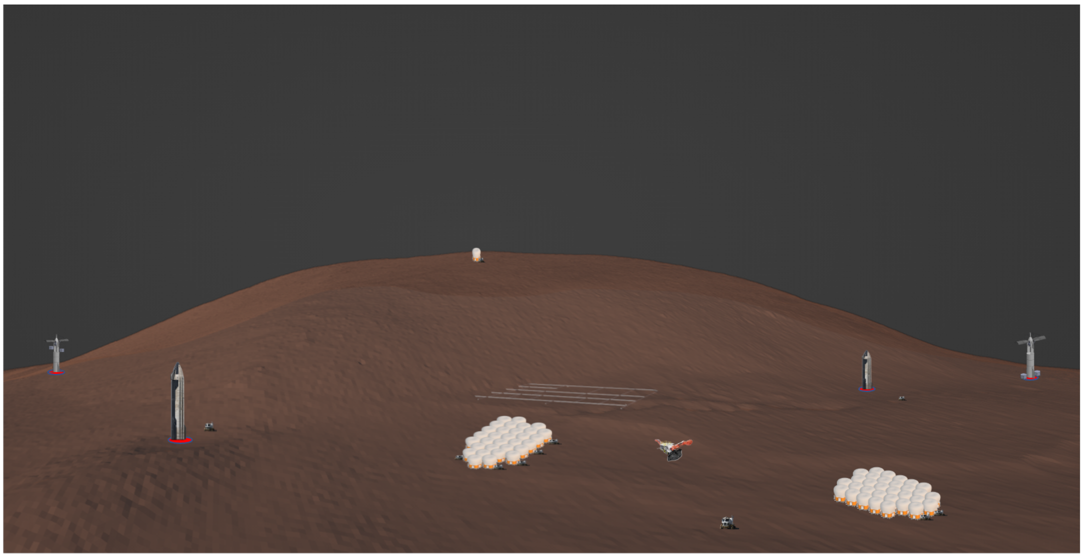
Massachusetts Institute of Technology
RASC-AL 2023: HOMESTEADING MARS THEME



Pale Red Dot

Polis-based **A**rchitecture for the **L**ong-term **E**xploration of the **R**ed planet, with **E**xciting and **D**iverse **D**evelopmental **O**pportunities to **T**hrive

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MIT: Pale Red Dot

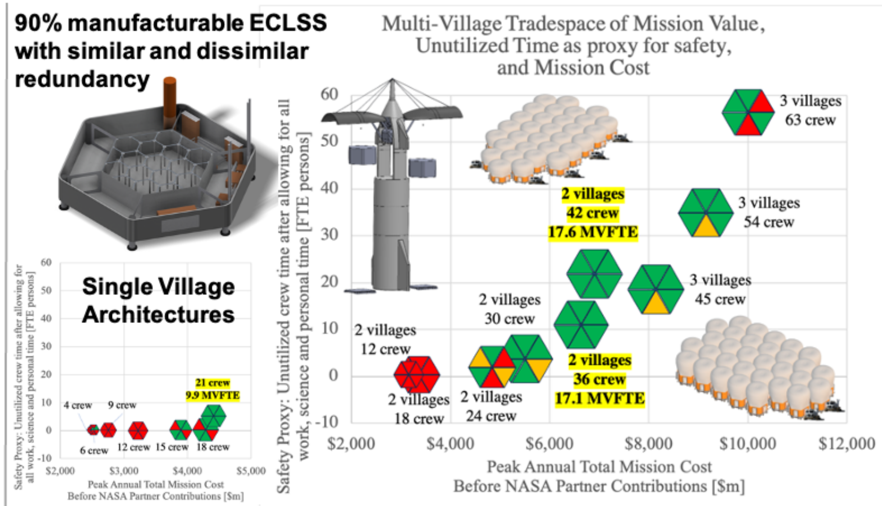
*(**P**olis-based **A**rchitecture for the **L**ong-term **E**xploration of the **R**ed planet, with **E**xciting and **D**iverse **D**evelopmental **O**pportunities to **T**hrive)*

RASC-AL

Theme: Homesteading Mars

Objectives & Technical Approach

- Safe, thriving homestead through a large, distributed architecture with ample resources for science, exploration, growth, in-situ technology development and time margin for contingencies
- Two nearby villages of 18, for 36 total crew. Collaborate daily, can rescue each other if needed
- Mars Makerspace and resource pipelines to enable >90% in-situ manufacturability of ECLS
- Modular (initial) and tunnel (final) habitat concepts to minimize radiation dose, maximize surface time
- Mars Mission Control: 'Houston' will be on Mars.



Key Design Details & Innovations

- 5828 T total mass transported in 81 Mars cargo flights using Starship, peaking at 13 launches per month
- Energy-rich, water-rich, food-rich and time-rich: 5 x 5MWe, 7,000 T water in distributed storage, 800m^2 of growing area, 17.1 mission value full-time equivalent persons on Mars (MVFTE), 10.8 contingency FTE
- Detailed modeling of small and large mission architectures shows that *only* large architectures offer all three of: **value, safety and sustainability**
- Models include: high-fidelity crew time, mission-sizing and costing model; and a low-to-medium fidelity in-situ manufacturing and Earth resupply model
- The Pale Red Dot concept was tested in a low-fidelity Mars analog in Maine, May 27th – June 1st, 2023

Schedule

- 2024-2030: Precursors, Artemis demonstrations
- 2030-2037: Technology demonstrations at site
- 2032-2039: Robotic deployment of surface assets
- 2039: First crew launch, land in 2040
- 2040-2042: Surface operations from modular habitats
- 2043-2050: Surface operations from tunnel habitats
- 2046: 1/3 of 2nd crew arrives for knowledge transfer
- 2048: rest of 2nd crew arrives for knowledge transfer
- 2050: Second crew arrives, handover, 1st crew departs

Costs to be shared with international partners

Lifecycle cost for two 36-person 'Artemis Accords' crews from 2023 – 2050 is $81,148 million. Lifecycle cost per full-time-equivalent person per year available for science, exploration and growth activities on Mars is $290 million.

Contents

1 Executive Summary

We propose a ten-year Mars mission to establish Earth-independence and support efficient, safe, and sustainable science and exploration goals. The campaign would be supported by 5 tons of supplies every two years and would involve a series of precursor missions, starting with the Artemis program, followed by robotic missions to perform site surveys and selection, de-risk technologies, and to start stockpiling in-situ water and propellant. Robotic Cargo Starships would depart in 2035 to deliver and deploy habitats, nuclear microreactors, farm modules, manufacturing and ISRU systems. In 2040, two Crew Starships carrying 36 persons would land on Mars to establish two close-proximity villages. The mission costs $81 billion with a peak annual cost of $6.6 billion.

The risks to human life and to critical systems increase exponentially over a minimally-resupplied, 7-10 year mission to Mars. Our approach focused on identifying capabilities to mitigate known and unknown risks. Using a high-fidelity crew time model, we found that large architectures, with their economies of scale and productivity gains from specialization, are essential to support the necessary capabilities with resilience. The model also shows that small 7-year missions of 12 persons or less cannot provide value in terms of free surface traverse time for science and exploration.

Given the necessity of a large, complex architecture, we then sought out efficiencies and synergies (value engineering) in order to make the mission feasible and affordable. In the process, we discovered more benefits that are enabled only by large missions, including the creation of a true community on Mars with sufficient social complexity for humans to thrive, and the geopolitically compelling option to include crew from every Artemis Accords signatory in the first human mission to Mars. When history comes calling, the United States and its international partners are capable of rising to the challenge of large logistical campaigns: the Berlin Airlift and the D-Day Normandy landings were large not by choice, but by the need of assurance of mission success. The challenge we address with Pale Red Dot is to provide a rationale, design and project plan for a necessarily large and complex, yet effective, feasible and affordable campaign.

2 Stakeholders Analysis

Alignment with NASA Strategy: Analysis of RASC-AL theme requirements and driving requirements for NASA's Moon to Mars Strategy and Artemis Program [139] results in recurring theme objectives to be addressed in this architecture, including:

- RT-1 International and Industry Collaboration: partner with international community and U.S. industry to achieve common goals and objectives.
- RT-2 Crew Return: return crews safely to Earth while mitigating adverse impacts to crew health.
- RT-3 Crew Time: maximize crew time available for science and engineering activities.
- RT-4 Maintainability: when practical, design systems for maintainability, reuse, and/or recycling to support the long-term sustainability of operations and increase Earth independence.
- RT-5 Responsible Use: conduct activities for the exploration and use of space for peaceful purposes consistent with international obligations and principles for responsible behavior in space.
- RT-6 Interoperability: enable interoperability and commonality (technical, operations and process standards) among systems, elements, and crews throughout the campaign.
- RT-7 Leverage Low-Earth Orbit: leverage existing infrastructure to support Moon to Mars activities.
- RT-8 Commerce and Space Development: foster the expansion of the economic sphere beyond Earth orbit to support U.S. industry and innovation.

Our Pale Red Dot architecture meets all these requirements, in addition to the theme requirements.

Value to NASA: Science, Exploration, Earth-independence and Mission Safety: Following the principle of "architecting from the right", our mission design aimed to maximize mission-value full-time equivalent (MVFTE) personnel hours dedicated to science, exploration, growth and in-situ technology development objectives, meeting NASA's stated Science-Enabling and Applied Science Goals [139] as well as other stakeholders' similar goals [75, 94]. Inclusion adds scientific output and mission value to NASA and other stakeholders. Further, in the event of contingencies or emergencies, the personnel hours earmarked for mission value represent invaluable 'surge capacity' which supports a broad range of self-rescue operating modes and capabilities.

3 Requirements, Lifecycle Properties and Design Principles

Compliance with Theme Requirements: In addition to the overarching themes stated above, specific RASC-AL requirements for the Homesteading Mars theme are met in this architecture. These include a 7-year minimum surface mission duration for a crew of at least 4, with first crewed landing by 2040; first crew return by 2050; establishment of a continuous human presence on the Martian surface; a maximum of 2 years' worth of logistics and spares deployed prior to or at the start of the crewed mission; and a maximum of 5000 kg resupply from Earth every 2 years. Crew time and resupply limits were identified as primary constraints for the mission, and thus, architecture components are designed to minimize resupply needs and enhance crew productivity.

Relevant NASA requirements that generally apply in human space exploration: NASA's current career space permissible exposure limit for spaceflight radiation is 600 mSv[137], while other space agencies use 1000 mSv[195]. As the key stakeholder is NASA, we have decided to design to the NASA limit. Sterilization procedures and monitoring of all open-loop components will be included to prevent forward contamination and follow accepted procedures for planetary protection[66]. Crew scheduling constraints will follow ISS schedules in nominal times (i.e. 8.5 hours/day for sleep, 1.5 consecutive days off/week)[137], however in what follows, we have calculated crew time margins using the minimum sleep recommendation for adults of 7 hours/day set by the National Sleep Foundation [88], so as to give smaller architectures an opportunity to work.

A close look at the interplay of all theme requirements: We reviewed the literature for past Mars surface architectures and found that nearly all NASA-sanctioned architectures involved a crew of between four to six [33, 56, 71, 157, 184], for surface stays of no more than 500 days, and with the food source mostly shelf-stable, freeze dried food brought from Earth. Juxtaposing this history against the new requirement for a 7-year minimum stay with minimal resupply and for limited pre-positioned spares and food, we decided to first investigate whether small architectures would actually have sufficient crew time to cope with repairs, maintenance, agriculture, as well as science, especially in the face of contingencies or emergencies that are bound to occur over the long 7-year stay and which might need to be addressed immediately. Literature on crew time utilization for Mars surface missions did not settle the matter as agriculture, in-situ manufacturing and crew time margin to deal with contingencies was not included in the crew time studies we reviewed [77, 78, 126, 174, 175]. We also noted that larger architectures may now be feasible and affordable given the ongoing development of a fully reusable transportation system, SpaceX's Starship [83], which is also the descent element for Artemis selected by NASA. For these reasons, we developed two innovative models to enable us to explore the design space for architectures from very small to very large: a high-fidelity crew time, mission sizing and mission costing model, coupled to a low-to-medium fidelity in-situ manufacturing and Earth resupply model. From this investigation, it is clear that crew time availability can easily become the driving constraint of all crewed architectures.

Pale Red Dot targeted Lifecycle Properties and Design Principles: Based on our analysis, the following design principles guided all architectural decisions for Pale Red Dot: high manufacturability and maintainability, modularity and commonality, and resilience through redundancy and healthy margins in systems, productive capacities, crew time, and commodity stockpiles.

4 Architectural Vision and Robustness

With the realities imposed by the theme requirements, as discussed above, we decided to investigate architectures of various sizes, including larger architectures that are not well represented in the literature. In addition, mission abort from Mars would take many months, if it is even possible at the time of the event [33]. It is therefore paramount to provide the crew with self-rescue capabilities and multiple options to deal with contingencies and emergencies. So we decided to also investigate multi-site architectures, an option that is even less explored in the literature.

The Pale Red Dot vision: Consistent with the above, the Pale Red Dot vision is for at least two energy-rich, water-rich, food-rich and capability-rich villages who can support themselves with minimal resupply from Earth. We envision our crews producing all the food and all the components they need for indefinite sustainment, while reserving substantial free time for thriving, growth and dealing with contingencies or emergencies.

Designed for Manufacturability and Maintainability: In Pale Red Dot, crew members would provide the necessary labor to maintain all the systems, while also maintaining their physical and mental well-being by expanding their habitat, adding to their stocks of resources, exploring and investigating Mars, and engaging in leisure activities. Systems are "designed for manufacturability" using 90% Mars mass content, with crew maintenance facilitated by a ́Mars Makerspace ́, supplemented by strategic imports of low-mass, high-complexity parts from Earth.

