Colonizing Mars: Reviewing Strategies and Challenges

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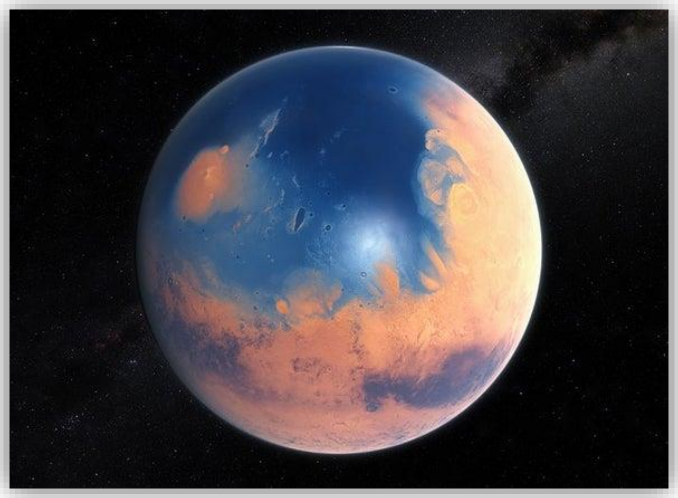

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Introduction

Major space agencies, private enterprises and research institutions worldwide are preparing to expand humanities reach into the solar system. In this pursuit, Mars is the most viable location for a permanent and self-sustaining settlement. The robotic exploration missions sent to Mars show evidence that the planet once had a warmer and wetter climate; with large quantities of water which carved out impressive canyons, and indicate that the planet may once have been habitable [1]. Yet, the current Martian environment is hostile to terrestrial life forms. Building an outpost on this planet will not be easy. In the initial phases of settlement, robotic missions will explore, prepare infrastructure, and secure resources for a base. Later, the human settlers will be carefully sheltered from the Martian environment at all times. In the long-run, the red planet could be terraformed to change its environmental conditions in order host a viable ecosystem. Achieving this vision introduces a wide range of interdisciplinary challenges. Many of these challenges are interconnected; which in some cases offers possibilities for synergistic solutions while in others presents bottlenecks. Many of the lessons learned from settling Mars will directly impact technology on Earth, particularly with respect to sustainable economic development and geoengineering. This paper outlines some of the basic strategies for settling Mars in the short and long term.

Some characteristics of Mars are fixed, such as gravity, while others may be changed by anthropogenic actions, such as temperature. Mars has 38% earth's gravity, 43% earth's incident sunlight, a similar day-night cycle, a comparable axial tilt leading to seasonality, similar mineralogy of regolith, and once had climatic conditions similar to Earth [2]. These comparisons are summarized in Table 1. Terraforming Mars is typically defined as increasing the pressure to allow humans to walk on the surface without pressure suits, i.e., pressure > ~6.3 kPa (the Armstrong limit), as well as warming the planet to support liquid water [2].

Table 1. Comparison of Mars and Earth.

Parameter	**Mars**	**Earth**
Surface Pressure	0.5 to 1 kPa	101.3 kPa
Avg. Temp.	-60 °C	+15 °C
Temp. Range	-120 °C to +25 °C	-80 °C to +50 °C
Atmospheric Composition	95% CO_2	78% N_2
	2.7% N_2	21 % O_2
	1.6% Ar	1% Ar
Incident light (avg. yearly)	149 W/m^2	344 W/m^2
Solar day	24 hr 40 min	24 hr
Sidereal year	687 days	365.26 days
Obliquity of axis	25°	23.5°
Avg. distance of Sun	1.52 AU	1 AU
Gravity	0.38	1

Short-Term

Habitat

A successful Martian colony will rely on in-situ resource utilization (ISRU). Vital resources will include shelter, dioxygen, clean water, nutritious food, energy, medical supplies, and waste management. Some of these requirements are elaborated on below.

Shelter is a critical necessity for Mars because its thin atmosphere combined with the lack of magnetic shielding make its surface constantly exposed to multiple hazards, such as radiation, dust storms, micrometeoroids, and extreme temperature fluxes [3]. With no magnetosphere, ionizing radiation is ubiquitous on the Martian surface. Any biological system will need insulation from solar energetic particles and galactic cosmic rays, which are typically high-speed protons or helium nuclei emitted by stellar objects that can cause cell damage and acute radiation sickness [4]. Insulating from radiation can be accomplished by a wide range of materials, including the Martian regolith [5]. Therefore, burying habitats into the ground appears to be a technically pragmatic approach [4]. Ironically, another widely promoted strategy is that our most modern explorers could emulate prehistoric men by dwelling in caves, such as those found in the dormant volcano of Arsia Mons [3]. Arsia Mons is part of the Tharsis Montes volcanic system which includes three volcanoes extinct for ~50 million years. What appears to be cave entrances to ancient lava tubes have been detected surrounding the Arsia Mons volcano [3]. The volcanic system and possible cave entrances are displayed in Figure 1.

