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Frontier In-Situ Resource Utilization for Enabling Sustained Human Presence on Mars

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Abstract

The currently known resources on Mars are massive, including extensive quantities of water and CO_2 and therefore C, H_2 and O_2 for life support, fuels and plastics and much else. The regolith is replete with all manner of minerals. In Situ Resource Utilization (ISRU) applicable frontier technologies include robotics, machine intelligence, nanotechnology, synthetic biology, 3-D printing/additive manufacturing and autonomy. These technologies combined with the vast natural resources should enable serious, pre- and post-human arrival ISRU to greatly increase reliability and safety and reduce cost for human colonization of Mars. Various system-level transportation concepts employing Mars produced fuel would enable Mars resources to evolve into a primary center of trade for the inner solar system for eventually nearly everything required for space faring and colonization. Mars resources and their exploitation via extensive ISRU are the key to a viable, safe and affordable, human presence beyond Earth. The purpose of this paper is four-fold: 1) to highlight the latest discoveries of water, minerals, and other materials on Mars that reshape our thinking about the value and capabilities of Mars ISRU; 2) to summarize the previous literature on Mars ISRU processes, equipment, and approaches; 3) to point to frontier ISRU technologies and approaches that can lead to safe and affordable human missions to Mars; and 4) to suggest an implementation strategy whereby the ISRU elements are phased into the mission campaign over time to enable a sustainable and increasing human presence on Mars.

1 Introduction

In recent years, measurements by rovers and satellites at Mars have indicated massive amounts of water in the form of ice beneath and within the regolith [1–46]. At times, during the Martian year, liquid water is observed on the surface of Mars (figs. 1 and 2). If the planet were flat and the ice melted, there would be an ocean many meters deep on the entire planet.

These huge deposits of water can be extracted [47–62] in several ways and combined with the large amounts of carbon residing in the 95% CO_2 atmosphere to produce life support fluids, fuels, oxidizers [63–86], and plastics for equipment, including rovers and spare parts [87–116]. To date, research has demonstrated at small scale the feasibility of various prospective disparate Mars ISRU approaches. Support of human crews at Mars would require large volumes of products from Mars resources and an overall system of systems approach utilizing emerging frontier technologies for optimization. This in turn enables a mission architecture that is both safe and affordable for sustainable human presence (from pioneering through colonization) of Mars, enabled essentially and uniquely by frontier ISRU [117–187].

Mission costs are highly proportional to the amount of mass initially placed in orbit. Affordability simply means that those costs can be accommodated by the prevailing budget. So, particular interest is given to reducing mass for staying within budget. There are three possible approaches to greatly reducing the up-mass in LEO, thereby enabling the cost margins essential to keeping a mission viable:

- Revolutionary Energetics – Positrons, LENR (Low Energy Nuclear Reactions), Energy Beaming, Magnetohydrodynamic Propulsion, to name a few. This is a long term approach and a decade of research will be required to sort out the efficacy of the various possibilities [333]
- Structural Nanotubes (Contiguous nanotubes, not nanotube composites). These posit a factor of some three to eight dry weight reduction and are at this juncture theoretical only; whether they actually can be produced is to be determined [333]
- Frontier ISRU, In Situ Resource Utilization. Often referred to as "living off the land". The technology and Martian Resources for extensive ISRU could provide outbound and return fuel from Mars, life support fluids, on planet equipage, transportation, habitats, via on planet manufacture including "printing" and other additive manufacturing approaches. These could be combined with a campaign architecture approach which transports the ISRU equipage on inexpensive "slow boats" (low energy, conjunction class electric propulsion, for instance) years ahead of time allowing small devices to, over time, produce large effects/results.

The first two approaches (revolutionary energetics and structural nanotubes) require substantial research and development costs and time. The third (ISRU) as described above does not require that same level of investment. The ISRU technologies necessary to sustain a permanent human presence on Mars either exist now or will reach sufficient Technology Readiness Levels (TRL) in time to be implemented into the first Mars-Humans mission expected to occur by 2037. Using that date, the research and development cycle for the technologies/approaches would end by 2025, allowing the subsequent decade to verify performance, including on Mars, over long periods of time at full scale.

ISRU is of course not a new concept by any means; there is a rich literature/history of ISRU discussions, suggestions and research [169–170]. For the most part, these previous studies only considered extracted resources from the Martian atmosphere to assess feasibility of the approach. However, since the discovery of massive amounts of water ice on-planet, there has not yet been a fully comprehensive, study of large-scale ISRU on Mars.

ISRU could conceivably enable, given the immense resources now known to be available on Mars, the following: a habitat incorporating significant Galactic Cosmic Ray (GCR) protection via burial beneath 5 meters of regolith; fuel for on-planet ascent, outbound, return and powered entry, descent and landing (EDL); life support systems for food, water and breathable atmosphere; habitable temperatures and pressures; and 3-D printing and other manufacturing approaches (including synthetic biology) along with a variety of hardware including equipage and on-planet transport vehicles.

There are many benefits of ISRU using current or emerging technologies, including:

- The requisite reusability and local manufacture to enable reliable and sustainable colonization and pioneering of Mars
- Enabling substantial "Commercial Space" beyond commercialization of government functions and positional "Earth Utilities"
- Demonstration of reliability, functionality and systems performance years before humans arrive, greatly improving prospects for mission success and overall safety
- Provides and proves out reusability and the huge cost benefits of reusable robotic systems, enables large cost reductions for future missions.
- In situ certification (for subsequent crew use during later missions) of a reusable Mars descent and ascent vehicle, called a Mars Truck, that lands large payloads (up to 20mT) to the surface, refuels from ISRU resources, and returns to Low Mars Orbit for landing additional payloads that were aerocaptured in orbit earlier (discussed in Section 4.7)
- Reduces dependency on resupply from Earth, leading to an Earth Independent Architecture

Despite its benefits, ISRU alone will not fully solve the initial affordability issue, especially considering the development and implementation costs of the complete spectrum of ISRU capabilities. Combining a phased approach to extensive ISRU with lower launch costs, via reusability and automation tied to cost-effective reductions would further enhance affordability.

Embedding an evolvable ISRU initiative within the Evolvable Mars Campaign strategy that focuses on reusability to reduce costs and on autonomy to boost productivity, "affordable and safe on Mars" can be realized without waiting for development of other advanced technologies. Initial versions of the technologies required for reusability, productivity, launch, additive manufacturing, surface habitats, and ISRU exist today for key areas such as extracting the fluids and solids needed by the colonists/pioneers. Technologies that are needed but that are currently unavailable (such as EDL of larger payloads and autonomy) should exist within the next decade for insertion into the campaign analysis and mission concept. Advanced technologies that could be applied to ISRU approaches/processes going forward include advanced robotics, machine intelligence, “printing” manufacture, synthetic biology, nanotube materials and autonomous systems.

The purpose of this paper is four-fold: 1) to summarize and highlight the latest discoveries of water, minerals, and other materials on Mars that reshape our thinking about ISRU there; 2) to summarize the previous literature regarding Mars ISRU processes, equipment, and approaches; 3) to consider technologies, new approaches, and new concepts concerning ISRU that might lead to safe and affordable human missions to Mars; and 4) to suggest an implementation strategy whereby the ISRU elements are phased into the mission campaign over time, enabling a sustainable human presence on Mars in a holistic, synergistic manner.

2 Current Known Resources on Mars

Understanding the amount and accessibility of water on Mars is vital to assess the planet’s potential for harboring life and for providing usable resources for future human colonization. For this reason, 'Follow the Water' was the science theme of NASA’s Mars Exploration Program (MEP) in the first decade of the 21st century. Discoveries by the 2001 Mars Odyssey, Mars Exploration Rovers (MERs), Mars Reconnaissance Orbiter (MRO), and Mars Phoenix Lander have been instrumental in answering key questions about water's abundance and distribution on Mars. ESA’s Mars Express orbiter has also provided essential data regarding the presence of water. The Mars Odyssey, Mars Express, MER Opportunity Rover, MRO, and Mars Science Lander Curiosity Rover are still sending back data from Mars, and discoveries continue to be made. In 2015, NASA confirmed evidence that liquid water flows on Mars today [45].

The suggested existence of water outside of Mars’ polar regions was tenuous prior to the high-resolution images from the Mars Odyssey spacecraft's Thermal Emission Imaging System combined with images from the Mars Global Surveyor spacecraft's Mars Orbiter Camera and Mars Orbiter Laser Altimeter. However, current understanding of the presence of water is more than sufficient to plan missions (Figure 1). In fact, if one considers the locations of dark liquid staining of the regolith, called Recurrent Slope Linea (RSL),, then there are a plethora of potential landing sites where liquid water may be available seasonally (Figure 2). Other criteria than just the existence of water will also be used for selecting landing sites [141, 175, 219, 225, 236] (MEPAG and Mars 2020 Landing Site Workshop).

The following is a summary of the resources available for Frontier ISRU at Mars.

Water: There is a very low concentration in the atmosphere, but massive amount of water ice at the poles, especially the North Pole. There is enough, if melted, to put a shallow ocean over the entire planet if it were flat. Near the polar regions there is as much water as ice within the regolith, adsorbed on minerals and available from sulfates and silicates. The water concentration in the regolith varies from some 3% to 8% near the equator to some 40% plus at 60 degrees latitude. Also, there are the recent indications of huge ice lakes near the surface, at least one the size of Lake Huron and with greater depth. This water could be extracted via heating, with “solar tents” and microwaving as obvious approaches. This plethora of water and its ready availability provides water constituents, H_2 and O_2.

