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Using the resources of the Moon to create a permanent, cislunar space faring system

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We have previously described an architecture that extends human reach beyond low Earth orbit by creating a permanent space transportation system with reusable and refuelable vehicles. Such a system is made possible by establishing an outpost on the Moon that harvests water and produces rocket propellant from the ice deposits of the permanently dark areas near the poles. Our plan is affordable, flexible and not tied to any specific launch vehicle or family of vehicles. Robotic assets are teleoperated from Earth to prospect, demonstrate and produce water from local resources. These robots are launched separately over several years, allowing the program to be implemented under constrained and uncertain funding conditions. In addition, the stepwise, incremental approach encourages and facilitates international and commercial participation. Humans arrive only after we have begun water production. Once there, the human mission begins to explore the potential for possible, practical, and affordable use of regolith for material production for outpost sustainment and growth. Consistent with the overarching goal to see if we can learn how to live off-planet, another objective of human activity on the Moon will be the experimentation of biological systems and their interaction and performance in the lunar environment. Our arbitrarily defined end stage is a fully functional, human-tended lunar outpost producing 150 metric tonnes of water per year – enough to export water from the Moon to orbiting propellant depots and create a permanent, extensible reusable transportation system that allows routine access for people and machines to all points of cislunar space. This cost-effective architecture advances technology and builds a sustainable space transportation infrastructure. By eliminating the need to launch everything from the surface of the Earth, we fundamentally change the paradigm of spaceflight. This lunar outpost serves as the vanguard for studying the practical employment of techniques, processes, and systems that allow humanity to effectively extend its reach off-planet.

Nomenclature

CEV	Crew Exploration Vehicle
CL	Cargo Lander
CTS	Cislunar Transfer Stage
CWS	Cislunar Way Station (fuel depot)
DoD	Department of Defense
DoE	Department of Energy
EELV	Evolved Expendable Launch Vehicle
EH	Excavation/Hauler
ESAS	Exploration Systems Architecture Study
GEO	Geosynchronous Orbit
GPS	Geographic Positioning System
HL	Human Lander
HLV	Heavy Lift Vehicle

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ISRU	In Situ Resource Utilization
LCROSS	Lunar Crater Observation and Sensing Satellite
LEO	Low Earth Orbit
LLO	Low Lunar Orbit
LM	Lunar Module
LRO	Lunar Reconnaissance Orbiter
Mini-SAR	Miniature Synthetic Aperture Radar (Chandrayaan-1)
M^3	Moon Mineralogy Mapper (Chandrayaan-1)
MEO	Medium Earth Orbit
MT	Metric ton (1000 kg = 2200 lbs.)
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Agency
PSLV	Polar Satellite Launch Vehicle (India)
RFC	Rechargeable Fuel Cell
RFT	Rover Fuel Tanker
RHL	Robotic Heavy Lander
RML	Robotic Medium Lander
RTG	Radioisotopic Thermal Generator
RWTL	Robotic Water Tank Lander
SPP	Solar Power Plant
SSM	Shuttle Side-Mount (launch vehicle)
VSE	Vision for Space Exploration or "the Vision"
WEFS	Water Electrolysis and Fuel Storage
WIE	Water Ice Explorer
WPS	Water Processing and Storage
WT	Water Tanker

I. Introduction

A key part of the 2004 Vision for Space Exploration (VSE) was learning how to use off-planet material and energy resources to create new space faring capability[1,2]. The Moon was selected as the initial destination for the human spaceflight program because it contains the raw materials needed to do this. The Moon's proximity and accessibility allows us to conduct a significant amount of this work in relative safety with robotic machines teleoperated remotely from Earth and from cislunar space prior to human arrival.

The objective of the Vision was not a series of Apollo-style expeditions or a human Mars mission but rather the extension of human reach to all of the Solar System, for the myriad of purposes imagined over many years. The high cost of launch to orbit is one barrier to widespread activity in space. Despite numerous and continued attempts to lower launch costs over the last 30 years, a cost plateau has been reached at around $5000/kg (based on the price of the two cheapest existing launch services, India's PSLV and SpaceX's Falcon 9.) Launch cost is a "Catch-22" problem: costs are high because volume (traffic to LEO) is low and volume is low because costs are high. In the future we may expect to see some improvement in launch cost numbers but a drop by factors of 2 or 3 (rather than by orders of magnitude) is most likely.

One approach to break this impasse is through the use of In Situ Resource Utilization (ISRU) to create new space faring capability by learning how to use what we find in space to sustain and extend our presence there. In contrast to the problem of launch cost, this approach has only recently been seriously considered. The architects of the VSE specifically included a return to the Moon as the first destination beyond low Earth orbit because of its resource characteristics and its proximity. Our objective in returning to the Moon is to learn how to live and work productively on another world. The Moon possesses the material and energy resources necessary to learn new skills to create new space faring capabilities. Its proximity to the Earth permits easy and routine access to its surface for just such an endeavor that, if successful, will serve as the catalyst and the true historical starting point for human expansion off-planet.

These goals are very ambitious and quite unlike those of any previous space program so there is no *a priori* guarantee of success. Lunar return under the VSE is an engineering research and development project; it is not known how difficult the extraction and use of off-planet resources might be. But because the amount of leverage provided through the use of space resources is so great, this effort is a task worth attempting. If the ultimate rationale for human spaceflight is to create new reservoirs of culture off-planet, it follows that learning to adapt and use the resources of space becomes essential and a critical skill necessary for the future survival of the human race.

Thus, our challenge is to craft an architecture that attempts the never-been-done with funding at less-than-usual levels. We believe this is possible through the development of an incremental, cumulative architecture that uses robotic assets for early and continual accomplishment. We go back to the Moon in small, discrete steps, interlocking with and building upon each other. We scale our return to the Moon to match the resources available. In lean years, we make less (but still positive) progress, while more money allows an accelerated pace of effort. The key to success is to make the incremental steps small enough such that progress is made even in the most financially constrained times. We go when we can, as best we can. But we go.

II. The Mission on the Moon

The mission statement of lunar return is provided by the VSE founding documents: We go to the Moon to learn how to live and work productively on another world. We do this by using the material and energy resources of the lunar surface to create a sustained human presence there. Specifically, we will harvest the abundant water ice present at the lunar poles with the objective of making consumables for human residence on the lunar surface, and propellant, initially for access to and from the Moon, increasing the production with time for eventual export to support activities in cislunar space. This architecture focuses initially on water availability and conversion into propellant because propellant is the holy grail of rocket mechanics; propellant mass is by far the dominant term in the rocket equation and is the most significant factor in cost for human missions. The availability of lunar consumables and propellant allows us to routinely access all the levels of cislunar space where our economic, national security and scientific satellites reside.

This mission objective defines the architecture of lunar return. We stay in one place to build up capabilities and infrastructure in order to stay longer and create more. Thus, we build an outpost; we do not conduct sorties[3]. We go to the poles of the Moon for three reasons: 1) near-permanent sunlight near the poles permits almost constant generation of electrical power from photovoltaics, obviating the need for a nuclear reactor to survive the 14-day lunar night; 2) these quasi-permanent lit zones are thermally benign compared to equatorial regions (Apollo sites), being illuminated at grazing solar incidence angles and thus greatly reducing the passive thermal loading from the hot lunar surface; 3) the permanently dark areas near the poles contain significant quantities of volatile substances, including hundreds of millions of metric tonnes of water ice.

We return to the Moon gradually and in stages, making use of existing assets both on Earth and in space. We emplace small robotic assets on the lunar surface first. These robots will establish a communication/navigation satellite system around the Moon, prospect for promising volatile deposits, conduct demonstration experiments to document the physical state and extraction potential of water, and conduct the initial preparation of the outpost site. In the second phase, larger, more capable robotic machines (also operated from Earth but with more autonomy) will begin production of water in quantity, which is then converted into its component hydrogen and oxygen and made into cryogenic liquids for rocket propellant. The third phase involves emplacing the elements and infrastructure of the lunar outpost, including a habitat, roads and landing pads, solar power arrays and distribution grid, thermal control systems, and communications systems. In the fourth phase, humans arrive on the Moon, where they live in a pre-emplaced outpost and begin using previously landed robotic machines to increase production and extend operations. This work proceeds as resources and technical development permit; schedule is the free variable. Our objective is to produce surplus water that is exported to cislunar space (e.g., Earth-Moon L-1) for processing into propellant and other products. Because this phase coincides with human lunar return, we also begin to use lunar resources to supply materials such as metals, glasses, and ceramics for use at the outpost. Finally, in the fifth phase, we study the biological interaction and practicality of supporting plant growth in the lunar environment as well as develop a transition plan to commercial or international interests in an effort to allow the foothold on the Moon to enter a new phase of growth toward extending the human reach off-planet.

Will this architecture be practical and cost effective compared to launching products from Earth? Only time will tell, but it is possible that this foray into the unknown for the explicit purpose of extending human reach could be similar to other life-changing technological events in human history. Thus far, we have concentrated on the production of water and cryogenic propellant derived from it. However, that is only the beginning of our use of lunar resources. Once humans are on the Moon, we will exploit what is there, including structural fabrication using local resources, experimenting with large structures for plant cultivation, ceramics manufacture and use, metal extraction and processing experiments, and prospecting for other usable resources in the local environment. A significant goal of lunar return is also to learn whether it is feasible to export lunar products to Earth orbit or beyond in addition to answering the question of local resource usefulness at an outpost on a planetary body. By laying out our objectives and specific aims beforehand, we create an architecture that is actually more flexible and sustainable than one that is designed to the still poorly understood requirements of a human Mars mission and staged completely from the surface of the Earth in an "Apollo" mode of operation. We have the knowledge, technology and assets to begin this lunar resource work now.

III. Destination Moon

The Moon is the closest planetary object to Earth and it contains the necessary material and energy resources to create new space faring capability. The proximity of the Moon to Earth is a key attribute: because round-trip light-time between Earth and Moon is only 3 seconds, we can control robotic machines on the lunar surface from Earth to accomplish a variety of tasks. This relation is crucial; it permits early and significant accomplishment on the Moon prior to human arrival. We use the proximity of the Moon to set up a functioning, productive lunar surface installation before the first human crew arrives. With constant availability of a launch window and relatively low Δv requirements, our Moon is the most accessible extraterrestrial body. This accessibility adds significant flexibility to our operational plans, as we can send or retrieve assets to and from the Moon at any time.

In the last two decades, an increasing variety of new sensors have explored the Moon from orbit and significantly changed our perception of its history, processes and composition. Our earlier understanding about the Moon as a volatile-poor object with a harsh and unforgiving surface environment came from studies of the Apollo samples and data. These samples are bone-dry; hydrogen found in returned lunar soil samples is present at a few parts per million concentration levels. Although we had tantalizing suggestions that water might be present near the permanently dark areas near the poles[4], previous data were inconclusive. In addition, we lacked high quality images and topographic maps of the poles to fully understand their lighting and thermal conditions.

