An Affordable Lunar Architecture Emphasizing Commercial and International Partnering Opportunities

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Abstract— **Since the cancellation of the Constellation Program, NASA officially has been focused on Mars as the next step for human exploration. Yet many in the space community believe that returning humans to the moon is more logical. Often-cited reasons for this include: (1) should Nature prove to be favorable, the moon could be the basis for expanding the space economy through Off-Earth Mining (OEM) and other commercial endeavors; (2) the moon is scientifically interesting and could serve as a platform for scientific facilities; and (3) useful experience could be gained there for the human journey to Mars.**

With this in mind, JPL's A-Team (Architecture Team) was tasked with developing conceptual lunar surface architectures that could simultaneously provide "living on another world" proving ground experience, but would also be affordable and offer truly significant commercial and international partnering opportunities. The task also required that the resulting architectures must eventually lead to and flow seamlessly into planning for human missions to Mars in the 2030s/2040s, if "things go well." This aspect has been critically missing in other lunar architecture proposals.

For continued NASA investment in any future human exploration architecture, affordability is a political imperative. This translates into managing the magnitude of the public investment by NASA in lunar infrastructure while doing those things that governments can do to stimulate new economic opportunities there. The menu of such potential strategic investments include: (1) engaging in science and exploration (e.g., Lewis and Clark); (2) reducing economic risks and resolving some technical uncertainties to create tipping points and real options for space entrepreneurs; (3) performing R&D/DDT&E and first buys of basic systems/services; (4) building public (lunar) infrastructure (e.g., roads, navigation aids, basic communications, logistics nodes, operational knowledge/de-confliction); and (5) acting as an anchor tenant.

While incorporating these strategic elements into the architecture development as a way to encourage private sector development of the space economy and international partner contributions, the A-Team also recognized that both off-ramps and on-ramps (and periodic decision points) were needed to ensure that public goals for human space exploration were being met. Key questions might include: (1) are private investors coming on board; and (2) are we ready to go to Mars?

In this paper, we present and describe the A-Team's lunar architecture that meets the requirements set out above using a high-level system-of-systems architectural view, which we call a "dance card." We then process the information in the dance card into an affordability view, commonly called a "sand chart." The method and model used for this is described in some detail, along with the sources of data. Lastly, we discuss the extensive commercial opportunities, which include *in situ* resource utilization (ISRU), cargo logistics, tourism, utilities for lunar activities, and construction, as well as the international partner contribution opportunities embodied within the architecture. We also review the viability of these commercial opportunities based on previous research.

TABLE OF CONTENTS

1. INTRODUCTION 1
2. AN AFFORDABLE LUNAR ARCHITECTURE 2
3. COMMERCIAL AND INTERNATIONAL PARTNERING OPPORTUNITIES 11
4. SUMMARY AND CONCLUSIONS 13
ACKNOWLEDGEMENTS 13
DISCLAIMER 13
REFERENCES 14
BIOGRAPHY 15

1. INTRODUCTION

Since the cancellation of the Constellation Program, NASA officially has been focused on Mars as the next step for human exploration. Yet many in the space community believe that returning humans to the moon is more logical. Often-cited reasons for this include: (1) should Nature prove to be favorable, the moon could be the basis for expanding the space economy through Off-Earth Mining (OEM) and

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other commercial endeavors; (2) the moon is scientifically interesting and could serve as a platform for scientific facilities; and (3) useful experience could be gained there for the human journey to Mars.

With this in mind, JPL's A-Team (Architecture Team) was tasked with developing conceptual lunar surface architectures that could simultaneously provide "living on another world" proving ground experience, but would also be affordable and offer truly significant commercial and international partnering opportunities. The task also required that the resulting architectures must eventually lead to and flow seamlessly into planning for human missions to Mars in the 2030s/2040s, if "things go well." This aspect has been critically missing in other lunar architecture proposals.[1]

The A-Team is JPL's way of exploring mission-level architecture tradespaces, generating innovative ideas, and forging creative solutions using a concurrent engineering process at the earliest stages of formulation. Each A-Team study draws upon a diverse set of participants within JPL who are creative thinkers, "grey beard" scrutinizers, and subject matter experts with both breadth and depth of experience and expertise [1]. The nucleus of this study's A-Team had extensive experience on the Constellation and ISS programs as well as robotics technologies and projects.

The A-Team architecture described in this paper is the result of four A-Team concurrent engineering study sessions that took place from July 2016 through May 2017. In between sessions, the architecture was matured, and new ideas and refinements were incorporated. Throughout the process, the programmatic cost of the emerging architecture was investigated using an enhanced version of a software tool developed by the Aerospace Corporation. Beyond developing a multi-decade, multi-system human spaceflight architecture that encompasses the moon and Mars, this paper is intended to show that high-level programmatic cost assessments can be integrated into the architecting process. Including cost as a factor in NASA's Journey to Mars feasibility studies was one of the recommendations set forth by the NASA Office of the Inspector General (OIG) in 2017 [2]. In part then, this paper is about enhancing the architecture definition process.

2. An Affordable Lunar Architecture

Essential Elements for Describing an Architecture

Human spaceflight architectures can be quite complex, which means that a well-defined architecture framework is useful in abstracting essential information from the underlying complexity and presenting it in the most unambiguous way possible. The information captured in the framework's data model provides the means to coherently describe the architecture from multiple "viewpoints." This is important because different stakeholder communities have different interests and needs.

We have found, along with others, that a data model for human spaceflight needs to contain artifacts, relationships, and information built around the concepts of operational nodes, systems, operational functions, milestones, measures, standards, flight types, and flights. (Those familiar with the Department of Defense Architecture Framework (DoDAF), a widely used formal architecture framework, may see the similarities of these artifacts to those in DoDAF's data model.) These artifacts, described in Table 1, are actually just a subset of the architectural artifacts in the Human Spaceflight Architecture Model (HSFAM), published in 2017 [3]. In some of our earlier work [4,5], we needed the full power of the HSFAM with extensions, but in this paper we need only a few of these artifacts to build the two views presented in this paper—the Dance Card view, which falls into the Operational Viewpoint category, and the Affordability view, which falls into the Project Viewpoint category.

Table 1. Architectural Artifacts in HSFAM

Name	Description of Architectural Content	Classes, Types, and Subtypes
Operational Nodes	Spatial locations in the solar system; locus of an operational function or activity	Surface locations (terrestrial and planetary); orbits; Lagrange points
Systems	Notional objects that fulfill a function; a hardware and/or software build	Based on broad system purposes, e.g., surface mobility, habitation
Operational Functions	Activities that transform inputs (resources) into outputs (other resources or end products), or change their state	Based on broad functional areas, e.g., mission operations, etc.
Milestones	Time-stamped identification of significant changes; milestones are four-dimensional as the spatial location (operational node) is also included	Based on capability achieved, e.g., initial operational capability (IOC)
Measures	Measurable (quantifiable) properties or attributes of interest	Mass, cost, quantity, etc.
Standards	Applicable technical, operational or business standards and rules	ISO, ANSI, Community of Practice (CoP), government-unique, etc.
Flight Types	Arcs (or edges) between operational nodes that form a feasible network along which systems can move	
Flights	Time-stamped assignment of flight types	

One of the most common views used in human spaceflight architectures is the "bat chart," which is intended to show how various systems in the architecture would be employed in accomplishing a mission. (In this view, vehicles at the destination appear to be hanging upside down, hence the

[1] See [7] as an example.

analogy to bats.) Figure 1 shows a bat chart used during the Constellation Program to show a crewed mission to the lunar surface. This operational view identifies a number of operational nodes—an Earth surface launch site, an Earth

