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Korolev Crater Special Administrative Region

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Abstract
The Korolev Crater Special Administrative Region (KCSAR) is a special administrative region of the United States of America established in the 2060s. It is located within the Korolev Crater, an ancient ice-covered impact crater, which houses one million residents in dome-like structures that are constructed into the ice. The city is largely self-sufficient: it is powered by an integral design nuclear reactor; it generates water using a novel TSSE wastewater treatment approach; and it applies a range of farming methods to meet its basic needs. It operates as an essential autarky, producing the vast majority of its economic resources, such as bulk chemicals and raw materials, in situ. To obtain the few resources it cannot produce itself, it exports a small range of goods and services in which it has a comparative advantage. Its political system operates as a delegative democracy and the government takes an interventionist stance in selecting for KCSAR colony settlers; in encouraging fertility; in providing incentives for important behaviours, such as a Universal Basic Income; and in directly regulating emerging natural monopolies. Perhaps most importantly, it takes a role in shaping the cultural development of KCSAR by investing in local initiatives and implementing an architectural style that celebrates human achievement. The future of KCSAR is bright. In the coming years, a substantial geoscaping operation will be undertaken to melt the frozen crater and create an environment that can support a new ecosystem, lush with life, and reminiscent of life on Earth.

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1. Introduction

Since the very first images of Mars, taken by Mariner 4 in the mid 1960s, became public, the red planet has made its way into the public consciousness, and has ignited a yearning for the human race to become a space-faring, inter-planetary civilization. A planet, so very like our own, lies within our sight, but just beyond our reach. In just the past few decades, significant advances in engineering, combined with a more nuanced understanding of social structures, has provided a platform to examine the ways that we can extend the upper-limit of humanity's existence, particularly in the face of a number of looming existential threats. The result has inspired a revolutionary idea - that of a human colony on Mars. This idea, now, more than ever before, seems possible within our lifetime. As technology continues to evolve at an alarming rate, addressing many of the challenges that have previously limited our ability to move deeper into space; the need to articulate an implementation strategy that presents a unified, tangible, and sustainable vision for what a Mars colony could look like, across the myriad paradigms of society, is necessary.

In this paper, we seek to concretize the dream for a Mars colony, into a simple outline of the central processes and systems that we believe will enable a substantial colony of one million people to not only exist on Mars, but indeed flourish and thrive. To provide a substantive analysis, we limit ourselves to dealing mostly with the processes that we think are most unique to the Martian environment that cannot simply be transplanted directly from modern societies on Earth, as well as those that are unique to the location of the initial settlement that we have selected, which is based on the Korolev Crater.

The Korolev Crater is an ancient ice-covered impact crater at 73 degrees North, 163 degrees East on Mars. The Crater was selected because it contains around 2000 km^3 of water ice, which provides an abundant supply of water and serves as a simple and cheaply implemented heat sink and radiation shield. The state itself, known as the Korolev Crater Special Administrative Region ('KCSAR'), is established in the 2060s, as a special administrative region of the United States of America. KCSAR is designed as a subglacial city, housed

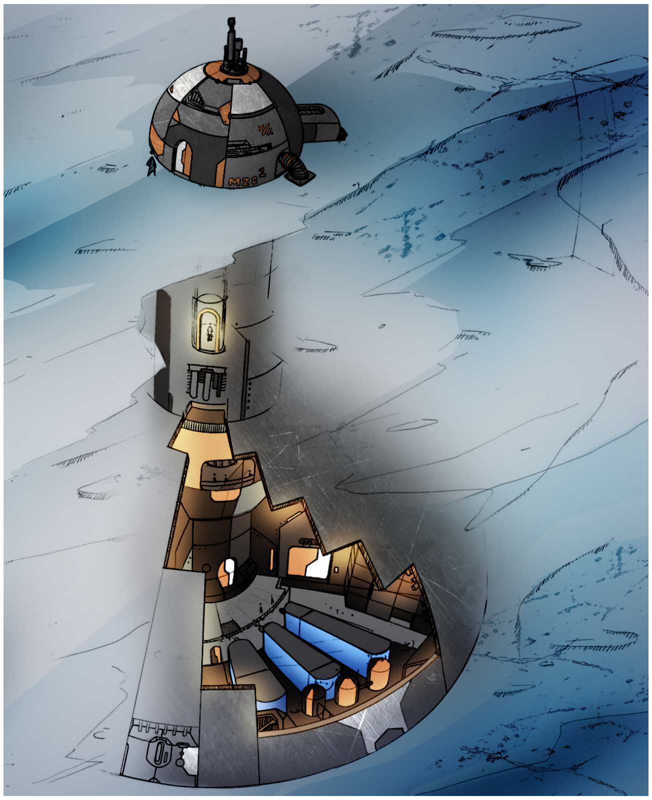


Figure 1. Artist's rendition of the dome under the ice.

within interconnected domes constructed into the ice, as seen in figure 1, and small domes that sit atop it to offer a means of egress to the Martian surface. It extends in a crescent shape from the northernmost point of the crater along its inner rim.

The structure of this paper has been divided into three key sections. The first explores the technical challenges associated with supporting life on Mars, and proposes a number of novel solutions to many of the essential components of life, such as generating power, creating a suitable atmosphere, accessing potable water, producing food, manufacturing bulk materials, mining raw materials, building consumables, and supplying internet. The second explores social engineering, presenting our vision for the social, economic, political, and cultural makeup of KCSAR - the key drivers of any modern society. Finally, we end this paper with a glimpse into the future of KCSAR - a self-sufficient, innovative, and vibrant society. While life on Mars is initially difficult, we envision KCSAR to evolve beyond its humble origins and become a society that is the envy of Earth's residents.

2. Technical Design

Due to the presence of high transport costs from Earth and the inherent risks of delays in the transport of critical imports; for human life to survive and ultimately flourish on KCSAR, the colony must be highly self-sufficient and operate as a close to autarkic entity. To achieve this, cost-efficient manufacturing processes of essential bulk materials are critical. In this section, we outline the engineering that underpins these processes, first dealing with necessities for human life, namely, power, air, water, and food; then addressing economic necessities by focusing on bulk materials, mining, consumables and the internet. Within each of these sectoral subsections, we introduce the structure and scale of resource dependence, before analysing the key production pathways (chemical, engineering, manufacturing) needed to achieve essential self sufficiency. We deal finally with the endogenous formation of a market for Martian products, by using a representative example from chemical manufacturing.

2.1 Absolute Necessities of Life

Given the resource scarcity, the systems for producing a number of the essential necessities proposed here are designed to operate synergistically with one another. This maximises productivity while enabling a futures market to arise from the multiple production processes with distinct production curves. The resulting overall system, therefore, is robust, efficient, and responsive to any market turbulence.

2.1.1 Power and Thermal Design

We begin with power consumption and generation, as all subsequent processes depend upon it. KCSAR requires on average $\approx$1GWe (with an upper limit of $\approx$3GWe) to sustain life for one million people. KCSAR's complete power generation model can be described as an interconnected system that encompasses thermal and electric power generated via two different processes: (1) a nuclear base-load plant that produces 12GWth power output from an integral fast-spectrum two-fluid molten-salt reactor operating at 750°C, of which, 4GWe power is obtained from a series of in situ mass-producible low pressure turbines; and (2) a cryogenic peaker plant that produces 4GWe power output derived from a cryogenic energy storage system ('cryobattery') that stores energy in the form of LN_2, with capacity of 96GWh, providing the energy requirements to meet peak demand. As seen in figure 2, this two-way system maximises the productivity of the power generated, by interacting with other energy producing processes. For example, during periods of peak demand, the risk to grid instability arising from network overload is ameliorated through the usage of a cryobattery, and, during periods of minimal demand, the excess thermal output can be redistributed for other uses, such as powering the chemical market to increase the production of bulk goods, or recharging the cryobattery. This system relies crucially on the presence of a sufficient heat sink, due to the heat density of the molten salt reactor design, and the particularities of the Martian context. The absence of large bodies of water and a thick atmosphere make thermal rejection particularly problematic. Opportunistically, however, KCSAR is located on water ice, which provides the necessary heat sink needed for the long-term viability of the system.

The reactor itself is an integral design made up of standard high temperature materials, and houses a single crucible that contains the entire assembly. It uses Hastalloy-N disposable fuel pins, which are filled with a fuel salt mixture that comprises Pu and ^{238}U. For this system, the pins are the only superalloys that are required to be produced and shipped from Earth. Since it is a fast spectrum reactor, there is no requirement to isotropically separate lithium for the FliBe mixed fuel salt to maintain acceptable neutronics, but it does require active moderation via control rods. By using this two fluid contained pin design, we can separate the fuel to simplify the reactor maintenance and construction, and therefore avoid the complications arising from (1) the potential condensation of fission products, and (2) the production of Xenon and Krypton. Additionally, as a liquid fuel, it can be burned more completely because the standard Xenon intercalation problems found in MOX are not present. The chloride based coolant salt is then wrapped in a Thorium salt 'blanket', allowing it to be bred for ^{233}U via ^{233}Pa for use in nuclear thermal vehicles, along with Kilopower style stationary reactors for use in mining colonies and the like. By operating under low pressure Argon on Mars, the usual corrosion problems associated with water or oxygen impurities in the fuel salt are eliminated. Overall, the reactor is designed to run at a 100% capacity factor, with redundant heat exchangers and turbines, and at $\approx$100% load factor between the electrical and thermal energy demands on the system, matching demand via a smart grid system [1].

The thermal energy generated by the reactor is converted to electricity via low pressure turbines. The benefit of using these turbines over standard high-pressure turbines is that they do not require precision manufacturing or advanced metallurgy, allowing them to be mass-produced in situ, on Mars. Inputs into the thermal distribution system are a combination of the rejected heat of the reactor fluids themselves, absorption chillers, and waste heat from chemical industrial plants, which are then used to generate various output loops at chemically useful temperatures, as well as a final rejection loop for any heat that is too low grade for industry, which is used to melt ice and for district heating. The combined heat and power system (driven largely by the reactor's excess thermal energy), produces 'plant heat' that can be used within various chemical plants to develop other essential goods such as food (refer to section 2.1.4) and fuel (refer to section 2.2.1), while also providing the necessary heat needed for natural ecosystems to thrive (e.g. by facilitating the growth of cold water fish and algae). Furthermore, waste heat from the reactor is also capitalised on to form large inlets of liquid water by heating the ice (an essential resource for life, that is discussed at great lengths in section 2.1.3). A second purpose of the waste heat from the reactor, is that it can address the challenge of cost-efficient chilling on Mars. By using a series of absorption chillers, such as a LiBr absorption chiller that produces water at 2°C, or an ammonia absorption chiller that produces a chilled methanol loop at -30°C, the waste heat has useful properties that allow for the chilling of objects below the temperature of the inlet.