New data from a variety of missions have documented the nature and occurrence of water on the Moon[5-7] and the unique lighting[8] and thermal environment[9] near the poles. Measurement of the surface temperatures[9] near the poles show large areas with temperatures lower than 100 K; some permanently dark areas are as cold as 25 K. These "cold traps" serve to collect and sequester water molecules and ice deposits may build up here over the billion year time scales of polar evolution. In addition to cold traps, the new mapping data show areas of near-permanent sun illumination[8] close the poles. Some areas are illuminated more than 90% of the lunar year (Fig. 1). Because darkness is primarily caused by local topography, eclipse periods occur at irregular intervals and have durations ranging from a few hours to a few tens of hours. For this study, we assume solar illumination for 80% of the lunar day, a conservative estimate that is valid for identified places near both poles. Periods of darkness are easily accommodated through temporary transition to power from batteries or rechargeable fuel cells. In addition to being suitable localities for solar arrays, these lit regions are also thermally more benign (surface temperatures on the order of -50° ± 10° C) than the equatorial regions, permitting extended operations for almost the entire 708-hour lunar day.

Water is present in the polar areas in several different modes of occurrence. Thin layers of water molecules are widespread over the high latitudes; the Moon Mineralogy Mapper (M^3) documented the presence of water[5] poleward of about 65° latitude, with amounts increasing with increasing latitude. Additionally, the impact of the LCROSS spacecraft in October 2009 kicked up a plume of dust, water vapor and ice particles[7]; water is present in this locality at concentrations between 5 and 10 weight percent. Finally, the Mini-SAR radar mapper[6] on Chandrayaan-1 found dozens of craters at both poles that appear to contain nearly pure (90-100%) deposits of water ice; estimates for the north pole suggest that up to 600 million cubic meters of water ice may occur within these craters (Fig. 1). The new data indicate the presence of pervasive and significant water ice at the poles of the Moon. For the purposes of this study, we assume a concentration of 10 wt.% water within our resource mining prospects. This is a very conservative estimate; our productivity and output will be commensurately higher with greater water concentrations. The polar regions contain resources of materials and energy that permit us to use the Moon as a logistics base for space faring within and beyond the Earth-Moon system.

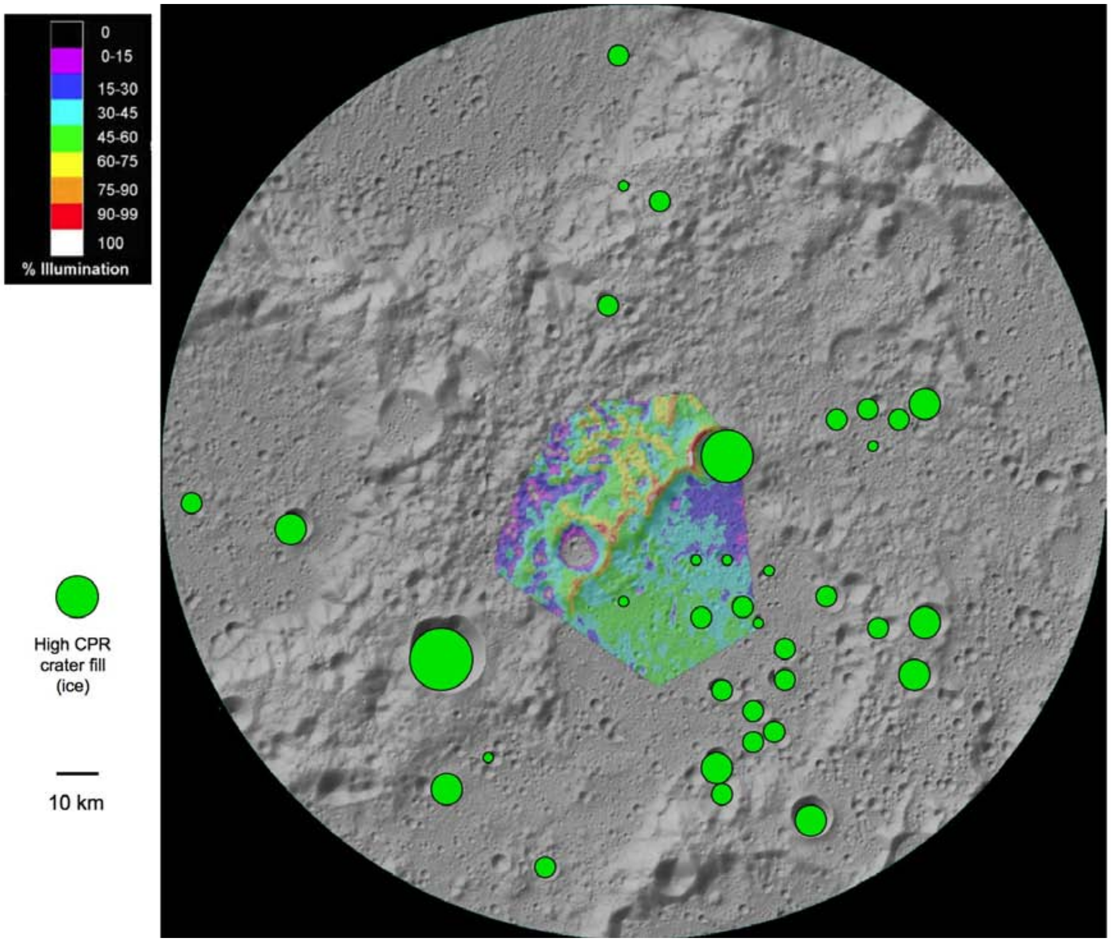


Figure 1. Resources map of the north pole of the Moon. Lighting duration near the pole is shown for northern summer; craters showing anomalous radar behavior consistent with ice are indicated in green.

At present, we do not know the optimum location for the lunar outpost based on the availability of water and illumination but existing data show several highly promising areas near the poles (Fig. 1). To find these optimum locations, we conduct surface reconnaissance at both poles early in our program.

IV. Launch Vehicles

At least three different studies examined the cost problems of the ESAS architecture and offered alternatives that cost less, take less development time, and are adequate for lunar surface return. One approach uses the commercially available Delta IV and Atlas V Evolved Expendable Launch Vehicles (EELV) and orbital propellant depots to perform lunar return[10]. This approach has the advantage of using existing launch vehicles but development of propellant depots is required to permit journeys beyond LEO. Two other approaches use existing Shuttle hardware to create new launch vehicles capable of launching lunar spacecraft in two or three pieces, which are then assembled in low Earth orbit for trips outward. Two concepts – DIRECT[11] and Shuttle side-mount (SSM)[12] – take advantage of the existing space industrial base, including tooling and assembly facilities, as well as the existing processing and launch infrastructure at Kennedy Space Center, to create new vehicles that can deliver tens of metric tonnes to LEO. The advantage of this approach is that we launch what is needed to go to the Moon complete and no depots are required; the disadvantage is that there is some new vehicle development needed.

We assume the use of multiple launch vehicles, using the best available LV assets to meet given payload and mission requirements, including EELV to launch early lunar surface robotic elements. These vehicles are coupled with use of propellant depots in both LEO and LLO as described below in the Architecture section, to make maximum advantage of the launch assets by significantly increasing lunar landed mass capability. A Delta IV Heavy and large Atlas V (551) can place 1-2 MT on the surface of the Moon. This payload delivers significant capability to the lunar surface. We begin by conducting detailed robotic site exploration and characterization of the poles. We know enough to pick promising landing sites, however, strategic knowledge about the physical state, distribution, conditions and quantities of lunar volatiles must be gathered from a lander and rover mission.

The development of a heavy-lift vehicle adds capability and flexibility to our architecture but is not a requirement for early missions, although we recognize that other strategic considerations (such as preservation of HLV infrastructure) may require the near-term development of such a vehicle. A Shuttle-derived vehicle has the least impact on existing facilities and the least amount of new development and thus, lower total cost. A single Shuttle side-mount (SSM) can launch about 70 MT to LEO and place 8-9 MT (including lander) on the lunar surface. Two SSM launches can fly an entire human lunar mission; this is a valuable capability for a lunar return program. Once we have established a foothold on the Moon and have the capability to at least partly supply ourselves from lunar materials, the need for a very heavy lift vehicle lessens. In fact, the best time for the creation of propellant depots is after we are able to supply them with lunar propellant. Such an approach makes human planetary missions easier; the dead weight of propellant (at least 80% of the total mass of the spacecraft for a human Mars mission) need not come from the deep gravity well of Earth.

Much of the current debate about launch vehicles stems from the mission or objective of human flights beyond LEO. We believe that the fundamental objective of such flight is to extend human reach and presence from its current limitation in LEO to all levels of space beyond. To that end, we are agnostic on the need for any specific launch vehicle solution; our goal is to make complete dependence on such vehicles unnecessary as rapidly as possible through the use of off-planet resources. If a heavy lift vehicle is available early in the program, we will use it. If one is not, we will use other launch vehicles. Because we must scope the total effort within an assumed budget profile that would be available to NASA for any launch vehicle development as well as all mission hardware development, we developed an architecture that accomplishes the goal while fitting under the budget. We assume that a medium heavy lift launch vehicle (~70 MT) will be available during the later phases of our program (when humans are needed on the Moon.) Our particular architecture uses such a vehicle and reflects the cost of its development and operations, but other solutions are possible within the assumed budget wedge used by the Augustine Committee[13] (2009). We couple this medium heavy lift capability with use of a LEO propellant depot to leverage a much larger payload on the surface (12mT of payload on the lunar surface – not including the lander) as opposed to a much larger launch vehicle (~150 MT), the approach proposed for Constellation. We assume that commercial launch vehicles should be able to supply the depot with water, which the depot will convert into propellant.

V. Architecture Summary

We have described our architectural approach and elements in some detail previously[14]. Here we summarize the basic features of the architecture, its phasing in time and its programmatic implications. In short, we envision landing robotic spacecraft on the Moon to characterize its resources in detail, demonstrate that water can be extracted, processed and stored, and begin to set up a resource processing system that is largely automated and supervised under human control from Earth. These assets are gradually built and expanded, leading to the robotic emplacement of the lunar outpost elements: habitats, power systems, thermal control systems, navigation and communication, along with surface infrastructure such as roads and landing pads made from fusing the lunar soil by microwave. In effect, we emplace the lunar outpost robotically so that when people arrive, they move into a turn-key facility. Human presence is needed to maintain and repair the processing machines, expand and extend surface operations and conduct local exploration. We envision a remotely operated, robotic mining station; we send people to cannibalize common parts, fix problems, conduct periodic maintenance, upgrade soft goods, seals, valve packing, inspect equipment for wear, and perform certain logistical and developmental functions that humans do best.

A key attribute of our architecture is flexibility – because we build surface infrastructure in increments with small pieces (Table 1), we emplace and operate surface facilities as opportunity and capability permit. International and commercial partners can participate at whatever level they desire, since we use small, incremental pieces. This allows a broader, more integrated participation in lunar return than was possible under previous agency plans. Smaller units (rovers and experiments) can be grouped together and launched on one large HLV or they can be launched separately on smaller EELVs. Such flexibility allows us to create a foothold on the Moon irrespective of budgetary fluctuations.

In our architecture, commonality occurs at the component level, with common cryo engines, valves, avionics boxes, landing subsystems, filters, and connectors to allow maximum use of the assets that are landed on the surface. This is significant because the lifetime of the landed elements in the hard environment of the lunar surface (dust, large temperature swings, radiation, extreme temperatures), without lower level maintenance, would be so low that it would make this strategy unsustainable.