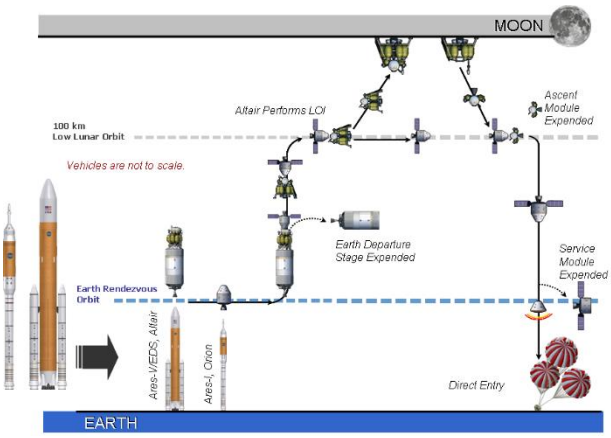

Figure 1. Example of a bat chart from the Constellation program

rendezvous orbit, a 100-km lunar orbit, a lunar landing site, presumably the lunar outpost, and an Earth surface landing site. The systems to be used in the view are shown as icons. The view also conveys some information regarding the sequence of events in the Concept of Operations (ConOps), but not timing or schedule information. One can surmise various flight types by the movement of the systems from one operational node to another. Bat charts are very useful for conveying how a mission is to be conducted, but it does not convey the information regarding the programmatic schedule and operational aspects of a multi-year or multi-

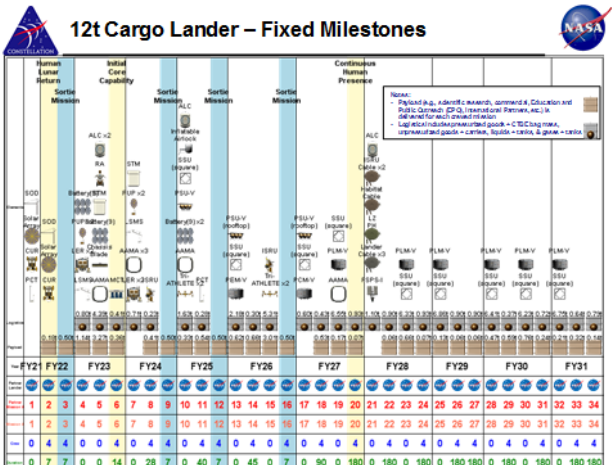

Figure 2. Example of a dance card from the Constellation program

decade enterprise (i.e., campaign). For that, a "dance card" view is better suited.

An example of a dance card used in the Constellation Program era is shown in Figure 2. In this operational view, one can infer only two of the operational nodes—an Earth surface launch site and a lunar outpost site. This dance card view conveys not only a sequence of flights, but year-by-year information regarding the schedule needed to execute this lengthy campaign. This view shows some critical information regarding the enterprise: the quantity of each system delivered to the outpost on each flight. However, one can only infer the launch vehicles employed by the type of payload (crew or cargo) and by the "partner" agency. The dance card identifies (in yellow) when some important milestones occur—human lunar return (HLR), initial core capability, and continuous human presence. A basic measure of human lunar activities is also shown, namely the length of each crewed mission measured in days on the lunar surface. While the dance card in Figure 2 conveys a great deal of worthwhile information, the dance card for the A-Team architecture to be presented is more complex as it needs to convey not only direct NASA activity, but related commercial and international partner activities in the simultaneous pursuit of multiple destinations (operational nodes) over a multi-decade period.

Overview of the A-Team Study Architecture

The A-Team study architecture has an initial focus on returning humans to the lunar surface, conducting basic research and exploration activities, and building basic infrastructure at a lunar outpost node, whose location was selected because of the availability of sunlight and other *in situ* resources. It is important to note here that the A-Team study architecture dance card in Figure 3 shows only NASA launches (using SLS) and commercial launches that are contracted by NASA for government purposes. It does not show commercial launches (and commercial infrastructure) contracted by commercial firms in pursuit of private sector market opportunities, e.g., space tourism. The reason for this is that in developing the sand chart view, we want to include only NASA expenditures—that is, expenditures that would be part of the NASA budget for human spaceflight.

Following a period (nominally ten years) of lunar exploration and infrastructure emplacement, the A-Team architecture shifts to a Mars focus. The Mars portion of the A-Team architecture is based on an updated and revised architecture first published in [6] in 2015. We will refer to this architecture as "Minimal Mars," because it would minimize large new development efforts and rely primarily on high TRL systems. The A-Team study architecture also includes testing of Mars hardware at the moon as well as the continual training of Mars crews in LEO.

The A-Team study architecture has specific milestone dates. In developing the architecture, the A-Team decided that an early HLR was important for strategic political reasons—mostly to sustain public interest. Other lunar architectures emphasize robotic exploration and resource exploitation first, not HLR [7]. In Figure 3, HLR occurs in 2027 with the first Mars system mission in 2037, followed by the first Mars landing mission in 2041. These dates are notional and can be moved to the right in the dance card as events may dictate. They were selected only to provide a starting point for programmatic assessment purposes. Nevertheless, the A-

Team also recognized the importance of being among the first to arrive at a new destination in space and to open it up for subsequent use and development by others by lowering the barriers to entry.

On the Role of the Government Sector in the Architecture—For continued NASA investment in any future human exploration architecture, affordability is a political imperative. This translates into managing the magnitude of the public investment by NASA in lunar infrastructure while doing those things that governments can do to stimulate new economic opportunities there. The menu of such potential strategic investments include:

- engaging in science and exploration (e.g., Lewis and Clark);
- reducing economic risks and resolving some technical uncertainties to create tipping points and real options for space entrepreneurs;
- performing R&D/DDT&E and first buys of basic systems/services;
- building public (lunar) infrastructure (e.g., roads, navigation aids, basic communications, logistics nodes, operational knowledge/de-confliction); and
- acting as an anchor tenant.

While incorporating these strategic elements into the architecture development as a way to encourage private sector development of the space economy and international partner contributions, the A-Team also recognized that both off-ramps and on-ramps (and periodic decision points) were needed to ensure that public goals for human space exploration were being met. Key questions might include: (1) are private investors coming on board; and (2) are we ready to go to Mars?

Off-ramps and on-ramps are ways to alter course in light of new information. What if private enterprises were still reluctant to invest in lunar activity, even after emplacement of substantial infrastructure by the government? For example, it may turn out that the production of propellant from lunar sources is technically too difficult, or the cislunar marketplace turns out to be too small to make a profit, or launching propellant to cislunar space from Earth using re-usable commercial rockets turns out to be less expensive. It may well make sense to scale back (off-ramp) government-funded lunar exploration and pursue other human exploration objectives. It is also possible that lunar-based propellant and other industries are successful. In that case, continued government investment may not be necessary to further grow the space economy as entrepreneurs find new profitable activities on their own. At this point, the government can reap the benefits of presumably lower prices (for propellant, habitation, power, etc.), and move on to (on-ramp) new human exploration activities. The point is that we do not know how things will turn out, but for programmatic assessment purposes, we needed a specific conceptual architecture. In the A-Team study architecture then, government lunar activity is assumed to stop in approximately 2036 as the focus shifts to human Mars missions. This is not to say that things will happen this way, only that building an architecture affordability view requires specific assumptions regarding timing.

The A-Team architecture to be described can have many variations, but the A-Team wanted to start with one that was in some sense "minimal." Specifically, the government-funded lunar infrastructure would be just enough to support minimal government activities described above, but sufficient to signal serious intentions regarding lunar exploration and development to commercial investors. This level of public investment in infrastructure precursors is intended to be in keeping with the pioneering spirit, but is careful not to displace private investments.

