Mars Manufacturing Settlement

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Envisioning a future Mars city and manufacturing center as if it were already built, this paper describes Leominster, a settlement accommodating several hundred people. The paper defines the potential manufacturing systems, technologies, and economic value of a Mars settlement. It also addresses the challenges of safety, pressure, temperature and radiation, which are often ignored in other designs. Novel architectural systems involved in Leominster's design include: regolith-based masonry, bricks, fiberglass, and ceramics made with a solar furnace. The settlement also uses cement, metals, regolith for shielding, and SpaceX Starships or similar landing craft in its construction. A new aspect of the design is a spacious park with the canopy tied down with cables, resembling a cathedral, as an answer to the hard-to-build domes of other designs. Some of the architectural elements are borrowed from previous Mars Foundation designs. There is significant reliance on plastics and carbon-based materials for polymer membranes, plastics, food, fuel, fabrics, and even fungi-mycelium-based furnishings. Such a Mars manufacturing settlement could demonstrate economical construction and living methods beyond the Earth. This could lead to economic development and spreading of life throughout the solar system.

Nomenclature

3D	=	three-dimensional
AL_2O_3	=	aluminum oxide
atm	=	atmosphere
$C_2H_2(CO)_2O$	=	maleic anhydride
C_2H_4	=	ethylene
C_4H_8	=	butene
C_4H_{10}	=	butane
$C_6H_6O_3S$	=	benzene
CH_3OH	=	methanol
CH_4	=	methane
Cl	=	chlorine
CO	=	carbon monoxide
CO_2	=	carbon dioxide
Fe	=	iron
H_2	=	Hydrogen
H_2O	=	water
ISRU	=	in-situ resource utilization
km	=	kilometer(s)
kW	=	kilowatt(s)
kWh	=	kilowatt-hour(s)
LOX	=	liquid oxygen
m	=	meter(s)
MWe	=	Megawatts (electricity)
Mg	=	magnesium
NH_3	=	ammonia
O_2	=	oxygen
PEMFC	=	proton exchange membrane fuel cell
PET	=	polyethylene terephthalate
sec	=	second
SO_3	=	sulfur trioxide
VPO	=	vanadium phosphorus oxide

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I. Overview

This paper describes a proposed future (late 21st century) Mars Settlement, "Leominster," the first large settlement on Mars. As an alternative to the ubiquitous domes seen in most Mars settlements, which are hard to anchor down, this new settlement features a spacious, pressurized "park," designed for minimal stress on the canopy fabric enclosing it, which is anchored from the ground. The park also features a wide, unobstructed interior. Water is integrated into the enclosing membrane above for radiation shielding. Other architectural features are borrowed from previous papers by the Mars Foundation and others, including: modular cylindrical habitats, multi-story masonry structures for a "business district," construction facilities, industrial areas, and other functions.[1,2,3] As described, the population is arbitrary, starting with a few hundred people, but could grow to a few thousand.

Leominster, The Plastics City: Leominster ("LEM-en-ster") is named after Leominster, Massachusetts, USA, Earth; which calls itself "Pioneer Plastics City." The original Leominster, Earth, saw production of Celluloid hair combs and plastic toys, as early as 1914, by the Viscoloid Company, now part of DuPont. It was also known for developing plastic injection molding; the home of Tupperware; and even the hatching place of plastic pink flamingo lawn ornaments.

On Mars, plastics and various polymers will be critical, ubiquitous materials due to the absence of lumber and good iron ore. Much of the manufacturing at Leominster, Mars, uses various plastic raw material, finished plastic goods, and reinforced sheets of polymers for inflatable habitats.

Social, Demographics: Although built for manufacturing, as the first major population center on Mars, Leominster is the de facto hub for social activities, education, and culture among the early settlements. Most residents are young adults—single or couples—who immigrated from Earth. To support their lifestyle and to save them time after work, Leominster features many restaurants, fast-food stands, evening activities, and self-service stores. Of special note are catalog pickup stores, where household items can be custom laser cut and 3D printed based on product patterns from Earth. There are 50 young children, all under age 10, many born on Mars. The total population just passed 1,000 people, so it feels more like a village. It is growing very quickly due to immigration from Earth.

Geographic Context: Leominster, located south of the three Tharsis volcanoes at 40 degrees south latitude, was built next to a large ice deposit to ensure a steady water supply. The settlement has grown from a manufacturing town into a small city and now includes an extensive network of agricultural farms nearby. All manufactured equipment, habitats, and greenhouses on Mars are now constructed in Leominster. This makes the settlement the least expensive place on Mars for food and living accommodations, as there are no long-distance transportation costs for goods.

With the settlement's lower cost of living and social amenities, most teleoperations jobs have long since been moved from Phobos down to Leominster. Indeed, teleoperations are the largest single occupation. Also, all work best done at a central location is situated there, including routine medical care, education, training, scientific analysis, administration, etc. Some of the residential units are designated for retired citizens who may need special assistance.

II. Architectural Features

Leominster has the mental and physical welfare of its citizens firmly in mind, with broad, comfortable, and enclosed spaces that allow room for family life, leisure, and aesthetics. To encourage residents to feel at home in their new lives, special emphasis is placed on activities, meeting spaces, vegetation, spaciousness, walkability, and available privacy (and of course safety). Most of the newer living quarters have a cathedral-ceiling living room, balcony, and private garden. The closer greenhouses are designed to be open for strolling. Some greenhouses are specialized gardens with private spaces. Hiking and bicycling routes are laid out through the distant greenhouses as well.

Parks. The Village Center (Figure 1) encompasses two large pressurized parks. Each park is 100 meters (m) wide east to west and 150 meters long. They occupy the center of the town, for recreational activities and spaciousness. Chapman Park has a Mediterranean climate, with fruit trees, nut trees, a vineyard, small athletic fields, a climbing wall, and a freshwater pond with paddle boats. Named for John Chapman (the original "Johnny Appleseed"), Chapman Park includes apple and other fruit trees. Chapman was essentially a land speculator, as are the settlers on Mars: aiming to create useful land and farms for future generations.

