EUREKA

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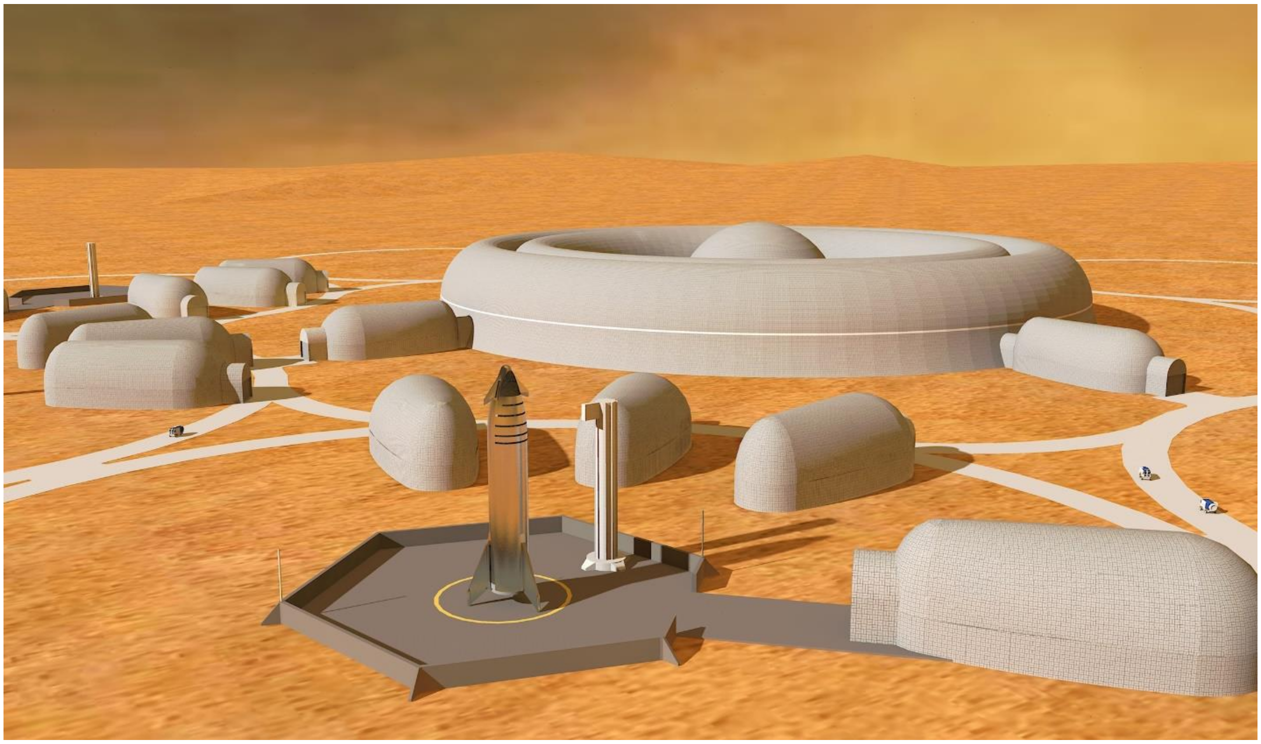
The Eureka concept is specifically created to surmount the technological and economic rationales opposing or deferring Mars settlement. This design assumes that every core argument opposing space settlement is valid. It then proposes the most practical engineering and financial solution set against that highwater baseline. For grand projects, it is often wiser to start with an overbuilt concept, then scale it back based on experimental evidence. If something is designed without this wholistic approach for an unknown environment, there is too much sponsor risk to justify the near-term expense. Conversely, systems that are overbuilt and overpriced due to risk aversion will eventually become a fiscal and technological dead end or will be stuck in analysis paralysis without leaving the ground. Difficult, remote environments require simple, rugged, affordable solutions to be maintained on site.[1]

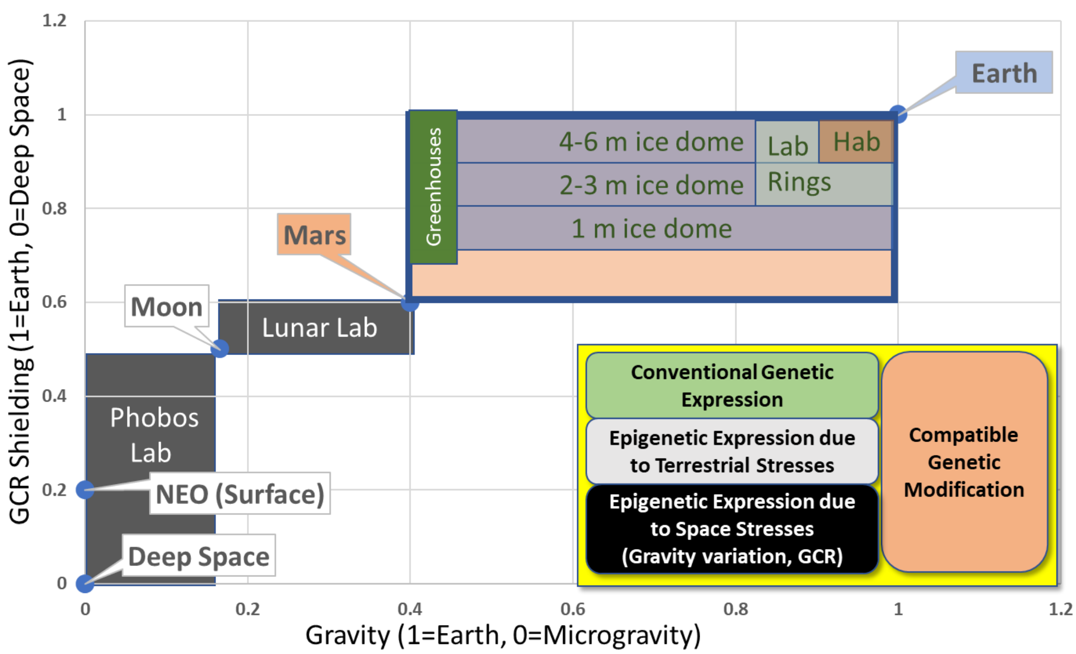


Eureka's construction methods are highly modular and adaptable to local conditions, unexpected assembly difficulties, and later repurposing. The settlement consists of a set of dome structures encircled by a pair of concentric rings. The central area contains elongated, LED-lit greenhouse domes, a 100-meter diameter recreational permaculture central dome, research labs, and manufacturing facilities. The rings contain interconnected modular living and work spaces on tracks that can spin at highway speeds to provide earth-level gravity. The foundational sizing units are the limits of the SpaceX Starship payload bay for hauling large equipment (9-meter full-diameter cargo, 4.5-meter conventional payload), and the dimensions of a functioning habitat centrifuge. The domes are made of interlocked, framed blocks of reinforced ice (Pykrete) or concrete, augmented with magnetic shielding against Galactic Cosmic Rays (GCR) and flares.