On the Role of the Space Launch System (SLS) and Orion—NASA has made a considerable investment in the Space Launch System and the Orion spacecraft. The A-Team study architecture makes extensive use of these two systems to send crews and cargo beyond LEO, as they were intended, in both the lunar and Mars portions of the architecture. The flight rate of the SLS is assumed to gradually ramp-up, starting at 1/year in the first half of the 2020s and then moving to 2/year in the second half of the decade. The flight rate increases to 2.5/year in the 2030s and 2040s. This launch tempo is needed to support the architecture's four-year cadence of human missions to Mars. In the A-Team study architecture, SLS Block 2 replaces Block 1B in 2028.

On the Role of the Commercial Space Sector in the Architecture—The government-funded portion of the architecture includes two kinds of developments. Those systems that take astronauts to the moon, land them, and provide surface habitation would be developed under NASA processes, but other surface systems such as power would be developed and then transported to the lunar surface using commercial services. In other words, in the initial period of lunar operations, the government would be the lead for those systems that transport and provide living quarters for humans. At some point, commercial entities can accept this responsibility, once the safety of those commercial systems has been demonstrated. This follows the partnering practices developed for the ISS commercial crew program. Almost from the start, however, logistics in support of human operations—the delivery of supplies and spare parts—is performed by commercial entities with the government as a customer.

The A-Team consensus was that lunar tourism and Off-Earth Mining (OEM) would be the most promising commercial opportunities, though the team noted the significant technological and economic difficulties of the latter. In the A-Team architecture, investment in these two market sectors is left entirely to commercial entities. The government's role in ISRU and OEM is limited to a pair of robotic lunar rovers—basically, the proposed Resource

Prospector I and a larger, more capable follow-on Resource Prospector II. These perform basic investigations of the lunar regolith with a goal of determining its composition, the extent and quantity of useful materials (e.g., water for propellant), and the engineering obstacles to actually mining it. This is part of the risk-reduction role for government mentioned above.

A true cislunar economy develops when commercial entities buy from each other. The A-team envisions this arising as a result of government investments in basic systems and services (e.g., habitation, power, cargo delivery, surface mobility, navigation, and communications); these basic lunar infrastructure investments are shown in Figure 3, the A-Team architecture's dance card. With the government as the first buyer of these systems and services, commercial entities would be able to buy incremental units at the recurring production (i.e., marginal) cost, rather than incurring all (or part) of the development cost. By reducing upfront capital costs, the government is effectively lowering the barriers to entry, but the private sector must determine for itself which cislunar market sectors are worthy investments.

The "Dance Card" View

The dance card view focuses on an architecture's year-by-year flights, and what systems/payloads make up the launch stack on each flight. (The "dance card" analogy is used to reflect the limitations of production and launch capacity for SLS, Orion, and other systems. Once the dance card is filled in a particular year, there are no more launch opportunities. The dance card effectively manages the timing of launches.)

In Figure 3, the upper half shows the assumed SLS-Orion and SLS cargo launches; the lower half shows the assumed NASA-contracted commercial launches. The period covered by the dance card is 2021 through 2050. The systems/payloads on each launch are identified using icons. A short narrative clarifies crew operations (for crewed flights) and identifies by name what systems/payloads are launched. All commercial launches are on a generic launch vehicle; no specific launch vehicle (other than payload class) or launch vehicle provider is implied.

In the A-Team study architecture, EM-2, the first flight, is assumed to occur in 2022. By 2034, seven four-person crews have been sent to the lunar surface, and the A-Team's "minimal" lunar infrastructure at the outpost consists of:

<u>Launched on SLS</u>

- Two (2) four-person habitation modules (each with active-active mating adapters and connecting transfer tunnel) [8, 9]

- Four (4) unpressurized crew rovers for short-range surface mobility

- Two (2) ATHLETE (All-Terrain Hex-Limbed Extra-Terrestrial Explorer) units [10]

<u>Launched on Commercial Launch Vehicles</u>

- Resource Prospectors I and II

- Three (3) solar power units (the last one as a possible replacement)

- Three (3) ATHLETE units (the last one as a possible replacement)

- One (1) pressurized crew rover for long-range surface mobility (with active-active mating adapter and connecting transfer tunnel)

- Two (2) multi-use supplemental power units (standard batteries or possibly Regenerative Fuel Cells (RFCs) or advanced Radioisotope Power Systems (RPSs))

- Navigation aids (short- and long-range)

- Bulldozing and sintering tools for ATHLETE

- Eight (8) pressurized logistics modules (with supplies, spare parts, and scientific equipment).

In Figure 3, the revised and updated Mars portion of the A-Team study architecture (Minimal Mars) is complicated by the need for multiple SLS launches that would overlap in time from one mission to another. Specifically, there are four launches for the Phobos mission concept, six launches for the opposition class landed mission concept, and ten launches for each conjunction class landed mission concept. To indicate which launches pertain to each mission, the dance card uses color codes shown in the legend.

The Phobos mission is assumed to begin in 2033 with the launch and departure of a Solar Electric Propulsion (SEP) tug delivering chemical Trans-Earth Injection (TEI) and Phobos Transfer stages. The crew is not launched until 2037, but in-space training missions for Mars crews begin as early as 2030 with the launch of Mars proving ground systems to Low Earth Orbit (LEO). Systems launched include a Deep Space Habitat (DSH) protoflight unit, a 40 kW solar electric power and propulsion bus, and a pressurized logistics module based on current ISS cargo resupply spacecraft. Similar in concept to the Deep Space Gateway, these systems form a facility whose main purposes are to provide (1) long-term operations experience and design validation (e.g., reliability) data for the final Deep Space Habitat, and (2) realistic training for Mars crews by simulating the transiting portions of Mars missions. All of these LEO elements and all training crews are assumed to be launched on commercial launch vehicles and commercial crew spacecraft.