Finally, any excess energy produced is stored within a cryogenic battery [2] made up of LN_2, that is used as needed to meet peak energy demands. LN_2 is heated by industrial waste heat to (1) form high pressure N_2 that turns the locally produced low pressure turbines, and (2) provides the means to both operate the LN_2 turbopump and pressurize the LN_2 tanks. To ensure that the cryogenic tanks remain chilled, a novel approach to radiative cooling is used. A solar absorber that is made up of an undoped Ge film, below an epitaxial GeO_2 scratch resistant layer, is used to create a shading mechanism for the black body radiative cooler through a ZnSe window. An anodized black-body radiator in a dewar then acts as a heat exchanger for He, which enters through the bottom and is cooled to create the cold loop that chills the cryogenic tanks. The chilled He can then be used to either liquefy boiled off gasses, or cool liquid gas as required. Given that there is a thin atmosphere on Mars,it is relatively simple to build larger vacuum chambers to support this system as needed [3]. This thinner atmosphere also radiates less IR at night as a black body, aiding in system efficiency. Some of the key benefits of using cryogenic batteries are: (a) they provide a sacrificial LN_2 blanket that reduces the loss associated with the relatively valuable LO_2 and CH_4; (b) economically, it creates elasticity in the supply of electrical energy, by ensuring demand for electricity from the reactor and offering the capacity to redistribute it as needed; and (c) since there is a market for both reactor heat and power that can be converted into each other, the fungibility of these resources softens the demand curve for each, ensuring a stable market equilibrium.

While developing a colony in the bitter cold of the Martian pole may seem like a brutal trade off for easily producible energy and living space; it is less brutal than one would initially assume. Most of the colony exists within the glacier in domes that are designed with striking similarities to Igloos, in that they take advantage of (1) the insulating properties of ice and (2) the large thermal mass of the glacier, in order to maintain a reasonable internal temperature. Furthermore, at the surface, even though the temperature itself may be below -100°C, the low pressure environment reduces convection losses, while the CO_2 atmosphere reduces conduction losses (compared to a N_2-based environment). This means that as a frame of reference, the engineering problem of heat conservation is actually comparable to the equivalent of much warmer temperatures on Earth.

2.1.2 Air and Atmosphere

Next, of primary concern is the supply of the chemicals that form the basis of survival: air and water. In this section, we explore the atmospheric conditions required for life on Mars, dealing first with oxygen, the foundation of human life. By far, the easiest method to produce oxygen on Mars is via photosynthesis. However, the challenge is that the supply needs must be determined long in advance (via building farms) and is reasonably unreliable. To mitigate this issue, cryogenic oxygen that is kept cold via the cryobattery's LN_2 that we introduced in section 2.1.1, offers a short term solution to stabilize the supply. In the medium term, or where farming is impractical, a Zn/S/I thermochemical cycle [4] is proposed to

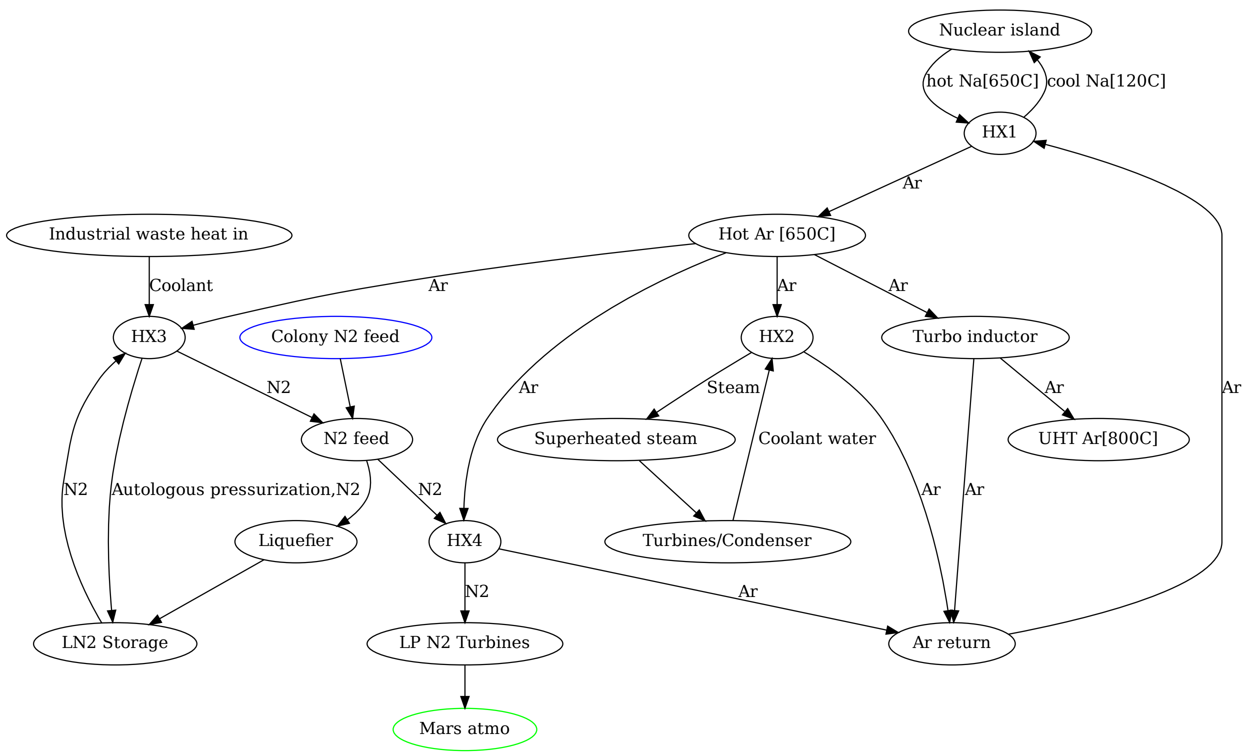


Figure 2. Reactor thermal distribution diagram. Colours: blue are fluid inputs, green are fluid outputs, acronyms: HX=heat exchanger, UHT=ultra high temperature, LP=low pressure.

produce oxygen from water at a reasonable cost, using a turboinductor heat pump to efficiently provide optimal operating temperature [5, 6]. The reactor would use an electrochemical bunsen stage [7], with a modular decomposer akin to [8], to save on complexity and cost. Similar designs would also be used to produce O_2 from CO_2 by omitting the HI decomposition stage, making them suitable for other things, such as life support on mining outposts, powered by kilopower style power plants. A further benefit to Zn/S/I systems is that they both produce the syngas needed for the direct reduction of iron, and consume the water/CO_2 generated from the reduction. The interrelationship of these processes used to generate atmospheric conditions are displayed in 3.

Given that KCSAR's atmosphere is primarily made up of low pressure Oxygen and Argon (Argox), the photosynthetic farms can capitalise on a CO_2 enriched atmosphere, which can produce an enriched Argox fraction when processed, by recycling the CO_2 back into the farms. This Argox fraction underpins the city's atmosphere, supplemented as needed using Air Handling Units(AHU) which maintain total pressure, along with things like temperature, the partial pressures of O_2/CO_2, and humidity. To ensure that excess atmosphere does not pose a serious threat during events such as a fire, a reject line is used; and any water produced via dehumidification is rejected via a drain line. Another potentially lethal threat on Mars is the issue of dust, which can lead to health problems such as chronic silicosis. To address this issue, cyclonic filtration with a second electrostatic stage, is employed as a scalable way to remove small particles. Provisions are also made for potential atmospheric failures. Respirators that enclose the ears and eyes are maintained at regular intervals to ensure that citizens have enough time to return to safety if they are unable to access a full pressure suit. Atmospheric monitors and alarms are built into each AHU that operates if pressure falls to a dangerous level, or if the partial pressure of oxygen or CO_2 moves outside of safe bounds. The potent odorant Ethanethiol is added to the emergency habitat pressurisation lines, to provide a warning for underpressure and hypoxic situations. While above the ice, depressurization due to pinhole leaks is a major concern, under the ice, the primary hazard is hypoxia or toxic gas buildup due to fire or a chemical leak that rapidly replaces the atmosphere with high pressure, unbreathable gas. An overpressure system within the AHU's allows for them to rapidly vent out the excess gas, preventing the problems associated with overpressure.

2.1.3 Water

Extending on our treatment of air, access to liquid water is equally critical, and, once again, the value proposition of settling on the Korolev crater presents itself. Since KCSAR is built into water ice, it is surrounded by an accessible water source if heat energy is available. To heat the ice, KCSAR capitalises on the heat exchangers from the reactor proposed in section 2.1.1. The high temperature output from the reactor produces waste heat that leads to the formation of local ponds, which, over time, transforms into an inlet of accessible liquid water, particularly as the heat dissipates through the surrounding ice walls. While the lake water is not initially potable, a novel two-stage temperature swing solvent extraction (TSSE) process [9], provides an effective solution for the bulk recycling of water. In the first stage, the solvent Diisopropylamine (DIPA) is heated to absorb water from the raw water inlet until it is saturated. It is then cooled so that the DIPA rejects excess water and forms an aqueous layer that can be removed [10]. In the second stage, Diethyl ether (Eth) is used to extract the remaining DIPA from the extracted water. Given that Eth is mostly immiscible with water, and has a low boiling point and high vapour pressure, it is easily extracted. Finally, the water is treated to maximise its safety using: (1) activated charcoal filtering (2) NaOCl is added as a disinfectant and (3) a buffered mixture of common ions to ensure that (a) the pH of the water remains slightly alkaline, (b) metal pipes passivate properly, and (c) leeched metal ions are insoluble. Minerals are also added to improve nutritional outcomes, such as NaF for dental health.