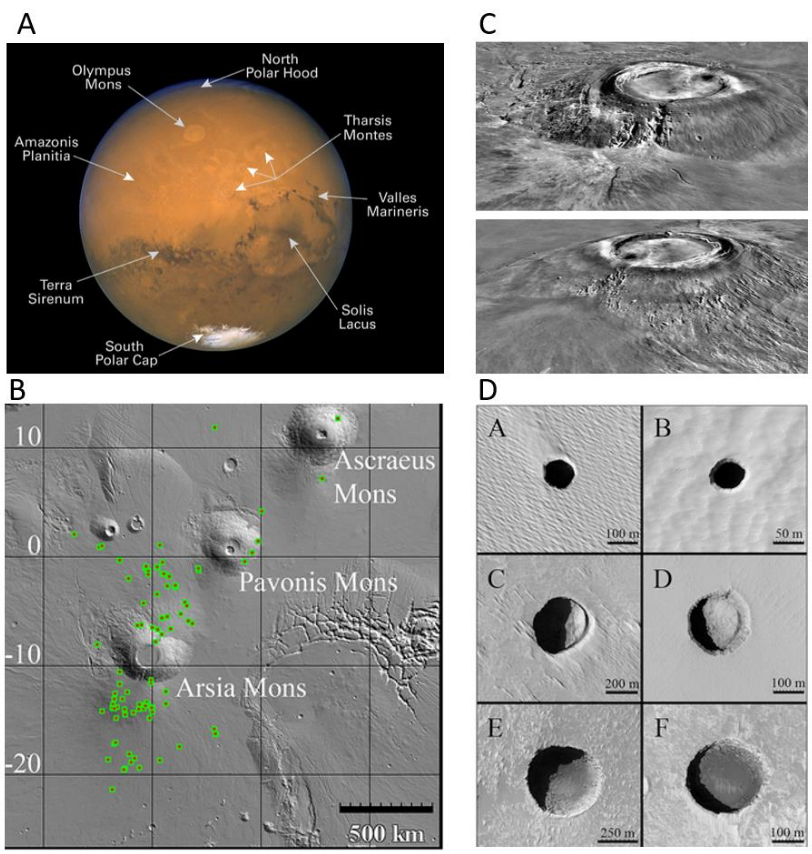

Figure 1. Tharsis Montes volcanic system and possible cave entrances surrounding Arsia Mons. **A)** Telescope image of Mars with annotations of prominent features (Image sourced from Hubblesite.org with illustration credit to Lisa Frattare at the Space Science Telescope Institute). **B)** Infrared imaging of the Tharsis Montes system by Mars Global Surveyor: NASA. **C)** Reconstructed relief images of Arsia Mons from Viking 1: NASA. **D)** Possible cave entrances around Arisa Mons, images from HiRISE: NASA, modified from the paper of Cushing et., al. 2015 [3].

Air revitalization

The life-support systems for humans in space must always carefully manage gases, namely, oxygen must be provided to the living space and CO_2 removed. Hence, regardless of design or location, any early Martian shelter will need to offer a closed-system for controlling gases. Deep space technologies will likely rely on both incremental improvements to current life-support systems, and novel technologies [6]. On the International Space Station (ISS) oxygen provision is accomplished by electrolysis, where water is split and separated into dioxygen and dihydrogen. So long as water and electricity are available, oxygen production by electrolysis in space is a solved problem as it relies on technology that is already at an advanced technological readiness level. It is also possible that some oxygen production on Mars could rely on oxygen extraction from minerals [7]. Many technologies that will be used on Mars will be tested on the Moon in the coming 5 years.

The metabolic waste CO_2 is toxic to humans in high concentrations and must be removed by life-support systems. Several competing technologies solve this problem. Older technologies work with disposable systems, while newer ones use renewable systems. On Apollo missions, cabin air was vented through canisters of powered lithium hydroxide (LiOH) that reacted to form lithium carbonate (Li_2CO_3). Once lithium canisters were used they were disposed.

$$CO_2\ (g) + 2LiOH\ (s) \rightarrow Li_2CO_3\ (s) + 3\ H_2O\ (l)$$

All generations of Russian Soyuz spacecraft have used an efficient potassium superoxide reaction, which also requires disposal of spent canisters. However, this technology poses higher risks since potassium superoxide is a strong oxidizer which can be explosive.

$$4KO_2\ (s) + 4CO_2\ (g) + 2H_2O\ (g) \rightarrow 4KHCO_3\ (s) + 3O_2\ (g)$$

The ISS employs newer technology which allows reusability. Cabin air is vented through a microporous mineral called zeolite that traps CO_2. The selective trapping gives this technology the name molecular sieve. Once saturated, the zeolite bed is heated causing CO_2 to desorb [8]. In the open-loop configuration the CO_2 is vented overboard. However, in a closed-loop system the CO_2

is reacted with H_2 (from electrolysis) in a Sabatier reaction in order to produce methane and water. Crucially, this allows increased water recovery. Methane is currently vented overboard on the ISS, but in future Mars missions it may be used as fuel. However, the contribution may be negligible compared to methane needs.

Similar reusable CO_2 trapping systems are employed in the emerging technology of Direct Air Capture of carbon dioxide (DAC). These are expected to play a role in future carbon dioxide removal of life-support systems [9]. DAC uses either a liquid reactant to precipitate CO_2 to carbonates, which are then heated to produce a pure CO_2 gas stream, or solid sorbents to reversibly sorb/desorb CO_2 [10]. DAC companies are becoming increasingly active on earth due to growing interest in decarbonizing flue gases, and even capturing atmospheric CO_2 to produce fuels (e.g Carbon Technologies, or Climeworks) [11]. CO_2 scrubbing in life-support systems will likely benefit from advances in terrestrial-based DAC technology.