Oxygen: Immense amounts of oxygen are present in the atmosphere [as CO_2] and obviously much more is available from water. In addition, the regolith is highly oxidized and it has been suggested that oxygen could be obtained by simply adding water to the regolith [186, 199]. Considerable oxygen is also available chemically from these oxides.

Carbon: The atmospheric CO_2 can be extracted easily via either cooling or compression, providing C and O_2.

Mars has H_2, O_2, C, and water. Therefore through chemical means, plastics, methane and hydrogen fuels, and life support fluids can be produced.

Inert Gases: There is argon and nitrogen present in the atmosphere for inert life support atmosphere composition.

Minerals: Various measurements indicate the presence in the regolith of nickel, titanium, iron, sulfur, magnesium, calcium, phosphorus, chlorine, bromine, aluminum, silicon, sodium, manganese, chromium, deuterium and possibly others minerals, localized in what, like Earth and Venus, is a volcanic geology which tended to concentrate minerals.

Ceramics and Glass: Clay-like minerals are also ubiquitous in the Martian surface soils, making the manufacturing of ceramics for pottery and similar purposes a straightforward enterprise. The most common material measured by the Viking landers on Mars was silicon dioxide (SiO_2) making up about 40 percent of both Viking soil samples by weight. Silicon dioxide is the basic constituent of glass, which thus can readily be produced on Mars using sand-melting techniques similar to those that have been used on Earth for thousands of years. Unfortunately for the Martian glass industry, however, the second most common compound (about 17 percent in the Viking samples) is iron oxide, Fe_2O_3. This poses a problem. To manufacture optical-quality glass, the sand used as feedstock must be nearly iron free, therefore, it will first be necessary to remove the iron oxide. This can be done by interacting the iron oxide with hot carbon monoxide "waste" from a reverse water-gas shift (RWGS) reactor [62], thereby reducing it to metallic iron and carbon dioxide, and then removing the iron metal product with a magnet. The iron can be used for making steel. Also, optical-quality glass is not required to make many important glass products, including fiberglass, an excellent material for constructing various types of structures.

3 Previous ISRU Approaches, Limitations, and Technologies

Prior to the discovery and identification of vast amounts of water in the Martian regolith, ISRU feasibility studies based their results on water extracted from the Mars atmosphere [47, 62, 64, to list a few]. Analysis was limited to the production of fuels and life support fluids necessary to support surface mobility and a growing colony of crew [173]. The possibility of on-planet fabrication and repair was not factored into those analyses for reducing mass in LEO or to reduce dependence on Earth.

3.1 Fuel and Life Support Fluids

There are many documented studies [47–62 to list a few] on extracting H_2, C, and O_2 resources from the Mars atmosphere. Initial ISRU studies that assumed little water on Mars showed substantial savings in MLEO (Mass in Low Earth Orbit) by extracting C and O_2 from the Martian atmosphere and bringing Hydrogen from Earth.

It was not until after 2008, following the Phoenix Lander Mission, that water was thought to exist on Mars in quantities sufficient to support life at one time. Satellite images of Mars indicate that during certain times of the Martian year, water rises to the surface of Mars from underground sources which are likely frozen most of the year. Since these discoveries, ISRU research has focused on extracting resources from the ice and regolith of Mars where concentrations appear higher. Hence, the more recent studies of ISRU at Mars focus on regolith processing or melting large pockets of ice believed to be buried in the regolith.

Once water was known to reside in the regolith in quantities meaningful to ISRU, extracting the water and placing it into the purification and ISRU equipment became the issue. At ambient temperature and pressure on the Mars surface, water freezes if it does not sublimate. This water could be extracted via heating, using "solar tents" and microwaving as obvious approaches, provided it is captured with minimal exposure to the atmosphere.

3.1.1 *Conversion of hydrogen, carbon, and oxygen into methane, oxidizer, and life support fluids*

Methane (CH_4) can be made from the C and H found on Mars. The Sabatier reaction which produces methane and water from carbon dioxide and hydrogen is written as

$$CO_2 + 4H_2 \rightarrow CH_4 + 2\ H_2O\ + \text{energy} \tag{1}$$

This reaction is exothermic, that is, it releases heat, and will occur spontaneously in the presence of a nickel or ruthenium catalyst (nickel is cheaper, ruthenium is more efficient both Spirit and Opportunity Rovers found nickel-iron meteorites sitting on the surface of Mars). Production yields of greater than 99 percent with just one pass through a reactor are routinely achieved. In addition to having been in wide-scale industrial use for about a hundred years, the Sabatier reaction has been researched by NASA, the U.S. Air Force, and their contractors for possible use in Space Station and Manned Orbiting Laboratory life-support systems. Hamilton Standard, for example, developed a Sabatier unit during the 1980s for use on the Space Station, and subjected it to 4,200 hours of qualification testing.

The fact that the Sabatier reaction is exothermic means that no energy is required to drive it. Furthermore, the reactors used are simple steel pipes, rugged and compact, that contain a catalyst bed. As the reaction (1) occurs, the methane so produced is liquefied either by thermal contact with the super-cold input hydrogen stream or (later on after the liquid hydrogen is exhausted) by the use of a mechanical refrigerator. (Methane is liquid at about the same "soft cryogenic" temperatures as liquid oxygen). The water produced is condensed and then transferred to a holding tank, after which it is pumped into an electrolysis cell and subjected to the familiar electrolysis reaction, which splits water into hydrogen and oxygen as follows:

$$2H_2O \rightarrow 2H_2 + O_2 \quad (2)$$

The oxygen so produced is refrigerated and stored, while the hydrogen can be recycled back to the Sabatier reaction (1).

Solid oxide electrolysis is another process for separating O_2 from CO_2. When necessary, CO_2 can be extracted from the atmosphere and placed in solid form by use of a cold plate. Storage of CO_2 or O_2 for use later is straight forward.

3.1.2 *Plastics From O_2, H_2, and C*

Because Mars, like Earth, possesses abundant supplies of carbon, oxygen, and hydrogen, opportunities to manufacture plastics are abundant. The key to plastics manufacture on Mars is the production of synthetic ethylene, which itself can be accomplished with an extension of the reverse water-gas shift (RWGS) reaction, which is also a means for making oxygen. The RWGS reaction is defined as:

$$H_2 + CO_2 \rightarrow H_2O + CO \quad (3)$$

Instead of feeding hydrogen and carbon dioxide in a ratio of 1:1 as suggested by equation (1) above, if they are instead fed a ratio of 3:1, to obtain

$$6H_2 + 2CO_2 \rightarrow 2H_2O + 2CO + 4H_2 \quad (4)$$

the water can be removed and cycled back through other processes for other needs. The key is to send the remaining mixture of carbon monoxide and hydrogen into another reactor, where the presence of an iron-based catalyst, enables

$$2CO + 4H_2 \rightarrow C_2H_4 + 2H_2O \quad (5)$$

C_2H_4 is ethylene, an excellent fuel and the key to the petrochemical and plastics industries. Reaction (5) is strongly exothermic, and so like the methane-making Sabatier reaction (1) can be used as a heat source to provide the energy needed to drive the endothermic RWGS (reverse water-gas shift). It also has a high equilibrium constant, making the achievement of high ethylene yields possible. Side reactions also typically occur, for instance producing propylene (C_3H_6), which is an excellent fuel and valuable plastic-making stock.

3.2 Habitats (Mars Surface)

Existing mission architectures define small on-surface habitat concepts, with closed-loop life support systems [200–245]. These concepts do not protect against GCR in any substantive fashion [246–248]. Little consideration has been given in the past to living underground.

3.3 Energy and Power Systems

Surface power considerations in previous ISRU studies were limited to solar and nuclear radiation "batteries". Micro nuclear reactor devices were thought to be too heavy to land using current EDL concepts as well as creating a risky potential contamination source if landed incorrectly [249–263].

3.4 Food

Food in extant ISRU studies is mainly brought from Earth. Some concepts [264–281] include "Grow what we know" (Earth-based, heritage) in surface greenhouses with access to sunlight (Figure 3) or in underground greenhouses (Figure 4).

Peat moss and compost are key to modifying the Martian soils [282–288] for agriculture. Sodium is managed also by algae and growing sodium tolerant plants termed halophytes. Mushrooms and insects factor into the dietary opportunities. There are some notions of growing trees, taking a plethora of insect species to Mars, and tri-culture concepts where rice, water ferns, and loach fish live together in a rice paddy aquaculture. All of these concepts involve considerable oversight (either by the crew or some autonomous monitoring and management system).

3.5 EDL (Entry Descent and Landing)

Missions thus far are based on direct entry which greatly limits the landing mass. Current EDL concepts have reached a traditional technology enabled capacity the order of 1 mT (Mars Curiosity Rover), which is limited by the characteristics of the Martian Atmosphere [301].

3.6 Spare Parts, Surface Transportation and Other Equipment

“Make on Earth and Ship to Mars” is the logistics approach considered in the extant reference missions. Additive manufacturing simply has not demonstrated sufficient throughput autonomously to be considered seriously by mission architects. (That will likely change soon). Printing with plastics is available commercially for everyday use for a variety of products and appears ready for utilization in space. Metal printing has not matured nearly as far or fast but is developing rapidly.

