

# Benchmarking of Crewed Lunar and Mars Mission Architectures

Skylar Eiskowitz,<sup>1</sup> Sydney Dolan,<sup>2</sup> Bruce Cameron,<sup>3</sup> Edward Crawley<sup>4</sup>

*Massachusetts Institute of Technology, 77 Massachusetts Avenue 33-409, Cambridge, MA 02139, United States of America*

Fuel selection is a strong driver of the mass fraction for many proposed lunar and Mars missions, but fuel technology trends have not been comprehensively evaluated for their impact on the system in literature. We evaluate the impact of fuel selection on overall lunar architectures. Our analysis shows that although hydrogen architectures have a higher wet mass cost, they provide more payload capacity to the lunar surface than non-hydrogen architectures given the same number of campaign launches. The Moon has been viewed as a stepping stone for future planetary exploration, so we evaluate both Mars and lunar architectures. We functionally decompose architectural decisions and compare key campaign decisions across 18 notable Mars architectural studies. The 18 landers are classified into four groups depending on which of the four the functional capabilities the lander performs, namely outbound transit, mars descent, mars ascent, and inbound transit. We find that there is no strong relationship between the Martian landers' wet mass and the length of crewed Martian surface. Furthermore, fuel type selection did not have a clear trend with the aforementioned capabilities. The lack of similarities across Mars architectures suggests the reference studies had a wide range of depths of analysis along with an array of different methods. Furthermore, they were completed at various points in history, some with high political pressure.

## I. Introduction

### A. General objective

The race to the moon has attracted the attention of government, academic, and commercial firms to pursue technical studies of proposed architectures and campaign details. These studies answer the questions of where to rendezvous, what should be launched, when, and what the masses of the vehicles are, which is a proxy for the cost of the mission. Similarly, the same types of organizations think further and develop studies for a crewed mission to Mars. These studies over time had different purposes, with different commercial or government funding sources that may drive the motives. Prior work studies how to size respective mission elements for a specific architecture, but these studies are not empirically driven, and insight from one mission cannot be applied broadly.

As crewed Mars missions are still years away, it is vital to determine which mission decisions will result in permanent architectural elements, and which decisions leave flexibility in the overall mission design. We collected notable mission architecture studies: 7 proposed lunar studies that result in 10 different architectures and 15 proposed Martian studies that result in 17 different architectures. These studies vary in their methods and as a result their level of depth, but they also vary in purpose and funding source. We focus on comparing the studies' functional decompositions, sizing of landers and the fuel choice of landers, all of which may take inspiration from Apollo missions, but which are never empirically driven in Mars missions. Comparing the outcomes of studies show the continuously evolving campaign ideas for both lunar and Mars missions and may drive future studies' choice of rendezvous points or choice of lander fuel.

---

<sup>1</sup> Graduate student, Department of Aeronautical and Astronautical Engineering

<sup>2</sup> Graduate student, Department of Aeronautical and Astronautical Engineering

<sup>3</sup> Director of System Architecture Group, Department of Aeronautical and Astronautical Engineering

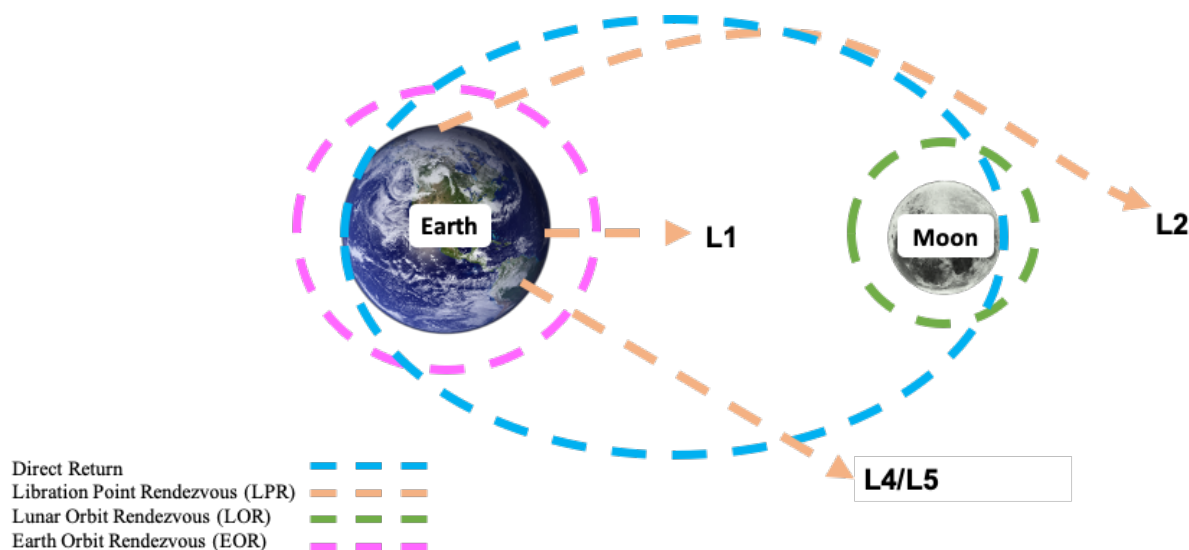
<sup>4</sup> Ford Professor of Engineering, Department of Aeronautical and Astronautical Engineering

