started immediately with the effect that the systems destined for the moon are ready to launch when the transport stream is completed. Initial crewed landing would occur in 2018. Either a single crewed mission per year coupled with 20mT of cargo or two crewed missions per year can be supported within the anticipated budgets. The assumed cost of transport to LEO ranged from 9.2 to 10.2 $M/mT depending on launch vehicle. This scenario also assumes the cost of flights to the ISS are included at a rate of 2/year commencing in 2013.

ACES first flight would occur with either a commercial or DoD payload nearly five years before the first crewed flight to the moon. The final six crew flights to ISS would be conducted using ACES and the Orion capsule. To demonstrate the lunar lander as quickly as possible a robotic lander mission is included in 2016 with a direct lunar descent

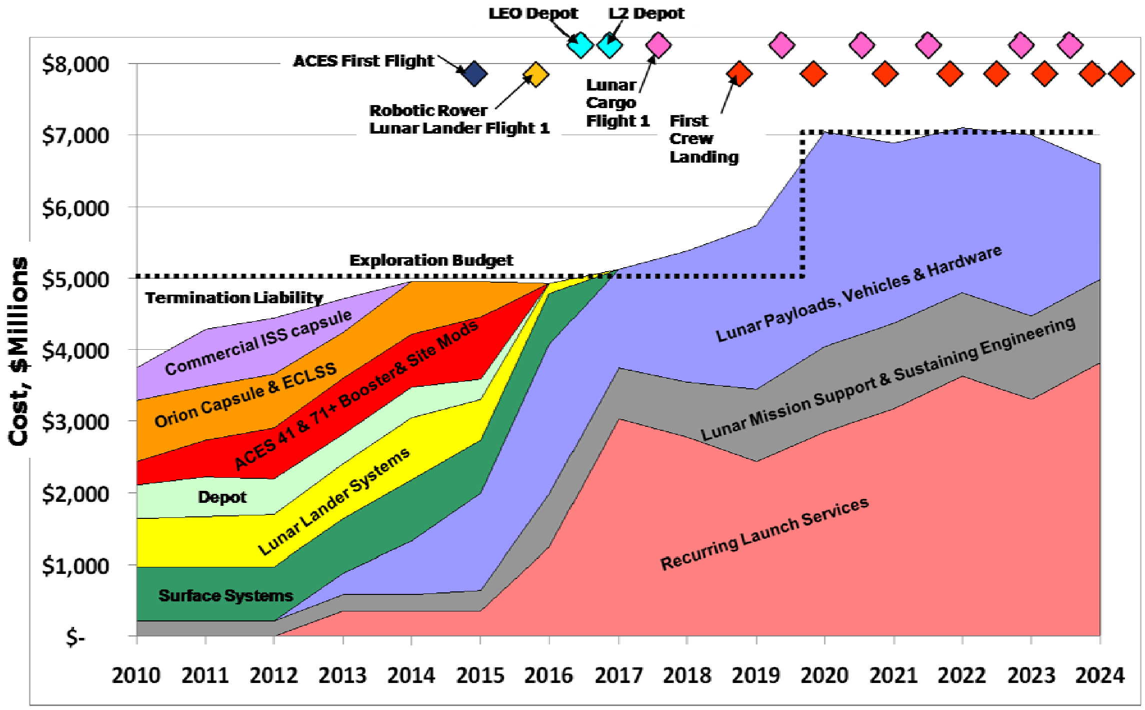

Figure 17 Non-recurring Development Transition to Flight @ 2 Missions/Year

VIII. UTILITY BEYOND LUNAR EXPLORATION

The establishment of an L2 propellant depot provides substantial utility to other exploration goals such as Mars, and the rest of the solar system. Direct launches to these various planetary bodies require substantial amounts of energy; the present spacecraft have effectively tapped the entire capability of existing launch vehicles. The Cassini orbiter presently at Saturn had a start mass of less than 6 tons and took nearly 7 years to arrive at Saturn after a launch on the most powerful ELV at the time. The proposed ACES based vehicles provide substantial performance growth and enable the delivery of substantially larger spacecraft using the direct launch approach.

Objects that are located at L2 have already had a substantial amount of energy pumped into them. They have effectively reached earth escape velocity while still being bound to the earth. This energy constitutes a substantial portion of the total delta V required to venture to Mars, for example. Many publications have advocated the use of the LaGrange points for departure to the planets but a dedicated depot just for the occasional Jupiter or Mars mission is clearly ineffective. With the road to L2 supported and maintained by Lunar Exploration these departure strategies become very attractive.

