Mission and Implementation of an Affordable Lunar Return

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ABSTRACT

We present an architecture that establishes the infrastructure for routine space travel by taking advantage of the Moon's resources, proximity and accessibility. We use robotic assets on the Moon that are teleoperated from Earth to prospect, test, demonstrate and produce water from lunar resources before human arrival. This plan is affordable, flexible and not tied to any specific launch vehicle solution. Individual surface pieces are small, permitting them to be deployed separately on small launchers or combined together on single large launchers. Schedule is our free variable; even under highly constrained budgets, the architecture permits this program to be continuously pursued using small, incremental, cumulative steps. The end stage is a fully functional, human-tended lunar outpost capable of producing 150 metric tonnes of water per year – enough to export water from the Moon and create a transportation system that allows routine access to all of cislunar space. This cost-effective lunar architecture advances technology and builds a sustainable transportation infrastructure. By eliminating the need to launch everything from the surface of the Earth, we fundamentally change the paradigm of spaceflight.

ACRONYMS

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
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
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

INTRODUCTION

The human race is remarkably fortunate in having so near at hand a full-sized world with which to experiment: before we aim for the planets, we will have had the chance of perfecting our astronautical techniques on our own satellite…the conquest of the Moon will be the necessary and inevitable prelude to remote and still more ambitious projects." – Arthur C. Clarke, 1951

A key part of the 2004 Vision for Space Exploration (VSE) – the long-range strategic path to extend human reach beyond low Earth orbit – was learning how to use off-planet material and energy resources to create new space faring capability. Because it contains the raw materials needed to do this and because we know quite a bit about it already, these techniques were to be applied first on our nearby Moon. The Moon's proximity and accessibility allows us to conduct a significant amount of this work in relative safety with robotic machines teleoperated from Earth and from cislunar space prior to human arrival.

Despite the advantages offered by this approach, implementation of the VSE floundered for several reasons. From the beginning, the National Aeronautics and Space Administration (NASA) did not embrace or understand the basic mission of the VSE, despite its clear articulation in both its founding documents and subsequent elaboration of the mission by many observers. The architecture the agency produced (the Exploration Systems Architecture Study or ESAS), while being technically capable of eventual lunar return, had the disadvantage of requiring more funding that could be made available within the time frame envisioned. The ESAS study was adopted as Project Constellation with relatively little consideration of possible alternatives and quickly became a programmatic straightjacket. For many, the ESAS became conflated with the VSE, but they are now (and have always been) separate and distinct – the ESAS is the architecture that the agency created to implement the VSE. ESAS is not the VSE and vice versa.

As budgetary problems with Constellation developed over time, it became a common contention that the VSE (Vision) in general and lunar return in particular was "unaffordable." This meme was cemented into the report of the Augustine Committee, which claimed that no path exists to get back to the Moon under the existing budgetary environment. In fact, that committee was presented with at least three alternative architectures that would have resulted in an affordable path to lunar return. As the imminent retirement of the Space Shuttle will leave the nation without an American system to access space, most of the work of the committee focused on launch vehicles. The selections and choices made in that decision process will have significant impact on our future space capabilities and thus, should receive careful consideration from a variety of perspectives, not simply from the viewpoint of making and operating the next American launch vehicle.

In large part, the VSE was not properly implemented because of uncertainty about the objectives of our national space program. The objective of the Vision was not a series of Apollo-style expeditions or a human Mars mission but rather something more ambitious and permanent. The goal of the Vision for Space Exploration was nothing less than 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. However, 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.

The VSE sought to break this impasse. In Situ Resource Utilization (ISRU) is a new and different approach that involves 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.

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 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.

THE MISSION ON THE MOON

Starting in 2004, NASA hosted a number of retreats, workshops, conferences and meetings to discuss and describe possible lunar surface activities. The planning activities were so inclusive and the resulting wish list of experiments and activities became so immense that a clear mission objective for lunar return became impossible to state. We believe that a critical (if not the most critical) problem with the ESAS architecture is its failure to specifically understand, articulate and design to a "mission" on the lunar surface. In this context, we mean a clear statement that encompasses the strategic goals, objectives and activities of establishing a presence on the surface of 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. The availability of lunar consumables allows us to routinely access all the levels of cislunar space where our economic, national security and scientific satellites reside.

This mission objective doesn't just imply but rather 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 (see Clarke, 1951). 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 more benign than equatorial regions like the 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 plan to 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, emplace a habitat, prepare roads and landing pads, erect solar cell arrays and thermal control systems, and deploy surface communications systems. In the third 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. In the fourth stage, we produce surplus water that is exported to cislunar space (e.g., Earth-Moon L-1) for processing into propellant and other products.

Will this architecture be practical and cost effective compared to launching products from Earth? Thus far, we have addressed only 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 to learn whether it is feasible to export lunar products to Earth orbit or beyond.

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.

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. Its proximity 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 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, previous data were inconclusive. In addition, we needed better images and topographic maps of the poles to fully understand their lighting conditions.

New data from a variety of missions have documented the nature and occurrence of water on the Moon (e.g., Spudis, 2006) and the unique lighting environment near the poles. 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 poleward of about 65° latitude (Pieters *et al*., 2009). Additionally, the impact of the LCROSS spacecraft in October 2009 kicked up a plume of dust, water vapor and ice particles; water is present in this locality at concentrations between 5 and 10 weight percent (Wooden et al., 2010). Finally, the Mini-SAR radar mapper on Chandrayaan-1 (Spudis *et al*., 2010) found dozens of craters at both poles that appear to contain nearly pure deposits of water ice; estimates for the north pole suggest up to 600 million cubic meters of water ice may occur within these craters (Figure 1). In total, the new results 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.

In addition to the presence of water ice, new mapping data show areas of near-permanent sun illumination close the poles (Bussey *et al*., 2005; 2010). Some areas are illuminated more than 90% of the lunar year (Figure 1). Because darkness is primarily caused by local topography, eclipse periods occur at irregular intervals and have durations ranging from a few hours to almost 60 hours. For this study, we assume solar illumination for 80% of the lunar day, a conservative estimate that is valid for many areas 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. 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 (e.g., Fig. 1). We conduct reconnaissance at both poles early in our program to answer these questions definitively. 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.