TSSE is an attractive candidate process because (1) it only requires simple mechanical equipment, and (2) it runs on low grade waste heat, at standard pressure, and with mild reaction conditions. This is preferred to more standard reverse osmosis systems that rely on high precision semi-permeable membranes that are complex to manufacture, and that require energy intensive high pressure pumps. Moreover, this TSSE process can internally recycle the low-grade waste heat using a recuperator, which makes it highly energy efficient, and only requires chemicals and materials that are easy to produce in situ. This ensures that the system is easily scalable as the population grows [9]. Particularly as the population grows, recycled wastewater is therefore the most efficient primary source of water and only supplemented by the energy-costly process of converting large blocks of ice into water where necessary. A relatively simple recycling process is used for 'greywater', produced from sources such as showers on Mars. Greywater does not contain harmful biological organisms, and therefore, the water can be passed through a simple filter stage and fed back into the aquaponic loop that we describe in section 2.1.4. 'Blackwater', by contrast, does contain harmful organisms that need to be removed, but also contains nitrates and phosphates that make it a good fertiliser, which is eventually used in farms. Thus, by diluting blackwater with greywater, and using NaOCl and thermal processing to sterilise it, it is also capable of being utilised in the aquaponics loop. This overarching synergistic water treatment process is laid out in figure 4.

2.1.4 Food

For an isolated community such as KCSAR, maintaining food security is vital. Producing a sufficient quantity of cost-efficient, nutrient-diverse foods, while maintaining efficient supply lines, is a prerequisite for the sustenance of life. In this section, we outline the artificial ecosystem that provides a varied diet for the citizens of KCSAR, building from the simplest (and most cost-efficient) food sources, to the most

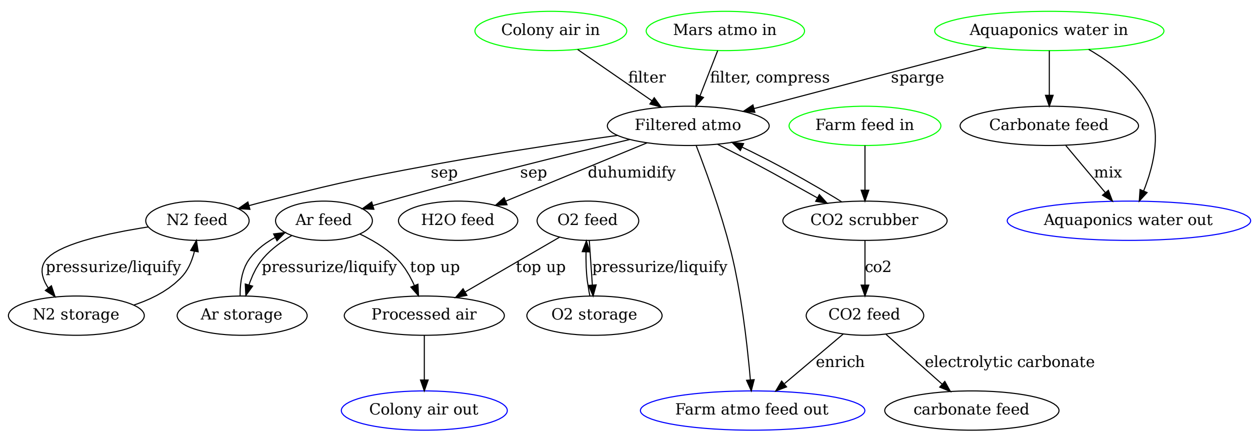


Figure 3. Flow of atmosphere between settlement, farms and industry. Colors: blue are inputs, green are outputs.

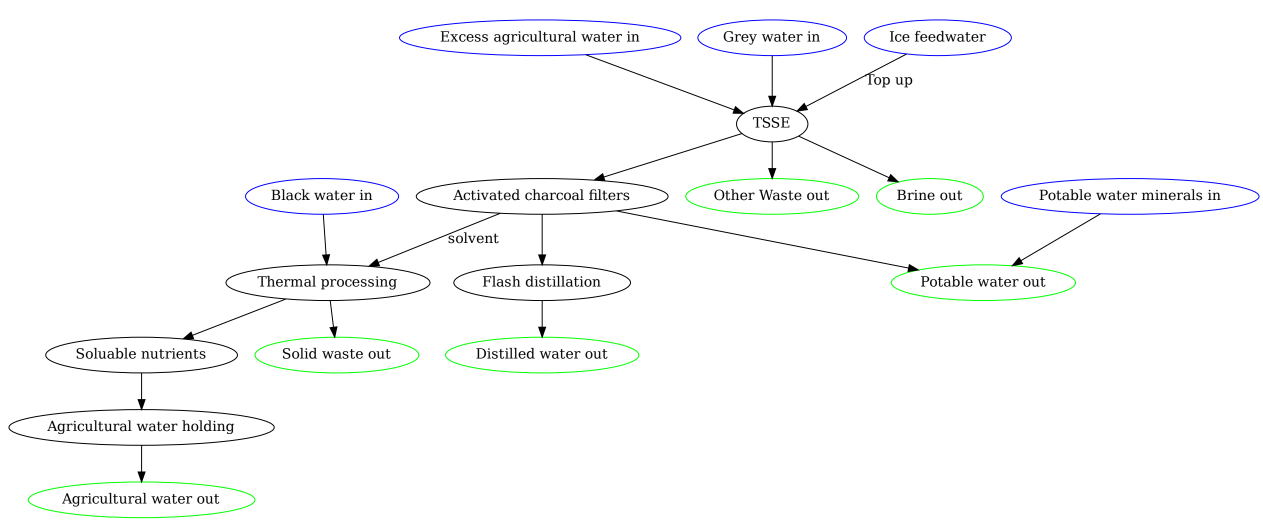


Figure 4. Settlement's artificial water cycle. Colors: blue are inputs, green are outputs.

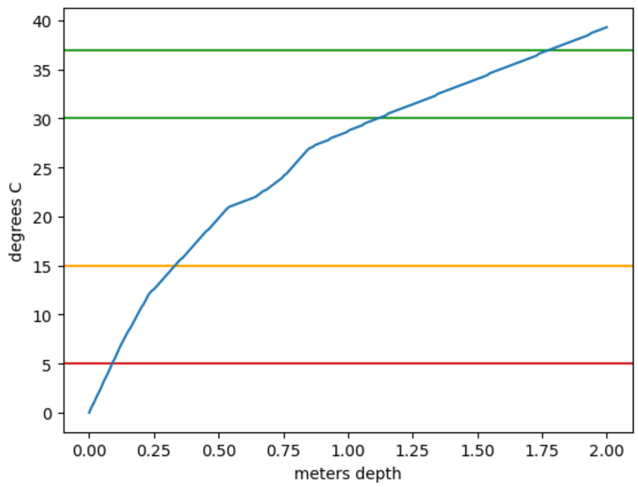


Figure 5. Depth of oleic acid vs. maximum water temperature

complex luxury goods. Given the complexity of maintaining food security, we have divided the treatment of this section into two sequential parts, answering the vital questions of: (1) What chemical processes are needed to enable the production of food? (2) How then, do we mass produce the food in a sustainable way?

The Chemical Pathways for Food Production Edible industrial products are an extremely cheap food source, and underpin food security, even when there are disruptions in the supply of other nutrient sources. They serve a dual purpose, forming inputs for the biochemical industry discussed in section 2.2.1 once they are processed. For example, edible glucose is converted into plastic and protein into ammonia. These edible industrial products are primarily produced in ditch-style farms and grass farms. Ditch-style farming involves injecting water into an earthen dam and covering it in a layer of oleic acid to protect it from the low pressure / temperature of the surface, so that optimal growth conditions are maintained. Figure 5 shows the depth of oleic acid needed to enable growth. Below the red line, no economically useful growth is possible. Between the red and orange lines, many forms of algae can be grown in useful quantities. The two green lines show the range of optimal growing conditions for Spirulina, a useful cyanobacteria that has adapted to very warm water environments. Within this range, it grows rapidly, producing nutrient rich biomass that feeds both people and animals. The cost-efficiency of producing candidate algaes is routinely reviewed to create an appropriate environment for rapid growth. This is achieved, for example, by rotating the crop, or adjusting the depth of the oleic acid. Since oleic acid is produced from biomass and is needed for biomass production, this forms a feedback loop that limits the growth of farming over time.

The primary obstacle to ditch-style farming is the method of gas perfusion. There is no viable natural path to enable CO_2 and N_2 from the Martian atmosphere to reach the aqueous layer for biosynthesis. Hence perfusion stations are used, replacing consumed dissolved gasses such as CO_2 and possibly N_2, and then extracting the dissolved O_2.

Mushroom farming is used to catabolise otherwise indigestible biomass into nutrients for future farming. This removes insoluble products that cannot be ground into a colloid and fed into hydroponic systems. Mushroom farming requires O_2 and waste biomass that can be seeded with spores to form edible mushrooms.

Given that nitrogen is critical to facilitating plant growth across the farms, either atmospheric nitrogen, or the artificial urea derived from the haber process described in section 2.2.1, will be used as a nitrogen source. While the N_2 found within the Mars atmosphere is cheaper to use and requires less processing, its primary drawback is that it results in slower growth. Artificial urea, on the other hand, is more effective, but subject to market fluctuations in the industrial price of urea.

The Sustainable Mass Production of Food Whilst building robotic greenhouses that can grow standard crops is a daunting technical challenge, automated farming of light grasses and particularly Miscanthus Giganteus (‘elephant grass’) have been reliably implemented. On KCSAR, this procedure is replicated to produce a cost-efficient source of industrial glucose. Small modular greenhouse sections are fused together and filled with low pressure CO_2-enhanced atmosphere. Quantum dots are employed as a layer on top of the greenhouse membrane to increase quantum efficiency by downconverting light that is unsuitable for the grass, such as UV light, into light that is most effective for photosynthesis. The growth beds resemble traditional hydroponic growth beds and are made from processed, crushed regolith. These are robotically mowed, with the farmed grass cracked into glucose by cellulases. Using a similar approach, hydroponic gardens will be used to grow more traditional foods including vegetables, grains and spices. Due to the complexity of harvesting, hydroponic gardens require laborers and a shirt-sleeve environment, making their output substantially more expensive.