Minimal Moon + Mars Concept

Human Lunar Return in 2027 with Mars system mission in 2037

SLS Launches	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Flight Type		SLS Blk-1b		SLS Blk-1b		SLS Blk-1b	SLS Blk-1b	SLS Blk-2		SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	
Flight Name Orion		EM-2 (8-21 days)		EM-3 (8-21 days)		EM-4 (8-21 days)	EM-5	EM-6		EM-7	EM-8	EM-9	EM-10	EM-11	
Co-manifested NASA															
Co-manifested IP				Comm Orbiter-1		Comm Orbiter-2 (for redundancy and full LSP coverage)									
Flight Type					SLS Blk-1b	SLS Blk-1b	SLS Blk-1b	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	
Flight Name NASA Cargo					Habitat-1 Habitat (>5000 kg) with A-AMA/ tunnel; ATHLETE mobility unit	DAV-1 DAV test (uncrewed)	DAV-2 (HLR) Unpressurized small rover (4 astronauts) with human lander	DAV-3 Unpressurized small rover (4 astronauts) with human lander	Habitat-2 Habitat (>5000 kg) with A-AMA/ tunnel; ATHLETE mobility unit	DAV-4	DAV-5	DAV-6 Unpressurized small rover (4 astronauts) with human lander	DAV-7 Unpressurized small rover (4 astronauts) with human lander	DAV-8	
Flight Type													SLS Blk-2	SLS Blk-2	
Flight Name IP Cargo NASA Cargo													Phobos SEP #1 TEL and Phobos Transfer Stages 100 kW SEP	Phobos SEP #2 100 kW SEP and Phobos Lander	
Flight Type															
Flight Name NASA Cargo															
Planetary Missions			Europa Clipper on SLS Blk-1b		Possible Europa Lander on SLS Blk-1b				Possible mission on SLS Blk-2						Possible mission on SLS Blk-2
Crew Operations		EM-1 (uncrewed mission) in 2019. EM-2 crew on a free return trajectory delivers		EM-3 crew monitors surface deployments from NRLO.		EM-4 crew performs a dress rehersal for HLR with uncrewed human lunar DAV using stretch version of Orion Service Module (SM); this SM is used on all subsequent lunar missions	EM-5 crew performs 7-14 day surface mission to include outfitting habitat module as needed and assessing previous deployments	EM-6 crew performs 14-28 days surface mission and continues to outfit habitat module with longer-term life support systems; performs repairs as needed		EM-7 crew performs 28-60 day surface mission; connects 2nd habitat and 2nd solar power system; prepares for pressurized crew rover and performs repairs as needed	EM-8 crew perfoms 28-60 day surface mission; completes integration and checkout of pressurized crew rover and performs repairs as needed	EM-9 crew of government and possibly commercial astronauts perform 60-90 day surface mission	EM-10 crew of government and possibly commercial astronauts perform 60-90 day surface mission	EM-11 crew of government and possibly commercial astronauts perform 60-90 day surface mission; connects 3rd solar power system; deploys longer range communication/ navigation aids	
Crew Return Vehicle		EM-2 Orion		EM-3 Orion		EM-4 Orion	EM-5 Orion	EM-6 Orion		EM-7 Orion	EM-8 Orion	EM-9 Orion	EM-10 Orion	EM-11 Orion	
Commercial Launches	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
Flight Type			Medium ELV	Heavy ELV		Heavy ELV		Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	
Flight Name Cargo Manifested			RP-I Resource Prospector I mission (tele-operated from Earth)	Lunar Lander-1 Stationary solar power system with cables; ATHLETE mobility unit to transport surface components		Lunar Lander-2 Pressurized logistics module (PLM) to be linked with habitat; contains supplies and tools for initial habitat setup; Bulldozing and sintering tools for ATHLETE; navigation aids		Lunar Lander-3 Pressurized logistics module (PLM) to be linked with habitat; contains supplies, spares, and scientific equipment; Resource Prospector (RP) II	Lunar Lander-4 Pressurized logistics module (PLM) to be linked with habitat; contains supplies, spares, and scientific equipment; solar power, cables; navigation aids	Lunar Lander-5 Pressurized logistics module (PLM) to be linked with habitat; contains supplies and spare or replacement ATHLETE	Lunar Lander-6 Pressurized crew cabin and CMC (4 astronauts); rover contains supplies, spares, and scientific equipment; connects to habitat with A-AMA/ tunnel	Lunar Lander-7 Pressurized logistics module (PLM) to be linked with habitat; contains supplies, spares, and scientific equipment; Li-ion batteries or RFCs for rovers	Lunar Lander-8 Pressurized logistics module (PLM) to be linked with habitat; contains supplies, spares, and scientific equipment; Li-ion batteries or RFCs for rovers	Lunar Lander-9 Pressurized logistics module (PLM) to be linked with habitat; contains supplies, spares, and scientific equipment; replacement solar power, cables; L-R navigation aids	
Flight Type					Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV
Flight Name Cargo Manifested					Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Mars DSH to LEO *LEO PG Systems* Protoflight DSH unit with 40kW pwr/prop bus to LEO	Possible commercial lunar landing missions	Uncrewed 1/2-scale Mars lander test	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions
Flight Type										Medium ELV	Medium ELV	Heavy ELV	Medium ELV	Medium ELV	Medium ELV
Flight Name Cargo Manifested										Logistics re-supply (mod Cygnus)	Logistics re-supply (mod Cygnus)	IP Chem Stage Test	Logistics re-supply (mod Cygnus)	Logistics re-supply (mod Cygnus)	Logistics re-supply (mod Cygnus)
Flight Type										Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV
Flight Name Cargo Manifested										LEO Trng Flt-1	LEO Trng Flt-2	LEO Trng Flt-3	LEO Trng Flt-4	LEO Trgn Flt-5	LEO Trgn Flt-6
Comments			Could be landed by a Lunar Lander as part of a multi-payload mission		Habitat delivered with large descent stage that serves as a protoflight DAV	Could possibly do Human Lunar Return (HLR) on EM-4		RP II can be operated from the moon or Earth		3-month mission; Cygnus modified with Orion docking adaptor	6-month mission; Cygnus modified with Orion docking adaptor	1/2-scale test at Mars could be performed by a single SLS Blk-2	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor

Assumed Missions								
	Third Mars landing mission	First Mars landing mission	Phobos mission	SLS-Orion mission				
	Fourth Mars landing mission	Second Mars landing mission	Mars lander test	SLS cargo mission				

Minimal Moon + Mars Concept

Human Lunar Return in 2027 with Mars system mission in 2037

SLS Launches	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Flight Type	SLS Blk-2	SLS Blk-2				SLS Blk-2				SLS-Blk-2				SLS Blk-2	
Flight Name Orion	EM-12 (Lander test crew at moon)	EM-13 (Phobos crew)				EM-14 (Mars-1 crew)				EM-15 (Mars-2 crew)				EM-16 (Mars-3 crew)	
Co-manifested NASA															
Co-manifested IP															
Flight Type			SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2
Flight Name NASA Cargo			Mars SEP #2 DSH-based logistics module and 100 kW SEP	Mars Lander #1 Mars DAV	Mars Cargo #1 Mars Surface Cargo Lander	EUS #2 EUS for Mars Surface Cargo Lander TMI	Mars SEP #4 DSH-based logistics module and 100 kW SEP	Mars Hab #1 Mars Surface Habitat	Mars Cargo #2 Mars Surface Cargo Lander	EUS #5 EUS for Mars Surface Cargo Lander TMI	Mars SEP #6 DSH-based logistics module and 100 kW SEP	Mars Hab #2 Mars Surface Habitat	Mars Cargo #3 Mars Surface Cargo Lander	EUS #8 EUS for Mars Surface Cargo Lander TMI	Mars SEP #8 DSH-based logistics module and 100 kW SEP
Flight Type	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2
Flight Name IP Cargo NASA Cargo	Mars lander test at moon Mars DAV	Phobos DSH MOI Stage Phobos DSH	Mars SEP #1 TEI and PWAV Boost Stages 100 kW SEP	EUS #1 EUS for Mars DAV TMI	Mars SEP #3 TEI and PWAV Boost Stages 100 kW SEP	Mars DSH #1 MOI Stage Mars DSH	Mars Lander #2 Mars DAV	EUS #3 EUS for Mars DAV TMI	Mars SEP #5 TEI and PWAV Boost Stages 100 kW SEP	Mars DSH #2 MOI Stage Mars DSH	Mars Lander #3 Mars DAV	EUS #6 EUS for Mars DAV TMI	Mars SEP #7 TEI and PWAV Boost Stages 100 kW SEP	Mars DSH #3 MOI Stage Mars DSH	Mars Lander #4 Mars DAV
Flight Type								SLS Blk-2				SLS Blk-2			
Flight Name NASA Cargo								EUS #4 EUS for Mars Surface Hab TMI				EUS #7 EUS for Mars Surface Hab TMI			
Planetary Missions															
Crew Operations	EM-12 crew conducts a full-scale test of the Mars DAV at the moon	EM-13 crew rendezvous and docks with the Phobos DSH; TMI is performed by the crew launch EUS; MOI is performed by the IP-provided chemical stage				EM-14 crew rendezvous and docks with the Mars DSH; TMI is performed by the crew-launch EUS; MOI is performed by the IP-provided chemical stage; Mars-1 is an opposition class (surface stay ~24 days) mission				EM-15 crew rendezvous and docks with the Mars DSH; TMI is performed by the crew-launch EUS; MOI is performed by the IP-provided chemical stage; Mars-2 is an conjuction class (surface stay >1 year) mission				EM-16 crew rendezvous and docks with the Mars DSH; TMI is performed by the crew-launch EUS; MOI is performed by the IP-provided chemical stage; Mars-3 is an conjuction class (surface stay >1 year) mission	
Crew Return Vehicle														EM-13 Orion	
Commercial Launches	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**	**2043**	**2044**	**2045**	**2046**	**2047**	**2048**	**2049**	**2050**
Flight Type															
Flight Name Cargo Manifested															
Flight Type	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV
Flight Name Cargo Manifested	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions
Flight Type	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV
Flight Name Cargo Manifested	Logistics re-supply (med C/S)	Logistics re-supply (med C/S)	Logistics re-supply (med C/S)	Logistics re-supply (med C/S)	Logistics re-supply (med C/S)	Logistics re-supply (med C/S)	Logistics re-supply (med C/S)	Logistics re-supply (med C/S)	Logistics re-supply (med C/S)	Logistics re-supply (med C/S)	Logistics re-supply (med C/S)	Logistics re-supply (med C/S)	Logistics re-supply (med C/S)	Logistics re-supply (med C/S)	Logistics re-supply (med C/S)
Flight Type	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV
Flight Name Cargo Manifested	LEO Trgn Flt-7	LEO Trgn Flt-8	LEO Trgn Flt-9	LEO Trgn Flt-10	LEO Trgn Flt-11	LEO Trgn Flt-12	LEO Trgn Flt-13	LEO Trgn Flt-14	LEO Trgn Flt-15	LEO Trgn Flt-16	LEO Trgn Flt-17	LEO Trng Flt-18	LEO Trng Flt-19	LEO Trng Flt-20	LEO Trng Flt-21
Comments	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor

Assumed Missions

Third Mars landing mission	First Mars landing mission	Phobos mission	SLS-Orion mission	Fourth Mars landing mission	Second Mars landing mission	Mars lander test	SLS cargo mission

Figure 3. The A-Team study lunar and Mars architecture dance card 2021-2035 (part a) and 2036-2050 (part b)

The Sand Chart View: Is It Affordable?

The sand chart view is certainly not new. It is intended to represent in graphic form the full programmatic cost of an architecture (or program) over time, and is built up by layering the time-phased cost of each constituent system (or project). To assess affordability in a simple way, one can then compare the full cost over time against the anticipated amount of resources to be received over the same period. The costs and resources can be measured either in constant dollars—dollars of constant purchasing power—or, if one so chooses, in budget (or then-year) dollars allowing for the anticipated amount of inflation.

Methodology Overview—An example of a sand chart for the original Minimal Mars architecture is found in [6], and for the updated and revised Minimal Mars in [2]. For the A-Team architecture, we used the same basic methodology to build the sand chart and assess affordability as in these publications, as well as in the National Research Council's 2014 report [11]. The software tool used to make the calculations, however, has undergone several improvements from the original software developed by the Aerospace Corporation. These improvements sought to align the way the user interacts with the tool and with the architectural artifacts in the Human Spaceflight Architecture Model (HSFAM).[2]

In the Aerospace methodology, system costs come in three "flavors"—non-recurring development costs,[3] recurring production costs when multiple copies of a system are flown, and recurring fixed costs per year when a system requires sustainment dollars whether or not it is flown at all. NASA ground operations costs are treated as sustainment costs that are associated with SLS. NASA mission operations costs are treated as sustainment costs that are associated with the architecture (or program) as a whole. Individual space systems may have sustainment costs as well, if they are flown regularly and thus require design knowledge retention and continuing logistics support. Once these quantitative values are entered, the software determines the aggregate year-by-year costs based on the architecture's systems, flight types and flight schedule.

The methodology and software used to assess the A-Team architecture provides the same level of fidelity (first-order estimates) as for the two publications cited above [2, 6]. Higher fidelity would certainly be more desirable, but would require more information than is generally available at the architecture definition stage. The methodology, however, can be used to filter out less promising architectures from an affordability point of view.

Cost Estimates for Lunar and Mars Systems— Credible cost estimates for advanced human spaceflight systems are always hard to obtain; some of the problems faced by cost analyst are discussed in [12]. For the systems used in the Mars portion of the architecture (i.e., Minimal Mars), costs estimates were obtained from the Aerospace Corporation. These estimates were generally based on analogies with systems already in their cost database. (These costs were compiled from publically available sources.) For systems used in the lunar portion of the architecture, some cost estimates came directly from earlier model-based estimates made during the Constellation Program. A small number of additional estimates were obtained by scaling ISS Estimate-At-Completion (EAC) costs as predicted in the early 2000s for actual ISS hardware.[4] For all new developments, a 50 percent margin was applied to the development costs and a 25 percent margin was applied to the production costs.

For on-going programs, like ISS, we used NASA budget documents to estimate the continuing sustainment costs through end-of-mission. For systems still in development, like SLS and Orion, we obtained actual development cost data and estimated production costs from NASA. For Solar Electric Propulsion (SEP) systems, we used internally generated cost estimates based on work performed under the previously proposed Asteroid Redirect Mission (ARM). For commercial launch vehicle services, we used current published prices.

The software that generates the sand chart requires costs in FY13 constant dollars, so whenever cost estimates were obtained in either budget (i.e., then-year) dollars or in constant dollars of another fiscal year, we applied the appropriate NASA-generated inflation factors to arrive at the needed cost inputs.

One of the more challenging systems for which we needed cost estimates was the conceptual human lunar descent and ascent vehicle. A bottoms-up (grass-roots) estimates based on a preliminary design would be compelling, but lacking such information, we had to rely on other approaches. On one hand, we had high-quality cost information for the Apollo Lunar Module from [13] covering the development and production period from 1963 through 1970. These data show a cost of just slightly over $20B in FY13 constant dollars, 40 percent of which was spent during the first four of the eight-year period. This sum included both development and production costs, so separating these two types of cost requires some assumptions regarding how many units were considered development articles and how

[2] The dance card view is intended to be a "human friendly" representation of the architecture, but in order for the software tool to execute the proper calculations, the cost analyst needs to create a precise, machine-readable database. The HSFAM fulfills that purpose.

[3] In the Aerospace methodology (and retained in our application of it), non-recurring development costs for some systems depend on what previous systems in the same product family have already been developed. In other words, development costs for a system may depend on the specific programmatic scenario being estimated.

[4] Scaling of costs were based on knowing the dry mass ratio between the new system and the existing one, and knowing the cost of the existing system. Cost are then scaled using the 0.6 rule—that is, cost of new = (cost of existing) * (mass of new/mass of existing)^0.6. The exponent, 0.6, is mid-range of the values seen in commonly used cost estimating relationships (CERs) for the exponent on dry mass.

many units were considered production articles. A second assumption is needed regarding how much of the $20B went for development versus production. The result is that there is a range of values that one could reasonably assign to development costs and to unit production costs from the Apollo data, and that could then be used to produce an analogy estimate for a contemporary human lunar lander.

On the other hand, we also had the Aerospace Corporation estimates for a conceptual Mars Descent/Ascent Vehicle (DAV), so we used those data to construct analogy estimates for development and production costs for a smaller four-person lunar version. A third cost estimate was generated using the NASA Advanced Mission Cost Model (AMCM) published in [14]. AMCM inputs include dry mass and other objective quantities, and a subjective input, "Difficulty". When this was set at its maximum allowable value, the model effectively reproduced the total Apollo Lunar Module cost ($19.937B estimated versus $20.040B actual). We then generated a new total cost estimate for a contemporary lunar descent and ascent vehicle based on new dry mass estimates and design heritage assumptions.

The resulting non-recurring development cost estimate we used for the conceptual human lunar descent and ascent vehicle was slightly lower than for the Apollo Lunar Module based partly on heritage assumptions from cargo lander developments, but mostly based on technology advances of the past 50 years in propulsion, avionics, and life support systems. The recurring unit production cost we used came in at the high end of the range for Apollo Lunar Module production costs. Our combined development and production estimates were consistent with AMCM's prediction. These comparisons are naturally all in constant dollars.

