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Quantifying the Impact of Cryo-Management, ISRU, and Fuel Cell Lunar Technology Infusion to a Notional Mars LOX/LH_2 Architecture

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Abstract

Liquid Oxygen liquid Hydrogen (LOX/LH_2) Mars architectures have historically been ruled out in favor of Liquid Oxygen liquid Methane (LOX/LCH_4) architectures due to a high perceived cost and risk in LH_2 cryo-management, which leaves a gap in literature and technology development in support of LH_2 architectures. Carbon is not thought to be abundant on the Moon, while recent discoveries suggest that water is widely accessible on Mars, presenting an opportunity. The challenges in meeting this opportunity are long-term LH_2 cryo-management and fuel in-situ resource utilization (ISRU). To investigate this opportunity, a LOX/LH_2 Mars architecture is modeled with combinations of the following technologies: passive and active cryo-technologies, fuel cells to produce water and power from the otherwise wasted boiloff, and fuel and oxidizer ISRU.

As these technologies are switched on and off in combinations, we compare the resulting mass that has to be sent to Earth's orbit (upmass), which is a proxy for campaign cost. With improved multi-layer insulation (MLI) and cryocoolers, we forecast upmass savings of 6%-10% compared to the LOX/LCH_4 baseline. The addition of fuel cells only gave a marginal benefit of 0.7% upmass savings, but they add operational flexibility for power and life support. Additionally, we show how much more payload could be landed on Mars given the same upmass as the baseline, and we project an improvement from 22 mT in the LOX/ LCH_4 baseline to 31 mT in a LOX/LH_2 architecture with cryocoolers and MLI. We also analyze ISRU in the context of multiple crewed campaign cycles and project that the added mass due to Mars water ISRU infrastructure pays off after the second crewed mission. These results suggest a Mars LOX/LH_2 architecture with improved MLI and cryocoolers will be competitive with the traditional LOX/LCH_4 architecture, especially under longer campaign plans.
Keywords: Mars, architecture, Hydrogen, lander, modelling, ISRU

Acronyms/Abbreviations
BoC – Basis of Comparison
DM – Descent Module
EDL – Entry, Descent, and Landing
HEO – High Earth Orbit
HLS - Human Landing System
HTV – Hybrid Transit Vehicle
ISRU – In-Situ Resource Utilization
LCH_4 - Liquid Methane
LH_2 - Liquid Hydrogen
LOX - Liquid Oxygen
MAV – Mars Ascent Vehicle
MLI - Multi-layer insulation
NRHO - Near Rectilinear Halo Orbit

1. Introduction
1.1 Motivation

Water ice is expected to be available in the permanently shadowed regions of the lunar poles, while carbon and organic volatiles are expected to be relatively scarce on the Moon[1]. Given this, lunar architectures are being designed around LOX/LH_2 [2][3][4], rather than LOX/ LCH_4, with a view to leverage lunar water ice ISRU to support large-scale operations in cislunar space and the surface of the Moon. With this strategic intent, as well as the associated architectural and technological investments, it is desirable to explore to what extent LOX/LH_2 technologies could enhance NASA's architectures for human missions to Mars. Historically, trade studies of Mars architectures have tended to eliminate LOX/LH_2 architectures fairly early on despite its higher specific impulse over LOX/LCH_4 [5]. The key challenge faced by Mars LOX/ LH_2architectures, which has in the past driven propellant selection to LOX/LCH_4, is boiloff control.

However, the recent discoveries of water on Mars, along with recent advances in technologies for cryogenic boiloff control are motivating a closer look at the questions of what a LOX/LH_2 Mars architecture could look like, and whether it might be competitive with or offer advantages over the more commonly studied hydrocarbon-based architectures.

1.2 Back*ground*

1.3 1.2.1 Mars 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 [5], 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 [6].

Design Reference Architecture 3.0 was a continuation of the 1997 study [7]. 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 [6]. In 2009, the NASA Design Reference Architecture was updated [8]. 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 [9] 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 architecture also utilizes a cis-lunar rendezvous to refuel the launch vehicle before its journey directly to Mars [10][11].