Aquaponic farming is also used to supplement the Martian diet with fish and aquatic lifeforms. Aquaponic farms are contained within large bioplastic boxes with an Oleic acid cap, placed in segmented areas cut into the ice. The box acts as insulation, keeping the water warm and separating out the nutrient-rich (particularly phosphate-rich) water that accelerates the growth of cyanobacteria and algae, from dilute water. As these organisms are at the bottom of an artificial food chain, the speed of their growth is highly correlated with the supply of fish of various kinds, that are a staple of the relatively wealthy.

While relatively expensive, meat is also sufficiently cheap to supplement the diets of most households with varying frequency. Battery poultry, rabbits and similar livestock are the primary source of meat as they may be grown relatively cost-efficiently, rapidly and in confined spaces, and they are farmed for eggs and meat. A substantial amount of farmed meat is processed, with cellulose 'padding' added (such as in chicken nuggets) to make it more affordable for consumers.

Yeast, farmed in bioreactors, is used to grow bulk substitute animal proteins, such as albumin from eggs and caseins from milk, from industrial feedstock. This allows for the creation of cheaper substitute products, such as artificial egg whites, as opposed to far more expensive chicken eggs. These are also mixed with processed meats or fish to form more complete processed foods, or even added to semi-natural pathways to create, for example, real cheese out of artificial milk [11]. Similarly, using artificial gluten and eggs enables the colony to bake bread and make pasta, which would otherwise be infeasible, thereby allowing for a more varied diet.

In the highest price bracket, are the imported foods from Earth that are infeasible to replicate on Mars such as chocolate and coffee. Where possible, these foods are produced using a mixture of local and imported ingredients. For example, chocolate is produced from combining artificial oils and bulk glucose produced on Mars with cocoa that is imported from Earth. To improve food flavour in a relatively inexpensive way, some spices are engineered chemically (such as simple esters) and biologically (such as limonene, linalool, among others), which makes the food more palatable to those familiar with traditional foods consumed on Earth. Spices that cannot be produced through these methods are imported from Earth. The change in the relative costs of ingredients provides the impetus for culinary innovation and the growth of a distinctive Martian cuisine.

While these diverse farming practices meet most of citizens' nutritional needs, some nutrient deficiencies arise because foods that are high in particular nutrients are difficult or expensive to produce. To address the possibility of widespread deficiencies and resulting health impacts, many foods are fortified with artificial sources of Vitamin C, Vitamin D and Iodine.

2.2 Economic Necessities of Life

In the previous section, we outlined the basic processes needed to sustain human life on Mars. In this section, we analyse the processes necessary to sustain a stable, working economy that can maintain those basic processes and provide for human consumer 'wants' as well as needs. As before, cost-efficiency and stability are the primary motivation for selecting particular production and maintenance processes.

2.2.1 Bulk Materials

The next most important chemical pathways are those that are economically essential for survival - the production of plastics and other bulk products. For simplicity, we have compiled a list of useful bulk products that are producible on Mars in table 1. A key consideration in the robust production of bulk materials is that there are multiple pathways with different production functions. As an example producing Aniline in a bioreactor requires very little in the way of capital outlay and so is easily scalable, but has a higher marginal cost per ton than building a dedicated plant to aminate phenol. A market that includes both, then, along with a robust futures market in industrial products, is able to produce cheaply, while scaling rapidly, in order to robustly meet market demand.

Another key consideration is that while some biological processes are directly useful, such as the production of bioplastics, Penicillin, Vitamin B12 and the like, there are many that are not. In these cases, we can augment existing biological processes with industrial chemistry to produce useful products. For example acetaminophen can be produced from biosynthetic Quinone, Nylon from synthetic Adipic acid [12], Rubber from ethanol [13] (via isobutene), Epoxy from phenol, THF from processed plant sugars [14], among many others. The symbiosis between biological and chemical systems is the bedrock of the KCSAR modern industrial economy.

2.2.2 Raw Materials and the Mining Process

There are a number of raw materials, such as iron and steel, that are required to build and sustain the economy of KCSAR, which can be acquired through mining. Mining bases on Mars need to be small and relatively self-sufficient, since transporting oxygen and water is not economically viable. As such, mining operations use a Zn/S/I oxygen generator, powered by a mass-produced kilopower-style [28] reactor. Water and CO_2 are extracted from the air using ionic liquids, which become inputs to the Zn/S/I plant and the water recycling plant. The water recycling plant takes in recycled waste water, extracted via the TSSE process detailed in section 2.1.3, and rejects concentrated brine as waste. This process is sufficiently efficient to allow for metabolic water production and imported foods to meet the water needs of the small base.

The majority of the mining operation is performed by semi-autonomous robots that are mass-produced using interchangeable parts found on KCSAR, as illustrated in 6. There is some oversight required by mining technicians, whose role it is to (a) ensure that the robots complete the desired tasks, without engaging in dangerous or counterproductive behaviours, (b) issue override commands to redirect robots in the event that they are incapable of completing the task, and (c) provide maintenance and repair support for the robots. The primary form of transport for personnel and cargo between the main settlement and the outlying mining settlement are autonomous trucks. However, trains are also used within areas that exhibit elevated congestion. To support the mining colonies, cables and pipes traverse alongside the roads to nearby settlements, so that there is access to power and copper or optical fiber for telecommunications.

While there are several resources that can be mined to support the Martian economy, this paper specifically focuses on the production of iron and steel, due to the fact that they are necessary to sustain a variety of industries on Mars, such as construction and manufacturing. Since oxygen is expensive to produce on Mars, the standard oxygen-intensive iron production method is prohibitive from a cost perspective. Therefore, instead, we propose that a water-splitting Zn/S/I cycle be used

Product	Production Process
Benzene and its derivatives	BXT [15], along with Phenol [16], Quinone [17], Aniline [18], among others [19] are produced from biomass, either directly through digestion, or via catalytic conversion of biological precursors.
Ammonia	This is produced through the combination of a catabolic degradation of protein [20] and a low pressure advanced haber reactor [21] utilising plant heat.
Ethene	This is produced via the dehydration of bioethanol, steam cracking of hydrocarbons, or directly from syngas through a Fischer Tropsch style catalytic process
Sulfuric / Phosphoric Acid	Generated from acid gases produced in the metal refining process observed in section 2.2.2.
Nitric Acid	This is produced by the oxidation of ammonia.
Methane	This is produced through the sabatier [22] process using reactor plant heat, along with bioalkane cracking [23, 24].
Hydrogen	This is produced from water via the Zn/S/I cycle, via steam reforming of methane [25], as well as via ammonia decomposition. Storage of hydrogen chemically then allows for the non-cryogenic storage of bulk hydrogen.
Biomass	Biomass is mass produced in farms and in bioreactors. Specifically using Methanotrophs (*Methylococcus capsulatus* et al) fed on methane/methanol.
Methanol, Alkanes	These are produced either chemically from Syngas via the Fischer Tropsch process or other catalytic processes and plant heat, or biologically from biomass.
Syngas (H_2, CO)	Syngas is produced via the Zn/S/I cycle (as seen in 2.1.2) as well as through the gasification of Biomass.
Bioplastics	PHB, PLA and other bioplastics are produced from biomass.
CO_2	CO_2 is scrubbed from both the Martian atmosphere as well as artificial atmospheres through amine or ionic liquid scrubbing [26, 27] as seen in figure 3.
NaOH, NaOCl, Cl_2	These are produced in a standard chloralkali plant.

Table 1. Production processes involved in a range of bulk materials.

Figure 6. Artist's rendition of the automated mines.

to produce syngas which is then used to reduce iron oxides and produce sponge iron powder.

Direct reduction iron is implemented as described in [29] using syngas regenerated via a Zn/S/I cycle reactor. The iron ore will be ground into a fine powder and injected into a H_2-filled ceramic reaction vessel that is kept at 800°C. At that temperature, H_2 and CO reacts with iron oxides to form Fe, CO_2 and H_2O, while converting sulfides and phosphides back into their corresponding acid gasses. Once the output syngas stream is cooled and processed, the product gasses can be easily extracted. The acid gases can then be further processed to form sulfuric and phosphoric acid for industry and as critical components in biomass formation. The cold syngas stream is then reheated by a recuperator and reintroduced to the reaction chamber. While the syngas volume is reduced by the reaction, it will be replaced through syngas regenerated from the generated CO_2 and H_2O. The majority of the syngas is thus recycled, with small amounts of H_2O and CO_2 periodically added to replace losses.

The iron produced is a sponge iron powder that is not immediately suitable for construction, due to silica contamination. Therefore, the sponge iron powder is placed in a furnace with carbon and other metals to form bulk steel, which can then be cast into various steel products. An important example of such a steel product is heavy presses. Presses can take in large sets of sheet metal and hydraulically press them to fit molds, enabling the creation of very large, precisely manufactured, load-bearing parts, that are otherwise impractical to produce. The presses can then be used to construct things such as industrial machines, curved panels of domes, and support beams. These manufactured parts may be used in the construction sector or in the production of capital equipment, contributing to the productivity of other Martian industries. Similarly, the iron powder is also refined through iron carbonyl [30] to form pure iron powder, which is suitable for laser or electron beam 3d printing. Electron beam metal printing is relatively practical on Mars, as the lower atmospheric pressure makes the construction and maintenance of large pressure chambers simpler, allowing for the creation of larger parts.

2.2.3 Consumables and Factories

One of the pertinent challenges that has pervaded much of our discussion of KCSAR is its reliance on domestic manufacturing due to the high cost of imports. Given the availability of several bulk and raw materials, as reflected in sections 2.2.1 and 2.2.2, it is possible to develop and manufacture a range of specialised goods and consumables directly on Mars through the industrial sector - a key component of the Martian economy. To put this in context, importing complete objects such as computers is uneconomical, however, importing specific parts such as bare silicon wafers are relatively cheap, and can then be cost-efficiently transformed into packaged silicon chips, which are crucial for many processes. To support the development of bespoke capital and consumer goods, capitalising on 3d printing and other additive manufacturing processes is important. However, it is worth noting that current 3d printing technology is prohibitively expensive and slow at scale, which forces KCSAR to rely primarily on more traditional manufacturing systems for bulk items, at least until the technology further develops. Electrical Discharge Machining is used to produce injection molds for the mass production of high precision plastic parts made from bioplastics, such as PHB. Since factory systems are only partially automated [31], a sizable labor force is required to produce goods for the local population, and as a result, factory workers make up a significant proportion of the population.