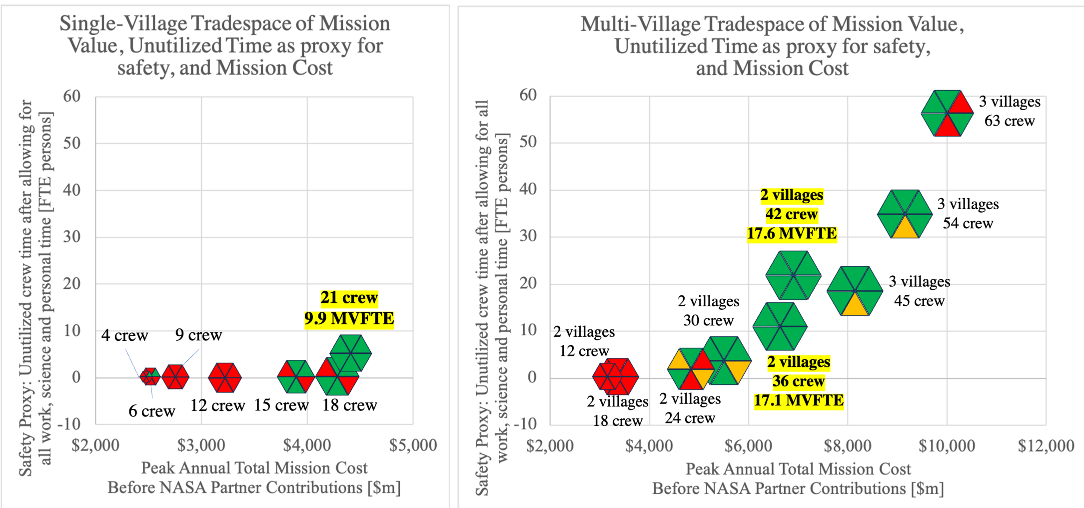
Thriving, not just surviving: Every aspect of Pale Red Dot is designed using human-centered principles to help foster the healthy psycho-social development of the 36 persons on Mars. However, thriving requires the presence of an adequately-sized group, where labor surplus is generated and diverse individuals contribute both breadth and depth of skills and unique quality-of-life improvements to the community as a whole.

5 Model assumptions, description and results

Questions addressed by model: We designed the model to support a search for answers to the most critical questions regarding the cost and benefit of different architectures. For each possible mission architecture of different scale, it is important to know what is the resupply requirement? Where should they live? Should they make all their food in situ, and if so what are all the implications, including for crew time and life support? What radiation dose will the average person receive, given a science program which scales up for larger missions, but less than linearly? What is the total burden on crew time from all activities, personal and work? How will they maintain their systems, with what equipment, and how much of their time will be needed? What will it cost to develop, transport, operate and sustain all the equipment and crew? Additionally, what transportation architecture should be used to optimize both cost and radiation dose during transit?

Modeling approach: When designing scenarios of different sizes for evaluation, we prioritized safety and crew health, ensuring that science capabilities are only considered once safety and health needs are fulfilled. Thus, we first modeled and optimized the transit with the goals of minimizing radiation exposure for the crew and minimizing the number of cargo launches. Then, we used the same transit assumptions with all surface architectures of all sizes, to evaluate them for lifetime cost and radiation dose on an equal footing. Specific assumptions came from sources including NASA BVAD [63], the Human Spaceflight Mission Analysis book by Larsen et al [103, 104, 105], and miscellaneous sources cited within the model documentation. The highest-fidelity part of the model is the crew time submodel which was built using the lists of hundreds of Mars surface tasks developed by Stuster et al [175] as a starting point. The model, including all assumptions and calculations, is implemented in Excel and provided in the Appendix F.

All our calculations and the full table of results are shown in Appendix F, while selected results are summarized in Figures 1a and 1b and Table 1.



(a) Single village results

(b) Multi-village results

Figure 1: Tradespace analysis of small, large, single-site and multi site mission architectures. Every hexagon is one architecture, with area proportional to Mission Value FTE (MVFTE). Key to the hexagonal stoplight colors, using compass directions: N = Effective Dose of radiation absorbed by crew over duration of mission (green if <600mSv). NE = Resupply demand (green if<5mt/2r). SE = Workweek length (green if <50hrs/wk). S = Carrying capacity growth (red if none). SW = Max FTE for surface time (red if none). NW = Unutilized FTE (red if none).

Model Results: Three viable architecture options for the Mars mission were identified: one village of 21, or two villages of either 18 or 21 each. Two-village options offer redundancy and an opportunity to establish norms of peaceful inter-communal relations from the onset. The 36-crew, two-village mission was selected due to its cost-effectiveness, high mission value, and unallocated crew time for contingencies. It is feasible within NASA's Human Space Flight (HSF) budgets and includes the potential for cost-sharing with partners like ESA and JAXA.

After accounting for personal and social time, survival-related work, and science tasks, the work-week is 48 hours. More metrics and comparisons are shown in Fig. 1 and Table 1. Large missions correlate with safety and value, thanks to economies of scale, specialization, and high manufacturability of systems from local resources. They also allow for the construction of permanent, zero-radiation habitats, promoting crew health and enhancing mission value.

The mission strategy includes precursor investigations and in-situ production of spare parts, with crew arrival slated for 2040 to allow sufficient time to mature low-TRL critical tunneling and habitat technologies. Collaboration in cost-sharing and risk mitigation presents a valuable proposition to NASA's international and commercial partners.

Table 1: Comparison table of metrics for 3 down-selected architectures. Note: where there was a need to manufacture life support systems for growth, this was modeled up to the outfitting need or to resupply limit, whichever came first.

	Resupply demand [tons/2yrs]	Useful time [MVFTE]	Total Cost [$B]	Peak Cost /year [$M]	Radiation dose /mission [mSv]
SINGLE-VILLAGE					
21 crew, 1 village	2.7	9.9	$55	$4,406	522
MULTI-VILLAGE					
36 crew in 2 villages	4.9	17.1	$81	$6,639	529
42 crew in 2 villages	4.9	17.6	$84	$6,907	498

6 Concept of Operations and Contingency Planning

Inter-village collaboration: To set norms and to maximize efficiency, the two villages will collaborate on a daily basis, so they must be near enough for visiting on foot. Each will gradually build out radiation-proof underground tunnel habitats, and in the future it may be decided to interconnect the tunnel networks. During nominal operations, both villages stockpile water, food, and build-ahead spare life support systems that could be used to expand the habitat by building new pressurized volume, or to expand the carrying capacity of the existing habitat. The goal of stockpiling is to increase the time and options available to react to contingencies. In the event of a catastrophic emergency affecting one of the villages, the excess productive capacities, stockpiled resources and crew time of the other village can be employed to rescue the crew and avoid an abort of the entire mission back to Earth.

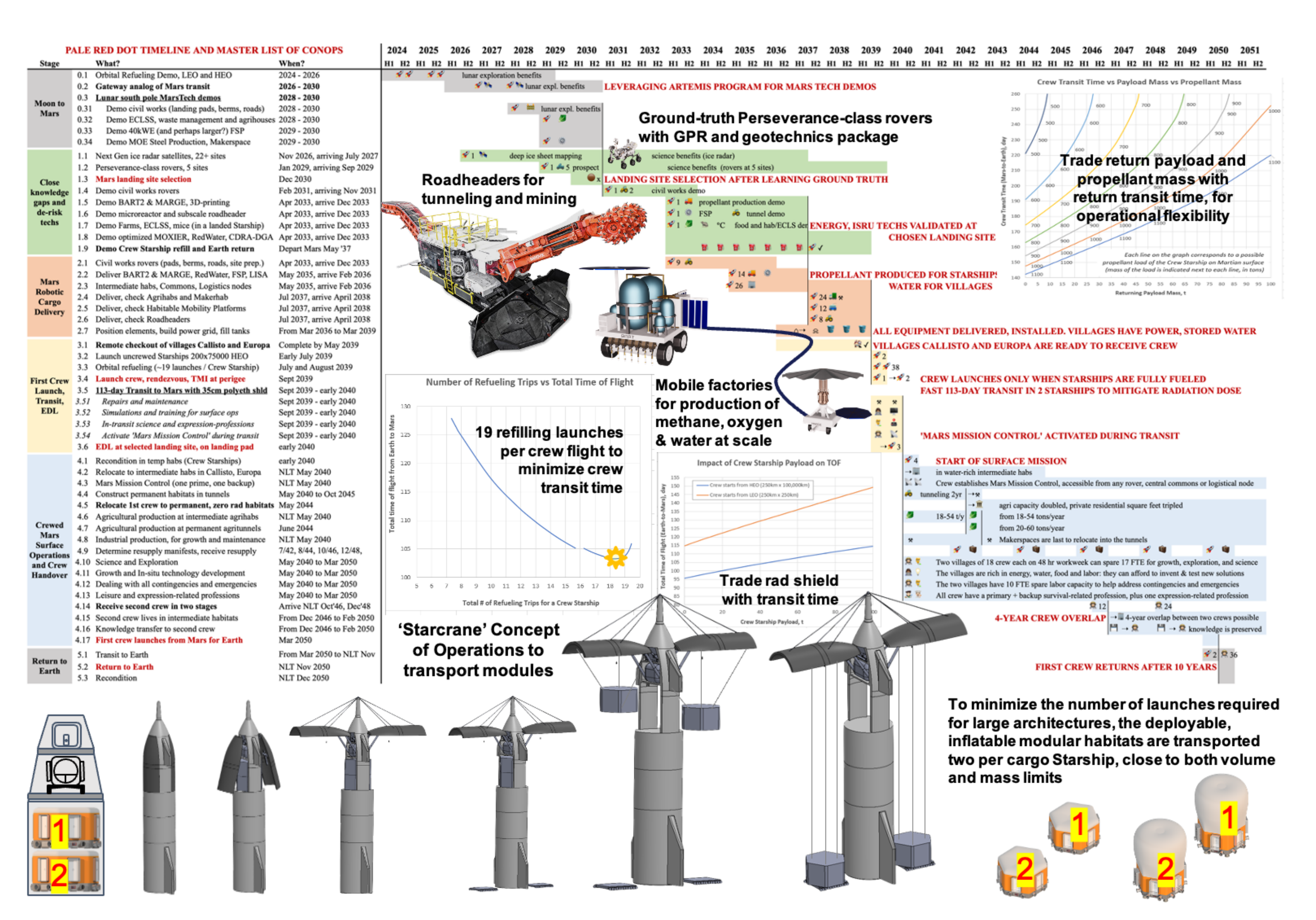
Campaign Timeline: Figure 2 shows the complete CONOPS for the 10-year surface stay, with associated precursor and robotic deployment missions. Select components are summarized below.

Starship operations from launch to pre-TMI: We will use the current SpaceX CONOPS for orbital refilling of cargo and crew Starships [83]. We assume that crew boards the Transit Starship once it is fully fueled, and that Crew Starships always initiate Trans-Mars Injection from 200 x 75000 HEO with a full load of propellant in the tanks, with the TMI burn at perigee. To minimize radiation exposure, we split the crew in two Starships and add a 71-ton 35cm polyethelene shield, resulting in a 113-day transit (Fig 2). Key technologies that need to be matured are Starship orbital flight, orbital propellant transfer, crew rendezvous in HEO and propulsive EDL on other bodies. All are scheduled to be tested as part of Artemis. We recognize that our architecture is predicated on Starship technology or an equivalent system from other US commercial companies.

Precursors phase: Precursors at Gateway and Artemis Base Camp will de-risk our Transit Starship design, and help mature the Westinghouse eVinci 5MW microreactors, our life support system modules, as well as our systems and CONOPS for civil engineering works. Mars orbital and surface precursors will be used to select one of five shortlisted candidate landing sites, by landing five rovers to obtain ground truth data for presence of water ice, rock composition, and surface radiation, among other features. Final technology demonstrations of key technologies, including power, ISRU and tunneling equipment, will take place at the downselected site.

Robotic infrastructure deployment phase: Our novel 'Starcrane' concept of operations for the large-scale delivery of modules and equipment to Mars is shown in Fig. 2. Robotic surface infrastructure will lay the foundation for the architecture including automated site preparation by creating landings pads and berms, roads, and preliminary site layouts. This is followed by pre-emplacement of assets including surface power, BART & MARGE, Water rovers, habitable rovers, as well as 30T - 50T modules for habitation, farming, science, mission control, commons, hygiene,

Figure 2: Pale Red Dot CONOPS, Mission Timeline and Comparison Table of Architectural Metrics



PALE RED DOT TIMELINE AND MASTER LIST OF CONOPS

Stage		What?	When?
Moon to Mars	0.1	Orbital Refueling Demo, LEO and HEO	2024 - 2026
	0.2	**Gateway analog of Mars transit**	**2026 - 2030**
	0.3	**Lunar south pole MarsTech demos**	**2028 - 2030**
	0.31	Demo civil works (landing pads, berms, roads)	2028 - 2030
	0.32	Demo ECLSS, waste management and agrihouses	2028 - 2030
	0.33	Demo 40kWE (and perhaps larger?) FSP	2029 - 2030
	0.34	Demo MOE Steel Production, Makerspace	2029 - 2030
Close knowledge gaps and de-risk techs	1.1	Next Gen ice radar satellites, 22+ sites	Nov 2026, arriving July 2027
	1.2	Perseverance-class rovers, 5 sites	Jan 2029, arriving Sep 2029
	1.3	**Mars landing site selection**	Dec 2030
	1.4	Demo civil works rovers	Feb 2031, arriving Nov 2031
	1.5	Demo BART2 & MARGE, 3D-printing	Apr 2033, arrive Dec 2033
	1.6	Demo microreactor and subscale roadheader	Apr 2033, arrive Dec 2033
	1.7	Demo Farms, ECLSS, mice (in a landed Starship)	Apr 2033, arrive Dec 2033
	1.8	Demo optimized MOXIER, RedWater, CDRA-DGA	Apr 2033, arrive Dec 2033
	1.9	**Demo Crew Starship refill and Earth return**	Depart Mars May '37
Mars Robotic Cargo Delivery	2.1	Civil works rovers (pads, berms, roads, site prep.)	Apr 2033, arrive Dec 2033
	2.2	Deliver BART2 & MARGE, RedWater, FSP, LISA	May 2035, arrive Feb 2036
	2.3	Intermediate habs, Commons, Logistics nodes	May 2035, arrive Feb 2036
	2.4	Deliver, check Agrihabs and Makerhab	Jul 2037, arrive April 2038
	2.5	Deliver, check Habitable Mobility Platforms	Jul 2037, arrive April 2038
	2.6	Deliver, check Roadheaders	Jul 2037, arrive April 2038
	2.7	Position elements, build power grid, fill tanks	From Mar 2036 to Mar 2039
First Crew Launch, Transit, EDL	3.1	**Remote checkout of villages Callisto and Europa**	Complete by May 2039
	3.2	Launch uncrewed Starships 200x75000 HEO	Early July 2039
	3.3	Orbital refueling (~19 launches / Crew Starship)	July and August 2039
	3.4	**Launch crew, rendezvous, TMI at perigee**	Sept 2039
	3.5	**113-day Transit to Mars with 35cm polyeth shld**	Sept 2039 - early 2040
	3.51	*Repairs and maintenance*	Sept 2039 - early 2040
	3.52	*Simulations and training for surface ops*	Sept 2039 - early 2040
	3.53	*In-transit science and expression-professions*	Sept 2039 - early 2040
	3.54	*Activate 'Mars Mission Control' during transit*	Sept 2039 - early 2040
	3.6	**EDL at selected landing site, on landing pad**	early 2040
Crewed Mars Surface Operations and Crew Handover	4.1	Recondition in temp habs (Crew Starships)	early 2040
	4.2	Relocate to intermediate habs in Callisto, Europa	NLT May 2040
	4.3	Mars Mission Control (one prime, one backup)	NLT May 2040
	4.4	Construct permanent habitats in tunnels	May 2040 to Oct 2045
	4.5	**Relocate 1st crew to permanent, zero rad habitats**	May 2044
	4.6	Agricultural production at intermediate agrihabs	NLT May 2040
	4.7	Agricultural production at permanent agritunnels	June 2044
	4.8	Industrial production, for growth and maintenance	NLT May 2040
	4.9	Determine resupply manifests, receive resupply	7/42, 8/44, 10/46, 12/48,
	4.10	Science and Exploration	May 2040 to Mar 2050
	4.11	Growth and In-situ technology development	May 2040 to Mar 2050
	4.12	Dealing with all contingencies and emergencies	May 2040 to Mar 2050
	4.13	Leisure and expression-related professions	May 2040 to Mar 2050
	4.14	**Receive second crew in two stages**	Arrive NLT Oct'46, Dec'48
	4.15	Second crew lives in intermediate habitats	From Dec 2046 to Feb 2050
	4.16	Knowledge transfer to second crew	From Dec 2046 to Feb 2050
	4.17	**First crew launches from Mars for Earth**	Mar 2050
Return to Earth	5.1	Transit to Earth	From Mar 2050 to NLT Nov
	5.2	**Return to Earth**	NLT Nov 2050
	5.3	Recondition	NLT Dec 2050

medical, makerspaces and logistics. Finally, electric roadheaders for permanent habitat tunneling will be delivered, power grid elements positioned and connected, and tanks filled.