## B. Background

### 1. Moon Architecture Tradespace Analysis

While NASA ultimately settled on a Lunar Orbit Rendezvous (LOR) architecture for the first missions to the Moon, several other possible architectures were investigated. As NASA wants to return to the Moon in 2024, to begin colonizing it, it is opportune to analyze the different architectures. Within an architecture, decisions about system concepts, the entities of function and form, and their relationships are defined as architectural decisions [1]. A key architectural decision for a lunar mission is where the rendezvous is performed. There are four main types of rendezvous points, shown in Fig. 1

- 1) Direct return, also known as lunar surface rendezvous (LSR): leaving from the surface of the Earth and arriving directly to the surface of the Moon.
- 2) Libration Point Rendezvous (LPR): rendezvousing with any of the libration points as a way to achieve a stable orbit away from the Earth or Moon.
- 3) Lunar Orbit Rendezvous (LOR): entering the moon's orbit before descending to the surface.
- 4) Earth Orbit Rendezvous (EOR): orbiting around the Earth before leaving for the moon.



**Fig. 1 A key architectural decision is the selection of rendezvous points in a lunar mission**

### 2. Mars Architecture Tradespace Analysis

Similarly, deconstructing existing studies of proposed Mars mission architectures allows us to isolate and characterize the fundamental features of such a mission. We evaluate literature generated by government, academia, and industry organizations including NASA's Evolvable Mars Campaign. A functional decomposition of these studies leads to the identification of six Mars mission phases shown in Fig. 2.

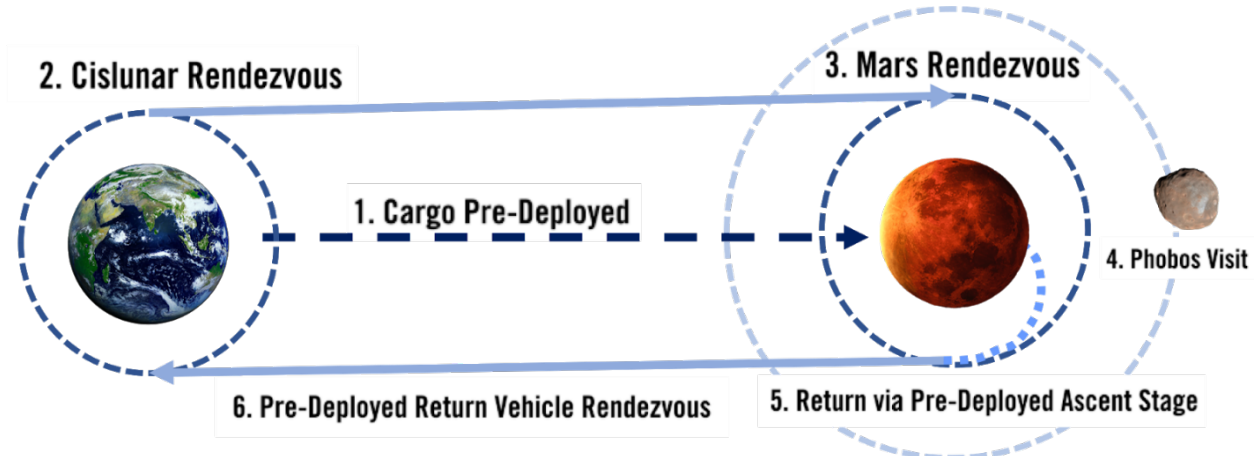


Fig. 2 A Mars mission is broken down into six key phases

### C. Overview

This paper is structured as follows: Section II traces the architectural evolution from Apollo (LOR) to the present day and analyzes proposed studies. As the Moon is often proposed as a testbed for Mars missions, in Section III, we analyze notable Mars mission studies, ranging from NASA Design Reference Architecture (DRA) 2.0 to a SpaceX architecture; Section IV presents the findings based on the lunar studies and Section V presents analysis on the Mars architectures; In Section V we conclusions and discuss possible future work.

## II. Lunar Human Landing System (HLS) Architectures from Apollo to the Present Day

A key concept on how to safely land humans on the moon is the lander rendezvous. One of the first studies to enumerate the possible rendezvous combinations was a study performed under the Bush administration. In 1989, George H. W. Bush commissioned a 90 Day Space Exploration Initiative to study how to send humans back to the Moon. The results of the study recommended an EOR-LOR approach. The generalized concept of operations begins with propellant tanks and the translunar vehicle Earth Descent System (EDS) being sent and assembled in LEO. Then, the astronauts are sent to the space station, and then ultimately rendezvous with a pre-deployed EDS. The astronauts transit to lunar orbit with the EDS and take the lander down to the surface. When surface operations have been completed, they ascend with the lander, and rendezvous with the EDS that was parked in orbit. After the rendezvous, the EDS takes the crew back to Earth.