2.2.4 Internet

The internet-based economy will be a key sector, both as an enabler of the export economy and in meeting domestic demand for communications and access to a forum for creating and sharing cultural products. The provision of stable, affordable internet service is therefore crucial. Long range lasers are used for packet forwarding at the link layer, from an HEO outer shell of the Starlink constellation on earth and a similar constellation in HMO. Both constellations form Autonomous Systems, extending the route advertisements of Earth and Mars to each other. Using the OSI model, this is then the L3 of the Martian internet.

The key issue is that, while packets can be routed and sent, the time delay prevents the use of higher level protocols. As such, KCSAR's ISPs provide L4/L7 proxy services, similar to a traditional VPN service, that proxies connections on Earth via a proxy that understands the time delay. Existing CDN technology, such as NAPs are then used to allow large scale content providers (such as Youtube) to deploy content on Mars, with application-level changes that adjust for the increased spooling delays. An example of such a change is that movies or content created by artists that a user has 'subscribed' to are uploaded automatically, making them accessible from a local data center. If an individual clicks on a link that is not cached, they will be brought to the holding page, while the page is spooled from Earth and added to the local cache. Once added, it can be accessed almost instantly. ISPs provide caching proxies for most users but for security reasons, many companies run their own, renting capacity from Earth.

2.3 A Market for Martian Products

In this section, we briefly outline the endogenous formation of a stable market for the products outlined in 2 thus far. We take the bulk products market as an important representative example, with a focus on the market for oxygen, to show how projected market demand drives the production of an appropriate range of goods in the most cost-efficient ways possible. We propose that the success of KCSAR's markets derives from its focus on maintaining different production pathways for the same goods, thereby enabling the creation of a futures market that stabilises supply chains, while optimising for the lowest cost production method at any particular time.

We consider a simplified model for the production of oxygen to show how the presence of two production pathways offers both stability and efficiency - photosynthesis in farms, and electrolysis. Even with robotic construction, the fixed start up costs associated with acquiring land and converting into a functioning farm are substantial. Once the farm is up and running, however, the per unit cost of oxygen is relatively cheap but it is slow to produce and there may be substantial variability in yield. By contrast, while a basic electrolyzer has a low cost per unit, the high cost of electricity makes the per unit cost of oxygen substantially higher than that produced through photosynthesis but it can be produced rapidly to meet consumer demand. As such, in this simplified example, the stable component, which forms the majority of oxygen demand, is produced via the farm method financed through a long-term business loan. The final volatile component of demand is met through the use of electrolyzers, which can ensure that consumer demand is met, at a higher marginal price.

The mechanism that efficiently allocates which production method is used is underpinned by the bulk goods market. The bulk goods market is based on two types of contracts: immediate sales contracts, which form the spot market, and future sales contracts, which underpin the futures market. The spot market enables instantaneous trades for consumers with fluctuating needs or producers that need to rapidly vary their productive output but levies a premium associated with the higher cost of rapid production (In our example, oxygen is produced through electrolysis to supply the spot market). The futures market, by contrast, enables suppliers and consumers to lock in long term production plans, minimising production costs but limiting their flexibility (by producing oxygen through farming). While individual consumers struggle to project their demand their individual demand, limiting the effectiveness of the futures market, financial intermediaries, generally banks, forecast aggregate demand and supply of bulk materials and operate as representative consumers. If their financial models predict a shortfall in the supply of methane, for example, these intermediaries buy up futures contracts at a an above market price and store the methane in space rented in the cryobattery. When the shortfall arrives, they then sell their methane stockpile, stabilising the market supply and helping to stabilise the long term price of commodities.

3. Life on Mars: Society and Economy

Having outlined the technical processes needed to sustain human life on Mars in 2, in this section, we lay out the defining characteristics of KCSAR's social and economic makeup. Throughout, we integrate commentary on the ways in which KCSAR's political, cultural and aesthetic makeup contribute to its vibrant society.

3.1 Governance

The KCSAR political system embodies the most direct feasible form of democracy, a delegative democracy. It has been argued that one of the greatest benefits of a direct democracy, is that it acts as a constraint on the actions of political elites, forcing them to represent the interests of the populace at large and to adopt cooperative rather than confrontational strategies [32]. In practice, the direct democracy of KCSAR is governed by four distinct branches, with government powers separated between the executive, legislative, judicial, and an auditor branch.

Procedural laws substantially limit the powers of each of the branches of government, enforcing substantial oversight from each branch upon the others and requiring that for any substantial change in policy or exercise of non-standard powers, the issue is put to a ranked choice vote by all citizens. Additionally, where matters of judicial interpretation or issues raised by citizens receive a sufficient amount of public support, they are put to a vote. Thereby, citizens directly determine government decisions.

These democratic arrangements are unpopular on Earth primarily because of the prohibitive time cost associated with voting on such a broad range of issues. In KCSAR, this cost is limited through a system of vote delegation by which citizens may delegate their voting right to other individuals or between individuals based on the subject area of the vote. For example, a citizen may delegate their military decisions to person X and economic decisions to person Y. These delegations may be changed at any time and are supported using cryptographic primitives such as homomorphic encryption and linkable ring signatures, allowing for both anonymous voting and cryptographic security [33].

To incentivize the emergence of delegates and enable them to publicize their voting positions, the government provides a stipend proportionate to the number of votes a delegate receives. Strict campaign financing laws prevent the use of external funds or exercising undue influence to promote a viewpoint. To ensure that decisions are data and logic-led and that a full range of opinions voting options are represented, 'index voters' - robot delegates that vote on specific issues which follow simple 'if then' logical statements or rely on more advanced techniques from machine learning - are employed. The data and logic used in their decision-making is open to the public and auditable.

3.2 The Malthusian Trap

The Malthusian Trap emerges where the average individual within an economy produces only as much as they require to live over their life cycle. Modern credit systems reframe the traditional problem by offering emerging economies the ability to finance the 'importation' of a high total factor productivity by utilising capital-intensive productive technologies. The viability the KCSAR economy thus turns on its ability to sustain a high enough economic output to exceed the combined costs of its existing debt burden (interest and loan repayments) and the costs of supporting its citizens. Hence, maintaining a high GDP per capita is the primary concern of KCSAR's emerging economy and its social design prioritises the maximization of GDP per capita, while supporting a more equitable distribution of resources than that found on Earth. Relatively equitable distribution of resources is important not only in ensuring that all citizens are provided for and live a life without poverty, helping to enhance social stability, but also in generating higher domestic demand and therefore enabling higher productivity gains through economies of scale. [34]

3.3 Immigration

Having highly productive citizens is a key priority of KCSAR. High demand to be part of Earth's first extra-planetary colony provided the opportunity to select for ideal candidates using an AI-based actuarial model of a citizen's lifetime production and an AI-based forecast of the skills needed by the colony. As re-skilling on Mars has a substantial time and monetary cost, having a diverse range of essential skills (detailed in 3.8) represented among the first settlers was a precondition for the success of the colony and avoiding critical skill shortages remains a key target of the education system. However, the cost of travelling to KCSAR (USD 500k approx.) made and continues to make it difficult for otherwise ideal candidates, who are young, well-educated and therefore have limited wealth, to immigrate. The government subsidizes or underwrites a portion of these individuals' ticket prices, enabling them to access commercial loans by reducing the risk to banks of their default. Friends and families of family members are also encouraged to pool collateral to further reduce the risk associated with commercial loans. Thus, government interventions provide the opportunity for Earth's 'best and brightest' to join KCSAR.

3.4 Fertility

In the presence of extremely high immigration costs, for an isolated colony to maintain its population, the fertility rate must remain above the replacement rate (approx. 2.1 children per person capable of bearing children). In most developed nations, the fertility rate has been rapidly declining and the direct importation of the culture surrounding fertility in those nations to KCSAR would result in demographic collapse. The incentivization of child-rearing is therefore a first order concern.

In KCSAR, direct economic incentives, are offered to guardians proportional to the number of children for which they care and these have been shown to improve fertility outcomes [35, 36]. For example, a Universal Basic Income ('UBI') is offered for each minor for which a guardian cares. Additionally, non-cash incentives such as additional leave and guardian allowances are offered. These incentives are routinely adjusted to maintain a stable fertility rate and help contribute to a culture that celebrates caring for large families while continuing to productively contribute to KCSAR society.

As the cost of raising children is substantial in both direct costs (such as providing food and atmosphere for the child) and indirect costs (such as the loss of productive labor of parents) KCSAR is concerned with the 'quality' of children - their capacity to contribute to GDP - as well as their quantity. 'Embryonic selection' is used to select for the most fit potential children. Gametes are extracted from parents and fused to form blastocysts [37]. A cell is taken from each blastocyst and its genome is fully sequenced using a nanopore sequencer. The full genome sequence is then processed to generate a polymorphism map that is analysed using artificial intelligence to determine a 'fitness' index score. To estimate this fitness function requires the search space be both explored and exploited simultaneously, posing a 'one-armed bandit' problem. Therefore, we use a regret minimising strategy to estimate the value to both individuals and society of particular phenotypes.

The KCSAR also faces a phenotypic diversity bottleneck created by the small size of its population. Studies have shown that a lower limit on a genetic bottleneck is in the tens of thousands, with higher estimates for K selective species like humans that have few offspring but vast resources available for them. As the population must thrive while adapting to the Martian environment, genetic diversity must be thought of as a resource with risk amelioration benefits even for a population as high as one million. Therefore, frozen gametes from screened and compensated individuals are imported to the KCSAR en masse. The transport costs are relatively low due to the light weight of the cargo.