First crew transit and EDL phase: After embarking the Transit Crew Starship in HEO, the crew will continue on a faster, non-Hohmann, 113-day interplanetary trajectory with the objective of minimizing radiation exposure in transit. Two Crew Starships will travel together with members from both villages on board, such that inter-village relationships are established during transit. Interior design of Starships will balance privacy with common spaces, for socialization, recreation, and collaborative mission planning. VR facilities will be available for communication with family and friends on Earth. The EDL phase will be performed via direct atmospheric EDL preceded by a propulsive capture to ensure a soft and on-target landing for the crew. Landing pads and surrounding berms were already constructed autonomously by robotic infrastructure in anticipation of crew arrival, with abort Crew Starships pre emplaced in case of a contingency.

Surface stay phase: The surface stay phase will begin with establishment of Mars Mission Control (MMC) on Mars to direct all surface operations without communication delays. MMC will communicate with Houston-based Mission Support via a high-bandwidth optical data network, relying on timely maturation of technologies demonstrated by the recent TBIRD mission [180]. After a short recovery period in the transit Starships (<1 month), crew will move into their pre-deployed intermediate habitats. All intermediate habitats have integrated 3m water tanks in their roof for radiation shielding, thermal mass and thermal management, and water-rich security; these were filled by the water rovers during the cargo delivery phase. Habitat modules will be organized radially around the mission control hub as shown in Fig. 4, including spaces for farming, industry, science experiments, socialization, physical exercise, quiet reflection, medical support, as well as private quarters, enabling an enriched daily routine that balances survival, science, self-expression, and social cohesion. By the end of year 2, the adjoining tunnel habitats and farms will be ready and interconnected with their village, enabling additional quality-of-life improvements while enhancing radiation protection and general habitat safety. Constructing the additional tunnelled habitats will strengthen sense of mastery, personal agency, collective autonomy, and collective responsibility, while serving as a shared aspirational objective that drives a team spirit and future orientation.

Crew Handover: To maximize the expanded living spaces and carrying capacity, one-third of the second crew will arrive in Dec 2046, with the remaining crew members joining in Dec 2048 for knowledge transfer and to bring new perspectives, enriching the social space.

Return transit phase: Return transit will closely parallel initial crew transit with an initial Transit Crew Starship launch to HMO, orbital refueling, and crew transfer to the Starship in HMO. The return transit trajectory will also seek to minimize radiation exposure with a non-Hohmann trajectory. Transit time can be traded with payload and propellant availability as shown in Fig. 2. Special attention will be given to Earth's EDL due to the extended presence of crews in reduced and microgravity. The mission concludes with crew reception and reconditioning on Earth.

7 Surface System Architecture

The surface architecture includes all habitat modules (pre-deployed intermediate habitats and tunnel final habitats), surface mobility systems (Habitable Rovers, civil works rovers, roadheaders), ISRU capabilities, surface power systems, and launch and landing zones.

Human-centered development for a thriving settlement: Design of human systems will prioritize the development of psychological and community resilience[113]. Crew members will receive preparatory training in core psycho-social competencies that will enable wellbeing and effectiveness. Crew will be assigned to two of 12 teams per village for primary and secondary survival-related specializations, such as farmer, machinist, medic, Mission Controller, etc. mitigating productivity losses from task switching as well as adding resilience through redundancy in daily operations. Each person will also choose an expression-related profession such as fitness instructor, interior designer, gardener, chef, etc. through which quality-of-life improvements will be offered to the community [115]. The two villages will interact regularly using the 12 rovers and airlocks, promoting social interaction and shared activities among crew members. Community resilience and a sense of belonging will be fostered through mutual support, shared work activities, and the establishment of long-term goals through community-wide visioning activities. Conflict prevention and resolution will be achieved through clear and equitable division of responsibilities, empathy, diversity appreciation, mediation, countering stereotypes, and, whenever conflict does occur, healing dialogues for reconciliation [43].

Location selection for purpose of exposition of architecture: We reviewed 27 initial site candidates from the NASA Exploration Zone 2015 and NASA-SpaceX 2019 workshops and down-selected to 5 sites based on: water ice, elevation, radiation, temperature, rock type for tunneling, surface level concentrations of potassium and iron, and thermal inertia. All five will be investigated in the precursor phase using remote sensing and Perseverance-class rovers. Our current frontrunner is Deuteronilus Mensae [81], but other sites may become the primary following the precursor phase. We have provisionally selected sites for the villages at altitude -3166m near a glacier water source, with a steep hill that may be suitable for tunneling. The locations are 39.342N, 24.721E and 39.347N, 24.721E, Fig. 3.

Civil Works: Roads, Berms, Landing Pads, Power and Heat Distribution: This is a key activity and we have provided for 7 civil works rovers with high commonality to our other industrial and tunneling-mining rovers. A detailed study remains future work. We assess that there is strong feed-forward between similar activities on the Moon which could be leveraged.

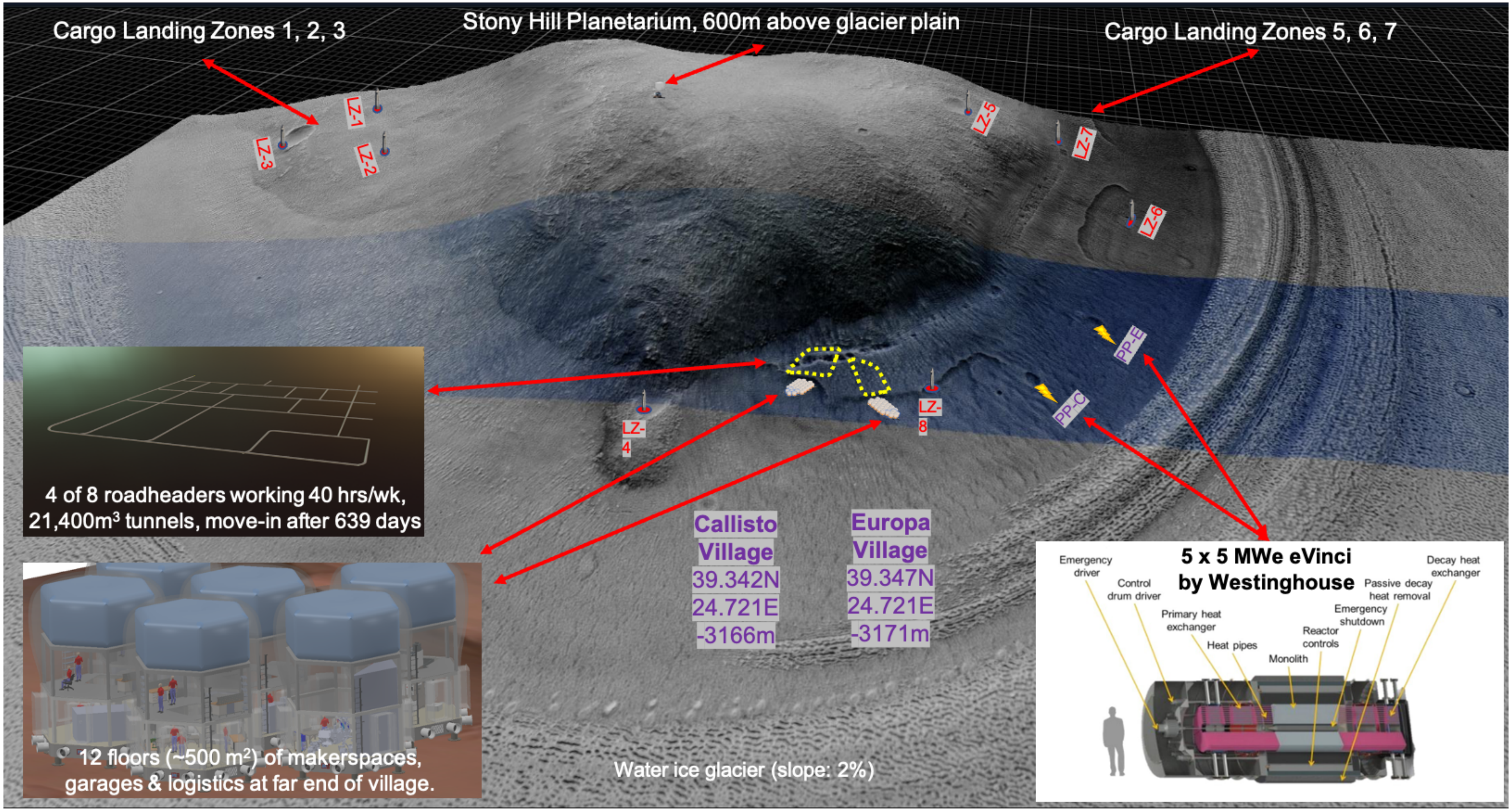
Energy Production, Storage and Distribution: The proposed architecture consists of two power plants, each housing up to three nuclear microreactors. Each reactor can deliver 5 MW of electrical power and approximately 13MW of thermal power. The dual-redundant power generation and distribution systems ensure reliability and reserve capacity for future growth. We plan to use a modified version of the "nuclear battery" design, like the one under development in the DoD's project Pele[189], capable of semi-autonomous operation. The Mars version of the microreactor, selected as Westinghouse's eVinci Microreactor (Fig. 3), will need a 106 sq.m. radiator for excess heat, robotic installation and refueling, autonomous control and remote monitoring.

Surface Mobility: We include 6 Habitable Rovers per village. These can be based on designs being currently matured by NASA, ESA, JAXA and their commercial partners. We assume commonality between their ECLSS and habitat ECLSS, endurance of three weeks, commonality with BART [69] chassis, docking ports to dock with habitat modules for shirtsleeve access, and 3 suitports per rover. Rover design will enable long traverses and a large number of rovers will support many emergency CONOPS and enable on-demand trips between the villages, enabling interactions for co-work (e.g., machinists gathering in one or other village for batch production runs), trade (e.g., trading specialist herbs or fruits) and recreation (e.g., visiting the bar of the other village, which will have a different bar menu). All this will contribute to normalization of harmonious inter-village relations and, therefore, prevention of conflict.

Mars Makerspace: For a seven-year mission to Mars, all systems must either be highly reliable, or highly manufacturable using Mars resources, or both. Even with highly reliable and state-of-the-art systems, the 2.5 tons/year resupply limit presents an almost insurmountable challenge. As a simple case study, we estimated that merely providing the steel picks consumed during tunnel excavation would require 7.5t of resupply. In contrast, an ISRU process would only require 30kg of critical consumables for the same output. In our architecture, we intend to utilize both high reliability of the energy and makerspace systems, and extensive utilization of in-situ resources to fabricate high-mass parts, combining them with low-mass, high-complexity parts from Earth to maintain habitat, farm and life support systems and build new ones for the purpose of expansion. This capability mix is proposed to increase independence from Earth and ensure the crew's safety.

Makerspace - from in-situ resources to feedstock materials: Feedstock materials including steel, concrete, polyethelene and rockwool will be required for construction of the tunnels and for the fabrication of parts that will be used to build or repair systems required by the villages. These will be high-volume materials and also sufficiently simple to make on Mars [152, 153]. To create and recycle steel for tunneling and other uses, we will take advantage of our energy-rich design to include a molten regolith electrolysis (MRE) reactor and an electric arc furnace. MRE is simpler than other steel production methods, and its lower TRL will be developed during ARTEMIS technology demonstrations. Polyethelene has many uses, one of which is to build best-in-class radiation shielding. It will be produced using a monomer synthesis micro-channel reactor and a slurry polymerization reactor. Rockwool can be made in the electric arc furnace by heating up basalt and limestone, and then processing the molten materials in a fiberizer, which spins the mixture rapidly to create the texture of rockwool. To create concrete similar to the durable Roman concrete recipe, we can use Martian regolith consisting of silicon dioxide, aluminum oxide, iron oxide, and titanium dioxide as aggregates, and calcium oxide as a binding agent. Water or humidity passing through cracks in the calcium oxide-rich concrete enables Roman concrete to self-heal by absorbing and depositing calcium oxide in the cracks [165].

Figure 3: Site Overview: Landing Pads, Roads, Power Generation, Villages. Water from glacier, natural radiation shielding from hill.



Makerspace - industrial capabilities for fabrication of parts: A large, flexible and efficient makerspace supports the fabrication of required parts from in-situ resources. By considering the primary objectives of flexible and relevant use, we selected the following major machinery: a 5-axis CNC mill, a powder-bed fusion metal 3D printer, a binder-jet metal 3D printer, and a fused deposition modelling (FDM) plastic 3D printer. This hardware is supported by auxiliary equipment, including common benchtop tools such as a bandsaw, miter saw, drill press, and hydraulic press; hand tools such as drills; and equipment for welding, grinding, and other post-processing and assembly operations. Furthermore, smaller, desktop 3D printers would be used to supplement the machine shop's existing capabilities. Safety is a critical concern, so first aid kits and fire extinguishers are located in every makerspace module.

