The Steel Seeds Plan to Start Human Settlement of Mars

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Introduction

There have been many more or less serious plans to colonize Mars, or just put humans on it.

The first noteworthy one was from Wernher von Braun (1948, 1953). It used a fleet of ten interplanetary spaceships to take seventy people to Mars and put them on its surface. The fleet would have been constructed in orbit around the Earth and 1000 three-stage rockets would have lifted everything up to the orbiting construction sites. Von Braun pushed for funding of a similar plan after the Apollo missions ended but was famously snubbed around Washington.

US President G.H.W. Bush ordered a plan to be written in 1989. This plan was called variously the Human Exploration Initiative, the Space Exploration Initiative (SEI) and the 90-Day Report (NASA 1989). Although this plan stated one of its goals was to get humans on Mars, it was not really a plan to go to Mars at all, but, rather, it laid out a smörgåsbord of goals and program outlines for potentially interested parties in Washington. This initiative's extremely high price tag ensured its quick demise in the US Congress and this demise consequentially set-off a long-term shift in how the National Aeronautics and Space Administration (NASA) has operated.

Spurred on by problems with the SEI, Robert Zubrin and David Baker developed an alternate plan called Mars Direct (Baker and Zubrin 1990; Zubrin 1996). Mars Direct was the first plan to feature pre-positioning of useful manufacturing assets on the surface of Mars prior to the arrival of humans on long-stay[1] missions on the Red planet. These assets would manufacture rocket propellant and oxygen using local Mars resources, which is an example of in-situ resource utilization (ISRU). Mars Direct was the first Mars plan to give detailed proposals of ISRU implementations for Mars. Mars Direct also required that a habitat unit ("hab") with a high mass (~40,000 kg) be landed on Mars in one piece. This land-a-giant-object-in-one-piece feature of Mars Direct meant it could not be implemented in the 1990s, the 2000s or now in the 2010s.

Buzz Aldrin (2008, 2013) has called for Mars settlement in which settlers should go to Mars with no intention of returning to Earth but with some capabilities to return, rather like the seventeenth century colonial settlers of the American colonies that eventually became the United States. Buzz Aldrin also had one of the most creative ideas for transport between Earth and Mars, variously called the Mars Cycler, Aldrin Cycler and Cyclic Trajectory Concept, in which a spacecraft continuously cycles back and forth between Earth and Mars and in which payloads are sent up to and dropped off from the cycling spacecraft (Aldrin 1985).

One recent Mars plan, from a NASA working group, would land the first humans on Mars not as settlers but as brief visitors (Naderi, Price and Baker 2015). This plan needs space vehicles, such as the Space Launch System (SLS), which are under development by long, established aerospace contractors.

When discussing plans to go to Mars and colonize Mars in July of 2016, there is a giant in the Mars community, Elon Musk, who is enormously influential at driving what might happen or will happen regarding the colonization of Mars. His rocket company, Spacex, has rapidly growing capabilities for sending cargo to Mars and landing cargo on Mars. Elon Musk is committed to colonizing Mars either in partnership with government agencies or, if necessary, through private efforts led by himself and Spacex (Musk 2012). In addition, the capabilities of Spacex, Tesla Motors (Mr Musk's car company) and OpenAI (an organization researching artificial intelligence (AI) that Mr Musk funds) for carrying out colonization operations on the surface of Mars are likely to grow to become very substantial. What is meant by that is that (i) Spacex, Tesla and Open AI have a wealth of hardware and programming skills and resources that can be applied to automated manufacturing and running semi-autonomous robots in digitally described environments, (ii) these technical capabilities will be key for establishing a first Mars base or seed settlement. Mr Musk has announced that he will

1 Over a year.

be presenting plans for the colonization of Mars at the International Aeronautical Congress in September 2016 (Musk 2016). His plans can have some flexibility through the array of capabilities that his companies and their partners have, or will soon have; however, he has indicated the importance of new, very large, reusable rocket boosted transporters that will, early on, transport a lot of equipment on to the surface of Mars and, as time progresses swap to transporting more people and less equipment (Musk 2012; Musk 2016).

On Mars, basic human life requirements, like breathing, will be enabled and sustained by technology, such as pressure vessels that contain interior living spaces and pressurized suits for walking around outside. Very often this technology will be vital, that is, on Mars humans will die without appropriate sustaining technology. This will also be true for the animals, plants, fungi, bacteria and other organisms that get transported from Earth to Mars. Life will be enabled and sustained by technology on Mars.

Although discussions of the settlement of life on Mars often focus on launch rockets and space ships, the settlement of life on Mars is becoming a big subject with many facets. Two of these facets might be called 'the seeding and germination of human settlement on Mars.' What is meant by this phrase is the landing on Mars of collections of equipment capable of mining, making and building useful things on Mars, along with the early operation of this equipment, to grow the capabilities of the equipment and its output to enable and sustain first human life on Mars, and, also, after the first people land on Mars, the immediate continuations to keep sustaining human life, grow the life enabling and sustaining technological infrastructure, and increase the number of people living on Mars.

A question arises, what technology should be landed on Mars for the seeding and germination of human settlement of Mars?

This draft plan proposes a specific answer: Redundant collections of equipment, and robots, capable of (i) generating electricity, (ii) mining iron ore, (iii) processing the ore to make fine steel powder, generate oxygen and liberate bound water, (iv) fabricating finished steel products, including spare parts, building structural elements and panels, as well as building fittings and fixtures and more, (v) carrying out repair and maintenance by the robots of themselves and of other pieces of equipment, (vi) making, on Mars, mostly steel, power generation sytems driven by small, solar parabolic dishes, (vii) making, with assistance from people on Mars, robotic steel trucks, with mostly steel engines, (viii) starting truck fuel/rocket propellant production to establish muscular ground transportation and abundant water collection, (ix) making, with some human assistance, additional pieces of equipment for gas compression, nitrogen and argon separation, ceramics and glass manufacture, soil improvement, fertilizer production and more. Re-phrasing the answer from describing the equipment and robots in terms of their capabilities to describing them as specific pieces of equipment, a single collection of equipment and robots would include the following (a) power units (or unit) (b) units for reducing iron and other transition metal oxides to metal and oxygen (and also liberating some bound water), (c) units for final refinement and powdering of the reduced iron and minor transition metals (collectively Martian steel powder) (d) a small, modular, gang-able Martian 3D metal powder printer, (e) a set of spare parts which are hard to make on Mars from steel, (f) a (somewhat smart) roving robot with at least two mechanical arms and multiple arm-end attachments. The plan needs multiple sets of these individual collections of equipment and robots to supply redundancy, to also supply multiple robots which can then take and make collective actions and operations (including complicated repair and maintenance actions), and to gang together several small, modular, Martian 3D metal powder printers into one printer with a large build bed.

Some practical points about such seed collections of equipment and robots include: (a) they can be made (*i.e.* they are feasible), (b) they can be operated by the robots with only occasional guidance from humans, (c) they can be made compact and light (using very little mass), (d) because of their compactness and small mass, a single collection of equipment and robots can be easily transported onto the surface of Mars in a relatively small landing craft (if necessary). This last point allows some implementations of this plan to avoid the land-a-giant-object-in-one-piece feature of several previous and current plans. This aspect of this plan is potentially very important for removing obstacles and delays that have occurred, and may well yet occur, in the development and funding of any very large systems required for landing a giant object in one piece on Mars.

This plan is called the Steel Seeds Plan to Start Human Settlement of Mars, which is shortened to the Steel Seeds Plan for the remainder. Each of the individual collections of equipment and one or more robots is metaphorically like a seed in that it lands on the Martian ground in something like a seed pod, *i.e.* the landing spacecraft, then, under its own stored energy and probably also using solar energy, the robot and equipment unpacks itself from the spacecraft and then starts operating mostly autonomously to grow, wherein this growth uses ore, carbon dioxide and water like nutrients and solar power like sunlight driving photosynthesis. This is all seed-like. These metaphorical seeds are steel seeds in that they focus on iron ore mining, steel powder production and finished steel object fabrication; although, this early seeding activity quickly branches from just steel activities to many other activities, with the expansion of power generation capacity and output being particularly important and happening very early as the first application of the first made-on-Mars steel parts. However, the seed metaphor is not wholly appropriate in that the operation of these collections of equipment and robots will be collective in some respects, particularly repair and maintenance and steel object fabrication, so that the group of collections are capable or more than the individual collections. With this steel work these steel seeds enable the fabrication and growth of the first human settlement infrastructure on Mars. This settlement infrastructure includes, at least, steel components for pressurized buildings for humans to live and work inside, furniture, fittings and tools to put in these buildings, most of the life support equipment, water and gases needed for breathing and recycling products of human respiration, digestion, perspiration *etc.*, a reservoir of water, means for collecting more water, storage tanks for the oxygen produced during steel-making, storage tanks for nitrogen and argon, the steel parts needed to construct new pieces of equipment needed for activities such as Martian agriculture, glass and ceramic manufacture, methane/oxygen fuel/oxidizer production, eventually also basalt fiber manufacture and other manufacturing activities and also, importantly, from an early point and continuing on, the manufacture and operation of new power generation equipment made almost entirely out of Martian steel and driven by sunlight.

These redundant collections of equipment and robots would work on Mars for at least two Earth/Mars synodic periods,[2] *i.e.* a 2 x 780 days, prior to the arrival of the first humans. However, this preparatory period could be extended to as many synodic periods as needed to properly prepare for the safe arrival of the first humans. Further, each synodic period after the landing of the first collections of equipment and robots can include the landing of extra supplies, spare parts and equipment as will be necessary for settlement success. The construction needed to turn the steel building components into buildings might be done starting with the landing of the first people, or before this human landing. It may well be better from a mission story perspective to have the first Mars settlers participate in the construction of their first Martian home.

Another important point arises out of the plan's scheduling possibilities: The longer a seed collection of equipment and robots is up and running on Mars the more valuable it becomes. This is because the total mass of all the useful, finished steel objects produced by a collection increases linearly with the amount of time the collection is up and running (the same is true for the total mass of oxygen generated by the same collection). In fact, the value increases more than linearly with the amount of uptime, since some of the steel objects made by a collection will be put to uses, like making solar parabolic dishes, that themselves increase overall capacity and capability. One way to think of

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2 The main launch windows for flights from Earth to Mars are separated by an Earth/Mars synodic period, which is very close to 780 Earth days in length.

this is that a relatively, small and inexpensive (in Earth dollars) group of collections of equipment and robots will eventually produce very high value results on Mars, so long as these collections are kept operating for long enough.

It is a key idea of the Steel Seeds Plan to structure all the plan's components such that the average working life of a collection of equipment and robots is long and very useful and valuable. To this end the plan builds in (a) redundancy, (b) steel spare part manufacture on Mars, (c) occasional spare part deliveries from Earth and (c) teams of robots with the mechanical and computing abilities to perform repair and maintenance tasks.

The combination of iron ore mining, ore to steel powder processing and finished steel part manufacture can collectively be a core technological capability, quite possibly the core technological capability, for the seeding and germination of human settlement on Mars. This technological capability enables the start and growth of extra power generation, water collecting and manufacturing capabilities, which, will start an upward spiral in life-sustaining capabilities. The net output from, steel-making, oxygen generation, steel fabrication and muscular water collection can provide the large majority of the mass of all the useful technological objects, liquids and gases that will be needed to enable and sustain human life on Mars in a first habitat and workshop.

The literature on steel-making on Mars is, at the moment, quite limited. Molten metal oxide electrolysis research has been carried out, with NASA funding, for the purpose of generating oxygen on the Moon (Curreri et al. 2006; Vai et al. 2010). Such electrolysis splits metal oxides to produce both oxygen and metal, the American Iron and Steel Institute funded a feasibility study to see whether molten metal oxide electrolysis could be practically implemented to produce iron (AISI 2005). Shaun Moss (2006) reviewed steel-making methods and techniques on Earth and recommended direct reduction techniques for Mars steel-making. Some prominent people have also made brief talking points on iron and steel-making on Mars.[3]

The rest of this plan draft is organized into sections as follows. **Capable, Slightly Smart Robots:** A description of the capabilities and specifications of the robots needed for mining ore and the operation of other pieces of equipment. **Massive Masses, Repair and Maintenance:** This section covers considerations of the mass of things, and how and why mass considerations should factor into the design of a plan for seeding and germinating the human settlement of Mars. **Mars Dust and Mars Sand:** In this section the composition of Mars dust and sand is looked at with the benefit of detailed sand and dust composition data gathered by NASA robotic rovers *Spirit*, *Opportunity* and *Curiosity*. In addition, an initial discussion is given of how this sand and dust might be very useful as a potential ore for steel-making, ceramic and glass manufacture and also for agricultural soil. **Martian Iron Ore Enrichment:** This section reviews how iron ore mining and iron ore enrichment (beneficiation) is done on Earth. This review serves to shows how very good it is to start iron ore mining and enrichment with an ore in sand or dust form. This is important for making small-scale steel-making on Mars mechanically feasible, as the small robotic rovers have only a little mechanical muscle. The section also points to fields of sand dunes on Mars which may be especially good for iron ore mining. **Steel-powder Making from Enriched Martian Iron Ore:** This section discusses the processes and equipment needed for the small-scale conversion of enriched, sand/dust iron ore into fine steel powder that is suitable to be used in three dimensional (3D) metal powder printing machines. **3D Metal Printing Machines on Mars:** This section discusses 3D metal printing machines on Earth and on Mars and the significant differences between such machines on Earth and Mars. The first 3D metal printing machine on Mars will have especially

3 Robert Zubrin was quoted saying "Iron oxide and silicon oxide are also common in Martian soil, so human pioneers would be able to make iron, steel and glass" (Wall 2013); while answering a conference question Elon Musk (2016) stated that if large numbers of people and goods were transported to Mars that this would create tremendous opportunities "for everything from creating the first iron ore refinery to the first pizza joint to something that does not exist on Earth."

low mass and low power consumption per unit printing bed area in comparison to those on Earth. Also, the first Martian machine will have a printing bed that is especially long. **Growing Power Generation:** This section discusses a developed power generation technology, *i.e.* solar parabolic dishes coupled with free piston Stirling engines/generators, that can provide electrical power on Mars that can be made almost entirely out of steel parts, that can be made at physical sizes that are small enough that (i) all the steel parts can be made-on-Mars by the first 3D metal powder printer using steel powder made from Martian iron ore and (ii) the rover robots will be able to assemble the parts into complete working systems. So that, *early human settlement of Mars can have all the electrical power it needs to grow by making the power plant on Mars*, if it starts steel-making and fabrication early. The section also points out that it would be very useful to have small-scale, parabolic dish systems that can output piped flows of hot, pressurized gas to provide thermal power to drive useful thermo-chemical processes and that, while no such hot gas dish system is close to be properly developed, that this development could be done in the coming few years. **Collecting Water, Muscular Ground Transportation:** This section discusses water sources on Mars, including the lack of certainty about abundant water sources in the most desirable, equatorial regions for living. The section also points out that large capacity trucks can be built locally on Mars from steel and also their engines and the solar powered systems needed to produce suitable fuel and oxidizers to run the truck engines. The introduction of a muscular transportation capability can then be used for all sorts of things including overcoming likely water supply problems by providing the capability to use distant water sources. **Making Other Equipment, Doing More Things:** This section gives a brief outline of other equipment that can be made on Mars using Martian steel and what this other equipment can do to make more useful things on Mars from local Martian ore resources. **Summary and the Start of Human Martian Life:** The summary gives an outline of the Steel Seeds Plan for seeding and germinating the human settlement of Mars; it re-iterates some key themes, needs, features and benefits of the plan; and, also, discusses when, during the implementation of the Steel Seeds Plan, humans should first land on Mars, and makes a few remarks about the relationship between people and the technologies used for settling Mars. An appendix to the section on Martian 3D metal printers, **Oxidation of Fine Steel Powder in the Martian Atmosphere**, is included.

