Kickstarting a New Era of Lunar Industrialization via Campaign of Lunar COTS Missions

Dr. Allison F. Zuniga[i], Mark Turner[ii], Dr. Daniel Rasky[iii] and Robert B. Pittman[iv]
NASA Ames Research Center, Moffett Field, CA 94035

and

Edgar Zapata[v]
NASA Kennedy Space Center, FL 32899

To support the goals of expanding our human presence and current economic sphere beyond LEO, a new plan was constructed for NASA to enter into partnerships with industry to foster and incentivize a new era of lunar industrialization. For NASA to finally be successful in achieving sustainable human exploration missions beyond LEO, lessons learned from our space history have shown that it is essential for current program planning to include affordable and economic development goals as well as address top national priorities to obtain much needed public support. In the last 58 years of NASA's existence, only Apollo's human exploration missions beyond LEO were successful since it was proclaimed to be a top national priority during the 1960's. However, the missions were not sustainable and ended abruptly in 1972 due to lack of funding and insufficient economic gain. Ever since Apollo, there have not been any human missions beyond LEO because none of the proposed program plans were economical or proclaimed a top national priority. The proposed plan outlines a new campaign of low-cost, commercial-enabled lunar COTS (Commercial Orbital Transfer Services) missions which is an update to the Lunar COTS plan previously described. The objectives of this new campaign of missions are to prospect for resources, determine the economic viability of extracting those resources and assess the value proposition of using these resources in future exploration architectures such as Mars. These missions would be accomplished in partnership with commercial industry using the well-proven COTS Program acquisition model. This model proved to be very beneficial to both NASA and its industry partners as NASA saved significantly in development and operational costs, as much as tenfold, while industry partners successfully expanded their market share and demonstrated substantial economic gain. Similar to COTS, the goals for this new initiative are 1) to develop and demonstrate cost-effective, cis-lunar commercial services, such as lunar transportation, lunar mining and lunar ISRU operations; 2) enable development of an affordable and economical exploration architecture for future missions to Mars and beyond; and 3) to incentivize the creation of new lunar markets through use of lunar resources for economic benefit to NASA, commercial industry and the international community. These cost-effective services would not only enable NASA to economically and sustainably achieve its human exploration missions to the Moon, Mars and beyond but it would also kickstart a new era of lunar industrialization. This paper will describe the goals, objectives and approach for implementing this new campaign of missions. It will also describe the potential benefits and progress that can be accomplished with these low-cost, Lunar COTS missions. Lastly, a preliminary economic analysis approach is proposed for understanding the cost and potential return on investment in the use of lunar resources to reach the goal of lunar industrialization and an expanded and sustainable human presence into cis-lunar space and beyond.

---

[i] Project Development Manager, Ames Space Portal Office and AIAA Associate Fellow.
[ii] Senior Systems Engineer, Engineering Directorate and AIAA Senior Member.
[iii] Senior Scientist, Ames Space Portal Office, and AIAA Associate Fellow.
[iv] Senior Engineer, Lockheed, Ames Space Portal Office, and AIAA Associate Fellow.
[v] Senior Analyst, Modeling & Analysis, and AIAA Senior Member.

Nomenclature

ACES	=	Advanced Cryogenic Evolved Stage
COTS	=	Commercial Orbital *Transportation* Services
CRS	=	Commercial Resupply Services
EDL	=	Entry Descent and Landing
ELA	=	Evolvable Lunar Architecture
EMC	=	Evolvable Mars Campaign
FAR	=	Federal Acquisition Regulations
FT	=	Full Thrust
FY	=	Fiscal Year
GER	=	Global Exploration Roadmap
GLXP	=	Google Lunar XPRIZE
GTO	=	Geostationary Transfer Orbit
HEOMD	=	Human Exploration and Operations Mission Directorate
HSF	=	Human Space Flight
ISRU	=	In-Situ Resource Utilization
ISS	=	International Space Station
IVF	=	Integrated Vehicle Fluids
JSC	=	Johnson Space Center
LCOTS	=	Lunar Commercial Orbital *Transfer* Services
LCROSS	=	Lunar Crater Observation and Sensing Satellite
LEO	=	Low-Earth Orbit
LH2	=	Liquid Hydrogen
LLO	=	Low Lunar Orbit
LOI	=	Lunar Orbit Insertion
LO2	=	Liquid Oxygen
LRO	=	Lunar Reconnaissance Orbiter
mt	=	Metric ton
NASA	=	National Aeronautics and Space Administration
NRC	=	National Research Council
PSR	=	Permanently Shadowed Region
ROI	=	Return On Investment
SAA	=	Space Act Agreement
SLS	=	Space Launch System
STG	=	Space Task Group
TEI	=	Trans-Earth Injection
TLI	=	Trans-Lunar Injection
ULA	=	United Launch Alliance
VSE	=	Vision for Space Explortion

I. Introduction

ON May 25, 1961, President John F. Kennedy addressed a special joint session in Congress to announce his ambitious goal of landing a man on the Moon and returning him safely to Earth before the end of the decade. At the time, the U.S. was in the middle of a Cold War with the Soviet Union and found itself falling behind in the "space race" with the recent launch of Soviet cosmonaut, Yuri Gagarin, first man to orbit the Earth on April 12, 1961. This geo-political environment threatened our national security which drove Kennedy to set this ambitious goal to ensure the U.S. would win the space race and demonstrate U.S. technical superiority to the rest of the world. As described by aerospace historian, Roger Lanius[1], "By any unit of measure the U.S. had not demonstrated technical equality with the Soviet Union, and that fact worried national leaders because of what it would mean in the larger Cold War environment. These apparent disparities in technical competence had to be addressed and Kennedy had to find a way to reestablish the nation's credibility as a technological leader before the world." In retrospect, this unique confluence of factors in 1961 made it possible for Kennedy to make such a bold decision to direct NASA to land a man on the Moon expeditiously which was met with immediate and overwhelming support by Congress and the American public.

Kennedy also made it clear that his Moon landing goal was a national priority as stated in a private meeting with the NASA Administrator, James Webb, and others on November 21, 1962. As stated by Dr. Robert Seamans, NASA Deputy Administrator, who was also present at the meeting, "The President's bottom line was absolutely clear. He stated that Apollo was NASA's top priority, important for international and political reasons. He added that except for defense, it was, along with one other, the top priority of the U.S. government.[2]" This declaration gave Webb the ammunition needed to secure the appropriate funding and resources needed to accomplish the Apollo Moon landing long after Kennedy was assassinated in 1963. As a result, NASA's annual budget increased from $500M in 1960 to a high point of $5.2B in 1965 (or $29B in 2009 constant year dollars[3]) with the overall Apollo program costing $129.5B (2009 constant year dollars) from 1961 to 1972. This abundant level of resources authorized by Congress ultimately led NASA to accomplish one of the greatest human technological achievements of the 20th century on July 20, 1969, by landing men on the Moon for the first time in human history.

Since the end of the Apollo program, the overall NASA budget has steadily decreased from it's peak of 4.5% of the federal budget in 1965 to approximately 0.5% over the last decade and where it remains today. During this steady decline, there have been several attempts to pursue follow-on human exploration programs beyond LEO but all have unfortunately failed or not even started due to insufficient funds. In 1969, President Nixon directed the Space Task Group (STG) to develop architecture options and recommendations for a post-Apollo strategy. The STG delivered a report[4] proposing three different options which included a fully-functional manned lunar base and a human mission to Mars before the end of the century. The funding for these options required significant increases to NASA's budget which varied from $30B to approximately $50B (FY2014) per year to accomplish these missions. For a variety of political reasons and funding limitations, Nixon decided not to pursue any of these options. Instead, Nixon decided to proceed with the development of a reusable space shuttle system with the goal of flying 50 missions per year to drive down space transportation costs. As a result the Space Shuttle Program was initiated in 1972 and was the main focus of NASA's workforce and resources for the next decade.