The crew is also able to build, maintain and repair electronics on Mars. The electronics workstation includes digital multimeters, digital inductance-capacitance meters, oscilloscopes, network analyzers, logic analyzers, spectrum analyzers, power supplies. There are also soldering kits and rework stations for repairing devices and replacing components, as well as desktop CNC mills to fabricate printed circuit boards. On the software and design side, inclusion of a 'standard' set of boards and microcontrollers minimizes overhead.

Assembly - Robotics, human labor and artificial intelligence: Automation will be used where possible in the makerspace, however this concept is not reliant on extensive automation for assembly as every job is likely to have unique features. However, all rovers in the field can be tele-operated.

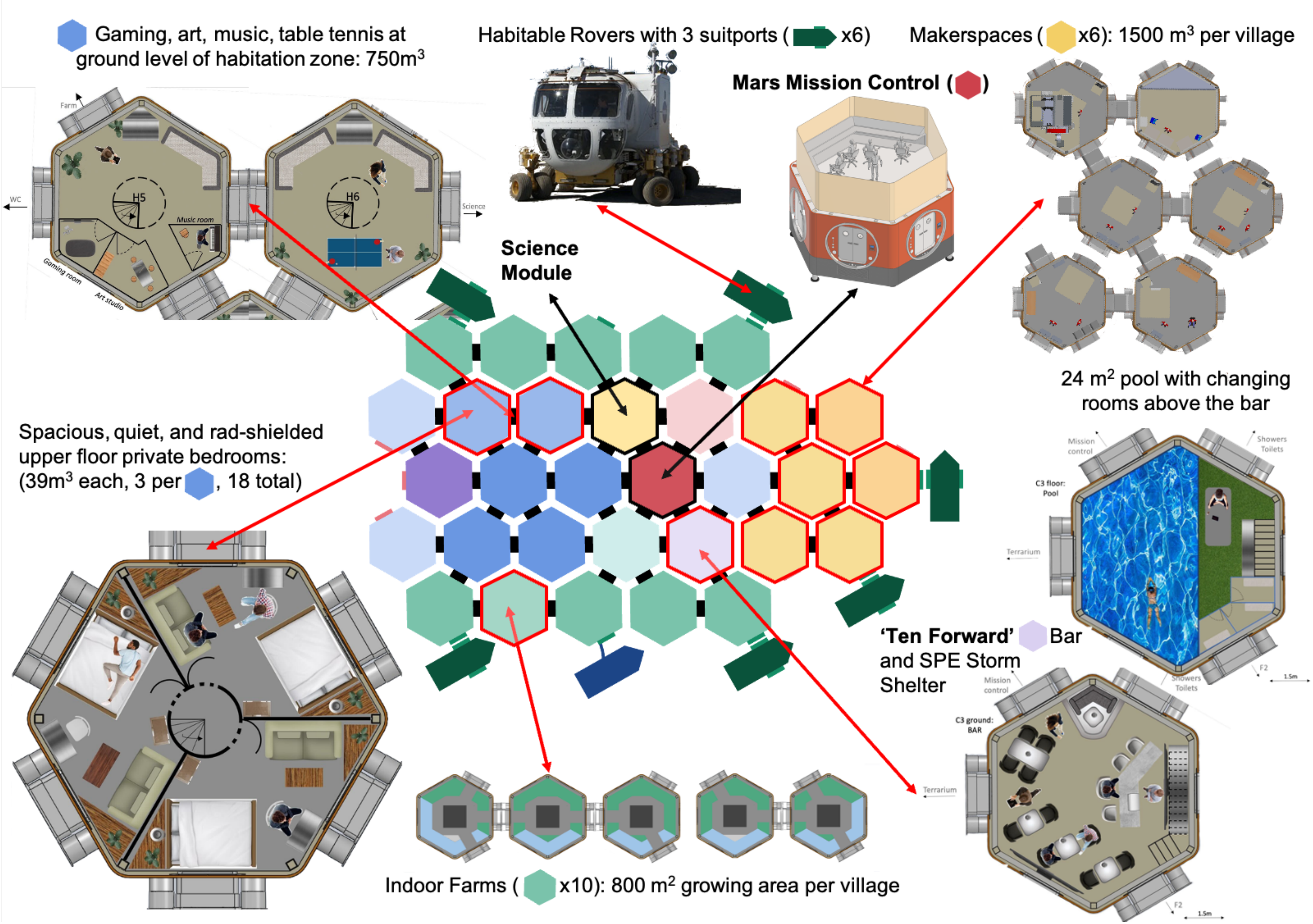
In-situ Technology Development: A side benefit of having 960 sq.m of makerspaces, machines and tools on Mars is that crew are likely to innovate in technology development. We believe that those who will be living and working on Mars will be best placed to come up with novel and innovative solutions to the problems they will face. A flexible makerspace is more likely to nurture innovation, when compared to a more rigid system dedicated to reproducing designs from Earth.

Intermediate Habitats: The intermediate habitats are designed around a modular inflatable unit which provides 249 m^3 of volume, 80 m^2 of floor space over two floors, 120 tons of water storage on the roof providing radiation shielding, water security and thermal management, a self-contained life support system with both open-loop and closed-loop capabilities, power, data, grey and dirty water interconnections, and up to six large openings to dock with other modules or rovers and build out a village. (Fig. 4 and Fig. 5). The modules have been analyzed and designed for gravity and pressure loading using finite element analysis. The material of choice is Aluminum 6061-T6 due to its lightweight and ability to withstand subzero temperatures. The final mass of the structure is 32 tons per module. The detailed structural analysis can be found in Appendix H.

Village urban plan: Each village, shown in Fig. 3, 4, 5 consists of 31 interconnected hexagonal modules and 1 offsite waste processing and ore processing module. Thus, each village has almost 2,500 m^2 of floor space and almost 7,700 m^3 of volume to support nominally 18, but up to 36 persons in an emergency. For comparison, the International Space Station has about 983 m^3 of volume for six persons. The modules are arranged in a dense configuration for connectivity and radiation protection. The overall architectural plan will contribute to a sense of community and safety, in a space that will feel lived-in, while providing opportunities for privacy as well as socialization, essential work as well as self-expression, effective leadership as well as collective dialogue and reflection.

Earth-sized, quiet, radiation-shielded **large private bedrooms** are on the upper floors in the habitation zone. They are designed for comfort, personal time, but also socialization, ensuring a balanced circadian rhythm. The ground floors below are public spaces with various small facilities, such as art studios, music rooms, and gaming rooms, that will cater to the recreation needs of individuals with diverse personalities. Directly to the west of the habitation modules are two **hygiene modules**, which feature toilets and washbasins on the ground floor and showers and laundry machines on the upper floor. To the north and south, there are 10 **farm modules** with a total growing area of 800 m2 per village, sufficient to meet the needs of the 18 inhabitants with a margin of 50%. The calculations are shown in Appendix F. The village also includes a **Science module, Mission Control and a Terrarium**. The science module has small labs on the ground floor, and an open collaborative desk-working space for scientists and researchers on the upper floor. The mission control module has is an open space for briefings and town halls, while the upper floor hosts the Mars Mission Control facilities. The terrarium module is double-height, with no upper floor, with trees planted in Terra Preta biochar (Black Earth) produced by the Waste Processing module. The terrarium offers an essential connection to nature, which will be vital for the emotional functioning and psychological grounding of crew members.

Figure 4: Village Zones and Modules: Farms, Habitation, Mission Utilization and Makerspaces



Permanent habitat construction: Upon arrival the crew begin excavating habitats in tunnels at a projected rate of 25 m^3 per day by safely teleoperating the roadheaders and the regolith removal rovers using radio repeaters laid in the tunnels. Construction takes 3 years (see Appendix F for calculations), but it is possible to move in by the end of the second year.

Crew Health - Radiation budget and protection: The entire mission duration including time spent in round-trip transit, initial habitats, intermediate surface habitats, and final tunnel habitats subjects crew to radiation exposure in the form of solar particle events (SPEs) and galactic cosmic radiation (GCR). Starships provide shielding in the fast, 113 day transit legs and initial, 30-day habitat phase through 35 g/cm^2 polyethylene shielding in all directions. The cumulative radiation dose must not exceed 600 mSv for the 10-year surface mission [58, 137]. On top of that, the crew should have a remaining dose budget available for surface exploration, to enable achieving the goals of the mission. Detailed calculations of radiation exposure in various habitat configurations reveals that spending a 7 year mission duration on the surface in habitats even with a 3m water shield on top and a 1m polyethylene shield on the sides results in >800 mSv cumulative dose. Therefore, in order to remain under the cumulative dose limit with time available for science and exploration, the architecture must include underground tunnels (Appendix C and F), as several meters of intact, compacted regolith provides shielding against GCRs that is not afforded by feasible levels of surface shielding. In all habitat configurations, crew are fully protected against SPEs.

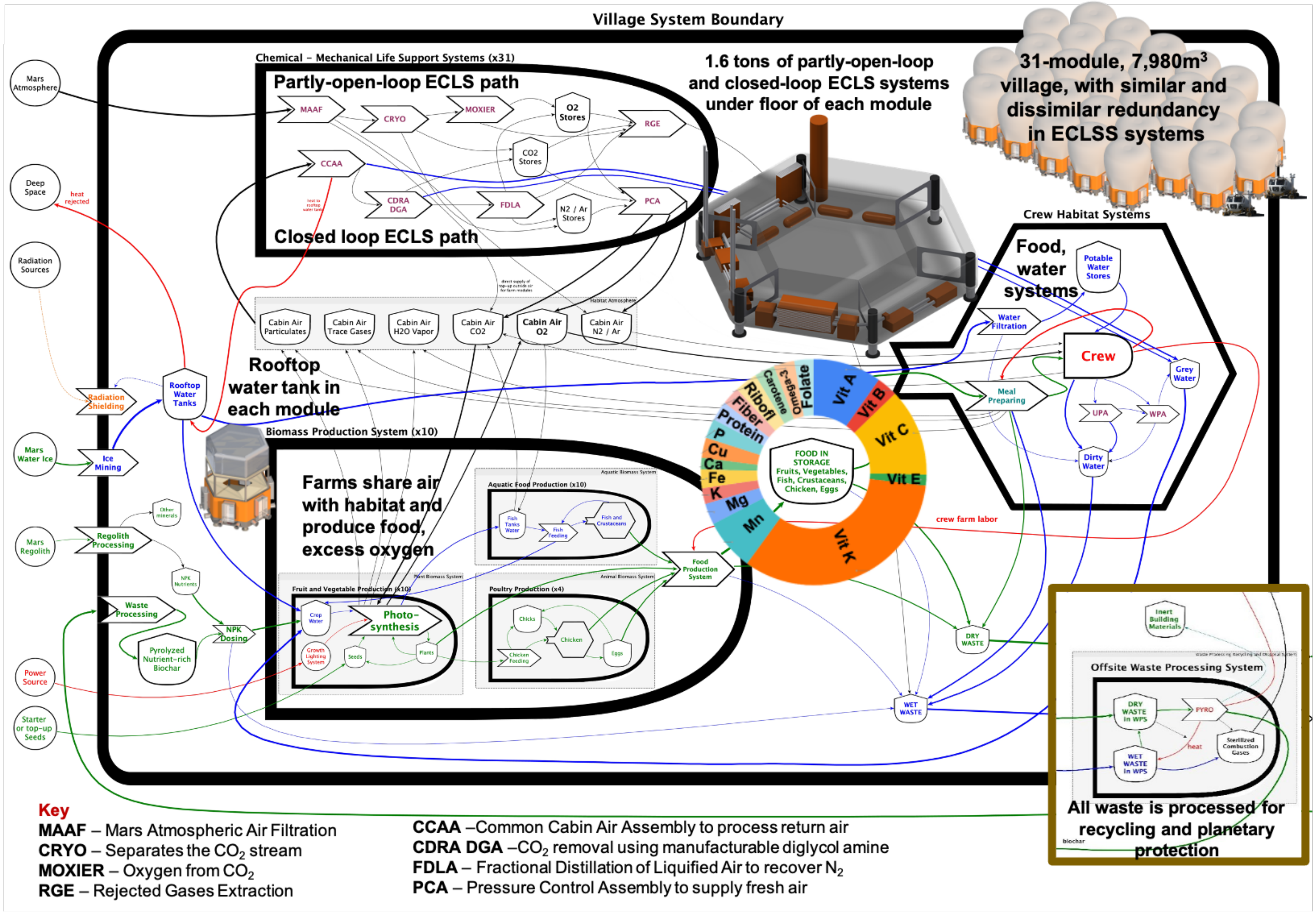
Medical and psychosocial care: Medical capabilities will build on Artemis and ISS plans to enable autonomy in mission medical care. A complete healthcare system is needed to enable a long-duration human presence; a medical module is included in each village to include emergency medicine, outpatient care, preventative medicine, and dental capabilities as well as quarantine spaces. The large mission (36 crew) makes it possible to include several on-site medical specialties including emergency medicine, orthopedics, cardiology and psychiatry to address the most immediate threats to crew on Mars. Crew medical officers will be fully trained in general practice for non-emergency times. Non-emergency specialist needs will be met via AI-based diagnostics and telehealth, with specialists in Mission Support on Earth to address non-urgent medical needs that can be supported outside of the round-trip light-travel time window ($\tilde{4}$3 minutes max). Psychosocial care is an integral part of crew health management, prioritizing recovery and resilience, sensitivity to personal transitions, and optimal functioning from a biopsychosocial perspective. Specialists offer individual counseling and psychotherapy and advise mission control on activities for psychosocial functioning and social cohesion.

The medical modules, one per village, provide a comprehensive Level V care facility, including advanced life support, basic surgical care, and ambulatory services [137]. The first floor includes an Imaging Unit with various diagnostic devices, a Pharmacy Unit processing supplements and managing medications, and a Doctor-on-call room for immediate medical response. Additionally, there are Exam rooms and an Emergency Department equipped for trauma care and first aid. The second floor stores medical supplies and features a Quarantine Unit with isolation capabilities, an Intensive Care Unit with various monitoring tools, and a Surgery Unit with complete surgical facilities. Medical equipment is mobile for versatile use across units.

Food and Life Support Systems Concurrent Design: The food and life support systems of the Mars colony are built on the principle of 100% food production, which poses significant challenges. Fluctuating food output and an imbalance of oxygen and CO_2 generation require food overproduction and storage, as well as a life support system with open and closed-loop capabilities that retains nitrogen while rejecting excess oxygen. All waste, including cabin air, is processed due to planetary protection considerations. Food production intersects nutrition, water management, and air revitalization, necessitating highly manufacturable systems for Mars. The makerspace used for system maintenance must be reliable and manufacturable, too. The village's life support system, illustrated in Fig. 5, controls cabin environment, water sources and recovery, and waste disposal. It includes 31 independent systems per village - one per module - for redundancy and operational flexibility. Its design maximizes commonality and minimizes complexity, allowing for efficient crew responses to contingencies. The life support system collaborates with the food production system to manage atmospheric conditions. Martian air, rich in CO_2, is filtered and supplied to the biomass production system. The farm maintains slightly higher pressure, enabling differential flow to other modules, integrating a comprehensive biological, physical, and chemical life support system.