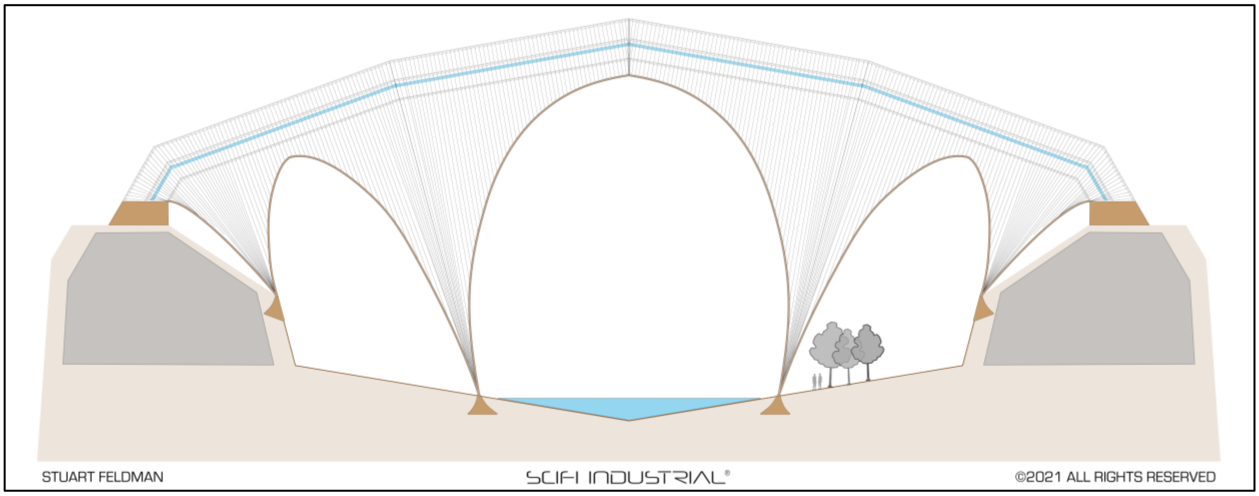

Figure 1. Cutaway view of Tahiti Park, the tropic climate park. Chapman Park is similar, with Underhill 3 on the east side and modular construction on the west. Canopy tie-down cables are routed through columns to the ceiling of quarried underground chambers. This allows a wide, spacious volume. Canopy walkways can be found among the canopy cables. (Feldman, Mackenzie)

Tahiti Park has a tropical climate, sidewalk cafes, beach, water park (Figure 2), saltwater pond for swimming and coral, zip lines, citrus orchard, and picnic and volleyball areas. Both parks have elevated walkways high among the canopy cables. The upper walkways and viewing platforms have evacuation stairs, poles, and slides that lead through airlocks to underground chambers for fast evacuation in the event of an air leak. Bike paths extend out to the rest of the village.

Park Construction. The canopy over these city parks comprises three layers of transparent, reinforced polyethylene terephthalate (PET) fabric. With air pressure pushing up and out, they are held down by a webbed network of fiberglass cables (Figures 3, and 4). Those in turn are tied to catenary cables, which run through vertical columns, down to rock anchors or underground chambers described later.

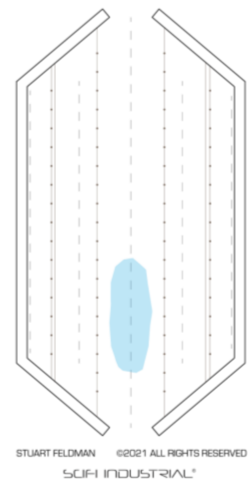

Figure 2. Tahiti Park, Tropical and Water Park, site plan (Feldman, Mackenzie)

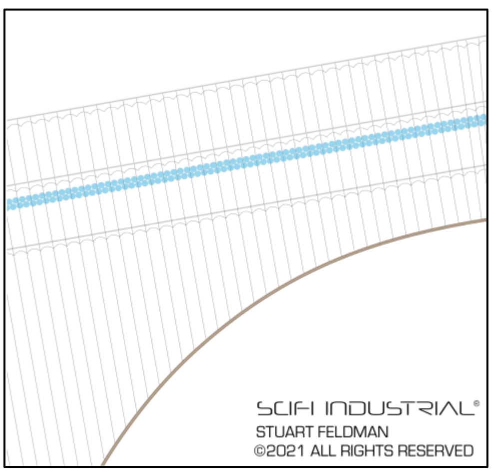

Figure 3. The canopy over parks, E-W section comprises three layers, water bags for shielding, and web cables to provide downward force. (Feldman)

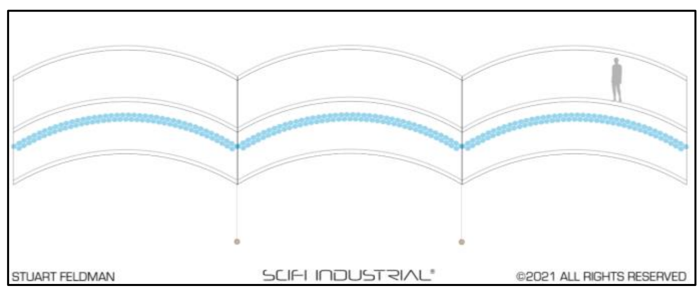

Figure 4. The canopy over Parks, N-S cross-section comprises three layers of 3 mil PET, with reinforced fibers. (Feldman)

At the ground level, an impermeable barrier under the soil keeps air from escaping. Note that this floor is not strong enough hold down the roof, instead it presses on the underlying rock, anchors, and cables, which in turn hold down the roof canopy.

Walkways and balconies are provided between these columns and just under the canopies. In case of a major air leak, pressurized stairways and evacuation slides lead down into the chambers.

Canopy Deployment. Although much research needs to be completed to validate the details, the team has worked out a proposal for the manufacture and deployment of the canopy over the parks, which can be described as follows. The settlers manufacture narrow strips of the reinforced PET sheets from locally produced polymers and fibers. This is done in long, narrow indoor workshops. The strips join along their edges by welding or gluing; winding into rolls, inside wider indoor workshops.

The cables are prepared as a webbing and tied into bundles to avoid tangling. They could be composed of high-density polyethylene (Spectra) or fiberglass produced from local silica sand and melted in a solar furnace, described later in this paper.

The site is prepared by excavating and grading, laying the impermeable membrane on the ground, and covering it with a protective layer of dirt. The support cables holding the park canopy down against internal air pressure must be anchored deep underground. By placing the anchors 20 to 40 meters into the rock, the upward force of the anchors is spread out by the rock to a wide area under the floor of the park.

Note that the internal air pressure is pushing down on the floor and underlying rock, so we are not relying solely on the weight and strength of the rock. Depending on the strength of the local rock, the required depth of the anchors is estimated to be 20 to 40 meters. Where we have quarried underground passageways and chambers, the tie-down cables can be fastened to anchors on the ceilings of these passageways. This also allows the cables to be inspected and replaced later, if needed.

