Building a self-sufficient colony on Mars using current science and technology: an evaluation of the options

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Abstract

This report investigates and evaluates the fundamental feasibility of maintaining a self-sufficient human colony on Mars. There are several challenges in doing this, but the ones this report examines include general resource acquisition approach (as a prerequisite), producing oxygen, producing water, and producing food. A wide range of key literature is used and referenced throughout to form comprehensive judgements about the viability of producing each resource.

There is currently a divide in the field of space exploration, between those who think humans can live self-sufficiently on Mars in the near future, and those who do not. While humans can (and likely will) 'go' to Mars very soon, it is unclear whether such a colony can live self-sufficiently there (that is, without help from Earth). Thus, this report aims to make an answer to the question on a fundamental level, demonstrating whether the basic requirements of humans can be met on Mars.

Focusing primarily on the practicalities, an evidence-based conclusion is drawn as to whether such a challenge can be achieved using science and technology that humans *already* possess. This contemporary emphasis makes it clear that humans *can* accomplish self-sufficiency on Mars in the near future. However, due the margin of safety being so small, there is no one currently willing to go forward with this particular Mars settlement plan. Thus, although it may be possible to achieve in the near future, the 'self-sufficient' milestone will not be reached until risk can be further minimised, and newer technologies have been developed.

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1 Introduction

Context

52 years ago, on July 24th, 1969, the Apollo 11 spaceflight delivered the first humans to the moon: Neil Armstrong and Buzz Aldrin. This was the conclusion of a 'space race' between the United States and the Soviet Union, which began just 12 years prior with the Soviets' launch of Sputnik 1. In only one decade, humans went from a species that had been bound to the Earth since it first evolved 7 million years ago, to a space faring civilisation that put a man on the moon. To this day, it is the greatest feat in the history of not just humans, but any species ever.

However, this rapid progress in space exploration swiftly plateaued. If it hadn't, humans would likely have landed on Mars only a decade or two later (Zubrin, 1996). And yet, in 2021, Mars is still uncolonised. This is primarily a result of a general attitude that has become known as 'the precautionary principle' (Foster, Vecchia and Repacholi, 2000), where the ambition of authorities and politicians has decayed in favour of making 'safe' decisions that pose a low risk of compromising their reputation if failure were to occur. This report tests that attitude, with a focus on the feasibility of Mars colonisation.

Why leave Earth?

The colonisation of Mars is unlike the race to the moon which, as described by Alex Ellery, was largely a political contest (Appendix C). Elon Musk describes two possible paths for humanity's future. The first being that humans can 'stay on Earth forever' and be wiped out in the next 'extinction event'. Or alternatively, 'become a multiplanetary species' (Musk, 2017).

In Earth's 4-billion-year life, extinction events (such as the Cretaceous-Paleogene which wiped out the dinosaurs) are not that irregular, occurring every 26 to 30 million years (Raup and Sepkoski, 1984). Furthermore, it is predicted that if the current rate of carbon emission continues, the Earth will reach a mass extinction threshold by 2100 (Nace, 2017). If this occurred, all that humanity has achieved would be wiped out forever. Much like an insurance policy, building a self-sufficient Mars colony ensures the unconditional continuation and success of humanity. That is the rationale for writing a report that evaluates the feasibility of such a task.

Why Mars?

As seen in Figure 1, Earth and Mars are very similar. An Earth 'day' and a Martian 'sol' only differ by about 41 minutes. The tilts of their axes are almost identical, meaning they both experience 4 seasons a year (only on Mars they are twice as long). Although the temperature seems vastly colder on Mars, it is important to note this is an 'average'. And in fact, some locations on Mars (such as the Hellas Basin on the equator) can maintain around 20 degrees C (Sherwood, 2017). Furthermore, any potentially poor climatic conditions, will ideally be mitigated by various technologies. For these reasons, within the solar system, Mars is by far the best option. That's why it's believed that 'if we can't get to Mars, we'll never leave Earth' (Zubrin, 1996).

	Earth	**Mars**
Average Distance from Sun / miles	93 million	142 million
Average Speed in Orbiting Sun / miles per second	18.5	14.5
Diameter / miles	7,926	4,220
Tilt of Axis / degrees	23.5	25
Length of Year / Earth days	365.25	687
Length of Day / hours	23.93	24.62
Gravity relative to Earth	1	0.375
Average temperature / degrees C	14	-63
Atmospheric gases	nitrogen, oxygen, argon, others	mostly carbon dioxide, some water vapor
Moons	1	2

Figure 1: The properties of Earth and Mars compared (nasa.gov)

Aim and scope of this report

This report evaluates the possible options for the main aspects of allowing self-sufficient human habitation on a Mars colony. The general resource acquisition approach (GRAA) is explored as a prerequisite, followed by the 3 key resources: oxygen, water, and food. Each presents its own challenges and requires the most viable process to be utilised if humans are to *effectively* build a self-sufficient colony. One must note that these are not the *only* factors that must be considered when living on Mars, for example, there are the matters of shelter, clothing and power. However, oxygen, water, and food are unique in that they are vital for humans to survive on *any* planet. They are the components which *allow* human life, whereas resources such as clothing and power are 'extensions' which *support* human life. Therefore, one can say they are the most important considerations, and thus, allows this report to assess the fundamental feasibility of Mars colonisation.

In addition, I emphasise the use of *current* science and technology. As it loosely associates a timeframe, whereby it is possible to judge whether self-sufficiency can be achieved in the near- or long-term future. If possible in the near-term, it would reinforce the case for investing more resources into Mars colonisation as soon as possible, ensuring humanity's continued survival. If not, humans will still be dependent on Earth for a substantial amount of time, confirming the importance of protecting this planet against challenges such as global warming. And so, to summarise, the question this report explores is: can humans build an effective self-sufficient settlement on Mars using currently available science and technology?

2 General resource acquisition approach (GRAA)

As a prerequisite to the exploration of the specific methods of gathering resources, it is important to understand the reasoning for the type of approach this report discusses. Counterintuitively, there would ideally not be a situation where the advantage of a self-sufficient colony is useful. In other words, there hopefully won't be a time where Earth is completely cut off from Mars. However, the purpose of self-sufficiency is so that in such a scenario, a Martian settlement would not be destroyed as an indirect result of the Earth's downfall. Thus, in this context, self-sufficiency means having a method of gathering resources that is entirely exclusive of Earth. On Mars, there are two approaches to this: asteroid mining and in-situ resource utilisation (ISRU).

Option 1: Asteroid mining

Asteroid mining is where materials are harvested from specific asteroids (mainly from the Asteroid belt and Kuiper belt), in the attempt to provide a clean and efficient method of acquiring resources. Even small asteroids can contain trillions of dollars of precious metals like platinum (Kurzgesagt – In a Nutshell, 2020), making them an incredibly attractive option. Thomas Clayson explained how if asteroid mining was feasible, it would be the clear option for acquiring materials due to the huge cost-return (Appendix C). Furthermore, it has the advantage of causing no direct damage to the planet one is using the materials on. Given the damage humans have done to Earth whilst gathering resources, asteroid mining provides a method of not making the same mistakes on Mars.