Capable, Slightly Smart Robots

Small rover robots perform the equipment operation tasks and iron ore mining tasks during the seeding and germination of the human settlement of Mars, both in the period prior to the arrival of the first human settlers and for some time after that.

Energy is delivered to these rover robots mostly through batteries charged from a large, distinct power source, although each robot will also have its own, on-board small array of photo-voltaic (PV) solar panels. The batteries will come in packs that can be popped in and out of a battery-pack port in a side of each robot. The pop-in, pop-out feature is needed so that each robot is available to work most hours of a Martian day (called a “sol”[4]), since maximizing the amount of time worked by each integrated collection is a high priority. Battery swapping will need to be carefully engineered to minimize Mars dust accumulations in battery-pack ports.

Most mechanical tasks rover robots will be required to do will be repeated many times over and will be well defined in terms of the forces that need to be applied and the required movements in space. One example of such a repeated mechanical task will be ore digging. This consists of placing a sand scoop (attached to the end of a mechanical arm) into a sand dune, moving/turning the scoop to fill it with sand, moving the mechanical arm to position the scoop over a sand-holding bin, turning the scoop

4 NASA personnel have introduced the word “sol” for the Martian equivalent of an Earth day. I like sol and will use it in this plan. The length of a sol is 24 Earth hours plus 37 Earth minutes, so a day and a sol are quite close in length.

to empty the sand into the bin and then moving the mechanical arm again to reposition the scoop next to the sand dune and then repeat the sequence. In this digging example, the sizes and angles of most of the physical movements carried out in one digging sequence can be computed deterministically, with precision and with no need for input data from sensors. Although, repositioning the scoop next to the sand dune should be aided by sensor input, for example, short, stereo video clips of adjacent sand volumes, or, more simply, force sensing when the scoop runs into sand in the dune. Another repeated task will be robot traveling movements in known locations, where the whole body of the robot moves. Traveling movements, in known locations, could be very short (a few centimeters) or quite long (over a kilometer). A location would be “known” when it falls inside a locale that has been digitally mapped to specify all the locale’s landscape surfaces to high resolution (*e.g.* to a resolution of around a centimeter) in all three space dimensions. This kind of digital surface mapping is already standard practice at many construction sites and mining operations on Earth. The information such surface mapping will provide at a Martian iron ore mine will make the decision-making required for problem-free traveling movements around a Martian mining locale not much more difficult than the traveling decisions made by machines working on automobile factory floors here on Earth. Most of a robot’s longer (10+ m) traveling movements will be done along robot tracks or paths. Such robot tracks should, along most of their lengths, require little or no road engineering. However, the robots will have some track improvement capabilities such as moving sand, pebbles and boulders (by lifting, rolling and even, light bull-dozing), hole and crack filling and light rock breaking and rock cutting. Track routes will be worked out to both run around particularly difficult obstacles and also be straightened out with improvements that can overcome minor obstacles (as on Earth). Traveling in unknown (i.e. not digitally mapped) locations will require more caution, probably human oversight and it should also probably proceed while actively performing new digital mapping to make the traveled areas known.

The interactions between a robot and the other equipment in an integrated collection will be both data transfers (with options for both wireless and wired connections) and also mechanical interactions to put things into, and take things out of, the material processing units and the 3D printer using highly predictable movements. There a variety of computer coding approaches that can produce suitable movement commands to control these mechanical interactions. Some of these approaches can use weak AI techniques but direct, deterministic programs with error checking using sensor inputs can also produce satisfactory control commands.

The ends of robot mechanical arms should be engineered to allow different arm end attachments to be fixed to and taken off the arm ends. Some arm end attachments should be part of the seed collections of equipment that gets landed on Mars, these include scoops, electromagnets and mechanical hands. Other useful arm end attachments can be made on Mars such as hooks, pincher grips, various welding heads and laser holders, jack hammers, screw-drivers, drills, screw finishers, rakes, spray nozzles, ladles, etc. The variety of possible robot arm end attachments enables the robots to be extremely versatile. Perhaps the most important arm end attachments are the mechanical hands, since they will carry out the most intricate manipulations required for equipment spare part replacement and equipment repair prior to the arrival of humans, These mechanical hands will, of course, be state-of-the-art with sophisticated touch sensors and finger actuators. Repair and maintenance are key for keeping all the equipment and the robots operational on Mars, prior to the arrival of humans. Humans will excel at repair and maintenance inside the first pressurized workshop on Mars and, humans, on Mars or on Earth, will be able to supervise the robots and guide the robots through non-standard manipulation tasks during tough repair jobs done outside on Mars which humans cannot perform directly themselves.

Small, wheeled (or tracked), rover robots, with mechanical arms, will be better than people at doing light mechanical jobs outside on the surface of Mars. There are several reasons for this but just one of these reasons is sufficient on its own to prefer robots over people for outside work. Outside on Mars people have to wear pressurized suits to avoid death. The pressure difference inside and the outside of such suits forces their hand sections into highly preferred, bulbous, blown-up shapes. To make even small changes to these preferred, blown-up shapes requires the generation of large forces by the hands of a person inside the suit, and even such small changes can quickly tire the person inside. Pressurized suits on Mars make it too difficult for people to make any finger movements beyond very simple, coarse movements over short durations.

Massive Masses, Repair and Maintenance

Many people use “massive” synonymously with big, huge, weighty, impressive, significant, and important. Physicists use massive to just mean having mass, *i.e.* one of the basic properties of physical bodies, which many people think of (inaccurately) as weight.

In this section masses are discussed which are massive both tautologically in the physics sense and also massive in the sense of being important for settling Mars. Considering issues involving mass clearly is a way to understand, test and evaluate plans to settle Mars.

The expense of transporting things to Mars is calculated on a payload basis, which is a per load mass basis. It is very expensive to transport to Mars, and then land on Mars, hundreds of thousands or millions of kilograms of payload. The transport and landing costs are the same for payload mass consisting of either computers or communication electronics or lasers or dormant plant seeds or metal compressors or metal building panels or liquid oxygen stored in metal protective containers or water. Transport and landing expense goes up with the amount of mass transported not with what kind of thing is transported (except for humans and other active living things[5]).

One main idea of the Steel Seeds Plan is that most of the things needed to build, outfit and provide essential life-support capabilities for a first settler habitat and workshop should be made from local Mars resources, so that, these massive things need *not* be transported from Earth and landed on Mars. For the human settlement of Mars, the minimization of the total mass of things transported between Earth and Mars is an overarching engineering goal. The Steel Seeds Plan uses ISRU and to an extent not previously considered.

Every 100 kilograms (kg) of mass shaved of the inter-planetary transportation payload, by making things locally on Mars, either allows some important extra biological seeds, eggs or bacterial or fungal samples, high-tech spare-parts/tools/equipment or people to go to Mars, or it reduces the total mass of things sent there and, hence, reduces the money spent on sending things to Mars. Reducing the mass of things that need be sent to Mars to set up, and maintain, settlements on Mars, by making those things locally on Mars is key to making such settlements affordable and, hence, key to making them practically achievable.

Another idea of the Steel Seeds Plan is that a single group of coordinated activities can produce, on Mars, from Mars resources, useful things that together have total mass which is the largest fraction(well over 90%) of all the mass of all the things needed for a human-settlement-starting, functional habitat on Mars. This group of coordinated activities is iron ore mining and processing, with steel producing (that simultaneously generates oxygen and frees bound water) and manufacturing of finished steel objects. Steel, oxygen and water can provide the largest mass of useful things needed for a first, operating human habitat on Mars. Useful things made of steel include the structure of the habitat (which has to contain breathable air that is pressurized to Earth atmosphere levels), the habitat’s furniture and fittings, workshop tools, engine and compressor components, robot spare parts, air conditioning and heating components, solar thermal mirrors and frames, storage tanks, kitchenware and on. In the Steel Seeds Plan, making finished steel objects, with simultaneous oxygen generation and

5 Humans, and other active living things, are exceptions to this transport cost by mass amount determination, since, in addition to humans’ own body mass, a large mass and volume of on-going life-support systems, food, drink, power etc. is required for inter-planetary human travel.

bound water liberation, from Martian ore is the core activity of the early period of human settlement of Mars.

This core activity also can enable the mass-efficient start of many other settlement activities. For example, it can provide the cutting tools needed for cutting basalt blocks for building radiation protecting walls, it can provide many of the tools and parts needed for ceramic, glass and rocket propellant manufacture and on.

Another idea is to avoid the need to land single items which, by themselves, are very massive. The other published Mars settlement plans require that the habitat units needed for first settlement are landed on Mars in one piece. While the designers of such whole habitat units try hard to minimize their total mass, proposed units have design masses of around 40,000 kg. Landing a 40,000 kg unit on Mars is extremely difficult. Nobody can do it right now. Both NASA and Spacex have systems in development that might do this. However, the expense to finish the development of these systems, and to regularly deploy them, is very high and this expense requires long-term budgetary and political support from many arms of the US federal government. The requirement for such various and long-term support will, likely, greatly slow the implementation of both these big lift and land efforts. A public program from a NASA working group on the deployment of NASA's big lift and land systems for going to Mars already plans a very slow deployment (Naderi, Price and Baker 2015).

Making things takes time. There are two kinds of time period relevant to robots and equipment that land early on Mars and make things there. One kind of time period covers the working life-spans of individual pieces of equipment and individual robots and, also, collective systems of robots and equipment. Consider a case that we would not want to happen: A robot stops working after a few Martian sols and then cannot be repaired and, so, remains stopped indefinitely. Such a robot would not contribute to the making of any new things (so, 0 kg of useful things are produced with this hypothetical robot), the robot becomes dead-mass that cost large sums to make on Earth and to transport onto Mars. In contrast, consider a group of collections of robots and equipment, with collective total mass of 10,000 kg, that operates together successfully for 6 Martian years (11.28 Earth years) and, in this 6 year time period, from local Mars resources, these robots and equipment collectively produce 650,000 kg of useful things made out of steel, ceramics, glass, basalt and also breathable oxygen, and drinkable water. Such equipment and robots would be highly successful as a producing collection and a historic, founding group of seeds for the settlement of Mars (if they are the first things landed on Mars dedicated to settlement).

These example cases help illustrate the importance of one more of the ideas of the Steel Seed Plan, that is, the landed collection of robots and equipment should have the ability to repair and maintain itself and manufacture spare-parts for itself, in order that the collection, and individual pieces of the collection can have long working lifetimes. Repair, maintenance and extending working lifetimes will become highly valued in the early settlement period of Mars. This contrasts with the recent decline in the value many of us put upon repair, maintenance and extending the working lifetimes of many everyday items, since, in ultra-modern, Earth globalized economies, so many things are produced, sold and delivered at so low costs that replacement with new items often makes more economic sense than making repairs and doing maintenance.

The other kind of relevant time periods for the Steel Seed Plan are the Mars/Earth synodic periods, *i.e.* the multiples of 780 days between each of the launch windows for launching rockets from Earth to Mars. One of these time periods, perhaps 2 x 780 days, will be the time between when a first seed collection of robots and equipment lands on Mars and the time the first human lands on Mars.

Returning to masses, key quantities for judging the effectiveness of the Steel Seeds Plan are the total masses of useful things produced on the surface of Mars, from local Martian resources, in time periods of 2 x 780 days and 3 x 780 days, by the producing robots and equipment relative to the total masses of these robots and equipment. An additional section will give detailed assessments of the size of these ratios of total masses. This additional section will appear in the second draft of this plan; however, there are enough solid results to state now that the total mass of useful objects produced with redundant seed collections of robots and equipment in 2 x 780 days will a large multiple of the total landed mass of those seed collections of robots and equipment.

Martian Sand and Dust

Martian sand and dust is found at most places on the surface of Mars either as a coating layer, or in small and large dunes. Samples of this sand and dust were found to have a remarkably uniform composition at three locales on Mars, separated by thousands of miles, by NASA rover robots *Spirit*, *Opportunity* and *Curiosity* with the guidance and analysis of many people here on Earth (Gellert *et al.* 2006, 2013; Blake *et al.* 2013). Martian sand and dust is colored from reddish tans through to rust colors due to its high iron oxide content which is the main component of rust and iron ore found here on Earth. The coating layers and dunes of Martian sand and dust cover so much of Mars that it gives The Red Planet most of its color.

Martian geologists and planetary scientists often call deposits of sand and dust, “regolith.” However, the use of regolith as a descriptive technical term is not uniformly used.[6] In the present text a definition convention is adopted such that “sand” overs all particles that could be blown into sand dunes on Mars; so, here, “sand” will cover sand, dust and all small-sized particles that can be moved by Martian winds into dunes. With this convention, material that is here referred to as “sand” might often be called “regolith” by other authors.