Current life-support technologies have all made use of physicochemical systems. However, future missions will likely also implement biology. Biological systems enable the combination of several complimentary processes, such as associating oxygen production with food production, and these may reduce payloads. Furthermore, biology offers humans a unique source of self-replicating nanotechnology. The most advanced research program in the bio life-support domain is the Micro-Ecological Life Support System Alternative (MELiSSA) developed by ESA and partners. The working principal is to use several organisms to close substrate/product loops (i.e the product of one component is the substrate of another). For example, the products of crew metabolism, CO_2 and digestive waste, are delivered respectively to photosynthetic organisms and anaerobic bacteria as substrate. While the waste of those latter two serve as substrate for other organisms. In this way loops are closed and matter cycles indefinitely, lost only by inefficient leakages. The simplified schema is shown in Figure 2.

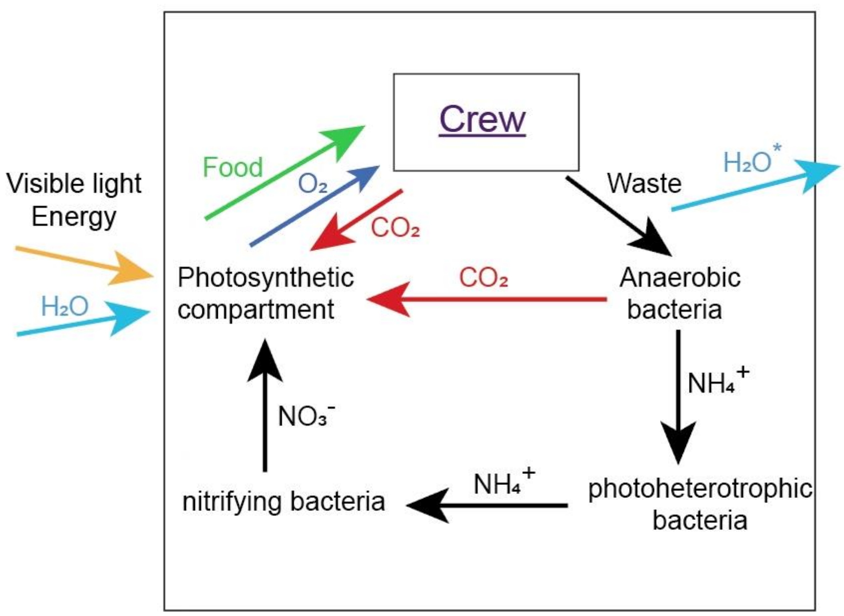

Figure 2. Simplified schematic of the Micro-Ecological Life Support System Alternative (MELiSSA) developed by ESA. The scheme shown here is a simplification compared to the complete system proposed by ESA. Note that the system is a closed-loop for nutrients but always demands input energy, and due to inefficiencies, there is some water and nutrient loss (denoted H_2O*).

In deep space missions, life-support systems must cycle atoms with minimal loss in order to preserve mass. This type of cyclic nutrient flow is driving innovation for industrial organization on earth. The development of circular economies aims to keep material in loops with as little loss to the environment as possible [12]. The advent of such systems will reduce the exploitation of scarce resources, and minimize production of noxious waste. As the appetite for goods and services continues to grow with global wealth, cyclic economies are vital for scarce resources, such as phosphorous [12]. Metals are a particular target for circular economic thinking, as they are often scarce, and their exploitation and disposal are polluting. For example, the company Batrec is developing technology to remove zinc from waste batteries [12]. One of the pioneers of circular economic thinking, Walter Stahel, states that "in a circular economy, the objective is to maximize value at each point in a product's life" [12]. As long as sufficient energy is provided to closed-loop systems, they can cycle a fixed amount of material almost indefinitely [13]. However, the environmental benefits greatly depend on the availability of clean energy.

Energy Production

The initial energy production systems for deep space missions will continue to rely on photovoltaics, after which there may be use of concentrated solar power, and in later stages nuclear power. However, since electrically powered thrusters (like ion drives, or plasma drives) cannot achieve the required specific impulse to reach escape velocity when lifting off objects larger than asteroids, combustible fuel is required for rocket propellant [14]. The ability to refuel ships on Mars is a primary driver to making trips faster, safer, and more economical. Hence, propellant production on Mars has received considerable attention. SpaceX advocates production of methane by the Sabatier reaction [15]. In this case, CO_2 and H_2 are reacted over a nickel catalyst to produce CH_4 (methane) [16]. H_2 would be derived from in-situ water electrolysis while CO_2 would be derived by DAC. A scheme of this system is shown in Figure 3.

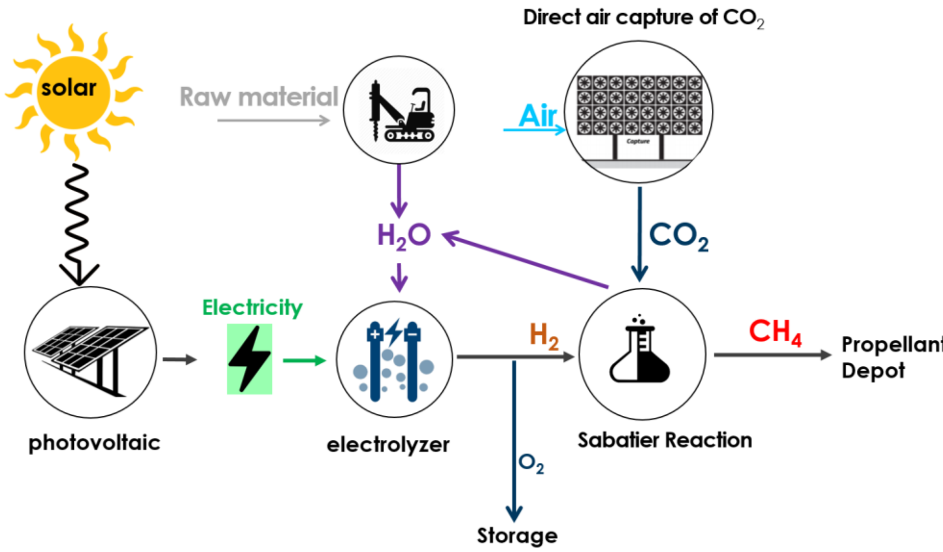

Figure 3: Water electrolysis and Sabatier reaction for fuel and oxidizer production. Using water and air as inputs, dioxygen and methane can be produced.