The problem with this method, however, is that it is not currently feasible, and likely won't be for decades due to *current* science and technology not being sufficient for such a task. Some experts claim it could be up to 50 years before the industry begins to become prevalent (Nowakowski, 2017). And so, it will not be a viable means of gathering materials for a self-sufficient Mars colony in the *short-term*. However, in the *long-term*, it may be the best option available. Interestingly, the same experts describe 3D printing (Appendix A) as a currently viable method of in-situ construction, which is in agreement with Ellery (Appendix C).

Option 2: In-situ resource utilisation

ISRU is the concept of gathering resources from the same place that one intends to use them. In this context, that means using resources already on Mars. In agreement, both Alex Ellery (Appendix C) and Robert Zubrin (Zubrin, 1996) describe how the key to self-sufficiency is being able to 'live off the land'.

Regardless of the specific chemical processes or technologies being used for ISRU, the physical abundances of the resources are the governing factor of its success. In this regard, humans are extremely fortunate on Mars. In a recent technical information paper, NASA have documented how there is a large abundance of useful resources already present on Mars (Moses and Bushnell, 2016). They used reliable data from numerous rovers and orbiters, such as the MGS and MSL. Thus, given a way to harvest them, humans *can* live self-sufficiently.

Figure 2: The 'heat shield rock' (Chappelow and Sharpton, 2006)

Found by the 'Opportunity' rover, the Martian 'heat shield rock' (Figure 2) has a mass of 40 kg and is composed of 93% iron. The fact that it is so rich in iron and was the first meteorite (of many) to be found on Mars makes it symbolic of the sheer abundance of resources present on the Martian surface as a result of its multi-billion-year history of meteorite collisions.

In addition to the carbon in the atmosphere, which can be used to produce plastic, the paper highlights examples of abundant metals including iron, titanium, nickel, aluminium, sulphur, and chlorine. In addition, clay-like materials are described as 'ubiquitous' in the regolith, allowing the production of ceramics. As a result of the Viking missions (Williams, 2006), a vast amount of silicon dioxide has also been detected, the basic constituent of glass. Therefore, there is no question that Mars is rich in resources making it a 'goldmine' for ISRU; thus reinforcing Zubrin's claim that Mars is humanity's best chance of extra-terrestrial expansion.

3 Oxygen

Humans use oxygen for respiration, making it essential to their existence. Oxygen is also a key component of rocket fuel. Thus, for Earth return missions to be possible, oxygen must be produced on Mars. On Earth, oxygen makes up 21% of the atmosphere (nasa.gov). On Mars, however, oxygen only makes up 0.13% of the atmosphere (Chang, 2019), and not only that, but the atmosphere is less than 1% as dense as Earth's. So, it is simply not possible for a colony to be built on Mars without an effective and reliable in situ oxygen production system in place. The two most promising candidates are the MOXIE and the brine electrolyser.

Option 1: MOXIE

The MOXIE (NASA Jet Propulsion Laboratory, 2019) is a first generation oxygen generator ('oxygenator') which has been developed in order to test whether technology can provide the required oxygen for a human Mars colony. Since 2014, the MOXIE has been the most well-known and likely candidate for in-situ oxygen production. It uses the fact that Mars' atmosphere, although lacking in *pure* oxygen, consists of 96% carbon dioxide (nasa.gov). Each CO_2 molecule consists of one carbon atom and two oxygen atoms, resulting in a net oxygen percentage of 72% per molecule. Thus, the MOXIE pulls in the Martian air (of which there is an 'unlimited' supply) and uses solid oxide electrolysis (like a 'reverse fuel cell') (Hauch et al., 2006) to electrochemically split the CO_2 molecules and liberate the oxygen.

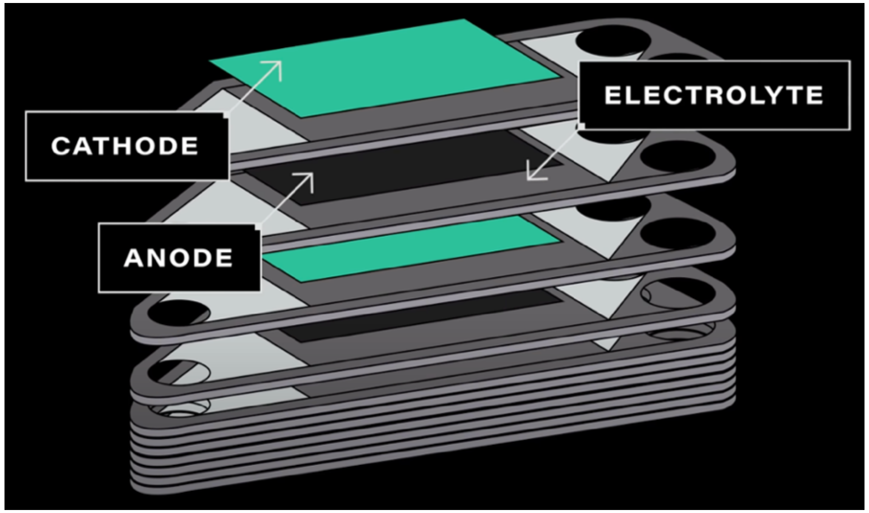

Figure 3: A layered 'reverse fuel cell' within a MOXIE (Seeker, 2020)

The thin ceramic cells (Figure 3) have a chemical property that allows them to conduct electricity using oxygen as the charge carrier. The 'hurdle' of this process is that the cells must be heated to roughly 800 degrees Celsius, thus requiring a lot of energy. The biproducts (carbon monoxide (CO) and other inert gases) are exhausted, while the oxygen is analysed for purity before being vented for direct consumption.

The current 'standard' MOXIE is a highly compact system; it has dimensions of 23.9 x 23.9 x 30.9 centimetres, roughly the size of a car battery. Each unit can produce up to 10 grams of oxygen per hour, enough to support one human. In fact, one was built into the 2021 Mars 'Perseverance' Rover (National Geographic, 2021). It has successfully used the MOXIE to convert carbon dioxide into breathable oxygen, confirming the claims of models, simulations and tests run by experts since the MOXIE was first developed (Hinterman and Hoffman, 2020). Despite this, one must still consider the large power demand of this machine (Appendix B), for energy will not be as accessible on Mars as it is on Earth (at least to begin with).