1.2.2 Technologies with potential moon to mars applicability

Although missions to the Moon and Mars are substantially different in terms of complexity and transit time, various technologies may be developed and matured on the Moon, which can serve as a 'test-bed' to future Mars missions. Several technologies are being or will be developed that are of interest to both Moon and Mars architectures:

- **Propulsion Systems and Entry, Descent, and Landing (EDL)**: Several LOX/LH_2 engines have deep throttle-ability and restart capabilities, to be demonstrated in terminal, precise lunar descent, which may be extended to Mars for similar purposes as well as for other EDL phases including supersonic retropropulsion.
- **Thermal control and power:** Reductions in effective emissivity of MLI to about 0.005 are likely feasible for the transit stage to Mars [12]. Active control via light-weight, 20K, modular Brayton Cycle cryocoolers with Carnot efficiencies of around 10%-20% will likely further improve propellant storage capabilities with the goal of a Zero Boil-Off (ZBO) condition [13].
- **Fuel cells:** Directing boiloff that would be otherwise wasted, into a fuel cell for power and water production may demonstrate a payoff in reducing upmass related to water and power supply.
- **ISRU and Resource Logistics:** Developments in water ISRU mining and electrolysis will improve the logistics picture for sustainable Mars campaigns. High-specific productivity systems (>3kg/hr for a 1.5t oxygen ISRU system) may reduce the criticality of boil-off control, or conversely, provide increased system-level redundancies. Potentially higher accessibility of water-ice on Mars than in the permanently shadowed regions on the Moon may yield a Martian water ISRU system that is in fact simpler than one demonstrated on the Moon.

1.3 Objective

This analysis takes a closer look at technology options to improve the performance of a specific Mars LOX/LH_2 architecture, framed in the context of NASA's latest Mars campaign thinking. We take into account recent lunar Human Landing System (HLS) cryogenic fluid management technology developments and model them in the form of technology switches in order to examine the question: might a LOX/LH_2 Mars architecture be competitive with traditional CH_4 architectures in terms of total upmass at the campaign level?

1.4 Overview

This paper is structured as follows: Section 2 provides an overview of the chosen architecture and campaign that we model. Section 3 details the different sub-models and their assumptions, and Section 4 presents and discusses the results of the model. Section 5 concludes the discussion and presents future research directions.

2. Methods

2.1 Selecting a Basis of Comparison Mars Architecture

Before performing an analysis of the extensibility of a lander and technologies in a lunar architecture to a Mars architecture, it is important to select a Mars Basis of Comparison (BoC) architecture. An ideal BoC architecture would be recent, credible and widely viewed as a likely architecture that NASA might implement, if NASA were to be given Congressional approval to proceed with a Mars mission. Following the above review of Mars architectures, and their features and trends, it was determined that the most appropriate Mars architecture is as defined in 'The Moon as a Stepping Stone to Human Mars Missions' by Connolly et al. [14]. This study takes inspiration from historic Mars campaigns and aligns tightly with NASA's Evolvable Mars Campaign. Impacts of some of the key technology developments discussed above are quantified by infusing them into a model of this architecture, first modeling the complete BoC campaign cycle with LOX/LCH_4/SEP propulsion to validate that the mass estimates generated by the model were similar to elements in [15], another credible lander study.

2.2 Detailed Campaign Description

The Mars BoC architecture assumes a series of 7-year campaign cycles. Each cycle includes 3 cargo missions and 1 crew mission for a total of 4 missions. The architecture uses the Gateway station located in NRHO as the assembly and departure point and High Earth Orbit (HEO) as the crew pick-up and drop-off point. The following elements are used throughout one cycle:

- **4 Hybrid Transit Vehicles (HTVs):** fully reusable 'space tugs' that travel from Near Rectilinear Halo Orbit (NRHO) to Mars orbit and return back to NRHO. Each HTV uses two types of propulsion: chemical LOX/LCH_4 propulsion for near-planet maneuvers, and solar electric propulsion (SEP) for heliocentric segments. The dry mass of each HTV without chemical-propulsion tanks (which are modeled separately) is assumed to be 21,100 kg. The specific impulses are 360 s and 2,600 s for the chemical propulsion and SEP, respectively.
- **3 Descent Modules (DMs):** disposable landers that take crew and cargo from Mars orbit to the Martian surface, and then stay on the surface of Mars. Each descent module uses LOX/LCH_4 propulsion with a specific impulse of 360 s and has the dry mass excluding the tanks of 17,350 kg. Within the BoC architecture, each DM delivers 22,000 kg of payload to the Martian surface.
- **1 Transit Habitat:** fully reusable habitat for the crew integrated with one of the HTVs. This is the habitat where the crew lives on their way to Mars and back. The mass of the habitat is 40,500 kg.
- **1 Mars Ascent Vehicle (MAV):** disposable vehicle to take the crew from the surface of Mars to a Mars orbit. The vehicle uses LOX/LCH_4 propulsion with a specific impulse of 360 s and has the dry mass (excluding tanks) of 6,600 kg. It arrives to the Martian surface with its fuel tank full and oxidizer tank empty; the oxidizer is produced on the Martian surface by ISRU of atmospheric CO_2.
- **Payload:** includes ISRU, the surface power system, the Martian rover, logistics (including water), and the surface habitat. The payloads are attached to their respective DMs and they are delivered to the Mars vicinity by HTVs.