4 New ISRU Approaches and Technologies

Utilizing the vast resources of Mars for human colonization more fully is possible using today’s technology and will improve as more is learned about the details regarding locations and quantities of resources. Ultimately, even from what is known about Martian resources and the evolving applicable technologies, there are reasons to believe that human colonization on Mars could become Earth independent. As an example of the utility of Mars resources, Martian atmospheric CO_2 could also be employed for nuclear shielding, metal fuel cells, carbon-for-carbon nanotube production, pressurized rockets, and even an in-atmosphere solar pumped CO_2 laser. The following is the current understanding of Martian resources, thoughts concerning extraction methods, and the technologies available for enhancing their utilization going forward:

4.1 Obtaining H_2, O_2, C from Martian Sources

Storing hydrogen via conventional cryogenics would be difficult on Mars due to rapid boil-off expected on the surface. ("A long-term ISRU process with cryogenic storage of hydrogen on Mars is unthinkable" [169, p. 235]. The energy required to store hydrogen in cryogenic form and compensate for boil-off losses over a long period of time is problematic when many other alternatives appear to be far less costly. As just one example, there are large amounts of magnesium within the regolith. Recent research [258] on hydrogen storage via magnesium hydride may offer a low-energy option for storing hydrogen.

The chemical processes previously discussed (Sabatier, Reverse Water Gas Shift, Solid Oxide Electrolysis) can be scaled-up to colonization-sized requirements. The devices could also purify the water, oxygen, and carbon. Condensing vapor on a cold plate seems a suitable means to isolate the impurities (dust and other chemical compounds).

Prior to implementing the extraction and collection methods, the water should be checked for life [289–299]. NASA LaRC has developed a non-invasive Raman instrument shown in Figure 5 riding on an autonomously controlled mobile platform that can analyze the water for signs of life in situ on a planet and report back its findings without the need for a sample return mission.

Solar tents for water extraction from the regolith would use sunlight to heat the surface layer and vaporize the water or produce liquid. Placing a microwave device on a rover could heat, vaporize, and collect the water trapped in the regolith beneath the rover as it moves from point to point. Both of these approaches do not require moving the regolith. For ice lakes with some regolith overburden, the overburden would need to be pushed aside so the ice could be melted, vaporized, and collected. There is also a concept, called ALPH [195–196], which places a 100KWe, 1MW thermal, micro-nuclear device on top of the ice cap and then melts its way to depths while collecting, purifying, and pumping the purified water to storage facilities where it can be refrozen for use later. The device creates shielding by sinking to sufficient depth in the ice. The crew habitats and other facilities could be placed nearby within the ice while still maintaining a safe distance from the nuclear device.

4.2 Making, Storing, Transporting Fuels & Life Support Fluids

A Sabatier reaction could produce methane (CH_4) using C from CO_2 and H from the water/ice without requiring long storage times for pure hydrogen. The requirements for the Sabatier reaction include moving the hydrogen, oxygen, and methane from tank to tank. This would require pumping and storage of these elements in liquid form, and establishes requirements for thermal control (and additive manufacturing on Mars discussed later herein).

Maintaining a transportable (liquid or vapor) state is vital to the performance of these devices. Freezing of the water within the device would likely destroy it and certainly hinder reusability, which is essential to affordability and safety.

Burying beneath the regolith seems the most prudent means to help protect water lines and storage tanks from freezing. Therefore, the mobile platforms used to offload landers and load the "Mars Truck" are outfitted with bulldozer attachments for pushing and moving small amounts of regolith at a time in the reduced-g environment which poses less structural loads on the equipment than here on Earth. Perchlorates offer an excellent source of antifreeze; however, they need to be removed from the water prior to use by the crew. Mars soils contain high concentrations of perchlorates which typically will not freeze at temperatures above -56 degrees C and above -70 degrees C for water – magnesium perchlorate. Another option for preventing freezing is to store fluids chemically or via hydrates. The water is simply removed later by heating at point of use when needed.

If placed underground, the storage areas could be separated from the water collection area within the device and placed nearby with piping and pumping operations between. Freezing the water after purification is a suitable option as long as the storage devices do not crack. Refreezing the collected water suggests the use of flexible plastics and other expandable (piping and bladder) materials.

4.3 Plastics and Metals

With large quantities of H available from the water/ice, other items such as plastics (C_2H_4 and C_3H_6) can be stockpiled for insertion into 3-D additive manufacturing printers for production of equipage and spare parts. Thus, the readily and easily available C is another key to storing hydrogen in some readily usable form.

In addition to extant "scrap metal", mostly aluminum, lying on the surface of Mars from previous missions, metals exist in lightly oxidized or ore-like rocks in the regolith. Additive manufacturing technologies existing today can transform those metals into spare parts or replacement devices or storage tanks, all useful for the extraction, refinement, and storage of ISRU byproducts stated above. Printing manufacture at the scale needed for extensive Mars ISRU will require further engineering of the existing additive manufacturing processes to standalone systems that can function autonomously. (See Section 4.5 on fabrication methods).

4.4 Food

There are a number of extant studies proposing greenhouse structures on the Mars surface for farming food [264–281]. Earth independence requires that the astronauts grow their own food or that the food be grown for them robotically. Such robotic agriculture exists now. Possible food sources which could be produced on-planet include mushrooms, insects, cyanobacteria (e.g. spirulina) and duckweed, along with many others. Plants can survive and function at pressures down to a tenth of an atmosphere. Via studies of extremophiles, genomics and synthetic biology, development of "plants for planets", especially for Mars is a current research interest. Since such plants currently require a reduced CO_2 partial pressure compared to the atmosphere, they will have to be grown in a protected atmospheric environment using sunlight. Artificial lighting is thought to be too energy intensive. However, recent efforts in Japan [276] demonstrate increased yields over traditional agriculture and greenhouse practices when growing plants such as lettuce indoors. Low voltage light bulb technology now allows plants to be grown quickly without access to sunlight. In addition to artificial lighting, Mars presents different stimuli with respect to higher radiation yet lower gravity. The processes to grow food there may be quite different than the successful processes here. Ultimately, what is desired are food sources that grow massively and quickly in the presence of high concentrations of CO_2 and (simulated) sunlight. Genomics, synthetic biology, and extremophiles are expected to supply such.

4.5 Fabrication on Mars (In Situ Fabrication & Repair)

The major new/rapidly-developing manufacturing application for ISRU on Mars is three-dimensional additive printing [87–91 for instance]. This technology, where you "grow" (add material) instead of "cut" (remove material), is becoming extremely useful and widely applicable. Multiple materials and imbedded electronics have been demonstrated.

3-D printing with plastics is, thus far, easier and simpler than printing with metals. This is partially because a hot plastic bead can touch the target deposition spot whereas hot molten metal must be deposited from a short distance onto the target deposition area using current techniques.

As previously described, the Martian resources provide an abundance of materials for plastics, which are extremely amenable to printing manufacture. Piping, wheels, entire roving vehicles, habitat equipage, storage vessels, etc. could be readily produced on-planet via printing using ISRU produced plastics. On-planet equipment can be crudely made, heavy and thick, as long as it functions. Where metals are required, these can also be printed and Mars is rife with metals and other materials. Other, conventional fabrication approaches include chemical, pressure, stress/impact, and cutting processes. Given a supply of ISRU materials and the robotic means to fabricate, assemble and operate such printing machines in-situ, much of the equipage that formerly was part of the huge up-mass into low earth orbit for crewed Mars campaigns could be produced on Mars using relatively small machines acting over lengthy (pre-human arrival) time frames. The materials necessary are essentially present on the planet.

4.6 Autonomous Robotics for ISRU

The key capabilities to enable application of extensive ISRU infrastructure development and frontier operation on Mars, are advanced autonomous robotics and machine intelligence [300–318]. There are three major ways forward in machine intelligence: soft computing, biomimetic and emergence. The latter is the way humanity possibly acquired its intelligence -- make something complex enough and it "wakes up". Biomimetics, wherein the neocortex is nano-sectioned and replicated in silicon, [e.g. the Human Brain Project in Europe and the U.S.] is thought to be the current probable best bet to achieve soonest machine intelligence approaching human. Whether this technology can be fully leveraged to that level for Humans-to-Mars remains to be seen. Finally, soft computing constitutes the more conventional "learning AI" developments such as neural nets, fuzzy logic, genetic algorithms which have become increasingly useful for application to complex problem problems including the stock market and medicine, and is included in much of society's infrastructure, as in "smart" devices. There are currently no clear paths to evolving soft computing into human-level intelligence.

Robotics is one of the most rapidly evolving technology areas, and combined with machine intelligence is rapidly replacing humans in many traditional areas of employment. The Department of Defense (DOD) has a robotic future mapped out and most of space exploration, except for the few human programs, has been robotic [300–318]. An early example of combined machine intelligence and robotics is the BART (Bay Area Rapid Transit) Transit system. The Japanese are making rapid progress with respect to humanoid robotic entities and have placed robots in health care facilities, as have others [342]. Given the usual 10 years of research and development for major projects such as Humans-to-Mars, the robotics and machine intelligence technologies to execute extensive ISRU for exploitation of the huge extant Mars resources for nearly everything required on-planet for human colonization and for transportation fuels and life support utilizing reusable robotic systems could all be available and usable.