Spreading the Costs— Development and production costs for each system are typically incurred over several years. The software tool we used to spread costs uses a 40/60 formula—that is, 40 percent of the cost is incurred by the mid-point of the development (or production) schedule. The remaining 60 percent of the cost is incurred during the last half of the scheduled duration. Table 2 shows the percentage cost for each year using this approach.

For systems still in development, we had actual data. The software tool allows the user to override the year-by-year costs calculated by the spreader formula and insert the actual data, which is the procedure we followed. We also recognize that the 40/60 spreader is only an assumption based somewhat on an idealized schedule, so the software tool also allows user-provided cost spreader parameters to be entered instead. This is useful for systems that may have a cap on peak expenditures.

Table 2. Percentage Cost Per Year (Rounded) for 40/60 Spreader

Year	1	2	3	4	5	6	7	8	9	10
1	100									
2	40	60								
3	16	53	31							
4	8	32	41	19						
5	4	20	33	31	12					
6	3	13	24	28	23	9				
7	2	9	18	24	24	17	6			
8	1	6	13	19	22	20	14	5		
9	1	5	10	15	19	19	16	11	4	
10	1	4	8	12	16	17	16	14	9	3

Results—In order to assess affordability of any future human spaceflight architectures, it is essential to recognize that the budget for human exploration and operations supports important on-going programs. These include exploration systems development (SLS, Orion, and Ground Systems), Commercial Crew, and exploration R&D, as well as current ISS operations. Any additional programs must fit within the wedge of resources between these programs and budgets that are likely to be available. How big that wedge is in the 2020s depends, not surprisingly, on how long NASA continues to fund ISS operations.

The A-team study lunar architecture returns humans to lunar surface in 2027 and continues to build a minimal infrastructure there. International partners may augment that infrastructure, and commercial enterprises may see profitable investments that also send systems to the lunar surface. In the 2030s, NASA may then opt to focus again on sending humans to Mars, if the cislunar economy is prospering and the technology is within reach, or it may delay such an endeavor. In the figures that follow, we show the former scenario, recognizing that it is just one of many possibilities.

The sand chart for the lunar portion of the A-Team architecture is shown as Figure 4. The vertical axis uses then-year dollars, and the dashed line indicates the FY16 NASA human exploration and operations budget indexed to the NASA inflation rate so as to maintain FY16 purchasing power.

The figure raises several issues. The HLR in 2027 will require resources that are above the dashed line, i.e., above the purchasing power of current budgets. Most of this real increase can be attributed to the development costs of a human lunar lander. Nevertheless, the increase is modest at least until the peak in the early 2020s. One solution to the peak is to push the HLR (and the pre-cursor cargo missions) to the right by about four years and accept the risk that others might have already established a human presence. Another solution might be to enlist an international partner with whom to partition the development of the human lunar lander and share the costs, as NASA has done with the Orion Service Module. (While we have not costed that scenario, the software tool has the capability to include integration costs resulting from such an arrangement.) In

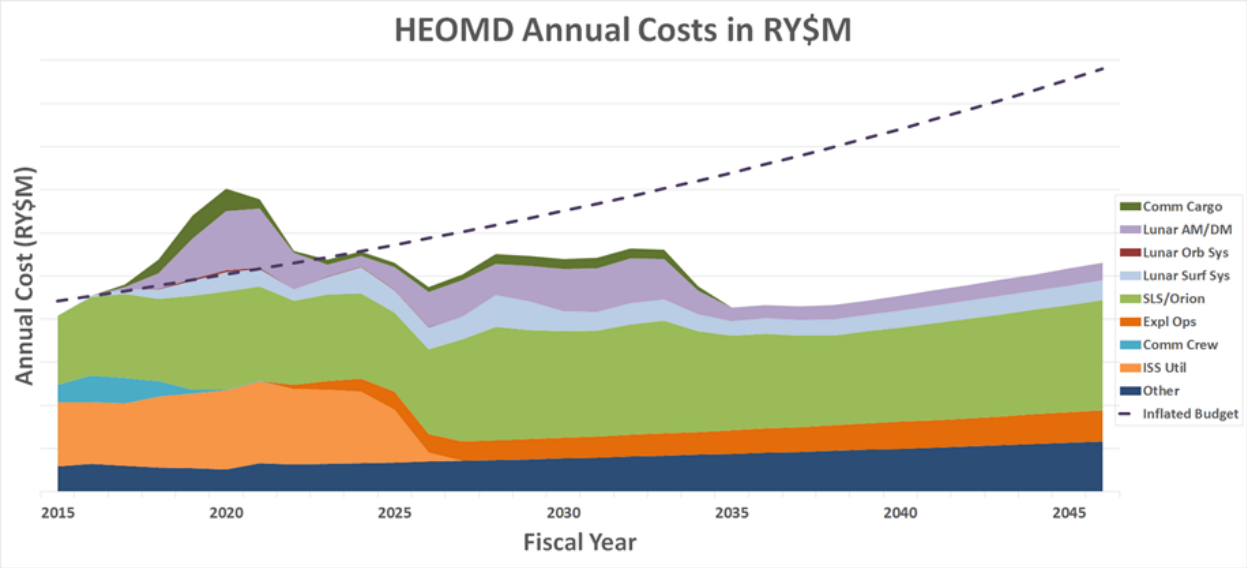

Figure 4. A-Team study lunar architecture sand chart with International Space Station operations to 2024

costing the architecture in Figure 4, the A-Team assumed that the heavy cargo lander was developed under a public-private partnership in which one-third of the estimated cost was private investment; this up-front private investment would breakeven in the 2030s with a 20 percent return on investment (ROI), even without any commercial demand.

The figure shows the wedge that is available after 2024 to NASA to either continue and expand lunar activities, or to begin the journey to Mars. That wedge is dependent on the ISS status after current agreements run out. As the NASA OIG has stated, "whether to extend the ISS beyond 2024 is a critical decision for NASA and its journey to Mars, particularly because of the funding shortfalls projected during the 2020s and the need for development of key systems during that time period" [2]. With this in mind, Figure 5 shows our projection of what would happen to the wedge if NASA funding for ISS were extended to 2028. The wedge of available resources after 2024 disappears and a second fiscal dilemma occurs at about the time of HLR as SLS flights ramp-up. (The A-Team lunar architecture is included in both Figs. 4 and 5.)

Figure 6 returns to the case represented in Figure 4, but with the addition of costs for the updated Minimal Mars architecture in the dance card (Figure 3). In this scenario, the A-Team made the assumption that the development, production, and sustainment of chemical stages, but not SEP tugs, are the responsibility of an international partner (with NASA incurring a fifteen percent integration cost during development). The development, production, and sustainment of the high-powered SEP tugs used are NASA's responsibility. The A-Team did not assume reusability of the tugs, but the costs would be a bit lower, if these were