After the first launch of the Space Shuttle in 1981, there was renewed interest at NASA once again to return to the Moon and develop plans for lunar exploration missions and lunar base development. NASA Johnson Space Center (JSC) took the lead in this endeavor developing engineering studies and holding scientific meetings. This resulted in a special report, *Lunar Outpost*[5], released by the Advanced Programs Office of NASA JSC detailing planning activities to return humans to the Moon. Then in July 1989, President George H.W. Bush publicly announced the Space Exploration Initiative (SEI) which was a new initiative and executive commitment to return to the Moon and on to Mars. Inspired by the 20th anniversary of the first landing of men on the Moon, President Bush gave a speech and declared the following:

"First, for the coming decade, for the 1990s, Space Station Freedom, our critical next step in all our space endeavors. And next, for the next century, back to the Moon, back to the future, and this time, back to stay. And then a journey into tomorrow, a journey to another planet, a manned mission to Mars.[6]"

Following this declaration, NASA created a task force to determine the requirements and make recommendations to fulfill this Initiative. This resulted in the following document, "Report on the 90-Day Study on Human Exploration of the Moon and Mars[6]." Among the findings of this report, the projected total cost of the proposed lunar and Mars projects, over 34 years, was estimated at $541B (in 1991 dollars) or $983B (in 2014 dollars). As a consequence of this exorbitant price tag, Congress zeroed the budget of the SEI as quickly as it was received. However, the newly re-named International Space Station (ISS) continued to be funded and was the focus of NASA's resources and workforce for the next decade. The initial assembly of the first two ISS modules, Russian Zarya module, and U.S. Unity module took place in December 1998.

Later in 2004, President George W. Bush announced a new policy entitled, the Vision for Space Exploration[7], (VSE) which outlined goals for human and robotic missions to the Moon, Mars, and beyond. These specific goals included 1) complete the International Space Station by 2010; 2) phase out the Space Shuttle after completion of the ISS; 3) launch a robotic orbiter and lander to the Moon; 4) send a human expedition to the Moon as early as 2015, but no later than 2020; and 5) conduct robotic missions to Mars in preparation for a future human expedition. The President went further on to explain his new policy and vision by stating the following, "the fundamental goal of this vision is to advance U.S. scientific, security and economic interests through a robust space exploration program.[7]"

In 2005, the NASA Administrator, Dr. Michael Griffin, established a new team to evaluate hundreds of potential configurations to meet the goals of the VSE under the newly formed Exploration Systems Architecture Study (ESAS). Another major objective for the team was to minimize the gap between the last Shuttle flight (planned for 2010) and the first flight of the new vehicle. The results of this study resulted in an architecture that was adopted by the newly formed Constellation Program. These architecture elements included the heavy-lift launch vehicle, Ares V, separate booster to launch the crew, Ares I, the Crew Exploration Vehicle, (CEV) and the Altair lunar lander.

Although Bush's Vision for Space Exploration consisted of well-established goals, its Constellation program required a significant increase in NASA's yearly human spaceflight budget, ranging from $3B per year in FY2008 to $9B per year in FY2012. Some estimates also showed that the total cost for a human return to the Moon by 2020 reached in excess of $100B. Therefore, after President Obama took office in 2009, he called for an independent review of the current human spaceflight plans. This review was led by Norman R. Augustine and a distinguished committee who reviewed the Constellation Program and its supporting programs. After months of review, this committee concluded that the current program of record was on an unsustainable trajectory and that its goals did not match the allocated resources as was reported in reference 3. As a result of these findings, Obama decided to cancel the Constellation program in February 2010.

It is also worth noting that the Augustine committee concluded that "the ultimate goal of human exploration is to chart a path for human expansion into the solar system[3]" and that "human spaceflight objectives should broadly align with key national objectives.[3]" They also went on to conclude that three basic objectives should be met in order to achieve the ultimate goal for human space flight which include: (1) physical sustainability (2) economic sustainability and (3) meet key national objectives. These national objectives may include national security, international cooperation, economic growth and secutiry, energy independence, reducing climate change, etc.

After the Augustine committee delivered its report, Obama established a new National Space Policy[8] of 2010 which set the goals for NASA to send humans to an asteroid by 2025 and on to orbit Mars by the mid-2030's. To accomplish these goals, NASA established the Exploration Enterprise and released its plans in its Journey to Mars[9] document. In this plan, it describes its goal as "NASA aims to extend human presence deeper into the solar system and to the surface of Mars." It also describes its plan including NASA's development of a heavy-lift launch vehicle defined as the Space Launch System (SLS) and a human–rated spacecraft named Orion. NASA has also initiated an Evolvable Mars Campaign[10] (EMC) to investigate architectures and conduct trade studies to define the additional capabilities and elements needed for a sustainable human presence on the surface of Mars. Under the EMC, NASA has also developed a Pioneering Space Strategy[11] with the objective of creating a sustainable human to Mars program which is described as "one that expands human presence into the solar system in a manner that is affordable and permanent." It should be noted that this strategy is very well aligned with the Augustine committee recommendations as previously cited. Furthermore this strategy is guided by a set of key strategic principles to achieve a sustainable, affordable space program. These principles, as listed in reference 11, include:

- Implementable in the ***near-term with the buying power of current budgets*** and in the longer term with budgets commensurate with economic growth*;*
- ***Exploration enables science*** **and science enables exploration***, leveraging robotic expertise for human exploration of the solar system*
- Application of ***high Technology Readiness Level*** (TRL) technologies for near term missions, while focusing sustained investments on ***technologies and capabilities*** to address challenges of future missions;
- ***Near-term mission opportunities*** with a defined cadence of compelling and integrated human and robotic missions providing for an incremental buildup of capabilities for more complex missions over time;
- Opportunities for ***U.S. commercial business*** to further enhance the experience and business base;
- ***Multi-use, evolvable*** space infrastructure, minimizing unique major developments, with each mission leaving something behind to support subsequent missions; and
- Substantial ***new international and commercial partnerships***, leveraging the current International Space Station partnership while building new cooperative ventures.

In staying aligned with these key strategic principles of EMC and the goals of Journey to Mars, this paper lays out a plan to initiate a campaign of low-cost, commercial-enabled lunar missions to prospect and extract lunar resources with the vision to ultimately achieve a sustainable and economical human exploration program beyond LEO. As the Journey to Mars states in its Proving Ground objectives, it is important to "understand the nature and distribution of volatiles and extraction techniques, and decide on their potential use in the human exploration architecture.[8]" In the following section, the plan for prospecting and extracting resources is described which should meet this objective.

In addition, from the lessons of the last 47 years of proposed human exploration plans since the first Apollo landing, we have learned that in order for future exploration programs to be successful they must be ***economically sustainable*** and ***meet key national priorities*** to obtain the Administration, Congressional and public support needed through the life of the program(s) which may be several decades long. Unfortunately, history has shown that proposed exploration programs that do not meet this criteria will ultimately fail to accomplish its goals. Although Apollo was hugely successful, it was an anomaly in that a unique confluence of factors came together at the perfect time making it a top national priority without having to be economically sustainable. Regrettably, the Apollo model set a bad precedent by giving NASA an unrealistic expectation that it would always obtain a huge increase in budget without having to include plans for economic development and sustainability. It is clear now that the conditions that made Apollo successful were unique to that era and will more than likely never occur again. After nearly 50 years of failed program planning without being able to send humans beyond LEO again, it is very clear that a new framework for program planning is needed, one that is focused on economic sustainability and meeting national priorities, for current and future human exploration programs to succeed. The following section will describe this new "Space Development" framework to help with current and future program planning.

In summary, the proposed initiative was developed in alignment with this new framework as well as the Journey to Mars goals and objectives and EMC's key strategic principles as just discussed. This new initiative proposes a new campaign of low-cost, commercial-enabled lunar exploration missions to prospect for lunar resources, determine the economic viability of extracting those resources and assess if those resources can enable NASA to develop an affordable and economical exploration architecture for human missions to Mars and beyond. As the Journey to Mars plan suggests, it is worthwhile to investigate the resources of the Moon to determine if its resources can be economically extracted and affordably utilized in a future Mars transportation architecture. The following sections describe the new framework for human exploration planning and an updated Lunar COTS plan that could lead to lunar industrialization and an economically sustainable human exploration program to meet the ultimate goal of human expansion into the Solar System.