Option 2: Brine electrolyser

A *very* recent study has demonstrated how hydrogen and oxygen can be produced efficiently from the Martian brine (salty water) via electrolysis (Gayen, Sankarasubramanian and Ramani, 2020). This is important because there are soluble salts in the Martian regolith known as perchlorates, which have been described as 'global' and 'ubiquitous' (Carrier and Kounaves, 2015). These salts are excellent at absorbing water, even in environments as dry as Mars. Therefore, perchlorate abundant sites are indicative of brine hotspots. Given this brine can be electrolysed/split into hydrogen and oxygen, such sites become a potentially vast source of oxygen.

Figure 4 shows liquid droplets of brine which formed on the struts of NASA's Phoenix lander. It was believed to be a solution of magnesium perchlorate, with the three images corresponding to days 8, 31 and 44 (respectively) after the lander touched down in 2008. The fact that a perchlorate abundant site such as this was found unintentionally demonstrates how much there could be across Mars. Although, there is some potential for this to be an anomaly; further research will have to be done to determine this.

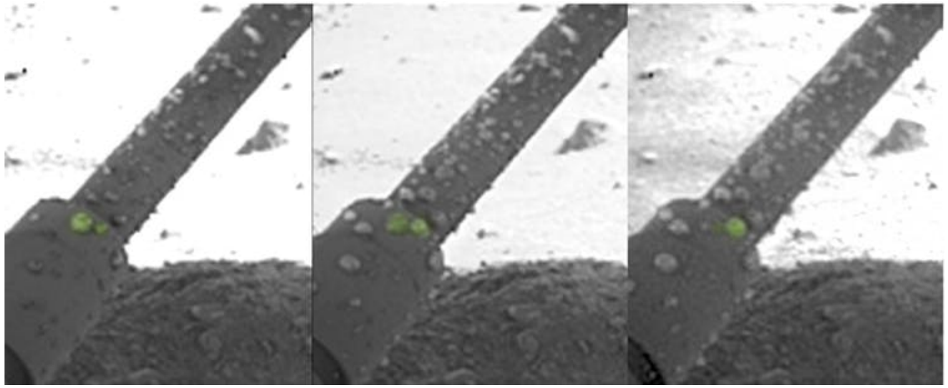

Figure 4: Liquid droplets on the legs of NASA's Phoenix lander (Gronstal, 2014)

As explained when evaluating the MOXIE, it requires vast amounts of energy to produce oxygen, making it a highly inefficient system.

Whereas the aforementioned study demonstrated how their brine electrolyser is *theoretically* 25 times as efficient as the MOXIE. That is, it can produce up to 25 times the amount of oxygen for the same input power. This increase in efficiency would be invaluable on a self-sufficient Mars colony, because every aspect of living (even minor ones not in this report) will require electricity (Appendix B). The extra energy saved by using this instead of the MOXIE could be distributed to these other processes, improving the feasibility of self-sufficiency.

Essentialism of integrity

Clearly, the brine electrolyser is more appealing in terms of raw performance, and to many, this makes it the obvious choice. However, the fact that the MOXIE has been popular for so long gives it the edge (at this stage). The MOXIE has been the most likely candidate for this length of time because it has been tested rigorously, and although its power composition is higher than ideal, there is the security of knowing that it works. On the other hand, the brine electrolyser is, as mentioned, a *very* new proposal, and thus has not had anywhere near the level of testing as the MOXIE. On a self-sufficient Mars colony, it is imperative that all machines and technologies have the highest level of integrity as possible, as they prevent colonists from succumbing to the inhospitable conditions of Mars. So, emphasising again that this report is focusing on *current* science and technology, the MOXIE should continue to be the choice for in-situ oxygen production (at least until the brine electrolyser has been tested and asserted an equally high level of integrity).

Extending the importance of integrity further: the problem with sending either a MOXIE (or brine electrolyser) with humans on their journey to the Red Planet, is that if such machines were to fail, they'd be helpless. Indeed, they may bring back-ups, but this attitude quickly becomes excessively expensive and loses integrity. In fact, Thomas Clayson explains how the largest problem with Mars missions is simply the challenge of getting there (Appendix C). Being roughly 60 million kilometres away at its closest, it takes about 6 months to get there (Hohmann, 1960). Consequently, if a certain system were to fail, 'people will almost definitely die' (Musk, 2017). In a similar fashion to the Mars Direct plan (Zubrin, 1996), a sensible decision would be to send large-scale MOXIEs *in advance* of human missions.

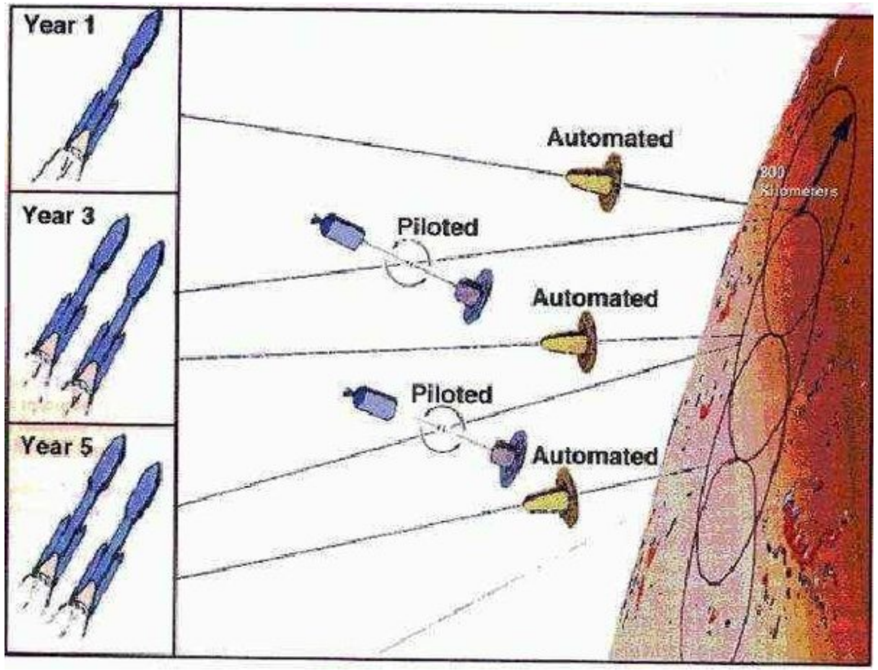

Figure 5: Mars Direct mission structure (Zubrin, 1996)

In the Mars Direct plan, Zubrin proposes that one human mission should be sent every two years, with a cargo mission over the same interval but beginning two years prior (Figure 5). This, however, was written before the MOXIE's time. And so, an ideal improvement would be to do the exact same but include a large MOXIE in each cargo mission (as opposed to just supplies like food), up until MOXIEs can be constructed directly on Mars. The advantage of this is that the MOXIE can produce oxygen over the period before humans arrive, meaning there is a definite supply on their arrival, thus minimising the potential catastrophe associated with relying on 'live' oxygen consumption. Such a supply can be designed to last them beyond the time it would take to construct a new MOXIE *on Mars* (in the case their one was to fail). So, given humans can build machines such as MOXIEs in-situ (Appendix A), oxygen self-sufficiency is achieved.