Food System Technologies: The primary mode of food production on Mars is based on hydroponics, specifically the Nutrient Film Technique as tested on the ISS. Nutrients for plant growth

Figure 5: Habitat Life Systems Diagram: Farms, Air revitalization and Water



are supplied from regolith and waste processing, extracting the necessary nitrogen, potassium, and phosphorus and are recycled by the aquaponics system, which also doubles as a radiation shield. The remaining area is organized into shelves where crops will receive nutrients from the module's main delivery system and lighting from LED light strips above each tray supplying the appropriate wavelengths for optimal growth. The nutrient will be pumped through each tray, flowing through the roots of the plants while Rockwool cubes housing the crops will maintain a healthy growing environment. Inedible or surplus biomass is fed to chicken to enrich the diet of the crew. A large variety of plants, including leafy greens, rooted vegetables, herbs & spices, fruiting crops, grains, legumes and mushrooms, along with aquatic protein (e.g. Tilapia, Jade Perch, Red Claw Crayfish) and animal protein (i.e., chicken and eggs), will provide varied nourishment and enable the expression of diverse cuisines. A full list of crops and livestock options is included in Appendix F.

Specialized Life Support Technologies: While inspiration and technically ready systems were chosen from past architectures such as the ISS, unique adaptions of life support systems were developed for our Martian site. A deep dive into our Mars-Habitat Air system is described in detail to show how we maintain N_2 in our system, while removing excessive oxygen and adding essential CO_2. With reference to Fig. 5, the **return cabin air** is handled by CCAA to remove particulates and trace contaminants and to control humidity and temperature. The CCAA is fitted with air handling, filters, dehumidifier, heat exchanger and Trace Contaminant Control (TCC), the latter using highly manufacturable thermally regenerated carbon beds (Russian). Then, the **filtered, dehumidified air** is put through our CDRA-DGA and Distillation to remove and collect CO_2 and H_2O, followed by cryocooling and distillation to **select only N_2** with high (99.999%) purity. We store the N_2 in our N_2 tank and send the excess oxygen and other gases to the waste stream for offsite processing. Having removed moles of O_2 from the habitat, for **mass balance** we must add an equal number of moles of oxygen in the form of CO_2 and provide it to the farms. The 31 ECLSS modules thoroughly mix the air among them to support plants, animals and humans. In the event of failure or downtime of even a majority of modules, as few as 10 life support modules can support 36 persons. In case of a **failure of the crops**, oxygen generation capabilities will be provided by MOXIER, (Mars Oxygen ISRU Environment Re-creation), a scaled-up version of the successful MOXIE technology demonstration [87]. Atmospheric CO_2 is obtained by pumping in from the Martian atmosphere and separating from N_2 and Ar in cryogenic chambers, to then be heated to high temperatures for solid oxide electrolysis.

Thus, in any anomalous condition of localized atmospheric imbalances, and in any off-nominal state of the distributed, modular physical-chemical-bioregenerative life support system, Mars Mission Control (MMC) can select their response among a large range of options. Moreover, the substantial size of the architecture means that the atmospheric composition mixes easily and the averages change more slowly compared to smaller villages, magnifying the control authority margins and increasing the time available to MMC to respond.

Design for manufacturability and maintainability: The overall life support system for one village to thrive has been studied in some detail, along with the estimated flow rates and potential for manufacturability on Mars. Using manufacturability as the primary design criterion, our entire system is targeted to be approximately 91% manufacturable by mass in steady-state. Each module of the habitat contains the systems shown in 5 while sharing a unified monitoring and control system. UPA will be located in the Hygiene modules and Medical modules. An assumed efficiency rate of 90% is used for all processes to determine the necessary inputs, with an additional safety factor of 1.5 being implemented in the design process. To demonstrate that manufacturability of this system is feasible, a deep dive of the ECLSS Air system was completed to five levels, where level five contains part level descriptions. In Table 2, the manufacturability of level 4 systems within ECLSS-Air System (Level 3) is shown. Level 5 part breakdown and its manufacturability is available within Appendix F.

Table 2: Manufacturability of Life Support Systems from in-situ materials

Level 4 Subsystems Of ECLSS-AIR System	Total Mass Per Subsystem [kg]	Manufacturability Percentage Per Subsystem	Mars-sourced Mass Per Subsystem [kg]
CDRA-DGA	298.40	96.56 %	288.13
CCAA	302.73	79.43 %	240.46
AM	9.55	30.00 %	2.87
MOXIER AA & CS	200.00	89.47 %	178.95
MOXIER SOE SAS	107.50	74.32 %	79.90
ORA	456.75	96.21 %	439.42
GS	204.00	98.04 %	200.00
Total ECLSS-AIR	1578.94	90.55 %	1429.73

Waste management: All gas, liquid and solid waste streams are sent to an offsite module where they will be processed using pyrolysis and incineration. The outputs are sterilized gases, inert solids and useful byproducts such as biochar (Terra Preta), recovered nutrients and building materials.

Science and Exploration: The entire architecture was developed by "architecting from the right" to ensure availability of crew time and sufficient radiation mitigation to support science and exploration. Moreover, our thriving Martians operating out of a safe and happy community are more likely to produce ground-breaking science results. In support of this, one $249m^3$ module and six habitable rovers per village are provided to support science and exploration. Specific equipment is open for later determination, but at a minimum ground-penetrating radar, geotechnical equipment and mass spectrometers will be included.

Mars Mission Control: Mission Control for our crew is located on Mars. Each village has three Mission Controllers and a module devoted to Mission Control, as shown in Fig. 4. All surface, mobile and Mars-orbiting systems can be monitored, diagnosed or teleoperated from here. One village will have the live Mars Mission Control Center and the other will serve as backup, running simulations. Mission Control will utilize principles of transformative and collaborative leadership to transform challenges into opportunities for growth [172].

8 Risk Management and Mitigation

The entire Pale Red Dot architecture and project plan was designed to mitigate risks to human health and the mission. We considered risks across several categories: endurance, human factors, health and well-being, mission infrastructure, delays in technology maturation, cost growth, and the mission's ability to endure for ten years. The overall system architecture was iterated to negate, avoid, or mitigate those identified risks. The Pale Red Dot CONOPS also includes steps throughout the system design and development phase to further mitigate risks and allow early detection of other unknown risks. Due to the large scope of the architecture, the Risk Register detailing 25 risks with preemptive and corrective mitigations is included in Appendix A. A sample of three risks related to energy, endurance and a systemic design flaw and their mitigations is presented in Fig. 6:

General Information		Causal Factors		Post Mitigation Risk		Pre-Mitigation Risk		Risk Reduction	
ID	Risk	Likely Causes	Knowledge Gaps	Likelihood	Severity	Likelihood	Severity	Preemptive Mitigation	Corrective Actions
Q-1	Reactor failure	Critical component failure or emergency shutdown	Lack of service data and failure modes on Mars	1	1	2	2	Triple redundant design - the power generation system can support a triple failure (one reactor could provide sufficient contingency power to both villages	Control system senses failure and ramps up power from spare reactors to meet power demand
E-5	Loss of Food Generation Capacity	Water contamination, grow light failures, or inappropriate soil chemistry	Long-term viability of plants in Martian habitats	1	4	3	5	Each village will be generating food in quantities to supply all three villages in the event any two villages fail. Plants will be taken on pre-cursor missions and grown in a scaled down version of the intended long-term growing method	Multiple crop types will be taken and backup seeds will be taken to have the option to grow additional crops
Sys-1	Systemic design flaw	Poor manufacturing quality, poor design quality, misunderstood use-cases, unexpected over-utilization, rushed to production design, etc.	Unexpected use-cases	2	2	3	5	The design team will rely on systems which have realistic chances of reaching TRL 9 in the next years. This will afford sufficient time to better understand the use-cases, perfect the system architecture, and work out any potential design issues. There will be sufficient time for testing the equipment and making incremental modifications well before the planned mission launch timelines.	Systems will maximize the use of Mars-producable products so designs can be fix and built on Mars with minimal need for Earth-manufactured goods.

Figure 6: Sample of Risk Register (full Risk Register in Appendix A)

Human Factors Contingencies: Analog Development and Testing: Given the novelty of our architecture, we have designed and executed a pilot Pale Red Dot analog mission to validate certain aspects of the design. A novel analog is necessary for testing the large-scale multi-site architecture, including the psychosocial aspects of large crew dynamics and governance and to what extent a growth-oriented architecture, with an emphasis on thriving and not just surviving, will enable that sense of home and well-being that will be required for such a long-term mission [114]. Taking into account judge feedback from the proposal stage, we have developed the first known study of a multi-site mission architecture that investigates the responses to inter- and intra-village conflict, as well as emergency response procedures through a series of simulated contingency and emergency events. Each crewmember is assigned to a primary and secondary survival-related profession and asked to select an expression-related profession. Throughout the mission, participants are asked to complete a daily psychosocial questionnaire to evaluate changes in perception of the lived experience in response to contingencies and emergencies, and also to complete a daily diary entry with prompts that investigate the interactions with and perceptions of crew both within the same village and in the other village. Embedded investigators record observations via structured data entry to capture crew dynamics in response to simulated conflict, contingency, and emergency scenarios.

This analog mission has received approval for human subjects testing (MIT COUHES Protocol #2302000904) and took place from May 27th - June 1st, 2023 near Grafton Notch State Park, Maine. Results will be presented at the Forum and will constitute a proof-of-concept test of both the crew dynamics and emergency operations procedures uniquely enabled by the multi-site architecture described here. Future development includes plans for a higher-fidelity analog facility to de-risk the overall architecture and train crew.

9 Cost and Feasibility

Total launches and total mass launched: Details on all launches, launch fairing packaging, method for unloading modules to the surface of Mars, monthly launch density and the dependencies / critical paths among them are provided in the CONOPS infographic Figure 2 and the number of launches and total mass is summarized in the table inset in Fig. 7.

Cost Metrics: The total lifetime cost of the architecture is $81,148m and the peak annual cost is $6,639m. The cost per mission-value full-time equivalent (MVFTE) crew member per year is $290m if we include all unallocated time over and above survival-related work and non-work personal and social time. Calculations are shown in Appendix F.

Cost and benefit sharing with international partners: We've analyzed the budgets of all NASA's Artemis Accords partners and the International Space Exploration Coordination Group (ISECG). Conversations with a senior ESA official suggest that ESA (and hence, also potentially JAXA) could contribute up to $10b in equipment each for a Mars mission. Without counting other possible contributions, such as from Canada, Korea, or India, the ESA and JAXA contributions could offset up to 25% of total mission costs. Our large architecture choice allows for international and commercial partnership, sharing costs following successful models like Commercial Crew and CLPS.

This results in total cost of $81,148 million for two 36-person crews, and cost per full-time-equivalent person per year on Mars will free time for science, exploration and contingencies is $290 million. DDT&E costs for each unique module were anchored on the successful Falcon 9 development ($400m) [198] while manufacturing and operations costs were anchored on New Space practices and costs. A PCEC calculation (not shown) produced a result about an order of magnitude higher, matching the finding from Zapata that Falcon 9 would have cost $4 billion to develop if it had been done in the traditional cost-plus approach embodied in PCEC [198].

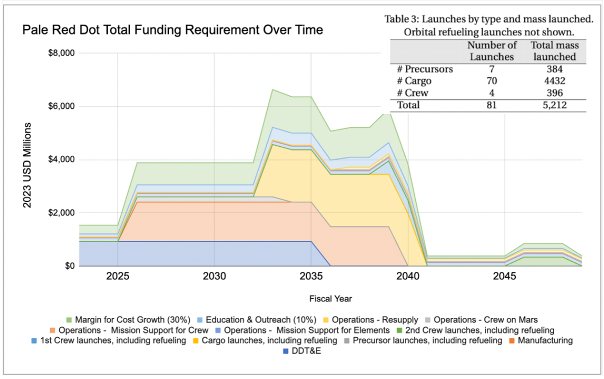


Table 3: Launches by type and mass launched. Orbital refueling launches not shown.

	Number of Launches	Total mass launched
# Precursors	7	384
# Cargo	70	4432
# Crew	4	396
Total	81	5,212

Figure 7: Pale Red Dot - Funding requirement over time

10 Discussion and conclusions

Pale Red Dot presents a resilient system architecture for supporting a large astronaut team on Mars for a decade, with multi-redundant designs sustainable for multiple missions and enabling permanent Martian presence. This large, distributed structure prioritizes safety, scientific exploration, growth, in-situ technology development, and includes all Artemis Accords partners. We believe that Pale Red Dot, with its large tent that has room for dozens of international and commercial partners, will turn out to be more sustainable technically, financially, and politically than a smaller project that has much less room for error when it comes to dealing with unexpected, potentially mission-ending contingencies.

References

[1] Evan Ackerman. *Your Robotic Avatar Is Almost Ready. What the Avatar XPrize revealed about the future of telepresence robots.* `https://spectrum.ieee.org/amp/xprize-robot-avatar-2659841487`. 2023.

[2] National Aeronautics and Space Administration Ames Research Center. *Mars Climate Modeling Center.* `https://www.nasa.gov/mars-climate-modeling-center-ames`. 2023.

[3] National Aeronautics, Space Administration Scientific, and Technical Information Program. "What Made Apollo a Success?" In: NASA SP-287 (1971).

[4] National Aeronautics and Space Administration Mars Human Landing Sites Study. *NASA Seeks Ideas for Where on Mars the Next Giant Leap Will Take Place.* `https://www.nasa.gov/journeytomars/mars-exploration-zones`. 2015.

[5] National Aeronautics and Space Administration Advanced Multi-Mission Operations System. *Mars Water Resource Maps.* `https://ammos.nasa.gov/marswatermaps/?mission=MWR`. 2023.

[6] European Space Agency. *Lunar Economy Applications Webinar.* `https://business.esa.int/funding/intended-tender/lunar-economy-applications`. 2023.

[7] JoeFromRIUSA et al. *Mars Colony Infrastructure.* `https://forum.spaceflight.com/index.php?topic=53443.0`. 2021.

[8] John Smith 19 et al. *Power options for a Mars settlement.* `https://forum.nasaspaceflight.com/index.php?topic=39785.0`. 2016.

[9] Lumina et al. *Envisioning Amazing Martian Habitats.* `https://forum.spaceflight.com/index.php?topic=41427.0`. 2016.