Next, the surrounding anchor wall would be built, including airlocks, emergency exits, and windows. These could be made of locally produced sorel cement or other concrete, glass blocks, and plastic.

The sheets are unrolled onto the site, carefully folded, if necessary. Adjacent strips are attached to each other and to cables and anchors, lifting them enough to work underneath. Once complete, the canopy is inflated by pumping Martian air at slight pressure (1-2 atm), into the channels between the upper and second layer of the canopy. Only two layers are needed for initial inflation. The canopy is then checked for leaks (and patched as needed), and the cables inspected before being lifted to its final height by pumping Martian air under it, at low pressure, into the future habitable space between the canopy and floor. Once fully inflated, leak checks are again completed and patched along the floor and surrounding wall. At this point, the canopy will have its final shape, but only two layers and lower pressure than when inhabited.

Additional rock anchors are drilled and emplaced to allow for increased upward force and increased pressure. Note this can now be done more easily at a partial air pressure with optionally heated air.

A third layer of sheet material is added under the first and second layers of the canopy. This should be done by lightweight robots or drones, as it requires working high above the ground. The new sheets must be laid between and attached to the existing tie-down cables. However, it will provide easier working conditions by providing partial pressure and warmth. Years later, when canopy material degrades and has to be replaced, we use the same procedure as above. This adds a new lower layer and we remove the upper layer, akin to sloughing off layers of dry skin.

With the canopy's final layer in place, the air pressure and heat are increased, while the Martian atmosphere is replaced with a breathable gas mixture of nitrogen, argon, and oxygen. Work can now be done in a safer, more comfortable shirtsleeve environment.

Water bags are installed on the second level of sheet in the canopy for radiation shielding. The bags are hooked onto a pre-installed net to avoid sliding down.

Elevated walkways and platforms are installed between cables to allow for later inspection and enjoyment while strolling or jogging. The floor is landscaped to include plants, trees, vineyards, grass, patios, picnic areas, athletic areas, exit hallways, slides, and a zipline into the swimming pond. The park is then ready to be enjoyed.

Advantages Over Domes. The tie-down lattice of the park canopy cables is a new feature, designed for minimal stress on the canopy fabric, unlike the round domes commonly seen for space city designs. With the tie-down cables spaced 10 meters apart, the radius of curvature in the north-south direction is about 7 meters, compared to a low dome perhaps 100 meters across, with a radius of curvature of several hundred meters. The stress is proportional to the radius of curvature (with a factor of two for cylinders compared to spherical curvature). Therefore stress on the fabric of a dome would be 50 times greater than in this tied-down design.

The sheets have a single direction of curvature; thus they can be produced by extrusion and rolling. The doubly curved surface of a dome on Earth is typically constructed from a large number of small flat sheets, or by stretching a flat sheet to curve in two directions; either method weakens it. We employ a three-layer canopy for redundancy, safety, and thermal insulation. Most dome designs do not include this, although they could. Also for redundancy, we could add partitions along some of the cables to isolate leaks; however, a large quantity of cables would be needed. This is hard to do for a dome without greatly distorting it. The cables can be a stronger opaque material while leaving the canopy transparent to allow in more light. Individual cables can be readily inspected and replaced, unlike sections of a dome. Note that an actual design would have cross-tied cables in each direction for redundancy. We did not show this aspect of design for simplicity of the diagrams and to more easily convey the basic tie-down cables.

Domes can be hard to tie down. Many Mars city designs show wide domes meeting the ground at a low angle. Thus the radius of curvature is much wider than the dome. Such domes must be anchored to the ground at the same shallow angle they meet the ground; therefore the angled anchors must be much longer. The entire upward force of the air pressure, plus the inward force of the dome, is concentrated on the outer ring of the dome. Depending on the exact size and angles, a dome exerts far more force on its anchors than this design with tie-down cables. Also, in this design, the upward forces of the cables are well spread out into the rock under the floor, with the forces transferred up through the rock to the floor. Forces are not concentrated around a narrow edge as they are for a dome.

Modular Habitats. A residential area on the west side of the park consists of fiberglass habitats (Figures 5 and 6) under a roof holding regolith for radiation shielding. Most have a diameter of 8 meters, with typical lengths of 20 to 30 meters. They are outfitted as two-floor living quarters, with a double-height living room in the middle. The upper floors have bedrooms at each end, with balconies overlooking the central living room. The lower floor has a kitchen at one end and telecommuting office at the other. Many residents can work from home, remotely supervising automated equipment or rovers elsewhere on Mars or on Phobos or Deimos or in orbit.

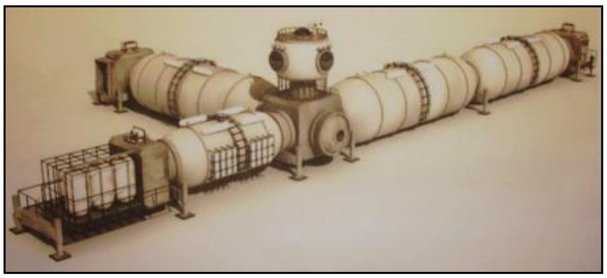

Figure 5. Close-up of cylindrical modular habitat modules. (Brian Versteeg)

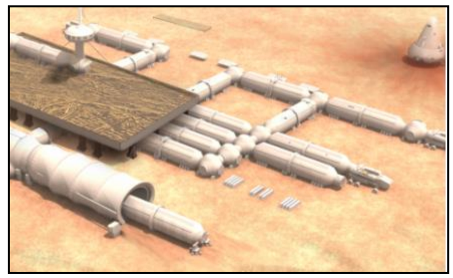

Figure 6. Modular Housing area, to the west of the Park, with regolith canopy for shielding

Modular Habitat Construction. The fiberglass living quarters are made from local ISRU materials wound from lower-quality spun basalt, and bonded with polyester resin. Higher-quality fiberglass and epoxy resins are used for vehicles and mobile habitats because they require lower weight. The spun basalt fibers are produced from local sand melted in a solar furnace depicted on in Figure 11. The polyester is produced in polymer chemical units (see section III). The composites are wound in a large, 15-meter-high tent (Figure 7).