4 Water

A secure supply of water is also crucial to the existence of life on Mars. Humans require water, not just for consumption, but for hygiene too. The demand for water differs slightly from oxygen in that, humans can survive in the range of days without water, whereas they can only last up to a couple of minutes without oxygen. However, this 'window' is still far smaller than the amount of time required to send resupplies from Earth (~ 6 months in the perfect scenario). But regardless of that, it is not actually possible to send water to Mars, for it is 'simply too heavy' (Zubrin, 1996). Thus, it is imperative that water can be produced on Mars. In that regard, water may be comparable to oxygen in that they are both *already* present on Mars if one knows where to look, and how to harness it.

Considering both consumption and hygiene needs, the average person (on Earth) requires about ~ 0.7 kilograms of water per hour (Ralphs et al., 2015). However, on Mars, one must not just consider the average person, but rather, consider the needs of a *growing* colony, such as regolith processing, plant growth and habitat maintenance. This increases the amount of water required to ~ 1.2 kg/hr/person. Fortunately, it is unnecessary to produce anywhere near as much as that, for a water reclamation system can be implemented.

Humans already have the technology to 'almost perfectly recycle water' (National Geographic, 2016). This is backed by Crispian Poon (Appendix C) who strongly promotes this idea, describing it as 'essential'. In fact, the International Space Station has a reclamation rate of 90%, and some sources even predict future rates as high as 96% (Bobe et al., 2007). But given the emphasis on current science and technology, a rate of 90% will be assumed. Thus, a settlement must produce 0.12 kg/hr/person via water ISRU. There are two potential sources of Martian water: the atmosphere and the regolith.

Option 1: Atmospheric processing

With a composition of 0.03%, water is not particularly abundant in the Martian atmosphere (Muscatello and Santiago-Maldonado, 2012). If an atmospheric processing system were to be implemented, such as a modified MOXIE, it is possible to extract water from the atmosphere. However, given that the atmospheric gases are essentially distributed uniformly, combined with the fact that there is such little water present, the plausible rate of water extraction is very small, at 0.02 kg/hr/person (Muscatello and Santiago-Maldonado, 2012). Furthermore, the primary function of these machines is the extraction of oxygen. Therefore, the amount of water produced will be proportional to that of oxygen, meaning that as oxygen demand decreases due to the use of closed loop / reclamation systems, the amount of water produced will also decrease. Knowing this, one can say that 0.02 kg/hr/person is a theoretical *maximum*, and that the rate is *non-constant*. For those reasons, the atmosphere is a very poor source of water for a self-sufficient colony, so there is no real further discussion to be had. Thus, another option is required.

Option 2: Regolith harvesting

Another method for acquiring water is from harvesting the regolith. In other words, rather than looking up to the atmosphere, one must look down at the ground. Unlike the uniform distribution of the atmosphere, abundance of ground water varies hugely depending on the site location. At latitudes of ± 30°, most water is found in icy soils and permafrost, increasing 'dramatically' with decreasing distance to each pole (Figure 6). Whereas, closer to the equator, most is found in hydrated minerals, where the water composition is far less (Audouard et al., 2014).

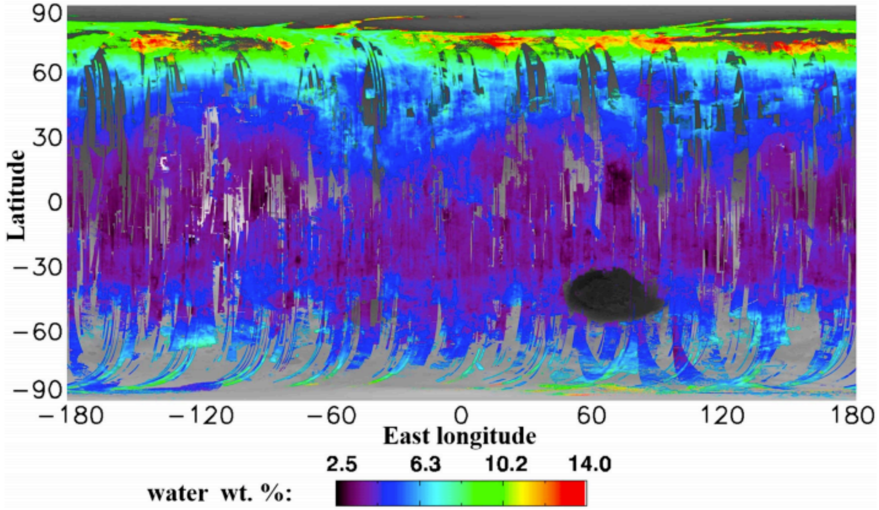

Figure 6: Global map of mean water %
(Audouard et al., 2014)

The preferable option would be to sublimate icy soils and permafrost, as their higher water composition means less energy is required to produce a given amount of water when compared to releasing water from hydrated minerals. However, (as experienced on Earth) moving towards the poles radically decreases average temperatures. At the equator, the temperatures can dip as low as -70° C at night. While at the poles, it can be as low as -140° (Sharp, 2017). To minimise the energy required for heating, it is important to ensure the colony is as close to the equator as possible. Consequently, regolith harvesting options will likely be limited to the equatorial hydrated minerals. Although this is still not ideal regarding energy, typically requiring an excess of 600° C (Audouard et al., 2014), it is still a far better option than atmospheric processing as there is no 'maximum rate'. If colonists *can* provide the energy (which is easier with equatorial temperatures), they can produce as much water as they require (and more for storage), making this the clear choice for water ISRU on a self-sufficient colony.

There are two feasible methods for extracting water from hydrated minerals. The first, is to use an auger-based system. It uses microwaves to penetrate the regolith and evaporate the water molecules to then be captured, with predicted rates as high as 0.3 kg/hr/person provided 1 kW of electricity (Santiago-Maldonado, 2012). The second is using a greenhouse system (Mungas et al., 2006), which traps the heat from the sun in a tent or dome. Then, using mirrors to intensify the radiation, the water can be released and captured.

The obvious advantage of a greenhouse system is that it uses the sun's energy, meaning it requires very little electricity. However, Martian solar power has limitations in that cannot not provide as much energy as an augur-based system (section 5 - option 2). Even then, as experienced on Earth, the intensity of the sun can vary massively throughout just one day, and this variation is much greater on Mars given that it is further from the sun than Earth and can undergo dust storms. Given the necessity of water for survival, a colony could not afford to have such an inconsistent supply. Thus, an auger-based system is preferable in most cases. However, there could be scenarios where the energy required to liberate water is less, meaning the sun's energy is sufficient for a greenhouse system to be implemented. As explained earlier, far less work must be done to release water from icy soils and permafrost. So, if a colony is fortunate enough to have an ice deposit within relative proximity (Figure 7), a greenhouse system could be used to provide additional water for minimal energy costs.