II. Update to the Lunar COTS Plan

Last year, the Lunar COTS plan was described in detail in an AIAA publication by the same principle authors entitled, "Lunar COTS: An Economical and Sustainable Approach to Reaching Mars.[12]" The term COTS came from NASA Johnson Space Center's program entitled, Commercial Orbital Transportation Services[13], which was very successful in developing and demonstrating cargo delivery capabilities to the ISS in partnership with industry. It was planned together with the ISS Commercial Resupply Services (CRS) contracts which awarded SpaceX and Orbital Sciences Corp. (now known as Orbital ATK) in 2008 to resupply the ISS on a regular basis with unpressurized and pressurized cargo. As a result of the COTS and CRS programs, 2 new launch vehicles and spacecraft were developed and have been successfully servicing the ISS program since 2012 with cargo transportation missions: 1)SpaceX's Falcon 9 launch vehicle and Dragon spacecraft; and 2)Orbital's Antares launch vehicle and Cygnus spacecraft. Recent studies have shown that government funding investments provided less than one half of the cost for these two commercial transportation systems[13](47% government funding for SpaceX and 42% government funding for Orbital). Also it has been estimated that the final development cost for SpaceX's Falcon 9 rocket was about $400M which is approximately 10 times less than projected costs for the same rocket using traditional cost-plus contracting methods.[14]

Earlier this year another round of ISS CRS contracts were announced awarding SpaceX, Orbital ATK and Sierra Nevada Corporation for more cargo delivery services to and from ISS from 2019 through 2024. Another extension of COTS is NASA's Commercial Crew Program which was originally planned as an option in the original COTS solicitation of 2006. This program has been making significant progress in reaching its goal of achieving safe, reliable and cost-effective commercial human transportation services to ISS and LEO in partnership with industry. In September 2014, the Commercial Crew Program awarded two industry teams, SpaceX and Boeing, to complete development of a human space transportation capability for eventual launch of astronauts to the ISS. From the early planning of COTS/CRS programs to today's routine commercial cargo delivery services to tomorrow's commercial human transportation flights to LEO, these programs have truly revolutioned the aerospace industry by expanding the commercial space markets in LEO and lowering the space transportation costs for the entire world market.

To continue on this successful path towards commercializing LEO and beyond, the principle authors, who supported the formulation of the original COTS program in 2005-06, initiated a study last year to extend the COTS acquisition model to cis-lunar space called Lunar Commercial Orbital *Transfer* Services (or LCOTS). The findings of this initial study as well as the COTS acquisition model was described in detail in reference 12. In summary, this LCOTS plan described a three-phase approach to develop and demonstrate cis-lunar capabilities and services by partnering with industry to share cost and risk for mutual benefit. The goals of the LCOTS plan are listed below:

1) Establish ***affordable and economical cis-lunar commercial products and services***.
2) Enable development of a ***sustainable and economical exploration architecture*** for future missions to Mars and beyond.
3) Encourage ***creation of new markets in cis-lunar space*** for economic growth and benefit.

The LCOTS plan included use of the COTS acquisition model which utilized a new progressive approach than FAR-based contracts normally used in traditional procurement practices. This new model employed Space Act Agreements (SAA's) where NASA entered into partnerships with industry for mutual benefit. The best practices of this COTS model were fully described in reference 12 and are summarized in the following for the reader:

1) NASA and commercial partners ***share cost, development and operational risk*** to demonstrate new capabilities and services for mutual benefit.
2) NASA makes ***long-term commitments to procure commercial services*** to help secure private investments.
3) NASA ***encourages commercial partners to target space markets*** outside Government to make their business case close. NASA is anchor customer but not sole customer.
4) NASA uses ***SAA's to enter into partnership*** with commercial partners to offer maximum flexibility in design solutions without the full demands and requirements of typical FAR-based contracts.
5) NASA includes ***pay-on-performance milestones in SAA's*** to provide several off-ramps and reduce programmatic risk.
6) Commercial partners ***retain Intellectual Property (IP) rights*** and operates and owns final product(s).

As mentioned, the LCOTS plan included a three-phase approach to allow for incremental development and demonstration of cis-lunar capabilities. This was described as a lower-risk approach since it allowed for several off-ramps to the program at the end of each phase and time for pause between phases to make sure its milestones and objectives were being met before proceeding to the next phase. The following table summarizes the goals for each phase.

Phase 1: Surface Resources and Hazards Assessment	Phase 2: Pilot Lunar ISRU Demonstration	Phase 3: Lunar ISRU Production and Delivery Services

• Demonstrate capabilities to transport payloads from Earth to lunar surface cost effectively;
• Prospect several sites for surface resources and hazards;
  • Provide ground truth data of various sites;
  • Assess potential sites for hazards and accessibility
• Demonstrate techniques for resource extraction and future ISRU operations.
	• Demonstrate capabilities for ISRU resource production, such as, H2O, LOX, LH2, and storage on a pilot-scale program;
	• Demonstrate feasibility and economics of scaling up production and capability to store several tons of resources on lunar surface.
	• Demonstrate capability to transport large payloads from lunar surface to cis-lunar space destinations for long-term storage.
		• NASA awards long-term contracts for Lunar ISRU production of H2O or LOX/LH2 on the order of several metric tons per year;
		• Awards are also made for delivery services to Cis-Lunar Depot;
		• Awards are made to multiple commercial providers to reduce risk and enable competition.

An update to the LCOTS plan was made to include the lessons learned from the past 58 years of NASA's history as was discussed in the previous section. It was discussed that an economically-sustainable plan is needed for a long-term human exploration program to send humans beyond LEO to finally succeed. This concept was further explored and investigated which lead to the Space Development Framework shown in Figure 1. This framework presents three different phases in space development leading towards the ultimate goal of sustainable settlement.

A. Description of Space Development Framework

These three phases are defined as Space Exploration, Economic Development and Sustainable Settlement. The first phase is focused on meeting objectives for space exploration, science and discovery. This phase is very important to acquire new knowledge and an understanding of the space environment and its challenges for future space explorers and pioneers. Figure 1 illustrates an example list of NASA missions under this first phase which are typically developed and operated with nearly 100% of government resources and control as shown by the red line in the figure. Figure 1 also illustrates 4 different space regions defined as Low-Earth Orbit, Cis-Lunar Space, Mars and its Moons and Beyond Mars. The NASA missions listed under Space Exploration are not meant to be all-inclusive.

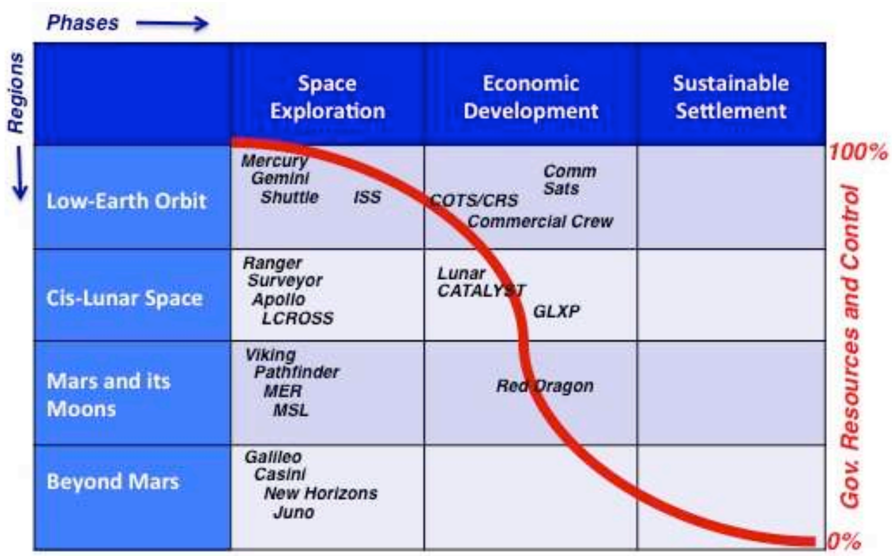

Figure 1. Space Development Framework

These are just a small sampling of missions to illustrate the point that most NASA missions have been mainly focused on meeting space exploration and science objectives and not yet moved into the next phase of Economic Development.

The second phase, Economic Development, is defined as the phase where the missions are focused primarily on spurring economic growth in space and providing economic benefit to the space community. It is essential for the missions in this phase to be planned to include achievable economic development goals and metrics. These goals can range from establishing more commercial services and products in space to creating and expanding space markets to increasing the number of people living and working in space which all result in growing the space economy. As figure 1 illustrates by the red line, the amount of government resources and control decline to a range between 75% to 25% in this phase. This is a transitional phase where a reduction in government control and ownership over space missions is needed while at the same time an increase in commercial development is encouraged and incentivized. The balance of these 2 forces, if done correctly, will create a favorable environment for a space economy to grow. The role of government in this phase should focus more on building an infrastructure to help foster economic development and look for ways to encourage and incentivize industry to take the lead and risk for conducting space missions and innovating new space products and services.

A good example of programs in the Economic Development phase were the COTS, CRS and Commercial Crew programs. These programs were created to meet economic development goals from their inception. The objectives for these programs, from the beginning, were to create partnerships with industry to develop capabilities, such as cargo and crew transportation, that can later be offered as services at a competitive price to NASA and the rest of the space community. The motivation behind setting these early objectives were to grow the space economy, significantly reduce the cost of space transportation and increase access to space to benefit everyone.