After Dan Goldin was appointed NASA administrator in 1992, there was a shift towards making lunar architectures significantly cheaper, and with faster production times. The output of that emphasis was the 1996 Human Lunar Return Study [2]. The study presented several mission architectures for a return to the Moon. This study was very similar to the aforementioned 1989 study, but with an emphasis on simpler, more mature technologies.. For example, the 1996 baseline architecture focused on an open-to-space cockpit lunar lander design, smaller crew size, and utilized a space station as a staging node. The general concept of operations mandated that an EDS would be sent to Earth orbit, as well as a lunar habitat sent to the Moon's surface ahead of time. Then, the crew would launch to the space station and rendezvous with the EDS. The EDS would take the crew to lunar orbit, and the lander would break away from the EDS, taking the crew to the surface. After surface operations had been completed, the crew would ascend and rendezvous with the EDS vehicle, and then return to Earth.

With the arrival of a new administration in 2005, NASA once again reevaluated the best methodology to go to the Moon. While the study continued to evaluate the same classes of mission (EOR, LOR, LPR), the desirability of an architecture was focused around Mars-forward technology demonstrations, and resource utilization [3]. As a result, the recommended architecture was an EOR-LOR type, with a concept of operations like the 1989 study. The study also recommended a shift to a LOX/methane architecture for the lander [2].

The 2005-2009 Constellation program marked another shift in NASA's vision to return to the Moon. The Lunar Design Reference Mission 1 (LDRM) consisted of a seven-day surface stay in the equatorial region of the Moon [4]. LDRM-2 includes global lunar access with a capability to return to Earth at daytime. LDRM-2 falls under the LPR-

LOR archetype. Phase 1 of LDRM-2 uses the Lagrange point L1 as a staging point, and Phase 2 uses LOR. LDRM-3 provides a surface stay of 30-90 days to a polar sight and adds multiple surface elements. The study argued that exploration objectives involving global lunar access and extended mission duration are naturally complementary with a L1 rendezvous. This can be attributed to the fact that a long-term crewed sustainable mission to the Moon means that there is a need for a range of access times to both the surface of the Moon and Earth. Using Libration points takes advantage of the fixed orbital relationships of the Earth, Moon, and L1 to provide the capability of anytime Earth return from the lunar surface [2].

A study performed by researchers at MIT in 2005 systematically generate lunar architectures, displaying the defining characteristics of each as their number and types of vehicles, their destinations, and how they interact with one another [5]. They highlight one architecture that performed well that can be configured for a lunar mission or a Mars mission due to the generalized approach in creating architectural decisions. A study performed by ULA in 2009 emphasizes a shift from the single purpose launcher Saturn V to a smaller, commercial launcher coupled with an orbital depot. They encourage lunar exploration to be thought of not as a single, disconnected mission, but as a continuous process.

Next, NASA begins to partner with commercial companies through grants or contracts, and we focus on studies with NexGen Space and Lockheed Martin. One study was performed by NexGen Space [6] in 2015, funded by NASA's Emerging Space Office. The study emphasized how commercial space capabilities and public-private-partnerships could aid in lunar architecture development and utilized a lunar rendezvous, either LPR or LOR. It assumes a nuclear power plant at the lunar poles and that hydrogen will be available on the lunar surface to produce propellant. They attribute the highest technical risk of their study as the possibility of not finding enough accessible hydrogen for economic production of lunar propellant. Similarly, Lockheed Martin published a study where they describe their work with NASA on the Lunar Orbiting Platform – Gateway [7]. The study focuses on lunar exploration systems that will be solutions for not only the Moon, but also Mars missions.

Table 1 below compares the main features of lunar architectures from Apollo to the present day. The different trajectories, masses and fuel of lander, and cargo to the surface are compared to later make meaningful conclusions. A review of these studies indicates that all architectures use similar vehicles to Apollo:

- Command Module (CM): Cabin for crew that usually returns to Earth
- Service Module (SM): Supports command module with propulsion, power, consumables
- Lunar Module (LM): Descent and ascent stage

While most architectures list nondescriptive names for these vehicles, both the 2009 ULA report [8] and the 2018 Lockheed Martin report [7] name their Command Module and Service Module Orion, and the 2005 NexGen report names their Dragon V2 [6]. Similarly, the 2019 ULA report references Altair as their lunar module, the lunar lander of the Constellation program. The studies varied in the lander fuel choices, and this effect will be compared in Section IV.

**Table 1 Summary of lunar architecture features from Apollo to the present day**

	Apollo [9]	2005 MIT Arch #567 [10]	NASA ESAS LOR [3]	NASA ESAS EOR-LOR [3]	NASA ESAS EOR-Direct Return [3]	NASA ESAS EOR-LOR CEV-to-Surface [3]	2009 ULA [8]	NexGen Space 2015 [6]	2018 LM Crewed Lunar Lander [7]	Blue Origin [11]
Trajectory Name	LOR	Direct	LOR	EOR-LOR	Direct Return	EOR-LOR	LEO and L2 Depot	LOR	Gateway	-
# Launches from Earth	1	4	2	2	3	3	1	8	-	-
Cargo to Lunar Surface	440 kg	-	3580 kg	3580 kg	3580 kg	3580 kg	3500-20000 kg	7000 kg	1000 kg	3,600 kg
Landing Site	Equator	-	Lunar South Pole	Lunar South Pole	Lunar South Pole	Lunar South Pole	Global Access	Lunar poles	Global Access	Lunar South Pole
Surface Stay Time	21 hours	-	7 days	7 days	7 days	7 days	1496 days	7 days	14 days	6.5 days
# of Crew to Surface	2	4	4	4	4	4	4	4	4	≥2
Lander Wet Mass	15,103 kg	11,300 kg	27,908 kg	27,908 kg	37,000 kg	47,000 kg	58,300 kg	19,147 kg	62,000 kg	-
Fuel of Lander	Hydrazine /UDMH /N2O4	Chemical	LOX/CH4	LOX/CH4	LOX/CH4	LOX/CH4	LOX/H2	NTO/MMH	LOX/H2	LOX/H2