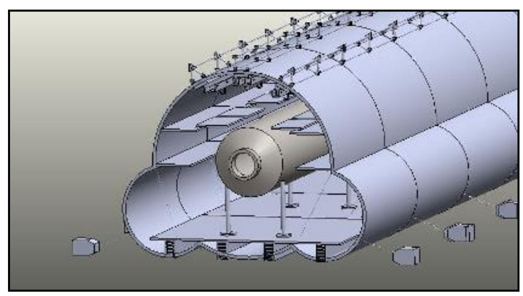

Figure 7. Inflated assembly tent, cutaway, for winding habitat modules, note work balconies, overhead crane

The lower Mars gravity, 38% that of Earth, must be taken into account when designing structures, but the basic design principles remain the same. For example, an overburden of regolith for radiation shielding would not be as heavy, nor would a truss supporting the architecture be as large or strong as it needs to be on Earth, which also reduces material mass.

Masonry Structures, Underhill 3. On the east (far right) side is a six-story 30-meter-high masonry complex, dubbed Underhill 3 (Figures 8, 9, and 10), with three levels of vaults six meters high and 5 m in diameter. The top floors are residential. The lower floors house commercial stores, offices for teleoperations, and light assembly areas. A café is shown in Figure 10. Midway across the complex is a large public atrium with more sidewalk cafés, balconies, and hanging plants (Figure 8). Above the six-story masonry structure are layers of compacted regolith to shield all radiation exposure. The west side of the settlement is mostly residential with sound isolation.

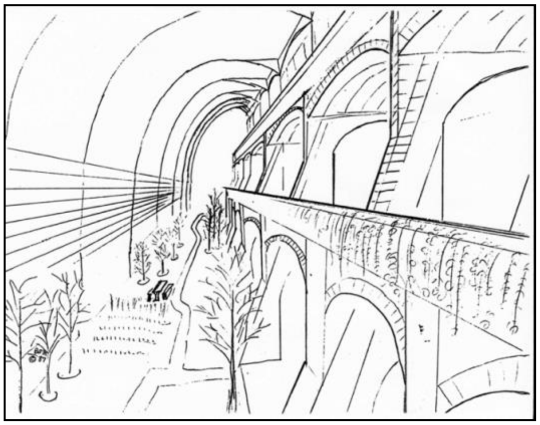

Figure 8. Open atrium, within the Underhill 3 area, showing multi-story masonry with balconies.

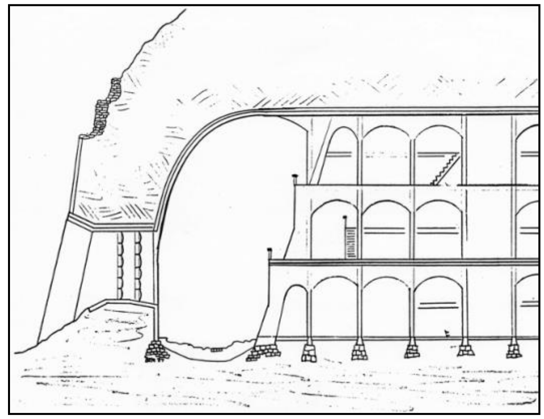

Figure 9. Cutaway of the Underhill 3 masonry structure. Upper 5th and 6th floors are residential. Middle floors include shopping, restaurants and commercial. Lower floors are for light assembly.

Masonry Structure Construction. The masonry structures on Mars will leverage well-understood, proven techniques used to make masonry vaults and arches for buildings and cathedrals on Earth. Every other ceiling is a curved vault. The walls must support considerable weight, but have arched doorways. For semi-automated assembly, standard-size cut stones are used for walls, columns, and vaults. Cast basalt is used for other shaped blocks, such as the keystones and joints between walls, floors, and vaults.

Figure 10. Cafe in Underhill 3, the masonry construction. (Phil Smith)

Air pressure dictates hidden aspects of the masonry. Multiple layers of an impermeable sheet are below the lowest floor tiles to stop air leakage. They are separated by sand with perforated pipes. Those pipes maintain lower pressure to recover leaked air, which is pumped back into the air separation equipment to recover oxygen, nitrogen, argon, and water vapor. The upper floor and side walls have similar multiple layers of impermeable barriers (see section IV, Figure 17). The top ceiling and exterior walls also use glazed masonry blocks with sealed mortar to lessen air leaks.

Underground Chambers. Underground excavated chambers or shelters below the park are 3-4 m in diameter and were carved to provide masonry stone, and to provide anchor space for the park canopy. They are now used for transportation corridors; secure greenhouses for seed crops and fungi (see section III A, Figure 13); selected manufacturing; storage; and emergency shelter or evacuation.

SpaceX Starships. A number of SpaceX Starships and other similar spacecraft used to establish the early settlement are still parked in the vicinity. With no plans to return them to Earth, much of the original equipment was permanently installed in the vehicles and used in place. This includes ISRU fuel production units; chemical equipment to make precursor chemicals for polymers such as ethylene; production of CO, CH_4, and LOX for rover fuel; and other low-performance fuel needs. These craft appear to be positioned at random because they landed wherever it was safe before the exact location of the settlement was established. They are operated in place, with their products stored in the lander's fuel tanks and then transferred by tank trailers.

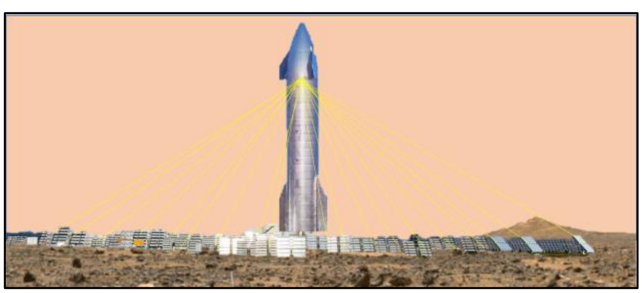

Figure 11. Solar furnace outfitted into a SpaceX StarShip, including electric power generator, kilns, chemical reactors, oxygen separators. (Leahy, Solúcar PS10, SpaceX)

Other early vehicles not slated to return to Earth were intended for permanent use by the early settlers on the surface. Their payload areas were outfitted as habitats, workshops, and labs. Their fuel tanks were pre-fitted with tie points for additional floors, walls, and equipment to be installed after arrival on Mars, much like the original 1970s plans for Skylab. For radiation protection, these vehicles are tipped on their side onto a trailer using a derrick and moved to the desired location. They are then covered with regolith for radiation protection while on their side.

III. Other Technical Design Details

Around the commercial area are modules connected by a network of shirt-sleeve environment corridors, including:

A. Settlement Structure Components

1. Salad Greenhouses are located inside or adjacent to most residential units' kitchens, for easy harvesting of salad greens before meals.

2. *Public Gardens* are small planted areas that produce a few useful crops. However, they are meant primarily for leisure, family picnics, swimming, seclusion, or memorial flower gardens. These gardens are scattered around the residential and commercial areas.