Element	Spacecraft or system	Dry Mass (kg)	Wet Mass (kg)	Power (W)	Purpose	Notes
Orbital	Comm/Nav constellation (4)	100	200	400	Comm and data for teleops; GPS	Poles have intermittent Earth view; need constant comm and geolocation
	LEO fuel 1	6500	20 MT water	25 K	Fueling depot for cislunar transport	Boil-off captured
	LEO fuel 2		75 MT water	50 K	Fueling depot for cislunar transport	Boil-off captured
	Cislunar way station		10 MT water	25 K	Fueling depot for lunar and cislunar transport	Boil-off captured EM L-1 or LLO
Landers	Robotic Medium	1200 (500 payload)		300 W	Delivers exploration rovers and small fixed payloads	
	Robotic Heavy	4200 (2300 payload)	7700 cryo		Delivers up to 2 MT	Launch empty; fuel at LEO
	Reusable Water Tanker	5020	3500 water (payload from Moon), 10500 cryo		Delivers 3.5 MT lunar water to LEO	Lands on Moon empty and remains until needed
	Human	10500	20000 cryo		Ferries crew to and from lunar surface	LM-class 30 MT taxi
	Cargo	8320 (12000 payload)	21900		Cargo version of human lander	Needs cislunar transfer stage
Rovers	Explorer/Prospector	500		200	Prospecting and mapping ice deposits	Can also haul small amounts of feedstock for demo
	Excavator/Hauler	2300			Digs and hauls feedstock to processors	Sized for delivery 1.5 MT feedstock/day
	Water Tanker Rover	500			Hauls water on power cabling on Moon	Connects elements of surface systems
	Roving Fuel Tanker	500			Hauls LO_2/LH_2 on Moon	From processors to RWT
Facilities	Water demo	500			Demonstrates water production from lunar feedstock	Tens of kg quantities
	Power plant 1	1100		25 K	Powers water plants; recharges surface rovers	Arranged on constant sunlight spot
	Power plant 2	1100		25 K		
	Power plant 3	1100		25 K		
	Power plant 4	1100		25 K		
	Power plant 5	1100		25 K		
	Power plant 6	1100		25 K		
	Power plant 7	1100		25 K		
	Power plant 8	1100		25 K		
	Water process/store 1	1200	4 MT water		Water production	48 MT/year
	Water process/store 2	1200	4 MT water		Water production	48 MT/year
	Water process/store 3	1200	4 MT water		Water production	48 MT/year
	Electrolysis/fuel storage 1	1200		-25 K	LO_2/LH_2	30 MT/year
	Electrolysis/fuel storage 2	1200		-25 K	LO_2/LH_2	30 MT/year
	Electrolysis/fuel storage 3	1200		-25 K	LO_2/LH_2	30 MT/year
	Electrolysis/fuel storage 4	1200		-25 K	LO_2/LH_2	30 MT/year

Table 1. Elements of the lunar return architecture

A. Phase I: Resource Prospecting

To begin our return to the Moon, we first launch a series of robotic spacecraft to: 1) emplace critical communications and navigational assets; 2) prospect the polar regions to identify suitable sites for resource mining and processing; and 3) demo the steps necessary to find, extract, process and store water and its derivative products (Fig. 2). The poles of the Moon have intermittent visibility with the Earth. This property creates problems for an architecture that depends on constant, data-intensive communications between Earth and Moon. Moreover, precise knowledge of location on the Moon is difficult and transit to and from specific points requires high-quality maps and navigational aids. To resolve both these needs with one set of assets, we envision a small constellation of satellites that serve as a communications relay system, providing near-constant contact between Earth and the various spacecraft around and on the Moon, as well as a lunar GPS system which provides detailed positional information both on the lunar surface and in cislunar space. This system can be implemented with a constellation of small (~250 kg) satellites in polar orbits (apolune ~2000 km) around the Moon. Such a system must be able to provide bandwidth (several tens to hundreds of Mbps) and positional accuracy (within 100 m, 3σ) necessary to support transit and navigation around the lunar poles.

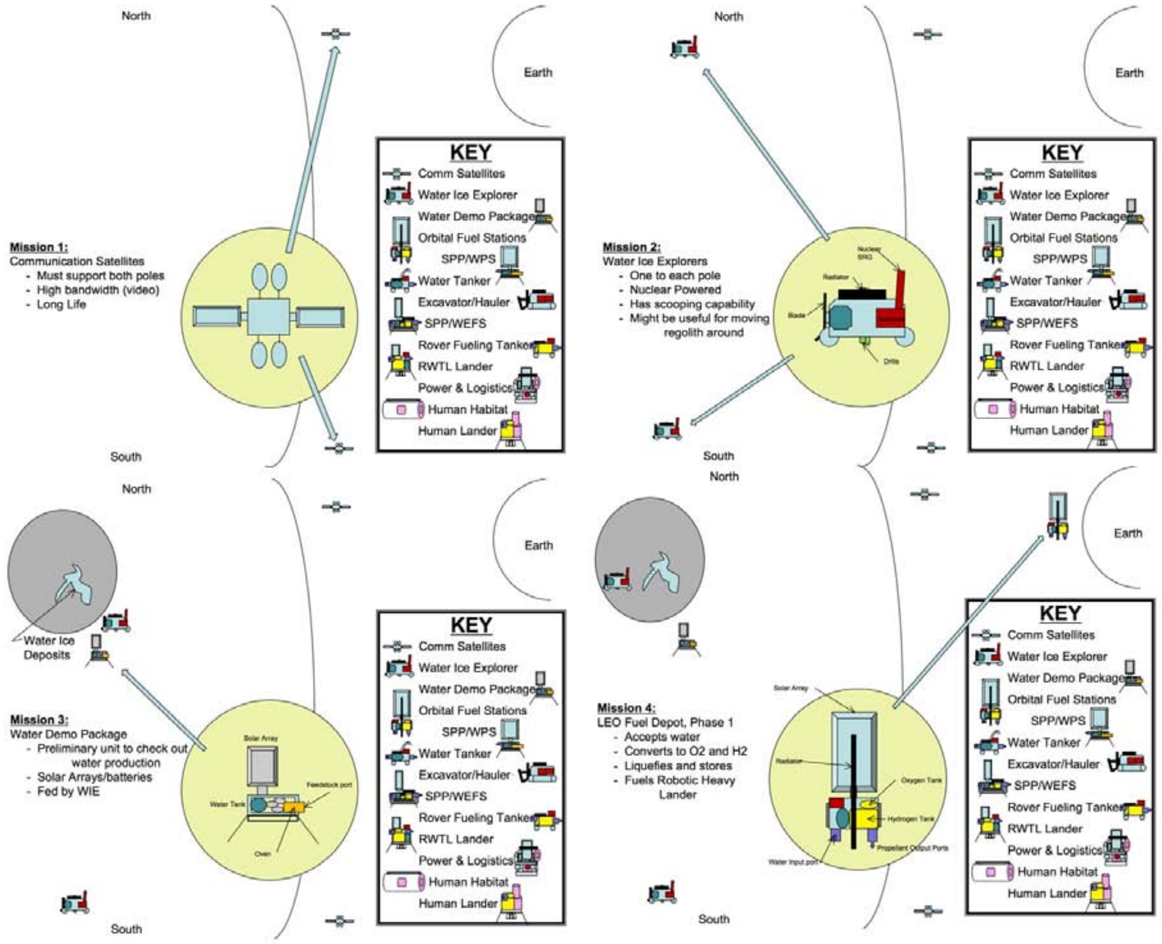


Figure 2. Phase 1 of the lunar return architecture. Orbital assets include the lunar comm/nav system and Earth departure depot. Surface elements include prospecting rovers (one at each pole) and water extraction demo unit.

Two rovers will be sent to each lunar pole to explore the polar light and dark areas and characterize the physical and chemical nature of the ice deposits. We must understand how polar ice varies in concentration both horizontally and vertically, the geotechnical properties of polar soils and access to and location of mining prospects. The rovers will begin the long-term task of prospecting for lunar ice deposits so that we may site the outpost near high grade deposits. In addition to polar ice, we must also understand the locations and variability of sunlit areas, as well as the dust, surface-charging and plasma environment. The rovers are about 500 kg and carry instrumentation to measure the physical and chemical nature of the polar ice[15] (e.g., GCMS, neutron spectrometer, XRF/XRD). In addition, they will excavate (via scoop, mole, and/or drill) and store small (kg) amounts of ice/soil feedstock for transport to resource demonstration experiments mounted on the fixed lander in the permanent sunlight. Power is best provided by some type of radioisotopic thermal generator (RTG) but rechargeable batteries or a Regenerative Fuel Cell (RFC) are possible non-nuclear alternatives for long-lived power.

A mission during this phase will launch the Phase 1 LEO fuel depot, which will be placed in a 400 km orbit (to allow for efficient fueling for spacecraft going to the Moon or to another future Fuel Station at L1 for Earth-Moon escape velocities and from altitude/debris avoidance considerations.) It will launch with some orbit station-keeping fuel with margin to allow a smooth transition to commercial water transfer and subsequent electrolysis and liquefaction. The depot will receive water initially from Earth and later from the Moon via space tugs, convert this water to GH_2 and GO_2, then liquefy and store it. The Phase 1 Station will fuel the Robotic Heavy Lander with roughly 8,000 kg of propellant. This propellant fueling results in a growth of landed payload mass by more than a factor of two. The depot must be flexible enough to control its attitude with varying inertias of docked vehicles. Our intent is to supply the depot by commercial launch of water to the Station, which can begin immediately after orbit emplacement and checkout. If no commercial providers emerge, a separate NASA mission can send water to the fuel depot.

B. Phase II: Resource Mining, Processing and Production

The next phase moves us from resource exploration and supporting assets to actual water production (Figs. 3, 4). We incrementally add excavators, dump haulers, soil processors and storage tanks to get, haul and store the water. Power stations generate electricity at the permanently illuminated (> 80%) peaks; equipment periodically connects to these stations to recharge their batteries. Our goals are to learn how to remotely operate these machines and begin to produce and store water for eventual use when people arrive. The processed water is easily stored in the permanent shadow areas. During this phase we also land our first electrolysis units to begin practicing the cracking of water, making the cryogens, and storage of liquid fuels. Because we would be learning an operational cadence as we go, it might take several months or a year to get into a smooth rhythm which results in maximized amounts of propellant produced per unit time. Large unknowns related to transit time between source and use site, thermal profiles, power profiles, lighting, sensor performance, metal fatigue, lubrication performance, and feedstock density remain to be discovered.