Equally as important to the economic development goals of this phase is the concerted effort for NASA's missions in partnership with industry to meet key national objectives in this phase as well, such as, national security, economic security, energy independence, climate change, etc. As discussed in the last section, Augustine's committee[3] recommended this objective of meeting national objectives as well to help our country solve critical national problems by using the resources of space and to acquire long-term Congressional and public support. Key to the success of our long-term human space exploration planning will be showing relevance to our national leaders and private citizens at home. To meet these objectives, it will be necessary to design missions to acquire resources, test new technologies, and develop new capabilities in partnership with industry to solve some of our nation's greatest challenges.

In summary, there will be many benefits to conducting more missions in the Economic Development phase. It will not only lead to a larger and stronger space economy but it will also lead to a gradual transition into the last phase of this framework which is Sustainable Settlement. As can be seen from Figure 1, there are no missions listed under the category of Sustainable Settlement. That is because we are still far away from entering this last phase. As history has shown, it normally takes a long period of time to develop the infrastructure needed for economic development to flourish in a certain region before sustainable settlement can take place.

B. Update to Phase I: Campaign of Low-Cost, Commercial-Enabled Missions

Phase I was introduced in reference 12. It has now been updated to include economic development goals as well as a campaign of low-cost, commercial-enabled lunar exploration missions in partnership with industry to explore lunar resources. It is important to include economic goals right at the outset of LCOTS to ensure this program will be affordable and sustainable and will aim to grow the space economy as previously discussed. Below is a proposed list of goals for Phase I:

1. **Conduct a campaign of low-cost, commercial-enabled lunar exploration missions** to prospect and extract lunar resources to meet NASA's mission needs and industry's commercial interests;
2. **Determine the economic viability of extracting resources** by testing various commercial tools, products and techniques in a lunar environment;
3. **Build an economic infrastructure** by partnering with industry to place in service power stations, lunar communication relay satellites, and lunar surface communication systems;
4. **Enable a robust cis-lunar commercial economy** by incentivizing industry to create new space products and markets;
5. **Inspire the next generation of space entrepreneurs** by conducting several educational and outreach activities.

To achieve these goals, it will be necessary to partner with industry using a COTS-like approach as previously described to prospect and extract lunar resources. As discussed in reference 12, there are a wide variety of lunar resources in the lunar regolith that can be useful to NASA's long-term human exploration missions to Mars and beyond. One major example is water-ice concentrations in the permanently shadowed regions of the lunar poles. Several remote-sensing, lunar missions in the last two decades including DOD's and NASA's Clementine[15] mission launched in 1994; NASA's Lunar Prospector mission launched in 1998; NASA's Lunar Reconnaissance Orbiter[16] (LRO) launched in 2009 and NASA's Lunar Crater Observation and Sensing Satellite[17] (LCROSS) mission launched in 2009 have all indicated the presence of water-ice deposits at the lunar poles. Furthermore, it has been estimated that the total quantity of water contained within the uppermost meter of all the PSRs may be 2.9×10^{12} kg (or 2900 million mt of water)[18]. Although these data are strong indications that the presence of water-ice is plentiful at the poles, ground truth data is needed to validate these results and determine the composition, distribution, and accessibility of these areas with high concentrations of lunar ice.

Several studies[19,20,21] have also shown that extracting these resources, such as water and oxygen, can be readily accomplished. In addition Miller and Spudis have examined the ISRU processes and facilities necessary to extract and convert the water into LO2 and LH2 propellants and have provided cost estimates for putting the infrastructure in place for creating the propellant and then delivering it to a cis-lunar propellant depot for use in a future Mars architecture. Although these studies have provided an excellent strategy and approach for creating propellant on the lunar surface, ground truth data from the Moon is needed to determine the exact methods, tools and machinery needed to extract the lunar ice and create the propellant for a more refined cost estimate. It is also best to obtain this ground truth data and develop extraction techniques in partnership with industry to share cost and risk as well as leverage on industry's capabilities and innovativeness in a competitive environment employing the COTS acquisition model. As mentioned previously, the original COTS program saved immensely in development costs, as much as tenfold, where total government funding totaled less than one-half of total investments made in a new space transportation system. Therefore, the goals of this first phase emphasize launching a campaign of low-cost, commercial-enabled missions in partnership with industry to prospect for resources and determine the economic viability of extracting these resources using commercial methods.

The authors recommend a campaign of missions instead of a single, large mission for this first phase. Prior to the Apollo missions, several pre-cursor missions including Ranger, Lunar Orbiter and Surveyor were executed using several campaigns. A campaign is advantageous over a single, large mission because you have several attempts to accomplish your mission objectives which increases your likelihood of mission success while lowering your risk posture on every successive mission. It also reduces cost per mission by taking advantage of economies of scale. A campaign will also provide data at multiple sites which expands your landing options to prospect for resources. The Ranger program opted to use a campaign and flew 9 missions from 1961 to 64. These missions were designed to take images of the lunar surface until impact to acquire knowledge of potential landing sites in preparation for the Apollo missions. The first 6 missions failed and the last 3 missions performed successfully. Similarly, the Surveyor program conducted a campaign of missions from 1966-68 were 5 of 7 missions landed successfully and achieved its mission objectives of evaluating the suitability of landing sites for the Apollo missions.

It is also recommended that substantial information be exchanged between NASA and its potential industry partners in the early stages to learn and understand industry's commercial interests to determine where these interests overlap and how best to develop capabilities that can best serve these common interests, such as lunar transportation and lunar mining. It is also important to learn and understand the maturity level of industry's capabilities, their readiness level and potential business plans. As with the original COTS program, this should be done prior to the formulation phase through industry one-on-one interviews and workshops. The results of these information exchanges will help shape this first phase by setting objectives and milestones that are achievable as well as a realistic and in building effective partnerships that seek to accomplish low-cost missions for mutual benefit.

Through these information exchanges, it will also be important for industry to learn and understand NASA's intentions and plans for mission objectives, frequency of lunar missions, infrastructure development, and payload requirements. As mentioned in the COTS best practices section, it is essential for NASA to make clear its long-term commitments for acquiring lunar commercial services to help its potential partners raise private capital.

Another important tactic used in the COTS solicitation was to request for the commercial space providers to include feasible and economical business plans in their proposals. It was recommended that the providers target markets outside of NASA and not solely rely on the government to close their business case. This tactic was used to encourage the providers to develop low-cost capabilities to capture new markets, expand their customer base and create new industries to further commercialize LEO space. Similarly, this tactic should be used in the first phase of Lunar COTS to initiate commercialization of cis-lunar space.

C. Partnership Strategy

The partnership strategy is a key aspect to the first phase in establishing cost-effective partnerships in several different capability areas including launch vehicles, lunar landers, lunar rovers, resource prospecting, power stations, communications and extraction equipment. It is important to determine which capabilities can be developed in partnership with industry using a COTS acquisition model and which ones will need to be acquired by other means such as a more traditional FAR-based approach. The Lunar COTS paper described an assessment tool for evaluating these industry capabilities against several criteria. These criteria included: 1) number of viable companies with enough technical and financial capability and strong interest to pursue LCOTS opportunity; 2) size of potential markets likely to emerge within 5 years to attract private investors; 3) level of affordability to fully develop capability within realistic budgets from NASA and private capital from industry; 4) strong potential for positive return on investment based on sound business plans; and 5) strong potential to reduce technical, cost or operational risk towards a Mars architecture. An initial preliminary assessment for the lunar capabilities was made in reference 12. This assessment is only valid for the period of time it was made. The assessment will need to be conducted again during the formulation phase of the first phase to make sure it is accurate and current. In the meantime, it is important to keep track of industry's progress for the range of capabilities needed for Phase 1. The following describes industry's capabilities for each of the elements needed for Phase 1.

The launch vehicle is an essential element of the partnership strategy. To keep costs low during the first phase, it is critical to identify available low-cost, secondary payload opportunities on medium-class, commercial launch vehicles. Table 1 below lists several domestic options for existing and future launch vehicles along with their estimated payload capacities to various destinations. For existing launch vehicles, United Launch Alliance's (ULA) Atlas V and SpaceX's Falcon 9 provide similar payload capacities with Atlas V being slightly greater to GTO and beyond. However, Falcon 9 Full Thrust (FT) capability was recently upgraded with 30% higher capability than its previous Falcon 9 v1.1 vehicle[23]. This increase was not taken into account when estimating its payload capacity to the lunar surface as shown in the table. These estimates were not intended to be exact but to provide a rough estimate of the payload mass that can be delivered to various destinations including the lunar surface. The table shows that both the Atlas V and Falcon 9 are capable of delivering approximately 1 mt to the lunar surface. As will be discussed in the following sub-section, this existing capability is sufficient for delivering small lunar landers and rovers to the lunar surface.