Production capacities can be estimated as follows. The solar constant during daytime near equator after passing atmosphere of Mars is ~ 0.5 kW/m^2 [17]. We can assume approximately 7 hours of full illumination per day with 15% reduction due to dusting, hence ~ 3 kWh/m^2/d. Given 20% solar cell efficiency, 70% efficiency of electrolysis and 80% efficiency of Sabatier methanation [18], then there should be combined ~10% efficiency in converting sunlight to chemical energy in methane. Therefore, 1 meter squared of solar panels receiving 3 kWh/m^2/d solar energy should produce 0.3 kWh (1080 kJ) of methane. Since methane has a combustion energy of 50 kJ/g, then ~ 20 g of methane can be produced per day per meter square of solar panel. However, this assumed no energy cost for water extraction and DAC, hence it may overestimate production. On the other hand, methanation is a highly exothermic reaction [18], and waste heat could be coupled to DAC CO_2 desorption needs. A holistic study of the energy costs of producing methane on Mars, or on the Moon, would make a valuable contribution to the literature. However, water extraction costs are not easily modelled with current knowledge, and empirical data on DAC energy costs available in the literature are based on earth atmospheric conditions. The cost of launch of proposed NASA Mars Ascent Vehicles is not provided in the literature, however, to give a point of comparison, the Saturn V launches requires some 700,000 L of kerosene to reach orbit [19]. Hence, it appears that methane production on Mars would need to be dramatically scaled-up in order to make any substantial contribution to the propellant requirements to lift-off Mars. Without such in-situ production, the Mars Ascent Vehicle will need to travel from Earth and land on Mars with all its fuel requirements, which increases launch cost and complexity.

While methane is the most likely rocket propellant for Mars [15], other energy needs, such as vehicles, could be fulfilled by carbon monoxide. Carbon monoxide production can be advantageous because several methods do not require water and lead to a dioxygen by-product [20].

$$2\ CO_2 \rightarrow 2\ CO + O_2$$

However, this technology is currently in a low technological readiness level.

Food Production

It is clear that early development of the Mars base will heavily rely on robotic operations [21]. However, a human presence will eventually be desired and necessary (e.g. to perform complex repairs). For short missions, food could be transported from Earth. However, for longer duration missions in situ food production could dramatically reduce launch costs. Several strategies are under consideration for food production. The growth of microbes to produce food has gained increasing attention in the last few years. Bacteria, algae, and yeast can be cultivated using CO_2, nutrients, and an energy substrate to produce high quality protein [22]. It is possible to use solar panels to drive the catalytic production of the energy substrate such as hydrogen, formate, or methanol [23]. In this case, it is also possible to upcycle waste N, and P from food residues and from human metabolism [24]. Such a system could thus be coupled to waste management.

Alternatively plants could be grown in greenhouses. A study from 2014 showed that it was possible to grow plants using Mars soil simulant [25], however, this study failed to mention perchlorate toxicity. Nonetheless, it is commonly assumed by space agencies that plants could be grown in greenhouses since soils could be detoxified.

Cultivated meat, also known as cellular agriculture, is also a rapidly growing market on earth [26], which will likely play a role in space exploration. As an example, Finless Foods, a fish cell cultivation startup sent experimental fish cultures aboard the ISS in 2019. They were able to demonstrate growth of fish meat on the ISS, which could purportedly provide a source of healthy protein for future astronauts on Mars.

Long term

Warming mars and increasing its atmospheric pressure are crucial prerequisites for developing a biosphere on the red planet.

Atmosphere

One of the most striking differences between Earth and Mars is that Mars has a very thin atmosphere, with a surface atmospheric pressure less than 1% that of Earth. This thin atmosphere poses a multifaceted challenge. For instance, it can hinder biological activity that is dependent on gases (e.g CO_2 fixation, N_2 Fixation, aerobic respiration) [2]. It causes large temperature swings between day and night, and generally leads to substantially lower ambient temperatures than found on Earth [2]. Moreover, the low pressure makes liquid water unstable on the surface [1]. Additionally, it allows high energy galactic cosmic rays, and UV light to damage any life forms which might try to wander unshielded on the Martian surface. Thus, an important long-term goal of Martian terraforming will involve generating a denser Martian atmosphere. Furthermore, the Martian atmospheric composition is markedly different from Earth's. While Earth has 79% N_2, 21% O_2 and 0.04% CO_2, Mars instead has 95% CO_2 and 0.14% O_2.