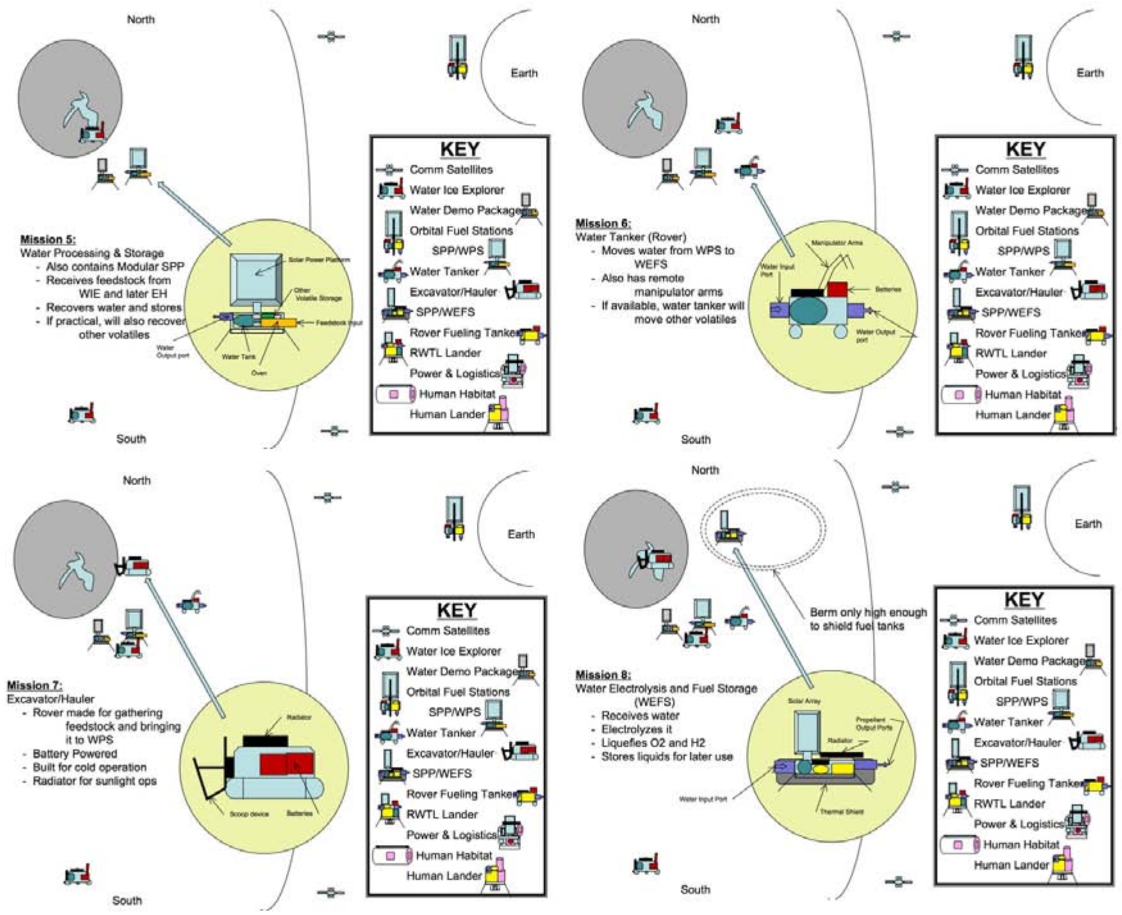


Figure 3. Phase 2 of the lunar return architecture. In Phase 2, we emplace and begin to use the water harvesting and processing units. Each landing adds capability to the processing stream with the aims of continually increasing production levels.

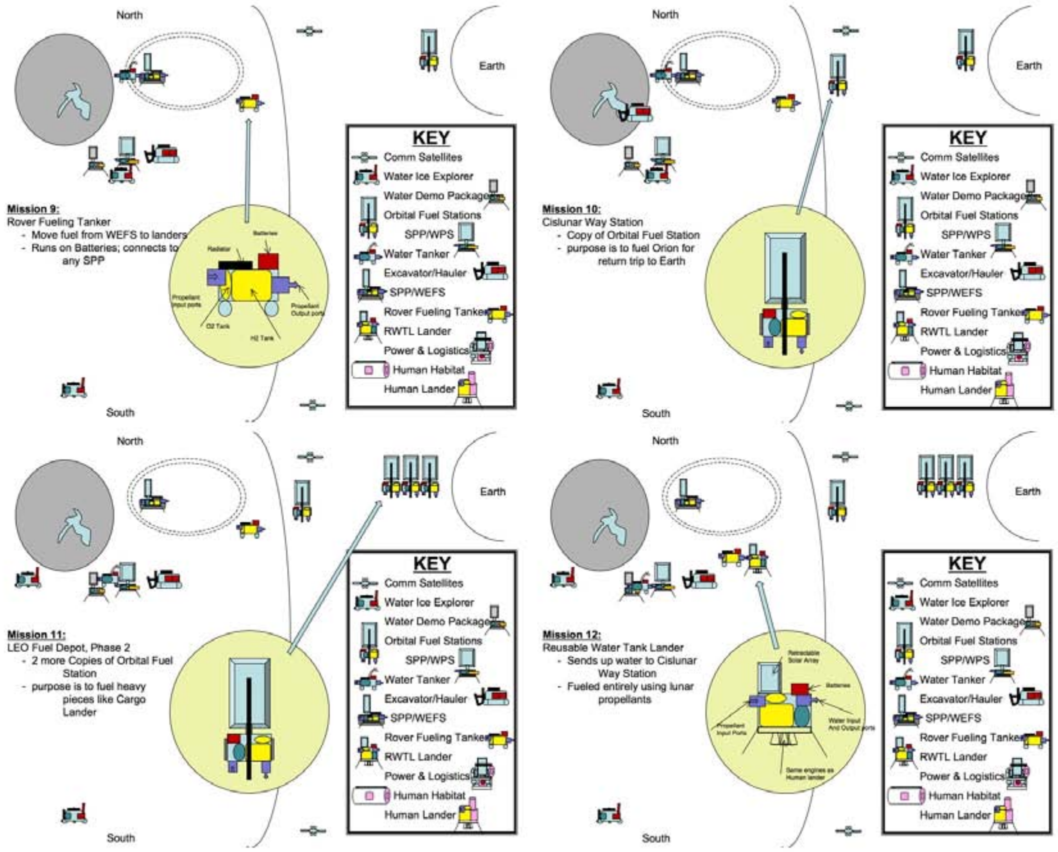


Figure 4. Phase 2 of the lunar return architecture (continued). Each landing continues to add capability to the processing stream with the aims of continually increasing production levels. In the latter part of this phase, we add a second propellant depot in LEO and one in low lunar orbit.

The equipment used in this phase is described in detail elsewhere[14]. The excavation rovers, processors, and power units are all on the order of 1200-1500 kg mass. Power stations are rolled solar arrays gimbaled about the vertical axis to track the sun; each generates about 25 kW. Multiple power stations can be arranged in serial or parallel to provide the power needs of the various robotic equipment. We intend to investigate the making of roads and work floors through the microwave sintering of regolith; many areas near the outpost site, particularly around the power stations, will get much repeat rover traffic and keeping raised dust to a minimum is necessary to maximize equipment lifetime and for proper thermal control.

C. Phase III: Outpost Infrastructure Emplacement and Assembly

The next phase brings to the Moon the pieces of the human lunar outpost (Fig. 5) and begins to prepare the outpost site, emplaces critical infrastructure for power generation and thermal control, and prepares the lunar surface transportation hub, which will receive and service the reusable robotic and human landers that make up our cislunar transportation system. We will also add to existing robotic assets, including the upgrading of surface mining and processing equipment, replacement of damaged items, and extension of processing capability. Our goal in this phase of development is to increase the mass output of water product in order to support human arrival.

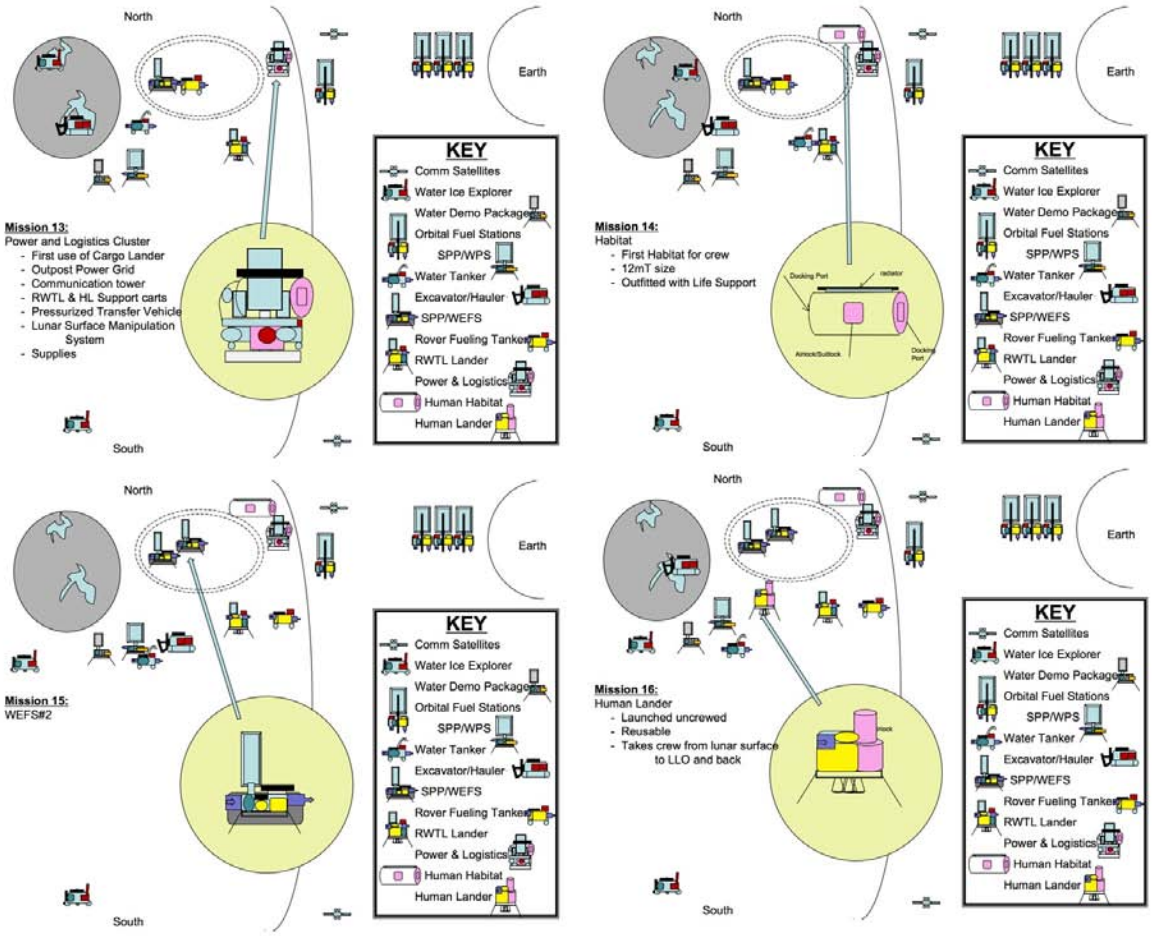


Figure 5. Phase III involves landing and installing the pieces of the lunar outpost. Robotic rovers and manipulators build the outpost and create supporting infrastructure, such as landing pads, roads, and blast berms. The human habitat is operational prior to the arrival of crew.

Propellant is needed on the lunar surface to re-fuel robotic and human landers that come to and return from the Moon. Returning cargo landers can carry payloads as water or as propellant; both options may be necessary, as propellant could be needed in the vicinity of the Moon to re-fuel transfer stages, but water delivered to low Earth orbit can be cracked and frozen there just as efficiently as on the lunar surface. We recognize that cryogens have a boil-off problem, particularly for the highly volatile LH_2. We also note that part of this architecture includes the energy required for liquefaction, which essentially removes a large amount of heat from the fluid, and in doing so should also address the challenge of keeping the hydrogen cold enough to preclude boil-off. However, it is a challenge that is recognized and should be addressed via selected technology development early in this campaign.

The first Heavy Cargo mission will bring all of the logistics and power necessary to support human habitation for the initial stay on the lunar surface. In this architecture, it was not assumed that there would be enough surplus energy from the modular power plants to support human needs, and therefore part of this cargo would include additional power plants with appropriate connectivity to power the habitat, arriving later. This initial cargo complement would probably not include enough battery power to weather an eclipse, but it is expected that this capability would arrive on the third cargo mission. Also part of this complement would be any supplementary equipment needed to attach to the habitat or otherwise make it usable (leveling equipment, high priority spares, filters, thermal shields, various pieces of support equipment, lifting equipment, mobile pallets, EVA Suit components, logistics supplies), including a method to transfer the crew to the habitat in the form of a tunnel/airlock so that the human lander could be streamlined as much as possible. We propose a small mobile human rover (4.5 MT) to interface between the lander and the habitat to allow shirt sleeve ingress, as well as local mobility to access all deployed equipment.