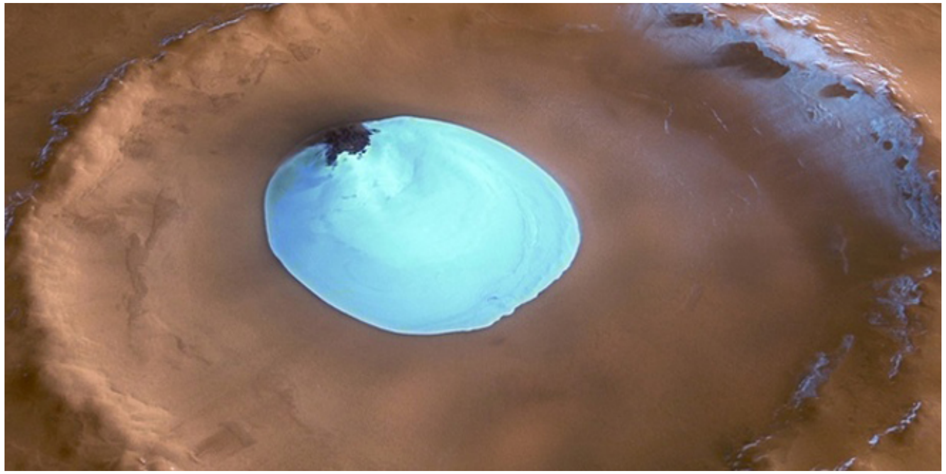

Figure 7: A Martian ice deposit (ESA)

5 Food

All the resources addressed so far are *already* present on Mars in one form or another. Food, on the other hand, is not naturally available. Thus, food is undoubtedly going to be 'the hardest thing to make locally' on a Martian colony (Cannon and Britt, 2019). Consequently, it is simply impossible to be *instantly* self-sufficient regarding food. Therefore, imports must be used to begin with (Appendix D). Although not instant, food self-sufficiency may still be achieved in the near-term through three sources: crops, insect farming, and cellular agriculture (Figure 8).

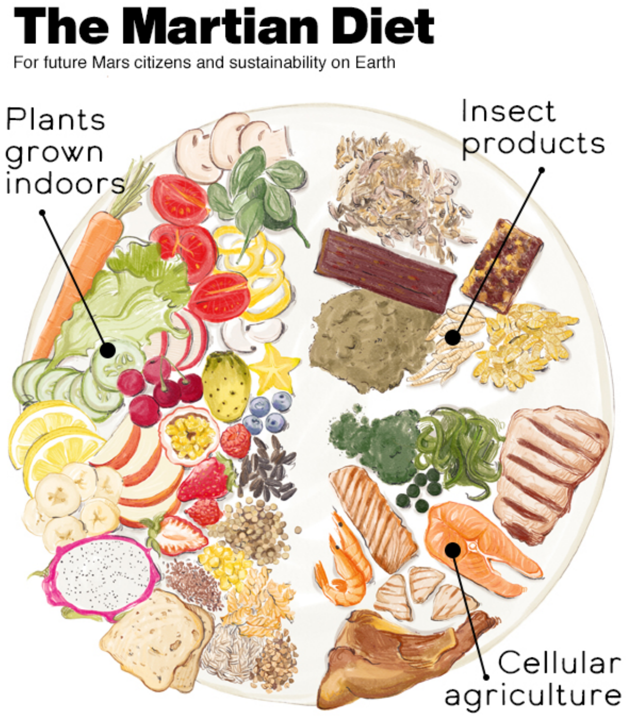

Figure 8: 'The Martian Diet' (eatlikeamartian.org)

Option 1: Insects

It is believed that 'bugs are the way to go, if people can get over the gross factor' (Cannon and Britt, 2019). The is largely down to the general efficiency of insect farming. Firstly, insects are extremely promising in that they have similar macronutrient contents per unit mass to crops and farm animals while having significantly higher yields per unit land (Alexander et al., 2017). This means they provide far higher calories for the same amounts of water and feed. Furthermore, coming mainly from spoiled foods and plant crops, the feed requires little energy to acquire and provide, and allows for the recycling of foods, reducing waste. Finally, due to the relatively static nature of insects when confined, most of the farming process can be automated. This allows for very low maintenance, meaning that this unused human work power can be dedicated to other demanding tasks. All these factors demonstrate how insect farms are favourable regarding efficiency, thus allowing for a faster colony growth and overall cheaper mission cost.

House crickets are one of the most promising examples of edible insects, and cricket flour has the potential to be incorporated into a variety of recipes. Despite this, there is a significant issue in that the idea of an insect-based diet is not particularly enticing to most people, and for some, is resentful. This is known as 'neophobia' and if forced upon colonists, may cause mental health related issues (Appendix E). There is a potential for this to cause people to avoid living on Mars, potentially decreasing the applicant pool. For this reason, it is imperative that there are viable alternatives for food.

Option 2: Crops

Many assume the Martian regolith to be unfavourable due to the ionisation from cosmic rays (Coady, 2017). However, if one considers *sub-surface* Martian regolith (i.e., has not received the same level of ionisation), the results are far more promising. After ten different crops were grown in simulated Martian soil (Figure 9), all but spinach thrived (Wamelink et al., 2019). They were harvested, providing edible produce including quinoa, radishes, and tomatoes; thus demonstrating that crop growth on Mars is feasible. In addition, an advantage of crops as a source of food is that they are healthy and allow for many more flavours and varieties than insects.

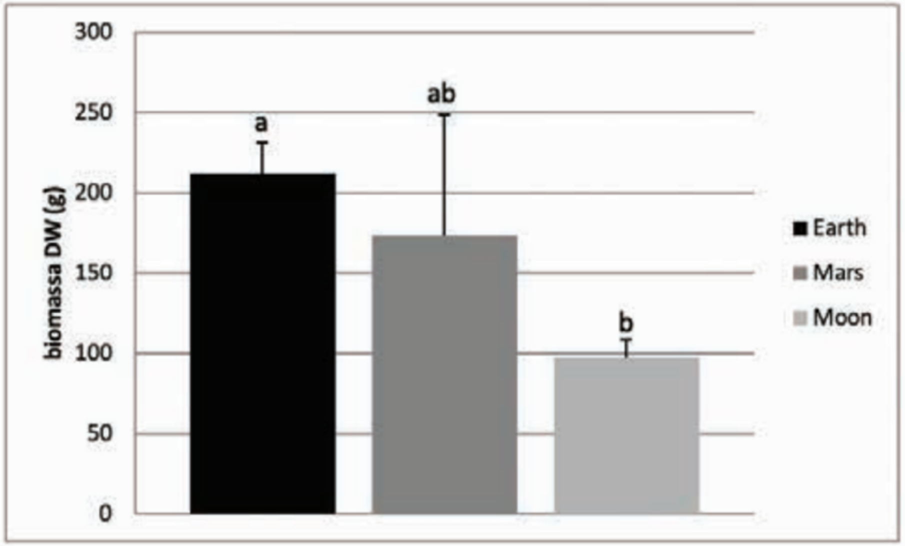

Figure 9: Total dry biomass produced for ten different crops on Mars and Moon soil simulant (organic Earth soil as a control) (Wamelink et al., 2019)