3. *Commercial-Scale Greenhouses* for most food crops are on the edges of the settlement. They include aeroponic, hydroponic, and soil-grown food plants. Other plants are grown for oils, biofuels, and fibers. (Figure 12).

4. *Secure Greenhouses* are located in the excavated chambers below the parks, in the masonry structures, and other underground locations. They house long-lived plants that should not risk depressurization when a greenhouse must be repaired, such as fruit trees and nut trees. They also house any seed crops and any other valuable plants that require lower radiation exposure.

5. Waste Processing. Biological wastewater processing and air filtration units are scattered throughout the village for redundancy. Tertiary water processing is performed in biological reactors, greenhouses, and by drip irrigation of plants throughout the living spaces to remove unwanted nutrients. Depending on how it is used, some water is also treated by reverse osmosis, ultraviolet light, or ozone. All filters and treatment equipment should be manufactured on Mars. An example: for water filters, activated charcoal can be made or re-activated by heating unused plant materials in the absence of oxygen. Soil filters can catch particles in water before reverse osmosis to lessen the fouling of those membranes.

Although plastics are widely used, the buildup of microplastics in water systems should be less of a problem than some places on Earth, because the residents are more aware of the need to recycle, and are not likely to discard plastic bags as trash to decay in sunlight. Finally, to avoid a buildup of anything the filters miss, such as heavy metals or the smallest microplastics, a fraction of the waste water is distilled in evaporation ponds, in greenhouses, or for industrial cooling. The resulting water vapor is collected as condensate on outer walls, especially in greenhouses. After evaporation, the remaining contaminated residue brine can simply be set aside as blocks of ice in a carefully isolated location outdoors. They may be reprocessed at a future date if the waste chemicals become valuable. Some undesirable chemicals can be bioaccumulated by certain bacteria and plants and discarded in a similar manner. Additionally, fungi help chemically degrade toxic substances and regolith with fungi to initiate soil formation inside the greenhouses, atriums, and greenery.

6. Automated Refineries and Chemical Units, producing polymers, paper, press-board, plastic filament for 3D printers, plastic sheet for laser cutting, wire, and cable.

7. Semi-automated, Custom Manufacturing Areas. The bulk of the products are injection-molded or vacuum-formed plastics. However, the busiest machines are the laser cutters, routers, 3D printers, and other small, flexible machines. They produce whatever small plastic items are required, especially household furnishings and parts for other machine tools. Most furniture is cut from plastic sheet and assembled by the user, in a manner similar to IKEA furniture. Leominster uses some metalworking and ceramics molding equipment as well. Additionally, pumps, valves, and electric motors are manufactured from 3D-printed and laser-cut plastic and metal.

8. Composite Molding. Large items are generally made from spun-basalt composites bonded with polyester. Where high strength is required, epoxy is used to bond fiberglass or S-glass, which are made from selected silica sand and other minerals brought from elsewhere on Mars. Small quantities of carbon-based Kevlar® are also produced. These larger items include

Figure 12. Greenhouse for seed production. Artificially lit, in a chamber to protect plant genomes from radiation. (Bryan Versteeg for Mars Foundation)

vehicle frames, airlock fittings, tanks, and pressurized habitats and laboratory modules.

9. Composite Winding Tent. As shown in Figure 7, a large-volume, 15-meter-tall inflated tent is outfitted to wind composite habitat modules from carbon fiber. The habitat modules' standard size is 8 meters in diameter, and up to 30 meters long, sized for an apartment. The resulting modules are joined at the end to spherical hallway modules with pressure doors. They serve as private residences, laboratories, assembly rooms, offices, shops, and all manner of habitable space, as shown in Figures 5 and 6.

10. Solar Power Farms. Solar thermal and solar photovoltaic panels are produced on Mars from in-situ materials. They generate electricity, heat for living spaces and greenhouses, and those industrial and chemical processes using medium temperature heat.

11. Solar Furnaces, or Heliostat towers, provide the extremely high temperature needed for some refining and manufacturing processes. Some heliostats were built into Starships before they left Earth, and operate where they landed. The towers are surrounded by steerable mirrors of inflated mylar from Earth, and other mirrors made on Mars. By focusing sunlight on different targets on the tower, we can either generate steam and electricity; melt sand to draw fiberglass; melt sand to form glass, sinter bricks, decompose CO2 into O2 and CO for fuel; or perform other steps needed to make polymers. (Figure 11).

12. Nuclear Fission Reactors, are needed for "base-load" electric power at night and during dust storms. They also provide heat for industrial and chemical processes. Reactor cores are one of the few cases where it makes sense to bring key components from Earth. Heavy components and all shielding were manufactured on Mars. Thorium or depleted uranium fuel is brought from Earth, which is safer to transport. The reactors are breeder reactors, so they convert the thorium to plutonium, and burn it as completely as possible without reprocessing the fuel pellets. This minimizes radioactive fuel wastes. When a reactor core is decommissioned after many years, it can be buried in place, without concern that groundwater would transport radioactive elements, since Mars has no liquid ground water. If a concentration of thorium is found, it can be used as a local nuclear fuel.

13. Smart Power Grid. A computer network tracks available electric power and heat. Various industrial processes and home appliances are directed to minimize energy use when power is in short supply. In particular, all vehicles are plugged into the grid when not in use to recharge batteries and top off fuel tanks. In emergency situations, vehicles are directed to burn their fuel in their fuel cells and provide electric power in reverse, back into the power grid.

B. Outlying Facilities

1. Outlying Grain Farms, i.e., greenhouses for grains and field crops that are not tended by humans except during planting, harvest, and emergencies.

2. Zygote, a science base on and under the South Polar ice cap. A nuclear powered, under-ice polymer factory is being constructed. It will take advantage of the easily available water ice and CO_2 dry ice, and will use the ultra-cold air to cool the polymer production equipment.

3. Phobos Space Elevators are used to export goods from Mars, thus paying for imports, as described in section VI. These space elevators are long ribbons, approximately 6,000 km long. Due to the lower gravity of Mars and Phobos, and shorter length required compared to Earth, they can be built with current materials.

The elevators are made in sections. Where low mass is important, they can be composed of carbon fiber, graphene, or a high-strength polyethylene such as Spectra. Any of these can be manufactured from carbon on Mars. The sections near Phobos can be heavier, so they are manufactured of fiberglass at Phobos.