EUREKA'S PURPOSE

With off-world life sciences, the most logical and ethical roadmap starts with something as close to Earth as possible and works out experimentally. Eureka is focused on epigenetic life sciences, working from known to unknown, across a broad range of plant, animal, microbiome, and human tests. It also develops mining, construction and industrialization methods for surface settlement. Mars is the ideal environment for a space settlement research facility due to access to ice shielding, higher surface gravity, and a broad spectrum of accessible resources.

Life sciences are notoriously "noisy" in terms of experimental versus environmental and control variables. Having a GCR-shielded centrifuge provides a large volume for experimentation with as close to a single variable test environment as possible. With similar (but smaller) bases in a large lunar lava tube and on Phobos, the remaining range of stresses can be explored. When combined with a centrifuge track complex, everything from a full simulation of Earth GCR/gravity levels to native conditions are available for industrial and biological development.



The large blue box (above) represents the range of facilities available at Eureka. The yellow inset box represents the range of biological research possible on earth (green and white). The black box represents off-world research facilities. With understanding the epigenetic expressions in these three environments, GMO elements (orange) may be added to expand the range further or take advantage of traits discovered in the silent gene research. Since many plants have far more chromosomes than humans, this opens a broad new window in understanding and extending the genomic expression of terrestrial life. These silent genes have potential use in improved strains for disease resistance, adapting to challenging environments, and other productive agricultural and industrial uses. Crops can expand into broader hardiness zone maps to reliably feed and fund populations. Further, epigenetic expressive work rather than pure GMO work is closer to the natural state of heirloom genomes for multigenerational study.

IDENTIFYING AND REMEDIATING TECHNICAL CHALLENGES

The table below identifies and classifies the grand challenges of space settlement. Areas currently addressed by SpaceX Starship are shown in green. Areas addressed by Eureka are shown in yellow. Gray is out of scope for this concept.

Launch/LEO	Deep Space	Moon/Mars	Settlement
Affordable Launch	Solar Flares	Moon Landing	Air/Water
Large Vehicle Launch	GCR: Cell Damage	Mars EDL	Power and Propellant
Orbital Refueling/ Mass Fraction beyond Earth Orbit	Medication/ Food Expiration	Spacesuit Lifespan	Base Construction
Space Junk	Life Support Closed Loop	Dust Issues	Food Growth
Microgravity (health issues)	Medical Entropy	Basic Propellant Production	Surface Mining and Extraction
Grand Challenges of Space	Psychology	Return Flight to Earth (speed, mass, etc.)	Hybrid Manufacturing
Settlement	Mechanical Entropy	Planetary Protection	Reproduction

For each challenge, the section below describes the *State* (planned remediation method for the settlement when operational) and *Goal* (the focus of Eureka's research). The goal solution set extends beyond Mars to deep space and surface habitats throughout the solar system.

Solar Flares and Galactic Cosmic Rays (GCR)

State: Permanent inhabited structures are covered in 2-5 meters of ice blocks reinforced with a fiber matrix. Some structures are augmented with magnets in Holbach arrays that bend the paths of incoming particles to maximize the GCR flight path through the ice, effectively making it a thicker shield. ***Goal:*** Find the optimum protective combinations of ice thickness and magnetic field arrangements and flux for remediation in environments (drier areas of Mars, the moon, NEOs, cyclers, etc.) where less shielding material is available.

Closed Loop Life Support

State: All main structures are at least triple-sealed and have multilayered construction with active air and moisture recovery at each layer. Greenhouses and permaculture parks form a basic natural ecosystem, supplemented with Sabatier systems as needed. Additional plants assist with trace contaminant removal in living and work areas. Systems are modular to allow adaptation and design optimization over time. Air is actively circulated through ducts and passively via the centrifuges and thermal convection patterns. ***Goal:*** Optimize and advance the suite of agricultural, mechanical, and environmental systems for future use in larger and remote facilities.

Medication Expiration and Nutrient Reduction in Deep Space

Reduced shelf life of food and medication in space due to radiation exposure.
State: Import dehydrated/preserved drugs from Earth and transport/store in deep radiation

protection. On-site crops and drug production with testing to reduce the risk of epigenetic issues with known methods (such as bacterial insulin factories for test purposes) and expansion into new methods. ***Goal:*** Develop nutraceutical, chemical, and GMO-produced replacements in local conditions based on in-house research for Intellectual property (IP) export. Individualize plans for nutrition, exercise, and radiation protection to reduce the need for medications.

Increased Pathogen Virulence in Reduced Gravity
This is an issue with some bacteria (C-diff, salmonella, etc.) in microgravity. This is a known issue in transit and a possible risk on the surface.
State: Determine the risk gradient in the full range of reduced gravity. Facilities and equipment (restrooms, kitchens, etc.) are built for automated cleaning and periodic decontamination.
Goal: Epigenetic virulence vectors allow isolation of the disease-causing genes to accelerate development of vaccines and other treatments. This is already being done with ISS research. This process would be expanded at Eureka.

Environmental Psychology
Avoiding "cabin fever", homesickness, and other stresses of being far from Earth.
State: A spinning living area has rooftop gardens with a projected ceiling that follows the habitats on the ring to give a sense of distance. The central dome has open permaculture gardens with trees, bodies of water, and a projected landscape and sky on the dome ceiling and walls. Settlers feel a reduced dread of cosmic radiation or other space risks due to thick shielding. Rounded ceilings with wrap-around sight lines avoid the monotony of seeing everything from one vantage point. For direct Mars surface views, there are shielded observation decks, periscopes, windows or 8K+ monitors to show the view outside. ***Goal:*** Test additional methods for use in other space settlements. Determine the scale of gardens, etc. and any risk factors with dual-gravity living over time.

Mechanical Entropy and Design for Unknowns
State: Both imported and site-built systems are highly modular to allow swapping, rearrangement, upgrades, and expansion to adapt to field use. Engineers design modular systems for a range of unknowns rather than overengineering a single, expensive configuration for anticipated risks. Mission-critical automation controls can be swapped out or bypassed with manual controls in emergencies. This reduces catastrophic risks from software or hardware failure, hacking, or supply chain isolation.   ***Goal:*** All key control systems, starting with manual bypass systems, would be manufactured locally to allow the option of independence from both imports and system failure. As construction of habitats and manufacturing systems are localized to a greater degree, and/or imported from non-terrestrial sources, then space settlement is no longer limited by launch capacity and may expand exponentially across the solar system.