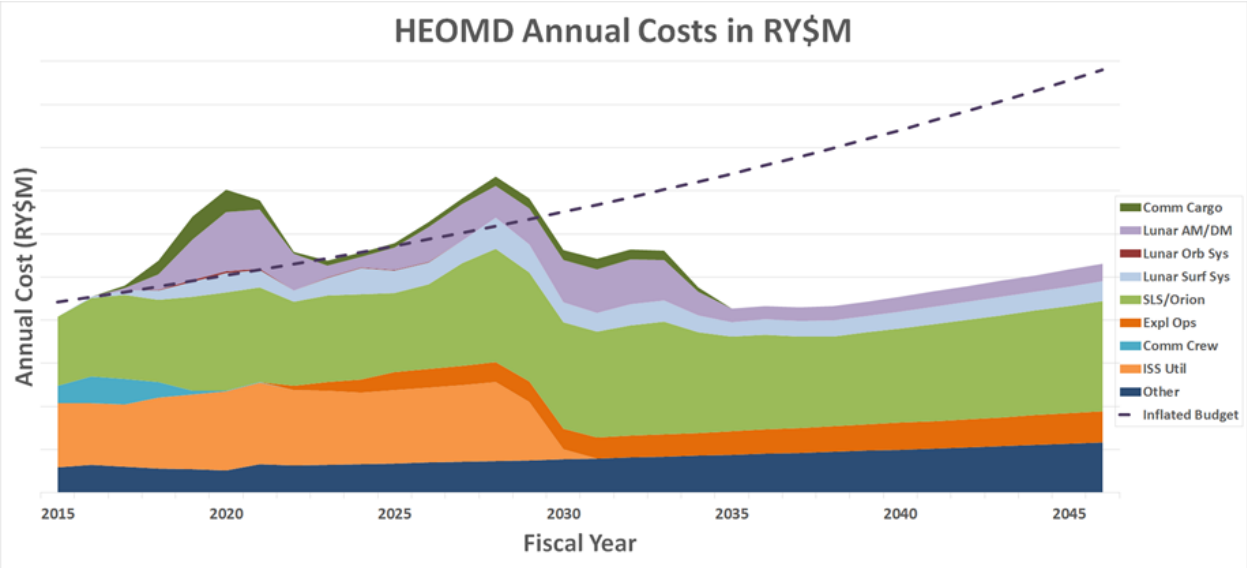

Figure 5. A-Team study lunar architecture sand chart with International Space Station operations to 2028

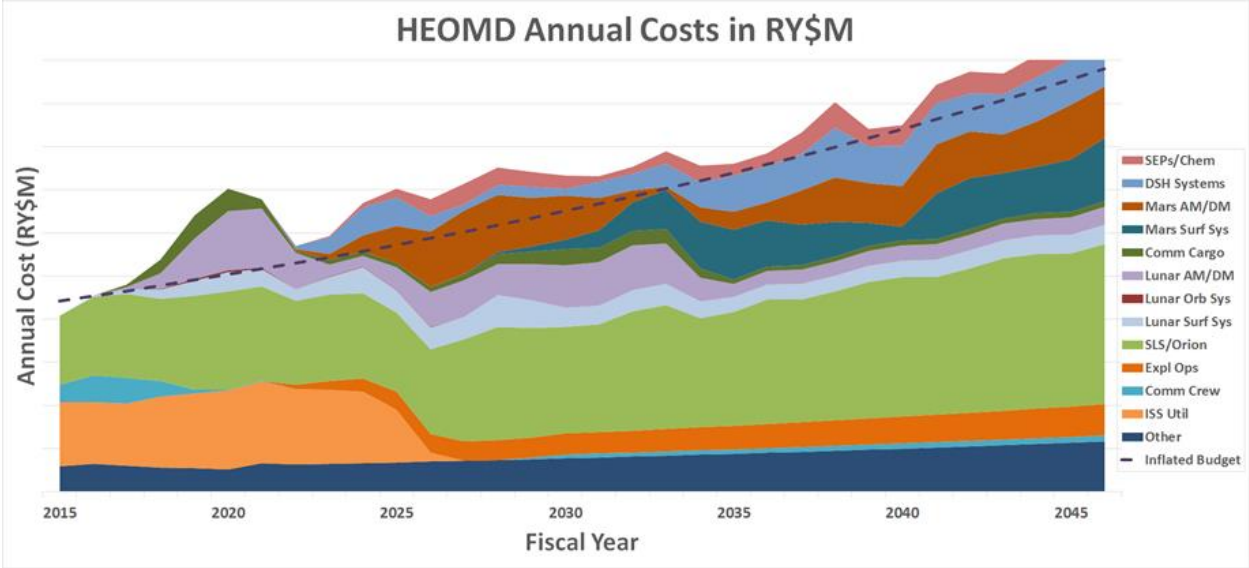

Figure 6. The full A-Team study architecture sand chart with first Mars system mission in 2037 and landing in 2041

returned to cislunar space and used again. The sand chart also indicates the extensive use of SLS in the Mars portion of the architecture.

In the Figure 6 architecture, the first crewed Mars system mission (to Phobos) takes place in 2037 and the first landed mission in 2041. By postponing the journey to Mars, NASA is able to mature multiple technologies (human-rated landers and surface systems) and to leverage operational experience gained at the moon. With some fine-tuning of the system development spending profiles, the peaks and valleys of the required resources can be mitigated. However, to implement this architecture the available budget resources need to have a higher trajectory, but not unrealistically so.

3. Commercial and International Partnering Opportunities

A True Cislunar Economy

As stated earlier, a true cislunar economy develops when commercial entities buy from each other. How this cislunar economy might grow is discussed here.

The 6 x 6 Leontief input-output matrix in Figure 7 illustrates how a cislunar private-sector-to-private-sector economy might work. In this very simplified representation, commercial enterprises are both consumers and suppliers of goods and services. Tourism enterprises buy habitat (hotel) services, surface delivery services (two-way for lunar tourists), and surface mobility services (using pressurized rovers to take tourists around very much as tour buses do.) Tourism also needs a tour guide, so it uses part of itself. Habitat enterprises buy power, surface delivery (of habitat units), and lunar-produced oxygen and water used in the habitat. ISRU/mining enterprises buy habitat services (for engineers needed to maintain the mining equipment), power (to run the equipment), surface delivery services (to emplace the equipment and spares), and possibly, surface mobility services (to take mining engineers to the mining sites). Surface mobility services enterprises buy power and surface delivery services.

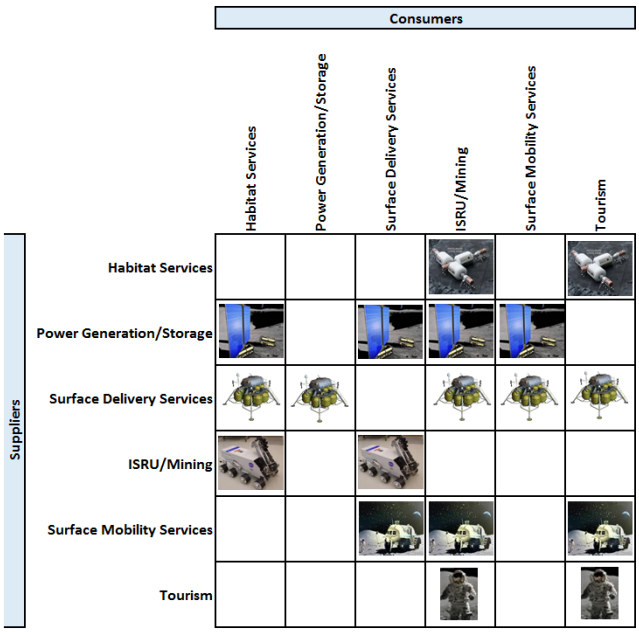

Figure 7. Notional Leontief Matrix for a Cislunar Economy

The notional input-output model of a cislunar economy (Figure 7) can be turned into an n-sector quantitative one as follows: let a_{ij} be defined as the amount of output of sector i needed to produce one unit of output in sector j. Let x_i be the total production of sector i and d_i be the total external

demand for the output of sector i, {i =1, 2, . . . , n}. The external ISRU/mining demand could be propellant from lunar resources (in kg per year delivered to cislunar space) and for tourism, the annual number of tourists seeking a two-week lunar holiday. We can then calculate how much each sector of the cislunar economy needs to produce to satisfy those demands using the Leontief input-output model in (1):

$$x_i = a_{i1}x_1 + a_{i2}x_2 + \ldots + a_{in}x_n + d_i \quad \forall i \qquad (1)$$

While the A-Team did not make these calculations even for a small number of sectors, the approach is time-tested, and would provide a method to assess how the cislunar economy would grow under various scenarios. Further, once the cost structure of each sector is clear, the market-clearing prices can be calculated.