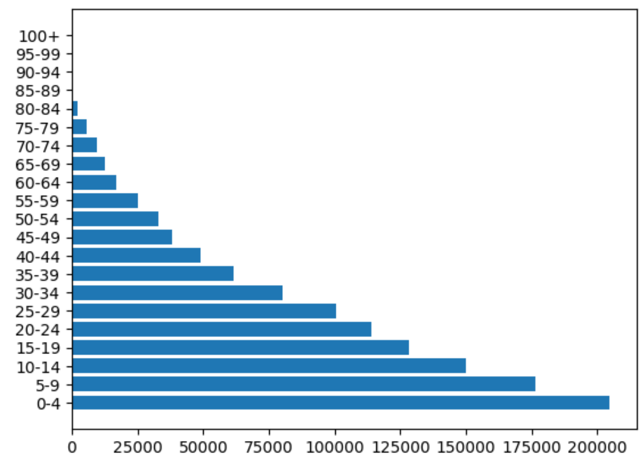


Figure 7. Implied demographic pyramid

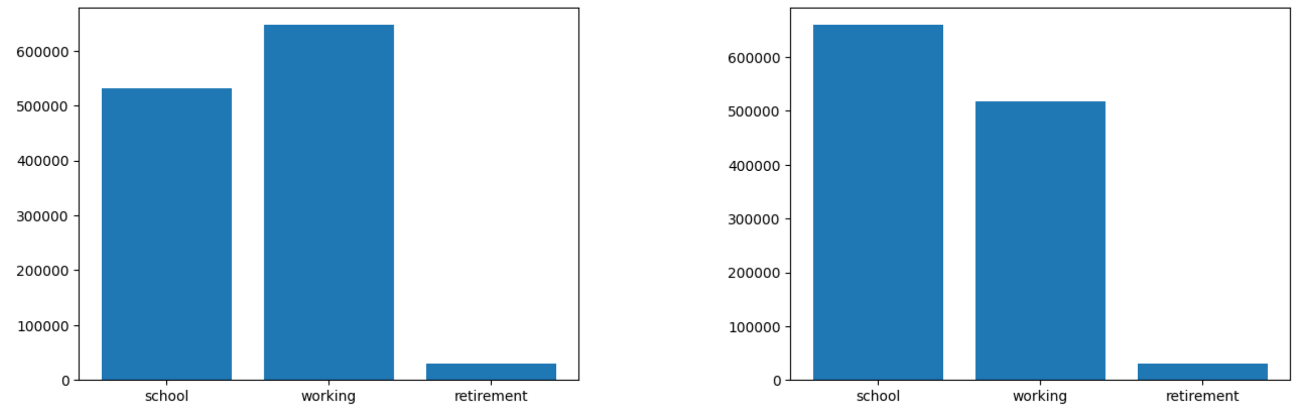
3.5 Demographics

To project KCSAR's population demographics, we scale demographics from Gambia, which has a similar fertility rate (3.5 children/woman) and population growth rate (40%). [38] In 7 we approximate a demographic pyramid for KCSAR.

Young children and the elderly are not part of the labor force and are provided for by the government. As the cost of providing for non-productive individuals is much higher on Mars than Earth, the proportion of people who are part of the working population must be relatively high. Assuming various cutoffs for the working age population, we project the occupations of citizens in 8. It shows that the age at which young people enter the workforce has a dramatic impact on the ratio of working age people to others in a society with such a high reproductive rate. While the proportion of the population entering retirement is low, children engaged in schooling are a substantial burden on KCSAR.

3.6 Education

Optimising the educational process and limiting the amount of time spent in education is one of the key methods to increase the size of the working population. With the advent of the information age, ever more efficient educational methodologies have emerged. KSCAR's educational facilities rely on developments in AI-assisted learning such as in optimising curriculum to the needs and abilities of individual students and in adapting examination difficulty to the level of students. Students are grouped together by ability, rather than age group and provided access to pre-recorded lectures, teaching assistants and learning materials from a variety of sources, enabling them to take ownership of maximising the speed of their learning experience. Curricula are simplified and specified to the greatest extent possible so that students are prepared to enter an occupation that reflects both their preferences and ability. Particularly for children, methods that focalize 'learning through playing' and student enjoyment are preferred to foster a culture that values and enjoys the process of learning and



(a) Workforce aged 15-64

(b) Workforce aged 20-64

Figure 8. Impact of working age cutoff on size of labour force

work.

3.7 Work

The majority of the workforce are engaged in key sectors laid out in KCSAR's technical design and the largest proportion are engaged as factory workers. KCSAR does not receive natural sunlight, so rather than relying on traditional day-night shift working cycles, KCSAR workers work to an eight-hour shift cycle that enables continuous work. To maximise the working population proportion, full employment is sustained through a federal jobs guarantee. All able-bodied workers are provided work at below market wages, enabling otherwise unemployed labor for government operations and ventures. Workers are also encouraged to engage in education to reskill to meet the needs of a dynamic labor market and are provided significant subsidies.

3.8 Critical services

Much as the mass production of goods is needed to fulfil the material requirements of the settlement, ensuring that the critical services are adequately staffed is crucially important for the settlement to function cohesively. Critical services range from the roles that require significant education, such as doctors and chemical engineers, through to traditional roles in the trades, such as electricians and plumbers. To ensure that there is a reasonable distribution of human capital across key service sectors, the Department of Labor is responsible for monitoring the economy and predicting the required number of each type of critical service worker. This process is facilitated by machine learning models that analyse the movements of the labor market as well as the supply of human capital from educational institutions. When these models predict that there is a shortfall in supply, policy levers are used to incentivize more citizens to become critical service workers.

3.9 Retirement

KCSAR follows the Singaporean model for retirement saving. Each employee pays 10% of their gross income to purchase units of the KCSAR Sovereign Wealth Fund ('KCWF'). The KCWF is a trust, managed by the government, which invests in the equity and debt of local businesses. The value of the KCWF grows at the roughly average rate of the market on KCSAR. On retirement, workers sell down their units to fund a pension. For most workers, this is a sufficient pension but the government contributes to pensions that do not meet a specified living wage cutoff. The sovereign wealth fund receives proceeds from the sale of land, mineral rights, patents generated by public universities and other public goods.

3.10 Wages

All KC citizens receive a Universal Basic Income ('UBI'), which is a cash payment indexed to the cost of a basket of essential goods and services. The provision of a UBI produces a society in which the basic needs of all citizens are met, which has four primary benefits:

1. On Mars, where space and air have material costs, unemployment and homelessness have even larger social burdens. A UBI provides a security net, helping to tide people over and thereby reducing the number of people who are initially part of cyclical or frictional unemployment from becoming long-term unemployed.
2. Studies have shown that there is a strong association between relative poverty and crime. In a Mars colony, where crime is relatively difficult and expensive to prosecute, making sure that all individuals have access to a living wage may be a cost-saving measure [39].
3. It provides support to unpaid care workers and individuals who are not engaged in the formal workforce. This in turn relieves pressure on public services that provide care to ill and differently abled people as well as incentivizing the growth of families.
4. It simplifies the provision of transfer payments to citizens by eliminating the need for secondary transfer payments.

The primary objections to a UBI are that it reduces motivation to work and that it perpetuates inequity, as the most wealthy individuals receive the same benefit as the poorest. Incentives to work still exist with a UBI as the receipt of a wage above the UBI award rate is associated with far greater access to luxury goods and particularly preferred foods such as fish and meat. Moreover, a UBI eliminates the structure of adverse incentives that may arise from other social security programs. Traditional social security programs may offer negative net wages for marginal increases in hours worked, whereas the return from work strictly exceeds the additional taxation burden under a UBI system. In KCSAR, the UBI also has a positive net impact on the equitable distribution of income as it is accompanied by a progressive taxation system such that for anyone of middle class or above, the total value of tax paid exceeds the value of the UBI.

While there is no economy-wide, government-mandated ‘minimum wage’ in the KCSAR, unions are formed within each major industry that then demand appropriate working conditions and remuneration for members. In guaranteeing that the returns of corporations are distributed to labor (rather than absorbed entirely by capitalists), labor unions serve an important role in allocating resources to the population most likely to spend them and encourage further growth, as the Marginal Propensity to Consume (‘MPC’) of workers is higher than that of wealthier business owners. These labor unions will operate as delegative institutions. As companies grow larger, the importance of their unions also grows and unions will take on a direct oversight role as members of the company board.

3.11 Taxation

The taxation mix broadly aims to incentivize taxpayers to engage in the most efficient economic activities (maximising GDP per capita) whilst remaining progressive (maintaining a minimum degree of inequitability). The largest component of the taxation mix is a simple income tax, that is highly progressive and ensures that the net effect of the UBI is positive for low income earners but negative for higher ones. Additionally, a substantial inheritance tax will be utilised to reduce wealth inequality and encourage social mobility. Lower wealth inequality is associated with higher capital mobility, as wealth is negatively correlated with MPC and higher social mobility likely improves labor engagement and provides incentives for hard work and innovation [40].

Taxation is also used as a lever to encourage productive economic behaviors. Capital gains taxes are levied on the increased value of capital goods with active asset rollover exemptions that allow for deferral or reduction of tax burden if the profits generated from the sale of a capital asset are reinvested in new capital assets. This creates an incentive for individuals to reinvest returns, helping to improve liquidity in the capital market and grow the economy as a whole. Land value taxes are levied on the unimproved value of the real estate of the colony (on shops, apartments etc.). This creates an incentive for land to be used for its most efficient purpose and thereby encourages the endogenous formation of regional specialisation. For example, if an area of land were an industrial zone, and it would be more productive for that land to be used for the creation of a shopping area, the tax provides an economic incentive for the industrial zone to relocate, likely to areas that already have a mass of industrial sites, where firms can benefit from the economies of scale of regional specialisation.

3.12 Property Market

Within the city of KCSAR, land is granted to private individuals for a fixed duration and may be traded, mortgaged and rented. As each new section of the city is built, the ‘land’ inside is sectioned off for land deeds with a fixed ownership term, which is its design refurbishment lifetime (around 30 to 50 years into the future). On the expiry of the grant, the land is returned to the government, refurbished, redivided and reallocated. This model leads to land growing cheaper over time, making it more accessible to first home buyers. Additionally, mortgages are easily bundled together into collateralized mortgage obligations and are traded between banks, providing a substantial source of liquidity for the short term loan market.

3.13 Regulation of Natural Monopolies

Many of KCSAR’s essential markets are natural monopolies in which the cost function of mass production is more highly correlated with the number of distinct designs produced, rather than the number of items that each produces. In particular, regulated modules are the building blocks of the multitude of designs required to service the colony’s needs. As these must be produced at scale, through an Original Design Manufacturing model, to minimise costs, they form a natural monopoly. To make these monopolistic industries profitable, while limiting the undue usage of monopoly power, a regulated utility corporation model is used. Candidate organisations are offered monopolitic control over a sector as well as cheap loans provided through the KCWF in exchange for significant public oversight. The charters offered to these organisations issue board seats that are mangaged by the community through delegative democracy. The audit branch is given additional powers to inspect company documents, ensure compliance and to provide the public a means of redress. This oversight also ensures that these corporations are extremely stable, making them ideal candidates for conservative investors.