Planetary Protection (Forward Contamination)
ISS studies indicate bacterial spores buried more than a meter under rock could survive over 70 million years in space[2]. Conversely, surface Mars dust is sterilized due to dust-storm turnover.
State: Initially, material inputs to the construction base are surface dust and rock, atmosphere, and subsurface ice. Any subsurface mining uses fully sterilized equipment, robotic controls, and an autoclave airlock for replacing worn parts. ***Goal:*** If no native life is found, some effort to

keep human contamination reversible remains in place to protect future settlers from possible pathogens. *If native or historically-transplanted life is found, see below.*

Planetary Protection of Crew from Possible Indigenous or Isolated Life
Given the ISS study mentioned above, lithopanspermia from Earth to Mars over the history of the solar system is a near certainty. Native life is also possible.
State: Surface and subsurface areas are explored with sterile robotic instruments. Core samples are examined for biomarkers prior to resource extraction. Mining sites are verified safe prior to actual mining. Samples are examined in telerobotic labs. The settlement is built in an older crater to ensure a GCR-sterilized surface. Returning spacecraft will not be exposed to the sub-surface or other potential active habitats (caves, etc.). See also, Water Production. ***Goal:*** If native life is found of terrestrial origin (lithopanspermia), or indigenous life is found, genomic compatibility and risks are assessed, and protection methods remain in place. Potential experimentation on genetic risk and compatibility would take place in deep space labs to avoid back contamination.

Air Production
State: Air components are extracted at the propellant plant (oxygen, nitrogen, argon, etc.) and by baking off from surface materials in the dust extraction plant (additional nitrogen). Carbon dioxide and contaminants are removed by plants, filters, and artificial systems such as Sabatier reactors as appropriate. ***Goal:*** Optimize the reliability and mix of these systems, while always maintaining enough backup systems to compensate for crop failure, partial hardware shutdown, or other contingencies. Refine system designs for other worlds and deep space.

Water Production
State: The main source is relatively clean subsurface ice (a nearby covered glacier), mined via hot CO[2] injection and steam extraction with sterilized equipment. This is transported to Eureka by pipeline. For ecosystem use, water is further purified to the needed levels. ***Goal:*** Expanded methods are tested for extracting water from lunar and NEO sources and dry Martian soils. Extensive recycling via anaerobic digesters, etc.

Power Production
State: Low enriched uranium (LEU) modular heat sources such as those in the Kilipower[3] designs are low risk and can provide heat for over 200 years. They are coupled with modular heat-differential generators (Stirling cycle, turbine, etc.). Turbines can also be used for direct mechanical work, such as driving compressors for atmospheric mining. To extract the large volume of water needed from the subsurface glacier, compressed atmosphere carrying reactor waste heat is channeled down the well shaft to both dump the heat and extract water. ***Goal:*** Build the heat exchangers and generators on site using imported LEU cores. Eventually, use local and other space-sourced resources for power, such as orbital solar platforms built in the asteroid belt, when they become available.

Food Production
State: With a backstop of dry goods and supplements from Earth, food production begins with stacked hydroponic beds and LED light sources in agricultural domes and epigenetic testing for possible health risks. Plants that require more earth-like gravity would be grown in the

centrifugal rings. Different fruit and vegetable species would be rotated into the system for dietary variety. ***Goal:*** With a fully characterized suite of basic species for a closed ecosystem, space settlement can be done wherever energy and resources are available. Research into genetic expression also aids food production for Earth that can grow in harsh conditions or with higher nutritional content.

Mining

State: Initial work is focused on ice, surface dust and rocks in the top meter for planetary protection and accessibility. Dust is separated magnetically, electrostatically, and chemically into useful materials. Igneous deposits with little chance of harboring biology would be next, followed by metamorphic and sedimentary. Any mined area is scanned (radar, x-ray, etc.) and core samples are stored for ongoing geological research. ***Goal:*** Expand the ability to mine any environment in the solar system using a mix of localized and universal equipment with experience gained in construction and extraction techniques at various settlements.

Manufacturing

State: The initial landings set up a propellant/water manufacturing base using Mars Direct principles and an LEU reactor power plant. This is expanded to include basic steel production (carbon monoxide and surface iron oxide feedstock), which is then formed into bulk structures using sand molds, additive and subtractive manufacturing, and imported parts. The first goal is local production of foundational construction base plates, pilings, and brackets. Experimentation with different gravity levels, mixes, and purities will take this production in novel directions. Chemical industries use a mix of local components and feedstock from Earth, with an emphasis on creating more feedstock from local materials over time as it proves more efficient. Industrial equipment, and its subcomponents, are modular and can be reconfigured for different production runs. ***Goal:*** All major systems for ongoing habitation, industrialization, and ecology expansion are built on site.

Reproduction – Plant/Animal

State: The normal range and epigenetic localized expressions are mapped for each species and strain according to gravity and limited radiation. As the epigenetic expression of each species is mapped, the range of species available for different settlement environments is expanded for new applications. ***Goal:*** Epigenetic and GMO research to expand ecosystems well into the solar system and beyond. Understand the full genome of all primary species, and gain knowledge with genetic and biological risks in reproduction across various gravity and radiation environments. Eventually engineer entire ecosystems for different artificial habitats, expanding options for future terraformers and exoplanet settlement.

Human Reproduction

State: After animal testing in the ring (most earthlike) environment, couples could start families within the ring. Pregnant women and young children remain in the earth-like environment and are monitored for stresses. Limited exposure to Mars gravity is allowed as children age with monitoring in the early generations. ***Goal:*** A practical set of guidelines on minimum gravity and shielding levels for multigenerational space settlements is defined to allow the human ecosystem to expand off-world. Gravity rings on Mars may eventually prove unnecessary.