### III.Mars Reference Architectures

Mars architectures have been studied for decades, with NASA proposing the first detailed mission to Mars in 1993. This mission, called the NASA Design Reference Architecture (DRA) 1.0, focused on limiting the time the crew was exposed to space and utilizing local resources to reduce mission mass. The mission involved pre-deploying mission hardware ahead of time to the Martian surface and relied on nuclear thermal propulsion for in-space transportation, as well as nuclear surface power.

In 1997, NASA iterated on their first design with Design Reference Architecture 2.0 [12], incorporating the work of the previous group as well as Robert Zubrin's concept of ISRU, where propellants would be derived from the Martian atmosphere [13].

Design Reference Architecture 3.0 was a continuation of the 1997 study [14]. The study was intended to identify system drivers for Mars missions that could be significant sources of cost, performance, risk, and schedule variation. Alternate scenarios explored additional rendezvous points like exploration missions to the Moon, asteroids, or other targets beyond Earth's orbit as a way to solve mission and technology challenges.

The development of the Design Reference Architectures, along with NASA's organization-wide goal to return to Mars, inspired others to propose Mars mission architectures. Zubrin proposed a Mars Direct method, which would also pre-deploy cargo, but used the same vehicle for crewed transit to Mars, descent, and subsequent return [13]. In 2009, the NASA Design Reference Architecture was updated [15]. The architecture involved pre-deploying cargo to the surface and orbit of Mars. The crew is launched to a Mars orbit where they rendezvous with the orbital assets and then descend to the surface. After the surface mission has been completed, the crew once again rendezvous with orbital assets and returns to Earth.

Building off this Design Reference Architecture, the Austere Human Missions to Mars [16] avoided the costliness of DRA 5.0 by avoiding high risk or high cost technology development while emphasizing development and production commonality. Additionally, the crew size was designed for four astronauts, rather than six. The architecture would also avoid a pre-deployed return vehicle, and instead use the same vehicle for descent, ascent, and subsequent return.

Public interest in a mission to Mars has increased recently, with Elon Musk stating his goal is to fly cargo to Mars by 2024. Musk's company SpaceX has proposed a Mars architecture that uses one of their rockets, Starship in a similar architecture to Zubrin's Mars Direct, with the main difference being that Zubrin's uses a pre-deployed ascent stage and return vehicle, while SpaceX's does not. SpaceX's utilizes a cis-lunar rendezvous to refuel the launch vehicle before its journey directly to Mars [17].

Table 2 shows the phases of a Mars mission that each reference architecture uses, as well as the number of elements required to execute their campaign. A campaign may be comprised of many separate missions, which serve to accomplish the larger goal of the campaign: sustain humans on the surface of Mars. The number of elements includes cargo pre-deployed, initial launch vehicle, transit vehicle, lander, ascent vehicle, return vehicle, boost stages, and refueling depots. An architecture having many of the phases of a Mars mission is a proxy for operational complexity in the campaign.

Nearly all Mars mission architectures plan for a cargo pre-deploy and a separate ascent and return vehicle, yet the total number of elements required varies widely. The varying relationship between the mission phases and the number of elements may be due to inconsistencies among length of campaigns, where some campaigns include many missions. Some reports may have chosen to wring out these details of how many copies of vehicles will be necessary, while others do not include these details and it was assumed no copies were necessary for the campaign.

**Table 2 The mission phases of the reference architectures, number of elements and ISRU type is tabulated for all reference architectures. A dash represents no information found on that feature.**

	NASA DRA 5.0 Short [15]	NASA DRA 5.0 Long [15]	NASA DRA 3.0 [14]	NASA DRA 2.0 [12]	Mars Society 1999 [18]	CalTech Mars Society [19]	Mars Direct [13]	Lockheed Martin [20]	Aldrin Cyclor [21]	SpaceWorks [22]	NASA ESAS [3]	NASA Evolvable Mars Campaign [23]	JPL Minimal Mars Architecture Short [24]	JPL Minimal Mars Architecture Long [24]	JPL Austere Human Mission to Mars [16]	Moon as a Stepping Stone [25]	SpaceX [17]
Cargo Pre-Deployed		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Cis-Lunar Rendezvous					X			X				X	X	X		X	X
Mars Rendezvous	X	X						X		X	X				X		
Phobos Visit									X			X		X			
Return via Pre-Deployed Ascent Stage			X	X	X	X	X		X	X			X	X		X	
Pre-Deployed Return Vehicle Rendezvous	X	X	X	X	X		X	X	X	X		X					
Number of Deployed Elements	2	5	7	7	4	6	3	4	6	5	4	3	5	7	5	9	4
Months on Mars Surface	1.5	18.3	17.3	16.7	20.4	18.4	18	0.7	6	16.7	16.7	16.7	0.8	10	16.3	13.3	26.3
In-Situ Oxidizer Usage	No	Yes	Yes	Yes	No	Yes	Yes	No	-	No	Yes	Yes	No	No	No	Yes	Yes
In-Situ Fuel Usage	No	No	Yes	Yes	Yes	No	Yes	No	-	No	No	No	No	No	No	No	Yes
ISRU Life Support Oxygen	No	Yes	Yes	Yes	Yes	No	No	No	-	No	No	No	No	No	No	Yes	No