An important point about the composition of Martian sand is that it is composed almost entirely out of chemical compounds that are good for making very useful materials, including: steel powder, oxygen, water, glass feed-stocks, ceramic powder, the inorganic components of agricultural soils, and fertilizer for plant growth.

This list of useful materials is quite impressive in that these materials can be used to do so much at a first human settlement on Mars. Indeed, with sufficient electrical and thermal power, the useful things that can be made from these sand derived materials, in combination with plant growth and liquid methane/oxygen rocket propellant production, both of which need water and carbon dioxide, along with some easy-to-make rock-based building materials (for example, cut basalt blocks) will be enough to make almost everything needed for a successful, long term human settlement of Mars. For years after human settlement starts, the only things that will need to be transported from Earth to Mars will be humans, seeds, eggs, some bacterial and fungal samples,[7] computers and other equipment using high-tech materials and parts, plastic components, and, in the first few years, dehydrated food. Key information and communications will usually be transmitted rather than transported.

The current Steel Seeds plan only really needs the following Martian resources for its early implementation: sunlight, sand and some atmospheric carbon dioxide.[8] Such a short list of needed resources, and the abundance of each, helps the feasibility of the Steel Seeds Plan. Mars sand collected in sand dunes will be the basic, raw ore for iron and steel-making done in the Steel Seeds Plan.

Table 1 lists the main component chemical compounds of Mars sand, with the mass percent

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6 The Earth's regolith covers a whole host of things, while lunar regolith often refers to very fine dust on the Moon. Mars regolith includes sand and dust but it might might also include granules, pebbles and small rocks up to 10 cm in diameter. The word regolith is constructed from two Greek words that literally translate as blanket and rock.

7 Craig Venter has suggested that biological samples need not be transported to Mars but, rather, transmitted to Mars as computer files which, using technology he is developing, would be constituted into embryo cells and then grown into full plants, animals *etc.*

8 During the early days of implementing the Steel Seeds Plan sufficient water can be retrieved from Mars sand, but tapping additional water sources is a priority, while simple, rock-based building materials could be done without (but will likely be made, due to their usefulness and relative ease of manufacture).

Chemical Compound Component of Sand	Mass % in Sand	Separation Method	Steel Powder	Oxygen	Water	Glass	Ceramic	Inorganic Parts of Soil for Plants	Plant Fertilizer	Cleaning Fluid/ Acid/ PVC
Iron Oxides & Hydrated Iron Oxides	19.19	Magnetic Attraction & Volatile Fractionation	✓	✓	✓					
Titanium Oxides	1.19	Magnetic Attraction	✓	✓						
Chromium Oxides	0.49	Magnetic Attraction	✓	✓						
Manganese Oxides	0.41	Magnetic Attraction	✓	✓						
Silicon Dioxide	42.88	Density Diff. (2.2/2.6 g/cm^3)				✓	✓	✓		
Soda (Sodium Oxide)	2.72	Density Diff. (2.3 g/cm^3)				✓	✓	✓		
Lime (Calcium Oxide)	7.28	Density Diff. (3.3 g/cm^3)				✓	✓	✓		
Magnesia (Magnesium Oxide)	8.69	Density Diff. (3.6 g/cm^3)				✓	✓	✓		
Alumina (Aluminum Oxide)	9.43	Density Diff. (3.9-4.1 g/cm^3)				✓	✓	✓		
Potassium Oxide	0.49	Density Diff. (2.1 g/cm^3) Water reaction				✓	✓	✓	✓	
Phosphate/ Phosphorous Pentoxide	0.94	Density Diff. (2.4 g/cm^3) Water reaction				✓	✓	✓	✓	
Chlorine	0.61	Volatile Fractionation								✓
Sulfur oxide/ Sulphates	5.45	Volatile Fractionation						✓		✓
	99.77									

Table 1. Chemical Compound Composition of Mars Sand with Component Separation Methods and Component Usage. The fractional percentage numbers for each component, shown in the second column, are reproduced from Blake *et al.* (2013) from a sample taken by the *Curiosity* rover robot. The third column indicates the physical method(s) for separating one component of Mars sand from (most of) its other components. The rightmost eight columns show, by tick marks, the likely material uses of each compound component of Mars sand. The sizes of the tick marks give *rough* indications of the relative importance of each chemical compound to the processing of the useful material.

fractions of each compound. It also lists methods for separating the various sand component compounds from each other and the uses to which each component can be put. Note, that the various component compounds are easily put into sub-groups of compounds both by separation method and also by material use. This simultaneous grouping by separation method and material use makes processing Mars sand easier than if, in an alternate situation, the separation methods did not tend to bring together compounds that can be used together in the same end materials. One group consists of the oxides of the transition metals *(i.e.* iron, titanium, chromium and manganese), these can all be separated from the rest by magnets and all of them are suitable components of steel. The rest of the discussion concentrates on steel-making and its utility for and determination of early human settlement of Mars. However, the section **Making Other Equipment, Doing More Things** will briefly discuss what can be done with the other nine compounds listed in Table 1.

Martian Iron Ore Enrichment

Ores used for steel-making on Earth go through "beneficiation" which upgrades (enriches) the quality of the starting iron ore. Iron ore beneficiation in North America consists of the following: (i) blasting rock ore from the sides of quarries using explosives; (ii) lifting large boulders of quarry ore into giant trucks; (ii) transporting the boulders to giant crushing and grinding machines; (iii) putting the unenriched ore through multiple rounds of crushing, grinding and size screening to break the rocks into small sand and dust sized particles; (iv) separating the desired transition metal oxides (principally the iron oxides hematite and/or magnetite) from almost everything else using primarily electromagnets with some additional hydro-flotation separation; (v) pelletization, which reforms the desirable, high iron oxide content sand/dust particles into porous pellets with 3/8" (1 cm) diameters (National Pellet Steel Pellet Co.).

The scale of iron ore mining and beneficiation on Earth, and the large mechanical and thermal processing problems overcome doing them, are remarkable. Mining engineer, Professor Cilliers of Imperial College, London University stated that about 5% of all the energy consumed by humans goes into just crushing and grinding rock for metal ore mining beneficiation (about 95% of all the world's metal production is steel production), this a staggering amount of energy (Cilliers, 2011). Another step in this beneficiation, *i.e.* pelletization, also consumes very large amounts of electricity and fossil fuel (US Environmental Protection Energy 2001).

In the Steel Seeds Plan beneficiation of Mars sand to an enriched ore for steel-making is simpler and requires fewer processes and fewer pieces of equipment than iron ore beneficiation done here on Earth. For example, (a) no explosives are used at all, (b) there is no need for giant-scale, specialized boulder lifting equipment, or (c) giant boulder transports, (d) no rock crushing and grinding is done at all, and (e) no pelletization is done at all. In the Steel Seeds Plan trucks are needed for transporting the raw ore to processing units; however, these trucks will not be specialized giant vehicles but, instead, multi-purpose rover robots on which ore-holding bins can be fixed (or pulled behind). Similarly, the lifting of raw sand ore into the transportation bins will be done with scoop attachments to mechanical arms of the rover robots. Separation of the transition metal oxides by magnetic attraction will be done with electromagnet attachments fixed on the rover robots' mechanical arms. Back in the 1970s, the *Viking II* lander made direct tests of the separation of magnetized particles in Mars sand from non-magenetized components by placing magnets in the sand and then withdrawing the magnets from the sand (Hargraves *et al.* 1979). Particle size screening on Mars will be done mainly by choosing which sand piles to scoop up, although simple, small-scale sieve screening might be done to fine tune particle selection prior to the main magnetic separation step.

Is Mars sand the best iron ore to use on Mars? This question should be split into two different cases. The first being, is Mars sand the best ore to use on Mars once you have established enough infrastructure and industrial capacity for a large-scale iron ore mining operation? While the second would be, is Mars sand the best ore to use on Mars, if you want to grow the first human settlement on Mars from an initial small size? While the answer to the first question is not known, and might be no, this first question is not the relevant question for starting human settlement on Mars, the second question is the relevant one. The answer to the second question is yes. There are five reasons for this: (i) At a first settlement site on Mars giant machines and the power sources to drive them are not available, while Mars sand is (ii) easily found (iii) with adequate iron oxide content, (iv) it is sand, which is easy to mine (*i.e.* scooped up), and (v) it is sand, *i.e.* a mixture of fine particles, hence, it does not require any crushing or grinding or any of the substantial machinery or power needed for grinding and crushing. The fifth of these reasons is probably the most important; however, adequate iron oxide content should be discussed. Among the more than 80 samples analyzed by robotic rovers *Spirit*, *Opportunity* and *Curiosity* most had iron oxide content above 15% and some had over 20% (Gellert *et al.* 2006, 2013; Blake *et al.* 2013). These rovers were not prospecting to find the sand with the highest iron oxide content, they were collecting data across a range of sand samples, and the samples were taken in small areas (but at three locales distant from each other).

The level of iron oxide content found by the local searches of robot rovers *Spirit*, *Opportunity* and *Curiosity* is below that of today's commercially mined iron ore (with ~28% iron content, 35–40% iron oxide content) in the Lake Superior iron ranges where some of North America's largest iron ore mines are located (National Steel Pellet Co.). However, such commercial operations compete with each other around the world and so only operate at very favorable ore locations. In contrast, during early settlement, steel-making on Mars is competing with the per kilogram cost of transporting metal objects from Earth to Mars, it can accept lower iron oxide content to gain the huge advance of mechanical feasibility of mining and processing sand when the available mechanical muscle is very limited.

Using colored satellite imagery, it will not be difficult to search all the equatorial regions of Mars to find substantial dunes of Martian sand with better than average transition metal oxide content; since, the color of Martian dust particles are good indicators of their levels of magnetization and those that are moderately to highly magnetized contain a lot of transition metal oxides (Madsen *et al.* 2009). It is quite possible that the HiRise camera on the Mars Reconnaissance Orbiter satellite has already imaged Martian sand dunes with better than typical levels of magnetically separable iron oxides. The left panel of Figure 1 shows part of a large image taken by HiRise of a large, sand dune, about 500 m long, with a dark brown-red color. The dune shown in the left panel of Figure 1 is just one in a large field of many similar dunes, part of this dune field is shown in the right panel of Figure 1 (HiRise/MRO). It will be valuable to make a close analytical search of the HiRise archive of images to find, large sand dune fields, with suitable iron ore colors that are located close to the Martian equator.

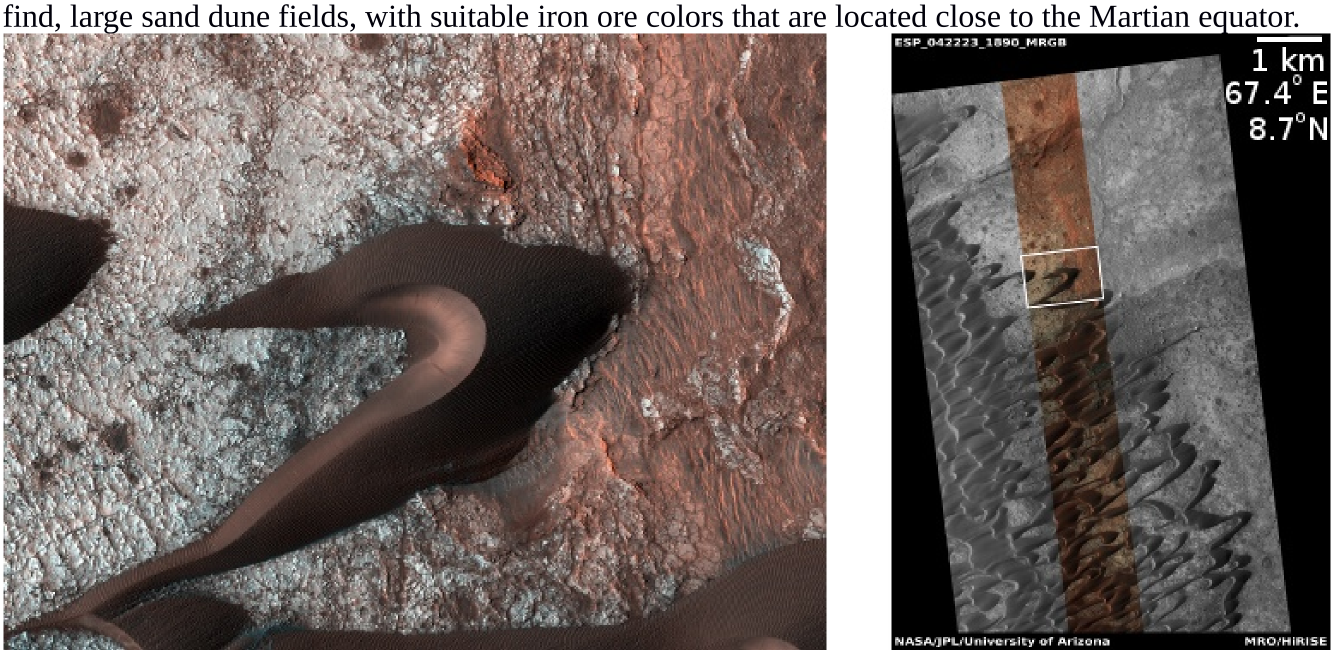

Figure 1. Dark Brown-Red Dune in a Field of Such Near the Equator of Mars. A white square on the right image indicates the cropping used to make the left image.

Another difference between iron ore beneficiation on Earth verses on Mars is that the remaining components of Mars sand (which are not attracted to the separating electromagnets) need not considered as mine trailings or “gangue,” that, on Earth, is usually disposed of. On Mars, this remainder can be considered as partially enriched ore for glass, ceramic, agricultural soil, and plant fertilizer production. Note, that this is remainder is enriched for components like silicon dioxide and the other components which are not attracted to magnets by virtue of the fact that a lot of the transition metal oxide content is removed from this remainder by the magnetic separation. As Mars settlement progresses, however, more and more mine sites will be found that are especially good for one mineral or another, when this happens and when a broad infrastructure of ground transportation has developed on Mars then resource mining on Mars may shift to using mining methods prevalent on Earth today where mines extract just one or two materials from their raw ores and produce large piles of trailings with relatively little value.