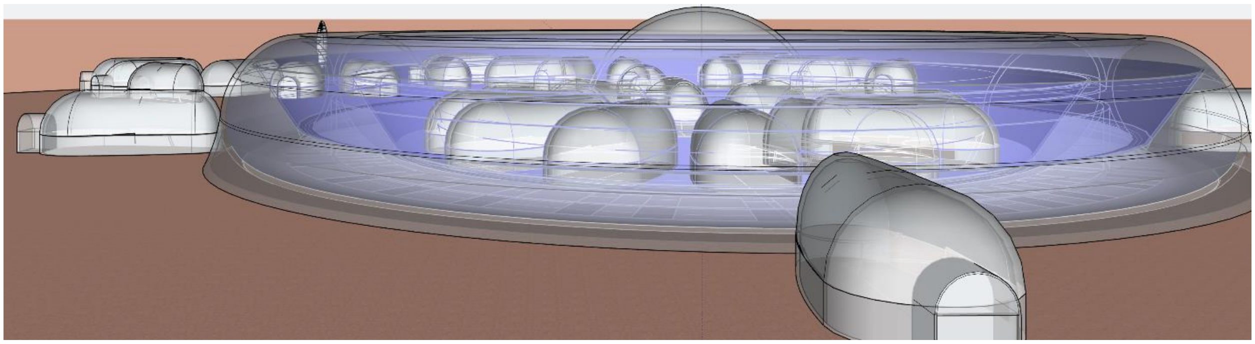
Shelter Construction

State: After site prep, structures begin with a set of steel plates anchored to the ground using sterilized steel pilings. Each interlocked base plate is 1-meter square and allows for an insulation/sealing layer above. From here, a light framework of flexible T-beams and stringers are assembled by robots into various structures and bolted together using a system that allows tracks for mounting of ice blocks, magnets, and utilities. Frames are typically two to five layers of gridwork, with each open cell within the beam structure sized as one cubic meter. Seals and insulation layers are clipped to the inner and outer surfaces. The ice block bags are clipped in place within those framed cells as construction progresses, with a middle utility gap. The full frame is assembled first and a dust barrier seal installed on the outermost skin. Then the contents of the remaining cells are filled in. The ice bags are filled with a fiberglass-like "fluff" of high strength composite filaments to add strength and heat capacity (thermal mass) to the blocks. Once robotically filled with water and frozen, they are stronger than concrete and block cosmic rays. The bags/blocks have dovetail arrangements to lock them together with the rails and each other while allowing for some expansion. This construction method allows flexibility and settling in assembly while still giving precision in the final build. Once available, base foundations are built of locally-made steel. The blocks are filled from the bottom row up and allowed to freeze and settle by layers until the inner wall is completed and partial pressure kept in the dome. Blocks that may be above freezing (thin internal foundation pillars, etc.) are filled with cement instead of water.

Pressurized to one atmosphere, structures must contain ten metric tons of internal pressure per square meter. This would require an ice dome 25 meters thick to offset this pressure by mass alone in Mars gravity. A 12-meter ice dome would offset cosmic ray exposure approximately as much as the Earth's atmosphere. A thinner dome partially offsets the pressure load by hanging components on cables from the ceiling, rather than placing them on the floor. A factory greenhouse, for example, would hang the plant tracks from the ceiling and use a thinner roof, because plants require less cosmic ray protection. Such a system could be tuned to different pressure loads by lowering the bottom-most hanging components to the floor. Hoop stress at the stem wall is offset with strong local-steel footings and a berm of the same ice blocks used for the roof or backing up to adjoining structures. Typical construction for the operational base would be two, 1-meter blocks of ice, a 1-meter service gap with the magnetic shield elements at 500 millibars, and another two meters of ice. If necessary, more layers can be added and pressure differentials adjusted. This system allows for structures of any size, shape, or thickness (in roughly cubic meter units) to be built, or rebuilt, ad-hoc by settlers to meet local conditions. Inhabitants can disassemble and reconfigure structural blocks and tracks over time in new buildings. The inner surface contains fiber optic lighting arrays and (where appropriate) sprinkler heads for watering plants and fire suppression. The ice walls would be insulated inside (from the heat of the habitat), and have an active temperature management system to prevent the inner surfaces from melting and reducing strength. Having the hardest, coldest ice on the outside and warmer, softer ice on the inside would mimic the structure of a quality knife blade or medieval castle wall and thus boost protection from meteor splash damage or launch accidents. Magnetic Holbach arrays (where the magnetic field is much stronger on one side) not only limit radiation but can help augment stress loads in the framework where needed.

Goal: The base plates, bags, structures, and conduits are eventually manufactured from local materials. Methods are invented for building them with materials from other worlds (lunar beta cloth, etc.) to expand the technique where temperatures allow for this option.

SITE CONSTRUCTION AND BUILD-OUT SEQUENCE



Site Location

The main city is in an 800+ meter older, dust-filled crater at or near a large deposit of subsurface ice. At a safe distance, a second crater 300+ meters in diameter hosts the spaceport, nuclear power plant, and initial manufacturing domes. In both cases, crater walls would provide a natural barrier from nearby meteor strikes or a launch accident. A subsurface radar and acoustic survey would find and remediate issues prior to site preparation. A roadway is cleared between the two, with an eventual pressurized surface corridor and pipelines built between facilities. The site location should also have areas of loose material for further mining.

Initial Landing Site

Soft areas are desirable for mining, but hard rock is desirable for landing. A Starship-scale rocket would risk burying its footpads if it blasted the focused exhaust plume through soft material on landing. Further, a soft surface may allow the vehicle to tip during unloading or refueling. The first landing would be on the nearest, most accessible, solid, flat area in proximity to a subsurface glacier. On-site landings could be done with a “blanket” landing pad anchored down by a crew to prevent engine erosion of the landing site, with a simple frame underneath to balance the mass of the Starship during fueling and takeoff. As such, the first mission may consist of landing, a “hop” to the proto-spaceport, then fueling and return. Conversely, a robotic starship hosting the fuel production plant may intentionally bury its footpads to help anchor it from the shock of being in proximity to future vehicles launching from nearby after fueling.

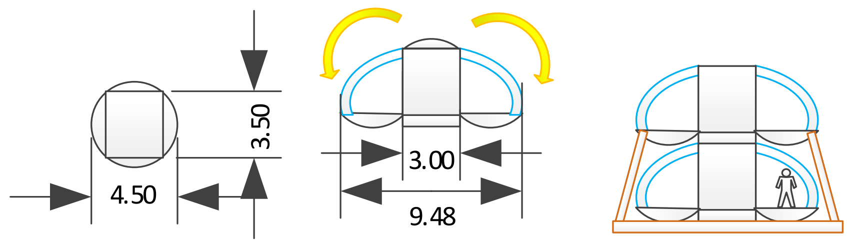
Initial Settlement Site Preparation

Dust/debris clearing machines gather all loose regolith from the surface to a reasonable depth and feed it into the refinement system. Both craters and the path between them are scrubbed to the base rock or frozen material. The subsurface scans are repeated and archival cores drilled.