The second Heavy Cargo mission will bring the habitat to the Moon. While it is envisioned that ultimately the human habitable areas at the outpost will be significantly larger than a single 12 MT module, initial needs are to have sufficient habitable volume to support 2-4 crew for a short period of time, with the crew size tradable with duration. Included in either this mission or the previous one would be the radiators and heat rejection equipment, as well as a fully-operational Environmental Control and Life Support System.

D. Phase IV: Human Lunar Return

During this phase, we prepare the outpost site, emplace the elements, and connect the pieces to create a "turn-key" facility, ready to use by arriving human crew (Fig. 5). These pieces include the power and thermal control systems, habitats, workshops, landing pads, roads, and other facilities. The initial outpost can support a crew of four for visits of several weeks each at least twice per year. The arriving crew will interact with, repair, service and operate the previously emplaced robotic assets in ensure maximum efficiency. At least part of the crew will have time to conduct local surface exploration and other science-related tasks. By the time of arrival of the first human crews, we plan for the production of 150 MT of water per year, enough to completely supply the lunar transportation system with propellant.

The lander for human missions is closer to a LM-class system (~30 MT) rather than Constellation's *Altair*-scale lander (~50 MT). Its primary mission is to transport crew to and from the lunar surface. It does not contain significant life-support systems, as the crew will live in pre-emplaced surface habitats while on the Moon; unlike the Altair lander, this lander is merely a mechanism for transport. This lunar taxi becomes a permanent part of the cislunar transportation system. It is re-useable and re-fuelable with lunar produced propellant and can be stored on the lunar surface or at the cislunar transport node. Because of the similarity in size and functionality for the HL and RWTL, it is important to develop common components so that the parts count for lunar surface maintenance can be minimized. Specifically, we again envision both landers using a common reusable cryo engine developed in part or totally by the RHL development, with both vehicles using a multiple engine complement for reliability and redundancy as well as cost. Single engines are designed to be serviced or changed out on the Moon, thus maximizing the lifetime of the vehicles in which they reside.

We also use a cargo variant of the human lander. It is launched on a HLV and can deliver 12 MT of payload to the lunar surface, with fueling at the LEO Fuel Station. Once on the surface, it will be used for scrap parts (another reason for a common parts list). The lander has a dry mass of 8300 kg, a propellant mass of 22000 kg and a payload capacity of 12000 kg. It is launched from the LEO station using a Cislunar Transfer Stage (CTS), which requires about 60,000 kg of cryo propellant to take the lander to the Moon. The CTS is another candidate for reusability, although we assume that it is non-reusable, at least initially. Once lunar propellant production is up and running, we can reuse this element by rendezvousing in LLO with the Cislunar Way Station. Future studies can examine the possibility of later reuse of the cargo lander to ship goods back to the Earth, or to LEO, or even to L1 as a staging area, depending upon the specific needs at the time. Note that this architecture does not presume full success with extracting lunar resources except for refueling for human Earth return. As this concept matures, and our understanding of the logistics, cost, and sustainability of this approach solidifies, lunar refueling can expand significantly (as much as the demand will allow) including incorporation of the cargo landers.

E. Phase V and beyond: Human Habitation of the Moon

Once the outpost has been established (Fig. 6), initial human occupancy will consist of periodic visits designed to explore the local site and to maintain and assure the proper operation of the mining and production equipment. These visits will be interspersed with the landing of additional robotic assets as our intention is to continually increase the production of water with the aim of exporting water to cislunar space. Our architecture stops after 30 missions and at a production level of 150 MT of water per year, the threshold for the production and export of surplus product.

Initially, the first objectives for the crew will be to assure the propellant and water production chain, including periodic maintenance and optimization of the operations concepts and timelines. With subsequent cargo deliveries, the crew will examine production techniques, procedures, technologies, and tools that allow a full revision of and expansion of the next step in utilization. Although many studies have been conducted on this activity, many unknowns need to be addressed, starting with basic technologies and technology applications in the lunar environment. In addition, techniques, tools, and extensive physical and metallurgical analysis of the properties of the final products need to be examined to obtain the best products for as yet undefined applications. Our objective in these ISRU efforts lead to the development of a pressurized surface habitat in which 90% of the mass of the structure uses local materials. This phase is vitally important to extending human reach in space, and so will be a long-term plan, although it is important to realize that habitat upkeep and propellant supply chain management has higher priority. This broad ISRU material investigation lends itself well to international participation and commercial development, since there is no single strategy or technology or method that works for every application and can be divided into discrete investigations. Toward that end, on one of the cargo missions a full unpressurized habitat as material laboratory for these investigations will be delivered. Next in line for crew time would be data on biological interaction and plant growth in lunar gravity. These investigations will examine the vitality, reaction, and long term logistical needs for developing a plant farm and its value to sustainable human habitation of the Moon.

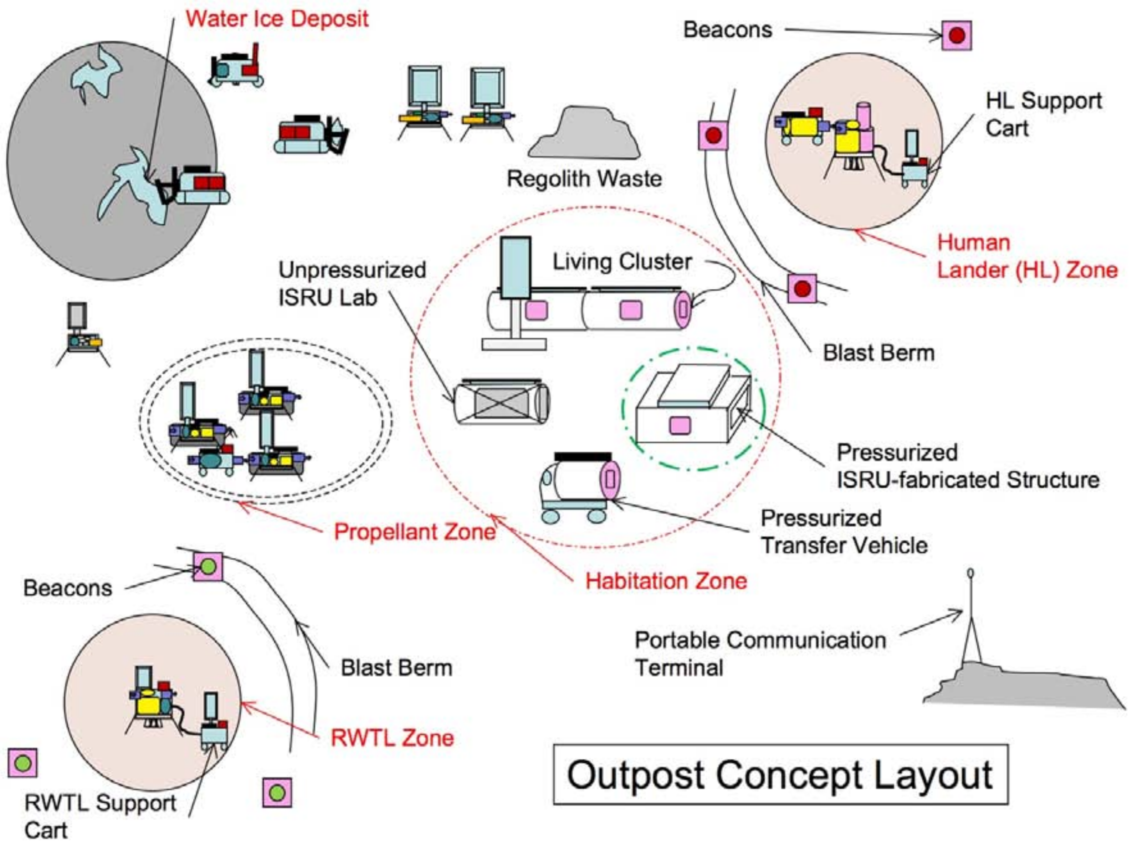


Figure 6 Final configuration of the working outpost, ready for human arrival.

At that stage, we anticipate that the resource outpost will be in a position to recoup our investment in it. Several possible models for the privatization of the water processing may be viable. We anticipate that the federal government will be an early and repeat customer for lunar water, not only for future NASA missions beyond the Earth-Moon system but also other agencies, such as the Department of Defense. Additionally, international customers could emerge and eventually, commercial buyers as well. Whether the production facilities are commercialized before or after these markets emerge cannot be easily foreseen at the this stage and in fact, is unimportant. The critical point is that we will be in a position to industrialize the Moon and cislunar space, a key step in making space part of our economic sphere. Furthermore, we will openly share the technology developments as well as the experiment undesirable outcomes and pitfalls so that others can leverage what we have learned. This will enable the commercial sector to take over many of the lunar activities and services. Transition to commercial activity may be early or late in outpost development. We recognize that part of NASA's ultimate purpose is to expand and enhance the nation's commercial and industrial base and we have attempted to encourage such industrial activity where possible.

VI. MISSION SEQUENCE

The systems and surface elements described above collectively comprise our lunar outpost. An advantage of keeping the individual pieces small is that we have considerable flexibility when we combine them into mission packages. For example, a group of small spacecraft (e.g., the comm/nav system and lander/exploration rover) could be combined into one launch. If cost or schedule precludes such an approach, these spacecraft can be launched separately on smaller launch vehicles. Moreover, few of the outpost elements require other pieces to be emplaced simultaneously; most can be launched and operated independently and begin operations immediately. We have crafted the sequence scenario below so as to get the outpost into production mode as soon as possible (Fig. 7). Depending on budgetary or programmatic considerations, alternative implementations are possible.