The concept of operations for a campaign cycle is shown in Fig. 1 and described below.

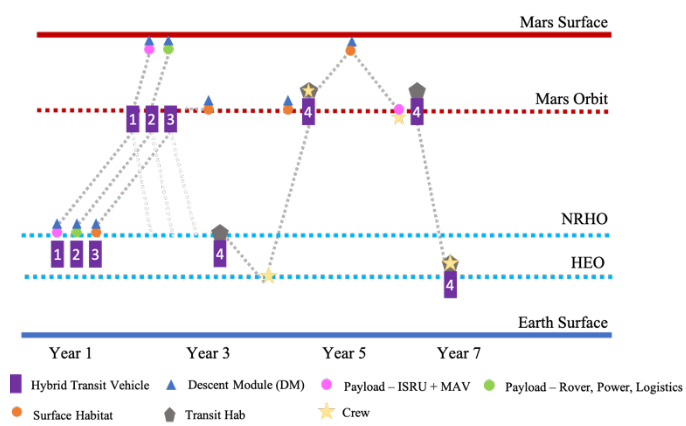

Fig. 1. The concept of operations for the Basis of Comparison Architecture, lasting 7 years

Three cargo missions start in parallel at the Gateway in year 1:

- HTV1 delivers DM1 with MAV and ISRU from NRHO to a Mars 5-sol orbit.
- HTV2 delivers DM2 with the surface power system, rover, and logistics from NRHO to a Mars 5-sol orbit.

- HTV3 delivers DM3 with the surface habitat to a Mars 5-sol orbit
- All HTVs undock with their DMs, wait for a launch window to Earth, and travel back to the Earth's NRHO.
- DM1 lands the MAV and ISRU on the Martian surface. DM2 lands its payload on the Martian surface. After the surface power system delivered by DM2 is connected to the ISRU, it starts producing oxidizer for the MAV. The MAV is fully fueled before the fourth mission, which includes crew, starts.
- The DM3 and surface habitat stack waits for the crew arrival in the Mars orbit.

The fourth mission, which brings the crew to Mars, starts in year 3, after the successful MAV fueling is confirmed:

- HTV4 integrated with the transit habitat travels from NRHO to HEO where it docks with the Orion crew vehicle which has delivered the crew from Earth. The crew moves from Orion to the transit habitat; Orion undocks and returns back to Earth.
- The stack of HTV4 and transit habitat travels from HEO to the Mars 5-sol orbit where it docks with the DM3 and surface habitat stack.
- The crew moves from the transit habitat to the surface habitat, and the DM3 and surface habitat stack undocks from HTV4 and transit habitat stack and lands on the Martian surface.
- HTV4 and transit habitat stack stays in orbit waiting for the crew return.
- The crew performs their exploration activities living in the surface habitat and using the assets delivered to the surface by the previous cargo missions.
- When the exploration is over, the fully fueled MAV with the crew onboard ascends to the Mars 5-sol orbit where it docks with HTV4 and transit habitat stack. The crew moves to the transit habitat, the MAV undocks, and HTV4 delivers the crew from the Mars orbit to HEO where it docks with a second Orion that was launched to pick up the crew.

The described campaign mission schedule is shown in Fig. 2 for two full campaign cycles.

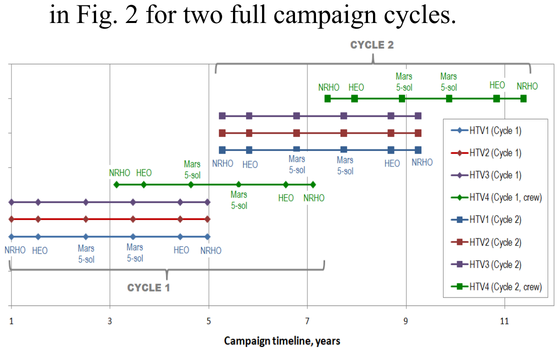

Fig. 2. The campaign mission schedule for two complete cycles shows how the crewed missions will overlap subsequent cargo missions.