[10] University of Arizona. *Giant mantle plume reveals Mars is more active than previously thought.* `https://phys.org/news/2022-12-giant-mantle-plume-reveals-mars.html`. 2022.

[11] Dale C. Arney et al. "Sustaining Human Presence on Mars Using ISRU and a Reusable Lander". In: *American Institute of Aeronautics and Astronautics* (2015). DOI: `10.2514/6.2015-4479`.

[12] Reynir Smari Atlason et al. "Energy Return on Investment for Aquaponics: Case Studies from Iceland and Spain". In: *Springer Journal of Biophysical Economics and Resource Quality* 2017 2:3 (2017). DOI: `DOI10.1007/s41247-017-0020-5`.

[13] Alec Auster et al. "Mars Ice Thermal Harvesting Rig & ISRU Laboratory (MITHRIL)". In: *ASCEND 2022*. DOI: `10.2514/6.2022-4249`. URL: `https://arc.aiaa.org/doi/abs/10.2514/6.2022-4249`.

[14] Anonymous Author(s). "MechSense: A Design and Fabrication Pipeline for Integrating Rotary Encoders into 3D Printed Mechanisms". In: *Association for Computing Machinery* (2022).

[15] Emiliano Bellini. *US startup begins producing 40%-efficient thermophotovoltaic cells.* `https://www.pv-magazine.com/2023/01/25/us-startup-begins-producing-40-efficient-thermophotovoltaic-cells/`. 2023.

[16] Adrienne Berard. *Traces of ancient ocean discovered on Mars.* `https://phys.org/news/2022-10-ancient-ocean-mars.html`. 2022.

[17] Eric Berger. *SpaceX is now building a Raptor engine a day, NASA says.* `https://arstechnica.com/science/2022/11/spacex-is-now-building-a-raptor-engine-a-day-nasa-says/`. 2022.

[18] Eric Berger. *A new report finds NASA has spent an obscene amount of money on SLS propulsion.* `https://arstechnica.com/space/2023/05/a-new-report-finds-nasa-has-spent-an-obscene-amount-of-money-on-sls-propulsion/`. 2023.

[19] Eric Berger. *Artemis program may face a budget crunch as costs continue to rise.* `https://arstechnica.com/science/2023/05/-leader-warns-agency-needs-more-funding-to-fly-artemis-missions/`. 2023.

[20] Eric Berger. *At long last, the glorious future we were promised in space is on the way.* https://arstechnica.com/space/2023/05/at-long-last-the-glorious-future-we-were-promised-in-space-is-on-the-way/. 2023.

[21] Eric Berger. *Lockheed Martin makes a big bet on commercial space and the Moon.* https://arstechnica.com/science/2023/04/lockheed-martin-makes-a-big-bet-on-commercial-space-and-the-moon/. 2023.

[22] Eric Berger. *Once again, NASA leans into the future by picking an innovative lunar lander.* https://arstechnica-com.cdn.ampproject.org/c/s/arstechnica.com/space/2023/05/blue-origin-wins-pivotal-nasa-contract-to-develop-a-second-lunar-lander/amp/. 2023.

[23] Aaron J. Berliner et al. "Towards a Biomanufactory on Mars". In: *Frontiers in Astronomy and Space Sciences* 8 (2021). ISSN: 2296-987X. DOI: 10.3389/fspas.2021.711550. URL: https://www.frontiersin.org/articles/10.3389/fspas.2021.711550.

[24] Beschizza. *Why aren't you using a more efficient chest refrigerator?* https://boingboing.net/2022/11/04/why-arent-you-using-a-more-efficient-chest-refrigerator.html. 2022.

[25] Loz Blain. *Cheap, fast induction tech enables unlimited-size 3D metal printing.* https://newatlas.com/3d-printing/rosotics-3d-induction-printing/. 2023.

[26] Peter Bleday. "The autonomous revolution is here: Level up with Danfoss autonomy". In: *LinkedIn* (2023).

[27] Michael Booth. "How two brothers plan to save the world by packing a whole farm into shipping containers on a Denver used car lot". In: *The Colorado Sun* (2022). URL: https://coloradosun.com/2022/11/24/vertical-farm-shipping-containers-denver-food/.

[28] James Lee Broyan Jr., Thilini Schlesinger, and Michael K. Ewert. "Exploration Mission Benefits From Logistics Reduction Technologies". In: *International Conference on Environmental Systems* 46th.ICES-2016-140 (2016).

[29] Tomorrow's Build. *A Swarm of Robots Built This Tunnel.* https://www.youtube.com/watch?v=bfJY0syocfU. 2022.

[30] Fraser Cain and Rick Davis. *How a Realistic Mars Mission Will Play Out.* https://www.youtube.com/watch?v=tujL0xrQ2Os. 2023.

[31] Kevin M. Cannon and Daniel T. Britt. "Feeding One Million People on Mars". In: *New Space* 7.4 (2019), pp. 245–254. DOI: 10.1089/space.2019.0018. URL: https://doi.org/10.1089/space.2019.0018.

[32] Susana Carranza, Darby B. Makel, and Brandon Blizman. "In Situ Manufacturing of Plastics and Composites to Support H & R Exploration". In: *AIP Conference Proceedings* 813.1 (Jan. 2006), pp. 1122–1129. ISSN: 0094-243X. DOI: 10.1063/1.2169293. URL: https://doi.org/10.1063/1.2169293.

[33] Timothy Cichan et al. "Mars Base Camp: An Architecture for Sending Humans to Mars". In: *New Space* 5.4 (Dec. 2017), pp. 203–218. ISSN: 2168-0256, 2168-0264. DOI: 10.1089/space.2017.0037. URL: https://www.liebertpub.com/doi/10.1089/space.2017.0037 (visited on 03/14/2023).

[34] Catherine Clifford. *Oklo has a plan to make tiny nuclear reactors that run off nuclear waste.* https://www.cnbc.com/2021/06/28/oklo-planning-nuclear-micro-reactors-that-run-off-nuclear-waste.html. 2021.

[35] Catherine Clifford. *How super-hot rocks miles under the earth's surface could provide limitless clean energy.* https://www.cnbc.com/2022/10/28/superhot-rock-geothermal-what-is-it-could-it-fight-climate-change.html. 2022.

[36] Sara Cody. *MIT design for Mars propellant production trucks wins competition.* https://news.mit.edu/2022/design-mars-propellant-production-trucks-wins-nasa-competition-0711. 2022.

[37] UNESCO World Heritage Convention. *Petra*. https://whc.unesco.org/en/list/326/gallery/. 2023.

[38] Daniel Cooper. *Formlabs' new automation accessories turn its 3D printers into mini factories*. https://www.engadget.com/formlabs-ces-2023-automation-ecosystem-150054185.html. 2023.

[39] Teaghan Cowles. *Astropharmacy*. https://contest.techbriefs.com/2019/entries/sustainable-technologies/9984. 2019.

[40] Ben Coxworth. *Structure-inflating construction tech could give 3D printing a run for its money*. https://newatlas.com/good-thinking/ifff-construction-inflatable-concrete-buildings/. 2022.

[41] Callum Cyrus. *Major redundancies confirmed at German vertical crop growing business Infarm*. https://tech.eu/2022/11/29/german-infarm/. 2022.

[42] Charles Dalton et al. "Conceptual Design of a Lunar Colony". In: *American Society for Engineering Education System Design Institute* (1972). DOI: GrantNGT44-005-114.

[43] Abiosseh Davis et al. "Mind the Peace: Integrating MHPSS, Peacebuilding, and Livelihood Programming - A Guidance Framework for Practitioners". In: *Interpeace* (2023). URL: https://www.interpeace.org/wp-content/uploads/2023/03/PiP_7-MHPSS.pdf.

[44] Richard Davis et al. *Criteria for Landing Site Selection*. https://blogs.nasa.gov/redplanetdispatch/2022/12/13/criteria-for-landing-site-selection/. 2022.

[45] R. A. De Hon. "Alcoves as Havens From a Harsh Martian Environment". In: *Journal of Geophysical Research: Planets* 127.8 (2022), e2021JE007022. DOI: https://doi.org/10.1029/2021JE007022. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2021JE007022.

[46] Deere and Company. *Reborn, Not Rebuilt: The Story of John Deere Reman*. https://www.deere.com/en/stories/featured/reborn-not-rebuilt-the-story-of-john-deere-reman/. 2023.

[47] Inc. Desktop Metal. *[50+] 3D Printed Parts*. https://www.desktopmetal.com/. 2020.

[48] Inc. Desktop Metal. *Design for Additive Manufacturing: Fine Features*. https://www.desktopmetal.com/resources/design-for-additive-manufacturing-fine-features?utm_content=235393954&utm_medium=social&utm_source=linkedin&hss_channel=lcp-10383111. 2022.

[49] Inc. Desktop Metal. *Design for Additive Manufacturing: Internal Features and Channels*. https://www.desktopmetal.com/resources/design-for-additive-manufacturing-internal-features-and-channels?utm_content=226699019&utm_medium=social&utm_source=linkedin&hss_channel=lcp-10383111. 2022.

[50] Inc. Desktop Metal. *The Shop System: The Benefits of Binder Jetting*. https://www.desktopmetal.com/resources/the-shop-system-the-benefits-of-binder-jetting?utm_content=232661408&utm_medium=social&utm_source=linkedin&hss_channel=lcp-10383111. 2022.

[51] Inc. Desktop Metal. *SolidCAM, Additive Manufacturing Custom Cutting Tool*. https://www.linkedin.com/posts/desktopmetal_solidcam-additive-manufacturing-activity-7036326643618959360-P6Cb/?utm_source=share&utm_medium=member_desktop. 2023.

[52] Emily Devine. *Redwire Wins NASA Contract to Advance New In-Space Manufacturing Capability for Journeys to Moon, Mars and Beyond*. https://redwirespace.com/newsroom/redwire-wins-nasa-contract-to-advance-new-in-space-manufacturing-capability-for-journeys-to-moon-mars-and-beyond/. 2023.

[53] Sydney Do. "Towards Earth Independence – Tradespace Exploration of Long-Duration Crewed Mars Surface System Architectures". Massachusetts Institute of Technology, 2016.

[54] Sydney Do. "Towards Earth Independence – Tradespace Exploration of Long-Duration Crewed Mars Surface System Architectures". Massachusetts Institute of Technology, 2016.

[55] Michael Robert Doyle, Philippe Thalmann, and Aurèle Parriaux. "Embodied Energy and Lifecycle Costs: Questioning (Mis)conceptions about Underground Construction". In: *Buildings* 9.8 (2019). ISSN: 2075-5309. DOI: 10.3390/buildings9080188. URL: https://www.mdpi.com/2075-5309/9/8/188.

[56] B.G. Drake. *Human Exploration of Mars Design Reference Architecture 5.0.* Tech. rep. 2009. URL: https://www.nasa.gov/pdf/373665main%5C_NASA-SP-2009-566.pdf.

[57] Brett Drake. *First Landing Site / EZ Workshop - Mars High Latitude 1a.* https://www.youtube.com/watch?v=is9B7EM4UN0. 2015.

[58] Marco Durante and Francis A. Cucinotta. "Physical basis of radiation protection in space travel". In: *Rev. Mod. Phys.* 83 (4 Nov. 2011), pp. 1245–1281. DOI: 10.1103/RevModPhys.83.1245. URL: https://link.aps.org/doi/10.1103/RevModPhys.83.1245.

[59] Elise Elsacker, Meng Zhang, and Martyn Dade-Robertson. "Fungal Engineered Living Materials: The Viability of Pure Mycelium Materials with Self-Healing Functionalities". In: *Advanced Functional Materials* (), p. 2301875. DOI: https://doi.org/10.1002/adfm.202301875. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/adfm.202301875.

[60] Martin Elvis, Charles Lawrence, and Sara Seager. "Accelerating astrophysics with the SpaceX Starship". In: *Physics Today* 76.2 (2023), pp. 40–45. DOI: 10.1063/PT.3.5176.

[61] Sandra Erwin. *Military to tap commercial industry for 'space mobility' services.* https://spacenews.com/military-to-tap-commercial-industry-for-space-mobility-services/. 2023.

[62] Michael Ewert and Chel Stromgren. "Astronaut Mass Balance for Long Duration Missions". In: *49th International Conference on Environmental Systems* (2019).

[63] Michael K. Ewert, Thomas T. Chen, and Camilah D. Powell. "NASA Life Support Baseline Values and Assumptions Document". In: *National Aeronautics and Space Administration Technical Reports* NASA/TP-2015–218570/REV2 (2022).

[64] Michael K. Ewert et al. "Comparing Trash Disposal to Use as Radiation Shielding for a Mars Transit Vehicle". In: *International Conference on Environmental Systems* 47th.ICES-2017-178 (2017).

[65] Jeff Foust. *NASA releases draft strategy for long-term robotic Mars exploration.* https://spacenews.com/-releases-draft-strategy-for-long-term-robotic-mars-exploration/?utm_source=dlvr.it&utm_medium=twitter. 2023.

[66] Kminek G et al. "Meeting Report: COSPAR Panel on Planetary Protection Colloquium, Bern, Switzerland, September 2015". In: vol. 195. Sept. 2015. DOI: 10.1016/j.srt.2016.03.013.

[67] Brian Gallagher. "Should People Live on the Moon?" In: *Nautilus* (2023).

[68] Chloe Gentgen et al. "BART & MARGE Bipropellant All-in-one In-situ Resource Utilization Truck & Mobile Autonomous Reactor Generating Electricity". In: *RASC-AL 2022: Mars Water-Based ISRU Architecture Theme* (2022).

[69] Chloe Gentgen et al. "BART & MARGE: A Resilient and Scalable Architecture for In-Situ Propellant Production on Mars Using Large Trucks". In: *ASCEND 2022*. 2022, p. 4315.

[70] Andrew Good, Karen Fox, and Alana Johnson. *NASA Retires Mineral Mapping Instrument on Mars Orbiter.* https://www.nasa.gov/feature/jpl/nasa-retires-mineral-mapping-instrument-on-mars-orbiter. 2023.

[71] Kandyce E. Goodliff et al. "Comparison of Human Exploration Architecture and Campaign Approaches". In: *AIAA SPACE 2015 Conference and Exposition.* AIAA SPACE 2015 Conference and Exposition. Pasadena, California: American Institute of Aeronautics and Astronautics, Aug. 31, 2015. ISBN: 978-1-62410-334-6. DOI: 10.2514/6.2015-4413. URL: https://arc.aiaa.org/doi/10.2514/6.2015-4413 (visited on 03/14/2023).