Equipment Boxes (Construction Camp Phase)

Equipment boxes are standardized modular architecture to enclose power, living, production, and related equipment. They are the space settlement equivalent to the intermodal shipping container standard. Modules vary in length, with a core 3.5 meters tall by 3 meters wide. They are designed to be loaded horizontally through a cargo bay door that could accommodate a standard satellite payload (4.5-meter diameter cylinder), and the boxes themselves may be part of a cylindrical module. Equipment boxes provide basic services while the building the spaceport, and accommodate settlement equipment for both surface and in-dome use. The sides of some units can unfold and be pressurized like a Bigelow habitat, and the mid-layer gap may be filled with water (below, in blue). This provides a dense block of hardware in the center section with shirtsleeve work access from both sides. Boxes are positioned on insulated, level skids and interconnected as appropriate.

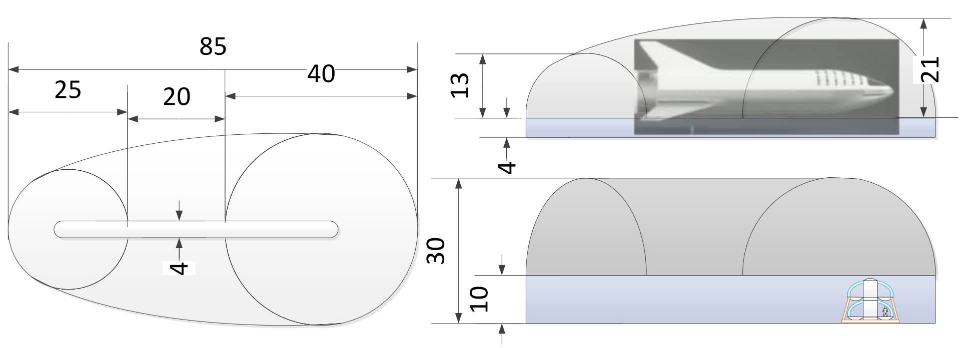
Some modules can be stacked, with support frameworks for the upper pressurized sections mounted to a wider ground pallet. Airlocks, ladders, and passageways are incorporated into the ends of some unit cores. Modules build in this way include power plants, basic surface habitats, fuel production, life support, vehicle servicing, dust separation and mineral/metal extraction systems, basic foundries, manufacturing systems, water extraction, and waste treatment. Elements are connected to pass power, crew, and feedstocks directly from between containers.



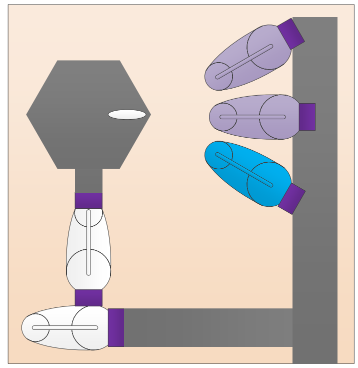
Long Dome Structures

Long domes provide ample workspace and are the principle static structures for manufacturing, hangars, and LED greenhouses. They are scaled to provide unloading and service hangars for Starship. They have either flat or tapered rooflines depending on the purpose.

Interior dimensions (shown) are in meters, with an equipment box at the lower right for scale. Walls are 1-5 meters thick. Stem walls of larger structures are 10 meters tall to permit full Starship cargo-scale hardware to fit through airlock doors and passages within the main base. The shorter dome with 4-meter stem walls is for remote installations like spaceport utility housing.

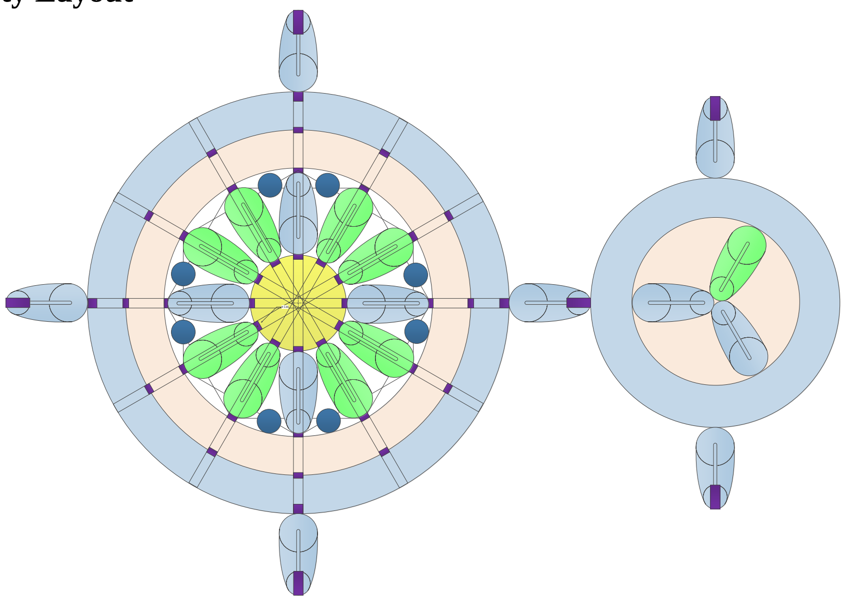


Spaceports



Each port would have a propellant plant (blue), two storage tank facilities (purple), the landing pad and roads (gray), and a pair of long domes turned at 90 degrees from each other for unloading starships. The domes have the smaller end toward the pad to minimize the effect of shock waves, with blast-out doors at the back to direct any tank ruptures away from other facilities. The ellipse on the landing pad is the crew gantry, cargo crane, and refueling arm. During early missions, propellant storage would be a few decommissioned Starships. Spaceports allow point-to-point expeditions to explore other parts of Mars, as well as missions of the asteroid belt.

Demo Ring and Main Facility Layout



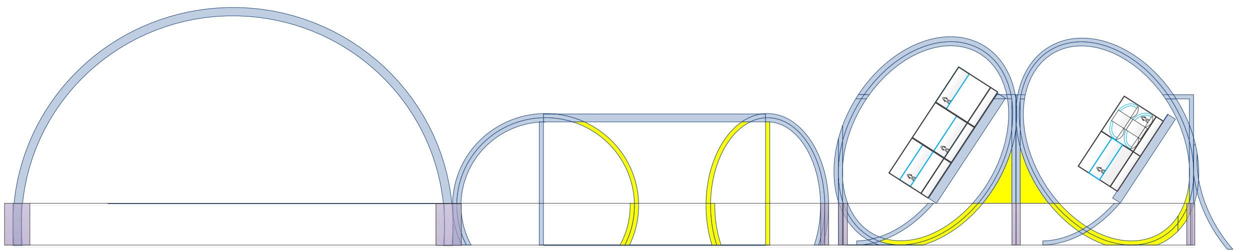
The main settlement consists of two concentric rings, various long domes for main airlocks, work areas, and greenhouses, and a central, 100 m dome. The entire structure has an outer 10 m stem wall backed by a berm outside the rings. This schematic is the main settlement adjoined to the smaller prototype settlement. For the main settlement, the outer ring being 440 meters in diameter. The dark blue cylinders are storage silos with dome ceilings, 25 meters in diameter. The green domes are agricultural spaces, and the blue ones are airlocks or work areas.