The major issue with robotics and machine intelligence for extensive ISRU is autonomy. The 20 minute plus speed of light delay between Earth and Mars requires an autonomous ISRU system of systems. Tele-operation from Earth is not feasible in most cases. The humans on Earth will obviously check in with and monitor after the fact, and alter instruction sets for the on-planet and in-space ISRU systems, but autonomy is required. The autonomy technology state of play is one of extremely rapid development, including self-driving cars and autonomous aerial delivery vehicles. Again, in another 10 years, the autonomy technology should advance to enable the huge cost savings and safety improvements associated with extensive Mars ISRU.

4.7 Reusable Up/Down "Mars Trucks"

The Mars Mission studies have long called for prepositioning the crew ascent vehicle, often called the Mars Ascent Vehicle (MAV), on-planet and the currently developing ISRU plans call for ISRU fuel for this vehicle, as well as for life support fluids. An intriguing possibility is to design this crew descent and ascent vehicle that travels between the surface of Mars and Mars orbit as a reusable "Mars Truck" to ferry up more than a human crew for the return mission. This Mars Truck could also be reusable for landing additional payloads as well as placing payloads in orbit. Other up-cargoes include fuel for in-space propulsion, both return and outbound, life support fluids for the same, fuel for powered EDL and even either the EDL capability or the entire entry crew capsule with EDL incorporated. This greatly repurposed, expanded capability Mars Truck would obviously be both highly reusable, wholly autonomous and extremely cost effective. When incorporated, combined with a reusable, autonomous in-space "slow boat"/cargo propulsion device and cargo ship (ostensibly the devices used to deliver the ISRU equipage initially) the Mars Truck enables very inexpensive delivery of outbound fuel to low earth orbit, at possibly less cost than other studies [188] that launch such equipage from earth.

The design of the Mars Truck then needs to emphasize reusability and maximize payload fraction to the greatest extent possible. Major quantities of ISRU methane fuel on Mars would be readily available to operate this Mars Truck/Rocket. Obvious and not so obvious design approaches include two-stage (with autonomous fly-back booster such as those currently under development at SpaceX); advanced, light weight, laser guided polymer stabilized water jets as ground assist to push it into the "air"; methane/LOX or magnesium/ CO_2 attached additional booster rockets; beamed energy/ MHD high thrust/ 2000 seconds of ISP propulsion; and PDW (pulse detonation wave) cycle propulsion. Overall, a viable Mars Truck design thus involves numerous trades, but successful development of the concept would help to better enable successful application of extensive ISRU for Humans-to-Mars.

4.8 Surface Mobility (Landing Site Utility & EVAs)

A recent study [118–119] shows that the single-stage Mars Truck allows for the landing of payloads up to 20mT to the surface of Mars and for the ascent of payloads up to 10mT to Low Mars Orbit. A two-stage system with a fly-back booster allows for much larger payloads to and from the Mars surface. Payloads are offloaded by a lifting arm (Lightweight Surface Manipulation Arm) attached to a mobile platform (Athlete or Chariot concepts) [307, 312]. The process is autonomous [305]. Portions of the payloads may have their own mobile platform and arm (Figure 6). Standards for chassis and other components will emerge to complement the two or so types in development today. Meanwhile, on-planet construction of rovers and hoppers to facilitate roving and exploration appears to be straightforward, given the technology level and availability discussed thus far.

4.9 Habitat Options

GCR on-planet radiation protection is of paramount importance to sustain human life. Mars has little to no planet-scale or remnant crustal magnetism (Figure 7) and only a thin atmosphere to provide radiation protection, thus producing a disconcerting GCR environment. Measurements indicate an on-planet surface GCR level of 37% of the inspace level, the reduction being due to some atmospheric attenuation and considerable planetary bulk/geometry obviation. A surface habitat, surrounded by Mars atmosphere, requires serious expense and development and provides little GCR protection. The least cost, least effort, and most effective radiation protection approach with many additional benefits is going underground, beneath some 5 meters or more of regolith (Figure 8). Such an underground habitat could be fabricated via an inflatable/expandable plastic habitat positioned underground either via ditching and burying or within an existing lava tube or cave [200, 201, 209, 240, to name a few]. Such an approach also provides significant thermal insulation and micrometeoroid protection. The usual alternative advanced habitat thus far is a surface metal structure which would have secondary radiation protection, but would not provide anywhere near the GCR protection of 5 meters of regolith and not that much thermal insulation. Such protections would have to be added, increasing the weight advantage of a buried expandable habitat even further relative to a surface structure.

Inflatable habitats can be stowed more easily and when expanded, offer triple the volume for the same amount of packaged weight. Layers can be added to the outer diameter of the inflatable to increase resistance to tears, punctures, and ruptures. Also, simplex computation indicates the weight of the 5 meters of regolith stresses the habitat at about the same level as the internal pressure necessary for the astronauts to feel comfortable. Even so, by design, structural elements inside the habitat will prevent collapse in the event of pressure loss as well as to separate and seal off areas.

Airlocks would need to be lightweight, durable, and repairable, and capable of removing dust [205, 319–325] brought in by the crew and equipment. Cleansing procedures to remove dust from the suits, rovers, and equipment could involve a water-based enzyme spray that carries the dust to floor drains where it is ejected from the airlock. Mars dust is a possible health hazard, because it is thought to contain hexavalent chromium, an extremely potent carcinogen, and known to contain perchlorates and many oxides.

Naturally occurring shelters, like lava tubes, caves, and ice caves, have been found planet wide [228] and would be useful habitats for achieving sustained human presence. Furthermore, like the previously considered surface habitats concepts that were placed near the largest water source, the habitats for sustaining a human presence would be placed underground near the largest water sources. The goal for current national Mars exploration missions is to more fully understand the locations of liquid water and underground access points for selecting suitable landing sites. Inflatable space habitats could be redesigned to fit within a lava tube or to be buried with regolith, thus reducing the development costs. Such habitats could be either (probably initially) brought from Earth or be manufactured (eventually) on planet.

4.10 Energetics for Mars ISRU and Sustainable Human Presence

A major key to viable Sustainable Humans-Mars is on-planet energetics to power ISRU extraction, refinement and fabrication; to provide habitat climate control (temperature, atmosphere, pressurization) production of life support fluids of all types; production of fuels for space transport and perhaps EDL; habitat lighting/food preparation; propulsion for on planet transport; etc. The Mars resources for energetics are many and varied [249–263] and some are not yet evaluated. There is ample sunlight, both in orbit and on planet, albeit attenuated due to distance from the sun compared to Earth but solar cells are becoming ever more efficient and lighter weight. For terrestrial Mars solar power there are problems with Mars dust collecting on the devices and dust storms. Then there is the need to store solar energy for night time.

Other on-planet energetics sources include possibilities for geothermal energy utilization Mars, like Earth (and Venus) is a volcanic planet and thus has geothermal potential. However, such capacity has, at this point, neither been discovered nor mapped for Mars. Then there is osmotic power, a new technology that utilizes the mixing of saline and fresh water to produce electricity directly. Since the result is a weaker saline solution, solar power can be used to evaporate/recycle the water and produce more fresh water. This energy possibility has not yet been seriously evaluated for Mars.

The obvious, state of the art, energy source for transport systems is chemical. Mars has immense resources for production of methane, oxygen, magnesium, CO_2 and other chemical energy/propulsion sources, utilized in either combustion systems or fuel cells. Frontier, non-chemical energetics possibilities include LENR (Low Energy Nuclear Reactions that requires a validated theory and scaling/engineering), thermionics and even long term storage of positrons [333].

However, at least initially, to ensure the timely production of fuels, the essentially unanimous choice for on-planet energetics is a micro-fission nuclear reactor. There is an especially appealing Japanese design [252] of about the right size/ capacity available. There is a need for both thermal and electric on-planet power and a micro nuclear reactor could supply both of these. There are now several means of converting thermal to electrical energy which could be employed for thermal sources, these include: thermal electric converters; thermal photo-voltaic converters; pyro-electric devices; and a plethora of thermal cycles/devices including Sterling motor-generator sets. Energy storage options include [248–262, 331] recent German research on Zeolites at 4 times water thermal storage, advanced metal air batteries then year (factor of 10 plus better than Lithium-Ion), high pressure gas and chemical species/ chemical reactions.

Of this range of options, the current best ISRU solution for energetics appear to be:

- A micro-fission nuclear reactor for on-planet power. This is an assured, high-capacity energy source that supplies power across the board.
- A lightweight back-up deployable solar array system to ensure life support in the event of operational issues with the micro-fission nuclear reactor.
- Utilization of the power from the micro-fission nuclear reactor to produce and store, from Mars resources, quantities of methane, oxygen, magnesium, CO_2, for use in transportation both on planet and in-space [ascent, outbound, return] and as backup energy for reactor malfunctions
- Research on advanced thermionics and LENR to determine their efficacy for Mars Utilization. These "nuclear" alternatives would enable "distributed/ local nuclear class energy density, orders of magnitude greater than chemical with potential utilization for transportation writ large as well as stationary on planet application.