The lower elevator hangs from Phobos downward to near the Mars atmosphere. A net on the lower end is hooked by a suborbital spacecraft launched from the Mars surface, similar to an aircraft catching an arresting cable while landing on an aircraft carrier (next section). Such a launcher only needs to climb about 300 km above the surface and accelerate to ~0.5 km/sec relative to the surface of Mars. By comparison, to launch to Phobos requires climbing to an altitude of 6,000 km and velocity of 2.14 km/sec.; requiring far more fuel. (Figure 13).

The upper Phobos elevator extends outward from Phobos, away from Mars. Because the outer tip travels a much larger circle, it moves faster than Phobos. A spacecraft can slide along this upper elevator and then release with enough velocity to reach Earth or some asteroids, such as Ceres. This greatly saves on the cost of exporting goods, since once a craft has caught the lower elevator tip, although it still needs some energy to climb to Phobos, it does not need any fuel to reach Earth, Lunar vicinity, or some asteroids.[4]

*4. Catapult Launcher***,** launches small cargo craft to the Phobos elevator. The launcher is located on Pavonis Mons, at less than 1° north latitude, just inside the east rim of the caldera. Although it needs a feasibility study, one author suggests a segmented, gas-powered catapult (a.k.a. a big gun), with a small second-stage rocket to launch durable cargo and catch the net at the lower end of the Phobos Space Elevator, thus saving most of the launch fuel. Alternatively, a small rocket could be launched from the surface of Mars to the net at the lower end of the elevator. See Figure 13.

5. Truck Routes, A north-south route connects the locations listed. A network of pre-surveyed, smooth routes connects outlying farms, mineral excavation areas ("mines"), and scientific sites. Portions have been graded to remove rocks. Paving of the more important routes is underway using solar and laser sintering machines.

6. Space Port. This area is located a safe distance north of Leominster. It is designed and paved for landing and launching of cargo landers and reusable spacecraft, some as large as the SpaceX Starship.

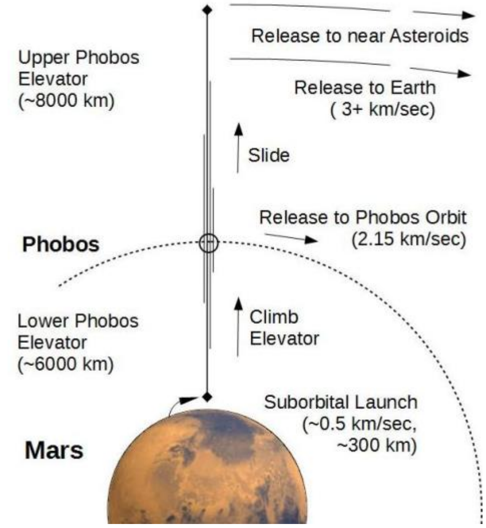

Figure 13. Phobos space elevators extending downward to near the Mars atmosphere and upward to Mars escape orbits. (Mackenzie/Weinstein)

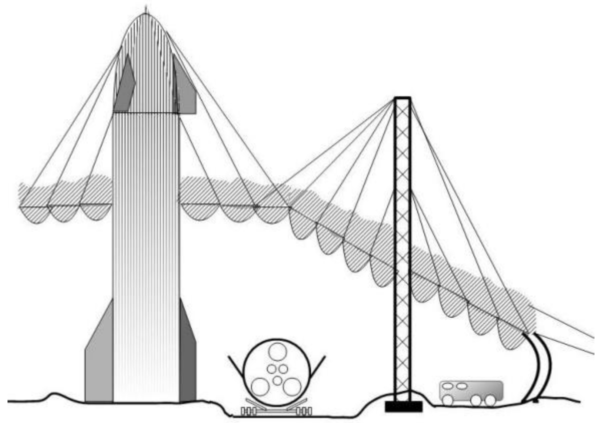

Figure 14. Hangar, for maintenance of spacecraft and large vehicles in shirt-sleeve environment. Regolith overburden supported by Starships and other columns. (Mackenzie, Mars Foundation)

7. Hangars. Multiple "hangars" and garages of varying sizes satisfy the need for large work areas; vehicle maintenance; storage without temperature extremes; and even for outfitting reusable heavy-lift launchers. The roof of a larger hangar is a locally produced fiberglass truss covered by regolith shielding and supported by masonry columns. Even without a pressure shell, it can be pressurized up to about 0.1 or 0.2 atm with compressed Martian CO_2 atmosphere. This allows work in an almost shirt-sleeve environment, but extreme care must be taken using haz-mat style breathing hoods providing pure O_2 (Figure 14).

8. Outfitted Landers. Although all new structures are constructed entirely of local building materials, there will be a few older structures built out of used spacecraft. Some landers were intended for one-way trips, or were not able to be re-launched. These are also outfitted as workshops, or are cannibalized for their components and materials (Figure 15).

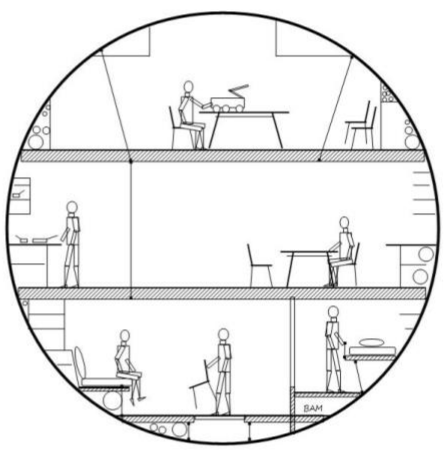

Figure 15. Three-Floor Workshop, built into a Starship. (Mackenzie, Mars Foundation)

IV. Regolith-Based Materials

Structural Foundations. Some Martian surface deposits contain levels of sulfur up to 37% SO_3 by weight[5]. As a result, construction vehicles can deploy footings to mitigate ground freezing and thawing and can mix Martian regolith with molten sulfur, establishing a sulfur-block-based foundation around excavated underground chamber locations. Sulfur is used as the binder for unprocessed regolith.