The smaller prototype ring on the right is 260 meters in diameter and is the minimum size to comfortably generate 1 G equivalent on Mars. It also contains three work/lab long domes in the center and has a 10-meter stem wall. If arranged as apartments, the prototype ring could house 1300 people. The mini-ring resolves any engineering issues prior to building the main settlement and would remain active as a secondary lab. More mini-rings with radial exterior domes would be built where appropriate as mining or manufacturing outposts.

Additional manufacturing and lab facilities are built using these common elements (long dome, storage towers, rings, central domes, etc.) and are interconnected with the main facility. The larger the ring, the greater the track speed needed to reach 1G. For this reason, it is better to build multiple rings in this smaller size range than to attempt a still-larger ring. Having three ring sizes here gives a range of experimental options for future replication as needed and allows different gravity levels to be used simultaneously for long term experiments.

The Ring Tracks

The cross-section below shows the central park dome, an internal long dome, and the inner and outer ellipsoid rings with a banked track. For 1G of centrifugal force, a track angle of 57 degrees is needed for Mars gravity (lunar version, 74 degrees; deep space, 90 degrees.). The tracks contain a tightly spaced series of rails, with some service ramps between rails that allow personal access in small cars, waste containers to be offloaded and supplies to be picked up. If an experiment requires a lower gravity setting, the railbed is adjusted to a different angle within the pressurized torus. Rails have dual-angle safety wheels allow both stationary and operational security, and may use magnetic or pneumatic systems to reduce noise and wear.



Track Service Cars: Each track has service cars that are 2 meters tall and approximately 10 by 10 meters wide and long. The cars are interlocked both around the ring and across the radial dimensions (two “lanes” for the outer ring, three for the inner ring). The cars use induction to power rail drive wheels, power the habitats, and recharge emergency/surge batteries in the service cars. The cars also house utility areas for water, electricity, waste management, and bulk storage. The car frames themselves are like gondola rail cars, with spaces where the wheels and utilities bolt into place. To allow for swapping of wheels and tracks, at least five rails are mounted under each module for stability. The rails themselves can be swapped out from the underside of the track from underneath as they wear out. Modules and equipment can be added or removed by cranes on an overhead gantry that would follow a module, lift it while in motion, slow it down, and drop it in a service bay. It could then return the module (or an exposed service car) to the track after repairs. This allows the ring to remain in motion for years at a time while components are replaced as needed. The mini-ring, inner hab ring, and outer ring move at 70, 110, and 125 kph respectively (45, 66, and 80 mph) to maintain 1G. The outer ring may operate at a lower G level/speed for experiments. Waste and sewage would be anaerobically digested, pasteurized, dried and compressed into blocks within the service cars themselves. The resulting blocks would be contained and removed via a service system under the tracks. Water input to the ring would be a separate track of containers “uphill” on the ring from the waste tracks, although with recycling it may be possible to simply condense and transpire water as needed from the ambient air in the torus. A third system handles mail, commuters, and supplies. Conversely, it may be best to put rails on the service cars and drive wheels on the tracks. Replacing moving rails would be challenging, but may be unnecessary if a pneumatic or magnetic bearing arrangement were used in conjunction with the mechanical safety rails.

Track Habitats: The habitat sections on top of the service cars are also modular and stacked into structures 10 by 10 meters at the base and up to 9 meters (three levels) tall. They could contain a fully-extended, double-stacked equipment box (top right of the cross-section, above).

The habitats include homes, work areas, restaurants, labs, and spaces for agriculture in near-earth conditions. The ring module arrangements are 112 total modules for the mini ring (2 tracks of 56 modules each), 260 for the outer ring (2 by 130), and 300 for the inner ring (3 by 100). This gives space for 672 habitat cubes. If a habitat box contained apartments for twelve people, Eureka could handle 8064 people as a pure "bedroom community" (though it can only feed 1200). If all habitats were three levels, Eureka would have 200,000 square meters of gravity-boosted space, plus 67,200 square meters of rooftops. Since airflow in the ring would be accelerated to roughly match the habitats, rooftop spaces would be open for small gardens under the illuminated curved surface of the track pressure vessel. Exterior visuals on the curved ceiling are projected and either match the speed or remain stationary, depending on which induces the least vertigo. Earth or other landscapes are projected at the lower edge, and animated like a rail journey through the mountains or whatever suited the population as an ever-changing landscape.

Given the steep angle, furniture would be built in, with interior and storage arrangements designed to allow for an emergency ring stop. An exit track on the inside of each lower wall would allow a safe exit if there were an evacuation.

Aesthetics

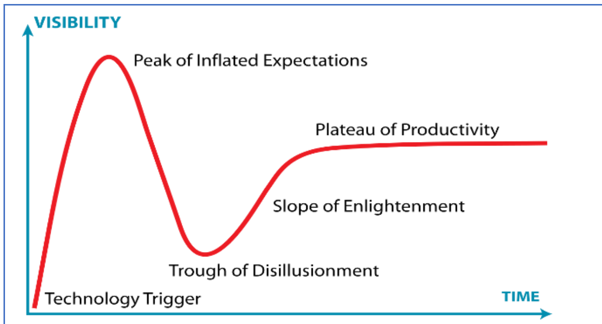
Eureka is designed to fill the senses with as many psychological prompts of comfort and inspiration as possible. Pastoral environments give a feeling of being outside in natural smells, sights, and daylight. The central dome provides a set of fruit trees, berry bushes, and other natural elements in a permaculture "food forest" that is both a park and a food source for the settlement, possibly with some wildlife. It also allows for epigenetic studies of trees and a mini-ecosystem at Mars gravity. Since trees at Biosphere 2 became embrittled by a lack of wind, the dome has systems that would provide artificial winds from various directions, rain, and seasonal temperature changes to maximize fidelity to the Earth-outdoor experience while isolating the variables for plant growth to gravity. The dome may include a "lazy river" pool and a central tower that overlooks the dome interior. Overlooks on the edges and in the core pillar would give a beautiful escapist set of garden spaces and plaza design opportunities. With the park domes and rings, an artificial "sky" is projected on the ceiling, with mountain or seascapes at the horizon edge changed regularly. Artificial sun LED skylights[4] throughout subsurface structures would bring a feel of daylight into the lower spaces, and some locations may use a sun tracker and mirror system to project actual sunlight into the facility. Eventually, a dome would be built for an ocean wave park with a beach and reef for diving and ecosystem experiments.