4.11 EDL Options for Humans-Mars ISRU Architectures

Compared to powered EDL using fuel brought from Earth, utilization of aerocapture and aero braking has clear advantages with a large overall mission payoff. However, the possibility of less "expensive" Mars-ISRU fuel in Mars orbit may shift that assessment toward powered EDL. The current best-bet for EDL is some variant of inflatable aeroshells to increase drag area. A key issue is the weight to be landed versus the atmosphere density/drag available. EDL becomes simpler if the cargo to be landed can be segmented into lighter bundles. Besides inflatable aeroshells and the possibility of powered EDL using Mars ISRU fuel, the other EDL options which should be studied and triaged, include:

- High lift, high drag in-atmosphere maneuvering to utilize integrated drag from "horizontal" flight to reduce flight speed.
- Several variants of atmospheric CO_2 ingestion, processing [pressurization/heating, or not depending upon Mach Number for intake and ejection] and forward injection, i.e. regenerative aerobraking.
- Similar to the above, but using advanced energetics such as thermionics or LENR to heat the ingested atmospheric CO_2 before forward injection. Alternatively, solar energy acquired during in-space transit and stored in the spacecraft skin/structure acting as an ultra-capacitor could be used to heat the captured CO_2.
- The magnetoshell utilizes magnetics to slow the vehicle. This approach still requires experimental verification and scaling
- Hypersonic/supersonic parachutes, arranged to produce, in the aggregate, greater overall total pressure recovery, closer to isentropic compression than a normal shock.

- Reusable Mars EDL, repositioned in/returned to Mars orbit via the Mars Truck. This could be either a complete reusable entry capsule and EDL combination or a detachable, reusable EDL package.

The currently favored EDL approaches are variants of the inflatable aeroshells. With the possibility of Mars ISRU fuel for powered EDL becoming an increasingly credible approach, the Mars truck concept deserves additional analysis. The other possibilities have potentially substantial systems penalties, increased weight and cost, and need to be studied further.

5 Toward Achieving Sustainability

Part of NASA's charter is to foster human presence in space, and to this end the agency has conducted a number of major programs including: Mercury, Gemini, Apollo, Skylab, Shuttle and the International Space Station. The next logical major target for humans in space and possibly pioneering/colonization is the planet Mars. The dominant metrics for an architecture that maintains a permanent presence on the planet are safety and affordability. Given unlimited budgets and the current state-of-the-art, a brute force, successful, Apollo-like campaign could be launched to place humans on Mars and support them there. In reality however, such budgets are not available and with anticipated budgets what is safe is not affordable and what is affordable is not safe when utilizing heritage technical approaches. However, utilizing extensive ISRU could possibly be the game-changer that achieves the requirements necessary for pioneering and ultimately colonization.

5.1 Enablers for a Sustained Mars Presence

A number of factors help to enable safety and affordability for human Mars campaigns. A first approach is stockpiling sufficient quantities of life support, fuel, oxidizer, and spare parts on Mars at the landing site and in Mars orbit, likely LMO (Low Mars Orbit). An efficient way of doing this is by aerocapturing all payloads into Mars orbit, including a Mars Truck and a surface nuclear power device, and then simply dropping smaller payloads to the surface using the Mars Truck. More specifically, this concept thus breaks EDL into two steps: 1) aerocapture of 60mT or more payload into Mars high orbit followed by propulsion burns to reach LMO; and 2) landing payloads on the order of 20mT to the surface using the reusable Mars Truck. The Mars Truck will be refueled using ISRU prior to returning to Mars Orbit for the next payload. A reusable heat shield is possible since the heat loads are around a relatively benign 50 Watts/cm2 during EDL from LMO to the Mars surface. Roundtrips by the Mars Truck certifies it for crewed flights later as the Mars Descent Vehicle and the Mars Ascent Vehicle (MAV).. Another enabling factor is to provide a ready-for-crew landing site, with an equipped habitat ready for occupancy, complete with life support, open loop environment, radiation protection, dust mitigation, and other necessities. This will improve safety and affordability by not putting landed crew into jeopardy in trying to assemble a base of operations. Finally, a last major enabling factor is to automate as many aspects of the architecture as possible. The crew is there to explore, and to colonize, not maintain and repair. Any time spent on "living there" and "housekeeping" should be minimized to an oversight role of robotic automated tasks.

Based on a literature review, a 60-day study, and consultations with those who have studied this problem for many years, an architecture that utilizes these enablers of stockpiling, creating a ready-for-crew landing site and automation will close the design process and can lead to sustainable Mars pioneering and eventual colonization (as described further in Section 6 "*A Phased Approach for a Sustained Human Presence on Mars*").

5.2 Addressing Safety

Specific safety issues that need to be addressed for human Mars sustainability include: radiation, micro to reduced gravity, Mars dust, and reliability. Both micro gravity and radiation adversely impact the immune system and have at this point unknown combinatorial health effects. The radiation of most concern is GCR -- up to some 50 GeV of iron nuclei. During the Apollo Program the astronauts were subjected to full GCR for a few days when they were beyond the Van Allen Belts. Currently there is no whole human effects data or modeling information applicable to this level of radiation, especially for protracted periods. Protection measures for GCR radiation on a spacecraft incur major budget impacts, huge mass in Low Earth Orbit increases, and additional SLS (Space Launch System) launches. In addition to radiation, Mars dust is also a safety issue since it is thought to contain hexavalent chromium (a carcinogen), and is known to contain perchlorates, which adversely impact the thyroid. The dust on Mars is extremely oxidative, and there are concerns about its impact upon habitation equipment and humans when present in habitat conditions that have a much greater temperature, pressure, oxygen and moisture than on the outside. The long duration (some 3 years) of human Mars campaigns in conditions including highly oxidative dust, also makes reliability a safety concern. Design elements should avoid having single points of failure (if they cannot be repaired or replaced cheaply and quickly there). Overall, the equipage for human Mars campaigns will have to protect humans from lethal atmospheric pressure, temperature, radiation, atmospheric composition and potentially lethal dust. Establishing a functioning infrastructure on-planet with demonstrated utilization life, before human arrival, would go far to ensuring reliability and safety.

5.3 Addressing Affordability

A usual surrogate for cost in crewed spaceflight campaigns is required mass in low earth orbit [MLEO]. For a conventional Apollo-like human Mars exploration/colonization campaign with some 4 to 6 crew, the required mass is the order of 600 to 1000 metric tons in LEO, the equivalent of several space stations. This mass would have to be reduced greatly to decrease cost sufficiently to ensure sustainability on Mars and associated Earth independence as shown in Figure 9. A large percentage of that mass is fuel and life support fluids to travel there and back and to subsist on the planet. That mass has the potential to be significantly reduced, however, through the use of extensive ISRU. Indeed from what is currently known [64, 66, 85–86, 119, 151–152, 185–187, 199, 263], the fuel and life support fluids to travel to and back from Mars may be readily obtained on or near Mars given the necessary in situ infrastructure. Moreover, realizing that objective is not too much of a stretch. Within the next decade, robotics and machine intelligence will exist to autonomously operate, service, and produce via ISRU practically anything utilizing additive manufacturing capabilities, including 3-D printing of plastics, metals, carbon nanotubes, fiberglass, silicon, and much more. Should this high level of In Situ Fabrication and Repair (ISFR) be reached, resources from Mars could be placed cheaply at other locations, even near Earth, to enable affordable exploration anywhere. Thus, the impact upon affordability of reusable intelligent robotics and ISRU is expected to be large and favorable, which will in turn enable improved safety and ultimately facilitate the larger goal of making Mars sustainability a practical venture.

6 A Phased Approach for a Sustained Human Presence on Mars

Given the understanding of the primary metrics of affordability and safety along with the assessment of current and future ISRU technologies, a possible scenario for permanent human presence can be advanced that heavily leverages extensive ISRU in a practical manner.

In creating an ISRU-leveraged architecture for Mars sustainability, several over-arching principles are set in place. First, exploit the abundance of Mars resources and do not manage scarcity of resources portaged from Earth. Second, solve EDL via advanced technologies (e.g. expendable aeroshells, ISRU-fuel for powered EDL, the mini magnetosphere, regenerative aerobraking, etc.). Third, solve GCR protection, health impacts caused by reduced gravity, dust infiltration, and other health related concerns via synthetic biology, active GCR protection (several approaches), dust control, etc. Fourth, solve reliability through testing for failure modes, monitoring for anticipating failure of emplaced systems in the Mars architecture, and utilize overall robust and fail-safe designs via advanced reusable robotic systems pre-human arrival.

In addition to the primary principles set in place for the mission architecture design, several underlying premises are also assumed in order to close the trade space. Foremost, it is presumed that there exist large ice deposits with minimal regolith overtop. Also, it is expected that the initial habitat can be placed underground for radiation, thermal, and micro-meteoroid protection. In addition, “small” pre-deployed devices are anticipated to produce large effects over long durations prior to human arrival. Next, the needed ISRU equipment could be made from technology available at that time. Finally, that ISRU, reusability, and automation may enable multi-mission cost advantages.

So with an initial set of principles and premises, an architecture for Mars sustainability is proposed. To stay within budget, and therefore affordable, the ISRU strategy would phase in capabilities (capacities and functions), according to envisioned pioneering stages while adding updated and frontier technologies as they provide opportunities to improve sustainability, reliability, safety, and affordability. The approach proposed here involves a six-phased pioneering campaign.