Table 1 also provides estimates for new launch vehicles being developed, including ULA's Vulcan and SpaceX's Falcon Heavy. Although these launch vehicles are not yet in operation, they are being planned to be active in the very near future, Falcon Heavy by 2017, Vulcan Centaur by 2019 and Vulcan ACES by 2023. Table 1 shows significant increase in capability for both new vehicles with lunar landed mass capability increasing from approximately 1 mt to 4 mt for both vehicles. In addition, Vulcan's capability significantly increases by approximately a factor of 3 to the lunar surface (from approximately 4 to 12 mt) using a distributed launch concept described by Kutter[24] et al of ULA where multiple launches are used to deliver cryogenic propellant in a separate drop tank and then transferring the propellant directly into a cargo-carrying upper stage, such as Centaur.

There are several options for identifying secondary payload opportunities on these existing launch vehicles. One option is working directly with the launch service providers, such as, ULA's rideshare program to identify excess capacity on one of their missions. Another option may be to employ a company, such as Spaceflight[vi] Inc., who specializes in finding low-cost, secondary payload opportunities for small payloads by finding excess capacity in commercial launch vehicles and integrating all of the payloads as one discrete unit to the launch vehicle. This business model provides an important integration function and offers the launch services at a less expensive rate to reach orbit compared to buying an entire launch vehicle. Using this business model or directly working with the launch service provider may yield good results in acquiring a launch for a small payload (<1 mt) at a competitive rate.

Table 1. Estimated Launch Vehicle Payload Capabilities

Launch Vehicle Options	LEO (mT)	GTO (mT)	C3=0 or Earth Escape	Lunar Surface (mT)
Atlas 551 or 552[22]	21	9	6.1	0.8 – 1.3[ref.23]
Falcon 9 FT[24]	22.8	8.3	3.6 – 5[vii]	0.5-0.93[ref.23]
Vulcan Centaur[24]	22	11	7.5	TBD
Vulcan ACES[25]	35	17	12	3.8[viii]
Vulcan ACES[x] Distributed Launch	N/A	N/A	30	12
Falcon Heavy[ix] (fully expendable)	54.4	22.2	13 [ref.24]	2.5 – 4.53[ref.23]

A lunar transportation system or lunar lander is another important capability to develop using the COTS model in the first phase. For this phase, the lunar lander can be modest in size with mass ranging approximately from 200 kg to 800 kg to fit within the existing launch vehicles as secondary payloads as listed in Table 1. It will be advantageous to leverage off the successful programs already in place that are incentivizing the development of lunar landers, such as, the Google Lunar XPRIZE (GLXP) and Lunar CATALYST programs.

NASA's Lunar Cargo Transportation and Landing by Soft Touchdown (CATALYST) Program is sponsored by NASA Headquarter's Human Exploration and Operations Mission Directorate (HEOMD). The purpose of the Lunar CATALYST program is to encourage the development of robotic lunar landers that can be integrated with commercial launch vehicles to deliver payloads to the lunar surface. In 2014, this program awarded un-funded Space Act Agreements to 3 domestic companies, including Astrobotic, Moon Express and Masten Space Systems, to develop lunar transportation systems. These companies have made considerable progress and are listed in Table 2 along with other teams competing for the Google Lunar XPRIZE.

The XPRIZE was initiated in 2007 by Google to encourage and incentivize space entrepreneurs from around the world to compete in a global competition to develop, build and operate lunar transportation systems. The competition offers $30M in prizes including $20M Grand Prize to the first team that successfully lands on the Moon, traverses 500 meters and transmits high definition images and video back to Earth. Although the teams must use mainly private funds (90%) to develop their systems, the guidelines do allow for governments to provide or purchase services from the teams at fair market value. Table 2 lists several of these GLXP lunar lander teams which have made significant progress. In addition, two of these teams, Moon Express and SpaceIL, have confirmed and

---

[vi] http://www.spaceflight.com/launch/
[vii] Estimate provided using Falcon v1.1 and not Falcon Full-Thrust (FT)
[viii] http://www.ulalaunch.com/uploads/docs/Published_Papers/Commercial_Space/2016_Cislunar.pdf
[ix] http://www.spacex.com/falcon-heavy

verified launch agreements as shown in Table 2. Most of these lunar lander teams will continue to be in business to deliver payloads to the Moon, long after the GLXP prize has been awarded. As an example, Astrobotic is aiming to become a lunar payload delivery service through a shared ride strategy. They are currently advertising to deliver payloads to the lunar surface at a cost of $1.2M/kg[x]. Germany's Part-Time Scientists in partnership with Audi are also offering delivery services to the Moon. Their website is advertising a cost of 700K to 800K Euros per kilogram to the lunar surface. If these and other lunar payload delivery services come to fruition, they will provide an opportunity to NASA and other organizations to acquire low-cost transportation to the lunar surface.

Although several of these GLXP teams are owned by foreign organizations, NASA may still be able to acquire these lunar transportation services through arrangements with the State Department which may include bartering instead of exchange of funds.

Table 2 also includes ULA's XEUS[26] lander which is derived from ULA's new upper stage named Advanced Cryogenic Evolved Stage (ACES).[27] The ACES stage is described as a large LO2/LH2 upper stage, about 3 times the size of Centaur, and integrates an innovative Integrated Vehicle Fluids (IVF) technology. Although it plans to outperform existing Delta Cryogenic Second Stage (DCSS) and Centaur upper stages, it plans to be built for the same or less recurring cost than Centaur which makes it very attractive. Also the IVF subsystem is an auxiliary power unit that runs solely on LO2 and LH2 eliminating the need for main vehicle batteries and helium bottles for tank pressurization. This technology enables ACES to be a fully reusable and long duration in-space stage that can be refueled with LO2 and LH2 which can be supplied from resources found on the Moon. Sowers[28] describes this system as the cornerstone to ULA's visionary Cislunar 1000 transportation system that plans to cycle back and forth between LEO and cis-lunar space powered solely by the resources of the Moon. In addition, their plan describes a transformation kit including thrusters, avionics and landing legs to be added to ACES to transform it into a lunar lander called XEUS. This lander will also be fully reusable and powered by IVF using solely LO2/LH2 propellant. Although this lander may be too large and costly for first phase, it is an excellent candidate for inclusion in second phase of LCOTS where the objective is to perform a pilot demonstration of ISRU resource production.

Table 2. Potential Lunar Landers

Lunar Lander Teams	Targeted First Mission and Capabilities
Astrobotic's[xi] GLXP Team - Peregrine Lander	Planned for launch in late 2017 to Lacus Mortis (45 deg N and 25 deg E). Peregrine capabilitiy ranges from 35 kg on first mission to 265 kg to lunar surface.
Moon Express[xi] GLXP Team	Signed launch agreement with RocketLab's Electron Launch Vehicle for 3 lunar missions from 2017 to 2020.
Masten Space Systems[xii]	Launch is TBD. Landers in development include Xaero, Xoie, Xombie and XEUS.
Israel's SpaceIL[xiii] GLXP team	Signed launch agreement via SpaceFlight with SpaceX's Falcon 9 for a late 2017 launch.
Germany's Part-Time Scientists[xiv] GLXP team	Planned for launch in 2017 to Apollo 17 landing site (Taurus-Littrow Valley).
ULA's XEUS, ACES derived Lander	Planned for launch early next decade on ULA's Vulcan launch vehicle. Lander capability is approx 3.8 mT to lunar surface for single launch and much greater using distributed launch.

Lunar Rovers are another an important capability to develop using the COTS model in the first phase. These rovers should be able to traverse long distances on the Moon carrying essential instruments that can identify key resources, such as hydrogen concentrations in water-ice deposits. These rovers should also be rugged enough to be able to navigate across rough, rocky and steep terrain as well as durable enough to withstand the extreme temperatures found on the Moon. The rovers must also be able to operate autonomously with limited command from

[x] https://www.astrobotic.com/
[xi] http://www.moonexpress.com/
[xii] http://masten.aero/
[xiii] http://www.spaceil.com/
[xiv] http://ptscientists.com/

the ground. Table 3 provides a list of potential lunar rovers that are being developed specifically to operate on the Moon to prospect for resources. All of these rovers are currently being developed for the GLXP competition.

Similar to the lunar lander teams, some of these teams are planning to continue their rover business on the Moon long after the GLXP competition is over. Astrobotic/CMU is presently advertising $2M/kg for delivery of payloads on their lunar rovers. Ispace Technologies business plan consists of mapping valuable resources on the Moon to determine economic value of resources and providing services to collect, store and deliver these valuable resources. These rover teams offer a great opportunity for partnership and delivery services to carry essential prospecting instruments on the lunar surface at various sites to meet the objectives of the first phase.