2.3 Technology Scenarios

The BoC architecture assumes no technology infusions and is modeled as a LOX/LCH4/SEP with passive boiloff control. All vehicles using chemical propulsion (HTVs, DMs, and the MAV) were assumed to be methane-based with a specific impulse of 360 s and an oxidizer-to-fuel ratio of 3. The passive boiloff control is MLI with 15 layers (resulting in α of 0.1 and effective emissivity of 0.01).

Five technology infusion scenarios were then modeled relative to the BoC architecture. With each technology infusion, the tanks are resized to accommodate for the added mass penalties or for the reduced heat leakages. The scenarios are summarized in Table 1 and described in detail below.

Table 1. The different technologies of passive boiloff control (using MLI), active/zero boiloff control (using cryocoolers), water production (using fuel cells), increased payload, and ISRU are tabulated for the different model runs that will be completed

		Technology Options				
	Minimizing Upmass / Maximizing Payload Mass	# of MLI Layers	Zero-Boiloff Cryocoolers	Fuel Cells	ISRU for Oxidizer	ISRU for Fuel
Scenario Options	1. Baseline Hydrogen Architecture	15			X	
	2. Hydrogen Architecture with Improved MLI	30			X	
	3a. Zero Boil-off Hydrogen Architecture	30	X		X	
	3b.Water Production Hydrogen Architecture	30		X	X	
	4. Increased Payload Hydrogen Architecture	30	X		X	
	5. Hydrogen Architecture with ISRU	15			X	X

1. **Baseline Hydrogen Architecture:** A Modified LOX/LH2 baseline assumed LOX/LH2 chemical propulsion for all relevant vehicles (HTVs, DMs, and MAV), with a specific impulse of 450 s and an oxidizer-to-fuel ratio of 5. This scenario assumes the same boiloff control as in the BoC architecture (15 layers, α=0.1, effective emissivity = 0.01). Additionally, this scenario assumes sufficient 20K cryocoolers on the MAV's descent module for near-ZBO control only during the surface phase.
2. **Hydrogen Architecture with Improved MLI**: This scenario is similar to scenario 1, changing only the MLI passive boiloff control to 30 layers from 15, resulting in α=0.01 and effective emissivity=0.05. We take into account the reduced leakage of heat and the increased mass penalty of these layers. No cryocoolers are installed on the MAV's descent module in this scenario (similar to the BoC reference scenario). The boiloff rate of the MAV in this scenario is 0.76 kg per day in LH2 lost on the surface of Mars.

3a. **Zero Boil-off Hydrogen Architecture:** Similar to scenario 2, we add additional cryocoolers for near-ZBO conditions in transit as well as for the surface phase, taking into account the reduced boiloff rate and the increased mass penalty of the cryocoolers.

3b. **Fuel Cell Water Production Hydrogen Architecture:** This scenario is similar to scenario 2, but instead of using additional cryocoolers as in 3a, we introduced fuel cell technology to offset the power system and water payload mass. The fuel cells take in the otherwise wasted boiloff, and output power and water. Beyond the net impact on upmass, the fuel cells provide increased operational flexibility to trade propellant for margin in the critical power and water ECLSS systems.

4. **Increased Payload Hydrogen Architecture:** This is identical to scenario 3a except that it maximizes payload delivered to the surface of Mars by transferring the mass savings from passive and active cooling to payload mass, such that upmass is equal to that for scenario 1 but payload mass is maximized.

5. **Hydrogen Architecture with ISRU:** This architecture is similar to scenario 1 except fuel for the ascent and logistical water are not launched, but are instead produced on the surface of Mars. The manifests would be modified accordingly to deliver the ISRU infrastructure only once, ahead of the first crewed mission. This change to the manifests is not reflected in our model; instead, we have carried out a special study of breakeven and cumulative benefit in delta landed payload mass.

3. Model

Two major figures of merit are used to compare the hydrogen architectures to the BoC architecture. The first is the total initial mass in near rectilinear halo orbit (IMNRHO), or the total upmass, defined as the sum of the wet masses of all vehicles participating in a campaign cycle at the start of the campaign in NRHO and the payload mass delivered by each DM to the Mars surface.

In order to estimate the IMNRHO for the BoC architecture and the technology infusion scenarios, we developed a MATLAB model which takes in the particular scenario inputs and an initial guess of the propellant masses of the campaign vehicles. The system of nonlinear equations is solved such that the remainders of the propellant in the vehicles at the end of the campaign is zero. The solution is then run through the vehicle models, and the final value of the IMNRHO is calculated based on the vehicles' wet masses obtained.