Phase 1: Landing Site Selection and Water Extraction Go-Ahead

Proper selection of the landing site is critical to the success of pioneering Mars. An initial going-in position by some scientists and mission planners is to select locations that have tremendous water ice deposits beneath less than 1 meter of regolith. The regolith could be scraped off and piled over the habitat for GCR, micrometeoroid, and thermal protection.

The exposed ice could be melted, purified, and stored for later processing by ISRU equipment.

Immediate and decisive in situ measurements for signs of life are also crucial. It is not practical to wait for a sample return to Earth for analysis and assessment of whether to extract the water at any selected spots at Mars. That could take years. A possible solution to this problem would be to use a compact remote multi-sensing instrument tested for non-invasive rover-based measurements at Mars. Recently, an instrument to meet this requirement called the Remote Raman, Fluorescence, and Lidar Multi-spectral Instrument has been prototyped at the NASA Langley Research Center [289].

Phase 2: Autonomous Preparation for Safe Landing and Habitation Prior to Initial Colonists/Pioneers

This phase involves prepositioning the initial ISRU equipment and habitat for making the chosen campsite at the selected landing site ready for the first crew to arrive later. The interplanetary transfer vehicle can be a "slow-boat" using solar electric, magnetic, or even chemical propulsion, or a hybrid thereof. The interplanetary vehicle aerobrakes into LMO so that the payloads are delivered to the surface in smaller portions in order to use existing EDL technologies. Fuel and life support fluids would be harvested from the regolith, ice, and atmosphere, and then stored. This version of ISRU equipment is unsophisticated but has proven reliable for yielding large quantities of products over long periods of time where efficiency is not as important.

The initial "safe haven" habitat, likely a combination of a solid structural base and some inflatable membranes complete with thermal, radiation, and micrometeroid protection, would be operational and monitored real time to deem it safe prior to sending the first crew. The preferred approach to habitation, if allowed within the MLEO budget for this initial mission, is to bury an inflatable habitat beneath five meters of regolith with a membrane consisting only of structural and tear resistant layers. Thermal, radiation, and micrometeroid protection would thus be provided by the regolith covering the habitat. A rover concept consisting of a bulldozer blade would be necessary to push the regolith into a mound over top of the habitat. A nuclear device [195–196, 252] is capable of powering the habitat systems as well as the ISRU equipment necessary for this portion of the campaign. With the completion of the habitat, the ascent vehicle would lift the fuel necessary for powered EDL to LMO to have it ready for use by the crew arriving years later.

Prior to human missions, the performance of all ISRU and emplaced surface and orbital assets can be monitored to assess and predict failure modes. This data will set the anticipated level of spare parts and replacement systems necessary going forward and will refine ISRU practices that reduce Mean Time Between Failures (MTBF), boost reliability and safety, and improve chances for achieving a sustainable architecture.

Phase 3: Arrival of First Astronauts and Preparation for Second Wave of Colonists/Pioneers

Once Mars is deemed safe, with the requisite systems in place, functioning, and evaluated for reliability within the confines of the chosen landing site, then the first crew will go there. By the time the crew departs Low Earth Orbit, life support fluids and fuel for EDL (and return to Earth) will have been brought up from the Mars surface by a reusable ascent vehicle, the Mars Truck. As discussed herein, the life support and fuel to go to Mars and return would be made on Mars. This greatly reduces MLEO, the major cost metric, for which to compare alternatives.

The first crew of four astronauts arrives at Low Mars Orbit through a series of aerocapture and deorbit maneuvers following a fast transit trajectory using chemical propulsion, possibly a liquid methane/LOX rocket. The interplanetary vehicle performs a rendezvous maneuver with a tank of fuel produced by the ISRU equipment and brought up to LMO for EDL to the surface. The now empty tank and the larger fuel tank within the interplanetary vehicle remains in orbit to be refueled later by the reusable Mars Truck for a possible return trip to Earth. Crew members land in pairs at the time of their choosing to avoid dust storms and to provide ample time to inspect the conditions of the habitation and landing site.

Phase 4: Enabling Exploration and/or Additional Landing Sites

The first two crews will have erected a small maze of sub-surface habitats with connectivity to storage areas containing vast amounts of fuel, life support fluids, and food. Waste is handled by way of recycling the water in conjunction with growing some food groups. Even initially, thanks to the initial ISRU campaign, much of the food comes from Mars. The life support and waste facilities are run partially open loop for the most part, as water and oxygen are readily abundant and to ensure functionality and minimize bacterial and other biohazards. By running the facility open loop, the issues associated with closed-loop life support systems experienced on MIR and ISS and the Biosphere Experiment are avoided. The issues associated with dumping waste products into the open environment are mitigated naturally, as the water evaporates leaving no transport method of the solid and other waste that is simply scooped up and used to grow plants.

Each subsequent crew adds new capacity and brings online new functional capabilities especially in additive manufacturing and other processes leading toward Earth independence. Rovers can now be completely built on planet using plastics made from Mars resources and metals refurbished from “EDL trash” as well as collected and processed from the regolith.

These subsequent crews focus on implementing surface mobility well beyond the initial habitation leading to extended on-planet EVAs to search for additional suitable habitation sites. The astronauts will live in the rover vehicles. This is the period of expansion on the planet whereby the technology revolutions on Earth begin to take hold in some shape or form at Mars.

Phase 5: Enabling a Prescribed Return to Earth

By the time the fourth crew of four astronauts arrives, the Mars Ascent Vehicle will be upgraded to a fully reusable two-stage Mars Truck with fly-back booster. The booster serves as the first stage to enable larger payloads to be lifted from the Mars surface. The fly-back booster allows for quicker refueling operations. The purpose of the Mars Truck is to place return fuel and life support in orbit (while placing EDL fuel for the next crew to fly down from orbit). The interplanetary vehicles that brought the crews to date are still available in LMO being refueled and resupplied from Mars resources via each autonomous rendezvous with the Mars Truck. Rather than sending a crew back to Earth, this may become the opportunity for sample return or simply sending back to Earth orbit the fuel and life support needed by the next crew to make the journey from LEO to LMO, thus not only illustrating some Earth independence but also serving as precedence of Mars supporting space faring at other locations in the inner solar system.

Phase 6: Advanced ISRU Comes of Age

In the final phase, Mars becomes the proving ground for many new technologies that not only improve Earth independence but set up Mars to become the supply source for fuels, oxidizers, life support, spare parts, replacement vehicles, habitats, and other products for space faring beyond LEO.

By now, many Mars and near-Mars missions, including on-planet and moon/asteroid landers, rovers, orbiting sensors of various flavors and earth/space based "astronomy" have now established the true vastness of the Mars and near-Mars resources suitable for Planetary and interplanetary ISRU [326–331].

Then, there are the advanced technologies that could emerge and be developed for improving the architecture [332–342].

7 Conclusion

There are massive resources on Mars obtainable from the atmosphere and extracted from the regolith which are capable of supporting human colonization. Using these resources, existing ISRU technologies could supply water, oxygen, fuel, and building materials to relax the dependence on Earth during the buildup of a colony on Mars. As technologies in the areas of additive manufacturing and robotics are tailored to improving reusability of ISRU, habitat, and mobility systems that includes Mars ascent and entry, descent, and landing (EDL) at Mars, then fuel, life support, and building materials become available in quantities not only capable of supporting colonies on Mars and crew return to Earth, but also missions to go elsewhere from LEO or from LMO, as well as space tourism in the inner solar system. Starting with the pre-deployment of ISRU and habitat systems to prepare Mars for the arrival of the first crew, each successful mission within the pioneering campaign yields greater confidence in this ISRU approach and ample opportunity to reach sustainable colonization that is both safe and affordable. Then, and only then, will colonization of Mars realize its Earth independence.

7.1 Suggested ISRU related Research Areas:

- For Energy: thermionics; micro-fission reactors; radiation-hardened, manufacturable on mars flat panel PV direct conversion and storage approaches writ large
- Habitat: lightweight inflatable habitat with molded-in air locks and "furniture"
- Resource Extraction and storage approaches
- Exploration of "underground Mars" for ice/water, Lava tubes/caves, especially ice caves, geothermal energy, concentrated mineral ores

- Food production on Mars
- Autonomous robotics
- Fabrication at 0.38g
- Mars Truck Design/optimization
- Evaluation of EDL approaches.
- Solution spaces for corrosiveness of Mars dust at interior Habitat Conditions