Hence, for aerobic life to exist freely on its surface, a Martian atmosphere must eventually be oxygenated. However, plant life could be achieved prior to oxygenation, and this may in turn contribute to oxygenating the atmosphere [2]. Yet, estimates show that oxygenating the atmosphere of Mars is a distant prospect which is beyond current technology and longer than human civilization timescales (e.g up to 100,000 years) [27]. Nonetheless, several authors note that should this one day be undertaken, it is promising that Martian regolith is highly oxidized. Hence, photosynthetically evolved oxygen will not be depleted by reacting with soils, as it happened on earth during the initial phases of the oxygen revolution [7]. Still, given the timescales suggested with current technology, this topic is not elaborated on further in this paper. For the foreseeable future, human settlers on Mars will live in shelters or domes, and carry oxygen supplies when outside.

Pressurizing the atmosphere could be accomplished by heating the planet. Mars has abundant reservoirs of frozen CO_2 and water in the poles which could be sublimated to form greenhouse gases (GHG). An image of the south pole ice cap is shown in Figure 4.

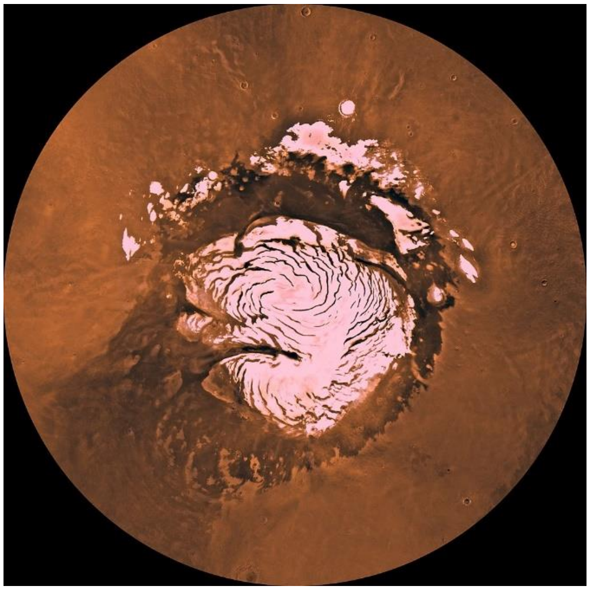

Figure 4. Martian South Pole image reconstructed from Viking Orbiter by NASA. Large permafrost water ice is visible in white.

Whether there are sufficient pools of CO_2 and water to cause a positive feedback loop of GHG release and global warming, so that a runaway greenhouse warming effect occurs is still debated. Early work by McKay and team (1993) estimated a sufficient pool of CO_2, while more recent estimations by Jakosky and Edwards (2018) concluded an insufficient amount is present [2,28]. The recent conclusions also emphasize that only polar CO_2 is easily accessible via heating, hence discounting the previous estimations that included releasing CO_2 from regolith carbonates [29]. McKay initially recognized three hypothesis of where atmospheric CO_2 may have gone: first, it was lost to space due to low gravity; second, it was precipitated and trapped in carbonate form (since there is no active tectonic cycle to release it again); third, it was lost to space due to lack of magnetic shielding [27]. The recent research by Jakosky and Edwards suggest that most of the early CO_2 found on Mars was not trapped in carbonates but was rather lost to space, and is no longer available for heating [29].

There are multiple strategies proposed for warming Mars which include: building orbital mirrors to direct sunlight on the poles, covering the poles with dust or soot [29], redirecting large asteroids to impact Mars, or producing artificial greenhouse gases (AGHG) such as fluorocarbons.

Artificial Greenhouse Gases

It is important to recognize that AGHG will be both lost to space and decayed by UV radiation. Hence, they must be continuously produced. If chlorofluorocarbons (CFC) are used as AGHG, then the production rate to trigger runaway warming on Mars has been estimated as greater than 10^{12} tons/year, which is 6 orders of magnitude larger than the production of CFC on earth in 1991 [2]. Additionally, CFC degrade ozone layers, thus allowing increased levels of UV radiation to penetrate the atmosphere. Since CFC are degraded by UV radiation, there is a problem with increasing their atmospheric concentration indefinitely, i.e. the more they are produced the faster their decay rate.

Indeed, artificial greenhouse gases which contain chlorine or bromine should be avoided because these catalytically destroy ozone [30]. Perfluorocarbons (PFC) do not degrade ozone, can reach high lifetimes, do not threaten the biosphere, and can be synthesized from materials present on Mars, and are hence promising artificial greenhouse gases [30,31]. The most commonly considered molecules are CF_4, C_2F_6, C_3F_8, and SF_6 [30]. The most effective use of AGHG would be a mixture of these gases that cover the IR spectrum [31]. Marina and team (2005) conclude that, given the limited amount of CO_2 present, AGHG may be the *only* viable option to achieve planetary warming by greenhouse gas effect [29]. Therefore, despite the large amounts required, it is worth exploring them in more detail. PFC absorb radiation in the wavelengths of 800-1200 nm; where CO_2 and H_2O have comparatively lower absorbance [30]. This allows CFC to "fill the gap" by absorbing and remitting upwelling IR radiation that would otherwise escape to space [30]. Since PFC have high band absorption coefficients, and because there is a comparatively higher photon flux density in this wavelength window compared to where CO_2 absorbs, the global warming potential of PFCs can be multiple orders of magnitude higher than CO_2 [30]. Octofluoropropane (C_3F_8) has received specific attention because its global warming potential is some 24,000 that of CO_2 [32]. McKay quantified the amount of warming possible as a function of PFC partial pressure, as shown in Figure 5.