[72] Kandyce E. Goodliff et al. "Logistics Needs for Future Human Exploration Beyond Low Earth Orbit". In: *AIAA SPACE and Astronautics Forum and Exposition.* DOI: 10.2514/6.2017-5122. eprint: https://arc.aiaa.org/doi/pdf/10.2514/6.2017-5122. URL: https://arc.aiaa.org/doi/abs/10.2514/6.2017-5122.

[73] Fabio Gori and Sandra Corasaniti. "Detection of a dry–frozen boundary inside Martian regolith". In: *Planetary and Space Science* 56.8 (2008), pp. 1093–1102. ISSN: 0032-0633. DOI: https://doi.org/10.1016/j.pss.2008.02.003. URL: https://www.sciencedirect.com/science/article/pii/S0032063308000354.

[74] Jeffrey B Greenblatt. "Design and Modeling of an Electrochemical Device Producing Methane / Oxygen and Polyethylene from In-Situ Resources on Mars". In: *Emerging Futures, LLC* (2019).

[75] International Space Exploration Coordination Group. *The Global Exploration Roadmap Supplement October 2022 Lunar Surface Exploration Scenario Update*. 2022.

[76] Casey Handmer. *How To Industrialize Mars: A Strategy For Self-Sufficiency*. https://docs.google.com/document/d/1pxQg51rGP6JtdD4Eix1xpVek1xX05eQVgc7Jbm6VtDw/edit?usp=sharing. 2018.

[77] A.J. Hanford. *Advanced Life Support Research and Technology Development Metric – Fiscal Year 2004*. Tech. rep. 2004. URL: https://ntrs.nasa.gov/api/citations/20040139875/downloads/20040139875.pdf.

[78] A.J. Hanford. *Subsystem Details for the Fiscal Year 2004 Advanced Life Support Research and Technology Development Metric*. Tech. rep. 2006. URL: https://docs.lib.purdue.edu/nasatr/2/.

[79] Anthony Hanford and Michael Ewert. "Advanced Life Support Research and Technology Development Metric – Fiscal Year 2004". In: *National Aeronautics and Space Administration Technical Reports* NASA/CR–2004–208944 (2004).

[80] Lindsay Hays. *Potential Exploration Zones for Human Missions to the Surface of Mars*. 2015.

[81] J. W. Head et al. "Mars Human Science Exploration and Resource Utilization: The Dichotomy Boundary Deuteronilus Mensae Exploration Zone". In: *First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars*. Ed. by LPI Editorial Board. Vol. 1879. LPI Contributions. Oct. 2015, p. 1033.

[82] Brian Heater. *Ally is building a dead-simple, no-code robot arm*. https://techcrunch.com/2022/10/19/ally-is-building-a-dead-simple-no-code-robot-arm/amp/. 2022.

[83] Jennifer L Heldmann et al. "Mission architecture using the SpaceX starship vehicle to enable a sustained human presence on Mars". In: *New Space* 10.3 (2022), pp. 259–273.

[84] Aloysius Hepp, Geoffrey Landis, and Clifford Kubiak. "A Chemical Approach to Carbon Dioxide Utilization on Mars". In: (Feb. 1997).

[85] Karl B. Hille. *NASA Turns to AI to Design Mission Hardware*. https://www.nasa.gov/feature/goddard/2023/nasa-turns-to-ai-to-design-mission-hardware. 2023.

[86] Joel Hiller. *Microreactors*. https://inl.gov/trending-topic/microreactors/. 2023.

[87] Eric Hinterman. "Multi-Objective System Optimization of a Mars Atmospheric ISRU Plant". Massachusetts Institute of Technology, 2022.

[88] Max Hirshkowitz et al. "National Sleep Foundation's updated sleep duration recommendations: final report". In: *Sleep Health* 1.4 (2015), pp. 233–243.

[89] Stephen J. Hoffman, Alida D. Andrews, and Kevin D. Watts. "Simulated Water Well Performance on Mars". In: *2018 AIAA SPACE and Astronautics Forum and Exposition*. 2018. DOI: 10.2514/6.2018-5293. URL: https://arc.aiaa.org/doi/abs/10.2514/6.2018-5293.

[90] Richard Hulskes. *3D Printing a Titanium Part Created By Artificial Intelligence*. https://www.linkedin.com/posts/richard-hulskes_3d-printing-a-titanium-part-created-by-artificial-activity-7036269586664554496-jMFR/?utm_source=share&utm_medium=member_desktop. 2023.

[91] HumanMars.net. *Mars Colonization Timeline*. https://www.humanmars.net/p/mars-colonization-timeline.html. 2022.

[92] Caterpillar Inc. *Meet Caterpillar's First Battery Electric Large Mining Truck*. https://www.youtube.com/watch?v=jt0k3TYFh3k. 2022.

[93] The Planetary Science Institute. *Subsurface Water Ice Mapping on Mars.* https://swim.psi.edu/. 2023.

[94] International Space Exploration Coordination Group. *In-Situ Resource Utilization Gap Assessment Report.* 2021.

[95] J. Jin et al. "Constrained C2 adsorbate orientation enables CO-to-acetate electroreduction". In: *Nature* 617 (2023), pp. 724–729. DOI: https://doi.org/10.1038/s41586-023-05918-8. URL: https://doi.org/10.1038/s41586-023-05918-8.

[96] David Karl, Kevin M. Cannon, and Aleksander Gurlo. "Review of space resources processing for Mars missions: Martian simulants, regolith bonding concepts and additive manufacturing". In: *Open Ceramics* 9 (2022), p. 100216. ISSN: 2666-5395. DOI: https://doi.org/10.1016/j.oceram.2021.100216. URL: https://www.sciencedirect.com/science/article/pii/S2666539521001620.

[97] Mikayla Kelley and Kai Staats. *Media Advisory: Crew to be sealed in pressurized habitat at Biosphere 2.* https://news.arizona.edu/press-release/media-advisory-crew-be-sealed-pressurized-habitat-biosphere-2. 2023.

[98] L. Kerber et al. *A Human Landing Site at Apollinaris Sulci: Life Inside a Yardang.* 2015.

[99] Ivan Khrapach and Space Ambition. *Overcoming challenges in Martian and Earth agriculture: a path to sustainable food production.* https://spaceambition.substack.com/p/overcoming-challenges-in-martian. 2023.

[100] Lee Klancher. *South Pole Traverse.* https://octanepress.com/content/south-pole-traverse_antartica_quadtrac_CaseIH_Steiger_McMurdoStation?utm_source=Octane+Blog&utm_medium=Web&utm_campaign=LinkedIn+Posts. 2017.

[101] Scarlett Koller et al. "Artemis Steelworks". In: *NASA 2023 BIG Idea Challenge: Lunar Forge* (2023).

[102] Wiley Larsen, Linda Pranke, and Roger Arno. *Human Spaceflight: Mission Analysis and Design (Space Technology Series).* McGraw-Hill College, 1999, pp. 447–476. ISBN: 978-0072368116.

[103] Wiley Larsen et al. *Human Spaceflight: Mission Analysis and Design (Space Technology Series).* McGraw-Hill College, 1999, pp. 539–573. ISBN: 978-0072368116.

[104] Wiley Larsen et al. *Human Spaceflight: Mission Analysis and Design (Space Technology Series).* McGraw-Hill College, 1999, pp. 477–512. ISBN: 978-0072368116.

[105] Wiley Larsen et al. *Human Spaceflight: Mission Analysis and Design (Space Technology Series).* McGraw-Hill College, 1999, pp. 575–606. ISBN: 978-0072368116.

[106] Nick Lavars. *Cheap sodium-sulfur battery boasts 4x the capacity of lithium-ion.* https://newatlas.com/energy/cheap-sodium-sulfur-battery-four-times-capacity/. 2022.

[107] Heidi Lavelle. *Mars Ep. 6: Eat Like a Martian.* https://www.NASA.gov/johnson/HWHAP/mars-ep6-eat-like-a-martian. 2023.

[108] Han-Joo Lee, Jorge Cañada, and Luis Fernando Velásquez-García. "Compact peristaltic vacuum pumps via multi-material extrusion". In: *Additive Manufacturing* 68 (2023), p. 103511. ISSN: 2214-8604. DOI: https://doi.org/10.1016/j.addma.2023.103511. URL: https://www.sciencedirect.com/science/article/pii/S2214860423001240.

[109] Victor J. Leon et al. "Externally Tunable, Low Power Electrostatic Control of Cell Adhesion with Nanometric High-k Dielectric Films". In: *Advanced Functional Materials* (), p. 2300732. DOI: https://doi.org/10.1002/adfm.202300732.

[110] Michelle Lewis. *This game-changing big 'brick toaster' battery is now on the market.* https://electrek.co/2022/11/21/rondo-big-battery-is-like-a-brick-toaster-and-its-on-the-market/. 2022.

[111] Michelle Lewis. *A Mars rover scientist is about to scale carbon-oxygen batteries.* https://electrek.co/2023/01/18/mars-rover-scientist-carbon-oxygen-batteries/. 2023.

[112] Vanesa Listek. *Ursa Major and EOS to Disrupt Space Production with 3D Printed Copper.* https://3dprint.com/295980/ursa-major-and-eos-to-disrupt-space-production-with-3d-printed-copper/?utm_source=dlvr.it&utm_medium=linkedin. 2022.

[113] Alexandros Lordos and Daniel Hyslop. "The Assessment of Multisystemic Resilience in Conflict-Affected Populations". In: *Multisystemic Resilience: Adaptation and Transformation in Contexts of Change*. Oxford University Press, Apr. 2021. ISBN: 9780190095888. DOI: 10.1093/oso/9780190095888.003.0023. eprint: https://academic.oup.com/book/0/chapter/350425087/chapter-pdf/49943739/oso-9780190095888-chapter-23.pdf. URL: https://doi.org/10.1093/oso/9780190095888.003.0023.

[114] Alexandros Lordos and George Lordos. "Preparing for the socio-behavioural challenges of a populous, semi-independent settlement on Mars through a new generation of multi-team, empowerment-oriented Mars analogue missions". In: *International Astronautical Congress - The CyberSpace Edition* 71st (2020). DOI: IAC-20-A1.1.10.

[115] George Lordos and Alexandros Lordos. *Star City, Mars*. 2019.

[116] George Lordos and Olivier L. de Weck. "Evaluating the Sustainability of Long Term Manned Mars Campaigns Using a Physical Economics Framework". In: *International Astronautical Congress - The CyberSpace Edition* 69th (2018). DOI: IAC-18.A5.2.8x47969.

[117] Komatsu Ltd. *Accelerating to achieve safe, highly productive, smart and clean workplaces of the future- Developed a concept machine for a medium-sized hydraulic excavator equipped with a hydrogen fuel cell, and began PoC tests*. https://www.komatsu.jp/en/newsroom/2023/20230512. 2023.

[118] Komatsu Ltd. *Komatsu Lunar Machine - Part 2*. https://www.linkedin.com/posts/komatsu_komatsu-lunar-machine-part-2-activity-7053653667664596992-ft5O/?utm_source=share&utm_medium=member_ios. 2023.

[119] MDA Ltd. *Satellite Systems Radar Imaging of Mars*. https://mda.space/en/sar-for-mars/. 2023.

[120] A. Machkenzie et al. *Commercial Planning Assumptions for the United States Space Force: Findings from the Space Futures Workshop and Industry*. https://www.linkedin.com/posts/erik-mudrinich_space-futures-workshop-report-2023-activity-7063618027522592768-ghC-/?utm_source=share&utm_medium=member_ios. 2023.

[121] Erin Mahoney. *NASA Details Strategy Behind Blueprint for Moon to Mars Exploration*. https://www.nasa.gov/feature/-details-strategy-behind-blueprint-for-moon-to-mars-exploration. 2023.

[122] Erin Mahoney and Brian Dunbar. *NASA's Moon to Mars Architecture*. https://www.NASA.gov/MoonToMarsArchitecture. 2023.

[123] Dharik S. Mallapragada et al. "Decarbonization of the chemical industry through electrification: Barriers and opportunities". In: *Joule* 7.1 (2023), pp. 23–41. ISSN: 2542-4351. DOI: https://doi.org/10.1016/j.joule.2022.12.008. URL: https://www.sciencedirect.com/science/article/pii/S2542435122006055.

[124] Colin Marshall. *How to Make Roman Concrete, One of Human Civilization's Longest-Lasting Building Materials*. https://www.openculture.com/2022/12/how-to-make-roman-concrete-one-of-human-civilizations-longest-lasting-building-materials.html. 2023.

[125] Lockheed Martin. *We're developing inflatable habitats to allow astronauts to have large, safe and reliable environments for work in deep space*. https://www.linkedin.com/posts/lockheed-martin_were-developing-inflatable-habitats-to-allow-activity-7008544273289682945-oaMP/?utm_source=share&utm_medium=member_ios. 2023.

[126] Bryan Mattfeld et al. "Developing a crew time model for human exploration missions to Mars". In: *2015 IEEE Aerospace Conference*. 2015, pp. 1–17. DOI: 10.1109/AERO.2015.7119243.

[127] Alex McColgan. *Starship to Mars! What Will the Journey of the SpaceX Ship to the Red Planet Be Like?* https://www.youtube.com/watch?v=OlON6o5Y5TU. 2022.

[128] Rebecca McDonald and Pascal Lee. *Remains of a Modern Glacier Found Near Mars' Equator Implies Water Ice Possibly Present at Low Latitudes on Mars Even Today*. https://www.seti.org/press-release/remains-modern-glacier-found-near-mars-equator-implies-water-ice-possibly-present-low-latitudes. 2023.

[129] Philip T. Metzger et al. “Affordable, Rapid Bootstrapping of the Space Industry and Solar System Civilization”. In: *Journal of Aerospace Engineering, ASCE* January 2013, 26(1) (2013), pp. 18–29.

[130] Forrest Meyen. “MOXIE Sets Consecutive Personal Bests and Mars Records for Oxygen Production”. In: *NASA Science Blog* (2022). URL: https://mars.nasa.gov/mars2020/mission/status/427/moxie-sets-consecutive-personal-bests-and-mars-records-for-oxygen-production/.

[131] Bryce Meyer. *Electrical Requirements for a Spectrum of Multi-Stage Space Farms.* https://spaceambition.substack.com/p/overcoming-challenges-in-martian. 2023.

[132] P. et al. Morthekai. “Modelling of the dose-rate variations with depth in the Martian regolith using GEANT4”. In: *Nuclear Instruments and Methods in Physics Research* 580 (2007), pp. 667–670.

[133] Raffaele Mugnuolo et al. *Dust Mitigation Gap Assessment Report.* https://www.globalspaceexploration.org/wordpress/docs/Dust%20Mitigation%20Gap%20Assessment%20Report.pdf. 2016.