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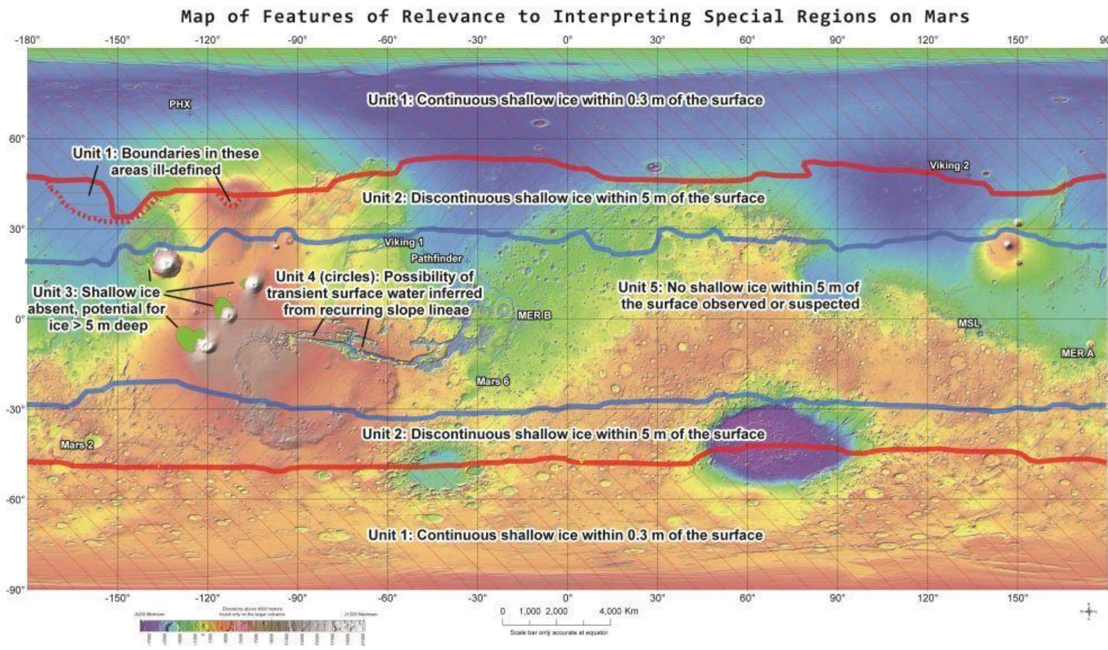

Figure 1. Presence of water on Mars. Source: MEPAG Report [175], September 2014, Figure 46.

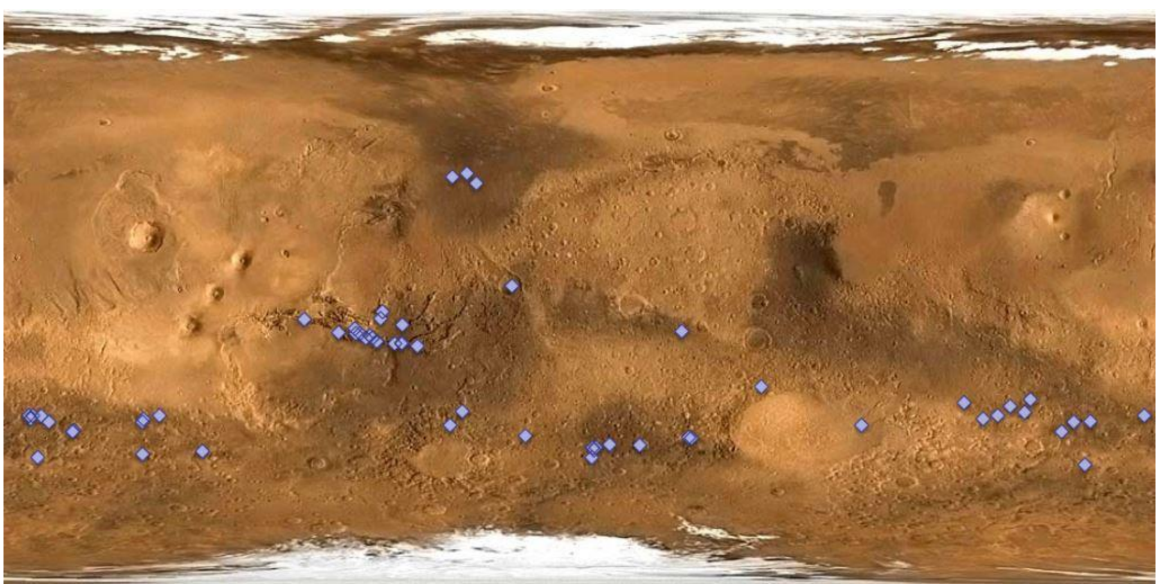

Figure 2. Global map of fully and partially confirmed Recurrent Slope Linea (RSL) sites documented by end of 2013 Source: MEPAG Report [175], September 2014, Figure 14.

Figure 3. Future astronauts may grow some of their meals inside greenhouses, where fruits and vegetables could be grown hydroponically.

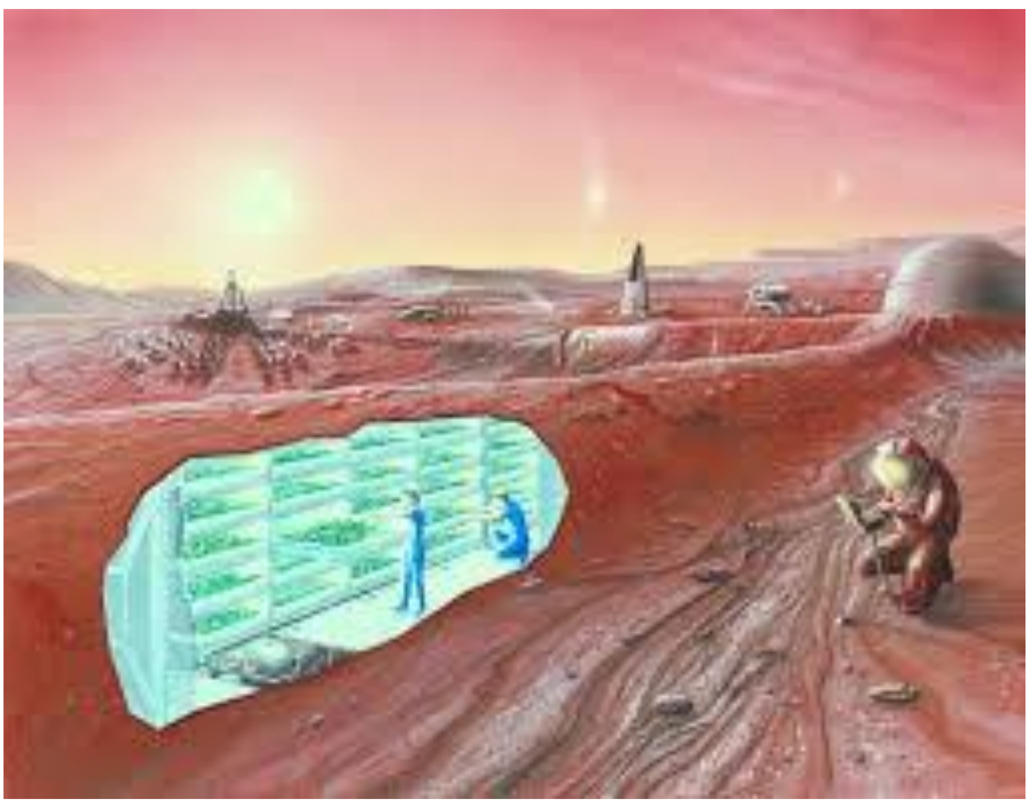

Figure 4. Future astronauts may grow some of their meals inside greenhouses underground.

Figure 5. Remote Raman, Fluorescence, and Lidar Multi-spectral Instrument.

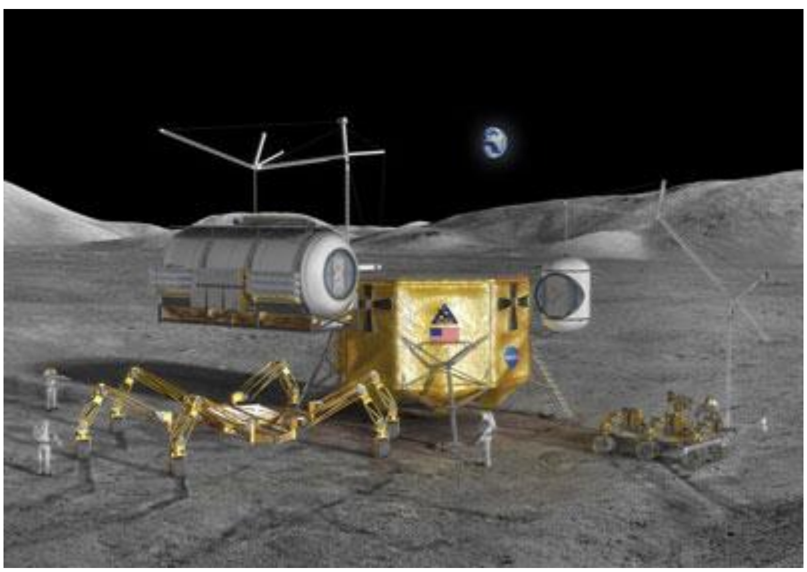

Figure 6. (Lunar) Surface Manipulation System for off-loading payloads (similar system can autonomously off-load ISRU equipment pre-game).