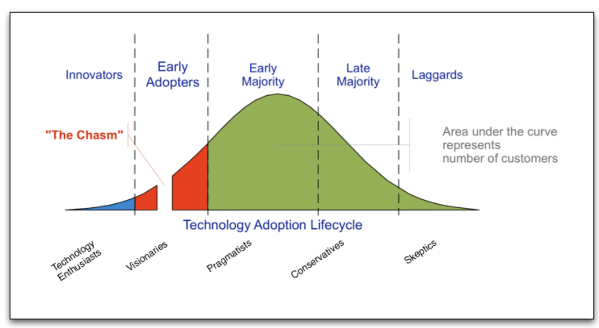
With the high stem wall, Eureka has the feel of a vaulted cathedral in the dome interiors. The internal architecture is a combination of right angle (Frank Lloyd Wright) elements in the factories and hydroponic farm spaces, flowing curved organic (Roger Dean) architecture in the ice domes, and angular yet flowing elements (Syd Mead, modern cars) in various equipment and mechanical systems. People also feel comforted with spacious city plazas and a feeling of permanence beyond a human lifespan[5]. The vaulted ceilings of the domes and rings with 10-meter base walls give this timeless feel along with a general openness. Observation decks on towers and the rings overlook the Mars environs while still being protected from GCR from above. Surface images on 8K monitors feel more like windows than televisions in indoor spaces, and show live feeds from the surface. Light shows on the ceilings and exterior, fountains, and 3D sculpted public works provide a unique art gallery to display local creativity.

Residences, restaurants, and offices would have an allotment of material that is then 3D printed and CNC carved into whatever furniture, art, and fixtures matched the tastes and needs of the space. A small home or public module (4 by 10 meters) in the ring could have a décor theme of steampunk, Sci-fi, Victorian, Parisian, medieval, the age of sail, garden, conventional, retro-future, or whatever suited the owners. A visit with friends would be like a microvacation - not only to anywhere on Earth, but to many historical periods and fictional worlds. Restaurants and businesses would have a similar flair to break the monotony with endless variety and creativity. If tastes or residents change, the interior can be traded or recycled into an entirely new space.

Good architecture avoids as many imperceptible annoyances as possible to avoid a form of subliminal, though cumulative, irritation. This stress dampening quality would be important to the health and happiness of the settlers. Since everything is built from a clean sheet to be maintained robotically, robots have a much lower AI threshold to do cleaning and organizing tasks. Power, light, and data systems would be universal and hacker-proof with quantum-resistant communications protocols and simplified software/hardware systems. Restrooms, labs, workshops, and kitchens use steam-cleaning robots. Manufactured goods are stamped with unique IDs that would also designate ownership in the blockchain. In short, the worries of information security, theft, cleaning house, or even the having the right plug for a given socket are largely remediated based on this clean sheet approach.

ECONOMIC MODELS





Technology revolutions have far more variables than company business models. At present, this is further complicated by the convergence of several technology revolutions in both digital and material sciences. Any start-up enterprise faces a phase called “the chasm” (above right), where early enthusiasm and seed funding wains and mainstream markets have not taken root. Similarly, new technologies face the Gartner Hype Cycle (above left) where early promises collapse and investment fades prior to a slow normalization and plateau of that technology as a “new normal”. Eureka’s business model must be strong enough to survive both collapses simultaneously, and do so at an unprecedented level.

Further complicating matters is the fact that many needed technologies on the Grand Challenge table have no practical pay-back model in the early stages of development. The early space settlement revolution is unlikely to support many large enterprises until the economic benefits are democratized. Successful technology revolutions typically begin with one or two lead efforts, followed by a wave of follow-on products from a broad spectrum of manufacturers.

The Limits of NewSpace

The hope by SpaceX, Blue Origin, et al is that the new affordable launch market will finance ongoing efforts to develop crewed deep space technologies. This entire interdependent matrix of Grand Challenge technologies (new surface suits, life support, etc.) must become affordable as a complete system, at the scale of global enterprises ($1 billion/year) to begin the process of normalization.

The NewSpace revolution enables and is inspired by the Space Settlement revolution, but it is not the same wave. NewSpace breaks the corner of the space settlement grand challenge table by providing affordable, heavy launch vehicles for existing satellite markets and opportunities for a convergent new market of high-speed satellite internet. While the market increases as launch costs drop and the high-speed satellite business model become viable, the launch market will have a mini-collapse of minor players much as the early PC market created and dropped many smaller enterprises. Without a transitional economic model, the NewSpace revolution may undergo a launch service hype cycle collapse just the space settlement revolution begins to need investment. Meanwhile, other technology revolutions such as AI have the potential to drain investment and cutting-edge talent away from space projects. Modern technology revolutions use agile methodologies. These methods enable rapid innovation. But they do so at the expense of being nearsighted in terms of strategic planning.

Harnessing Concurrent Technology Revolutions

That said, this concurrent set of technology revolutions has the potential to combine into a powerful economic engine if each revolution's products are intentionally used together in a greater machine. This is often called convergence or multifactor productivity. Further, the difficulties of settling and industrializing the space environment can be turned into advantages in biological and material sciences. Eureka's parent organization combines the experimental environment on Mars, affordable sensors to gather data, artificial intelligence to analyze multi-variable data, and quantum computing as a back-end calculator to model difficult elements such as complex proteins, material chemistry, and genetic expressions. This mutually-supportive engine, along with Earth labs built on the same model to further expand the knowledge base, would drive very fast iterations in experimentation, discovery, and invention.

Getting Started

Assumptions: The foundational infrastructure of Mars missions will be created by SpaceX and joined by Blue Origin, more competitors and systems added later. SpaceX plans a Martian outpost for refueling and power near a buried glacier for ease of water extraction, as outlined earlier. Eureka's parent organization then provides the foundation for ongoing work past this foothold.