3.14 Law and Order

On Mars, the cost of incarceration is prohibitive, as the cost of space and providing for individual citizens are extremely high. KCSAR implements a rehabilitative rather than retributive model of justice that aims to limit the incentives for crime and to prevent the emergence of environments that may encourage radicalisation. It prioritises early intervention programs that identify and satisfy the needs of citizens experiencing hardship. The political and economic system outlined above also ensures that every individual has a say in government decision-making as well as access to meaningful work and the promise of a bright future. This removes some of the key incentives around which larger scale structural crime might develop [41]. Policies and monitoring are also implemented to prevent ghettoization, and thereby structural disprivilege that may lead to structural crime.

3.15 Leased Rockets

An increasingly mature market for leased rockets is pivotal in the reduction of costs associated with interplanetary travel and for the viability of interplanetary trade. A leasing market for reusable rockets enables relatively small companies involved in interplanetary travel and commerce to operate despite extremely high startup costs. As rockets are extremely expensive purchases and proper actuarial models to determine the risk associated with the asset did not yet exist, an insurance policy for the potential shortfall was created to ensure the profitability of investing in rocket ownership. The insurance policy relies on the usage of catastrophe bonds and government intervention through targeted reinsurance programs that restrict the unhedged risk to the insurer to standard commercial risks (a Credit Default Swap). This enables the repackaging and reselling of debt with the same credit rating as the insurer and thereby the on-selling of leases on the wholesale debt market, refilling the initial fund and including extra profit on the lease. As the market continues to mature and the asset risk is better understood, liquidity continues to improve.

3.16 Significance and Composition of Trade

As an isolated colony, KCSAR remains dependent on key imports from Earth including pharmaceuticals; chemical reagents that are prohibitively expensive or impossible to produce on mars; silicon dies; and other consumer and capital goods. As the cost of transport is prohibitively high at $500/kg, these goods are imported in their most weight efficient form. For example, bulk pharmaceuticals are transported as active ingredients and undergo final transformation on Mars. To incentivize importation of capital goods to improve firm productivity, the KCWF is also used to subsidise the import of capital goods.

To purchase these crucial imports, KCSAR must produce a sufficient quantity of exports. The prohibitive costs of transporting goods to Earth ($200/kg) requires that only products with extremely high value-add to weight ratios be exported. These products include:

1. Precious materials are mined from asteroids near Mars by 'Honeybee-style' automated robotic mining [42]. Modelling of the price elasticity of demand for gold, platinum and other precious metals indicates that significant quantities may be exported before oversaturation of supply makes it uneconomical. The movement of mined goods and intra-colony trade is facilitated by 'nuclear hoppers' - relatively cheap reusable single stage nuclear thermal rockets that use martian CO_2 as propellant [30].
2. Fuel mined from comets is exported to refueling stations around the solar system. These stations enable spacecraft that would only able to reach Low Earth Orbit to reach Mars and the outer solar system via an on orbit refueling stage.
3. Creative and productive intellectual property produced on Mars serves as a key export. In particular, on Mars, there is a greater imperative to semi-automate or completely automate tasks, producing a comparative advantage in the creation of some AI systems, designs and datasets. Where applications for efficiency gains in Earth-bound processes are found, these assets are exported with close to zero marginal cost.
4. The sale of debt and equity will also serve as a key 'export' that will finance ventures on Mars, helping to stabilize the balance of trade. In particular capital intensive projects such as mining ventures and infrastructure projects will require external financing which will be recorded as a credit on the capital account.
5. Mars will also has a competitive advantage in the building and operation of telescopes, probes and landers that are to be launched to the far reaches of the solar system. For example, the building of large scale mirrors is far easier on Mars due to its low gravity and access to a vacuum. Some peaks on Mars, such as Olympus Mons also serve as a good location for deep field astronomy.
6. Mars is an ideal candidate for large scale nuclear production, so isotropic extraction from spent fuel will be a significant source of revenue. Nuclear isotopes such as ^{238}Pu, ^{90}Sr, ^{241}Am and ^{60}Co are extremely expensive on Earth but would be relatively easy to produce on Mars. In particular, ^{238}Pu is a major component in radiothermal generators, used in deep space probes that are likely to be built nearby. Extraction of fission product rare earth elements also provides a non-terrestrial source of these indispensable elements.
7. In the future, it's likely that more uses for zero and low gravity, large vacuum environments and large ultracold environments will emerge. It is already clear that some types of research and some types of production are either only possible or substantially easier in these environments. Leasing out space in KC and providing labor to conduct experiments and create these goods may therefore constitute a substantial source of revenue. Examples of these include Quantum Physics research, the production of ultra-low loss ZBLAN optic fiber[43], the production of various alloys of reactive elements[44], and 3d printing of organs[45]. As the price of trade falls, as discussed in 3.17, there will be more accessible opportunities to capitalise on the comparative advantage of these environments accessible in the KCSAR.

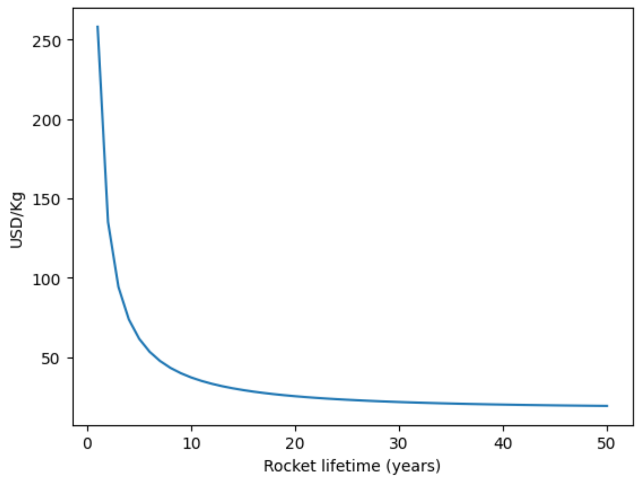


Figure 9. Launch price to mars vs. reusable rocket lifetime

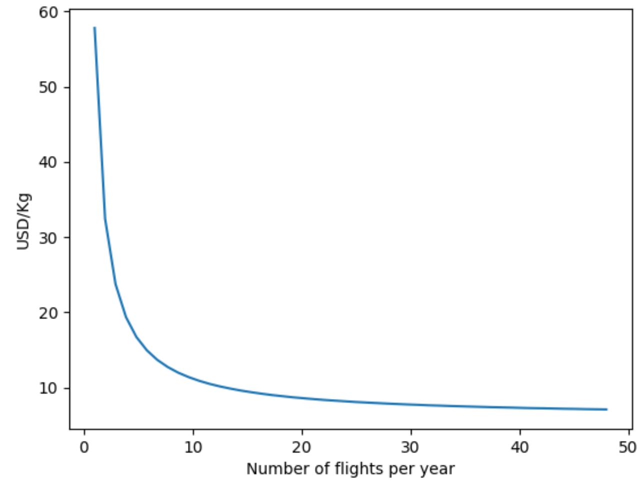


Figure 10. Launch price to mars vs. number of flights per year at fixed 10 year lifetime

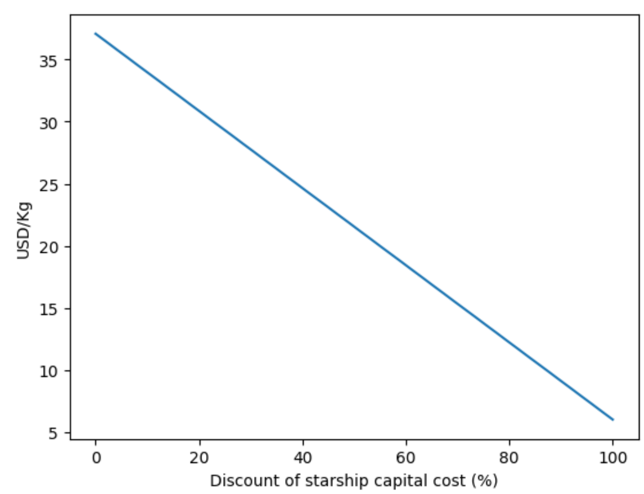


Figure 11. Launch price to mars vs. discounted capital cost

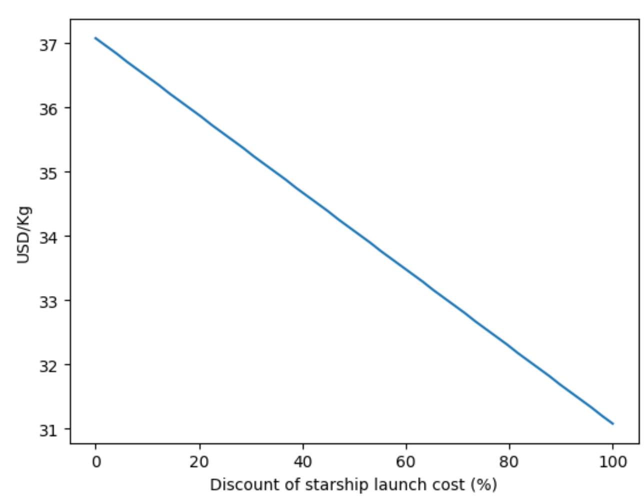


Figure 12. Launch price to mars vs. discounted launch cost

3.17 The Mechanics of Trade

The exchange of packages through the inter-planetary postal services is the basis for trade between KCSAR and earth-bound parties. The KCSAR is a member of the United Postal Union (UPU) and therefore part of the standard postal infrastructure between member states. The distribution network relies on 'multi-modal' routing, by which packages are carried by the most cost (or time, depending on the cargo) efficient mixture of trucks, trains, boats, planes and cargo rockets, which form the final step in transport from Earth to Mars. Cargo is transported in standardized containers, allowing for the economies of scale created through standardized packing and handling that have been realised on earth to dramatically reduce the cost of transporting goods to Mars [46].