Next, we focus on the lander and decompose its functionality into four functions where we evaluate if the lander holds crew members during that phase. A lander functionality can thus be broken down into the following four functions:

- Out-bound Transit: from an Earth orbit to a Mars orbit
- Mars Descent: from a Mars orbit to the Martian surface
- Mars Ascent: from the Martian surface to a Mars orbit
- In-bound Transit: from a Mars orbit to an Earth orbit

**Table 3 Lander functional capabilities span four main phases of the mission and result in five unique groupings depending on when the lander is responsible for the crew throughout the mission.**

Organization	Lander Functional Capability			
	Out-bound Transit	Mars Descent	Mars Ascent	In-bound Transit
JPL Minimal Mars Architecture Short				
JPL Minimal Mars Architecture Long				
Austere Human Mission to Mars				
Battat Architecture 2647				
Moon as a Stepping Stone				
SpaceWorks				
CalTech Mars Society				
Aldrin Cyclor				
NASA's Exploration Systems Architecture Study				
NASA DRA 5.0 Short				
NASA DRA 5.0 Long				
Lockheed Martin				
Mars Society 1999				
NASA DRA 2.0				
NASA DRA 3.0				
Mars Direct				
NASA EMC				
SpaceX				

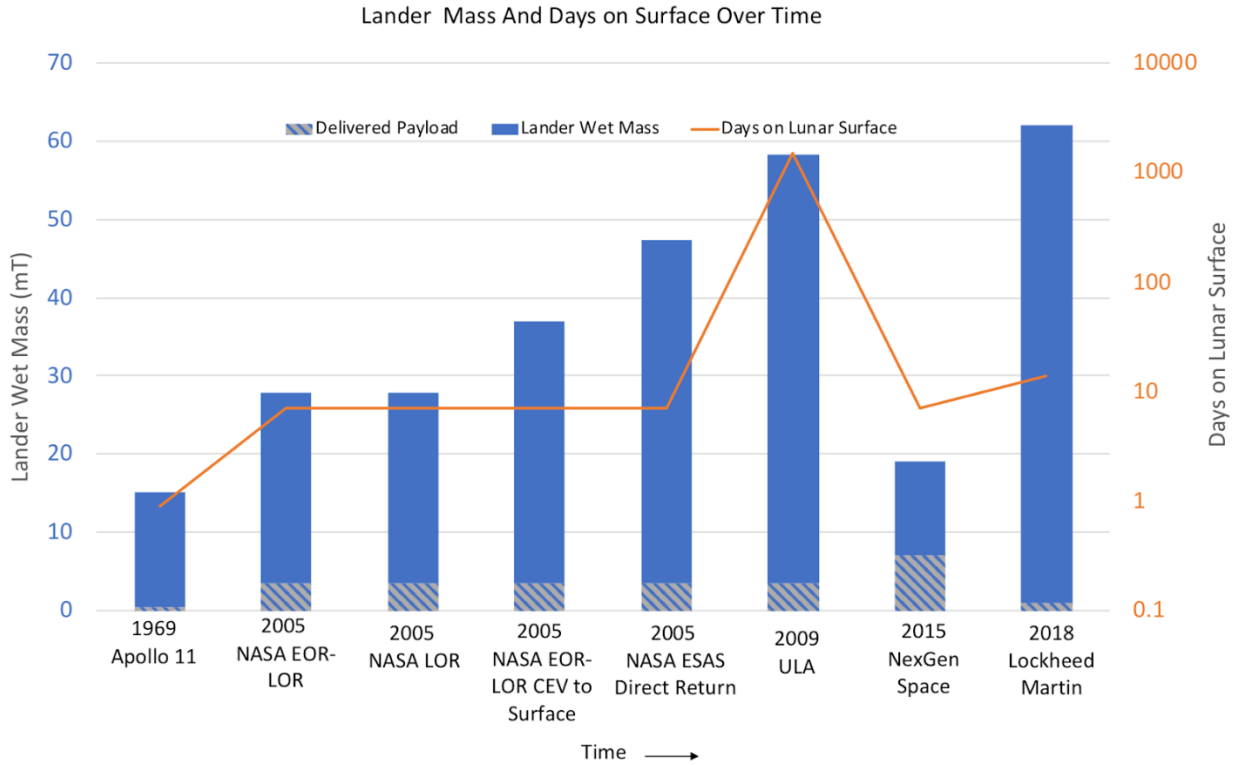
#### IV. Lunar Architecture Trends

When contextualizing NASA's lunar HLS architecture, there has been a clear shift towards commercial space involvement in the past decade. Furthermore, the general trend is that larger scale landers will be necessary to be able to support a sustained presence on the Moon (with the exception of NexGen Space), shown in Fig. 3. NexGen Space is an outlier because the study mostly focused on how to bring commercial partnerships into lunar architectures, rather than evaluating specific architectures, and the study makes aggressive assumptions on power and propellant already on the lunar surface.