Table 3. Potential Lunar Rovers

Lunar Rover Teams	Capabilities
Astrobotic/Carnegie Mellon[xv] University (CMU) GLXP Team	Multiple rover options including Andy rover for first mission and Polar rover with excavation and planetary cave exploration capabilities.
iSpace Technologies[xvi] operates Japan's Hakuto GLXP Team	Multiple rover options for resource prospecting and tethered rovers to explore polar craters and caves.
Chile's AngelicvM[xvii] GLXP Team	The Unity Rover plans to deliver small payloads on first and follow-on missions.
Germany's Part-Time Scientists[xviii] GLXP team partnered with Audi	The Audi Lunar Quattro is equipped with a 4-wheeled electrical drive chain, titable solar panels, rechargeable batteries and science grade HD cameras.

Table 4 below provides a list of potential prospecting instruments that may be carried on a lunar rover or lander. It is preferable, of course, to be fitted on a rover in order to be able to obtain data at several locations. However, these instruments may also be fitted on a lunar hopper or other type of lander. These instruments vary in size and mass, ranging from 1 to 6 kg, and can be modified to fit within the payload volume of some of the lunar rovers listed in table 3. Although the rovers and instruments are small systems, they can provide valuable data to help identify where areas of high concentration of water-ice deposits and other volatiles exist.

Table 4. Potential Resource Prospecting Instruments and Equipment

Instrumentation Options	Capabilities
Neutron Spectrometer System (NSS)	Senses hydrogen-bearing materials (eg. Ice) in the top meter of regolith.
Near-Infrared Volatile Spectrometer System (NIRVSS)	Identifies volatiles, including water form (e.g. ice bound) in top 20-30 cm of regolith. Also provides surface temperatures at scales of <10 m
Camera, LEDs plus NIR spectrometer	Provides high fidelity spectral composition at range.
Drills	Captures samples from up to 1 m; provides more accurate strength measurement of subsurface.

[xv] https://www.astrobotic.com/
[xvi] http://www.economyinspace.com/
[xvii] http://www.teamangelicvm.com/
[xviii] http://ptscientists.com/

III. Lunar Industrialization Planning

Lunar industrialization planning is not a new concept. There have been numerous studies[29,30,31,32,33,34] since the 1950's to present time, investigating potential lunar industries that may yield economic benefits and value to Earth inhabitants and/or future lunar dwellers. These industries range from lunar mining, manufacturing, propellant production, power stations, helium-3 production, communication satellites, lunar rovers, lunar habitats to lunar tourism. Although there have been several market studies[35] conducted that show promising projections of lunar markets and revenue streams, there is no stand-alone business plan to date that makes a compelling enough case to its investors to ensure a profitable return on investment within a reasonable time frame. The challenge to these businesses is the large size of investments needed upfront to put in place all the elements of the infrastructure needed to make their business plans successful. This is where government can help to offset this economic burden from the individual businesses and help with the development of the infrastructure. As shown from industrialization efforts of the past, government can be a catalyst to lunar industrialization by partnering with industry to build the infrastructure needed for new lunar businesses to succed and a new space economy to flourish. Some of the elements of this infrastructure has already been discussed, such as, lunar transportation, power stations, communication satellites and resource prospecting. Other elements may include landing pads, navigation systems, human habitats and surface transportation and communication systems. All of these elements do not have to be put in place at once. This should be a gradual development in partnership with industry to meet both NASA's and industry's needs. This infrastructure development will not only help accelerate the emergence of lunar industries but it will also provide extensive benefits to NASA and our nation by lowering infrastructure costs and addressing some of our nation's critical problems, such as, climate change, resource depletion, energy independence, etc.

One very important infrastructure element needed for all emerging industries are power stations. There are several options for power stations including solar power systems, nuclear power systems and power beaming from solar satellites. The lunar surface presents several challenges to development of power stations including long night time periods of 14 Earth days where no sunlight is available at equatorial locations. For solar power systems, this challenge requires long-term energy storage systems or high tower power stations installed on a mountain or at high elevations in the polar regions. To overcome the long lunar nights, nuclear power stations may be preferable but also present many other challenges such as potential radiation hazards to humans and equipment as well as safety and environmental concerns on launch. Solar power satellites are also an attractive solution since they can be placed in high orbits to collect continuous solar energy. However power beaming to a ground station is in its early conceptual stages and may require a long development time before being fully operational. All of these options will require some development time to overcome its challenges. To accelerate this development, it will be advantageous for NASA to partner with industry to develop and demonstrate these power and storage capabilities using the COTS model. Once these capabilities have been developed, new lunar power industries will emerge ready and capable to provide its power services at cost to its customers including NASA and other government agencies. Similarly, lunar communications relay satellites should be developed as well using the COTS model to incentivize industry to develop these capabilities to provide future communication services from Earth to various sites on the Moon.

Although government does play an important role in building an infrastructure on the Moon as discussed, industry should take the lead in conducting its lunar missions to determine which other industries are economically viable enough for them to pursue. One example of a potentially economically viable business plan is mining platinum group metals (PGMs), such as platinum, iridium, osmium, rhodium, and palladium. Wingo[31] describes a hydrogen economy which revolves around replacing combustion engines with hydrogen fuel cells to power automobiles. Hydrogen fuel cells are much more efficient than combustion engines as well as hybrid engines. However, fuel cell efficiencies are highly variable depending on the fuel source (hydrogen vs. hydrocarbons) and catalyst (platinum). The real advantage of using fuel cells over combustion engines are in their low level of pollutants exhausted as compared to combustion engines. In a hydrogen fuel cell, the only output is pure water. Therefore it may be advantageous to use hydrogen fuel cells for rovers and other machinery to be operated on the lunar surface which can be fueled by resources found on the Moon. This advancement in fuel cell technology can also provide benefits to the automotive and other industries on Earth to help accelerate the growth and use of hydrogen fuel cells.

Another good example of a successful lunar industry is creating propellant, such as LO2 and LH2, on the Moon. The Evolvable Lunar Architecture (ELA) study, as described in reference XX, presented an affordable and economical plan for establishing a permanent commercial lunar base that can create and deliver up to 200 mt of propellant per year to cis-lunar space for a total estimated development cost of $40B over a 10-12 year period. If this plan is realized and lunar-derived propellant can be produced and delivered at economical rates, then this will have a dramatic impact to future human Mars mission concepts as the initial mass to LEO without the propellant will be significantly reduced as well as the required number of heavy-lift launches, making future Mars concepts more affordable. However, more economic assessments are needed to refine the estimates of how much it will cost to create an ISRU facility to create the propellant and deliver to a cis-lunar propellant depot. The next section describes a preliminary life-cycle cost and economic assessment to refine these estimates to understand the risks and potential benefits from this lunar industry.

IV. Preliminary Life Cycle Cost and Economic Assessment

Life cycle cost and/or economic assessment for the case of extracting lunar resources, creating lunar-derived propellant, delivering to a cis-lunar depot, and transferring the propellant to some customer presents an assortment of challenges. Prior work[20,36] generally develops an architecture for which costs are estimated, consisting of a launch vehicle, spacecraft, landers, or even a lunar ISRU's conceptual layout.[37] Given the diverse subject matter expertise required across all elements of an architecture, from specific launchers to specific ISRU chemistry, cost estimates will suffer from a long list of uncertainties. For example, using the NASA Air Force Cost Model (NAFCOM) can provide a cost estimate for a space system element in idealized circumstances, but it may not provide a realistic cost estimate in actual circumstances, where the realistic estimate can be multiples of the ideal. Similarly, an analysis developed by subject matter experts in one part of the architecture may not fully appreciate the way costs will realistically behave in another part of the architecture.

With this background in mind, the following is a preliminary, new approach in developing a life cycle cost and/or economic assessment for using lunar resources, especially lowering cost risk. First, it should not be assumed that government will provide all the infrastructure needed as previously discussed. A more consistent picture assumes lunar resources as a cost to a customer, any customer, at a delivery interface, making no further claim. Having purchased a truck, or just a ride, it is not a requirement that a customer must also own and operate the gas station. Second, and similarly, non-government customers will be treated the same as government customers where neither owns the lunar resource capability. It should be assumed that a third-party entity with private investment will provide the lunar resource capability, such as lunar-derived propellant. This in turn means any cost estimates for using lunar resources would be cost estimates in a commercial paradigm, as with the Commercial Cargo or Crew programs supporting the ISS.