Steel-powder making from Enriched Martian Iron Ore

On Earth different steel grades are made which are all composed mostly of iron but for which the remaining compositions vary between grades (such as, 316 stainless steel and A615 rebar steel). Here on Earth, steel-makers have numerous processing refinements to produce all the grades the various steel customers want. However, in the Steel Seeds Plan, the start of steel-making on Mars is kept as simple as possible. Accordingly, the alloy composition of Mars steel is not designed, changed or adjusted, rather, this alloy composition is simply determined by the transition metal oxide composition in Mars sand and also by carburization (carbon adding).

Small-scale steel-powder making on Mars has four steps to transform iron oxide enriched sand into a high grade steel powder mixture suitable for direct laser metal sintering or melting that does 3D metal printing. The final powder product has purity in transition metals plus carbon of over 99.0% and it is made from sphere-shaped particles with diameters between 1 micron and 10 microns. This size is sufficiently small to allow high quality 3D metal printing with layer thicknesses of 20 microns or 40 microns and achieve high metal densities, hence high strengths, for the finished steel products made by 3D metal printing.

The details of the four steps to go from iron oxide enriched sand to a high grade steel powder for 3D metal printing are shared on a need-to-know basis, they are not given in this plan draft.

3D Metal Printing Machines on Mars

3D printing of metal powder using direct laser metal sintering or melting has developed since 1971 (Shellabear and Hyrhila 2004). There are a host of different terms used for this additive, layered solidification of metal powders, such as DLMS, SLM, laser cusing. Each of these terms were coined by various machine manufacturers to differentiate their own machines. Modern machines can do both metal sintering and metal melting and can vary between these in different parts of the body of the same print job. In what follows the term “3D metal printing” is used in place of the different terms used by machine manufacturers.

3D metal printing is a key to the Steel Seed Plan because it is so versatile: A single machine can produce any shape of metal body small enough to fit inside its build bed volume. Given a source of suitable steel powder, the combination of the material versatility of steel and the versatility of a 3D metal printing machine (with a suitably sized build bed volume) can provide the capability to make most metal things needed at an early, first human settlement on Mars.

There will be significant differences between 3D metal printing machines on Mars and Earth.

To avoid unwanted oxidation of fine metal powders during 3D metal printing on Earth, such machines do the printing in specially maintained inert nitrogen, argon gas mixtures with a very low oxygen content, which avoids long exposure to all the oxygen in Earth's atmosphere. 3D metal printers on Earth use nitrogen generators and flow nitrogen/argon mixtures through their part build chambers.

A 3D metal printer on Mars will be able to print metal powder in the local Martian atmosphere while having acceptably low levels of powder oxidation, a Martian 3D metal printer will not need a nitrogen generator. An analysis of oxidation of fine steel powder in the Martian atmosphere is included in an appendix (Oxidation of Fine Steel Powder in the Martian Atmosphere). Not needing a nitrogen generator will significantly reduce the overall volume, mass and power consumption of a 3D metal printer relative to another 3D metal printer that does use a nitrogen generator with the same size part build chamber. This reduced volume, mass and power consumption is important to increase the effectiveness of the sets of equipment sent to Mars to make steel in the Steel Seeds Plan.

3D metal printers sent to Mars should be thoroughly refined to take all sensible opportunities to reduce total printer mass.

Relatively small 3D printers landed on Mars in small individual spacecraft, such as Spacex Dragons, should be designed so that several of them can be ganged together, such that their individual part build chambers combine into a single build chamber with a long powder bed length along one of its horizontal directions.

A long powder bed need not work on a single part. A long bed is very flexible for part manufacture scheduling. A great variety of assorted part jobs can be printed simultaneously, or only a few large parts and also parts with lengths similar to the whole bed length can be printed. The need for one extended bed length is so that a ganged together 3D metal printer will be capable of making large size components suitable for building structures such as beams, conduits and panels. Given the need for parts made at architectural scales, a minimum acceptable long bed length would be around 2.0 m, while a better target long bed length would be 3.0 m and as much as 4.0 m.

Such a bed length is much longer than those found in 3D metal printers used on Earth. However, there is no strong engineering barrier to building a printing bed with a 3.0 m bed length. On Earth economic competition from alternate metal fabrication techniques for large-scale parts is the barrier to making 3D metal printers that are capable of making large parts.[9] However, during the early period of Mars settlement there will not be an established infrastructure of many metal fabrication machines which, together, have a large range of specialized capabilities which can be used to lower fabrication costs for various end products. Rather, during early settlement of Mars there is a need to be able to make as large a variety of useful parts as possible with as few different fabrication machines as possible. So, for early Mars settlement there is a great need for a 3D metal printer with a long build bed length.

A long build bed length requires many lasers to cover the bed. Increasing the number of lasers increases the finished part output capacity, which is desirable. Using the performance specifications for the SLM 500 3D metal printer (SLM), the build speed from a single 400 W laser outputs close to 0.2 kg per hour of finished steel parts, so that with around thirty 400 W lasers working together for close to 16 hours per Martian sol a production rate of finished steel products of around 100 kg per sol would be achieved. These figures give a rough idea of how big a 3D metal printing machine would need to be for it to be integral part in a set of robots and equipment that would be effective at making finished steel products for a seed settlement of Mars.

Growing Power Generation

The last paragraph touched on a important topic for any Mars settlement plan, power resources.

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9 3D metal printing on Earth has developed and flourished because it fills niche markets making some small things with shapes that other fabrication machines cannot make or with custom one-offs (like individual dental inserts).

For Mars settlement, power resources can be divided into two kinds: (i) those that can be transported from Earth to Mars and landed-on-Mars, and (ii) those that can be made-on-Mars.

In the Steel Seeds Plan there is a great focus on making-on-Mars. This focus is intense for making new power generation systems on Mars, and it is a distinctive feature of the Steel Seeds Plan. In other published Mars Plans this feature is not described either at all or with little emphasis or detail (Von Braun 1948, 1953; NASA 1989; Baker and Zubrin 1990; Zubrin 1996; Aldrin 1985, 2008, 2013; Naderi, Price and Baker 2015; Musk 2012, Musk 2016).

What brought the making-on-Mars of new power generation systems into the foreground of the Steel Seeds Plan to turn it into a feature of the plan? A partial answer is the realization that power generation technologies are available that ***can*** be made-on-Mars almost entirely out of steel, and, hence, these can be made into power plant very early in the settlement of Mars. These technologies will be discussed soon, later in this section. The rest of the answer are the realizations that actually making such power plant early in Mars settlement can set into motion an exponential growth of the first settlement on Mars and that early made-on-Mars power generation enables all the other requirements of settlement to occur. The benefits of making power generation systems on Mars, early during settlement, are so good and free of drawbacks, that once its realized that it can be done it has to be featured in a Mars settlement plan.

The Steel Seeds Plan does need some landed-on-Mars power generation capacity at the moment the steel seeds land on Mars. This initial landed-on-Mars power generation capacity is now considered; although, as will later be illustrated, the ability to make new power generation capacity on Mars renders the choice of what initial landed-on-Mars power generation technology to use relatively unimportant, just so long as there is some landed-on-Mars power generation capacity that works.

There are two candidate electrical power technologies for systems that can be transported, complete, from Earth and landed on Mars and used as the initial power systems for the steel seeds of the Steel Seeds Plan: small nuclear reactor systems and solar PV panel systems. NASA's rover robot *Curiosity* uses a small nuclear reactor system, called a multi-mission radioisotope thermoelectric generator (MMRTG) by its manufacturers. This system is rather inefficient at turning thermal power (2000→1600 $W_{thermal}$, produced in the nuclear reactor) into electricity, its peak electrical power output is modest (125→100 $W_{electrical}$), while its transport specific electrical power (*i.e.* power output divided by transported system mass) is 2.8→2.2 $W_{electrical}/kg_{transported}$ [10] (NASA 2008). The older NASA rovers *Spirit* and *Opportunity* use solar PV panel systems. NASA swapped to the nuclear system for *Curiosity* because of its greater dependability, since, dust accumulations on the solar panels of *Spirit* and *Opportunity* greatly reduced the effectiveness of these rovers for extended periods. However, the dust induced dependability problem can be reliably solved in integrated systems, like the steel seeds, that include robots that can clean off layers of dust from PV panels. With this problem solved, systems that use the latest high-conversion efficiency solar PV panels, and use PV panel mounting with panel re-orientation, can achieve sol-time (*i.e.* day-time) transport specific electrical power of more than 10 $W_{electrical}/kg_{transported}$ which, for an equatorial location, averages out over a whole sol (including the night-time) to around 5 $W_{electrical}/kg_{transported}$. Since, both of these specific power values are noticeably better than the specific power value of the MMRTG, solar PV panel systems are favored initial power systems for the Steel Seeds Plan.

The solar PV system specific power numbers are calculated out in a footnote ; one thing should be made clear about these calculations, a distinction was made between a system's mass and its transported mass. The content of this distinction is illustrated by examples. For an MMRTG system working on the surface of Mars, its transported system mass equals its absolute system mass (*i.e.* the actual mass of the MMRTG); this is because all of the mass of the MMRTG has to be transported from

10 The arrows ranges on these power quantities are due to the declining power output from the nuclear reactor over about fourteen years of operation.

the Earth for it to work on Mars. However, for the mounted solar PV system, capable of continuous re-orientation (to put the PV panels optimally normal to the incident sunlight) part of this system need not be transported from Earth to Mars, so that, for these mounted solar PV systems, their transported mass is less than their system mass by the mass amount that was not transported.

So what parts of such mounted, re-orientable solar PV systems do not have to be transported from the Earth to Mars? The answer is the frames and jointed mounts that the PV panels are eventually mounted on and that provide the ability to re-orientate the panels so that they are, during sol-time, always optimally turned toward the incident sunlight. These frames and jointed mounts can be made-on-Mars out of steel by the steel seeds.

While these frames and jointed mounts are being made on Mars, the solar PV panels would operate sub-optimally, without re-orientation, and only some of the steel seeds would be operating some of the time. However, as the frames and jointed mounts get made, more and more of the panels are mounted on them, and each of these mounted PV panels start to operate optimally. The average power output from all of the PV panels in such a system steps up each time one of the PV panels goes from static, sub-optimal operation, to optimal, mounted operation with continuous re-orientation. As this average power goes up, more of the steel seeds can operate more of the time, which, for a while, produces exponential increases in both the average power output and also the average up-working-time of the steel seeds. A virtuous spiral upwards in power capacity will be created by focusing the earliest activities of the steel seeds on manufacturing the frames and mounts for the solar PV panels.

This early phase of exponential growth stops when all of the solar PV panels are mounted for optimal re-orientation. However, this early phase can be immediately followed by a second phase that keeps the exponential growth going. In this second phase a different power generation technology will be made-on-Mars. This technology will be one of several variants that all use parabolic dishes to reflect and concentrate sunlight to a solar receiver that reaches high temperatures.

The most widespread application of parabolic dishes is for satellite television dishes which concentrate weak signals, but they are also used in various other antenna, mirror telescopes, radio telescopes and for solar power generation. Both large mirror telescopes and solar power dishes principally focus light. Both do roughly the same thing, but parabolic mirror telescopes have to focus very small amounts of light and focus this light much better that solar power dishes. This means that the manufacturing tolerances for solar power dishes are much less strict than those of good telescopes, hence, solar power dishes are much easier to make than parabolic mirror telescopes.

Another thing that makes things easier is that there is so little oxygen in the Martian atmosphere[11] that polished steel will maintain its reflectivity for years and can be used for the light reflecting surfaces of Martian power dishes, so that no glass is needed.

Among the variant technologies that can couple with and be driven by solar parabolic dishes some output heated gas flows for driving thermo-chemical reactions, while others output electricity. Only one of these variant dish-coupling technologies is currently very well developed and close to ready for deployment on Mars. To keep things near-fetched, this developed, dish-coupling technology is described right now.

This technology is the free piston Stirling external heat engine. It has been developed for NASA space exploration by William Beale of Athens, Ohio. Professor Beale, who recently died, wanted his engines to work with parabolic dishes to generate electricity from sunlight here on Earth. His free piston Stirling engines are likely to be a big success on Mars. Beale's free piston Stirling engines attracted the attention of NASA for several reasons. They are hermetically sealed, have very few moving parts and use low-wear gas bearings. These properties make these engine very reliable, so reliable that NASA expects them to run without maintenance for years while they power

11 The partial pressure of oxygen in Earth's atmosphere is more than 20,000 times that of oxygen in the atmosphere of Mars.

space-exploring craft crossing the solar system. These engines can be made with small electrical outputs that cover a range that is very useful for early Mars settlement, *i.e.* 100 $W_{electrical}$ to 10,000 $W_{electrical}$. Best of all, Beale's hermetically sealed free piston Stirling engines have excellent specific power numbers 60+$W_{electrical}$/$kg_{absolute}$. This is very impressive specific power, however, because most (50–75%) of the mass of these engines is steel that can be made-on-Mars, the transported mass specific power for these engines is a truly remarkable 120–240 $W_{electrical}$/$kg_{transported}$. The final specific power numbers will not be this good, since to turn dishes into practical solar power dishes a few, extra, small-mass parts will need to be transported from Earth. These parts include control electronics to control movements of the solar parabolic dishes to keep them optimally orientated to the incident sunlight and one or two small drive motors to power such re-orientations (although, quite quickly, most of the components of such drive motors will also be made-on-Mars). Factoring in the transported mass of these extra pieces will give an exceptionally good transported mass specific power of 90–180 $W_{electrical}$/$kg_{transported}$. After factoring night-time, dish non-performance, these specific power numbers are about 25 times better than the power unit of robot rover *Curiosity* and 9−18 times better than re-orientable, high efficiency solar PV panels. These specific power numbers mean that the parabolic dish/free piston Stirling engine has truly overwhelming advantages over the standard power unit choices.

The ability to start manufacture of new power generation capacity right after the landing of the steel seeds allows the design of the steel seeds to incorporate another useful feature. That is, the mass loading of the steel seeds' equipment and robots into their Mars landing craft can be biased so that many *fewer* solar PV panels are loaded into the landing craft than are required to run, at full capacity and simultaneously, all the other pieces of equipment and robots (for iron ore mining, enrichment and steel reduction, refinement, powdering and fabrication activities). This biased under-loading of solar PV panels is allowed because of the made-on-Mars power ability and this PV panel under-loading also allows the freeing of payload in the landing craft which can then be taken up by putting more of the other steel-making equipment and robots into the landing craft.