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 (Zegler *et al*., 2009). This approach has the advantage of using existing LV assets but we need to develop propellant depots 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 and Shuttle side-mount (SSM) – 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. The use of existing Shuttle piece parts keeps this to a minimum.

We assume the use of multiple launch vehicles, using the best available assets to meet given payload and mission requirements, including EELV to launch early lunar surface robotic assets. A Delta IV Heavy and large Atlas V (551) can place 1-2 mT on the surface of the Moon. This is enough payload capacity to deliver significant capability to the Moon. 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 to our architecture but is not an absolute 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 on the lunar surface. Two SSM launches can fly an entire human lunar mission; this is an important capability in the 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 limitations of low Earth orbit 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 (2009).

ARCHITECTURAL APPROACH AND ELEMENTS

To preview our general strategy, we envision the flight of robotic spacecraft that land on the Moon, characterize its resources in detail, demonstrate that water can be extracted, processed and stored, and that begin to set up a resource processing system which is largely robotic 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.

We first describe the needed pieces of our architecture (Table 1) and then the order of flight elements to give us various capabilities on the Moon and in cislunar space over time. A key attribute of our architecture is flexibility – because we build surface infrastructure in increments with small pieces, 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 the ESAS architecture. 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.

CISLUNAR AND LUNAR ORBITAL ELEMENTS

Communication/navigation system – 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 or in halo orbits near the Earth-Moon L-1 and L-2 libration points. The L-point variants require higher power and bandwidth due to their greater distance from the Moon (approx. 80,000 km). Such a system must be able to provide bandwidth (several Mbps) and positional accuracy (within 100 m) necessary to support transit and navigation around the lunar poles.

Low Earth Orbit (LEO) Fuel Stations 1 and 2 – We develop and use orbital propellant depots in two stages. Phase 1 is a propellant depot designed to re-fuel cislunar transport elements that can store up to 20 mT of water. Initial sizing of the depot is for re-fueling the heavy robotic lander, the workhorse spacecraft of early lunar return. Phase 2 is a larger propellant depot designed to re-fuel other cislunar transport elements and stores up to 75 mT of water and 70 mT of cryogenic propellant. The depots store water and make gaseous O_2 and H_2 using solar array electrolysis, which are then liquefied into fluids. Sizing is for re-fueling the cislunar transfer stage (Table 1). As with many elements of this architecture, the Phase 1 and Phase 2 stations are intended to be modular, for the reduction and containment of costs, and so the Phase 2 station might simply be 2 more Phase 1 modules connected together, which was the assumption for this study.

Cislunar Way Station – This facility is a propellant depot near the Moon designed to support cislunar and lunar orbital mission elements. This element begins to take advantage of the high degree of cost and payload leveraging for return fuel and therefore return mass from the Moon to Earth. While we have not really addressed the natural expansion of this capability to improve the logistics return supply pipeline other than for humans at this point, the concept of a Cislunar Way Station can have a huge positive benefit after first demonstrating the capability and proving its viability. The depot can service unmanned and human spacecraft and is designed to be capable of accepting water from the lunar surface and converting it into cryogenic LO_2 and LH_2. While the initial needs are for a smaller facility than its LEO variants, cost containment and modularity have driven this study to assume a copy of the Phase 1 LEO fuel station for the Cislunar Way Station. The initial need for the cislunar depot is to store about 10 mT of processed, cryogenic fuel. It requires about 25 kW of electrical power from solar arrays. We have initially placed this facility in low lunar orbit (~100 km circular) but it could also be located at Earth-Moon L-1. We plan to trade the relative advantages and drawbacks of the two localities before making a final decision.

LUNAR LANDERS

We use landers in a variety of sizes and for a variety of purposes. We begin small, with the objective of collecting strategic information about the nature and conditions of the lunar polar prospect but rapidly transition to utilitarian landers that deliver pieces of surface infrastructure for long-term use. These robotic elements constitute the early emplacement and operation of the lunar outpost. Data on specific hardware elements are given in Table 1.

Robotic Medium Lander (RML) – A small (1200 kg) lander is designed to operate as a single point base station or to deliver a small, exploration rover. Early payloads (~500 kg) are designed to gather strategic information, specifically to prospect the polar ice deposits, characterize their physical properties and map their distributions and to acquire and analyze samples. In addition, specific bench-scale experiments can be delivered to the Moon to experiment with different resource extraction techniques and processes. These landers are not designed to be part of the permanent outpost systems or to last for significant lengths of time, but remain on the surface near the outpost site, available to future crews for refurbishment and use or a source of spare parts, if desirable. They would incorporate features like cameras and beacons that would be useful in the future.

Robotic Heavy Lander (RHL) – The heavy lander (4200 kg) is designed for continual and constant delivery of payloads (~ 2.5 mT) to the lunar surface with each landing. This lander delivers a variety of robotic surface assets, including excavators, haulers, water processors, power plants, electrolysis units and storage tanks. It will become the workhorse lander of the robotic outpost. This lander ends its mission with delivery of its payload to the surface; like the smaller version, such landers could be re-used in the future during an advanced stage of outpost operation. In the paradigm of modularity and affordability, the RHL development is assumed to include the engine development that will be used on later landers because of similar sizing, including the human lander so that cost is minimized over the entire lunar architecture. This lander fuels at the LEO Fuel Station, and so consists of a LO_2/LH_2 propulsion system that allows early validation of as many components as practical that will later be used on reusable systems.

Reusable Water Tank Lander (RWTL) – This unit is designed to store and deliver lunar surface-produced water from the Moon. The vehicle is about 5000 kg in mass and can deliver 3500 kg of water to depots in cislunar space. Because of the mission architectural dependencies on propellant and mass sizing, our point of departure sizing assumes the delta velocity needs for a LLO location for the Cislunar Way Station; a change to an L1 location would necessitate a different size vehicle. Initial landing ends on the surface with dry tanks. The tanks are filled with lunar-produced water for transport back to cislunar (LLO or L-point). This vehicle is designed for multiple trips as a water transporter from the lunar surface and so must possess long-lived systems. Its main propulsion system and Attitude Control System use the cryogenic fuel made on the Moon, and therefore will leverage off of the development of the RHL described earlier. The vehicle is parked at the landing pad of the outpost until needed for flight.