Since the payload mass delivered by each DM to the Martian surface of the BoC architecture was not given in [14], it was determined using our model by treating the DM payload mass as an additional variable and holding the IMNRHO fixed at the BoC value which was stated. The campaign model and the chemical vehicle model on which the code was based are described in the subsections below.

3.1 Campaign Model

We model the 4-mission campaign cycle as a sequence of 23 discrete events (see Table 2), which allows us to define certain trajectory constants such as the start and end days of the trajectory segments, the respective delta-Vs, times of flight, and the average distances from the Sun. We use this model to track changes to the vehicles' masses (affected by the propulsion burns, boiloff, water production onboard, and MAV fueling), as well as vehicle stack configurations as defined by the architecture.

Within each event, the respective changes to the vehicle masses are treated as instantaneous. To model the propulsive burns, we apply the rocket equation to the respective stack configurations. To model the boiloff and water production we determine the boiloff and water production rates corresponding to the current trajectory segment of known duration. Lastly, we model the MAV fueling from ISRU as an instantaneous increase in the MAV oxidizer mass before its ascent.

Table 2. The model comprises 23 campaign events where the ΔV and boil-off are separately calculated.

	Start (day)	End (day)	Event Description	ΔV (m/s)	TOF (days)	Average Distance (a.u.)
1	0	0	NRHO Departure	100	0	1.00
2	0	200	NRHO > HEO	0	200	1.00
3	200	550	HEO > Mars SOI	3500	350	1.25
4	550	550	Mars SOI > Mars Orb	280	0	1.50
5	550	550	Mars Orb > Mars Srf	850	0	1.50
6	550	900	Mars Stay	0	350	1.50
7	900	900	Mars Orb > Mars SOI	280	0	1.50
8	900	1250	Mars SOI > HEO	3500	350	1.25
9	1250	1450	HEO > NRHO	0	200	1.00
10	1450	1450	NRHO Capture	100	0	1.00
11	-	-	*Timeline Correction*	-	-670	-
12	780	780	NRHO Departure	100	0	1.00
13	780	980	NRHO > HEO	0	200	1.00
14	980	1330	HEO > Mars SOI	3500	350	1.25
15	1330	1330	Mars SOI > Mars Orb	280	0	1.50
16	1330	1330	Mars Orb > Mars Srf	850	0	1.50
17	1330	1680	Mars Stay	0	350	1.50
18	1680	1680	MAV Fueling	0	0	1.50
19	1680	1680	Mars Srf > Mars Orb	5500	0	1.50
20	1680	1680	Mars Orb > Mars SOI	280	0	1.50
21	1680	2030	Mars SOI > HEO	3500	350	1.25
22	2030	2230	HEO > NRHO	0	200	1.00
23	2230	2230	NRHO Capture	100	0	1.00

Legend

	HTV chemical propulsion		DM chemical propulsion
	HTV electric propulsion		MAV chemical propulsion
	Boiloff events (applied to all chemical vehicles)		

3.2 Chemical Vehicle Model

The block diagram in Fig. 3 shows the relationships between each of the technologies and sizing functions within the model for all campaign vehicles using chemical propulsion. This model is iterated under the closure loop until a solution is found. The blocks highlighted in green represent inputs to the system, which are dependent on the particular scenario. Each of the blocks in light blue represent sub-functions within the model.

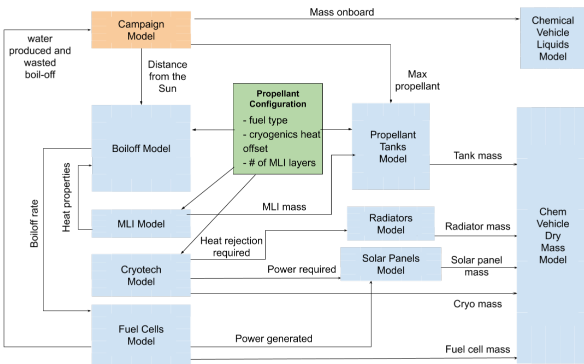

Fig. 3. The model block diagram shows the inputs and outputs of each sub-model, with the propellant configuration block driving many of the models' parameters

The assumptions used for modelling the technology infusions are outlined below:

3.2.1 Cryocooler Model

The cryocooler model is based around a performance estimation model found in [16]. The performance estimation model was designed conservatively, which results in the highest input power estimations. The non-ideal effects, such as the competing mass flow and heat transfer mechanisms surrounding the cryocooler, are captured in an efficiency term, η. The following assumptions were made:

- The coolers are operating near peak cooler efficiency, since efficiency varies slowly near the peak efficiency [16].
- The multi-stage cryocooler (which is required for an LOX/H_2 architecture) will use a reverse Brayton cycle [13].