As Mars is crucially reliant on imports of some necessities, the economic viability of the transportation system that underpins trade is a primary concern. The key results of a sensitivity analysis, shown in 9, 10, 11 and 12, indicate that the primary mechanism for reducing the transport cost for delivery of freight to Mars is increasing the lifespan and reusability of leased rockets (at least to the 10-year mark). We take the partial derivative of price with respect to a vector of potentially explanatory input variables to provide an indication of how much a change in each factor would impact price. While the rocket lifespan effect dominates, secondary factors such as reducing launch costs (by, for example, connecting the launch complex on Earth to a natural gas pipeline) and reducing the cost of rockets would have significant impact. The technological innovation and reduction in cost of factors of production necessary to change these key factors is most easily stimulated through economies of scale. To enable these economies of scale, a significant market must be generated to enable producers to benefit from scaling up production facilities and investing in research and development.

Two mechanisms are used to generate stable demand for interplanetary trade and thereby capitalize on scale economies:

government intervention in its futures market and competition regulation. A futures market for interplanetary trade emerged endogenously, helping to stabilize the demand for and price of traded goods and thereby enabling small and marginal producers to reduce their exposure to liquidity risk and enter the market. It also encouraged more efficient allocation of resources over time. The government intervened by providing a demand floor for interplanetary trade by consistently buying futures for freight transport and using them to transport mail, capital and other government materials. This provided the stable demand requisite for the realization of economies of scale, which, in turn, reduced the cost of transport, increased the quantity of trade traffic, and the broadened the composition of trade as lower prices make more trades profitable. This increased and broader trade base then stimulated economic growth both on both Earth and Mars.

An independent watchdog monitors, reports and provides recommendations to the government on non-competitive behaviors in the rocket production industry. Due to the substantial start-up costs and competitive advantage associated with holding intellectual property in the industry for producing and maintaining rockets. The emergence of vertically integrated firms and firms with substantial market (monopolistic) power is therefore likely. Through the use of the leased rocket model, non-integrated rocket production companies can easily support an ecosystem of launch providers if they are encouraged to through substantive oversight. A substantially competitive market will keep the costs of production low and encourage innovation amongst competing firms.

3.18 Culture and Architecture

Given that the residents of KCSAR face extraordinary labor and resource scarcity and live in closely contained quarters, it is critical its emerging culture is one that: (a) cultivates a passion for work that is motivated by a desire to advance the collective interests of the colony, (b) values close communal relationships, (c) fosters and applauds innovative thinking, (d) promotes an appreciation and love for both knowledge acquisition, and knowledge sharing, through a life-long pursuit of education, and (e) celebrates large families. To develop these cultural tenets, many of the societal superstructures (e.g. the design of shared spaces, immigration selection criteria, human resource allocation, food manufacturing, among others), are implemented in a way that aligns with and encourages this cultural ethos.

Perhaps the most powerful example of such cultural 'nudges' is in the aesthetic and architectural design of KCSAR's city. While on the surface, the architecture appears to be dominated by function over form with small pressure domes being the norm, as seen in figure 1; it is underground where the culture is brought to life with a sophisticated style that captures the cultural significance of the various spaces, and the cultural essence of the society as a whole. For example, industrial areas are of the brutalist style, made up of blocky, cheaply mass-produced segments, reflecting the role of these areas as

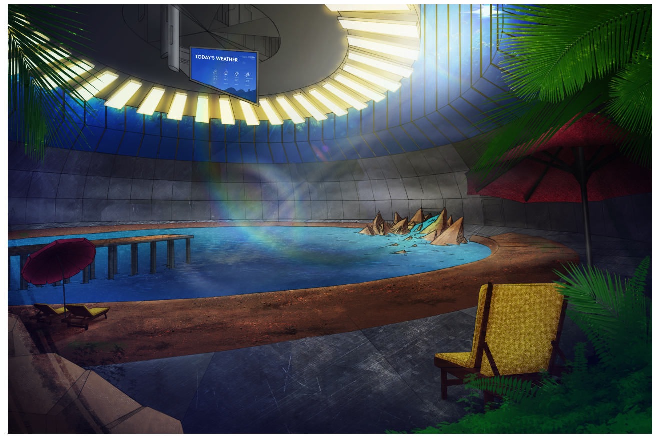


Figure 13. Artist's rendition of the underwater beach

the functional drivers of KCSAR's economy. Government buildings, by contrast, use a formal neoclassical style as a reminder that the people, and their government are the living heart of KCSAR's culture, while emphasising the government's role as servant to its people. In recognition of the cultural aspects of human achievement and our need to be in spaces that encourage unity and collaboration, while simultaneously reminding the people of KCSAR that life extends beyond the confines of factory labour; the important common social areas such as opera houses, and theatres provide the most compelling of designs. Using the design tenents of Parametricism, these buildings are 3d printed into unique and visually striking shapes that capture the artistic essence of the space. With values of openness, communication, and collaboration at the epicentre of KCSAR's cultural epoch, common spaces are specifically built with a design dogma that aims to reflect these ideals through the thematic concepts of 'green space' and 'blue space'. In practice, this means that there is an emphasis on local gardens, plants, and water features, along with more striking transparent plastic segment walls that look up into the ice or subglacial lakes. Fountains and other natural water features are used to dual effect. On the one hand, they enhance the natural aesthetics of the environment, while on the other hand, they functionally aid in maintaining the atmosphere. Lights under the transparent segment also illuminate the environment, while providing the stimulation needed for the seeded photosensitive marine life.

Two extremely unique pieces of architecture in KCSAR that really capture its values, are (1) the government mandated and government-subsidised cultural centre that exists at the focal point of all domes, and (2) the underwater beach (13) that is designed to give residents a place to unwind after a challenging day at work.

The cultural center is made up of three concentric circles defined by an open plan aesthetic that encourages social engagement. In the innermost circle exists a place where community members are provided with a range of amenities. These include free access to the internet, luxurious recreational seating, local food delicacies. Here, they are also encouraged to engage in prize-giving activities that foster intellectual expression, such as debates and hackathons. To reach the innermost circle, community members make their way across the two outermost circles, which are designed to share and celebrate local achievements. For example, local artists and hospitality workers are encouraged to express themselves in the outermost circle, with public displays of original music, food, and art. Government grants are available for the creation of such works. In the middle circle, virtual presentations adorn the walls, showcasing the accomplishments of local scientists, innovators, and business champions. In this way, a cultural ethos that simultaneously perpetuates artistic expression, intellectual inquiry, originality, innovation, and collaboration is encouraged.

The underwater beach is a dome segment that is set under the ice, such that the water pressure on the outside of the segment is equal to the air pressure inside the segment. This then allows for small openings to be made through the dome, which facilitates the free movement of marine life between a small artificial pond in the sand and the wider sub-glacial lake beyond. The segment itself has a transparent roof and wall, overlooking the lake itself. Consequently, this almost transforms into an artificial subtropical biome, with a base that is mostly filled with crushed regolith as sand, overhead lights, and waste heat from the reactor, which makes it an ideal home for a teeming artificial ecosystem. The vista of the surface through the ice is illuminated by a set of floodlights, providing a stunning view that makes the seating around it a popular space for KCSAR citizens to rest and unwind after a hard day's work.

It is also worth noting that the government takes a more direct role in encouraging socially beneficial behaviours, by providing economic incentives for individuals to engage in things like childrearing and education (as detailed in sections 3.4 and 3.6), as well as providing educational campaigns such as TV infotainments that reinforce certain cultural tenets (i.e. the importance of communal engagement). Since living and working in the difficult close contact conditions of a Mars colony has ramifications for people's mental health and life satisfaction, these programs encourage people to form tight-nit relationships with their close neighbours and provide information about how to form supportive relationships that improve mental health outcomes. Self expression through the arts and recreational activities are also highly encouraged and subsidised through government grants.

4. The future of KCSAR

To this point, we have laid out the bare bones social and economic processes needed to support a colony of one million people facing pressing existential risk. We turn now, by way of conclusion, to look at what the future will hold.

Over the coming years, a substantial geoscaping operation will be implemented to make the Crater habitable for humans. A central aluminium space frame-style construction with a series of support pillars will hold up a cover, consisting of a thin PHB or other bioplastic layer and a clear layer of lipid-derived wax, acting as a counterweight to the air pressure beneath and as thermal insulation. This greenhouse structure will be filled with the potent greenhouse gas, SF_6, until it raises the Crater's temperature above 0°C. The Crater's ice layer will then melt, forming a stable glacial lake as the Albedo drops. Evaporation of water vapour from the lake then occurs, enhancing the atmospheric pressure within the Crater beyond the Armstrong limit. O_2, N_2 and Ar will then be pumped into the atmosphere to make it habitable for human and other air-breathing life.

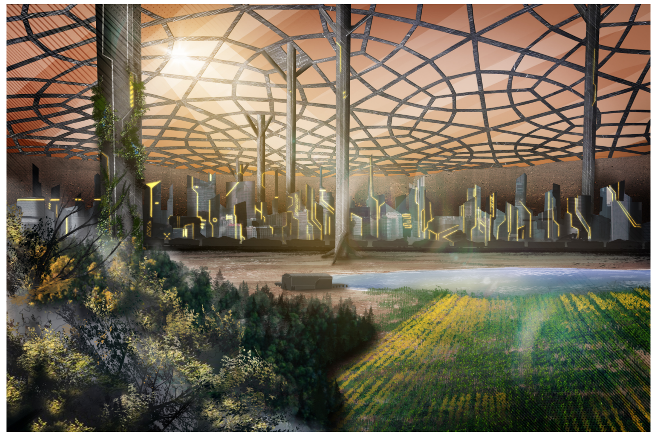


Figure 14. Artist's rendition of the future terraformed crater

The lake will be seeded with nutrients, including metal trace nutrients, sulfates and phosphates to make it habitable for plants and algae. Azolla and algae will be added to produce food and oxygen, whilst fixing nitrogen from the atmosphere. Once it is habitable, the lake will be seeded with fish that will become an important food source for the KCSAR colonists. The upper barrier will form artificial rain clouds as it cools warm moist air that condenses into water and falls as rain. Animals will be able to walk freely about the surface and the lake will be green with life. An artists rendition of this end state, the dream of the Korolev Crater, is depicted in 14.

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