Human Lander (HL) – 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.

Cargo Lander (CL) – This vehicle is a 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. Further, 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.

LUNAR SURFACE ASSETS

The orbital and lander elements of the transportation system deliver a variety of surface equipment and infrastructure elements, all designed to work together to create a system to harvest, store and use lunar resources. Our initial objective is the production of water from polar ice deposits. Water extracted from the Moon supports the outpost, but our goal is to produce enough water for export to cislunar space. Initial consumption will be by government users and our international space partners – NASA, the space agencies of other nations, DoD, NOAA, DoE and others with need for space access. Excess product will be made available to commercial space users. We envision a transition over time to a dominantly commercial market with operations in cislunar space and on the lunar surface.

Although water is the principal focus of our architectural design, we recognize that other volatile species are likely present in the polar deposits. We plan to characterize these other substances and save those that might be useful. For example, nitrogen, carbon, methane and simple organic molecules are present in cometary ices and probably exist within the polar ice. All of these substances have potential use for future habitation on the Moon.

SURFACE ROVERS

Rovers provide us with the surface mobility needed to begin prospecting and using lunar water. All rovers are capable of control both remotely from Earth and by human crew on the Moon or in cislunar space. Most work will be done via Earth control, particularly in the early to middle phases of outpost establishment and resource harvesting. As operational conditions and procedures become better established, we can automate most surface operations, requiring robotic teleoperations only to repair broken systems or if unusual or unexpected conditions are encountered.

Surface and terrain conditions in the polar areas are similar to those encountered at highlands sites elsewhere on the Moon. Slopes can be quite high, up to 35° or more in the walls of fresh craters. The abundance of large rocks varies, but is typically less than a couple percent for rocks larger than 30 cm in dimension. We do not know the physical nature of the ice deposits in polar shadow, but evidence from the LCROSS impact plume (Schultz et al., 2010) suggests that the deposits consist of fluffy aggregates of ice and soil particles instead of solid, dense crystalline ice. Navigation across such deposits is unknown and unpredictable, but rovers that can traverse steep slopes should be able to handle these terrains as well. Rovers must be capable of surviving and functioning in extreme environments, including cold zones with temperatures as low as 25 K.

Rover 01 – Water Ice Explorer (WIE) – The first rover to the lunar poles will explore the polar light and dark areas, characterizing 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. This rover will begin the long-term task of prospecting for lunar ice deposits such that the closest, highest grade deposits are found proximate to the outpost site. 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 rover has a mass of about 500 kg and will carry instrumentation to measure the physical and chemical nature of the polar ice (e.g., GCMS, neutron spectrometer, XRF/XRD). In addition, it will be able to 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 for this rover 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.

Rover 02 – Excavator/Hauler (EH) – This large rover (2300 kg) is the workhorse of early lunar resource processing activity. It will dig and move water-bearing soil (feedstock) from the prospected deposits, carry it across the surface in a dump pan, and deliver the feedstock to the processors located near the main outpost site. It may be powered by RTG, RFC or batteries. The EH rover may also need to perform some lunar surface "roadwork" to allow easier surface transport if steep slopes prove to be difficult to reliably traverse. Since these rovers are modular, the campaign can start producing water with one unit, with further production resulting when additional rovers are delivered. However, it is possible that the mining of the water ice resource and the delivery mechanism that this rover provides does not result in a full duty cycle for this rover (conservative timing and logistics estimates have been used), in which case production can be increased simply by increasing the duty cycle of this unit. We reserve this mass as one rover but the nature of lunar surface mining may require the development of two or more specialized vehicles, depending upon knowledge gained from this point to the actual design of the rovers. Therefore, this mass is more of a resource allocation than an actual physical realization of a particular device or vehicle at this point. The basis for the estimate uses the Lunar Architecture Team ISRU numbers, along with a large uncertainty factor added for realism.

Rover 03a – Water Tanker (WT) – This vehicle transports water from the extraction plants to the electrolysis plants for cracking into O_2 and H_2. It is relatively small (500 kg) as it is in constant use, so each load is relatively small. As it is always in the sunlit areas, it can be battery powered, recharging from the solar power plants when necessary. In addition to water transport, this rover can also haul minor cargo, such as the cabling need to wire together the surface solar power plants. To accomplish this kind of manipulation-intensive work, it is equipped with "Robonaut" remote effectors, controlled from Earth by teleoperation. It also has the capacity to conduct routine maintenance and inspection via cameras on the end effectors as well as doing change out of surface parts and machinery.

Rover 03b - Rover Fueling Tanker (RFT) – The small rover (500 kg) is similar to the water tanker described above but is equipped to transfer and convey processed cryogens from the electrolysis plants to storage, to fuel waiting landers ready to return to cislunar space, or to be sent as filled fuel-tank cargo to other spacecraft waiting at the staging nodes. Because of modularity, it shares the same chassis and electronic hardware as the Water Tanker for cost containment and ease of logistics maintenance and repair. It is battery powered and recharged at the solar power plants.

SURFACE PAYLOADS, FACILITIES AND ASSETS

The following elements make up the surface infrastructure on the Moon that creates and constitutes the lunar outpost. It includes both initial demonstration experiments and technology development platforms as well as operational and production equipment. All elements are emplaced and operated through robotic teleoperations from Earth. There is a limited capability for robotic self-repair but we believe that eventually people will be needed to assure the smooth and complete functioning of the entire end-to-end system. The scale of envisioned operations determines the number of each asset; we here estimate the minimum necessary number of units to give our critical initial level of capability and product production. The scale of surface operations (and commensurate level of capability) can be easily increased through delivery of additional units.

Water Demonstration Package (WD) – This is a lander-mounted experiment designed to determine the optimum techniques and conditions for the extraction of water and an evaluation of its purity. It takes feedstock brought from the prospect area by the WIE, heats and extracts water and stores it for analysis, and future retrieval and use. The experiment is demonstration scale and is only designed to determine the optimum conditions for water processing but it can produce water at the tens of kilograms-scale. The mass of the system is less than 500 kg, including power source and waste discarding equipment.