However, there are two significant issues with plant growth on Mars. The first is the reduced sunlight which is required for photosynthesis. Due to the extra distance between Mars and the Sun (compared to Earth), during the day the surface receives an average of 600 watts per square metre. That's 60% of Earth's average of 1000 watts per square metre, or the equivalent of when the sun begins setting (~ 35° above the horizon) (Petranek, 2014). Furthermore, Mars succumbs to massive annual dust storms which can last up to 2 months. These can potentially reduce the intensity to as low as 22% of Earth's average. Thus, the natural light on Mars provides suboptimal conditions for natural plant growth. To overcome this, agricultural-focused *artificial* lighting will be used. While this will certainly help, with our current science and technology, some specific wavelengths of natural light cannot be replicated (Volente, 2019). Poon suggests that future advancements in artificial lighting may improve the feasibility of plant growth on Mars (Appendix C), but currently, perfect Earth-like conditions cannot be simulated on Mars. The second issue is that of physical space. Plants provide far fewer calories per unit land than almost all other sources of food, and this is emphasised as a result of the reduced sunlight (Cannon and Britt, 2019). Consequently, to provide a significant amount of nutrition via crops will require huge amounts of money and energy to be invested into building the space for them to grow (Figure 10). Poon also suggests how certain layouts/designs such as vertical farming may improve this (Appendix C); however, the issue is largely something humans will always have to deal with on Mars. For these reasons, plants are like insects in that its unfeasible to rely solely on them.

Option 3: Cellular agriculture

Cellular agriculture is a very new concept, launching commercially for the first time in 2020. The basic premise is harvesting cells from animals and then multiplying them in a laboratory. This process makes it possible to produce many animal products such as burgers, fish, and even eggs and milk from 'just a few animal cells' (Agroop - Intelligence of Farming, 2018). There are numerous advantages to this. For one, it has a relatively high-calorie yield per unit land, making it favourable regarding efficiency – but still not as efficient as insect farming (Figure 10). Furthermore, it allows for a diet which is very similar to a typical 'Earth diet', likely making it the most appealing option regarding taste. The main disadvantage of this process, and perhaps the reason that many assume it to be an unfeasible option (hence why food production is believed to be so difficult on Mars), is the very high cost.

However, the cost factor has changed drastically over the past few years with investors putting very large amounts of money into the industry so that the technology can be refined, and the cost can be driven down (Cannon and Britt, 2019). As well as this, it's seen a huge surge in popularity from an environmental standpoint for the obvious reason that it does not require animals to be killed. In fact, the price of a cultured meat burger patty has fallen from $325,000 to just $11 in the last 2 years (Cannon and Britt, 2019). Thus, it appears that the one downfall of cellular agriculture (cost) is now obsolete; making it a viable option on a Martian colony.

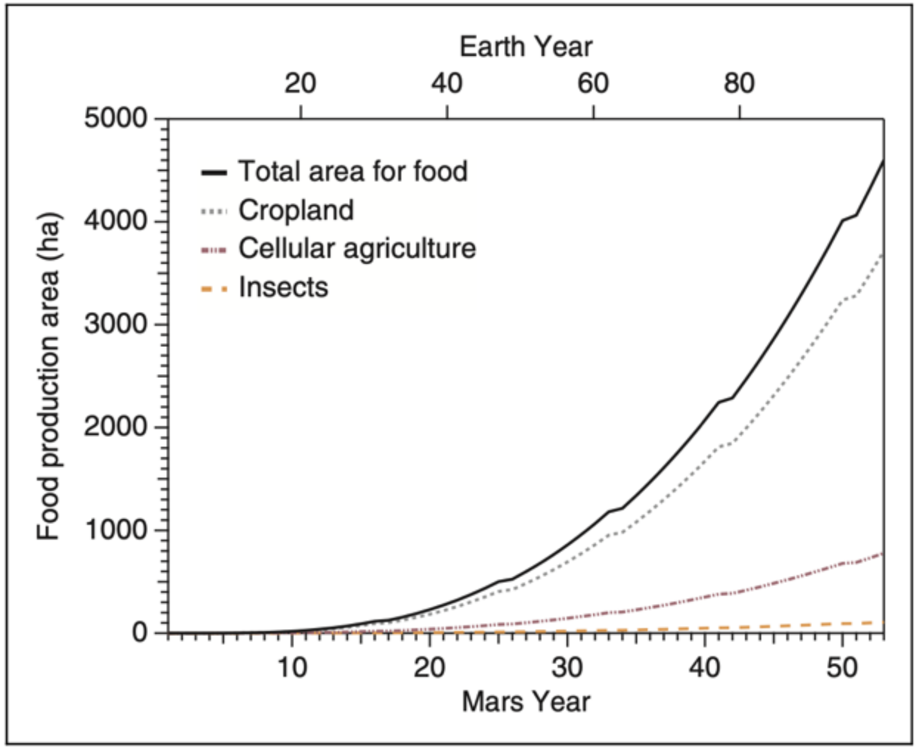

Figure 10: A prediction of the amount of land required to provide the required amount of food to a growing colony over a century (Cannon and Britt, 2019)

6 Summary and conclusion

So, can humans build a self-sufficient colony on Mars using current science and technology? From the research gathered and the evaluations made, this report demonstrates that this can be accomplished. However, it must be emphasised once again, there are other factors required for humans to live on Mars. But what this report does show, is that the science and technology required to meet the *basic* survival requirements of humans on Mars in a self-sufficient manor do exist. And on a broader scale, it demonstrates the *fundamental* feasibility of Mars colonisation. One could extend this report, and emphasise its importance, by exploring not just the fundamental feasibility, but the *entire* feasibility. This should serve as proof that humans don't need to wait for future advancements, and they should pursue this as soon as possible.

Unfortunately, this does not necessarily mean humans will build a self-sufficient colony on Mars in the near future. The very small margin of safety minimises the likelihood of such a mission going ahead. As demonstrated in the oxygen section, integrity cannot be an afterthought on Mars. But rather, it should be at the forefront of every decision that is made. Although Mars' conditions are reasonable compared to other planets in the solar system, it still remains inhospitable without the aid of advanced science and technology. If one aspect of a settlement was to fail (and some form of backup was not in place), all the colonists could perish. Unfortunately, due to many of the core technologies of this plan being *new* concepts, one cannot guarantee this high level of integrity and redundancy has been reached. This combined with the aforementioned 'precautionary principle' poses a very small likelihood of this mission plan going ahead in the near term.