Sintered Ceramics. Depending on the minerals in the local regolith, Leominster citizens may be able to separate clay-like particles to manufacture ceramics in the conventional manner by making a wet mud, molding and drying it before firing it in a kiln. The kiln is heated in the solar furnace, by burning CO and O_2, or electrically to in-situ manufacture stable ceramic geometries such as tiles, electronics, bricks, cookware, toilets, sinks, and much more.[6]

Masonry Structures. The masonry structures on the east side are made from sintered Martian bricks and concrete blocks. Glassy particles of magnesium (Mg)-rich olivine, Mg-rich pyroxene, and iron (Fe) oxides in loose regolith powders are pressed into bricks and fused by direct compression or sintering. Such bricks could be used for masonry construction.[7] Construction bricks are made by compressing regolith in a rectangular mold and sintering it in a furnace. Some of these have special interlocking shapes to lock together without mortar.[8]

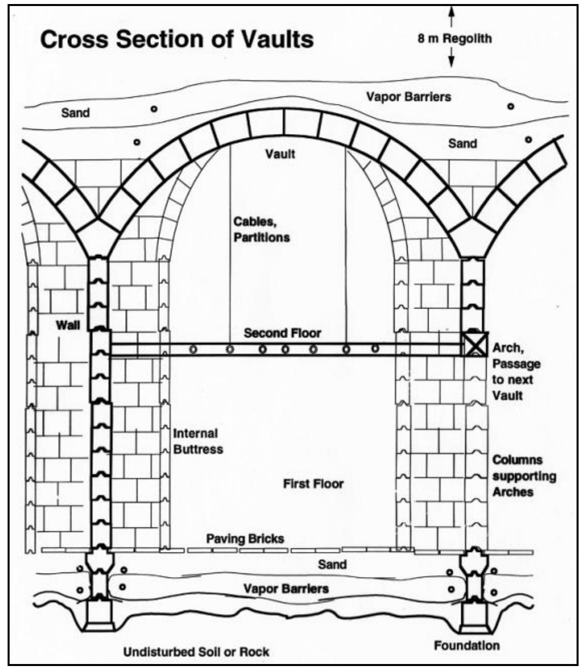

Figure 16. Details of masonry construction, Underhill 3 area. Note multiple layers of vapor barriers to catch gas leaks. Second level is fiberglass and bamboo panels suspended by cables. (Mackenzie, Mars Foundation)

Normally, vaults are assembled by laying small bricks on a curved temporary form. For speed of assembly and to avoid formwork, the locals make custom-curved concrete blocks 1 to 2 meters across, and lift several into place simultaneously with a custom forklift-like machine.

The cafe in Underhill 3, shown in Figure 10, is of masonry construction. The balconies are of bamboo, fabric, and fiberglass. Details of the masonry floor can be seen in Figure 16. Note that multiple layers of vapor barriers are provided to catch gas leaks. The lowest tier of masonry rests on a foundation of solar-sintered soil, or Martian concrete made with Sorel cement, Mg-O-Cl; where masonry is not subjected to humidity, it is made of sulfur-based cement and aggregate.

Solar Furnace. An array of large, sun-tracking mirrors focus sunlight on a receiver at the top of the tower. The furnace also includes a water boiler. The furnace deploys an array of steerable mirrors on the ground called heliostats to focus sunlight on the boiler to make steam; heat a greenhouse; generate heat for making plastics; or power a Sabatier reactor to make carbon monoxide (CO) and oxygen (O_2) for fuel. The mirrors also can use silicate sand to make fiberglass. These units are modelled after solar thermal power towers, with the boiler on top. Steam goes down to a turbine to make electricity; condensed water goes back up to become steam for the boiler. A decommissioned Starship serves as the base of the solar furnace.

Sol-gel Reactors. As silicon dioxide (SiO_2) comprises ~60% of the crust on Mars, compact sol-gel reactors are used to form a solution, gelation; to dry supercritical CO_2; and to synthesize common oxides such as SiO_2. Downstream products from these reactors support in-situ manufacturing of fiberglass, glass, cables, catalysts, paints, dopants, radiators, and absorbents (of heavy metal) from water; supercapacitors; carbon aerogels; anti-rust coatings; greenhouses; and thermal insulation for electronics and windows, all while using minimal mass and energy.

V. Carbon-based Products

With the absence of obvious metal ore deposits or any natural lumber on Mars, the carbon from the air becomes a critical resource. Much of the manufacturing will be carbon-based polymers, graphite, biofuels, and agriculturally based products.

Methane Fuel Production: Starting with water from the nearby ice deposit, the water is electrolyzed to produce H_2 and O_2, The O_2 is used for breathable atmosphere or reactants for fuel cells or rockets (Figure 17). Using a Sabatier reactor, Martian air and the H_2 are pumped across a catalyst; where they combine to form methane fuel (CH_4) and H_2O. The water can be condensed for drinking, or re-electrolyzed to create more O_2 and hydrogen. The resulting methane is compressed or cooled and can then be transported to a launch vehicle, much the way we transport compressed or liquified natural gas on Earth. Methane is also used as a fuel in ground vehicles, pressure suit fuel cells, emergency backup power; for chemical production; and as a convenient way to export hydrogen and carbon.

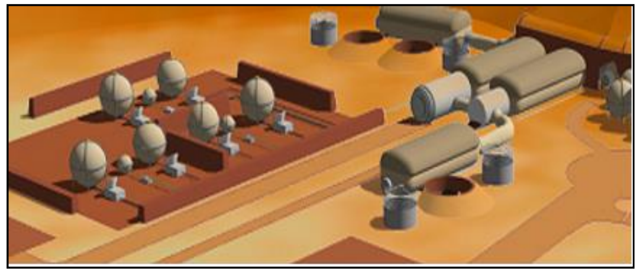

Figure 17. Fuel Production at Launch Site, nuclear reactors, storage for CO fuel and LOX, and repair shops (G. Petrov)

Water Production and Extraction:

Wells: One of the ways water is extracted from the nearby ice deposit is with a hot well field. Martian air is compressed, heated in a solar thermal collector, and forced down a central well, thus subliming the ice into water vapor. "Recovery wells" drilled around the central well allow the water vapor to rise, where it is captured and condensed. Initially when opening a new, remote well field, a soot bomb explosive is used in the central well to fracture ("frack") the ice. However, for well fields near existing structures, high-pressure pumps are used for the initial fracking. Similar methods were used at Camp Century on the ice cap of Greenland and in the oil fields of North Dakota.

Water Tents: Also, transparent solar tents use a greenhouse effect to extract water from smaller ice deposits and permafrost where there is a small percentage of water ice. A similar method is used for obtaining emergency drinking water in deserts on Earth.

3D Bioprinter for Fungi-based furnishings. Plastics are fused with fungi mycelia from nearby mycoremediation feedstocks to form a bioplastic filament that is inserted as feedstock into a large 3D bioprinter and soaked in water.