Solar Power Plant (SPP - 8) – The solar arrays that power the lunar surface facilities arrive on the heavy lander (RHL) along with the water processors on three of these flights (described below) and become part of the fixed infrastructure of the outpost. Each power plant (1100 kg) consists of deployable arrays that generate 25 kW, with storage batteries for eclipse periods, transitioning to rechargeable fuel cells during later stages of surface presence. The arrays can be rotated about their vertical axes, allowing the sun to be tracked over the course of a lunar day. The landers have power ports to which the surface equipment (e.g., rovers) can plug in and recharge. Over the course of the program we will land eight identical lander/power units on the Moon. Modularity is a key design philosophy to contain cost. They may operate individually in series or together in parallel to provide electrical power to all the facilities of the lunar outpost.

Water Processing and Storage Package (WPS - 3) – Arriving on the Moon with one of the 25 kW solar arrays (SPP) is a self-contained water processing and storage unit. The initial buildup to two human flights per year will require two of these units. Each processor is about 1200 kg, including a tank for water, capable of storing 4000 kg. It is packaged with a SPP described above but can also share power with and from other landers as needed (cabling is carried and installed by robotic teleops and surface rovers). Each unit is designed to produce about 48,000 kg of water per year and also recharge the batteries of the surface rovers. Three water processors will be installed over the initial lifetime of the program, making up a water production capability of almost 150 mT of water per year by the end of the program cycle (assuming that the units can be maintained with periodic maintenance and repair). Note that this does not take into account the system limitation of electrolysis to turn the water into fuel, discussed with the Water Electrolysis and Fuel Storage Package element below. If this turns out to be too optimistic, we launch new replacement units, with some negative (but not fatal) impact to the architecture schedule.

Water Electrolysis and Fuel Storage Package (WEFS - 4) – After water is extracted from the lunar feedstock, it is transported to electrolysis units (1200kg) that crack the water into its component gases, cryogenically freezes the gases into liquids and then stores these cryogens for use as propellant. 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 WEFS has mass of about 1200 kg and requires about one kW per day to crack and freeze 4.5 kg of cryogen. Three electrolysis plants (coupled to the 3 power plants co-mounted on the RHL landers) can produce 32 mT of cryogen per processing unit, for a total production of 96 mT of propellant per year (assuming that lifetimes can be maintained with periodic maintenance and repair). It may be possible to cross wire the power plants to the WEFS units to increase power to increase yield, but this has not been assumed for this initial architecture evaluation, resulting in an initial lunar oxygen/hydrogen yield of just under 100 mT per year, enough to fully close 2 human missions per year, but nothing else. Future study can examine increased production by either increased power or by simply increasing the WEFS modules dedicated to water electrolysis and liquefaction.

HUMAN SURFACE FACILITIES AND ASSETS

The following elements make up the human surface systems needed to support an outpost. Other than the first 2 Heavy cargo launches to the lunar surface prior to the first human mission, at this time the remaining two cargo launches are allocated as mission wedges, but not manifested; we will determine what is necessary at a later date. However, the initial 2 Heavy cargo launches (12 mT each) will deliver enough to support initial habitation for a astronaut crews for durations to be determined by further analysis of mass and logistics needs for various lengths of stay, and various payload complements to support the campaign objective of an ISRU-based architecture to learn how to live off-planet.

Human Power and Logistics Cluster – 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 were 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, 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. If a small human rover were needed, it would be part of this complement of 12 mT.

Human Habitat – 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.

Cargo Mission Wedge #1 – This mission in the architecture is fully costed, but unassigned to any particular elements at this point. Future study will further allocate this 12 mT payload wedge to either another Habitat, or more equipment, or a rover, or reserved for spare parts, or even more lunar processing equipment as needed.

Cargo Mission Wedge #2 - This mission in the architecture is fully costed, but unassigned to any particular elements at this point. Future study will further allocate this 12 mT payload wedge to either another Habitat, or more equipment, or a rover, or reserved for spare parts, or even more lunar processing equipment, as needed.

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 (Table 2; Figure 2). Depending on budgetary or programmatic considerations, alternative implementations are possible.

Mission 1: Communications satellites with lunar GPS (Total mass: 1000 kg, Atlas 401, storable propellant)

> This asset is needed to assure constant communications with surface assets in the polar regions (which include Earth-shadowed zones and the far side). Trade studies will determine whether a constellation of small-sats in high lunar orbit or slightly larger satellites in L-point halo orbits, is the best implementation of this essential piece of outpost infrastructure.

Mission 2: Robotic Medium Lander (RML) to the Moon to characterize polar ice deposits (landed payload mass: 500 kg, Atlas 401)

> Although we have obtained much high-quality remote sensing data for the lunar poles from recent missions, many details about water ice concentrations and states are unknown. We believe that a detailed surface reconnaissance is required to choose which pole offers the best ISRU prospects and thus, we must examine the local conditions at both poles to assure ourselves that the optimum location for the outpost is selected. This mission consists of 2 identical Landers (RML 01 and 2) each with a single WIE Rover, to prospect the surface at both the North and South Poles each. Our mission goals are to understand the distribution, physical state, concentration and composition of the water ice. We need to understand how to get to, excavate and haul the ice/soil feedstock. The rovers should have bench-scale excavation/scooping capability and will bring the feedstock to future Landers RML 02 and RHL 001. These rovers should be powered by RTG (trade with batteries or RFC).

Mission 3: RML to the Moon to demonstrate and experiment with ISRU water extraction process (landed payload mass 500 kg; Atlas 401)

> This mission will use Lander RML 02 with a Water Demo Package, and lander unique solar arrays. Rover 01 (from Mission 2) will bring several different feedstock samples to Water Demo Package for processing of multiple samples in individual and batch mode. The goal of these experiments is knowledge of the required masses, power needs, product

yields and waste products. The results of these experiments will set the requirements for the large-scale surface systems.

Mission 4: LEO Fuel Depot, Phase 1 (8000 kg Dry plus 3000 kg propellant, Atlas 551 launch)

This mission will launch the LEO fuel station, 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. 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. It 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. The depot must be flexible enough to control its attitude with varying inertias of docked vehicles. Our intent is to use 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.