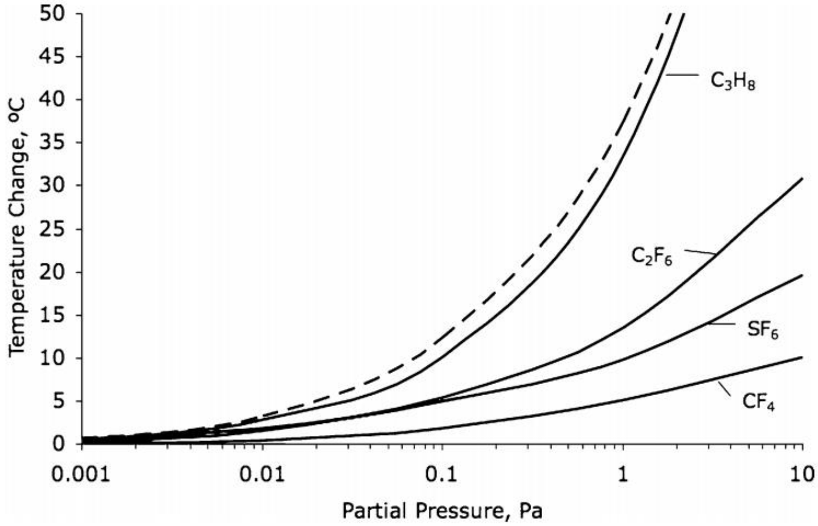

Figure 5. Relationship between partial pressure of artificial fluorocarbons on Mars and temperature change. Image sourced from Mckay 2011 [27].

The question then arises; can these compounds be synthesized using Martian resources? Industrial production of fluorocarbons is achieved via either the Fowler process or electrofluorination [33]. The Fowler process is a two-step production. First, a substrate of cobalt (II) fluoride (CoF_2) is reacted with fluorine (F_2) to produce cobalt (III) fluoride (CoF_2).

$$2\ CoF_2 + F_2 \rightarrow 2\ CoF_3$$

Second, a hydrocarbon is introduced to be fluorinated under high temperature, and cobalt (II) fluoride (CoF_2) is regenerated.

$$C_3H_8 + 16\ CoF_3 \rightarrow C_3F_8 + 8\ HF + 16\ CoF_2$$

The alternate production process is called electrofluorination. This reaction applies a low voltage to a solution containing hydrogen fluoride (HF) and an organic compound ($R_3C–H$) , which electrolyzes (by oxidizing) C-H and H-F bonds at the nickel-plated anode to form C-F bonds, and produces H-H bonds at the cathode.

$$R_3C–H + HF \rightarrow R_3C–F + H_2$$

Several authors state that production of PFCs should be possible with starting materials present on Mars. This assertion seems optimistic with currently available information. While fluorine is present on Mars [34], it is unclear in what form it is. Furthermore, the presence of cobalt on Mars could not be confirmed in the literature. However, clearly some key resources needed in small quantities such as cobalt could be transported. Organic compounds such as alkanes are unlikely to be present, however, these could be synthesized on Mars. Alkane synthesis could begin with DAC to produce methanol (e.g using the Carbon Engineering Air to Fuel process [11]). Methanol could then be used to form longer chains of alkenes via the methanol to olefin process (i.e. methanol to alkene) [35]. Then alkenes could be converted to alkanes by catalytic hydrogenation (i.e. reduction) [35] . Finally, alkanes can be converted to the desired length by alkane metathesis [36]. In addition, it is possible that synthetic biology could develop microbes which generate specialized alkane products from simple compounds such as CO_2 and energetic substrate such as dihydrogen [37]. While an even more valuable target is the use of synthetic biology to directly produce organofluorines [38–40], which is exemplified by the EU Horizon 2020 project, SinFonia. Such synthetic biology tools could represent game changing additions in the Mars colonization toolbox.

Redirecting Asteroids

Redirecting asteroids is part of a suit of technologies which space research has deeply explored in the veins of planetary defense strategies, early solar system sciences, and more recently for ISRU. NASA has been working on demonstrating aspects of space tug missions via the Asteroid Redirect Mission (ARM) [41], however, this specific mission was cancelled in 2017. Nonetheless, there are several technologies possible to redirect asteroids.

Arguably, asteroids which could serve as Mars impactors would likely come from the pool of Mars-crossing minor planets, or from the Kuiper belt. These asteroids are typically orbiting the Sun and with sufficient energy they could be redirected into a collision path with Mars. In addition to the direct heating of an asteroid impact, these could increase the presence of the strong GHG NH_3. However, with a sparse ozone layer, NH_3 will have a very short lifetime [31].

The most commonly described methods of redirecting technologies are: kinetic impact, gravity tractor, mass driver, Yarkovsky effect, laser ablation, and tether-assists [42,43]. Yet, many of these proposed technologies face a complex challenge of asteroid spin. Most theoretical methods of redirection mentioned above would require the spin to be arrested, or precisely understood [41]. Furthermore, some methods require a good understanding of the inner composition of asteroids [44]. However, a gravity tractor does not require asteroid spin to be halted, is indifferent to composition, and is also energetically efficiency [44]. Hence, at first approximation the gravity tractor methods appear the most promising. In this scenario, a large space ship orbits above the asteroid (in the direction of desired travel), so that the gravitational attraction of the ship and asteroid slowly pull the pair towards each other (See Figure 5). Meanwhile, the spaceship can use solar electric propulsion, such as ion thrusters, or a solar sail to maintain its distance from the asteroid [44]. Therefore, in summary the asteroid is continuously attracted to the orbiting ship while the ship maintains its distance.