The introduction of fuel depots in space, as presented in ULA and Lockheed's architectures, allows for the existence of more massive landers, since the resupply of fuel allows for more dry mass to be sent to space. Therefore, recent lander designs may be heavier, but they are also more capable because they rely on existing infrastructure in their campaign.

Another interesting concept to note that has emerged in the past decade is the shift away from EOR. While preliminary studies like the 1996 and 2006 studies suggested the EOR would be a viable option as a way to reduce cost through established assets in orbit, the current NASA and commercial plans have pivoted away from EOR.

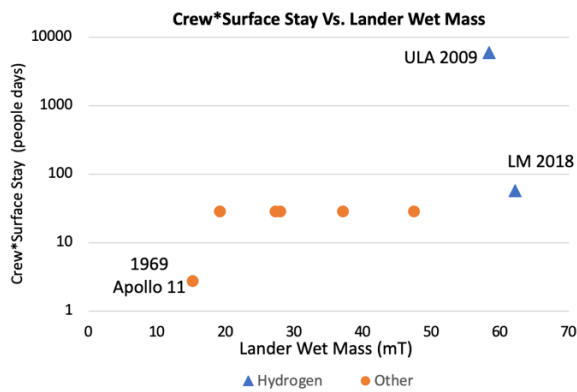




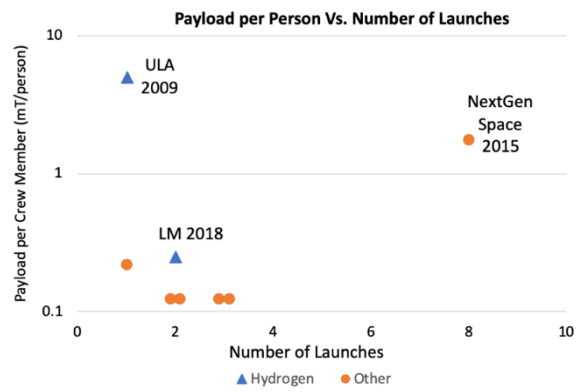
**Fig. 3. Over time, the mass of the lander generally increases, which is correlated to the number of days on the surface**

Both the Lockheed Martin and ULA's landers rely on liquid hydrogen as their propellant. Liquid hydrogen allows for a single stage lunar lander from Gateway, which is a proposed outpost orbiting the moon, eliminating the significant additional cost and complexity of a multiple stage system. [7] argues that a LOX/methane lander would likely require very lightweight systems, increasing technology development costs and risk and decreasing reliability and factors of safety. Secondly, they deem water the most essential part of human exploration. Sustainability in space depends on this key commodity, and thus the self-sustaining nature of easily extracting, refining, transporting, and storing liquid hydrogen fuel from water is critical.

In order to compare across different mission designs, we define utility as the product of number of crew members and number of days on the lunar surface. Fig. 4 shows an increased utility with the choice of hydrogen fuel. Although the lander wet mass is highest in both the ULA and Lockheed Martin architectures, they offer more crew time on the lunar surface, and Fig. 4 shows that these hydrogen architectures also provide more payload capacity to the lunar surface than architectures using the same number of launches for the campaign.



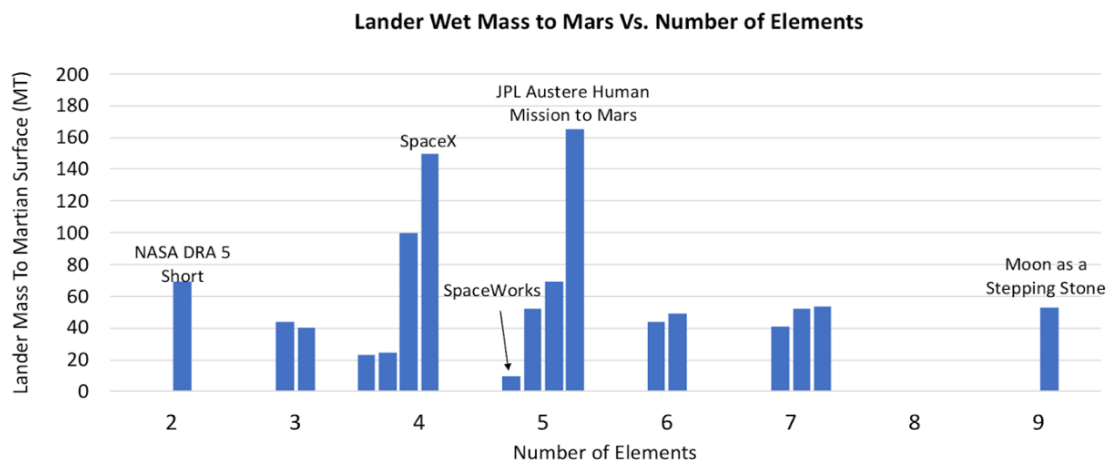
**Fig. 4** The Y axis shows a measure of productivity (the product of the number of crew members and the amount of days on the surface). Plotted against the lander wet mass, it is clear the Hydrogen architectures provide more productivity at a higher wet mass.