Mission 5: RHL to the Moon to bring Water Processing Plant to Moon (Atlas 551)

The first heavy robotic lander (RHL 001) will carry two packages, the Water Processing and Storage Package (WPS; 1200 kg), and Power Plant #1 (PP 1; 1100 kg). All RHL missions are launched dry, fueled with propellant at LEO Depot 1 and then proceed to the Moon. The WPS receives power from Power Plant #1 but this mode does not preclude a plug-in from an alternate power source. The WPS will ultimately receive its processing feedstock from EH Rover 02 (to be launched on Mission 7) and process it into water and discard the waste, and then store it in liquid form. We may start processing operations at a reduced level with Rover 01 while awaiting arrival of the EH rover.

Mission 6: RML brings Water Tanker rover to the Moon (Atlas 401)

Lander RML 03 will bring a Water Tanker (rover) that will be used to move produced water from the Water Processing and Storage on Lander RHL 002 and transport to the Reusable Water Tank Lander (to be delivered on mission 12) for upload to LLO propellant depot. This vehicle will plug into any surface Solar Power Plant for recharge. This element is delivered early to hedge against any needed manipulation of components, connections, and inspections that might need to be done by this element as part of its overall functionality.

Mission 7: RHL to the Moon to bring ore Excavator/Hauler (Atlas 551)

Lander RHL 002 will bring Rover 02 (Ore Excavator/Hauler) to the Moon for the surface transport of ice ore to WPS on Lander RHL 002 and may also carry additional equipment for mining and excavation. This lander might also carry an additional SPP, to be determined. Assume for now all the mass (2300kg) is defined in one Rover (02). The EH rover will need power from either secondary batteries (baseline), RTG or RFC.

Mission 8: RHL to the Moon to bring Water Electrolysis and Fuel Storage Package (Atlas 551)

Lander RHL 003 will bring 2 packages, the Water Electrolysis and Fuel Storage Package (WEF) to receive the harvested lunar water, then electrolyze, liquefy, and store the propellant O_2 and H_2. The lander will also emplace an additional SPP (#2). The WEF receives power from SPP #2 on the same lander but may also plug-in from an alternate power source. With the arrival of this asset, we begin production of lunar propellant.

Mission 9: RML to the Moon to bring Rover Fueling Tanker (Atlas 401)

Lander RML 04 will transport the Rover Fueling Tanker (RFT) to the fuel processing area. Its function is to fuel both the Reusable Fuel Tanker and the Human Lander. It will plug into one of the Solar Power Plants for battery recharge.

Mission 10: Cislunar Way Station (Atlas 551)

This depot will be placed in LLO by an upper stage (to be determined). We will trade to determine the size and operational concept of the Way Station, although the point of departure at this point is simply a copy of the LEO Phase 1 station, sized at roughly 8000 kg dry. Our point of departure is that the LLO Way Station will actually rendezvous with LEO Fuel Station and get fueled for part of the journey, requiring a cryo stage. Its function will be to offload water from the Reusable Water Tank Lander, store it and electrolyze the water into LO_2 and LH_2 and then store this propellant for later use by the unmanned CEV. Note that it may take a month or longer to phase the CEV after handing the crew off into the Human Lander in order to phase the orbit to rendezvous with the LLO Way Station. The LLO way station will refuel the CEV, and so it will need to have enough power to electrolyze water into H_2 and O_2 and then liquefy and store it. We will trade the location of this depot. Earth-Moon L-1 has larger arrival and departure Δv but LLO needs significant orbital maintenance and has a more severe thermal environment, increasing cryogen loss from boil-off.

Mission 11: LEO Fuel Station, Phase 2 (Atlas 551)

This is Phase 2 of the LEO fuel depot, required for larger volumes of propellant to produce from water and store. To take advantage of the existing LEO Fuel Station Phase 1, the Phase 2 Station will mate to Phase 1 to offer combined capability. Phase 2 will launch on an Atlas 551, and as point of departure, consists of 2 modules of the Phase 1 Fuel Station. For the Cargo Lander launching on a Heavy Lift Vehicle, it will need to load approximately 60,000 kg of propellant for its journey to the Moon. Our intent is to use commercial launch services to provision water to the LEO Fuel Station, which begins immediately after orbit checkout. If water provision from commercial sources is not available, a separate NASA mission can send water to the fuel station.

Mission 12: Reusable Water Tank Lander – RWTL to the Moon (HLV)

This mission will take the RWTL to the lunar surface. We will launch to the LEO Fuel Station with the first flight of the Cislunar Transfer Stage, although this first mission is not as taxing as the nominal Cargo Lander Mission. At the LEO Fuel Station, it will fuel and perform the TLI burn. From there, the RWTL will perform the LOI and landing. Once at the surface, it will be refueled by the RFT. The function of this reusable spacecraft is to transport water to the LLO fuel depot and return to the lunar surface for more water.

Mission 13: Cargo Lander (CL 01) to the Moon with Power and Logistics Cluster (HLV)

An Outpost Cargo Lander 01 with the first load of equipment separate from a habitat is sent to the Moon. It includes power systems, communications, radiators, rovers and any additional equipment not flown in the habitat, which will be sent later. To maximize payload, the payload with the Cislunar Transfer Stage will rendezvous with the LEO Fuel Station to fuel the CTS; the CTS will perform the TLI burn and drop. The Cargo Lander will perform both LOI and landing, and it will be fully fueled at launch.

Mission 14: Cargo Lander (CL 02) to the Moon with habitat (HLV)

This Cargo Lander 02 delivers the human habitat module to the lunar surface. To maximize payload, this mission profile is similar to the previous cargo lander. The HLV will launch into LEO and the payload with the Cislunar Transfer Stage will rendezvous with the LEO Fuel Station to fuel the CTS and then the CTS will perform the TLI burn and drop. The Cargo Lander will perform LOI and landing and it will be fully fueled at launch.

Mission 15: RHL to the Moon to bring Water Electrolysis and Fuel Storage Package #2 (Atlas 551)

Lander RHL 004 brings 2 packages to the lunar surface, the second Water Electrolysis and Fuel Storage Package (WEF #2) to receive water, electrolyze it and store the propellant LO_2 and LH_2 and Power Plant #3. The WEF receives power from Solar Power Plant 3 on the same lander, but this does not preclude a plug-in from an alternate power source.