Actual power unit loading in the steel seeds landing craft will only be at a level to generate between 10% and 20% of the electricity needed for simultaneous, full capacity operation of the other equipment and robots carried in the steel seeds complement. The other 80–90% of the power generation capacity gets made-on-Mars and then much more additional power generation capacity gets made-on-Mars after that. The choice of whether to use small nuclear reactors or solar PV panels for the initial landed-on-Mars electrical power generation units is relatively unimportant because the total landed-on-Mars power capacity will be (relatively) very small in the Steel Seeds Plan.

Making the first few dozen solar dish/Stirling engine power units will produce the second phase in early settlement growth. This second phase will also bring exponential growth of both the first settlement's power generation capacity and its iron ore mining, enrichment, plus steel reduction, refinement, powdering and fabrication activities; since, in this second phase, all of the output from steel-making goes to increasing the power generation capacity and all of the increased power generation output goes to increasing steel-making activities.

This second phase growth will, quite quickly, reach its end-point when there is enough power to run all the landed-on-Mars steel-making equipment at close to full capacity at close to all hours of Martian sols. At that point the growth in steel-activities levels off for some time, and will only return to more growth when more steel activity equipment and infrastucture is either made-on-Mars or landed-on-Mars. However, with the initial plateauing of steel activities, the output from these activities can then be applied to many other priority jobs. Many of the new high priority jobs will require additional power capacity over and above that needed for steel activities. So a third phase of growth in the first settlement's power generation capacity will be needed beyond the first two phases of growth. The sections following this one and the summary will discuss some of the high priority jobs that will be under-taken after the first two, brief phases and the growth that will occur during the longer-lasting third phase.

Parabolic dish power systems, particularly parabolic dish/Stirling Engine systems, are very suitable for early manufacture on Mars for a number of reasons: They can be made mostly of steel; they can be made at small sizes; Beale's free piston Stirling engine/generator is well developed, highly reliable, the hot end of this external heat engine forms the core part of the solar receiver (the most technically challenging solar sub-system) and its specific power is excellent; the delivery of useful, generated power off a moving dish system to the power's end uses is easy to do/engineer when this power is electrical; the difficultly of making/engineering solar parabolic dishes that can generate temperatures of 600 ºC to 850 ºC at their receivers is not high, while such 600–850 ºC receiver temperatures are suitable for driving both heat engines and some important thermo-chemical reactions.

The array of different power generation technologies that can be made-on-Mars can be made more diverse if some ceramic parts are used with new equipment and, also, if power system components can be made physically bigger than the limitations put on component size by the dimensions of the first 3D metal printer and also the ability of the first settlement's robots to manipulate and assemble large parts. This discussion, focused as it is on the early settlement period, is not going to describe ways how to make and build/assemble bigger power systems on Mars except to say that, after firmly establishing the first settlement, a larger power generation technology that is natural to consider building is a solar power tower. A brief consideration is now given of small-size, parabolic dish designs for generating useful power in the form of hot (750–850 ºC), pressurized gas flows that need some ceramic parts (as would solar power towers).

First of all, such hot, pressurized gas flows would be very useful for driving at least two thermo-chemical processes, the iron oxide[12] reduction process of steel-making and the production of the methane/oxygen fuel/oxidizer pair. The production of methane, and sufficient oxygen to combust it, is very useful as methane/oxygen can be used: (i) as a rocket propellant that allows people to return from Mars to Earth (Baker and Zubrin, 1990; Zubrin 1996; Musk 2012); (ii) as a fuel/oxidizer for gas turbines that mechanically drive, for example, surface transportation vehicles and electricity generators; (iii) as a fuel/oxidizer for very high temperature furnace processes such as ceramics manufacture and basalt fiber manufacture; (iv) as a means for storing energy that then, for example, might drive gas turbines for nighttime electricity generation. The great need for both iron oxide reduction and methane/oxygen production will mean there is a high demand for both, which creates a strong motive for efficient iron oxide reduction and methane/oxygen production. Both solar PV panels or combinations of the solar dishes and free piston Stirling engine/generators can drive this oxide reduction and fuel/oxidizer production, and its important to underline that these well developed technologies can these drive processes; however both of these reduction and production processes could be driven more efficiently with high temperature, pressurized gas flows. Hence, while there are not yet well developed solar parabolic dish systems that can pipe hot, pressurized gas flows to thermo-chemical reactors that can be conveniently placed stationary next to dynamic solar dishes, there is a motive to develop such parabolic dish systems. This development does not face any strong technical barriers to carry it out, rather it requires some ceramic parts as well as steel parts, thorough detailed engineering development, and an elegant solution to a tricky subsystem engineering problem (Two Planet Steel has one solution to this problem). It would be good, but not completely necessary, for successful Mars settlement, to have this extra technology up and ready to go in the next few years, as it would make growth of the first settlement easier and more rapid.

Each solar power dish, plus its supporting frame and column, and most of the parts for a free piston Stirling engine and generator driven by the dish's solar heat can be made entirely of steel. All of

12 plus other transition metal oxides

these can be made from steel components made by the first 3D metal printer on Mars, the robots will then do simple assembly of the components to construct the solar dish/Stirling engine power units.

It is hard to over emphasize the practical importance of this for the settlement of Mars: *Firstly*, it is important that there exists ***some*** power generation technology which can be made on Mars, almost entirely out of local, non-transported materials, early on in the planet's settlement; *secondly*, this small-sized combination of free piston Stirling engine/generators driven by solar energy concentrated by parabolic dishes is a power generation technology that can be made-on-Mars with a very small and narrow manufacturing infrastructure, wherein this infrastructure is so small that it can be landed on Mars without using giant landing craft that require giant rockets to lift them to Mars; *thirdly*, this technology makes possible a large growth in the first settlement's power generation capacity which, in turn, makes many other things needed for settlement growth possible.

Collecting Water, Muscular Ground Transportation

While basic survival of a few humans can be achieved with a tiny reservoir of water coupled with radical water-recycling, unless much larger reserves of water can be collected not much more than continuing basic survival of a few people can happen.

Where and how to collect water on Mars are big, mostly unanswered questions.

Water is relatively abundant in both polar regions and in far northern and far southern latitudes. However, these far northern and southern regions are, during their respective winters, so cold that this cold, by itself, will discourage year-round settlement in them. In addition, the severe cold causes large parts of the Martian atmosphere to just freeze, something that is very alien to Earthlings, and this freeze is accompanied with large, relative atmospheric pressure drops and very fast winds into the extremely cold polar regions. From a water perspective, extreme latitude water is likely to be very distant from human settlements. This water can only get to human settlements with huge water transport infrastructure. It would be such a big logistic and engineering challenge to build such infrastructure that it will not occur early in settlement and it will only occur if other easier-to-access water sources become insufficient.

Large numbers of water glaciers have been discovered in mid-latitude zones both north and south of the equator (Head et al. 2006; Karlsson, Schmidt and Hvidberg 2015). The closest such glaciers get to the equator is around 30º N and 30º S, while a particularly large concentration of them are in the Ismenius Lacus quadrangle, (i.e. north of 30º N and between 0º E and 60º E) (Kieffer, H.H. 1992). The dark sand dunes shown in Figure 1 are about 1500 km south and east of the south-east part of the Ismenius Lacus quadrangle. Collectively these glaciers hold roughly 150 cubic kilometers of water (Karlsson, Schmidt and Hvidberg 2015), which is about 31% the volume of Lake Erie in North America or about 170% the volume of Lake Geneva in Switzerland, or 250% the volume of Toyko Bay in Japan.

At the moment it is unclear that establishing settlements close to these glaciers would be an optimal strategy. Choosing such a settlement location would have the disadvantages, relative to equatorial settlement locations, of a colder climate, reduced solar power generation resources and increased thermal heating requirements. It would be nice to have both the relative warmth and solar resources of an equatorial region combined with such glacial water resources. The process to make a combination like that a reality might start soon after human settlement starts with the beginning of muscular ground transportation.

Large-wheeled, large capacity trucks could be made, out of steel, with the settlement technologies already described for the Steel Seeds plan. These trucks would use water-recycling, heat recuperating gas turbine engines (made mostly out of steel parts fabricated on Mars) and run on the liquid methane/liquid oxygen, fuel/oxidizer pair favored by Baker and Zubrin (1990), Zubrin (1996) and Musk (2012; 2016) for rocket propellant. With the methane/oxygen combination, such trucks would have long ranges and these ranges could be extended to thousands of kilometers by placing fueling stations at remote trail-side locations. A fueling station would consist of a local methane/oxygen generation system, pressurized, steel-made storage tanks and a steel-made, solar parabolic dish to provide the necessary power. A cycle is formed between, on the one hand, methane/oxygen generation systems and, on the other, water-recycling, heat recuperating gas turbines which is particularly efficient and appropriate for the harsh Mars environment.[13]

This process would start off by making one truck and building one solar powered methane/oxygen unit. This one truck would be able to travel tens and hundreds of kilometers from its home location to transport things to and from mine locations and to and from any useful water resources within the truck's range.

Even if no really abundant water resources are found within a few tens of kilometers of the first settlement landing area, there are solid indications that, in equatorial regions, the levels of water bound to sand can vary substantially, and up to several percent levels, at quite small local scales (Feldman *et al.* 2002) and that sub-surface aqueous perchlorates can liquefy on warm sols and flow downhill (Martín-Torres et al. 2015), so that high water content sand locations will be found within the range of a single truck, as well as relatively wet locations at the foots of hills and mountains within the same truck range. Making and running the first Martian made truck will, at a minimum, enable a big percentage increase in the initial, small free water reserves available to early human settlers.

Some people hope that quite abundant water resources are available in equatorial regions just a few meters below the ground's surface (for example, Michalski et al. 2013). This may well be true and it may also occur quite close to a first landing area. If this does occur then it would provide a large increase in available water reserves with relatively little engineering effort and enable relatively large influxes of human settlers to Mars to go ahead early.

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13 This cycle is chemically described as follows:

(1) methane/oxygen generation: $CO_2 + 2H_20$ + (heat, from solar dish) -> $CH_4 + 20_2$
carbon dioxide + water -> methane + oxygen

(2) combustion: $CH_4 + 20_2$ -> $CO_2 + 2H_20$ + (heat, for gas turbine)
methane + oxygen -> carbon dioxide + water

Equations (1) and (2) can actually work for methane/oxygen generation coupled with either rocket engine combustion or gas turbine combustion. However, the water made by gas turbine combustion (the right-hand side of (2)) can be 100% *re-captured* into storage containers and then poured into the methane/oxygen generator (i.e. re-cycled) as input (to the right-hand side of (1)) for methane/oxygen generation (this 100% re-capture can *not* happen from the exhaust from a rocket engine). When this re-cycling is done there is no net use of water. Also a truck that needs to be refueled at a fueling station, nicely and efficiently, brings just the water needed for the fueling station to go on and make more fuel. Since water on Mars is so precious, there is a great benefit and impetus to carry out water re-capturing and re-recycling on Mars (it is not done with gas turbine's on Earth). Note, Equation (1) is the sum total consequence of several reactions, it does not occur in one step.

Although methane/oxygen generation is often (rightfully) touted as very useful for rocket transport, there is another way to look at this generation, that is, as a really useful alternate, large capacity way to store solar energy which can be taken out of storage to do useful things such as mechanical work, like powering a truck, or running gas turbines to run electricity generators at night. This energy storage feature is also basically made-on-Mars, unlike electrical batteries which will be too difficult to make on Mars for years after human settlement is begun.

However, if we do not find abundant water supplies a few meters below the equatorial surface then such a lack of water can still be replaced with the distance glacier water with (i) a fleet of trucks (which can start off small and then grow), and (ii) a water trail to the glaciers with a system of trail-side fueling stations. And, if such a long distance water trail gets established, then the grander engineering feat of constructing a long-distance water pipe can be considered.

This is a good place to point to another piece of equipment that should be landed on Mars, as part of the seeding equipment, in addition to the several, redundant collections of robots and steel-making and steel-fabrication equipment making up the main part of the seeding and germination equipment for human settlement of Mars. This extra piece of equipment would be a robot-controlled truck, powered through electrical batteries, with greater transport capabilities than the other robots. This first truck would be needed on the ground early to allow transport between the locations where the different individual landing craft land each one of the several redundant collections of robots and equipment that carry out steel-making and steel-fabrication. Such a first truck will likely be needed because efficiently landing a ship on Mars cannot be done with such pinpoint accuracy that all of the steel-seed landing craft land next to each other. Since, to ensure such pinpoint accuracy would require a significant part of each landing craft's payload to be taken over by fuel reserves that would enable local maneuvering that would guarantee pinpoint landings to cluster the landing craft together; however, reserving as much of each craft's landing payload for robots and equipment has a higher priority than adding extra fuel for extended, maneuvered landings. Without maneuvered landings, the landing sites of the individual landing craft are likely to be well separated from each other. The first, small electrical transporter would have two big initials tasks and thereafter just everysol trade and transport work duties. The two really important tasks would be (i) to help unload and position the robots and steel-making equipment at locally optimal iron ore locations, (ii) to ensure that the individual, small 3D metal printer units are bought together in one location and then help with the ganging together of these small units into one large 3D metal printer.

Successful growth of early human settlement on Mars will be largely determined by the extent of growth of power generation capacity, the mass of finished steel products made and the size of usable water reserves. Everything else that might be needed, or just wanted, at early human settlements will be obtained to a degree determined by the availability of power, usable water and finished steel products.

Of the three, power, water and steel-making, most people might think that power and water are more fundamental to the success of human civilization than steel-making. However, on Mars, with just a small initial power supply, steel-making can enable the growth of power generation up through levels which include enabling a handful of people to live through a rapidly growing first settler's period and then on up to levels which can sustain a modern industrial and agricultural economy that creates abundance for a Martian society; in addition, steel-making coupled with increasing power generation can solve the tough problems involved with collecting enough water on Mars to supply the needs of growing Martian human abundance.