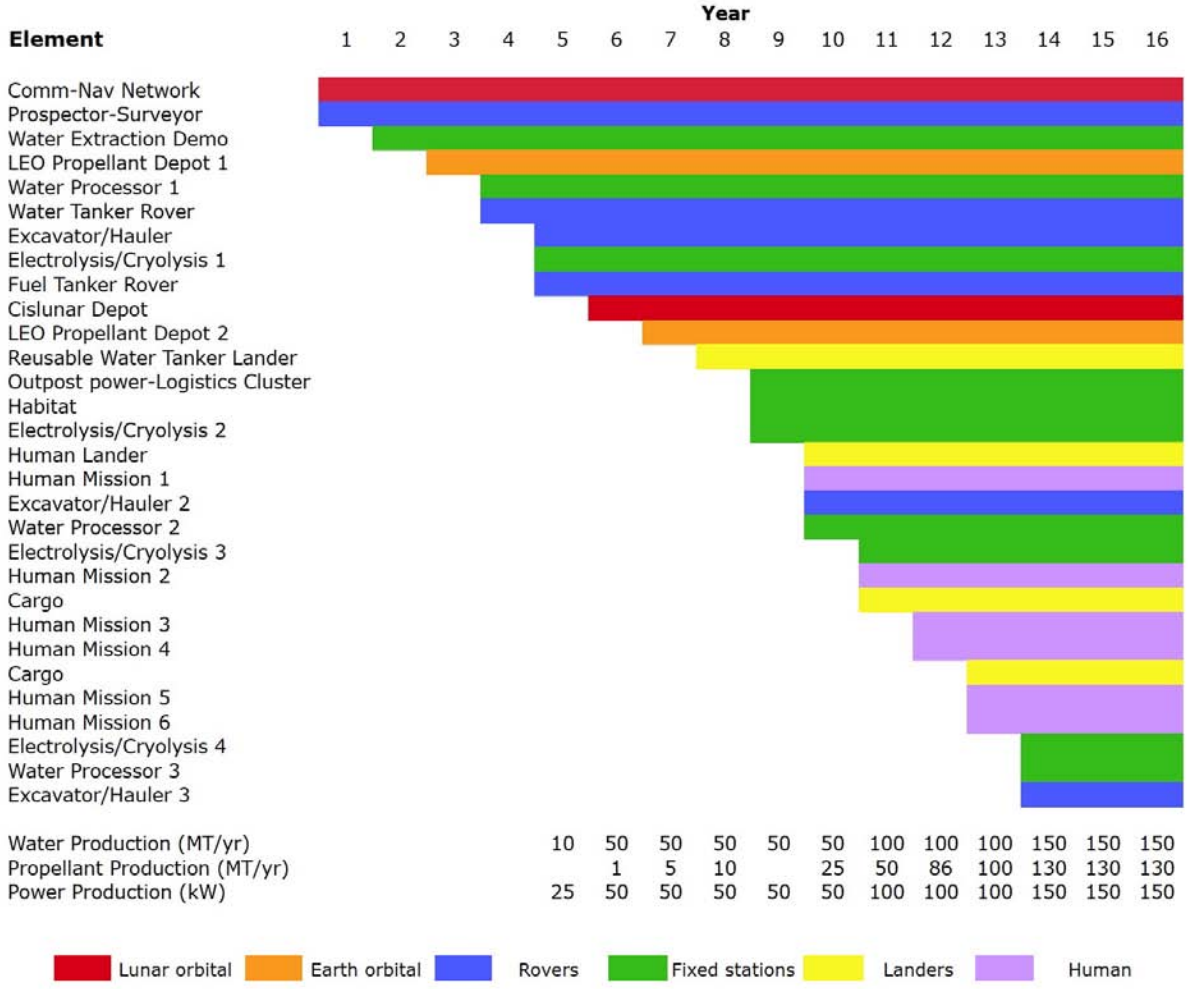


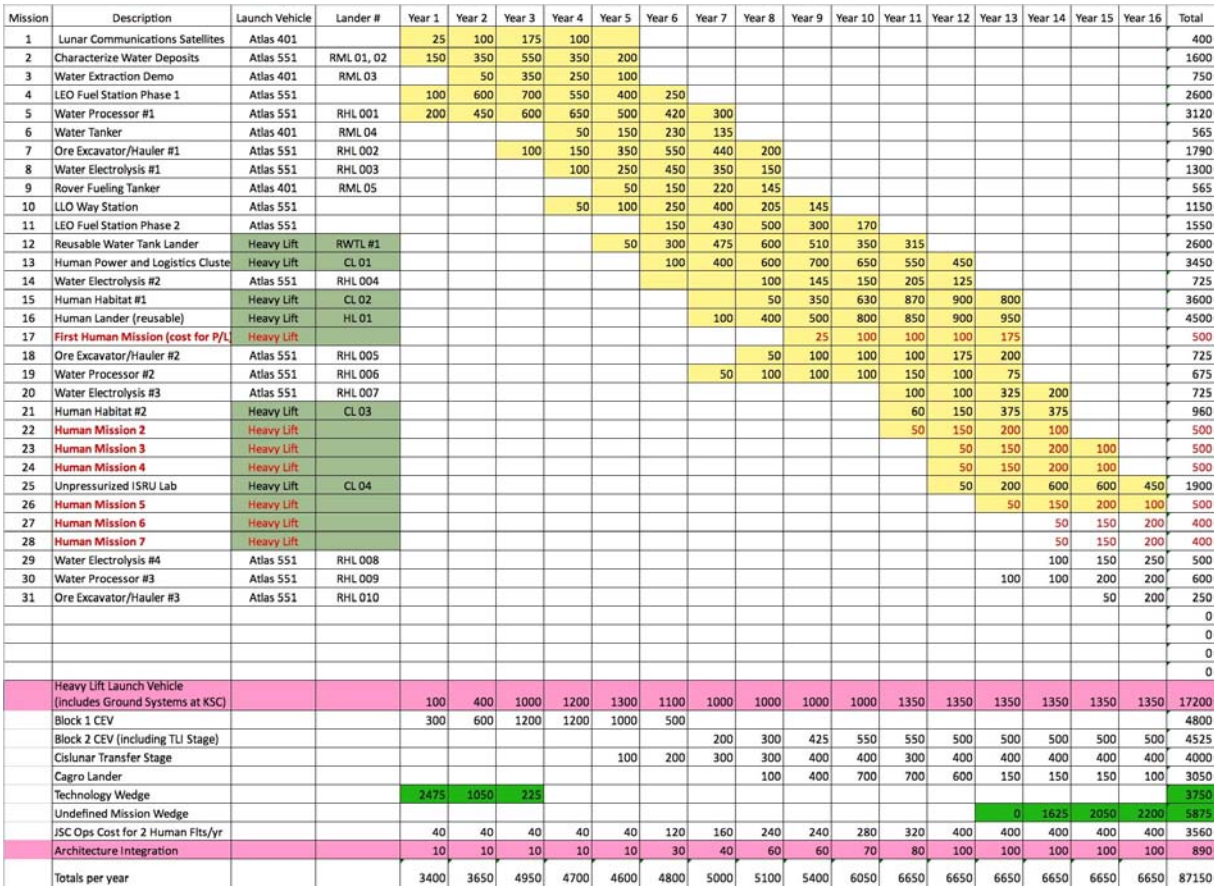
Figure 7. Sequence of missions and architectural elements. Each piece is designed to work by itself and in conjunction with other elements so that cumulative capability increases with time.

Our estimate of capabilities within a 16-year initial window shows roughly 5 human missions, 4 Heavy Cargo Missions (two of which are 12 MT wedge mass and cost allocations at this point), and a lunar surface resource production of roughly 100 MT per year of cryogenic propellant. As there are unallocated resources during this 16-year period, more capability could be added if desired and assessed as to its efficacy. We plan to continue study of possible options and augmentations of this architecture to fully understand its possibilities.

VII. Cost and Schedule

Costs are summarized in Table 2 and details are given in the appendix. We estimate that a fully functioning lunar outpost – capable of producing ~150 tonnes of water per year and roughly 100 tonnes of propellant – can be established for an aggregate cost of approximately $88 billion (Real Year dollars), including peak funding of $6.65

billion starting in Year 11. This total cost includes development of a Shuttle-derived 70 MT launch vehicle, two versions of a CEV (LEO and translunar), reusable lander, cislunar propellant depots and all robotic surface assets, as well as all of the operational costs of mission support for this architecture. The outpost is deployed and operations are fully implemented within 10-15 years of program start, but as the use of robotic assets early in the program makes the schedule flexible, we can either accelerate or slow the progress of the program, as fiscal circumstances require. Human arrival comes relatively late in the process, after we have established a productive resource processing facility but within a few years of the arrival of robotic surface assets. Still, this architecture provides for 5 human missions within the 16-year time window that we studied and many more after that at rates of 1 or 2 per year.



Mission	Description	Launch Vehicle	Lander #	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Total
1	Lunar Communications Satellites	Atlas 401		25	100	175	100													400
2	Characterize Water Deposits	Atlas 551	RML 01, 02	150	350	550	350	200												1600
3	Water Extraction Demo	Atlas 401	RML 03		50	350	250	100												750
4	LEO Fuel Station Phase 1	Atlas 551		100	600	700	550	400	250											2600
5	Water Processor #1	Atlas 551	RHL 001	200	450	600	650	500	420	300										3120
6	Water Tanker	Atlas 401	RML 04				50	150	230	135										565
7	Ore Excavator/Hauler #1	Atlas 551	RHL 002			100	150	350	550	440	200									1790
8	Water Electrolysis #1	Atlas 551	RHL 003				100	250	450	350	150									1300
9	Rover Fueling Tanker	Atlas 401	RML 05					50	150	220	145									565
10	LLO Way Station	Atlas 551					50	100	250	400	205	145								1150
11	LEO Fuel Station Phase 2	Atlas 551							150	430	500	300	170							1550
12	Reusable Water Tank Lander	Heavy Lift	RWTL #1					50	300	475	600	510	350	315						2600
13	Human Power and Logistics Cluste	Heavy Lift	CL 01						100	400	600	700	650	550	450					3450
14	Water Electrolysis #2	Atlas 551	RHL 004								100	145	150	205	125					725
15	Human Habitat #1	Heavy Lift	CL 02								50	350	630	870	900	800				3600
16	Human Lander (reusable)	Heavy Lift	HL 01							100	400	500	800	850	900	950				4500
17	**First Human Mission (cost for P/L)**	Heavy Lift										25	100	100	100	175				500
18	Ore Excavator/Hauler #2	Atlas 551	RHL 005								50	100	100	100	175	200				725
19	Water Processor #2	Atlas 551	RHL 006							50	100	100	100	150	100	75				675
20	Water Electrolysis #3	Atlas 551	RHL 007											100	100	325	200			725
21	Human Habitat #2	Heavy Lift	CL 03											60	150	375	375			960
22	**Human Mission 2**	Heavy Lift												50	150	200	100			500
23	**Human Mission 3**	Heavy Lift													50	150	200	100		500
24	**Human Mission 4**	Heavy Lift													50	150	200	100		500
25	Unpressurized ISRU Lab	Heavy Lift	CL 04												50	200	600	600	450	1900
26	**Human Mission 5**	Heavy Lift														50	150	200	100	500
27	**Human Mission 6**	Heavy Lift															50	150	200	400
28	**Human Mission 7**	Heavy Lift															50	150	200	400
29	Water Electrolysis #4	Atlas 551	RHL 008														100	150	250	500
30	Water Processor #3	Atlas 551	RHL 009													100	100	200	200	600
31	Ore Excavator/Hauler #3	Atlas 551	RHL 010															50	200	250
																				0
																				0
																				0
																				0
	Heavy Lift Launch Vehicle (includes Ground Systems at KSC)			100	400	1000	1200	1300	1100	1000	1000	1000	1000	1350	1350	1350	1350	1350	1350	17200
	Block 1 CEV			300	600	1200	1200	1000	500											4800
	Block 2 CEV (including TLI Stage)									200	300	425	550	550	500	500	500	500	500	4525
	Cislunar Transfer Stage							100	200	300	300	400	400	300	400	400	400	400	400	4000
	Cagro Lander										100	400	700	700	600	150	150	150	100	3050
	Technology Wedge			2475	1050	225														3750
	Undefined Mission Wedge															0	1625	2050	2200	5875
	JSC Ops Cost for 2 Human Flts/yr			40	40	40	40	40	120	160	240	240	280	320	400	400	400	400	400	3560
	Architecture Integration			10	10	10	10	10	30	40	60	60	70	80	100	100	100	100	100	890
	Totals per year			3400	3650	4950	4700	4600	4800	5000	5100	5400	6050	6650	6650	6650	6650	6650	6650	87150

Table 2. Cost of the lunar return architecture in Real-Year (RY) dollars. Total cost includes development and building of a medium (70 MT) heavy lift launch vehicle (Shuttle-derived), two versions of the human CEV (Block II is lunar-capable) and a reusable refuelable lunar lander. All estimates include a margin of 25-30% for cost growth.