To make the ISRU business case assessment much more manageable, Figure 2 (1) shows an approach separating the more definable from the more uncertain, (2) introduces a "price point" from which more definable costs can "bound" the ISRU challenge, and (3) separates the lunar resource customer from the ISRU business. The basic idea behind Figure X will be familiar to anyone who has ever thought about the business, economic or budgetary feasibility of a concept by asking - "what if all of these items are free, but not that – then what would that still add up to"?

Consistent with the LCOTS concept, costs estimates for the elements involved in providing transfer services in Figure X (in this scenario - propellant delivery in lunar orbit) start with recent experience in the NASA Commercial Cargo and Crew programs[xix]. An initial estimate is how NASA would assist in developing elements in Figure X on a commercial basis. With NASA as a zero-equity investor, and private capital investment incentives aligned to succeed, costs for these elements on a commercial basis drop dramatically while preserving a credible basis of estimate and lowering cost risk.

"Cost baseball cards" (Figure 3) of numerous space system elements are being developed along this line of reasoning, addressing assorted scales of elements and assorted acquisition approaches, cost-plus or commercial. From this, assorted options for elements in the "more definable" category of Figure 2 help define that ISRU investment challenge which would remain – all investments that could be part government, part private.

Preliminary results for In-space Stages (Figure 3) as well as Landers, all of assorted scale and acquisition approach, show great promise toward closing a lunar ISRU investment case. The critical parameters after the more definable costs of in-space stages, landers, etc. are (1) the price point for delivered propellant at the interface to the customer and (2) the scope of the surface facility, the ISRU challenge.

The price-point is that cost per kg for usable commodities that a customer (like NASA or others) would pay having gotten as far as reaching some location in lunar space. For example, IF the Price Point is $5,000 per kg, paid for delivered commodity in lunar orbit, and IF "more definable" costs (lunar orbit storage, transport, etc. Figure X) are $2,000/kg, THEN the ISRU "challenge" is to not add more than about $5,000 minus $2,000 = $3,000 costs per kg of revenue generating commodity.

[xix] The successful experience of NASA with the commercially developed SpaceHab, among other examples, also applies.

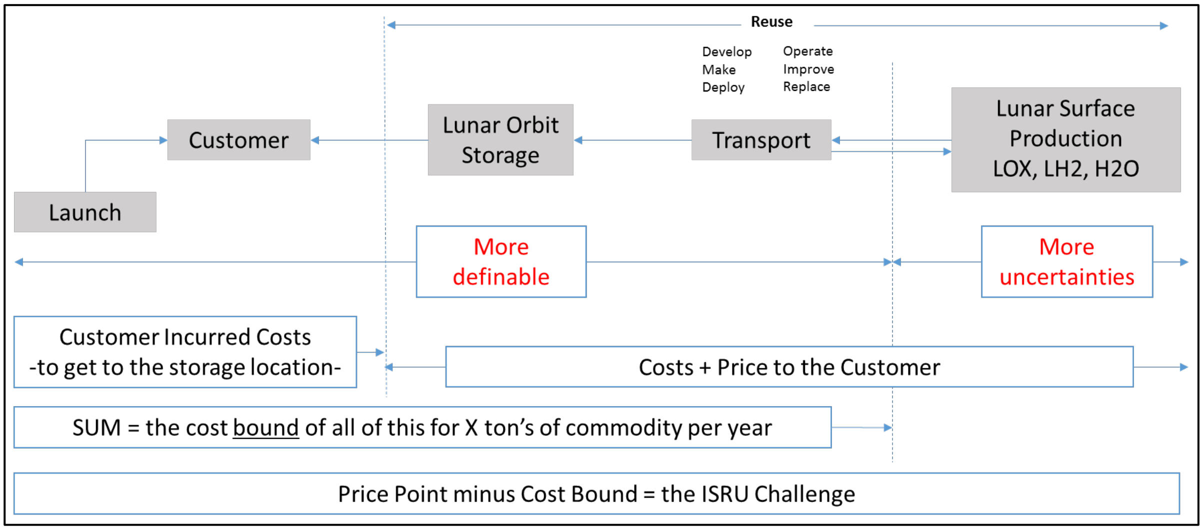

Figure 2 An approach for a more manageable economic assessment of lunar ISRU resources for customers.

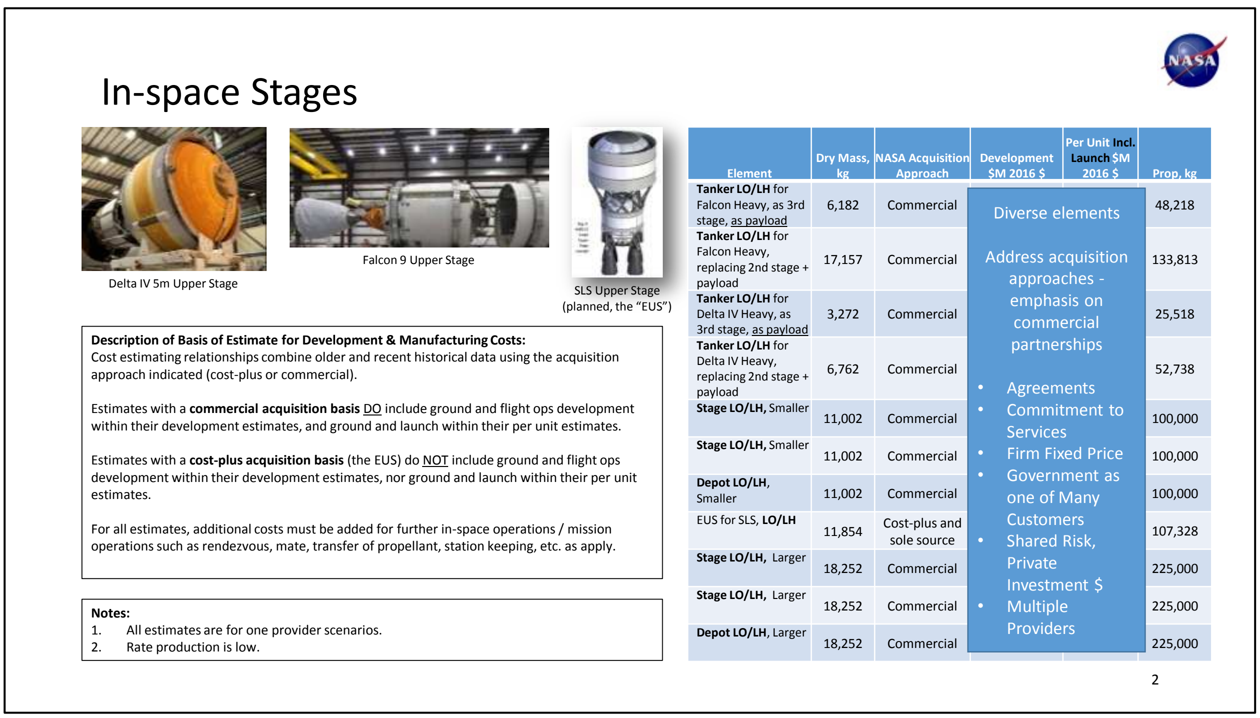

Figure 3 Unlike Element Performance Baseball Cards with features and mass statements, the Element *Cost* Baseball Card here assists with life cycle cost and economic assessment, without which elements may be imagined, but never achieved, having neglected establishing a proper business case.

The prior would require leaving room for profit, financial factors, a valuation perspective, etc. Preliminary results show promise in these business cases, depending especially on the factors that tell how technically reusable the assets placed once into service actually prove to be. A storage location (depot, hub, etc.), transports/landers for taking propellant from the moon to the storage node, and the associated space operations and traffic management, are at the end of day all reusable assets competing against expendable alternatives. The expendable alternatives would be customers with more and/or larger stages/systems, more assortment of stage sizes, more launches of all of this, with surge concepts, etc. all using this hardware once, discarding it all, and building it all anew for the next go-round. Vertical vs. horizontal business integration concepts also compete (for example, the propellant storage site in lunar orbit may be a company entity un-related to the surface facility).

As this work continues, it will add more detail to the work to date, continuing to assess portions of the ISRU investment question in this systematic approach. This more manageable LCOTS approach to a life cycle cost and economic assessment provides for a credible basis of estimates, and significantly more affordable elements of an ISRU system of systems, from a customer and from a public and private investment point of view. Consistent with NASA's experience in public private partnerships, technical challenges will see unexpected innovation. As well, the overall business case improves with one essential ingredient - having the government be one customer of many, alongside private sector business cases and operations.