Departure from L2 is further aided by incorporating a powered Earth gravitational assist into the mission design. Objects being sent from L2 to Jupiter for example require only a small nudge to place them in a trajectory towards earth with a very low perigee. As the departing spacecraft nears perigee it conducts a burn when it is at an already high velocity. This activity effectively maximizes the delta V that can be achieved from a fixed propellant mass. Rather than assembling stupendous propellant masses in LEO, as is often proposed for a crewed mission to Mars, we can use this L2 departure strategy to gradually pump energy into the objects we wish to send to Mars by caching them at L2 and also get a large delta V leverage at the final departure. Much larger spacecraft can be sent to high C3 destinations using this approach.

The L2 depot and the design of the Altair vehicle means that a crew can be put in a wide variety of locations that are presently off limits due to the high delta V demands and long transit times. Maintenance of high value space telescopes or other crucial assets could be undertaken with manageable risks. This extends their operational life and prevents unforeseen events from disabling these costly assets for years. A single one of these contingency “rescues” would justify the presence of the L2 depot.

Mars Exploration and ISRU Applications

The vehicles and methods proposed here for lunar exploration can be very effectively scaled for Mars applications. The mastery of long duration cryogenic propellant storage is effectively mandatory for going to Mars due to the large delta V’s and large payload masses required. It is a foundation technology. The vehicles and personnel going to Mars must have a long heritage of depot operations, propellant transfer and thermal management otherwise the most effective architectures envisioned for going to Mars, invoking in-situ resource utilization, are effectively closed to them.

The proposed ACES/Altair vehicle has the ability to be fully fueled with lunar surface synthesized LO2 and LH2, moved without complex ground infrastructure to a liftoff site, lift off with minimal thrust to avoid ground installation damage, flown with minimal gravity losses back to L2, deliver 7 tons of propellants and then return to the lunar surface. It represents an initial effort at an orbital refueling tanker that is wholly reusable. This precise machine is mandatory for Mars operations where the intent is that return propellants are synthesized at Mars.

The equivalent Mars Altair must be larger than the Lunar Altair but it is a straightforward scale up of tank volume and engine thrust. The delta V from the Martian surface to Mars orbit is not enormously different than that required to get to L2 from the lunar surface. The proposed ACES/Altair shape is fundamentally adaptable to endoatmospheric flight. Performance is sufficiently high that a reentry that is partially or mostly propulsive in nature can be considered since the propellants would be made on Mars. This permits a drastic reduction in heat shield mass and enables the use of multi-piece decelerators suitable for stowage when not in use and capable of unlimited reentry cycles without intolerable mass. Mars permits a long standing dream of space designers: a single stage to orbit/ fully reusable launcher with a substantial payload capability. Having such a machine is an enormous advantage for the exploration of a world.

The Mars architecture would be derived from the lunar architecture with orbital depots, surface chemical processing and power systems pioneered on the moon. The ascender vehicle workhorse for moving crews and cargo around the Martian surface would be applied though of course the power and propellant demands are higher on Mars. In short the proposed architecture, hardware and lessons learned are all directly applicable to the Mars exploration task.

IX. SUMMARY

The proposed lunar architecture illuminates how the powerful leveraging effects of simple orbital depots can enable small expendable launch vehicles, compatible with existing DoD and commercial payload needs, to establish, support and expand a lunar base with a continuous human presence. The costs and protracted schedule associated with the development of extremely large boosters and multiple in-space stages can be eliminated and the resources applied to the lunar lander, propellant tankers and depots built around a common in-space stage. The simplicity of the architecture enables development that actually fits within projected budgets which is in sharp contrast to the present approach. The door to lunar exploration is presently shut due being simply unaffordable with the present architecture. The proposed architecture reopens that door.

By separating out propellant delivery the architecture not only encourages economic production rates for multiple launch suppliers but provides a commodity task that fosters innovation for new launch suppliers, enables contributions from foreign sources and truly effective international cooperation. In many ways it is the functional equivalent of the establishment of airmail as a commodity activity for the fledgling aircraft and airline industries of the early 20th century.

The architecture simulates in nearly every respect what is required for Mars exploration and enables the maturation of key technologies that will be required on Mars. It can directly support all planetary missions and opens the door for the very high mass spacecraft required for serious exploration of the solar system. It effectively builds a road to the sky that will be built upon by coming generations to meet needs that can now only be guessed at.

In short this architecture concept suggests a new path that has a greater utility, lower cost, foreshortened schedule, the best possible safety and reliability and the greatest engagement of industry and government- the ingredients for a successful and permanent lunar presence and ultimately the exploration of our solar system.

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