**Fig. 5** ULA and LM Hydrogen architectures achieve more payload to the surface given the same number of launches as other studies. NextGen Space may be an outlier due to the study's focus on commercial involvement.

## V. Mars Architectures: Comparing Estimates of Wet Mass

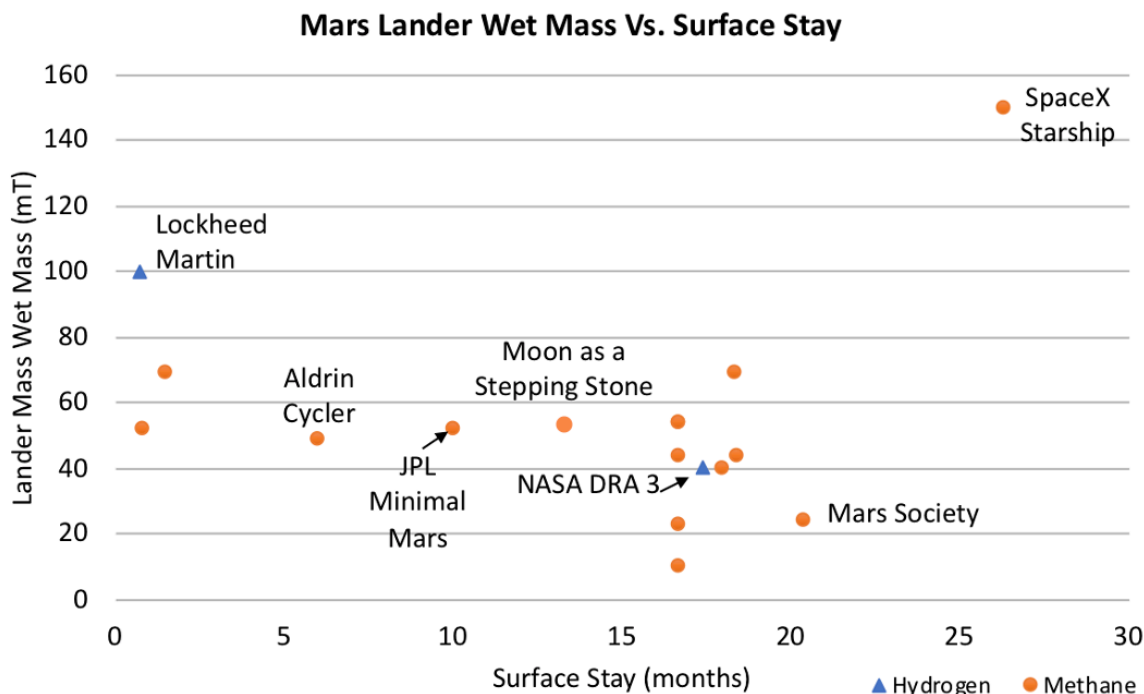
As the number of campaign elements varies among the different architectures, one may expect that campaigns with more elements would allow for a decreased lander wet mass. However, Fig. 6 shows no clear relationship, surprisingly indicating that notable improvements of lander mass to the Martian surface is independent of the number of elements proposed in a Mars architecture. Even though some architectures propose more elements, they don't see a decreased lander wet mass.



**Fig. 6** There was no clear relationship between number of deployed elements and resultant crewed lander mass. The labeled architectures had varying levels of complexity regarding staging and rendezvous points, but the accretion of those assets did not translate.

It was also noted that a strong trend did not exist between the Martian lander wet mass and the length of time spent on the surface, most likely due to the different studies working from a wide variety of assumptions e.g., margins of

safety and risk tolerances, and also from a wide range of times at which point different technologies were available. Fig. 7 shows this comparison and also identifies the landers that are methane and hydrogen fueled. Between these two fuel types, we see that the lander size shows no general trend with surface stay and the lander mass is predicted to be around 50 mT.



**Fig. 7** The graph demonstrates that extended surface stay does not necessarily correlate to higher lander mass to the surface. Despite varying levels of surface stay, many of the architectures project a lander mass of around 50 M.

## VI. Conclusions and Future Work

As the world is making strides towards the next crewed lunar mission and planning for the first crewed Mars mission, government, academic, and commercial firms are studying different architectures and evaluating essential mission elements. Key decisions include rendezvous points in a lunar mission and amount of mission elements in a Mars mission. While trends in architectures may be shaped by politics, there has been a growing moment towards commercial involvement and higher productivity on the Moon. As we have less information and existing knowledge to pull upon about Mars, Mars mission designs are still in their nascent stages. It is difficult to draw strong conclusions about trends, as reports display varying levels of detail. Our conclusions here are based upon assumptions that could be wrong out in future studies.