This projected cost and schedule profile falls under the projected budget run-outs supplied by NASA to the Augustine Committee[13]. In contrast to the conclusions of that committee, we believe that productive and useful human lunar return is possible under this budgetary envelope. Our program creates a reusable, extensible space faring system that uses the material and energy resources of the Moon. The Flexible Path scenarios developed by the committee[13] continue the existing use-and-discard paradigm of spaceflight in which everything is launched from the bottom of the deep gravity well of Earth, leaving us with few permanent capabilities in space.

VIII. What will this give us?

Establishing a permanent foothold on the Moon opens the space frontier to many parties for many different purposes. By creating a reusable, extensible cislunar space faring system, we build a "transcontinental railroad" in space, connecting two worlds (Earth and Moon), as well as enabling access to all points in between. We will have a system that can access the entire Moon, but more importantly, we will have the capability to routinely access all of our space assets within cislunar space[16]: communications, GPS, weather, remote sensing and strategic monitoring satellites. These satellites will then be in reach to be serviced, maintained and replaced as they age.

We have concentrated on the water production attributes of a lunar outpost because the highest leveraging capabilities that are most easily exploited are associated with the availability of propellant. However, there are other possibilities to explore, including the paradigm-shifting culture to eventually design all structural elements needed for lunar activities using lunar resources. These activities will spur new commercial space interest, innovation and investment. This further reduces the Earth logistics train and helps extend human reach deeper into space, along a trajectory that is incremental, methodical, sustainable and within projected budget expectations.

Instead of the current design-build-launch-discard paradigm of space operations, we can build extensible, distributed space systems, with capabilities much greater than currently possible. Both the Shuttle and ISS experience demonstrated the value of human construction and servicing of orbital systems. What we have lacked is the ability to access the various systems that orbit the Earth at altitudes much greater than LEO – MEO, GEO and other locations in cislunar space.

A transportation system that can access cislunar space, can also take us to the planets. The assembly and fueling of interplanetary missions is possible using the resources of the Moon. Water produced at the lunar poles can fuel human missions beyond the Earth-Moon system, as well as provide radiation shielding for the crew, thereby greatly reducing the amount of mass needed to be launched from the Earth's surface. To give some idea of the leverage this provides, it has been estimated that a chemically propelled Mars mission requires roughly one million pounds (about 500 metric tonnes) in Earth orbit[17]. Of this mass, more than 80% is propellant. Launching such propellant from Earth requires more than five Ares V-class launches, at a cost of almost $2 billion each. This does not establish true exploration capability. A Mars mission staged from the facilities of a cislunar transport system can use the propellant of the Moon to reduce the needed mass launched from Earth by a factor of five.

This return to the Moon is affordable and can be accomplished on reasonable time scales. Instead of single missions to exotic destinations, where all hardware is discarded as the mission progresses, we instead focus on the creation of reusable and extensible space systems, flight assets that are permanent and useable for future exploration beyond LEO. In short, we get value for our money. Instead of a fiscal black hole, this extensible space program becomes a generator of innovation and national wealth. It is challenging enough to drive technological innovation yet within reach on a reasonable timescale.

Propellant and water exported from the Moon will initially be used solely by NASA, both to support lunar surface operations and to access and service satellites in Earth orbit[16] and to re-fuel planetary missions, including human missions to Mars. Over time, other federal agencies such as the Defense Department (intelligence satellites) or NOAA (weather satellites) may need lunar propellant for the maintenance of their space assets. Additionally, international partners or other countries may require propellant for access to their own satellites and space platforms. Finally, lunar propellant would be offered to commercial markets to supply, maintain and extend the wide variety of commercial applications satellites in cislunar space as well as enabling other emerging space ventures.

The modular, incremental nature of this architecture enables international and commercial participation to be easily and seamlessly integrated into our lunar return scenario. Because the outpost is built around the addition of capabilities through the use of small, robotically teleoperated assets, other parties can bring their own pieces to the table as time, availability and capability permit. International partners can contemplate their own human launch capability to the Moon without use of a Heavy Lift vehicle. This feature becomes politically attractive by simply providing lunar fuel for a return trip for the international partners. This flexibility makes international participation and commercialization in our architecture much more viable than was possible under the previous ESAS architecture.

We have described only the initial steps of lunar return based on resource utilization. Water is both the easiest and most useful substance by far that we can extract from the Moon and use to establish a cislunar space faring transportation infrastructure. Once established, we imagine many different possibilities for the lunar outpost. It may evolve into a commercial facility, which manufactures water and propellant and other commodities for sale in cislunar space. It could remain a government laboratory, exploring the trade space of resource utilization by experimenting with new processes and products. Alternatively, it could become a scientific research station, supporting detailed surface investigations to understand the planetary and solar history recorded on the Moon. We may decide to internationalize the outpost, creating a common use facility for science, exploration, research and commercial activity. By emphasizing resource extraction and use early, we create new opportunities for flexible growth and evolution beyond our initial operational capability.

IX. Conclusion

We desire to extend human reach in space beyond its current limit of low Earth orbit. The Moon has the material and energy resources needed to create a true space faring system. Recent data show the lunar surface richer in resource potential than we had thought; both abundant water and near-permanent sunlight is available at selected areas near the poles. We go to the Moon to learn how to extract and use those resources to create a space transportation system that can routinely access all of cislunar space with both machines and people. Such a goal makes our national space program relevant to national security and economic interests as well as to scientific ones. This lunar outpost serves as the vanguard for studying the practical employment of techniques, processes, and systems that will allow humanity to effectively extend its reach off-planet.

This return to the Moon is affordable under existing and projected budgetary constraints. Creation of sustainable space access opens the Solar System to future generations. Having access to the Moon and the ability to use its resources is more important than how we go or how soon we get there. This architecture can relax schedule to fit any monetary or programmatic shortfall, as well as accelerate schedule if funding increases. But regardless of program pace, our goals and tactics remain the same; open the space frontier for a wide variety of purposes by harvesting the material and energy resources of the Moon. The decisions we make now will determine if our long-delayed journey into the cosmos can begin and be sustained over time.

Appendix

A. Cost assumptions and Ground rules

1. The cost of crew to ISS is not budgeted in this portfolio, consistent with the funding profile provided to the Augustine Commission for a lunar architecture.
2. This architecture relies upon a Design To Cost philosophy at NASA such that performance and to a certain extent risk is secondary to cost; NASA is undergoing that paradigm shift evaluation now. This architecture has robust performance margins such that performance can be sacrificed if cost growth is too high. All cost in Real-Year dollars.
3. The Heavy Lift Development cost thru first flight (including KSC DDTE) but not including cost of any future flight is \$9.4B for a 75mT LV. Profile shows dip in the middle to get KSC pad modifications performed early. This is consistent with the current planning for the SLS Program.
4. Heavy Lift Operations cost is \$1.2B per year (from HLLV Ops cost in Implementation Plan) plus \$150M/yr for upgrades, assuming 2 flights and flight sets, and includes all KSC and MSFC costs to launch 2 flights per year (any mix of crew and cargo).
5. Lunar resource processing will be procured from private endeavors when and if they can first demonstrate viability on the lunar surface. In the interim, this architecture assumes that NASA will develop resource producing capabilities and use them throughout the 16-yr duration of this architecture. Viable demonstrations by commercial entities will reduce the cost of the total architecture, but are not assumed here.
6. The fuel producing infrastructure on the Moon (EH, WPS and WEFS) has a 10 yr life with on-site maintenance.
7. The acquisition approach for the various landers is assumed to be one contractor for the robotic landers (RML and RHL), and one contractor for the larger landers (RWTL, HL, and CL). Because of similar designs, parts, components, tooling, and test systems, certain cost savings can be realized. These have not been shown and constitute hidden cost margin for the DDTE of three of the 5 landers.
8. The acquisition approach for the various power systems is assumed to be a single contractor. All power systems on the robotic landers to support lunar water extraction and electrolysis are a single, modular design with only one DDTE cycle.
9. All transport from LEO to LLO (except for the robotic landers) will use the CTS. The variable mass of payloads will be accommodated using propellant offload.
10. JSC Ops Cost (prior to first human mission) includes development of EVA suits and all JSC activity supporting Flight and Mission Ops (from FY02 cost of \$450M including everything for Shuttle). There is probably margin in this allocation, but we have not studied this number in detail.
11. This architecture assumes two CEVs per year cost \$500M total.
12. The Rovers (WT, RFT) have a 15 yr life with on-site maintenance.
13. The Solar Power Plants have a 20 yr life.
14. JSC Ops cost (after the first human mission) for Ops for two crewed missions per year assumes worst-case 6-month stays and costs \$400M/yr (see cost of Shuttle program, above in #10).
15. The RHL DDT&E will include a new cryogenic engine that will also be used for RWTL, HL, and CL.

16. All Atlas 551 launches except LEO Fuel Station include $50M for water to the LEO Fuel Station, assuming a launch cost of ~$5000/kg.
17. Cislunar Transfer Stage Ops cost is $400M/yr for two missions, either crew, cargo, or mix, including hardware, integration, and flight support.
18. The cost of the first flight of the Water Processor System includes the DDT&E cost for the Solar Power Plant and the Robotic Heavy Lander.
19. The Atlas 551 cost is assumed to be $200M; Atlas 401 is assumed at $150M (reference cost data from ULA web site)
20. Year 13 has three heavy-lift launches. Assume that the LV hardware for the first launch is paid for with prior year dollars (only one launch in previous year) and stored for a while.
21. The LLO Way Station should be as close to the LEO Fuel Depot design as possible, with a goal to be exact, leading to one DDTE development for modular assets in LEO and LLO. The LEO asset is three identical, modular units. The acquisition approach for these assets is a single contractor.
22. The HL is derived with the same basic structure and systems as the CL, developed at the same time.
23. The Outpost Power Grid is the same basic design as the Power Plants, but with the ability to transport them.
24. Management, Integration, and SE&I are 10% of the cost of all the pieces unless specified. When there is only a single piece launched, the cost of those three pieces is embedded into that element cost.
25. All Elements include between 25 and 30% cost margin as part of their cost allocation. Cost growth is addressed by a reduction in performance down to a floor, and then schedule slippage for the architecture.
26. All integration activity for integrating more than one element into a launch is performed by NASA.