Making Other Equipment, Doing More Things

This section takes a short glimpse at some activities that might be started toward the end of the early seeding and germination of human settlement on Mars as it transitions to a long, extended growth, building and expansion period.

A single 3D metal printer on Mars will not be enough, even a large one, to fabricate everything needed for growing the first settlement. To reach for abundance on Mars a lot of new manufacturing equipment will need to be made-on-Mars and this equipment will need to start making-on-Mars.

Some of the new equipment should be devoted to increasing iron ore mining capacity and to iron ore to steel processing capacity and, also, steel fabrication. Any equipment that can produce some useful intermediate product, like sheet steel, steel wire, I-bar steel or steel screws etc., opens up alternate ways to make finished products using steel, and, thus, increases overall production capacity and also reduces over-reliance on individual pieces of equipment (such as the first 3D metal printer) and, hence, increases the robustness of settlement growth and eventually societal growth. The more ways to make-things-on-Mars the better.

More ways to make-things-on-Mars should be applied to start making things on Mars with materials besides steel. Several of the compounds found in Mars dust and Mars sand are found in ceramics, glasses, agricultural soil and fertilizer (see Table 1). In fact, all of the main component compounds of soda-lime glass (used for bottles and windows on Earth) and common refractory ceramics (used for lining furnaces and for insulation) and the inorganic components of some good agricultural soils are found in Mars sand.

Let us briefly consider using Mars sand as a raw ore that can be enriched into useful feedstock for ceramic and glass manufacture. After magnetic separation removes most of the transition metal oxides (*i.e.* the iron ore components) from the sand, dry (water free) density separation methods applied to the remaining sand can create two enriched feedstocks, one of which is suitable for baking refractory ceramics while the other will be suitable for glass-making. At the moment, there are some significant unknowns about how to best carry out density separation (for example, should the separation method be completely dry or can it use some water), and also cost-benefit uncertainties, including finding good balances between the sharpness of density separation verses the practical value of various degrees of separation sharpness verses the time and effort put into separation. The best answers to these unknowns will change with time and, in particular, will change according to the availability of water reserved for separation and agriculture and also the tendency for mining to specialize as discoveries of locations with especially good, specialized raw ores are made. However, early on, the first refractory ceramics and first glasses made can be quite crude but still be have a big practical impact; for example, by enabling a crude, early furnace which then enables better ceramics and better furnaces.

A few more things are quickly mentioned and then the section is wrapped up to remain close to this text's core, the seeding and germination of human settlement of Mars. Plastics, yes, it would be nice to be able to make plastics on Mars soon after the first humans land but this will not happen early; Martian plastics manufacture will probably start after agriculture becomes established on Mars. Basalt, Mars has lots of basalt, it can be turned into useful insulation material and also into long fibers that can be woven into basalt fabrics; making other kinds of fabrics on Mars will be relatively difficult, to the point that basalt fabrics will often likely be preferred on Mars and will likely become associated with Mars. Potassium, it would be a useful to find on Mars enriched mineral sources, beyond what is typical in sand, of this macro-nutrient for plants and ourselves.[14] If no enriched potassium sources are found then it may become necessary to transport concentrated mineral nutrient supplements from Earth to Mars. However, using closed-cycle agriculture (*i.e.* with very strong recycling of water and nutrients), the mass of available mineral nutrients needed per person, would be small and manageable (on the order of 1–10 kg per person). The mineral nutrients in dehydrated food and nutrient mineral concentrates transported to feed the first settlers will, after human digestion, provide a usable reserve of nutrients to grow the first plants on Mars. On Earth people need plants but plants do not need people, while, on Mars, plants and people will live in symbiosis.

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14 Using the composition data from Blake et al. (2013), the percent masses of potassium and phosphorus in sand are close to equal, however, healthy plant grow needs close to 5 times the percent mass of potassium as that for phosphorus (Epstein 1965). The first settlers' own feces and urine will be very valuable sources of potassium and other nutrients.

Summary and the Start of Human Martian Life

The Steel Seeds Plan implements small-scale iron ore mining, raw ore to steel-powder processing and the fabrication of finished steel objects on Mars.

It does this by landing multiple, redundant collections of equipment and robots on Mars wherein each individual collection then performs mining, ore-to-powder processing and finished, steel object fabrication.

Each of these individual collections is compact and low mass enough that each could be landed on Mars inside a single, relatively small landing craft.

Each of these individual mining/processing/fabricating collections includes: an initial power generation system which is most likely an array of solar PV panels; one, or more, rover robots with at least two mechanical arms that can have multiple arm-end attachments; units for reducing ore iron oxides and other transition metal oxides to metals; units for refining the reduced products and turning these into fine steel powder suitable for 3D metal printing; a small, modular 3D metal printer; and, also, a complement of critical spare parts that cannot be fabricated out of steel.

Iron ore exists on Mars in the form of sand dunes. This is important, since, this makes it possible for small, rover robots with only limited mechanical strength and limited power supplies to carry out iron mining and ore enrichment.

The rover robots perform the ore mining which simply consists of scooping sand (the raw ore) off sand dunes and placing it into each robot's holding ore bin. The mined sand dunes should be chosen in advance so that their sand has above average iron oxide content.

The rover robots perform ore enrichment by magnetic separation of the magnetized transition metal oxides from the rest of the non-magnetic material in the sand. These robots do this separation using electromagnets attached to the end of one their arms.

Each rover robot loads enriched ore into its collection's main ore reduction unit, operates these reduction units to get them to reduce the ore's metal oxides to metals and generate oxygen. Each rover robot also unloads the reduced steel metal from its collection's reduction units.

Similarly, each rover robot loads the reduced metal into its collection's refining and powdering units, operates these units and unloads fine steel powder from these units and also separately unloads the non-metal, impurities that the input reduced metal contained.

In addition to the landings of multiple, redundant mining/processing/fabricating collections another landing is recommended. The main piece of equipment bought down to Mars in this additional landing would be a relatively large rover robot. This robot would be specialized for surface transport. It would connect together the other mining/processing collections which may well be separated from each other through the process of multiple spacecraft landings.

Although the small modular 3D printer units could operate separately at first, each of the small, modular 3D metal printers landed in each of the collections should be bought together and then ganged together into a single large 3D metal printer. This would be carried out by the large transport robot rover and as many of the mining rover robots as necessary.

Martian 3D metal powder printers will be much lighter and more energy efficient than corresponding printers used on Earth (with equivalent build bed sizes) because the Martian printers do not have to have special machinery for delivering inert gas flows into their build chambers to avoid powder oxidation, rather Martian printers can operate in the normal Martian atmosphere and not have a powder oxidation problem. Martian metal printers should be optimally made-on-Earth to avoid all unnecessary printer mass.

All of the mining rover robots and the transport rover robot should be capable of operating both the small unit 3D metal printers and the ganged-together large 3D metal printer.

Some things to notice about these steel-making activities are that the rover robots are the main, on-site agents (*i.e.* they start processes, make transitions between processes and also do the ore mining and beneficiation), also all of the actions the robots do are simple and uncomplicated. These things point to the feasibility of the Steel Seeds Plan, since, robotic technology has long since been capable of making robots that can take such actions. Further, recent advances in robotic sensing, control, programming and artificial intelligence will ensure that steel-making, Martian rover robots will be able to perform their humdrum steel-making tasks largely autonomously.

The rover robots will also work tirelessly, so long as there is power available and they can be kept in good working order.

Keeping the rover robots and all the other equipment running as much as possible and for as long a possible is a key goal of the Steel Seeds Plan. The value generated by the robots and the other equipment on Mars is value that keeps increasing as the numbers of hours they work increases and this value is practically realized here on Earth as reduced-cost-value; since, every useful object that is made-on-Mars is a useful object that does not have to be made-on-Earth and expensively transported from Earth to Mars. A benefit of attaining the up-and-running goal is that a relatively, small and inexpensive group of collections of equipment and robots will eventually produce very high value results on Mars.

The plan keeps the robots and equipment running through multiple plan features including: redundancy (by having multiple, redundant steel seeds, *i.e.* collections of equipment and robots); steel spare part manufacture on Mars (made possible by the local steel powder production and steel part fabrication by 3D metal powder printer); occasional spare part deliveries from Earth; and teams of robots with the mechanical, computing abilities and human communication capabilities to perform both simple and tough repair and maintenance tasks (each robot in a team can attach state-of-the-art mechanical hands to carry out intricate repair and maintenance manipulations with humans guiding the robots through non-standard manipulation tasks).

Other features of the plan that, like its enhanced repair and maintenance capabilities, add robustness to the plan are some of its scheduling and checking features, such as landing the steel seeds on Mars well before (at least two synodic launch windows before) the arrival of the first humans. With human guidance from Earth, the rover robots will be excellent safety and preparation checking agents. That is, these robots, with human guidance, can check that all the on-Mars details necessary for a safe human landing and settlement are properly in place and working before a final decision is made to send the first people to Mars. This allows the plan to insert a safety delay (of another synodic period) into the scheduling to ensure the first people landing on Mars will have a properly working habitat and workshop to live in.

This robustness and safety cannot be matched by any land-a-giant-object-in-one-piece plan that lands the first settlers in a landing craft that also forms the habitat and workshop those settlers are supposed to live in. In such plans any serious problem or damage that might occur during any operation to land the spacecraft/habitat is a problem that threatens the safety of the first settlers. In contrast, the first people settling Mars can be completely safe with any landing of a landing-only-spacecraft that is completely safe but also with any landings that suffer some damage such that the first settlers can get out of the landing craft. With the Steel Seeds Plan, the just-landed settlers can rely on the pre-built, pre-checked, on-the-ground settlement infrastructure ready waiting for their arrival. In order for any plan that attempts to land a whole habitat unit with a single landing to match the built in safety features of the Steel Seeds Plan that other plan cannot have the first settlers land with their habitat; instead, the habitat would need to be landed without people, then safety checked and only after another 780 day cycle could the settlers land, in another landing craft, with the high safety levels the Steel Seeds Plan delivers.

Smallness, lightness, compactness are all preferred features of the plan which fulfill important needs, provide big benefits and provide connections to the seed metaphor that appears in the plan's name; while the unpacking of the plan's robots and equipment from their small landing craft and their subsequent actions also share similarities with the germination of seeds and their subsequent early growth into plant shoots. Although it would be possible to carry out most aspects of the Steel Seeds Plan using initial landings that land-a-giant-object-in-one-piece, and it also appears that Elon Musk will propose an early settlement plan in September 2016 that would use a series of land-a-giant-object-in-one-piece landings, there is no necessity for the use of giant landing craft with the Steel Seeds Plan and there are plenty of benefits that come with the use of small landing craft that land small, compact, low mass, redundant collections of equipment and robots. These benefits include: low-cost per landing; the avoidance of the need for broad and long-term political and government departmental support in Washington; the avoidance of probable delays such political and governmental support often entails; the use of redundancy which allows a few things to go wrong or break while maintaining wider viability and robustness; the flexibility to have some things go wrong can reduce sub-system development times and cost over-runs, since systems that are highly fault tolerant have to be tested much less than fault intolerant systems that have to be tested in great detail and usually require many detail redesigns and retests; the flexibility to more closely match the total mass and capacity of the transported robots and equipment to the available funding levels and funding sources; and the ability to fully take advantage of the feature that a seed settlement, with key growth capabilities like made-on-Mars power generation manufacture, will eventually make many things on Mars and become a large settlement with a broad array of life-supporting and abundance-generating capabilities.

Another key point about the steel seeds is simply that they can be made (*i.e.* they are feasible).

The initial output of finished steel objects from 3D metal printing should be highly focused towards rapid increases in the nascent settlement's power generation capacity.

Assuming the initial landed-on-Mars power generation systems are solar PV systems, then the first steel products fabricated on Mars with the 3D printer would be steel stands and movable frames to mount the PV panels so that, during sol-light, these panels can be continuously re-orientated to be optimally normal to the incident sunlight. The change from an initial laid-out-flat configuration for the PV panels to a mounted, optimally orientable configuration will produce a significant increase in power output from the PV panels. This production of frames and mounts covers a first phase of growth in steel activities and power generation. This growth is exponential for both, since as each set of steel frames and mounts is made it produces an increase in average power output, and each increase in average power output increases the average rate of all steel-making activities. This first phase ends when all the solar PV panels are properly mounted and become continuously re-orientable. At the end of the first phase the various steel-making pieces of equipment, landed-on-Mars, will still be working well below their designed peak outputs and this equipment will not be working full time.

The first phase quickly leads to a second phase with made-on-Mars manufacture of many small power systems that each consist of a parabolic dish driving a free piston Stirling engine/generator. This second, brief, phase also exponentially expands all steel activities and the total power generation capacity and output. This early exponential growth phase ends when all landed-on-Mars pieces of steel-making equipment are working at close to their designed peak capacity and for most hours in each sol.

The electrical power systems that start getting made-on-Mars in the second phase are very important for the settlement of Mars. Even at an early stage of settlement, a large majority of the material needed to make these power systems can be made-on-Mars steel powder and the 3D metal powder printer can turn this steel powder into the most massive parts that these power systems need to work. This means that, these made-on-Mars power systems can deliver any amount of electricity that a growing settlement can demand. These power systems will be made well beyond the end of the second phase, as growth in power demand continues well beyond the end of the second phase. It is important that the most technically challenging subsystem of these power systems, *i.e.* the free piston Stirling Engine with a built in electrical generator, is already a highly developed for the power needs of spacecraft that explore the solar system. The performance demands of such solar-system-exploring engines are very high and very suitable for the power systems needed for the human settlement of Mars. That is, the engine/generators must be so highly reliable that the expected continuous working operation of these engines, without any repair, maintenance at all is above several years, and these engine/generators have high specific powers.

For Mars settlement, the really important specific power values are transported mass specific powers; the values of these transported mass specific powers for these power systems are very good indeed because very little of their mass needs to be transported from Earth to Mars because almost all the mass of these systems can be made-on-Mars. The ability to make power systems on Mars, with very little of their mass transported from Earth, will be a huge enabler of the settlement of Mars.