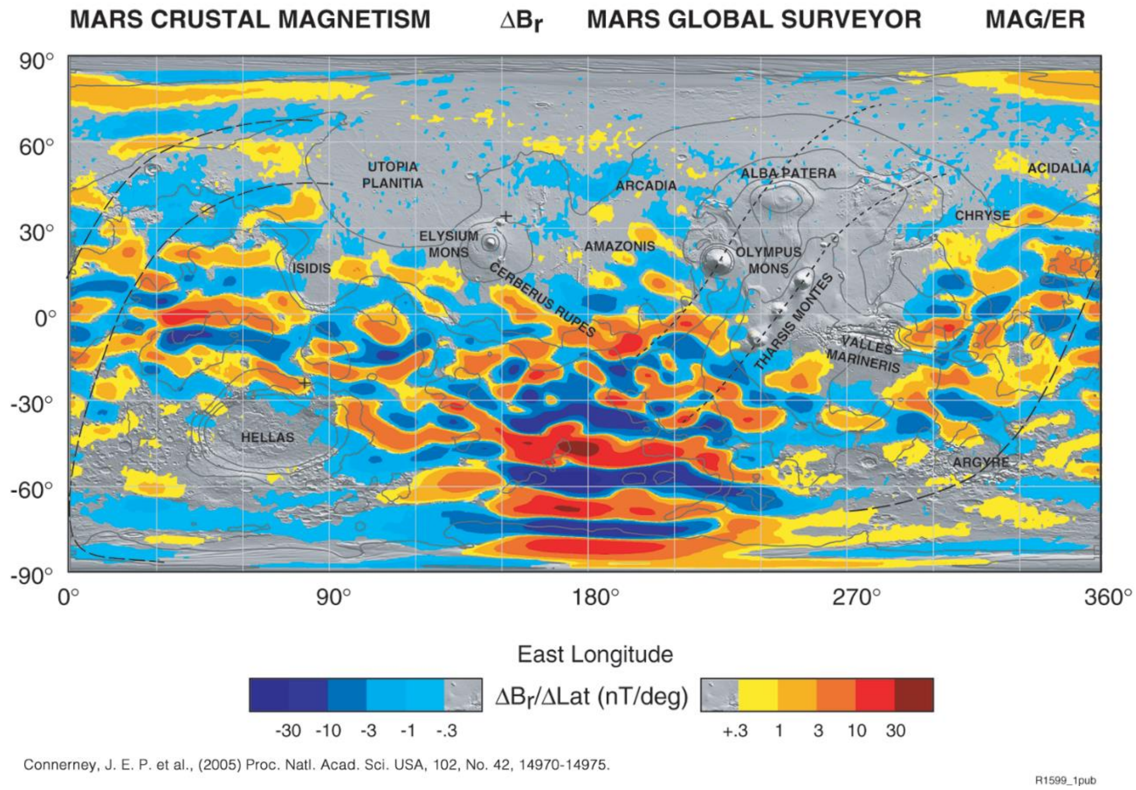

Figure 7. Mars Crustal Magnetism from Mars Global Surveyor Data.

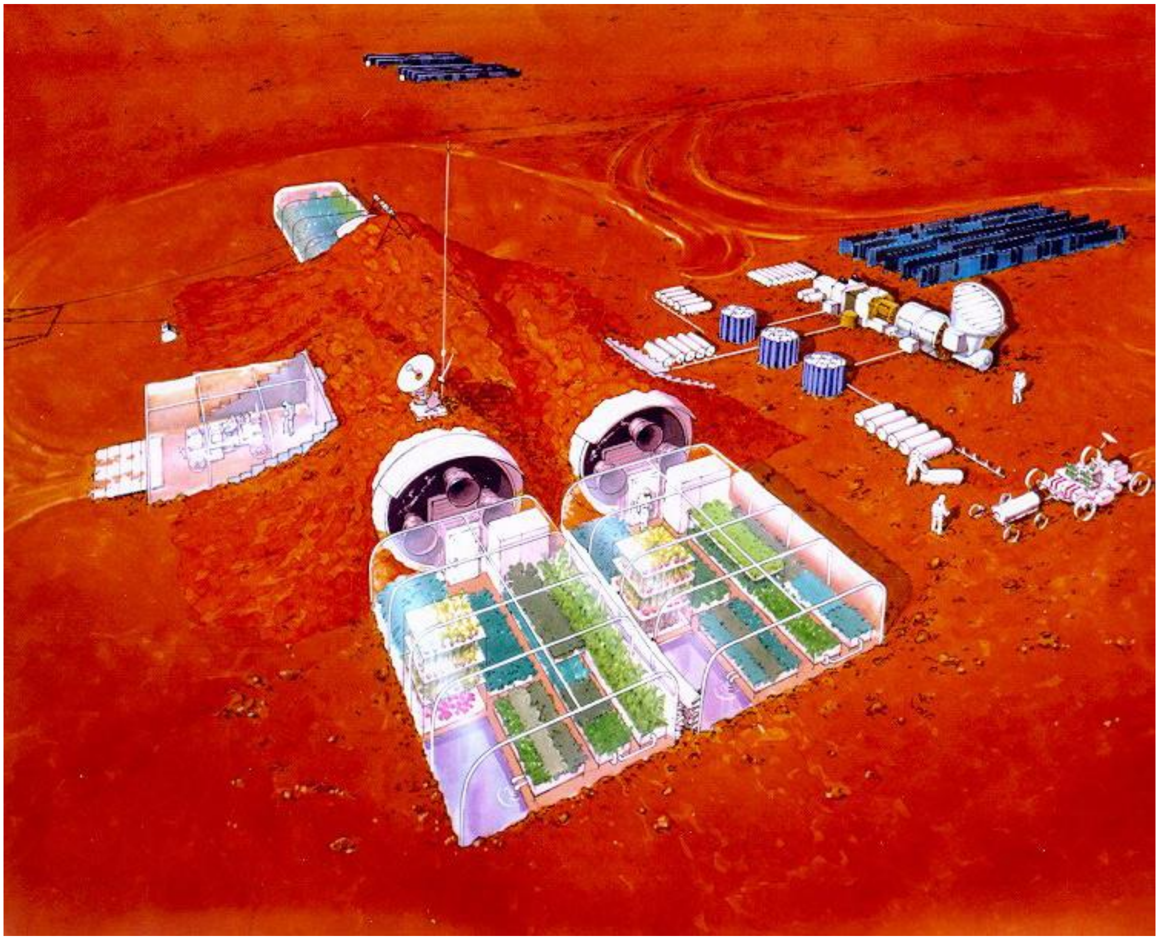

Figure 8. Another Mars Base Concept showing habitats under the regolith.

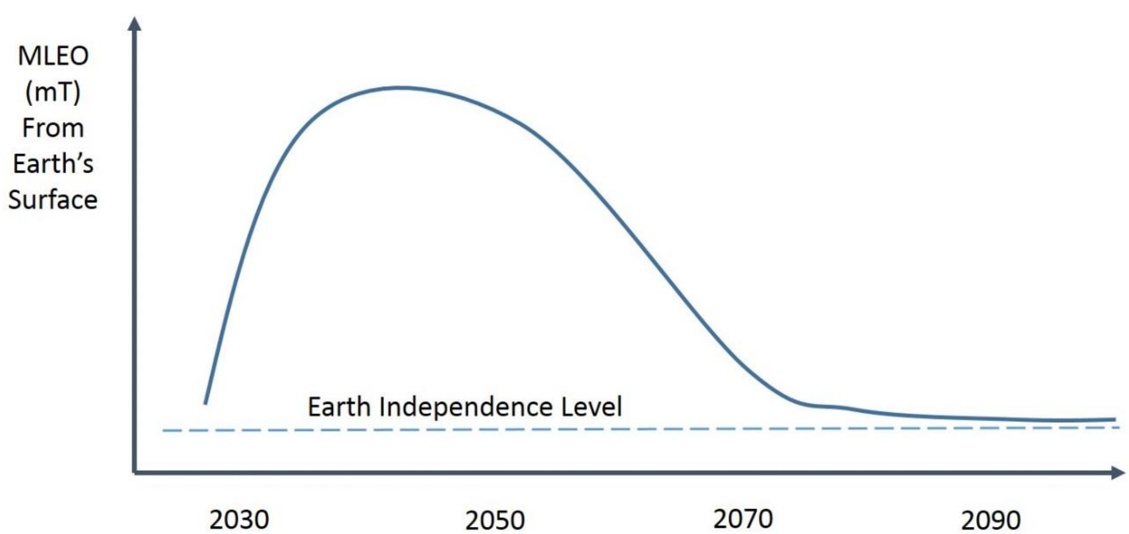

Figure 9. One Metric for Illustrating Earth Independence.

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14. ABSTRACT
The now known resources on Mars are massive. There is much water and CO2 and therefore C, H2 and O2 for life support and fuels and plastics and much else. The regolith is replete with all manner of minerals. ISRU applicable developing technologies including robotics, machine intelligence, nano, synthetic biology, 3-D printing and additive manufacturing will enable serious, pre and post human arrival ISRU to greatly increase reliability and safety and reduce cost for human colonization of Mars. Various system level transportation conceptualizations using mars produced fuel would enable the Mars resources to constitute an effective inner solar system Walmart for, eventually, nearly everything required for space faring and colonization. Mars resources and their exploitation via serious ISRU are the key to a viable, both safe and affordable, human presence beyond Earth. The purpose of this paper is four-fold: 1) to highlight the latest discoveries of water, minerals, and other materials on Mars that reshape our thinking about ISRU there; 2) to summarize in one document the previous literature on Mars ISRU processes, equipment, and approaches; 3) to point to technologies, new approaches, and new thought about ISRU that can lead to safe and affordable human missions to Mars; and 4) to lay out an implementation strategy whereby the ISRU elements are phased into the mission campaign over time for enabling a sustainable human presence on Mars.

15. SUBJECT TERMS
Additive manufacturing; Earth independence; In Situ fabrication; Mars colonization; Mars truck; Mission strategy; Permanent presence; Phased campaign; Resource utilization; Sustainable pioneering

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