Mission 16: Human Lander (HL 01) to LLO way station (HL on HLV)

This Human Lander (unmanned) is launched to the Moon using the Cislunar Transfer Stage. To maximize payload, the HLV will launch into LEO and the payload with the Cislunar Transfer Stage will rendezvous with the LEO Fuel Station to fuel the CTS and then the CTS will perform the TLI burn and drop. The Human Lander will perform LOI and rendezvous with the LLO way station; it will be fully fueled at launch.

Mission 17: Human Lunar Return (CEV on HLV)

At this point, all elements are in place to begin human missions to the lunar surface. Durations of several weeks at a time, one visit per year during the local summer phase is baselined for early missions. As capability is built up, more lunar propellant producing capacity can be added to increase the frequency of human visits to two or more visits per year. This ramp up occurs after Mission 19, which includes the third WEF, bringing the water production capability up enough to handle 2 flights per year in year 14 of the program.

The standard scenario for a human mission starts with an HLV launching the CEV plus TLI Stage into orbit; the TLI Stage will perform the TLI burn and then drop off. The CEV will perform LOI and will rendezvous in lunar orbit with a fully fueled Human Lander (HL). Once docked to the HL, the crew transfers to the lander for descent to the surface. The crew will execute the surface mission while the CEV autonomously phases its orbit and then docks to the Cislunar Fuel Station until needed for return to Earth, refueling just prior to the HL launch from the Moon. HL in the meantime is refueled from rover fueling tanker while on the surface. When crew is ready, HL then takes crew to orbit to rendezvous with CEV for return home. The HL will remain in orbit after crew transfer to the CEV due to a propellant optimization trade, although that could be revisited based upon the maturity of effective technologies to mitigate and minimize cryogenic boil-off.

Our estimate of capabilities within a 16-year initial window shows roughly 5 human missions, 4 Heavy Cargo Missions (2 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.

COST AND SCHEDULE

Costs are summarized in Table 3. 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.

This projected cost and schedule profile falls under the projected budget run-outs supplied by NASA to the Augustine Committee (2009). 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 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.

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 (Spudis, 2010): 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. 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 (Table 4) 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 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 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.

CONCLUSION

"If God wanted man to become a space-faring species, He would have given man a Moon." – Krafft Ehricke, 1985

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 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 will determine if our long-delayed journey into the cosmos can begin.

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Table 1. Elements and assets of the lunar resource outpost architecture

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 LO2/LH2 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	LO2/LH2	30 mT/year
	Electrolysis/fuel storage 2	1200		-25 K	LO2/LH2	30 mT/year
	Electrolysis/fuel storage 3	1200		-25 K	LO2/LH2	30 mT/year
	Electrolysis/fuel storage 4	1200		-25 K	LO2/LH2	30 mT/year

Table 2. Mission manifest and capabilities of the lunar outpost as a function of time

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
1	Lunar Communication Satellites	Atlas 401																	
2	Characterize Water Deposits	Atlas 551	RML 01, 02																
3	Water Extraction Demo	Atlas 401	RML 03																
4	LEO Fuel Station Phase 1	Atlas 551																	
5	Water Processor #1	Atlas 551	RHL 001																
6	Water Tanker	Atlas 401	RML 04																
7	Ore Excavator/Hauler #1	Atlas 551	RHL 002																
8	Water Electrolysis #1	Atlas 551	RHL 003																
9	Rover Fueling Tanker	Atlas 401	RML 05																
10	LLO Way Station	Atlas 551																	
11	LEO Fuel Station Phase 2	Atlas 551																	
12	Reusable Water Tank Lander	Heavy Lift	RWTL #1																
13	Human Power and Logistics Cluster	Heavy Lift	CL 01																
14	Human Habitat	Heavy Lift	CL 02																
15	Water Electrolysis #2	Atlas 551	RHL 004																
16	Human Reusable Lander	Heavy Lift	HL 01																
17	**First Human Mission (cost for P/L)**	Heavy Lift																	
18	Ore Excavator/Hauler #2	Atlas 551	RHL 005																
19	Water Processor #2	Atlas 551	RHL 006																
20	Water Electrolysis #3	Atlas 551	RHL 007																
21	Cargo Mission Wedge	Heavy Lift	CL 03																
22	**Human Mission 2**	Heavy Lift																	
23	**Human Mission 3**	Heavy Lift																	
24	**Human Mission 4**	Heavy Lift																	
25	Cargo Mission Wedge	Heavy Lift	CL 04																
26	**Human Mission 5**	Heavy Lift																	
27	**Human Mission 6**	Heavy Lift																	
28	**Human Mission 7**	Heavy Lift																	
29	Water Electrolysis #4	Atlas 551	RHL 008																
30	Water Processor #3	Atlas 551	RHL 009																
31	Ore Excavator/Hauler #3	Atlas 551	RHL 010																
	Lunar Water Prod. Capacity per year									10mT	50mT	50mT	50mT	50mT	50mT	100mT	100mT	100mT	100mT
	Lunar Surface Propellent Prod/yr										1mT	5mT	10mT	10mT	25mT	50mT	86mT	45mT	86mT
	Lunar Power for all loads									25kw	50kw	50kw	50kw	50kw	75kw	100kw	100kw	100kw	100kw
	Supplemental Power									5kw	5kw	5kw	5kw	5kw	5kw	10kw	10kw	10kw	10kw
	Lunar Water at LLO per year													3.5mT	3.5mT	7mT	14mT	7mT	14mT
	LEO Propellant per year needed									8mT	16mT	10mT			130mT	76mT	68mT		60mT
	Number of Crewed missions/yr															1	1	2	1

Table 3. Cost of architectural elements and systems (Real Year dollars)