This does not mean humans won't go to Mars soon. So far, Elon Musk is the only person to take on the challenge, with plans to land on Mars in the next decade (Duffy, 2021). His sights, however, are on building a base with a heavy use of importations from Earth, with self-sufficiency being achieved in the long-term. As a result, newer and safer technologies will have likely been developed by the time his colony reaches the self-sufficient milestone. At that point, those will be used rather than the options discussed in this report.

However, due to the clear reliability, integrity, and scalability of the MOXIE, it is highly likely this particular machine will be used in these upcoming Mars missions; thus, it is likely that oxygen self-sufficiency will be achieved. Although this report demonstrates how self-sufficiency in more areas than just oxygen could *theoretically* be achieved in the near-term, any mission to Mars would be the biggest challenge humans have ever faced. So, although not aiming for self-sufficiency, Musk's plans are still an admirable step for humanity. As he puts it, many people 'will probably die', but it will be a 'glorious adventure'.

The model for meeting basic human survival requirements self-sufficiently on Mars:

GRAA	Oxygen	Water	Food
As a result of Mars' rich resource abundance, and for lack of any other currently viable option, in-situ resource utilisation will be the emphasis for the acquisition and utilisation of all resources on the colony. In the long term, asteroid mining may become a more rewarding alternative.	Oxygen is the resource that humans can survive the smallest time without, making it the most vital. Due to its rigorous testing and confirmed integrity, the MOXIE will be the machine of choice. A 'Mars Direct style' approach will be employed to allow for definite oxygen supplies to be in place prior to humans landing, further ensuring the security of oxygen on Mars.	An auger-based system will be used to release water from the Martian regolith. This should prove effective on its own, but if a settlement was to have a nearby ice deposit, an artificial greenhouse system could be established on top of it for an additional, low-energy cost supply of water.	Due to the lack of in-situ organic material, food will initially be imported. Eventually, imports will be phased out. When this occurs, the Martian diet will consist of insects produced in insect farms with an emphasis on high calories per unit land, crops grown with artificial lighting for healthiness and variety, and cellular agriculture/lab grown animal products for protein and simulating 'Earth-like' meals.

Glossary

Biomass	Plant material used as fuel
Brine	High concentration solution of salt in water
Electrolysis	The use of an electric current to drive a chemical reaction
GRAA	General resource acquisition approach
In-situ	Locally
ISRU	In-situ resource utilisation
Kuiper belt	Circumstellar disc 20 times as wide as the asteroid belt
MARSS	Mars atmosphere resource recovery system
MGS	Mars Global Surveyor
MOXIE	Mars Oxygen In-situ Resource Utilisation Experiment
MSL	Mars Science Laboratory ('Curiosity')
Neophobia	Fear of anything new, unfamiliar or unconventional
Perchlorate	A type of salt containing the perchlorate ion
Prefab	Prefabricated buildings (built on Earth before sending to Mars
Sol	One Martian day (24 hours 37 minutes)
Sublimate	Convert a substance's state from solid to liquid

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Appendix A: Construction methods

Option 1: 'Prefabs'

A prefab usually stands for prefabricated home, however in this context, it applies to anything imported from Earth that has already been constructed, one such example being a prefabricated, modular Martian habitat. While these do have some merit, by definition, a prefab juxtaposes what it means for a Mars colony to be self-sufficient. Thus, prefabs should not be employed as a *primary* means of construction. However, prefabs may serve as useful in certain scenarios. The main example being, as highlighted by Ellery (Appendix C), that in the early stages of a colony, where it is likely that the infrastructure for complete in-situ resource production may not be present. In this case, prefabs could provide that initial 'boost' on the path to self-sufficiency, demonstrated in the MOXIE plan described earlier.

Option 2: 3D printing

The premise of 3D printing is where a machine can produce 3D objects based on pre-existing digital designs using 'layer-based' fabrication (Markforged, 2019). Unlike traditional 'subtractive' methods where a pre-existing block is strategically sculpted, 3D printing begins with unformed raw material and builds a model *layer by layer*. The advantages are: the model starts from nothing, much less material is wasted in the fabrication process, and it is a more machine-oriented process.

Ellery explains how he intends to implement this concept on the moon. The aim is to develop robots which may harvest minerals on the Moon and use them to 3D print replicas of themselves (self-replicating robots). His end goal is to have these robots grow exponentially, and thus be able to 3D print solar panels to be placed in orbit around the Earth to provide low cost, renewable energy (5minofscience, 2017). Implementing these robots on Mars may be the key to providing a large scale, low cost, material acquisition and infrastructure construction process.

In fact, such an idea has already been proposed by an architecture firm, Forster + Partners, during NASA's 3D printed habitat challenge (Harbaugh, 2016). It harnesses the concept described above, where 3 types of robots (digging, melting, and transporting) are used in unity to build the first houses on Mars. The 3D printing process would involve using microwaves to fuse the Martian regolith together. A simplified version of this process can be seen in Figure 11.

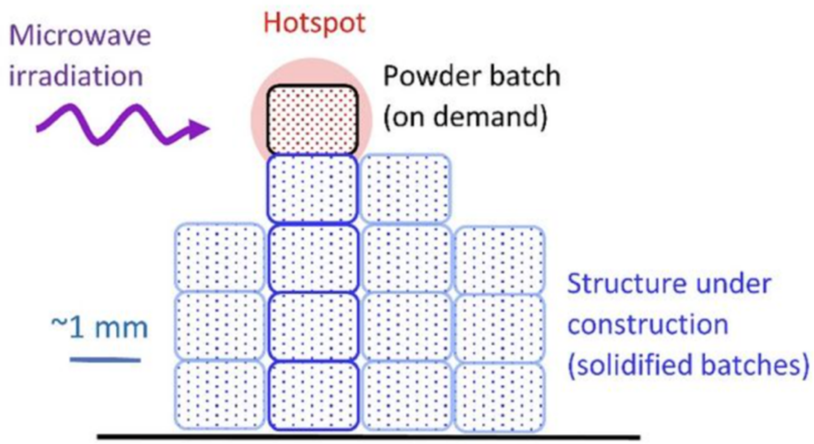

Figure 11: Fusing materials via microwave irradiation (Stevenson, 2020)

Appendix B: Power

One of the main purposes of this report is to evaluate how a settlement may cope *without* help from Earth, through in-situ resource utilisation. With power, however, there is no question that it will be produced locally, for importing it is simply not feasible. Furthermore, the method of producing power is almost definitely going to be nuclear, as the other options are simply not viable on Mars – a claim agreed by a range of credible sources including Stanford University (Black, 2017) and Kurzgesagt (Kurzgesagt – In a Nutshell, 2019). Given there is little evaluation to be made, it was not included in the main report.