3.2.2 Solar Panel Model

The solar panel model follows the methodology in [17]. The basic methodology involves calculating the power that must be produced, then determining the estimated power output for a given solar cell which depends on the material properties and expected solar flux, and then calculating how the system will degrade over time. For these calculations, the degradation of the solar panels and solar flux were based on numbers that the system would incur around Earth. The solar panel calculations were designed around the system at Mars, making them conservative estimates. For a higher fidelity model, the system would need to account for complex nuances in trajectory like the orientation of the system at given points in time. The following assumptions were made:

- An average constant solar flux is used at 608 W/m^2, a conservative estimate based on the solar flux at Mars.
- The solar panels use gallium arsenide solar cells (the highest efficiency of any solar material currently available) with an areal mass density of 2.7 kg/m^3 for its material efficiency [17].
- Inherent degradation of 0.77 is used at 2.75% per year [17].
- A solar incidence angle of 23.5 degrees is used, which is the worst case on Earth.

3.2.3 MLI Model

The MLI is modeled as separate layers with the number of layers being a parameter adjusted in each scenario, valid for 5 to 30 MLI layers. Various sources are used to compute the effective emissivity [12], efficiency, and alpha [18].

- Each MLI layer consists of one reflector layer of Aluminized Kapton and one spacer layer of Nomex netting [12].
- The silvered Teflon outer cover has an emissivity of 0.8 and absorptivity of 0.1 [12].
- The heat flow is limited to 0.25 W/m^2 with an area density of 1567 g/m^2 based on the demonstration in [19] of limiting heat flow to < 0.5 W/m^2 with an area density between 1500 and 3000 g/m^2.

3.2.4 Radiator Model

To calculate the projected radiator area, we apply Stefan-Boltzmann's Law, using the heat rejected calculated through the MLI model. The areal mass density of the radiator is calculated to be 14 kg/m^2, a conservative result compared to the areal mass density of the ISS at 8.8 kg/m^2. The following assumptions were made [20]:

- The radiators are assumed to be thin plates.
- The temperature of the radiators is set to 300K and the temperature of the environment is set to 2.7K.

3.2.5 Fuel Cell Model

The ratio of power and water output based on flow rate of LH_2 and LOX in are conservatively modeled as scaling with the fuel cells used on the Space Shuttle [21][22]. The outputs of the fuel cell reaction are then computed based on the limited reactant driving the reaction. The outputs are the wasted boiloff of LH_2 and LOX, the water produced, the fuel cell mass, and the power produced. The following assumptions are used:

- The ratio of mass flow rates, power output, and mass of fuel cells scale linearly from the fuel cells on the Space Shuttle ($5x10^{-4}$ kg/s of oxygen and $7.6x10^{-5}$ kg/s of hydrogen at 115.7 kg).
- The boiloff has infrastructure to be fed into the fuel cells at a workable operating temperature and pressure.
- To validate the model, the output of power density is computed as 50-128 W/kg and compared to a parametric model derived by NASA of 100-110 W/kg [23].

3.3 ISRU Model

The ISRU model is implemented in scenario 5. It is treated separately from the rest of the model in not just a single crewed campaign analysis, but multiple crewed campaign level analysis. This highlights that after the first crewed campaign, the ISRU infrastructure will already be on the surface of Mars and significant mass savings occur.

The sizing of the electrolysis-based water ISRU system for the LOX/ LH_2 propellant production for the MAV assumes 45.5 kg of regolith delivered per hour. The water diverted to life support was increased enough to target sufficient LH_2 production while minimizing the increase in mass of LH_2 liquefaction and associated power.

The assumptions and preliminary outputs of the ISRU analysis are shown in Table 3.