A third phase begins in which steel-making activities broaden their output to make things for other high priority settlement jobs. These other settlement jobs could cover a large number of different things. The Steel Seeds Plan does not prescribe what all these other high priorities are or might be; however, some obvious priorities were discussed here. These priorities include: making and operating equipment for methane/oxygen fuel/oxidizer manufacture, making and operating steel transportation trucks/water-collectors, making parts for and building various pressurized steel storage tanks for liquid oxygen, nitrogen, argon, methane and water/ice, making and operating gas turbines, electrical engines, compressors and cryo-coolers, making steel parts for and building the first pressurized structure for the first human habitat and workshop, making steel fittings and furniture for the first human habitat and workshop, making and operating life-support equipment for breathing and recycling (products of human respiration, digestion, perspiration *etc.*), making and operating equipment for the density separation of components of glass and light soil from components of ceramics, making and operating furnaces for simple ceramic, glass and basalt fiber manufacture, the beginning of fertilizer production.

Whereas the first two phases will finish quite quickly (they are likely to be over in a few months), the third phase will last many years and go well beyond the steel seeds period of first settlement; but the third phase will start in the steel seeds period. It will start before the arrival of the first humans on Mars and start with the early, third phase, high priority jobs.

The net output from, steel-making, oxygen generation, steel fabrication and water collection will provide the large majority of the mass of all the useful technological objects, liquids and gases that will be needed to enable and sustain human life on Mars in a first habitat and workshop. As such the Steel Seeds Plan can greatly reduce the mass of supplies and equipment transported to Mars from Earth needed to establish a first habitat and workshop on Mars relative to any other plan that does not have similar levels of made-on-Mars parts, equipment, gases and liquids.

As has been laid out so far, the Steel Seeds plan, has a significant period, prior to the landing of the first humans, where robots are making things on Mars with only occasional guidance from humans (located either on Earth or on a spacecraft orbiting Mars). At some point this early period will end with the historic first landing of humans on Mars. However, almost nothing has yet been said about when the historic first human landing should be relative to the early progression of making things on Mars with robots. All that has been said is that this first landing should be safe for the people, or person, landed and that they will have a safe habitat to live in. Another necessary condition for any viable settlement plan is that a safe *and long-term* habitat be assured for the settlers. Viable plans can provide a safe and long-term habitat for the first settlers by three broad plan routes: (i) either such a safe, long-term habitat is landed on Mars in one piece; or (ii) one is constructed on Mars (to at least some minimal acceptable level) prior to the landing of the first settlers, entirely by robots from components that can either be transported-to-Mars or made-on-Mars or both; or (iii) the first settlers go to Mars and temporarily live in a small habitat (such as, the interior of a landing craft) and, while living in the temporary habitat, the first settlers join in the construction of their own first, long-term habitat while being aided by robots.

All three of these routes for securing a safe, long-term habitat for the first settlers can be accommodated in a variety of plans that all could be said to incorporate the Steel Seeds Plan; although the first of these, resorting to land-a-giant-object-in-one-piece, goes against the spirit of some the main ideas of the Steel Seeds Plan.

Another problem with the land-a-giant-object-in-one-piece approach is that, with this approach, the first long-term habitat for the settlers will be rather small and confining and liable to put severe relationship pressures on the settlers. Ideally, a long-term habitat for the first settlers should be large and spacious enough that there is plenty of room for both public and private spaces and therefore enable relatively normal personal relationships between the first settlers. Both plan routes (ii) and (iii) can provide a first long-term habitat that is large and spacious and easily livable for the first settlers. Although, if the Steel Seeds Plan is implemented then it will provide, for any plan using any of the three long-term habitat routes, most of the capabilities needed to build subsequent habitats and public buildings on Mars, and these subsequent buildings can have the desirable generosity of interior space that will enable mostly normal personal relationships between settlers. However, in order to do such construction-on-Mars there are somethings needed which have not yet been described.

These missing things need to provide the capabilities to lift building components to their intended build positions and to fix them in these positions (by welding or other techniques). There may be room to be highly inventive with new technology to get these lift and fix construction tasks done, but sticking with basics used on most construction sites here on Earth will also work. These old basics would be a crane, scaffolding and something that can do what regular construction crew members do to climb (scaffolding and partially built structures) and fix building parts into their intended places. The output from the collection of steel seeds can easily include sufficient sets of scaffolding. A crane is a bit more challenging. One approach to this would be to design the landed transport robotic rover (or the smaller mining robotic rovers) to be capable to carry out crane lifting tasks with some add-ons, such as outrigger components for stabilization, counter-weights for stabilization and an extra-large mechanical crane arm. All of these add-ons could be made-on-Mars out of steel by the steel seeds. The operation of such a crane could be done locally by one of the first settlers or semi-autonomously by the robots with occasional human guidance. The most interesting part in this would be the something that can perform the position-fixing tasks of regular construction crew members. Perhaps, an obvious candidate for this is a settler working outside in a space suit. However, there is a set of technologies, that will be described shortly, that will be much better than a settler in a space suit, that can be elegantly controlled by a settler. Indeed the role of the settlers operating this technology in construction can be very important and give the settlers (and us all) a much more inclusive, direct, hands-on sense of being needed in the story of settlement and, importantly, make for better settlement images and a better settlement story. For these last reasons, I personally prefer the third habitat building route.

People in space suits in the Martian atmosphere can do almost none of the actions a robot can. Since, these suits are pressurized and make people almost useless for many simple actions, for example, loading a reduction unit with enriched ore. Under any Mars settlement scenario, it will be much more efficient, and safer, for robots to do tasks that need to be done in the Martian atmosphere. So that, likely, Martian settlers will rarely walk around in the Martian atmosphere; rather settlers will spend almost all their time inside pressurized buildings, or very, large pressurized glass-house-like structures or inside pressurized vehicle cabins.

However, people will be able to go outside in a real but unfamiliar sense. Full experiences of walking around, discovering things and doing work on Mars will be available to the settlers on Mars using technologies, that are rapidly developing right now, for advanced prosthetic limbs, humanoid robots and virtual reality interfaces. Even 2016 versions of these technologies can provide the ability for people to have rich sensory and motor experiences of walking around, and directly interacting with most Martian outdoor environments, including those, such as construction sites, at the first settlement location. The current state-of-the-art in prosthetic limbs (Johannes *et al.* 2011, JHU APL 2015) allows people to send messages through their body's own motor neurons (which provide the messages to control muscle and limb movement) to tell robotic limbs to move as their own limbs move (or for amputee's motor neurons to instruct robotic limbs to move in the way they want their lost phantom limbs to move). Progress is also ongoing in providing these robotic limbs with touch sensors that can send electrical signals to the body's sensory neurons, so that robotic limbs will provide some level of touch/feel messages that can be felt by the settlers' skin rather like a natural touch. Of course, such prosthetic robotic limbs can be incorporated into humanoid robots. While, the current state-of-the-art in humanoid robots allows them to walk and do many other physical tasks largely autonomously. These humanoid robots, of course, have camera systems and sophisticated image interpretation systems. The real-time images the camera systems take can be provided to both the humanoids on-board image interpretation systems but also to monitors, or other virtual reality interfaces, for human settlers to look at and react to, in real-time, while these settlers are safely inside comfortable rooms filled with breathable air. The settlers inside will be able to use their own motor neuron signals to command the humanoid robots to do things outside that the settlers want, such as manipulate a welding torch or turn its neck to look around and take in a view. As such, the movements of the humanoid robots will be controllable both by signals from human motor neurons and also by internal, on-board limb movement control systems of the robots. The people's body movement signals will take precedence over the robots' on-board systems but the on-board systems will be able to control and complete tasks when the people are not actively involved.

Of course, these Martian outdoor experiences will be recorded digitally and they will be made available for people on Earth to experience. For some time Earth people will be willing to pay for such an experience, so this could be one of many ways to generate money to fund the settlement of Mars. Although generating a bit of immediate cash is generally quite important, the use of the technologies just described in a way that allows people to (a) have a rich experience of being in an environment which is, in some way, harsh or dangerous for humans to be in and (b) to directly interact with and manipulate elements of such harsh environments can have, probably will have, rather broad, long-term utilitarian/practical influences and also ubiquitous cultural influences. On the utilitarian/practical side such technologies allow humans to be in environments like the surface of Mars, the ruins of the Fukushima nuclear reactor site, and many others which humans normally cannot safely be in. As a ubiquitous cultural influence such technologies (and some others that are or soon will be deployed) will change our views of, and expectations of, our own bodies. These changes will ripple across our own futures and those of our descendants; they will be seen as good by some, bad by others and will probably turn out to be a bit of both; although, I belief the balance will be for the good. There have been many reasons given by others to go to or not go to Mars. I will finish here with one more reason. It may not be the best or worst reason but I have not heard anybody else give this reason. Going to, and settling, Mars will provide a collective story that will in some sense organize huge currents and themes of change that are going on, and will go, in the twenty-first century (mostly on Earth), that will be difficult for many (probably most) of us to cope with; the story of settling Mars will help us cope with the rapid change by forging new twenty-first century stories with mythic elements that will put everything into some kind of perspective that will help us stay grounded and able to participate in the change.

Appendix: Oxidation of Fine Steel Powder in the Martian Atmosphere

In this appendix an analysis is carried out to see whether the oxidation of a mixture of iron, titanium, chromium and manganese, in fine powder form, in the Martian atmosphere is low or slow enough that such a powder mixture can be practically used in a 3D metal printer on Mars wherein the printer's build chamber starts filled with the Martian atmosphere.

An analysis is made to decide how much oxidation could occur under a worst case assumption in which all of the possible oxidizing agents in a sample of Martian atmosphere filling a 3D metal printer's build chamber actually oxidize metal powder in the build chamber. This line of analysis yields a definite answer to the question of most concern regarding the oxidation of steel metal powders inside 3D metal printers, which start with their build chambers filled with a volume of normal Martian atmospheric gas. It turns out that even in the worst case, such that all the potential oxidizing molecules do oxidize metal atoms, there is so little oxidizing agent that the amount of metal oxidized in the worst case is so small that this oxidation will not greatly affect the end finished metal products of 3D metal printing. Further, in the worst case, in so far as deleterious metal oxidation might occur and this is considered a problem worth solving, this small amount of oxidation could be excluded from effecting the finished steel object by use of a sacrifice method in which a small amount of the steel metal powder is deliberately oxidized to convert the main oxidizing agent, carbon dioxide, into a reducing agent, carbon monoxide, prior to starting main build sequences inside the printer's build chamber.

The percent mole fraction composition of the Martian atmosphere (as measured by the robot rover *Curiosity* close to the Martian Equator) is given in Table A1.

Gas Name	Gas Formula	% mole fraction
carbon dioxide	CO_2	95.97
argon	Ar	1.93
molecular nitrogen	N_2	1.89
molecular oxygen	O_2	0.146
carbon monoxide	CO	0.0557
Total		**99.9917**
water vapor	H_2O	0.0010-0.0060

Table A1. Molar Composition of the Atmosphere of Mars Measured Measure by Robot Rover *Curiosity* in Gale Crater. The data for the variable water vapor content is taken from NASA MSL (2016), while the data for the other components of the Martian atmosphere is taken from NASA MSL (2013). The unaccounted for remainder is mainly methane (CH4) and nitrogen oxide (NO) (NASA MSL 2013).

There are three components of the Martian atmosphere that could act as oxidizing agents, carbon dioxide, molecular oxygen and water vapor. Carbon dioxide dominates the molar composition of the atmosphere. Each mole of carbon dioxide can potentially donate 1 mole of oxygen atoms to oxidize metal atoms while the carbon dioxide is converted to the reducing agent carbon monoxide. For this worst-case analysis, an even-worse-case is assumed, that is that the entire 100% composition of the Mars atmosphere is carbon dioxide. This even-worse case assumption bumps up the number of moles of oxygen atoms that can potentially be used for oxidation from 0.96–0.97 mole of oxygen atoms per mole of atmospheric gas to 1.00 mole of oxygen atoms per mole of atmospheric gas.

Thermodynamic analyses using the enthalpies of formation, across a range of significant temperatures (200 K to 400 K), of iron, titanium, chromium and manganese, the various oxides of these metals, as well as those of carbon dioxide and carbon monoxide were done, where the standard enthalpies of formation and temperature dependent heat capacity data were taken from the Chemistry WebBook of the National Institute of Standards and Technology, (NIST). The purpose of these analyses was simply to find the most thermodynamically favored oxidation reaction among the possible oxidations of the four transition metals. The oxidation of titanium to titanium (II) oxide,

A1 $$Ti + CO2 \rightarrow TiO + CO,$$

is the most thermodynamically favored oxidation among all those relevant to the analysis. It is quite strongly exothermic in the 200 K to 400 K temperature range. For this worst case analysis it is assumed there is no activation energy barrier to stop or slow this titanium II oxide oxidation and that all the available carbon dioxide in the 3D printer build chamber is used to oxidize titanium to titanium II oxide until either the available carbon dioxide or titanium is exhausted. In an actual experiment alternate oxidation reactions will occur (particularly titanium to titanium IV oxide, chromium to chromium II,III oxide and manganese to manganese II oxide), however, the assumption that all the oxidation produces titanium II oxide is the worst case assumption as it concentrates the deleterious oxidations on one metal.

In this analysis a simple model is assumed for the construction of the 3D metal printer, particularly its build chamber. It is assumed that the build chamber can be sealed off so that gas cannot flow at all (or negligibly slowly) from the inside of the build chamber to the outside or vice-versa, and that during 3D metal printing the build chamber is so sealed. This assumed sealing is easy to engineer and, as such, this sealing assumption poses no problems to practically achievable results. The enclosed volume above a 3D printer's build bed is constrained by the build chamber's walls and these walls need to be sized and shaped to allow laser beams to point from the lasers in the top of the build chamber to hit all (or almost all) of the build bed's top surface. These laser positioning and targeting necessities, as well are required border areas needed for the powder distribution head to move, force the volume in the bed chamber above the bed surface to be around 0.6 m^3, or more, per square meter area of the top of the build bed. In this worst case analysis it is assumed that the build chamber volume is the build bed, area A_{bed}, times 1.0 m. In this worst case, this build chamber contains pure carbon dioxide at the beginning of a build and this volume of carbon dioxide (A_{bed} x 1.0 m) is available to oxidize titanium in the build bed.