Mason Black's (researcher at Stanford University) conclusion on power production on Mars:

> *'Though solar is increasingly popular on Earth, its intermittency, especially in the face of extreme weather events like long-lasting dust storms, makes it is less attractive on Mars. Considerable storage would be necessary to provide adequate backup power, which would result in a very heavy system. In contrast, nuclear power could provide both steady electricity and a constant source of direct heat. Thus, from a reliability perspective, nuclear power appears better suited to powering a Mars colony. However, this is not to say that nuclear power is necessarily the best technology for extra-terrestrial planetary outposts - it does introduce a set of safety and environmental concerns that may necessitate further testing and research to address.'*

As explained by Ellery (Appendix C), the infrastructure for large scale projects will likely not be in place to begin with in a Mars colony. The impact of this is that a colony will not have nuclear power plants in the near-term. Thus, radioisotope thermoelectric generators (RTGs) are the best candidate. These are self-contained, modular systems that convert heat from non-fissile radioisotopes (such as Pu-238) into electricity, on a very small scale.

Black's review of the RTG:

> *'Radioisotope thermoelectric generators (RTGs) have already been proven effective in multiple space missions, including the Pioneer and Voyager spacecraft as well as the more recent Mars Science Laboratory (Curiosity) rover … (comparing to alternative nuclear technologies) the RTG design may yet win out due to safety considerations.'*

Appendix C: Interview summaries

Interview 1: Crispian Poon

Crispian Poon is the co-founder and CEO of Pelation. Pelation is a cycle technology company that deploys innovative design and engineering to eliminate sustainable mobility barriers. Their aim is to eliminate the stress that cyclists in London feel on a weekly basis.

Key points:

- They key to effective life support on a Martian colony is the implementation of a recyclable system
- A settlement must be able to recycle water, food, and oxygen in a 'closed-loop' architecture
- Exoskeletons could combat bone degradation due to reduced gravity
- Mental health of colonists will be the biggest challenge for a sustainable colony
- Very difficult to remain resilient when living with the same people for years in a confined space
- Supporting mental health of colonists should be the top priority (e.g., variety of foods)
- Could overcome the reduced light intensity on Mars by using artificial light instead
- Vertical farm layouts have the potential to improve cropland efficiency
- Excited for the impact of gravitational waves in the future of astrophysics

Interview 2: Alex Ellery and Thomas Clayson

Alex Ellery is a full Canadian research professor at Carleton university, working in the field of mechanical and aerospace engineering. His work surrounds self-replicating planetary rovers, 3D printing, lunar base infrastructure development and space-based manipulators.

Thomas Clayson is the co-founder and CTO of Magdrive. Magdrive is a start-up company which is developing a revolutionary new plasma thruster design for rocket propulsion. The technology aims to allow entirely new missions and business models surrounding space travel.

Key points (Ellery):

- On Mars, humans must 'live off the land'
- Should use the Moon for resources and launch rockets from the moon to circumvent high Earth-to-orbit costs
- Moon could act as a 'pitstop' to Mars
- The Apollo missions were largely a political contest
- NASA have not done many 'useful' things since^ (e.g., the ISS was almost a waste of time)
- Believes there is a place for his 3D printing, self-replicating robot concept on Mars
- In the early stages of Mars colonisation, the infrastructure will not be in place for large scale projects

Key points (Clayson):

- The biggest challenge of Mars colonisation will be the distance between Earth and Mars
- If a machine goes wrong (and there's no backup), people will die
- Asteroid mining, if possible, would be the ideal option for gathering resources due to its high-cost return whilst doing no damage to the planet
- Disagrees with the likes of Zubrin and Musk that Mars is the way forward for humanity
- Believes it would be more efficient to build a colony in space (i.e., O'Neil colony)

Appendix D: Importing foods

Before sufficient infrastructure for food production is established, a colony has no other option than to use importations from Earth. Although this appears to 'break the rules' of self-sufficiency, one must understand that regardless of whether a colony is self-sufficient or not, there will be some *guaranteed* missions. For example, the cargo missions prior to the first colonists landing, or the delivery of new colonists. If these do not occur, there will be no colony to call self-sufficient. Thus, to overcome the food challenge, humans can and should use (the first few) planned missions to their advantage.

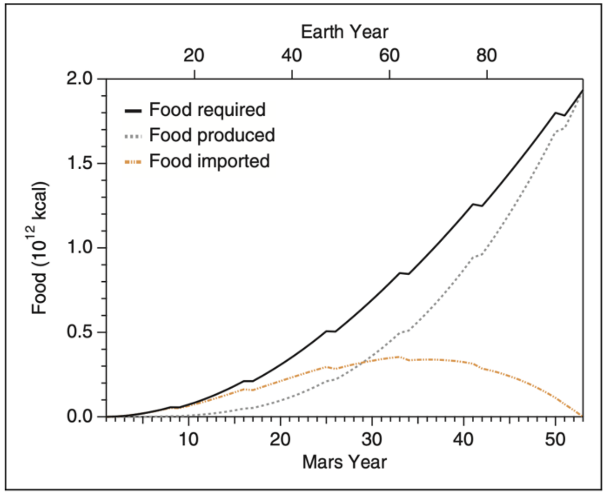

Figure 12: Total calories required, produced, and imported for a colony which reaches a population of one million people within a century (Cannon and Britt, 2019)

To survive at any given time on a colony, the sum of the locally produced food and imported food must be greater than or equal to the net food requirements of the colony. The smaller the fraction of imports, the closer the colony is to being self-sufficient. Figure 12 shows a prediction of the food required, produced, and imported if a colony was to become self-sufficient within a century (Cannon and Britt, 2019). At roughly the end of the (Earth) century, self-sufficiency is achieved. However, these predictions are based on reaching a population of one million people. If fewer resources were dedicated to the rapid growth of the colony, and instead were appointed to in-situ food production infrastructure, its predicted that self-sufficiency could be achieved by 'as close as year 5'.

Appendix E: Mental health challenges

An often-overlooked challenge to a Mars colony is that of mental health. The psychological challenges the first colonists will face is unprecedented in that, at least to begin with, they'll be confined to a small base with the same group of people for a minimum of 18 months (not including the 6 months journey each way in a tiny rocket capsule). These first few settlers will experience feelings of isolation and loneliness, which could lead to 'psychological problems such as anxiety or depression' (Weir, 2018). Even the most resilient candidates will struggle mentally, meaning it is of upmost importance that they are given as much support as possible. This is backed by Crispian Poon who explained how he believed the largest problem on a Mars colony will be trying to 'tackle the mental aspect' (Appendix C).

Albert Harrison's (psychology professor at the University of California) opinion on the mental challenges of Mars colonisation:

> *'… some of the most difficult challenges future space explorers may face will be psychological - because delving farther into space than anyone ever has before means great danger and also grinding monotony … unprecedented periods of confinements, people being away for three years or more, the period of isolation, the lack of capability to rescue people - all these things become intensified in the case of Mars.'*