Commercial Opportunities

Commercial partnerships within the A-Team study architecture occur early in implementation and are essential for later infrastructure deployments and for the Earth-moon supply chain. The A-Team study architecture calls for a heavy lunar cargo lander to be developed as a public-private partnership, with NASA assuming two-thirds of the cost and the private sector the remainder. The sand charts in Figures 4, 5, and 6 reflect this assumption. Over an approximately 10-year period, the services (including commercial launch) of lander production units are bought by NASA at a negotiated price that provides a market return-on-investment (ROI) on the private capital. These cargo lander units, with a payload capacity on the order of 5 mt, deliver NASA infrastructure and pressurized logistics to support astronauts on the surface. The government is the anchor user of the heavy lunar cargo lander services, but we expect other private enterprises would be customers as well. While not specifically in the architecture, smaller lunar cargo landers, already under development, could augment operations under similar arrangements.

Other public-private partnerships could be instituted for the development of surface power systems, unpressurized crew mobility systems, navigation aids, and surface robotics. Depending on the assessed financial risk, surface power systems could be privately developed (or possibly with government loans in lieu of direct subsidies) as power is likely to be demanded by nearly every commercial sector operating on the lunar surface.

ISRU/OEM is likely to be a magnet for private investment, if initial government robotic explorations (i.e., Resource Prospector I) yield favorable risk-reducing data. Private investment in systems for prospecting, mapping, regolith characterization and assessment may occur initially, followed by later investment for regolith extraction and processing, should Nature prove bountiful. If this is the case, one might expect to see markets develop for the delivery of lunar propellants, life support gases, and regenerative fuel cell reactants.

Lastly, lunar tourism could be a driver of the cislunar economy enabled by the A-Team architecture, with its emphasis on safe transportation to and from the lunar surface. Privately financed hotel services would create demands for other goods and services produced on the lunar surface. This is the vibrant cislunar economy modeled above. However, one needs to recognize the inherent financial risks in all of these commercial endeavors.

International Partnering Opportunities

In Figure 3, international partner flights and contributed systems were not explicitly identified unless they were co-manifested on NASA flights. This was done because we wanted to include only the programmatic costs that NASA would bear. As previously mentioned, when international partner systems were launched on SLS flights as an integral part of the architecture, NASA integration costs were estimated for those systems and included in the sand chart.

The A-Team study architecture offers a number of international partnering opportunities. Foremost, international partners could augment the A-Team minimal infrastructure with additional differentiated systems or they could buy additional units of planned NASA systems, e.g., solar power arrays. International partners could supply the communications infrastructure, which would directly reduce NASA costs. They could also provide other surface systems such as science rovers and perhaps large construction equipment. The latter could play an important role in berm, landing pad, and road building, as well as site preparation and construction of a large telescope.

In the A-Team architecture, Orion spacecraft are used to transfer astronauts from Earth to a low lunar parking orbit, where they rendezvous with the lunar human lander. This mission design is currently not feasible with the current Orion Service Module (SM) due to Δv limitations. Consequently, the most important international contribution, which would be needed prior to the EM-4/HLR full-scale test in 2026, is a “stretched” version of the Service Module with larger propellant tanks. For the Mars portion of the architecture, the A-Team assumed that the family of chemical stages needed for Mars Orbit Insertion (MOI), Trans-Earth Injection (TEI), Phobos Transfer, and Mars Ascent Vehicle (MAV) Boost would be provided by an international partner. While not necessary that the partner be ESA, the long-standing relationship with ESA for such vehicles (Ariane Transfer Vehicle (ATV) and Orion SM) cannot be ignored.

For international (and commercial) partnerships to be effective, the A-Team noted that various universal standards would need to be developed and introduced. Interface standards would enable inter-operability, allow for the transfer of resources between in-space vehicles and between surface systems, and improve safety. Logistics standards would enable better planning and mutual support among international partners.

4. SUMMARY AND CONCLUSIONS

In this paper, we presented a conceptual multi-decade human spaceflight architecture, developed by the JPL A-Team, that reflects a strategy of returning to the moon first, gaining knowledge and experience there while fostering a cislunar economy, and then sending humans to Mars, when that becomes public policy. The architecture was neither a government-only approach, nor a commercial-only approach, but rather a blend that emphasized commercial and international partnering opportunities. We recognized that the magnitude and timing of NASA funding are important considerations in evaluating an architecture, so we provided an affordability assessment for the NASA portion of the architecture. In that regard, one of the major decisions facing the ISS partnership concerns the amount of funding allocated to ISS operations. This decision has significant impact on the resources available to pursue human exploration beyond LEO.

The A-Team used the same methodology to assess affordability that was used in the National Research Council 2014 report [8], but with major upgrades in the sand chart-generating software tool to handle the complexities in the combined lunar and Mars A-Team architecture.

The lunar portion of the architecture is designed to accomplish four goals: (1) performing basic science and exploration (e.g., no commercial regolith processing, only regolith research); (2) returning humans safely to (and from) the lunar surface; (3) reducing risk and lowering the barriers to entry for commercial ventures by providing basic surface infrastructure systems; and (4) enlisting international partners in extending that lunar infrastructure. SLS and Orion systems are used extensively in both the lunar and Mars portions of the A-Team study architecture. Commercial launch vehicle services play a substantial role as well, particularly for the deployment of lunar surface systems and lunar logistics.

The A-Team architecture sought a "minimal" NASA-funded lunar infrastructure in order to lower costs, but included a human-rated lunar lander to signal serious intentions to the private sector and to capture public interest. The ability of (government and commercial) astronauts and tourists to access the lunar surface safely adds significant capability to commercial robotic operations there and unlocks the prospects for lunar tourism. To make the architecture feasible, however, the Orion Service Module would need to be "stretched" to meet the Δv requirements of a low lunar parking orbit.

The Mars portion of the A-Team architecture was based on an updated version of Minimal Mars first published in [6]. In the update, a proto-flight Deep Space Habitat launched in the 2030s to LEO serves to test life support technologies, and also serves as a long-term in-space training facility for Mars astronauts. After launch, commercial spacecraft then resupply the facility and ferry astronauts there for simulated Mars missions. The facility could be a wholly separate free-flyer or attached to a commercial LEO space station.

The A-Team architecture offers early lunar commercial opportunities, starting with a heavy lunar cargo lander public-private partnership with NASA as the anchor user of such services. The costing and partnership assumptions allowed a market ROI even without non-NASA customers. We expect, however, that other private sector customers for such services will emerge as the price falls. Initially, ISRU/OEM enterprises are likely to buy such services, though we also recognized the substantial financial risks of private lunar ISRU/OEM investments until further data confirm the location, quantity, and characteristics of lunar resources.

This effort was intended to create an affordable architecture around the idea of a lunar proving ground, while simultaneously encouraging private investment in the cislunar economy and providing a pathway to Mars. That architecture was represented in an architectural view called a "dance card." To assess affordability, we converted the dance card's programmatic data regarding systems, flight manifests, and flight schedules into an architecture database, which could then be read directly into our sand chart-generating software. The results indicated that modest real increases in the resources available for human exploration are needed to implement the A-Team architecture.

Whether the A-Team architecture is conducive to private investment is for the market to decide, but the typical next steps in the architecting process would be to refine the parameters of each system, modify the architecture as needed, improve the cost estimates, and retest the affordability results. The same iterative analyses should be performed on other proposed architectures. There are many visions (and visionaries) for human spaceflight beyond LEO, but every vision, whether implemented by public or private entities, carries a fiscal burden. In turning a vision into a reality, it would seem prudent to quantify the magnitude and timing of that burden early in the process.

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The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

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