[134] Elon Musk. “Making Life Multi-Planetary”. In: *New Space* 6.1 (2018), pp. 2–11. DOI: 10.1089/space.2018.29013.emu. URL: https://doi.org/10.1089/space.2018.29013.emu.

[135] James Myers. *Op-ed | U.S. leadership of cislunar space hinges on foresight and planning.* https://spacenews.com/op-ed-u-s-leadership-of-cislunar-space-hinges-on-foresight-and-planning/. 2023.

[136] Surabhi Naik, S. K. Venu Gopal, and Priti Somal. “Bioproduction of polyhydroxyalkanoates from bacteria: a metabolic approach”. In: *World Journal of Microbiology and Biotechnology* 24.10 (2008). DOI: 10.1007/s11274-008-9745-z. URL: https://doi.org/10.1007/s11274-008-9745-z.

[137] “NASA Space Flight Human-System Standard: Volume 1: Crew health, Revision B”. In: 1 (Jan. 2022).

[138] Engineering National Academies of Sciences and Medicine. *Space Radiation and Astronaut Health: Managing and Communicating Cancer Risks.* Washington, DC: The National Academies Press, 2021. ISBN: 978-0-309-47966-0. DOI: 10.17226/26155. URL: https://nap.nationalacademies.org/catalog/26155/space-radiation-and-astronaut-health-managing-and-communicating-cancer-risks.

[139] National Aeronautics and Space Administration. *Moon to Mars Objectives.* 2022.

[140] J. N. Nielsen. *The Space Settler as Environmentalist.* https://medium.com/@humanspaceprogram/the-space-settler-as-environmentalist-4054a43a3400. 2022.

[141] Adrianna Nine. *Unveils Interior of Simulation Mars Habitat for Future Missions.* https://www.extremetech.com/aerospace/-unveils-interior-of-simulation-mars-habitat-for-future-missions. 2023.

[142] JSC SMA Flight Safety Office. *Significant Incidents & Close Calls in Human Spaceflight.* https://forum.nasaspaceflight.com/index.php?topic=39785.0. 2019.

[143] Mike Oitzman. *Slip Robotics launches new trailer pallet unloading solution.* https://www.therobotreport.com/slip-robotics-launches-new-trailer-pallet-unloading-solution/. 2023.

[144] XPrize Organization. *Nimbro Announced as Winner of the $10M ANA Avatar XPprize.* https://www.xprize.org/prizes/avatar/articles/ana-avatar-xprize-winners. 2022.

[145] Blue Origin. *Blue Alchemist Technology Powers our Lunar Future.* https://www.blueorigin.com/news/blue-alchemist-powers-our-lunar-future/. 2023.

[146] Andrew Charles Owens. “Multiobjective Optimization of Crewed Spacecraft Supportability Strategies”. Massachusetts Institute of Technology, 2019.

[147] Thomas Page. *Mars on Earth: NASA researchers will spend a year living in a simulated habitat.* https://www.cnn.com/2023/05/16/world/chapea-nasa-mars-analog-spc-scn-intl/. 2023.

[148] Jacqui Palumbo. “Would you live in a cave? These architects believe we should”. In: *CNN* (2022). URL: https://edition.cnn.com/style/article/architects-sustainable-cave-living/index.html.

[149] Desiati Paolo and D’Onghia Elena. “CREW HaT: A Magnetic Shielding System for Space Habitats”. In: *International Conference on Environmental Systems* 51st.ICES-2022-80 (2022).

[150] Antonio J Paris et al. “Prospective Lava Tubes at Hellas Planitia”. In: *Journal of the Washington Academy of Sciences* (2019).

[151] Joon Sung Park et al. *Generative Agents: Interactive Simulacra of Human Behavior*. 2023. arXiv: 2304.03442 [cs.HC].

[152] Richard Pettegrew et al. “In-flight manual electronics repair for deep-space missions”. In: *2007 IEEE Aerospace Conference*. IEEE. 2007, pp. 1–16.

[153] Richard Pettegrew et al. “Repair of Electronics for Long Duration Spaceflight”. In: *45th AIAA Aerospace Sciences Meeting and Exhibit*. 2007, p. 1364.

[154] Tracie J. Prater et al. “NASA’s Habitat Outfitting Portfolio: Technology Development to Support Future Habitation Systems”. In: *ASCEND 2022*. DOI: 10.2514/6.2022-4289. URL: https://arc.aiaa.org/doi/abs/10.2514/6.2022-4289.

[155] Eric Ralph. *SpaceX rapidly builds, tests Starship Moon elevator for NASA*. https://www.teslarati.com/spacex-starship-moon-elevator-nasa-prototype/. 2021.

[156] Eric Ralph. *Elon Musk teases expendable version of SpaceX’s reusable Starship rocket*. https://www.teslarati.com/spacex-starship-expendable-variant-elon-musk-2023/. 2023.

[157] Donald Rapp. *Use of Extraterrestrial Resources for Human Space Missions to Moon or Mars*. Cham: Springer International Publishing, 2018. ISBN: 978-3-319-72694-6. DOI: 10.1007/978-3-319-72694-6. URL: http://link.springer.com/10.1007/978-3-319-72694-6 (visited on 03/14/2023).

[158] Laura Reiley. “Cutting-edge tech made this tiny country a major exporter of food”. In: *Washington Post* (2022). URL: https://www.washingtonpost.com/business/interactive/2022/netherlands-agriculture-technology/.

[159] Eric E. Rice and Orbital Technologies Corporation. “Final Report on Advanced System Concept for Total ISRU-Based Propulsion and Power Systems for Unmanned and Manned Mars Exploration”. In: *Innovative Advanced Concepts* (2002). DOI: UnderResearchGrant07600-041OTC-GS-0096-FR-2002-1.

[160] Linda Rivera. *OffWorld Europe and Luxembourg Space Agency Collaborate in New Lunar ISRU Exploration Program*. https://www.businesswire.com/news/home/20230418006222/en/OffWorld-Europe-and-Luxembourg-Space-Agency-Collaborate-in-New-Lunar-ISRU-Exploration-Program. 2023.

[161] Annika Rollock. *ECLSS Primer: Atmosphere Management*. https://www.annikarollock.com/blog/bioastro-primer-atmosphere. 2023.

[162] S. Rosenthal, M. Hahn, and A.E Tekkaya. “Deep drawability of additively manufactured sheets with a structured core”. In: *International Journal of Material Forming* 16.20 (2023). DOI: https://doi.org/10.1007/s12289-023-01739-2. URL: https://link.springer.com/article/10.1007/s12289-023-01739-2%5C#citeas.

[163] Sarah Scoles. *Prime Mover: Starship will be the biggest rocket ever. Are space scientists ready to take advantage of it?* https://www.science.org/content/article/space-scientists-ready-starship-biggest-rocket-ever. 2022.

[164] Joe Scott. *The Full Plan For Artemis Part 3: The Moon Base And Beyond*. https://www.youtube.com/watch?v=rU_LiVJp3xg. 2022.

[165] Linda M Seymour et al. “Hot mixing: Mechanistic insights into the durability of ancient Roman concrete”. In: *Science advances* 9.1 (2023), eadd1602.

[166] Niko Simos and Henry Gordon-Smith. *Meet the Two Biggest Enemies of Indoor Farming.* https://foodinstitute.com/focus/meet-the-two-biggest-enemies-of-indoor-farming/. 2022.

[167] Ideal Simulations. *Negative Pressure Rooms And Positive Pressure Rooms.* https://www.idealsimulations.com/blog/negative-and-positive-pressure-rooms/. 2023.

[168] Tony C. Slaba, Christopher J. Mertens, and Steve R. Blattnig. "Radiation Shielding Optimization on Mars". In: *National Aeronautics and Space Administration Scientific and Technical Information Program* NASA/TP–2013-217983 (2013).

[169] Cameron M. Smith. "An adaptive paradigm for human space settlement". In: *Acta Astronautica* 119 (2016), pp. 207–217. ISSN: 0094-5765. DOI: https://doi.org/10.1016/j.actaastro.2015.11.017. URL: https://www.sciencedirect.com/science/article/pii/S0094576515004233.

[170] Michael Smith, Vito Cacucciolo, and Herbert Shea. "Fiber pumps for wearable fluidic systems". In: *Science* 379.6639 (2023), pp. 1327–1332. DOI: 10.1126/science.ade8654. URL: https://www.science.org/doi/abs/10.1126/science.ade8654.

[171] S. W. Squyres et al. "Ice in the Martian Regolith". In: *Mars* A93-27852 09-91 (1992), pp. 523–554.

[172] Timothy Stagich. "Collaborative leadership and global transformation: Developing collaborative leaders and high synergy organizations". In: Global Leadership Resources, 2006. URL: https://books.google.com/books?hl=el&lr=&id=EPFNkVDP2zMC&oi=fnd&pg=PA8&dq=transformative+and+collaborative+leadership&ots=nqpZgJtTPD&sig=AI3Y184K87YKWXUDMTJCQh_XIVc.

[173] Simon C. Stähler et al. "Tectonics of Cerberus Fossae unveiled by marsquakes". In: *Nature Astronomy* 6.12 (2022). DOI: 10.1038/s41550-022-01803-y.

[174] Chel Stromgren et al. "Assessment of Crew Time for Maintenance and Repair Activities for Lunar Surface Missions". In: *2022 IEEE Aerospace Conference (AERO)*. 2022, pp. 01–10. DOI: 10.1109/AERO53065.2022.9843431.

[175] Jack Stuster et al. *Human Exploration of Mars: Preliminary Lists of Crew Tasks.* 2018.

[176] Natalia Supolkina et al. "External Communication of Autonomous Crews Under Simulation of Interplanetary Missions". In: *Frontiers in Physiology* 12 (2021). ISSN: 1664-042X. DOI: 10.3389/fphys.2021.751170. URL: https://www.frontiersin.org/articles/10.3389/fphys.2021.751170.

[177] U.S. Geological Survey. "Field-trip guides to selected volcanoes and volcanic landscapes of the western United States". In: *USGS Publications Warehouse* (2017). DOI: 10.3133/sir20175022. URL: http://pubs.er.usgs.gov/publication/sir20175022.

[178] US Geological Survey. *Geologic Map of Mars.* https://www.usgs.gov/media/images/geologic-map-mars. 2014.

[179] Tricia et al. Talbert. *Mars Human Landing Site Workshop Presentations.* https://www.nasa.gov/feature/mars-human-landing-site-workshop-presentations/. 2017.

[180] Frank Tavares. *NASA, Partners Achieve Fastest Space-to-Ground Laser Comms Link.* https://www.nasa.gov/feature/ames/tbird-milestone. 2023.

[181] Teague. *To the Moon and beyond. Teague Featured Concept | Space Habitat | Lunar Living.* https://teague.com/work/moon-mission?utm_campaign=HCD%20in%20Space&utm_medium=email&_hsmi=232950380&_hsenc=p2ANqtz--6haPVGJkK_h8y5MZKbsc2hsyeoPv11iqMPfkldcqHr1_KtNRsfey1c-f7V2yE-Q8jPUIaWp27P4YqRXl4ZVAx0hqs-c5O3FpsaJzIqcAKaD9lMQM&utm_content=232950380&utm_source=hs_email. 2023.

[182] Andrew Thoesen and Hamid Marvi. "Planetary Surface Mobility and Exploration: A Review". In: *Current Robitics Reports* 2.3 (2021), pp. 239–249. DOI: 10.1007/s43154-021-00056-3. URL: https://doi.org/10.1007/s43154-021-00056-3.

[183] Yunsheng Tian et al. "Assemble Them All". In: *ACM Transactions on Graphics* 41.6 (2022), pp. 1–11. DOI: 10.1145/3550454.3555525. URL: https://doi.org/10.1145%5C%2F3550454.3555525.

[184] Larry Toups and Marianne Bobskill. "Human Spaceflight Architecture Team (HAT) Mars Destination Operations Team (DOT) FY 2013 Final Report". 2014.

[185] Larry Toups et al. *Mars Surface Crew Operations Study Com.* http://www.nasa.gov/directorates/heo/reports.html. 2013.

[186] Traclabs. *BioSim, An Integrated Simulation of an Advanced Life Support System for Intelligent Control Research.* https://traclabs.com/projects/biosim/. 2008.

[187] U.S. Department of Transportation Federal Highway Administration. "Technical Manual for Design and Construction of Road Tunnels — Civil Elements". In: FHWA-NHI-10-034 (2009).

[188] Pat Troutman and VPM Science Matters. "A Blueprint for Human Habitation for Mars". In: (2017).

[189] U.S. Department of Defense. *DoD to Build Project Pele Mobile Microreactor and Perform Demonstration at Idaho National Laboratory.* https://www.defense.gov/News/Releases/Release/Article/2998460/dod-to-build-project-pele-mobile-microreactor-and-perform-demonstration-at-idah/. 2022.

[190] Michelle Urbina. "Medical System Concept of Operations for Mars Exploration Mission-11". In: *National Aeronautics and Space Administration Human Research Program* HRP 48021 (2019).

[191] USGS. *Mars Global Cave Candidate Catalog (MGC^3)$v1Cushing$.* https://astrogeology.usgs.gov/search/map/Mars/MarsCaveCatalog/mars_cave_catalog. 2021.

[192] Cantos Ventures. *The Future is Radiant.* https://medium.com/cantos-ventures/the-future-is-radiant-b3bc1fdaf340. 2022.

[193] Robert Waldinger and Marc Schulz. *What the Longest Study on Human Happiness Found is the Key to a Good Life.* 2023.

[194] M. Mitchell Waldrop. *The road to low-carbon concrete.* https://knowablemagazine.org/article/technology/2022/low-carbon-concrete. 2022.

[195] L. Walsh et al. "Research plans in Europe for radiation health hazard assessment in exploratory space missions". In: *Life Sciences in Space Research* 21 (2019), pp. 73–82. ISSN: 2214-5524. DOI: https://doi.org/10.1016/j.lssr.2019.04.002. URL: https://www.sciencedirect.com/science/article/pii/S2214552419300331.

[196] Brianna Wessling. *Reports of layoffs at Iron Ox.* https://www.therobotreport.com/reports-of-layoffs-at-iron-ox/#. 2020.

[197] Raymond Wheeler. "NASA's Contributions to Vertical Farming". In: *National Aeronautics and Space Administration's Scientific and Technical Information Program* (2020), TM–20205008832. DOI: https://doi.org/10.1002/adfm.202300732.

[198] Edgar Zapata. "An Assessment of Cost Improvements in the NASA COTS-CRS Program and Implications for Future NASA Missions". In: *AIAA Space 2017 Conference.* KSC-E-DAA-TN44427. 2017.

[199] J.L Zigler and Kathryn Nimz. *Mars.* https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/thumbnails/image/6-Mars-a1.jpg. 2014.