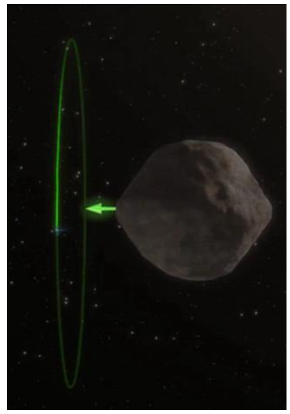

Figure 3. Artist depiction of a gravity tug. The spaceship orbits above the asteroid in the direction of travel while maintaining its distance. From Nasa: http://www.nasa.gov/content/asteroid-redirect-mission-planetary-defense-demonstration/

Asteroid redirection technologies will likely develop further regardless of their use as Mars impactors because asteroids will inevitably play a key role in the space economy. For example, asteroids can provide construction material or propellant in space. This obviates the need to lift such material into orbit, thus substantially reducing costs. Delta-V is a measure of the impulse required to perform a certain maneuver with spacecraft, and indicates energy costs and feasibility of missions. The delta-V associated with exploiting resources on asteroids will likely be much lower than exploiting them on the Moon, and both are order of magnitudes lower than hauling resources out of Earth's gravity well [41]. As such, near earth metal and water-rich asteroids are will eventually be highly valued as the space economy matures. Water bearing asteroids in particular will be high valued since water can be used for propellant production, radiation shielding, thermal control, human consumption, and several other roles such as watering plants [41].

Orbital Mirrors

Orbital mirrors have been under consideration for several decades as a means of geoengineering. Geoengineering is typically separated into two categories, carbon dioxide reduction and solar radiation management. Orbital mirrors are a technology to deflect incoming radiation on Earth [45]. However, they are also considered for concentrating sunlight into certain areas, such as solar energy stations, or in the case of Mars, to heat the poles [2]. A major hindrance to orbital mirror technology has been to make the very large mirrors amenable to volume-restricted launch vehicles [14].

On-orbit Fabrication

Fabrication of spacecraft components on-orbit enables order of magnitude lower costs and larger sizes of space infrastructure. Current launches face volumetric restrictions based on launch vehicles, and have high costs associated with deployment mechanisms, and deployment testing [14]. Space fabricated satellites would be launched only as a core backbone with necessary material, and coupled with assembly instructions to fabricate the final design in space [14]. The most advanced technology for on-orbit fabrication is SpiderFab Bot by NASA (shown in Figure 6). This technology will allow substantially larger satellites to fabricated space at lower costs due to reduced complexity of deployment. Eventually, when raw materials are sourced from asteroids, the bulk of spacecraft may be constructed directly in space. This type of technology is a perquisite to the deployment of large orbital mirrors [14].

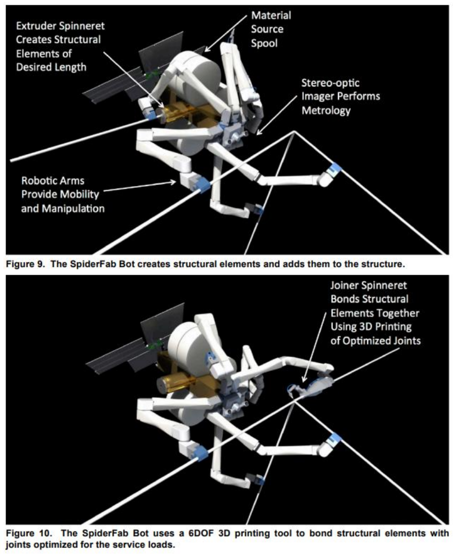

Figure 5. SpiderFab Bot, and on-orbit fabricator in development by NASA that aims to reduce constraints on satellite size and dimensions. Image sourced from:https://www.nasa.gov/sites/default/files/files/Hoyt_2012_PhI_SpiderFab.pdf

Magnetosphere

While generating an atmosphere amenable to life on Mars is one challenge, maintaining that atmosphere is another challenge altogether. Scientists believe that Mars once had a thick atmosphere which was lost to space because the Martian magnetosphere shut down some 3 to 4 billion years [30]. Since then cosmic rays and solar winds have constantly stripped away the Martian atmosphere. To maintain an atmosphere, an artificial magnetic shielding must be established. Furthermore, such a shield would help protect biology from dangerous ionizing radiation. The strategy which has received the most support thus far is to deploy a solar-powered dipole magnet at the Mars-Sun L1 Lagrange point. The proposal was outlined by NASA scientist Jim Green in the Planetary Science Vision 2050 Workshop held in 2017 (illustrated in Figure 6) [46].