B. Costing of individual missions

Mission 1:

Launch Cost:	$150M (Atlas 401)
Launch Payload:	
Comm Satellites	Several
Upper Stage Solid	one
Final payload:	Multiple communication satellites in LLO
Final Payload Mass:	1000kg
Payload cost:	$250M (including upper stage solid)
PM, SE&I, etc	$0 (Included in payload cost)
Total Mission Cost:	**$400M**

Mission 2:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
RML First Unit	$500M
RML Second Unit	$125M
WIE First Unit	$400M
WIE Second Unit	$100M
Final payload:	2 WIE's, one to each pole
Final Payload Mass:	1000kg
Payload cost:	$1125M
PM, SE&I, etc	$175M
Special Req'ts	$50M (Nuclear)
	$50M (Upper Stage solids)
Total Mission Cost:	**$1600M**

Mission 3:

Launch Cost:	$150M (Atlas 401)
Launch Payload:	
RML Third Unit	$125M
Water Demo Pkg	$400M
Final payload:	Water Demo Package
Final Payload Mass:	500kg
Payload cost:	$525M

PM, SE&I, etc	$50M
Special Req'ts	$25M solid
Total Mission Cost:	**$750M**

Mission 4:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
LEO Fuel Station	$2400M
Final payload:	LEO Fuel Station part 1
Final Payload Mass:	8000kg
Payload cost:	$2400M
PM, SE&I, etc	$0 (included in payload cost)
Special Req'ts	None
Total Mission Cost:	**$2600M**

Mission 5:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
RHL First Unit	$2000M
WP&SP First Unit	$500M
PP First Unit	$200M
Final payload:	WP&SP unit plus PP on the surface
Final Payload Mass:	2300kg
Payload cost:	$2700M (including upper stage solid)
PM, SE&I, etc	$370M ($100M more than 10%)
Special Req'ts	$50M (10,000kg of water for fuel)
Total Mission Cost:	**$3120M**

Mission 6:

Launch Cost:	$150M (Atlas 401)
Launch Payload:	
RML Forth Unit	$125M
Water Tanker	$250M
Final payload:	Water Tanker (rover) on the surface
Payload cost:	$375M (including upper stage solid)
PM, SE&I, etc	$40M
Special Req'ts	None
Total Mission Cost:	**$565M**

Mission 7:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
RHL Second Unit	$400M (2x the nth copy cost for the 2nd unit)
EH First Unit	$1000M
Final payload:	Excavator/Hauler on the surface
Final Payload Mass:	2300kg (may be more than 1 piece)
Payload cost:	$1400M
PM, SE&I, etc	$140M
Special Req'ts	$50M (10,000kg of water for fuel)
Total Mission Cost:	**$1790M**

Mission 8:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
RHL Third Unit	$200M
WEFSP First Unit	$700M

PP Second Unit	$50M
Final payload:	WEFSP and PP on surface
Final Payload Mass:	2300kg
Payload cost:	$950M
PM, SE&I, etc	$100M
Special Req’ts	$50M (10,000kg of water for fuel)
Total Mission Cost:	**$1300M**

Mission 9:

Launch Cost:	$150M (Atlas 401)
Launch Payload:	
RML Fifth Unit	$125M
RFT First Unit	$200M
Final payload:	Rover Fueling Tanker on surface
Final Payload Mass:	500kg
Payload cost:	$375M
PM, SE&I, etc	$40M
Special Req’ts	None
Total Mission Cost:	**$565M**

Mission 10:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
LLO Way Station	$800M (mostly a copy of LEO Fuel Station)
Final payload:	LLO Way Station in LLO (10,000kg fuel)
Final Payload Mass:	8000kg
Payload cost:	$800M
PM, SE&I, etc	$100M (Included in payload, plus complicated ops)
Special Req’ts	$50M (10,000kg of water for fuel)
Total Mission Cost:	**$1150M**

Mission 11:

Launch Cost:	$200M (Atlas 551)
Launch Payload:	
LEO Fuel 2nd copy	$600M
LEO Fuel 3rd copy	$600M
Final payload:	LEO Fuel Station Phase 2 in LEO (75,000kg fuel)
Final Payload Mass:	16000kg
Payload cost:	$1200M
PM, SE&I, etc	$100M (some included in payload cost)
Special Req’ts	$50M (10,000kg of water for fuel)
Total Mission Cost:	**$1550M**

Mission 12:

Launch Cost:	$0 (Heavy Lift cost entered elsewhere)
Launch Payload:	
RWTLFirst Unit	$2100M
CTS First Unit	$0 ($1.8B DDTE entered elsewhere)
RWTL Support Cart	$150M
Final payload:	Reusable Water Tank Lander on surface
Final Payload Mass:	5020 kg
Payload cost:	$2250M
PM, SE&I, etc	$200M
Special Req’ts	$150M (30,000kg of water for fuel)
Total Mission Cost:	**$2600M**

Mission 13:
Launch Cost: $0 (Heavy Lift cost entered elsewhere)
Launch Payload:
  HPLC:
    Personnel Transfer Vehicle $2000M
    Outpost Power Grid $200M
    Portable Comm Terminal $100M
    LSRS Heavy $100M
    HL Support Cart $150M
    Logistics supplies $100M
  Cargo Lander 1st unit $0 ($2500M DDTE entered elsewhere)
  CTS 2nd Unit $0 ($200M Unit cost entered elsewhere)
Final payload: Human Power & Logistics Cluster on surface
Final Payload Mass: 10,000kg
Payload cost: $2750M
PM, SE&I, etc $400M ($125M Extra for complex integration)
Special Req'ts $300M (60,000kg of water for fuel)
Total Mission Cost: $3450M

Mission 14:
Launch Cost: $200M (Atlas 551)
Launch Payload:
  RHL Fourth Unit $200M
  WEFSP 2nd Unit $175M
  PP Third Unit $50M
Final payload: WEFSP #2 and PP on surface
Final Payload Mass: 2300kg
Payload cost: $625M
PM, SE&I, etc $50M (Repeat, so cost below 10%)
Special Req'ts $50M (10,000kg of water for fuel)
Total Mission Cost: $725M

Mission 15:
Launch Cost: $0 (Heavy Lift cost entered elsewhere)
Launch Payload:
  Habitat First Unit $3000M
  Cargo Lander 2nd unit $0 ($300M Unit cost entered elsewhere)
  CTS 3rd Unit $0 ($200M Unit cost entered elsewhere)
Final payload: Habitat #1 on surface
Final Payload Mass: 10,000 kg
Payload cost: $3000M
PM, SE&I, etc $300M
Special Req'ts $300M (60,000kg of water for fuel)
Total Mission Cost: $3600M

Mission 16:
Launch Cost: $0 (Heavy Lift cost entered elsewhere)
Launch Payload:
  HL First Unit $2100M
  CTS 4th Unit $0 ($200M Unit Cost entered elsewhere)
Final payload: Human Lander (reusable) on surface
Final Payload Mass: 10,000kg
Payload cost: $4000M
PM, SE&I, etc $200M (easier than 10% because of RWTL synergy)
Special Req'ts $300M (60,000kg of water for fuel)
Total Mission Cost: $4500M

Mission 17:
Launch Cost: $0 (Heavy Lift cost entered elsewhere)
Launch Payload:
  Block 2 CEV 1st Unit $0 ($6925M DDTE for Block 1& 2 covered elsewhere)
  CTS 5th Unit $0 ($200M Unit Cost entered elsewhere)
  Misc Payload $50M
Final payload: First Human Mission to Outpost
Final Payload Mass: 1000kg
Payload cost: $350M
PM, SE&I, etc $0 (included in payload cost; Ops cost covered elsewhere)
Special Req'ts $150M (30,000kg of water for fuel)
Total Mission Cost: $500M

Mission 18:
Launch Cost: $200M (Atlas 551)
Launch Payload:
  RHL Fifth Unit $200M (unit cost)
  EH Second Unit $225M (unit cost)
Final payload: Excavator/Hauler #2 on the surface
Final Payload Mass: 2300kg (may be more than 1 piece)
Payload cost: $625M
PM, SE&I, etc $50M (duplicate of Mission 7, so <10%)
Special Req'ts $50M (10,000kg of water for fuel)
Total Mission Cost: $725M

Mission 19:
Launch Cost: $200M (Atlas 551)
Launch Payload:
  RHL Sixth Unit $200M
  WP&SP 2nd Unit $125M
  PP 4th Unit $50M
Final payload: WP&SP #2 plus PP on the surface
Final Payload Mass: 2300kg
Payload cost: $575M (including upper stage solid)
PM, SE&I, etc $50M (duplicate of Mission 7, so <10%)
Special Req'ts $50M (10,000kg of water for fuel)
Total Mission Cost: $675M

Mission 20:
Launch Cost: $200M (Atlas 551)
Launch Payload:
  RHL Seventh Unit $200M
  WEFSP 3rd Unit $175M
  PP 5th Unit $50M
Final payload: #3 and PP on surface
Final Payload Mass: 2300kg
Payload cost: $625M
PM, SE&I, etc $50M (Repeat, so cost below 10%)
Special Req'ts $50M (10,000kg of water for fuel)
Total Mission Cost: $725M

Mission 21:
Launch Cost: $0 (Heavy Lift cost entered elsewhere)
Launch Payload:

Habitat Second Unit $600M
Cargo Lander 3rd unit $0 ($300M Unit cost entered elsewhere)
CTS 6th Unit $0 ($200M Unit cost entered elsewhere)
Final payload: Habitat #2 on surface
Final Payload Mass: 10,000kg
Payload cost: $600M
PM, SE&I, etc $60M
Special Req’ts $300M (60,000kg of water for fuel)
Total Mission Cost: $960M

Mission 22:
Launch Cost: $0 (Heavy Lift cost entered elsewhere)
Launch Payload:
Block 2 CEV 2nd Unit $0 ($ covered elsewhere)
CTS 7th Unit $0 ($200M Unit Cost entered elsewhere)
Misc Payload $50M
Final payload: Second Human Mission to Outpost
Final Payload Mass: 1000kg
Payload cost: $350M
PM, SE&I, etc $0 (included in payload cost; Ops cost covered elsewhere)
Special Req’ts $150M (30,000kg of water for fuel)
Total Mission Cost: $500M

Mission 23:
Launch Cost: $0 (Heavy Lift cost entered elsewhere)
Launch Payload:
Block 2 CEV 3rd Unit $0 ($6925M DDTE for Block 1& 2 covered elsewhere)
CTS 8th Unit $0 ($200M Unit Cost entered elsewhere)
Misc Payload $50M
Final payload: Third Human Mission to Outpost
Final Payload Mass: 1000kg
Payload cost: $350M
PM, SE&I, etc $0 (included in payload cost; Ops cost covered elsewhere)
Special Req’ts $150M (30,000kg of water for fuel)
Total Mission Cost: $500M

Mission 24:
Launch Cost: $0 (Heavy Lift cost entered elsewhere)
Launch Payload:
Block 2 CEV 4th Unit $0 ($6925M DDTE for Block 1& 2 covered elsewhere)
CTS 9th Unit $0 ($200M Unit Cost entered elsewhere)
Misc Payload $50M
Final payload: Fourth Human Mission to Outpost
Final Payload Mass: 1000kg
Payload cost: $350M
PM, SE&I, etc $0 (included in payload cost; Ops cost covered elsewhere)
Special Req’ts $150M (30,000kg of water for fuel)
Total Mission Cost: $500M

Mission 25:
Launch Cost: $0 (Heavy Lift cost entered elsewhere)
Launch Payload:
Unpress ISRU Lab $1500M
Cargo Lander 4th unit $0 ($300M Unit cost entered elsewhere)
CTS 10th Unit $0 ($200M Unit cost entered elsewhere)
Final payload: Unpressurized ISRU Lab on surface

Final Payload Mass:	10,000kg
Payload cost:	$1500M
PM, SE&I, etc	$100M
Special Req'ts	$300M (60,000kg of water for fuel)
Total Mission Cost:	**$1900M**

Mission 26:

Launch Cost:	$0 (Heavy Lift cost entered elsewhere)
Launch Payload:	
Block 2 CEV 2nd Unit	$0 ($ covered elsewhere)
CTS 7th Unit	$0 ($200M Unit Cost entered elsewhere)
Misc Payload	$50M
Final payload:	Fifth Human Mission to Outpost
Final Payload Mass:	1000kg
Payload cost:	$350M
PM, SE&I, etc	$0 (included in payload cost; Ops cost covered elsewhere)
Special Req'ts	$150M (30,000kg of water for fuel)
Total Mission Cost:	**$500M**

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