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	500	400	200												1600
3	Water Extraction Demo	Atlas 401	RML 03		50	300	250	150												750
4	LEO Fuel Station Phase 1	Atlas 551		100	600	700	600	450	350											2800
5	Water Processor #1	Atlas 551	RHL 001	200	450	750	500	600	450	250										3200
6	Water Tanker	Atlas 401	RML 04				50	100	250	200										600
7	Ore Excavator/Hauler #1	Atlas 551	RHL 002			100	200	300	400	450	250									1700
8	Water Electrolysis #1	Atlas 551	RHL 003				100	200	400	400	300									1400
9	Rover Fueling Tanker	Atlas 401	RML 05						50	100	250	150								550
10	LLO Way Station	Atlas 551					50	100	250	300	350	250								1300
11	LEO Fuel Station Phase 2	Atlas 551							150	350	400	400	300							1600
12	Reusable Water Tank Lander	Heavy Lift	RWTL #1					50	200	300	400	500	600	450						2500
13	Human Power and Logistics Cluster	Heavy Lift	CL 01						100	250	350	600	600	700	400					3000
14	Human Habitat	Heavy Lift	CL 02						50	350	400	550	800	1000	850					4000
15	Water Electrolysis #2	Atlas 551	RHL 004									50	150	350	250					800
16	Human Lander (reusable)	Heavy Lift	HL 01							50	200	400	750	800	950	900				4050
17	**First Human Mission (cost for P/L)**	Heavy Lift										25	100	150	150	75				500
18	Ore Excavator/Hauler #2	Atlas 551	RHL 005										50	200	300	300				850
19	Water Processor #2	Atlas 551	RHL 006										50	200	250	250				750
20	Water Electrolysis #3	Atlas 551	RHL 007											50	150	350	250			800
21	Cargo Mission Wedge	Heavy Lift	CL 03										50	100	300	800	750			2000
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	Cargo Mission Wedge	Heavy Lift	CL 04												50	250	500	700	500	2000
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														50	150	250	450
30	Water Processor #3	Atlas 551	RHL 009															50	200	250
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	1300	1300	1300	1300	1300	1350	1350	1350	1350	1350	1350	18600
	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	200	200	200	200	3200
	Technology Wedge			2475	1050	175	0													3700
	Undefined Mission Wedge															625	1800	2450	2450	7325
	JSC Ops Cost for 2 Human Flts/yr			50	50	50	50	50	150	200	300	300	350	400	500	500	500	500	500	4450
	Totals per year			3400	3650	4950	4700	4600	4800	5000	5100	5350	6050	6650	6650	6650	6650	6650	6650	87100
				3400	3650	4950	4700	4600	4800	5000	5100	5400	6050	6650	6650	6650	6650	6650	6650	

NOTES:

1. Heavy Lift recurring cost is $1.2B per year (from HLLV Ops cost in Implementation Plan) plus $150M/yr for upgrades, assuming 2 flights, and includes all KSC and MSFC costs to launch 2 flights per year (any mix of crew and cargo)
2. The Fuel producing infrastructure on the Moon (EH, WP&SP, and WEFSP) have a 10 yr life
3. JSC Ops Cost (prior to first human mission) includes development of EVA suits and all JSC activity supporting Flight and Mission Ops
4. Assumes 2 CEVs (plus LOI, and TEI prop system) per year cost $500M
5. Rovers (WT, RFT) have a 15 yr life
6. Power Plants have a 20 yr life
7. JSC Recurring cost for Ops for 2 crewed missions per year assumes worst-case 6-month stays and costs $500M/yr
8. Deleted
9. All Atlas 551 launches except LEO Fuel Station include $100M for water to the LEO Fuel Station
10. Ciclunar Transfer Stage Ops cost is $200M/yr for each Mission, including hardware
11. The cost of the first flight of the Water Processor Unit mission also includes the DDT&E cost for the Power Plant and the RHL

Table 4. Technical and Programmatic Challenges

Significant and Critical

- Prospecting and characterizing water states and distribution on Moon
- Ability to collect water-bearing feedstock for transport
- Reliable, Long-life Excavator/Haulers (work at temperatures of 25-30 K)
- Ability to routinely transit the distance from mining prospect to Water Processor
- Ability to produce propulsion grade LO_2 and LH_2
- Reusable engine for Human Lander and Reusable Water Tank Lander
- Remove and replace the Reusable Engine on the Lunar Surface
- Efficient and low-loss cryogenic propellant transfer
- Routine and constant production of electrical power from permanent sunlight

Important and Pressing

- Gaseous O_2 and H_2 liquefaction (and associated boil-off control via heat extraction)
- Ability to produce large amounts of water (on the order of 50mT) per year
- Effect of cryogenic boil-off on architecture (not in Significant category because it could be accommodated with higher rate of replenishment)
- High density Electrolysis
- Desaturation of water from O_2 Production
- Shirt-sleeve ingress/egress from Human Lander to Lunar Surface
- Cryogenic fluid logistics (helium, nitrogen, etc)
- Solar Array placement (8-12 units) with occultation avoidance/minimization

Figure 1. Resource map of the north pole of the Moon, showing locations of ice deposits and quasi-permanent sunlight. See Bussey et al. (2005; 2010) and Spudis et al. (2010).