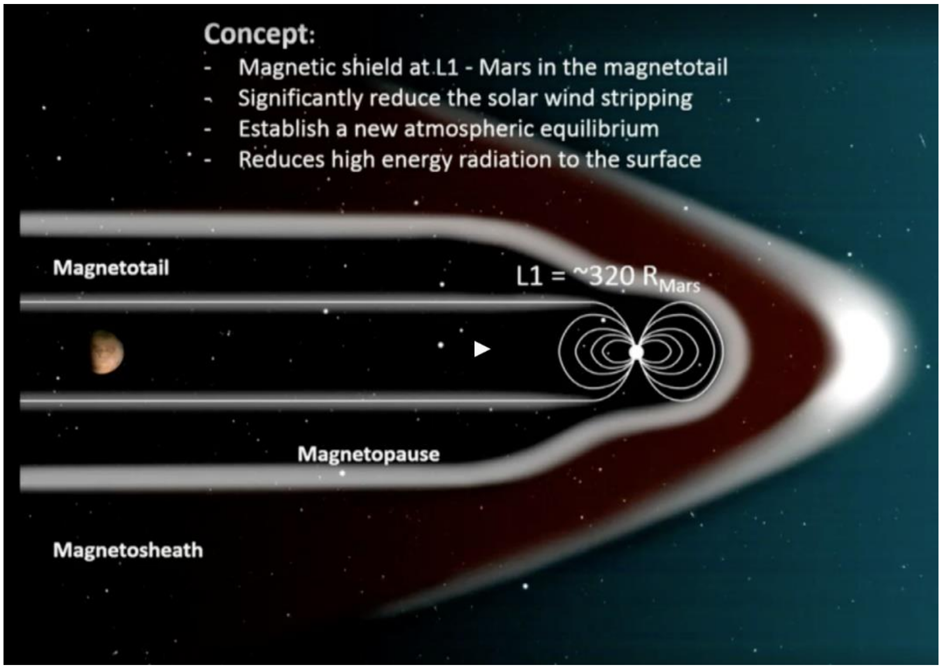

Figure 5. Graphic representation of artificial magnetic shield proposed by Jim Green, NASA. The L1 Lagrange point is a stable position between the gravitational attractions of Mars and the Sun. Modified from Jim Green [46]

Detoxifying soil

Martian regolith has similarities with Earth. It contains the most important elements for life such as N, P, K, S, Mg, Fe, Na, and Ca [47,48]. However, it also has an abundance of perchlorates (ClO_4^-), which is toxic to almost all terrestrial life [49]. Detoxifying Martian soil is a relatively young field of study. In 2017, NASA created a Phase I project led by Adam Arkin called "A Synthetic Biology Architecture to Detoxify and Enrich Mars Soil for Agriculture". This project aims to develop organisms which can fix nitrogen and reduce perchlorate in the Martian environment. The initial plan is to use *Pseudomonas stutzeri PDA*, which is a perchlorate reducer that can also fix nitrogen [50]. Similar ideas to develop hydrogen oxidizing perchlorate reducers were proposed by Llorente et al., 2018 [51]. Others have suggested to use plants for bioremediation of perchlorate containing soils [52]. More research is needed in this field, and much more progress will be achieved with the first Mars sample return missions.

Planetary Ecosynthesis

The goal of ecosynthesis is to develop functional ecosystems via a succession of species. As planetary geoengineering proceeds, rising temperatures, pressure, and moisture, will enable increasingly complex lifeforms to add functions to the Martian ecosystems. The first viable conditions for simple terrestrial life would have a climate resembling that of the Antarctic Dry Valley, or Arctic Polar deserts [1]. The pioneer species proposed are cyanobacteria and certain types of lichens. Example species are the lime-boring cyanobacterium *Matteia*, *Chroococcidiopsis*, and *Arthrospira spp.* [1,48]. Following these would be bryophytes, and finally flowering plants. The timeline proposed by Graham (2004) to reach flowering plants in some zones is approximately

500 to 1000 years [1]. However, the validity of such estimates is questionable given the incredibly complex nature of the geoengineering and biological adaptations considered. Graham notes that if moisture is abundant, then peatlands will form, but if moisture is restricted than a barren arctic ecosystem will emerge with sparse lichens and mosses [7]. Later the temperature and moisture ranges will largely control what type of ecosystems can develop and large regional, and altitudinal differences are expected, as on Earth [7]. It is worth noting that perchlorate toxicity of soil must be handled prior to implementing higher plants. Hence, perchlorate toxicity is a key bottleneck for planetary ecosynthesis.

The current atmosphere of Mars could support CO_2 fixation. It is estimated that C3 plants become completely inhibited by CO_2 at a partial pressure of less than ~0.15 mbar and partially inhibited before, whereas C4 plants can continue fixing CO_2 at very low concentrations [2]. Since the Martian atmosphere has a pressure of 6 mbar at the surface with CO_2 concentration of 95%, the partial pressure of CO_2 of ~5.7 mbar should suffice to support plant growth.

However, plants may face difficulties with acquiring N from N_2. N_2 fixation becomes limited at partial pressures of 10 mbar and less, whereas the 2.6% N_2 in the Martian atmosphere implies a 0.15 mbar N_2 partial pressure [2]. Hence nitrogen fixing bacteria may not be able to provide N to plants. However, large amounts of reactive N is present in Martian soil as nitrate, which should thus be in plant available form [47]. This nitrate could theoretically also increase the N_2 partial pressure by introduction of denitrifying bacteria.

Yet, it is not only the abiotic conditions which can be geoengineered to suit terrestrial plants, but plants that can be bioengineered to suit the Martian conditions. For instance, plants may need to invest much less energy and material in rigid stems when faced with less than half the gravitational forces of Earth. Furthermore, plants will have to adapt to a 2 year seasonal cycle, and ~50% light intensity. It is inevitable that plants will either evolve or be synthetically optimized for Martian life. There is considerable interest already in adapting plants to the lower light conditions that prevail on the red planet [51]. This naturally brings the questions of human adaptations. Will human be genetically modified to be better suited to 40% Earth's gravity? In the far future, if humans spread to multiple planets, the tree of life will branch in dramatic ways according to the chain of planets that life has descended from. All these nodes will lead back to Earth, as the last common planet.

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