Table 3. ISRU assumptions and outputs

Excavation and Regolith Processing	
Water acquisition rover (RASSOR) mass (kg)	66 [24]
Number of RASSOR rovers	2 [24]
Regolith mass delivered per hour (kg regolith/hr)	45.5[24]
Regolith dryer mass requirement (kg)	500 [24]
Regolith dryer power requirement (W)	5,000 [24]
Anticipated water content (polyhydrated sulfate) [at 150C]	8.60% [24]
Water production rate (kg water / hr)	3.91
Water diverted to life support (kg water/hr)	-1.17
Electrolysis of Water into H2 and O2 gas	
For every 1kg of water electrolyzed, we obtain:	
Hydrogen mass: (kg)	1/9 [25]
Oxygen mass: (kg)	8/9 [25]
Sizing electrolysis system (mass) (kg)	30.7 [25] [26]
Sizing electrolysis system power (W)	6,686 [25]
H_2 flow rate (kg/hr)	0.30
O_2 flow rate (kg/hr)	2.44
Liquefy and Compress	
Sizing H2 liquefaction cryocooler @29K (mass)	H_2 flow rate (kg/hr) * 28,400 [kg] [25]
Sizing H_2 liquefaction cryocooler @29K (power)	H_2 flow rate (kg/hr) * 603,000 [W] [25]
Sizing O_2 liquefaction cryocooler @113K (mass)	O_2 flow rate (kg/hr) * 2,600 [kg] [25]
Sizing O_2 liquefaction cryocooler @113K (power)	O_2 flow rate (kg/hr) * 62,400 [W] [25]
Total cryocooler mass (kg)	14979
Total cryocooler power requirement (W)	335575
Δ Sys Mass Changes	
Power system mass increase (kg/KW)	100 [25]
ISRU system mass decrease (kg)	-1000
Water logistical mass decrease (kg/hr)	-3.91

4. Results

The model results are summarized in Fig. 4. The horizontal axis is organized by the different scenarios of the architecture in a logical order of increasing technology infusions. At each step, different technology options are infused into the earlier version, and the upmass is recalculated for the entire 4-mission campaign while holding the payload per mission to Mars constant at 22 mT. The Y-axis represents the change in total mass at NRHO relative to the dotted line BoC architecture. Beginning at (1) along the X-axis, the BoC architecture is modified only to replace LOX/LCH_4 with LOX/LH_2. This modified LOX/LH_2 baseline architecture closes with a similar upmass to the LOX/LCH_4 original, showcasing the close tradeoff between the added benefit of using LH_2 as fuel and the