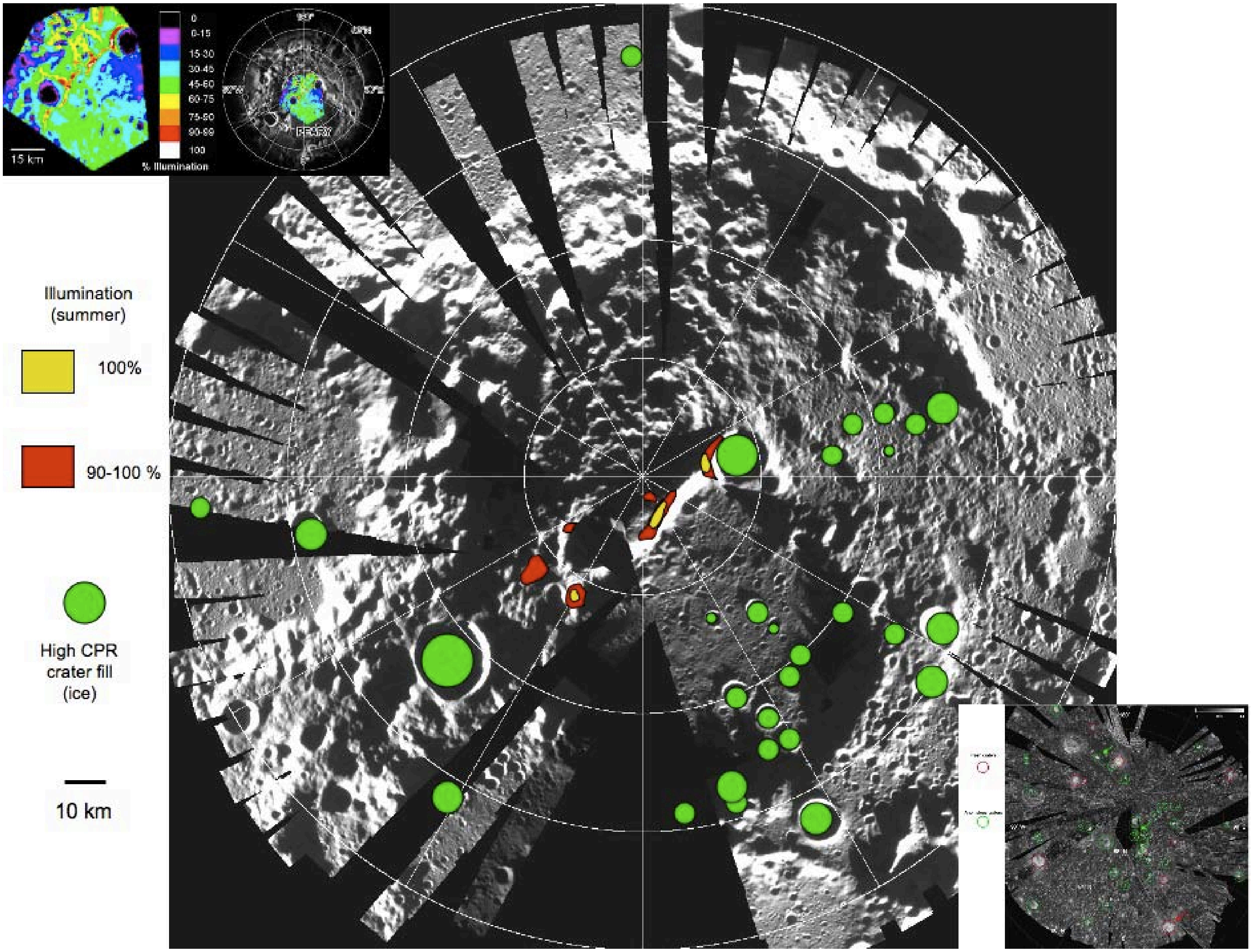

Figure 2. Timeline of activities and capabilities of the lunar resources architecture.

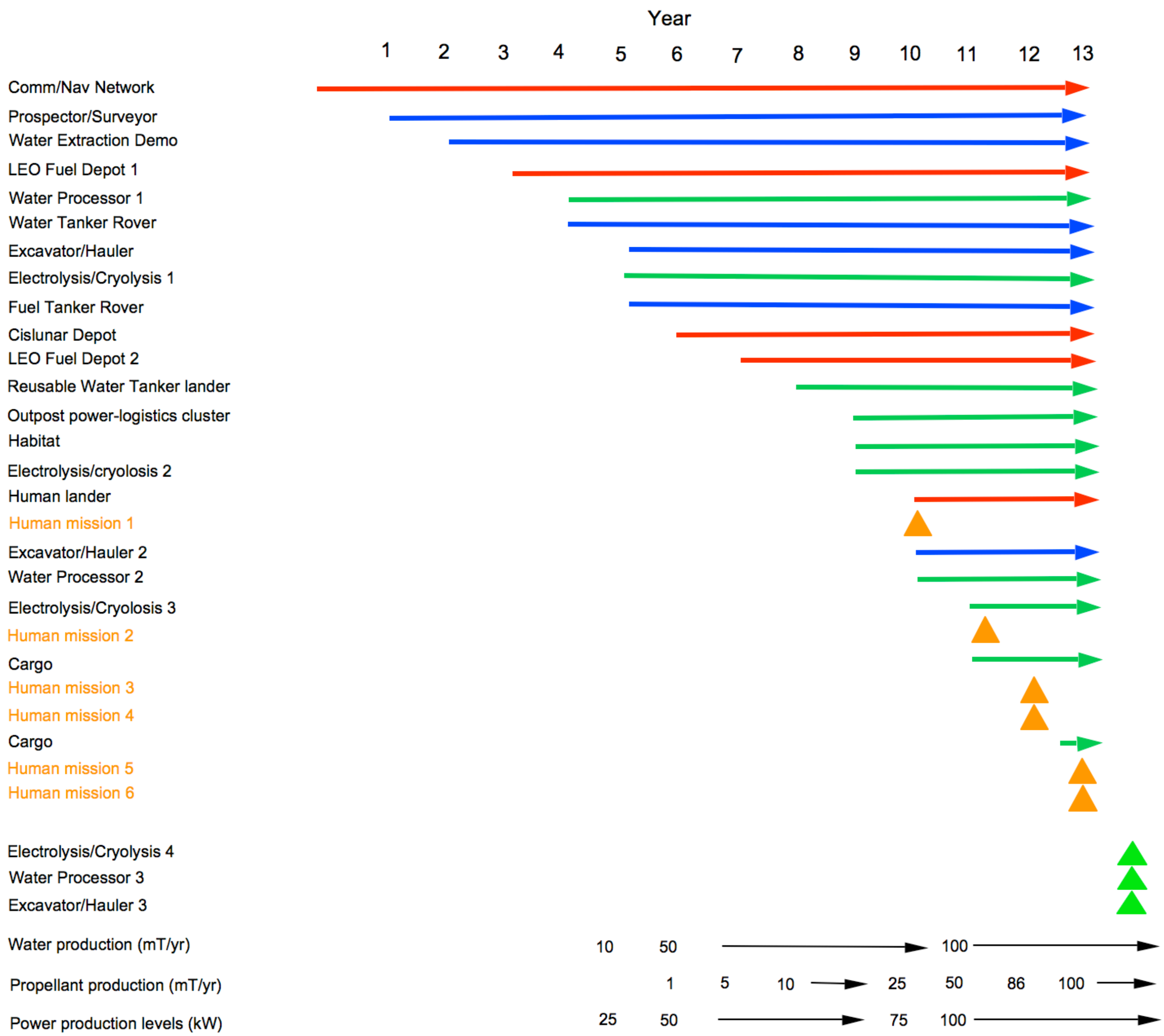

Figure 3. Artwork showing conceptual design of elements (rovers, excavators, haulers, water plants, fuel depots) (courtesy Mark Maxwell, Dennis Wingo, Pat Rawlings, Jack Frassanito)