V. Concluding Remarks

In summary, an update to the Lunar COTS plan was provided outlining a new campaign of low-cost, commercial-enabled missions to prospect for resources, determine the economic viability of extracting those resources and assess the value proposition of using these resources in future exploration architectures such as Mars architectures. A Space Development framework was also presented that stressed the importance of an Economic Development phase where the missions are focused primarily on spurring economic growth in space and providing economic benefit to the space community. With these principles in mind, new economic goals for Phase I of Lunar COTS were presented which included:

1. **Conduct a campaign of low-cost, commercial-enabled lunar exploration missions** to prospect and extract lunar resources to meet NASA's mission needs and industry's commercial interests;
2. **Determine the economic viability of extracting resources** by testing various commercial tools, products and techniques in a lunar environment;
3. **Build an economic infrastructure** by partnering with industry to place in service power stations, lunar communication relay satellites and lunar surface communication systems;
4. **Enable a robust cis-lunar commercial economy** by incentivizing industry to create new space products and markets;
5. **Inspire the next generation of space entrepreneurs** by conducting several educational and outreach activities.

To meet these goals, a three-phased approach was described to develop and demonstrate cis-lunar capabilities and services by partnering with industry to share cost and risk for mutual benefit using the well-proven COTS acquisition model. These capabilities and services needed to accomplish the Lunar COTS goals were also described which included launch vehicles, lunar landers, lunar rovers, resource prospecting instruments, power stations and lunar relay communication satellites. A partnership strategy to develop these capabilities and services was also described along with the infrastructure needed to accomplish these goals. Development of these cost-effective services would not only enable NASA to economically and sustainably achieve its human exploration missions to the Moon, Mars and beyond but it would also kickstart a new era of lunar industrialization.

Acknowledgments

The authors would like to acknowledge several members of Ames Space Portal who contributed to this paper including Lynn Harper, and Mark Newfield. Authors would also like to acknowledge the Ames management team for supporting this work including Gary Martin and Rose Grymes.

References

[1] Lanius, R.D., "Apollo: A Retrospective Analysis," NASA History Office, NASA Headquarters, Washington D.C. , reprinted July 2004.

[2] Seamans, Jr., R.C., "Project Apollo: The Tough Decisions," Monographs in Aerospace History, Number 37, SP-2005-4537, NASA Office of External Relations, Washington, DC 2005, pg. 60.

[3] Augustine, N. R., et al, "Seeking a Human Spaceflight Program Worthy of a Great Nation," Review of U.S. Human Spaceflight Plans Committee, Oct 2009.

[4] Space Task Group, "The Post-Apollo Space Program: Directions for the Future," September 1969.

[5] Alred, J., et al, Lunar Outpost, Advanced Programs Office, NASA Johnson Space Center, Houson, TX, 1989.

[6] "Report of the 90-Day Study on Human Exploration of the Moon and Mars," NASA, November, 1989. http://history.nasa.gov/90_day_study.pdf

[7] Aldridge, Jr., E.C., Report of the President's Commission on Implementation of United States Space Exploration Policy, "A Journey to Inspire, Innovate, and Discover," June 2004.

[8] "National Space Policy of the United States of America," Office of the President of the United States, Washington D.C. URL: https://www.whitehouse.gov/sites/default/files/national_space_policy_6-28-10.pdf [cited 28 June 2010].

[9] "NASA's Journey to Mars – Pioneering Next Steps in Space Explortion," National Aeronautics and Space Administration, Sep. 2015.

[10] Williams, G., Crusan, J., "Pioneering Space – the Evolvable Mars Campaign," NASA Headquarters, Washington, D.C. URL: https://www.nasa.gov/sites/default/files/files/20150408-NAC-Crusan-EMC-v7a.pdf [cited April 2015].

[11] Craig, D., Troutman, P., Herrman, Nicole, "Pioneering Space Through an Evolvable Mars Campaign," AIAA 2015-4409, AIAA Space 2015 Conference, Sep 2015.

[12] Zuniga, A., Rasky, D., et al, "Lunar COTS: An Economical and Sustainable Approach to Reaching Mars, " AIAA Paper, AIAA Space 2015 Conference, Sep 2015.

[13] "Commercial Orbital Transportation Services – A New Era in Spaceflight," National Aeronautics and Space Administration, NASA SP-2014-617.

[14] NASA, "Falcon 9 Launch Vehicle NAFCOM Cost Estimates," August 2011, NASA Assoc. Deputy Administrator for Policy, http://www.nasa.gov/pdf/586023main_8-3-11_NAFCOM.pdf.

[15] Williams, D. R., "Ice on the Moon - A Summary of Clementine and Lunar Prospector Results," *NASA*, URL: http://nssdc.gsfc.nasa.gov/planetary/ice/ice_moon.html [cited 12 May 2014].

[16] Spudis, P.D., Bussey, D.B.J., Baloga, S.M. (et al), "Evidence for water ice on the Moon: Results for anomalous polar craters from the LRO Mini-RF imaging radar," *Journal of Geophysical Research: Planets*, Vol. 118, 2016-2029, 2013.

[17] Colaprete, A., Schultz, P., Heldmann, J. (et al), "Detection of Water in the LCROSS Ejecta Plume," *SCIENCE Journal*, Vol. 30, No. 6003, 2010, pp. 463-468.

[18] Crawford, I., "Lunar Resources: A Review," *Progress of Physical Geography*, 2014.

[19] Miller, C., Wilhite, A., Cheuvront, D. (et al), "Economic Assessment and Systems Analysis of an Evolvable Lunar Architeture that Leverages Commercial Space Capabilities and Public-Private-Partnerships," NexGen Space LLC under a grant from NASA, 2015. URL: http://science.ksc.nasa.gov/shuttle/nexgen/rlvhp.htm [cited 22 July 2015].

[20] Spudis, P.D., Lavoie, A.R., "Using the Resources of the Moon to Create a Permanent, Cislunar Space-Faring System," AIAA 2011-7185, AIAA Space 2011 Conference & Exposition, 27-29 Sep 2011, Long Beach, CA.

[21] Sanders, "Lunar Polar ISRU as a Stepping Stone for Human Exploration," presented to Lunar Exploration Analysis Group (LEAG) Workshop, Oct 2013.

[22] Atlas Launch System Mission Planner's Guide", January 2007, http://www.ulalaunch.com/docs/product_sheet/Atlas_Mission_Planner_14161.pdf

[23] Henderson, E.M., et al, "Commemorate the 50th Anniversary of the Apollo 11 Moon Landing," AIAA/ASME/SAE Joint Propulsion Conference, Salt Lake City, UT, July 2016.

[24] SpaceX Falcon 9 User Planner's guide, http://www.spacex.com/falcon9 Aug 2016

[25] Kutter, B., Monda, E., Wenner, C., "Distributed Launch-Enabling Beyond LEO Missions," AIAA Space 2015 Conference, AIAA Paper 2218578, Sep 2015.

[26] Kutter, B. F., "Robust Lunar Exploration Using an Efficient Lunar Lander Derived from Existing Upper Stages," AIAA Space 2009 Conference, Sep 2009..

[27] Barr, J., "ACES Stage Concept, New Capabilities, at a Lower Recurring Cost," AIAA Space 2015 Conference, Pasadena, CA, Sep 2015.

[28] Sowers, G., "Transportation Enabling a Robust Cislunar Space Economy," Space Access and Northeastern Astronomy Forum, April 2016.

[29] Awdry, G., "Development of a Lunar Base," Journal of the British Interplanetary Society, Vol. 13, pp. 166-169, 1954.

[30] O'Neill, G., "Space Resources and Settlements," NASA Ames Research Center, NASA SP-428, 1979.

[31] Ehricke, K, A., "The Seventh Continent:Industrialization and Settlement of the Moon," The Kraflt A. Ehricke Institute, La Jolla,CA, 1986.

[32] Wingo, D., "Moonrush-Improving Life on Earth with the Moon's Resources," Apogee Books, Ontario, Canada, 2004.

[33] Eckart, P., "The Lunar Base Handbook," Second Edition, The McGraw Hill Companies, 2006.

[34] Schrunk, D., Sharpe, B., Cooper, B., Thangavelu, M., "The Moon, Resources, Future Development and Settlement," Second Edition, Praxis Publishing Ltd., Chichester, UK 2008.

[35] "Google Lunar XPRIZE Market Study 2013", London Economics, October, 2013.

[36] Woodcock, G.R., "Architecture and Evolutions to Enable Lunar Development,"

[37] Charania, A.C., DePascuale, D., "Economic Analysis of a Lunar In-Situ Resource Utilization (ISRU) Propellant Services Market," SpaceWorks Engineering Inc., International Astronautical Congress, India, 2007.