Afterward, the fungus mixes with water and grows into the desired mold and framework to form lightweight solid structures used to in-situ manufacture furnishings, tables, fence posts, frames for weather stations, and work canopies. These products also can be used for custom manufacturing and exports. For many identical objects, or larger objects, fungi can be grown in a mold to be any desired shape. 3D printers are inefficient for large objects, so objects such as chairs, partitions, bookcases, bricks, and other furnishings can be "grown" from most any waste organic materials, such as corn stalks or soybean stems. The plant wastes are shredded, mixed with fungi spores, and pressed into molds of the desired shapes. After the mycelia grow to fill the mold, the objects are dried, sterilized, and optionally coated with a plastic or varnish, and ready to use.[9,10]

Carbon, Polyethylene, Plastic Production. Plastics, i.e., carbon-based polymers, are the primary material for most small household utensils and furnishings. On Earth, most plastics are produced in a series of several steps, starting with processing natural gas. On Mars, it only takes a few extra steps to produce plastics from atmospheric carbon dioxide (CO_2), and hydrogen from ice deposits. Polyester is used as a binding agent in locally produced reinforced composites, including fiberglass, basalt fiber, hemp, vehicles, and modular habitats. The plastics are produced in various forms, including film, sheet, filament, trusses, panels, and especially as used for laser cutters and 3D printers elsewhere in the solar system (Figure 18).

Figure 18. Automated Polymer Production, and atmosphere compression, separation. (Carter Emmart)

Clothing and Fabrics. Starting with limited clothing sets in Leominster, early settlers primarily used polyester-based garments and algae to produce cellulose material, which are spun into organic cloth. They now manufacture continuous thin filaments to construct woven products such as rope, textiles, or clothing in addition to the artistic aesthetics of fashion on Mars. Styrene is used to make many copolymers and packing materials.

Polyester is synthesized and manufactured by chemical processing equipment using available in-situ minerals and gases on Mars. The process occurs in the following manner:

Starting with Martian atmosphere, the CO_2 can be either adsorbed, or frozen out of the air. The remaining N_2 and Ar are useful mixing gases and for agriculture. The CO_2 is then compressed. One way to produce CO is to decompose atmospheric CO_2 in the solar furnace into CO and O_2, which is also useful for breathing or to burn fuels. Using a

Zeolite catalyst, carbon monoxide, H_2, and gaseous CO_2 are combined to form methanol (CH_3OH). Alternatively, CO_2 from Martian atmosphere and water can be reacted to form methanol through a different electrocatalytic reaction mechanism. Thus, methanol reacts with hydrogen on a Raney nickel catalyst to generate butene (C_4H_8). Butene is then generated from the oxidation reaction of methanol and O_2 on a vanadium phosphorus oxide (VPO) catalyst to form butane (C_4H_{10}). Later, unsaturated polyester resin is derived from maleic anhydride $C_2H_2(CO)_2O$, which forms from the reaction with butane. Additionally, ethylene glycol, a useful industrial compound found in many consumer products, is derived from steam and oxirane from the reaction of ethylene and silver and Al_2O_3 catalysts). Ethylene (C_2H_4), an easy-to-transport liquid fuel, is an olefin converted from methanol. Additionally, benzene ($C_6H_6O_3S$) can be formed by using a zeolite catalyst to react with carbon dioxide, O_2, H_2, and H_2O. Benzene and a zeolite catalyst forms ethylbenzene, which can further be catalyzed on an iron catalyst to produce styrene, a chemical used to produce latex, synthetic rubber, and polystyrene resins.[11]

Explosives are helpful for excavation and water extraction. A "Soot Bomb," or Oxyliquit, is the least expensive explosive to make from Martian materials. The soot is made by burning waste leaves without oxygen, thus driving out all elements except the carbon, then crushing them to dust. A ceramic canister made on Mars is filled with the soot and fitted with a filling tube and ignition wire. The canister is lowered into a drill. Then liquid oxygen (LOX) is forced down the tube, saturating the soot. The wire ignites the mixture, and the bomb explodes. The reaction is akin to a dust explosion inside a grain silo

VI. Economy, Trade, and Export

The major purpose of Leominster is to manufacture equipment, habitats, and other goods. This paper provides a high-level overview of the settlement's likely economy, growth on Mars, and exports to elsewhere in space. A detailed analysis of such an economy would require multiple papers like this one.

Although most of the manufactured goods are consumed domestically for growth of the settlement, many are used to establish small camps, outposts, and mines elsewhere on Mars.

Phobos Launch: Manufactured components for spacecraft are transported by road to the Pavonis Mons catapult and then launched to the Phobos space elevator. At Phobos, they are assembled into full spacecraft, under teleoperated control from workers on Mars (where the cost of living and dangers from microgravity are less). The finished craft and bulk goods slide outward on the outer Phobos tether and are then released with enough velocity at the proper moment to reach many asteroids, Earth, Luna, and orbital settlements near the ecliptic plane.

Export from Mars: *Bulk Volatile Exports, Carbon Fiber Tanks, and Structures:* The various fluids (CH_4, CO, LOX, NH_3, H_2O) are exported in carbon fiber tanks, which are generally reused. Other carbon fiber exports include spacecraft frames, trusses, antennas, and rocket motor expansion nozzles. *Other Exports Include:* Food, bulk manufactured items, asteroid mining equipment, spacecraft, launch vehicles, orbital tugs, cycling greenhouses, tethers, pumps, valves, and electric motors.

Real Estate: Some people on Earth could save money and sell their house to buy a one-way ticket to Mars; a down payment on a pre-made condo; and a supply pre-grown food until they can get a job in manufacturing or an outlying facility such as a farm. Settlers already on Mars manufacture and build the homes and set aside stockpiled food for these new arrivals.

VII. Conclusion

The Leominster settlement was conceived with self-sufficiency in mind, using as much local material as modern ingenuity allows. Starting with the regolith to fashion the bricks and the atmospheric gases to develop plastics, chemicals, and other materials and tools, Leominster was designed up front to reduce the need to import materials and machinery from Earth. In addition to "living off the land" as much as possible, Leominster can serve as a seed settlement, constructing the habitats, greenhouses, and other tools needed to build additional settlements elsewhere on and off Mars. Yet it's not just about building and manufacturing: Leominster has the mental and physical welfare of its citizens firmly in mind, with broad, comfortable, and enclosed spaces that allow room for family life, leisure, and aesthetics. As a key manufacturing and cultural center, Leominster has what it takes to become the capital of Mars as well as a jumping-off point for places farther out in the solar system.

VII. Acknowledgments

Numerous people contributed ideas included here, many presented at various conferences. Some architectural elements were incorporated from earlier design project of the Mars Foundation, and credit goes to those authors.

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