The maximal number of moles, n_{CO2}, of carbon dioxide in this volume can be computed using the ideal gas law (*i.e.* n = pV/RT) along with a maximal, expected pressure, p, and a minimal expected temperature, T. NASA's Mars Science Laboratory recently released climate data recorded by rover robot *Curiosity* covering a two Martian year period (3.76 Earth years) (NASA MSL 2016). Using this climate data a good maximal value for the pressure, p, is 1000 Pa, while a good minimal value for the temperature, T, is 200 K. Using these maximal and minimal values and $V = A_{bed}$ x 1.0 m in the ideal gas law yields n_{CO2} = (0.60 mol) x (A_{bed}/1.0 m^2).

Now, the number of moles of titanium, n_{Ti}, in a build bed of area, A_{bed}, and depth, d, in a steel powder mixture of typical composition is computed. Useful data for this computation is in Table A2. If the solid fraction in the powder bed is 0.5 (a typical value for such beds) then the solid volume of the powder bed is $0.5A_{bed}d$. Multiplying that volume by the solid volume fraction for titanium, 0.0881, in a typical steel powder gives the solid volume of titanium in the bed, multiplying that titanium volume with titanium's density, 4510 kg/m3, gives the mass of titanium in the bed, and dividing this titanium mass by its molar mass, 0.04787 kg/mol, gives the number of moles of titanium in the bed,
n_{Ti} = ((4510/0.04787)mol)(0.0881)(0.5)($A_{bed}d$/1.0 m^3).

So, with these mole number results, the ratio of the number of moles (n_{Ti}/n_{CO2}) is given by

(A2) $$(n_{Ti} / n_{CO2}) \approx 7000(d/1.0 \text{ m}).$$

One thing that Equation (A2) tells us is that if the bed depth, *d*, is more than 1 cm, then there is much more titanium in the bed than carbon dioxide which could oxidize some of that titanium (or some of the other metals) in the worst case that titanium is rapidly oxidized at lowish temperatures. In other words, for reasonable sized print depths, in a worst case rapid oxidation scenario, oxidation of the steel powder is at most a small, nuisance problem. The oxidation rates of these transition metal powders in

Metal	Mass Fraction	Density (kg/m^3)	Molar Mass (kg/mol)	Solid Volume Fraction
iron	0.9046	7870	0.05585	0.8671
titanium	0.0527	4510	0.04787	0.0881
chromium	0.0231	7190	0.05200	0.0242
manganese	0.0196	7210	0.05493	0.0205

Table A2. Compositional and Mass Data for Metals in a Typical Martian Steel Powder. The mass fraction column numbers are computed from the mass percent data for the four transition metals oxides in Table 1 of the main text (taken from Blake et al. 2013), after adjusting for their oxygen content and after normalizing to just include the four transition metals. The data in the Density and the Molar Mass columns are taken from the Wikipedia entries for each metal. The Solid Volume Fraction values are computed from the values in the Mass Fraction and Density columns.

a low pressure gas, that is mostly carbon dioxide, are not known, but from the point of view of deciding whether or not oxidation of metal powders is a problem, either the reaction rates are so slow that oxidation is not a problem, or the titanium oxidation reaction rates are fast relative to printing times, in which case oxidation is either a minor problem and ignored or it is a minor problem and it is dealt with using the sacrifice method mentioned above. This sacrifice method would work as follows, for the case of rapid oxidation, all the nuisance carbon dioxide can be turned into the un-problematic, reducing agent carbon monoxide by sacrificing an initial thickness of the steel powder at the bottom of the build bed, i.e. by letting, perhaps encouraging, a sacrificial thickness layer to be oxidized so that the main (non-sacrificial) parts of a build are done in a gas dominated by carbon monoxide and hence free from oxidation. Due to the stoichiometry in Equation (A1), the sacrificial layer thickness, d_{sac}, would be the thickness value, *d*, in Equation (A2), such that the left-hand-side of Equation (A2) is 1, *i.e.* the sacrificed number of moles of titanium equals the initial number of moles of carbon dioxide in the build chamber. So from Equation (A2),

(A3) $$d_{sac} \approx 1.0 \text{ m}/7000 \approx 140 \text{ microns.}$$

The take home message is that there is *some* good way to deal with steel powder oxidation while starting a 3D metal print job with a normal Martian atmosphere filling the build chamber and without having to resort to heavy-duty, nitrogen generator methods to change the atmosphere inside the build chamber.

3D metal printing machines on Earth *continuously flow* a nitrogen/argon mixture through the build chamber. This continuous flow is unnecessary for preventing oxidation; however, in such machines, the outflowing nitrogen/argon gas extracts heat from the build chamber. There are very different flow rates between the machines of different 3D metal printer manufacturers (*i.e.* multiple factors of 3 to 5). Such different flow rates are due to a wide range of build bed temperatures that are considered acceptable by the different manufacturers. This indicates that there is an, as yet, poorly defined engineering issue, *i.e.* bed temperature control, for 3D metal printers on Mars which needs to be investigated. Two points relevant to this cooling issue are that (i) the ambient temperatures outside on Mars are typically 30 K to

120 K lower than interior temperatures on Earth, (ii) the Martian atmosphere is very thin.

References

AISI (2005). Technical Feasibility Study of Steelmaking by Molten Oxide Electrolysis. American Iron and Steel Institute, Factsheet 9956. Available online at http://www.steel.org/~/media/Files/AISI/Public%20Policy/9956factsheet.ashx .

Aldrin, E. E. (1985). Cyclic Trajectory Concepts. SAIC presentation to the Interplanetary Rapid Transit Study Meeting, Jet Propulsion Laboratory.

Aldrin, E.E. (2008). Mars pioneers should stay there permanently, http://phys.org/news/2008-10-mars-permanently-aldrin.html

Aldrin, E.E. (2013). *Mission to Mars My Vision for Space Exploration*. Washington D.C.: National Geographic Society.

Baker, D. and Zubrin, R. (1990). Mars Direct: Combining Near-Term Technologies to Achieve a Two-Launch Manned Mars Mission. *Journal of the British Interplanetary Society*, Vol. 43, pp.519.

Blake et al. (2013). Curiosity at Gale Crater, Mars: Characterization and Analysis of the Rocknest Sand Shadow. Science, 341; pp 1239505-1 – 1239505-7. DOI: 10.1126/science.1239505

Cilliers, J. (2011). Interviewed in video "Naked Engineering- Separating Minerals." https://www.youtube.com/watch?v=twmWdVhIkiY

Curreri, P.A., Ethridge, E.C., Hudson, S.B., Miller, T.Y., Grugel, R.N., Sen, S. and Sadoway, D.R. (2006). Process demonstration for lunar in situ resource utilization— Molten oxide electrolysis, NASA Report TM-2006-214600. MSFC Independent Research and Development Project 5-81. Huntsville, Alabama, USA: NASA Marshall Space Flight Center.

Epstein, E. (1965). "Mineral metabolism." In J.Bonner and J.E. Varner, (eds.), Plant Biochemistry, pp. 438-466, London: Academic Press.

Feldman, W.C., Boynton, W.V., Tokar, R.L., Prettyman, T.H., Gasnault, O., Squyres, S.W., Elphic, R.C., Lawrence, D.J., Lawson, S.L., Maurice, S., McKinney, G.W., Moore, K.R., Reedy, R.C. (2002). Global Distribution of Neutrons from Mars: Results from Mars Odyssey. *Science*, Vol. 297, Issue 5578, pp. 75-78. doi: 10.1126/science.1073541

Gellert, R. et al. (2006). Alpha Particel X-ray Spectrometer (APXS): Results from Gusev Crater and calibration report. *J. Geophys. Res.* 111, E02S05. DOI: 10.1029/2005JEOO2555.

Gellert, R. et al. (2013). Initial MSL APXS activities and observations at Gale Crater, Mars, *45th Lunar and Planetary Science Conference*, March 2013, Published on CD by the Lunar and Planetary Institute, Houston, Texas, Abstract 1432.

Grover M.R., Sklyanskiy E., Steltzner A.D., and Sherwood B. (2012). Red Dragon-MSL Hybrid Landing Architecture for 2018. JPL, Caltech, Concepts and Approaches for Mars Exploration, 2012.

Hargraves, R.B., Collinson, D.W., Arvidson, R.E. and Cates, P.M. (1979). Viking Magnetic Properties Experiment: Extended mission results. *Journal of Geophysical Research*, doi:10.1029/JB084iB14p08379 .

Head, J. W., et al. (2006). Extensive valley glacier deposits in the northern mid-latitudes of Mars: Evidence for Late Amazonian obliquity-driven climate change. *Earth and Planetary Science Letters* 241.3 , pp. 663–671.

HiRise/MRO. Image and of sand dune. http://www.uahirise.org/ESP_042223_1890 .

Johannes, M.S., Bigelow, J.D., Burck, J.M., Harshbarger, S.D., Kozlowski, M.V. and Van Doren, T. (2011). An Overview of the Developmental Process for the Modular Prosthetic Limb. *Johns Hopkins APL Technical Digest*, Vol. 30(3), pp. 207−216.

JHU APL (2015). The Robot-Arm Prosthetic Controlled by Thought. Video available at https://www.youtube.com/watch?v=sk1NkWl_W2Y

Karlsson, N.B., Schmidt, L.S. and Hvidberg, C.S. (2015). Volume of Martian midlatitude glaciers from radar observations and ice flow modeling. *Geophysical Research Letters*, Vol. 42(8), pp. 2627–2633. doi: 10.1002/2015GL063219View/save citation

Kieffer, H.H. (1992). Mars. University of Arizona Press. ISBN 978-0-8165-1257-7.

Madsen, M.B. et al. (2009). Overview of the magnetic properties experiments on the Mars Exploration Rovers. *Journal of Geophysical Research*, DOI: 10.1029/2008JE003098 .

Martín-Torres, F.J. et al. (2015). Transient liquid water and water activity at Gale crater on Mars. *Nature Geoscience*, Vol. 8, pp. 357–361. doi:10.1038/ngeo2412

Michalski, J.R., Cuadros, J., Niles, P.B., Parnell, J., Rogers, A.D. and Wright, S.P. (2013). Groundwater activity on Mars and implications for a deep biosphere. *Nature Geoscience*, Vol. 6, pp. 133–138. doi:10.1038/ngeo1706 .

Moss, S. (2006). Steelmaking on Mars. Published, with permission, by the Mars Society. It was downloadable from http://www.marspapers.org/papers/Moss_2006_2.pdf .

Musk, E. (2012). SpaceX and the future of space exploration. Talk to the Royal Aeronautical Society, 16 November 2012, London. Video at https://www.youtube.com/watch?v=wB3R5Xk2gTY .

Musk, E. (2016). Interview at Code Conference 2016, by Recode, California. Video at https://www.youtube.com/watch?v=wsixsRI-Sz4 .

Naderi F., Price H. and Baker J. (2015). Human Journey to Mars Thoughts on an Executable Program. Talk at Humans to Mars 2015 Conference. Video of talk at https://www.youtube.com/watch?v=nsy-UP68fEwU , Slides of talk at http://www.nasa.gov/sites/default/files/files/Naderi_JPL_Study_of_Humans_to_Mars_NAC_Final_TAGGED.pdf

NASA (1989). Report of the 90-Day Study on Human Exploration of the Moon and Mars. NASA Report, NASA-JSC Technical Library Call No: TL 789.8 US R463 1989 C3, Washington, DC

NASA (2008). Multi-Mission Radioisotope Thermoelectric Generator.
http://solarsystem.nasa.gov/docs/MMRTG_Jan2008.pdf

NASA MSL (Mahaffy, P.R. et al.) (2013). Abundance and Isotopic Composition of Gases in the Martian Atmosphere from the Curiosity Rover. *Science*, Vol. 341, Issue 6143, pp. 263–266. doi: 10.1126/science.1237966

NASA MSL (2016). Second Cycle of Martian Seasons Completing for Curiosity Rover.
Informational webpage at http://www.jpl.nasa.gov/news/news.php?feature=6512.

National Steel Pellet Co. Iron Ore Processing for the Blast Furnace. Explanatory brochure for the American Iron and Steel Institute:
http://www.steel.org/~/media/Files/AISI/Making%20Steel/Article%20Files/ironore.PDF.

NIST. NIST Chemistry WebBook. Found at http://webbook.nist.gov/chemistry/

Shellabear M. and Nyrhilä, O. (2004). 'DMLS-Development History and State of the Art', in M. Geiger & A. Otto (eds), Laser Assisted Netshape Engineering 4, Proceedings of the 4th LANE 2004, pp. 393-404, ISBN 3-87525-202-0.

SLM. Data sheet for SLM 500 3D metal printer. From http://slm-solutions.us/slm-500hl/

Spacex (2016). Online brochure for Falcon Heavy at http://www.spacex.com/falcon-heavy

U.S. Environmental Protection Agency (2001). National Emissions Standard for Hazardous Air Pollutants (NESHAPs) for Taconite Iron Ore Processing Plants. Background Information Report for Proposed Standards. Washington, DC: U.S. Environmental Protection Agency.

Vai, A.T., Yurko, J.A., Wang, D.H. and Sadoway, D.R. (2010). Molten oxide electrolysis for lunar oxygen generation using in situ resources. In BQ Li et al. (eds.), *Jim Evans Honorary Symposium*, The Minerals, Metals & Materials Society (TMS), pp301-308. Hoboken, New Jersey: John Wiley & Sons.

Von Braun, W. (1948). *Das Marsprojekt*. Frankfurt, Germany: Umschau Verlag.

Von Braun, W. (1953). *The Mars Project*. Translation of *Das Marsprojekt* by H.J. White. Urbana-Champaign, Illinois: University of Illinois Press.

Wagner D., Devisme O., Patisson F. and Ablitzer D. (2006). A laboratory Study of the Reduction of Iron Oxide by Hydrogen. Kongoli F. and Reddy R.G. (eds.) *Sohn International Symposium*, TMS, vol. 2, pp. 111-120.

Wall, M. (2013). Incredible Technology: How to Live on Mars. Space.com at
http://www.space.com/22342-how-to-live-on-mars-colony-technology.html

Wikipedia 1. Selective laser melting. https://en.wikipedia.org/wiki/Selective_laser_melting

Zubrin, R. (1996). *The Case for Mars*. N.Y : Touchstone Books.