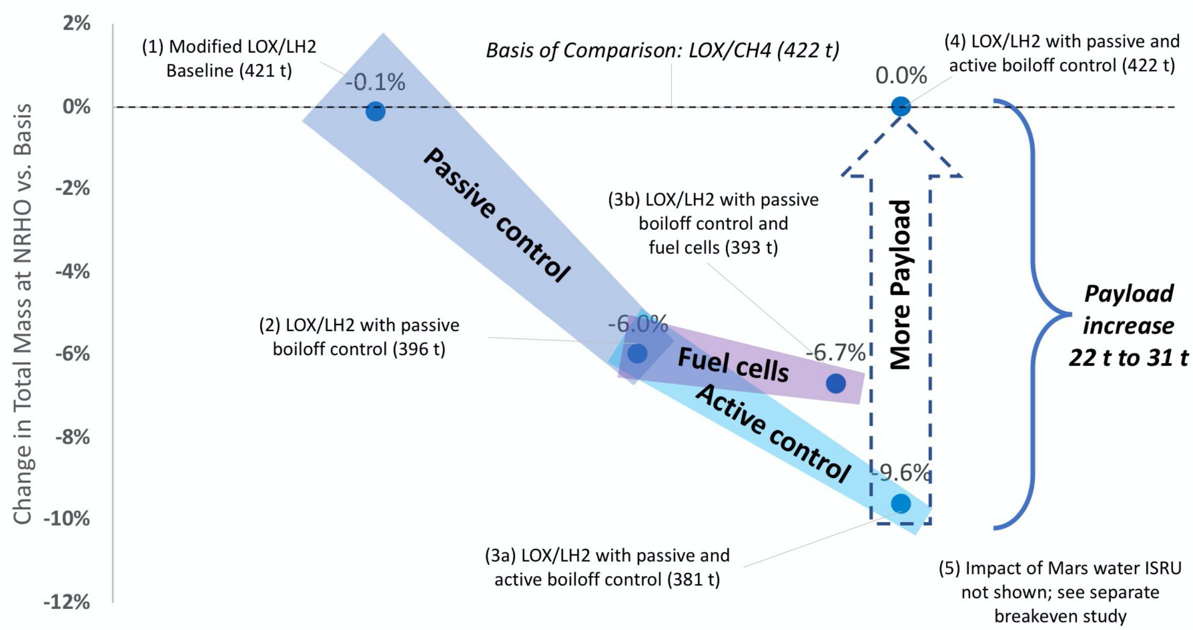

Fig. 4. The modified LOX/LH_2 baseline (scenario 1) includes standard passive control. Upmass can be reduced by investing in low effective emissivity MLI technology (scenario 2) and in efficient 20K cryocoolers (case 3a). The resulting upmass reduction can be traded for increased payload (case 4). Fuel cells (case 3b), are an alternative to cryocoolers, trading the reduced mass saving for greater operational flexibility provided to power and life support. Impact of water ISRU (case 5) shown separately. The width of bars notionally represents error margins.

extra mass needed in an LH_2 architecture due to higher boiloff rates.

Next, architecture (2) is that of (1) plus improved passive boiloff control (sheets of MLI). Architecture (3a) is the same as (2), plus advanced active boiloff control (cryocoolers). Alternatively, architecture (3b) takes architecture (2) and directs the boiloff to fuel cells. Note that using both passive and active boiloff control leaves insufficient boiloff to put through a fuel cell.

All technology paths from (1) to (3) are based on iso-performance, meaning they hold the payload to Mars constant at 22 mT per mission. An alternative view is to switch to an iso-cost analysis, increasing the payload delivered to Mars until the upmass of (3a) is the same as the BoC. This answers the question: for the same price in upmass, how much more payload can be delivered to the surface? This is represented in Fig. 4 by architecture (4), which ends on the same horizontal line as the LOX/LCH_4 BoC architecture (identical upmass), but which delivers 31mT to Mars per mission instead of 22mT.

Lastly, ISRU was analyzed separately, as it requires a change to the campaign in order to deploy the infrastructure. Shown in Table 4, in the scenario of 1.17 kg of water per hour diverted to life support, the mass of LH_2 produced over 480 days is 3,507 kg, exceeding the required 3,440 kg. Furthermore, the cumulative mass of both systems pays off after the second mission, where both the ISRU and the power system are already on the surface of Mars.

Table 4. The cumulative mass impact of launching ISRU and power system pays off in just the second crewed mission

Crewed mission number	1	2	3	4
Add landed mass (power, ISRU) [mT]	49	2	2	2
Minus landed mass (hydrogen, water) [mT]	-26	-26	-26	-26
Net Mass Impact [mT]	23	-24	-24	-24
Cumulative mass impact (mT)	+23mt	-1mt	-25mt	-49mt

Based on this analysis, we find that continued technology development of LH_2 engines, low effective emissivity MLI, higher efficiency (20 W-20 K) cryocoolers, and improvements in passive and active boiloff control may support a competitive LOX/LH_2 NASA Mars architecture. With these technologies, our model outputted a 6% to ~10% reduction in upmass or up to 25% improvement in landed payload on. Processing boiloff through fuel cells being developed in partnership with GRC/JSC [27] may result in marginal upmass savings while also providing operational flexibility in power and life support. Furthermore, development of water ISRU systems [28] may potentially augment a Mars LOX/LH_2 architecture and deliver cumulative landed mass benefits after the second crewed mission. These benefits arise by displacing logistical liquid hydrogen and water from future mission manifests. Infusing these technologies can improve boiloff control to the point where LOX/LH_2 Mars architectures are competitive with the more traditional LOX/LCH_4 Mars architectures.

5. Conclusions

In this paper we have modeled a Mars campaign with various technology switches to emphasize certain technologies that should be developed for lunar missions, acting as a 'test-bed' for Mars missions. High level models with built-in margins are used. For example, we assumed maximum sun-facing tank area for the worst-case boiloff rate and did not assume the use of a sun-shade. With our conservative model, we find that a LOX/LH_2 Mars architecture with improved MLI and cryocoolers are likely competitive with LOX/LCH_4 architectures, resulting in 6%-10% upmass saving or an increase in landed mass from 22 mT to 31 mT. Next, we analyze ISRU and include its effect on the campaign as additional infrastructure that will need to be launched. We find that Mars water ISRU breaks even after the second crewed mission.

Modeling the thermal performance of spacecrafts (including boiloff performance) without a detailed design is necessarily an approximation. To extend and verify these results, a detailed Mars LOX/LH_2 mission analysis is required. Further, in this paper, we only focused on only one Mars architecture, the BoC from [14]. An architectural tradespace exploration should explore various Mars campaigns and compare the results between the different architectures.

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