To extend the work here, tracing assumptions and modeling the studies may explain the wide discrepancies in masses of vehicles. Additionally, studies can explore the impact of technical decisions in greater detail by modeling the campaigns and switching on different architectural decisions to identify the consequences of different architectural decisions. Lastly, a full tradespace exploration and architectural enumeration may shed light into the key decisions.

## VII. Acknowledgments

The authors would like to thank Blue Origin for their financial support and feedback during the development of this work.

## VIII. References

- [1] Crawley, E., Cameron, B., and Selva, D. *System Architecture: Strategy and Product Development for Complex Systems*. Prentice Hall Press, 2015.
- [2] Lindroos, M. Lunar Base Studies 1996: Human Lunar Return. <https://space.nss.org/lunar-base-studies-1993-lunox/>.
- [3] NASA. "Exploration Systems Architecture Study." 2005, p. 758.
- [4] NASA. "Constellation Design Reference Missions." 2008, pp. 1–69.
- [5] Simmons, W., Koo, B., and Crawley, E. Architecture Generation for Moon-Mars Exploration Using an Executable Meta-Language. In *Space 2005*.
- [6] Miller, C., Wilhite, A., Zapata, E., Davidson, H., Hall, A., Ball, J., Dibello, F., Greason, J., Muncy, J., and Woodcock, G. "Economic Assessment and Systems Analysis of an Evolvable Lunar Architecture That Leverages Commercial Space Capabilities and Public-Private-Partnerships." 2015.
- [7] Cichan, T., Bailey, S. A., Burch, A., and Kirby, N. W. "Concept for a Crewed Lunar Lander Operating from the Lunar Orbiting Platform-Gateway." *Proceedings of the International Astronautical Congress, IAC*, Vols. 2018-October, No. October, 2018, pp. 1–5.
- [8] Zegler, F., Kutter, B. F., and Barr, J. "A Commercially Based Lunar Architecture." *AIAA Space 2009 Conference and Exposition*, 2009, pp. 1–26.
- [9] NASA. NSSDCA - Spacecraft - Details. <https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1969-059C>.
- [10] Simmons, W. L., Koo, B. H. Y., and Crawley, E. F. "Architecture Generation for Moon-Mars Exploration Using an Executable Meta-Language." *Collection of Technical Papers - AIAA Space 2005 Conference and Exposition*, Vol. 2, No. September, 2005, pp. 927–943. <https://doi.org/10.2514/6.2005-6726>.
- [11] Weitering, H. Blue Moon: Here's How Blue Origin's New Lunar Lander Works. <https://www.space.com/blue-origin-blue-moon-lander-explained.html>.
- [12] Hoffman, S., and Kaplan, D. I. *Reference Mission of the NASA Mars Exploration Study Team*. 1997.
- [13] Zubrin, R. M., Baker, D. A., Gwynne, O., Astronautics, M. M., and Box, P. O. "Mars Direct: A Simple, Robust, and Cost Effective Architecture for the Space Exploration Initiative." 1991.
- [14] NASA. "NASA DRA 3.0." No. June 1998, 2020.
- [15] Mars Architecture Steering Group. *NASA DRA 5.0*. 2009.
- [16] Price, H., Hawkins, A. M., and Radcliffe, T. O. "Austere Human Missions to Mars." *AIAA Space 2009 Conference and Exposition*, 2009, pp. 1–20. <https://doi.org/10.2514/6.2009-6685>.
- [17] Making Life Multiplanetary. <https://www.youtube.com/watch?v=tdUX3ypDVwI>.
- [18] The Mars Society. "A Human Mission to Mars The Time Has Come to Embark on a Simple, Robust and Cost Effective Approach for the Human Exploration of Mars." *Agenda*, No. January, 2001.
- [19] Hirata, C., Brown, N., & Shannon, D. "The Mars Society of CalTech Human Exploration of Mars Endeavor." 2006, pp. 2006–2006.
- [20] Napier, G. "Mars Base Camp." *68th International Astronautical Congress*, No. September, 2017, p. IAC-17 A5.
- [21] Aldrin, B., and David, L. *Mission to Mars: My Vision for Space Exploration*. National Geographic Books, Washington, DC, 2013.
- [22] Germain, B., Olds, J., Bradford, J., Charania, A., DePasquale, D., Schaffer, M., & Wallace, J. "Utilizing Lunar Architecture Transportation Elements for Mars Exploration." 2004, pp. 1–19.
- [23] Crusan, J. *Evolvable Mars Campaign Development*. 2015.
- [24] Price, H., Baker, J., and Naderi, F. "A Minimal Architecture for Human Journeys to Mars." *New Space*, Vol. 3, No. 2, 2015, pp. 73–81. <https://doi.org/10.1089/space.2015.0018>.

- [25] Connolly, J. F., Drake, B., Kent Joosten, B., Williams, N., Polsgrove, T., Merrill, R., Rucker, M., Stecklein, J., Cirillo, W., Hoffman, S., and Percy, T. “The Moon as a Stepping Stone to Human Mars Missions.” *Proceedings of the International Astronautical Congress, IAC*, Vols. 2018-Octob, 2018, pp. 1–18.