The Eureka Foundation (TEF – working title): Eureka's parent organization sets standards, performs testing, and routes requests for proposals (RFPs) for equipment needed for space settlement to competing organizations. Qualified participating manufacturers would then submit designs and products for certification and flight evaluation. Companies entering competitions would retain partial ownership of their flight articles as part of the financial incentive model for participating in these historic missions at reduced organizational cost.

Sponsorship Hardware Development: The cost of getting city-scale shipments to Mars will be prohibitive if done without a democratized sponsorship model. Mars-to-Earth exports (discussed later) need a mark-up of 10 times or more to offset the cost of imported equipment and supplies for the first large settlement. A shrewder approach is needed to bridge the fiscal gap from exploration to settlement- one that monetizes and democratizes the historicity of the moment.

The supplies for early expeditions have unique historical and promotional value. First, the company that builds the first XYZ device judged good enough for use on Mars would be motivated to sponsor that equipment for promotional purposes. Second, if that equipment could be shipped back, in whole or in part, then it becomes a historic collector's item far more valuable than a terrestrial copy. Third, the equipment is then tested in Mars conditions and may be marketed for commercial off-world use. These are three key motivations for manufacturers to sponsor or discount equipment. Other investors could sponsor additional equipment they didn't manufacture such as electric motors or other small items, with the understanding that possession of the returned collectibles would revert to those investors. The supplier contract would have a value in the meantime as a tradable financial document. More on all this later.

MarsSpec: TEF sets standards for testing and certification of hardware or software exported to an off-world space settlement. These systems must be maintainable with site-manufactured parts where possible, highly reliable and secure, have electronics encapsulated into replaceable units, use a new universal set of ports, common bolt sizes, and so on. Right to Repair must be expanded to include "Right to Bypass" (replace existing machine controls with simplified systems) also added for emergencies or independent on-site support. As with fire engines and other mission-critical technologies, manual bypasses must be available in emergencies to prevent hackers, misinformed AI, or software errors from putting key infrastructure at risk. Crews would be trained in manual systems and drilled to avoid skill erosion. This kinesthetic practice mentally grounds them in the principles of how the systems work that allows the base to exist, enhancing the depth and integrity of future site-created inventions. Components must be modular and interconnect with other systems on the same standard and be "stackable" to create larger capacity systems. This also makes equipment adaptable to unexpected situations. By making standardized systems work together, there is a built-in terrestrial market for ruggedized or luxury equipment. For example, if a luxury car or home builder can do MarsSpec product lines, that differentiates the product (and manufacturer) from the competition. This same halo effect and research model is why automotive manufacturers invest heavily in racing and concept cars. Conversely, field-maintainable equipment on the low-end of the cost spectrum would be useful in developing economies and remote locations. The specifications are compartmentalized in such a way that these spin-offs could benefit both low- and high-end markets on Earth.

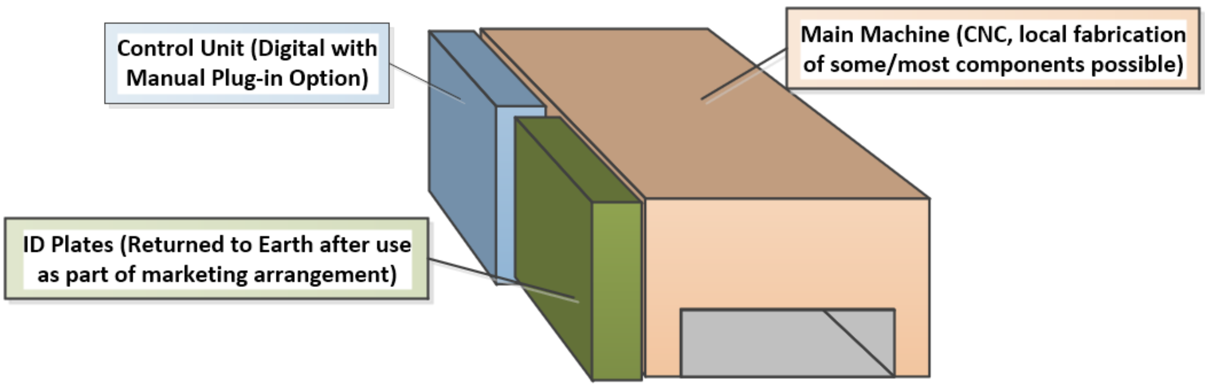
Since the qualified systems are simple, maintainable, and reliable, they will often be affordable to fabricate due to the prevalence of additive and subtractive manufacturing techniques. As the standards expand, there will be catalogs of MarsSpec component parts to further democratize the manufacturing ecosystem. NASA could have some involvement in this effort, just as their predecessor, NACA, set universal standards for airfoil designs that are still used today. The organization would also help avoid intellectual property issues such as led to the "sewing machine wars" in the mid-twentieth century.

LaunchFest: Each year, the operational authorities of planned missions, bases, and settlements would put out RFPs for equipment needed for the next few missions, including lunar and Mars missions. Finalists would attend a massive exhibition and stress test competition to select winning products and equipment. It would have a similar dynamic to Shark Tank, EAA AirVenture, and the University Rover Challenge combined for products across the board. As with any fair, judging would be held early, or as a prerequisite to entering the show, so that the competitors could show off their awards early to the public. A second festival cycle would invite the manufacturers (and their VIP clients) to the appropriate spaceports to see their handiwork launched into history during the next 26-month launch window. A similar ritual would celebrate the return of ships with used hardware for analysis, collectible sale and promotional display.

Certification Seals: For space settlement to be self-supporting, we need economic jujitsu to monetize unique aspects of the space environment itself. Something that can be done from deep space (Dear Moon, etc.) is a GCR-etched flight certification seal. This would be a clear layered material that is highly susceptible to being etched with cosmic rays. While the earth's surface experiences cosmic ray spallation at the nuclear level, seals exposed to deep space over long periods would contain tracks from higher energy cascades through layers with reactive chemistry. The key feature is that the seal should contain a set of tracks based on GCR exposure, which can then be non-destructively observed, recorded and validated as unique.

Seals would be assigned to vehicles, missions, astronauts, and equipment and would continue to gain more tracings as they spent more time in deep space. Upon return to Earth at retirement, the occlusions would be recorded and put in a blockchain journal to certify the seals as authentic space-flown materials. (A similar method is currently being used to validate mined versus synthetic diamonds by documenting their occlusions in a shared journal on a blockchain.) In the end, seals could be affixed to space-flown equipment and the unique properties of both the seal and the equipment before and after flight would be added to the blockchain. Flight certification seals would prevent forgeries of space-flown equipment on Earth from undermining the sponsorship model above. Since this equipment is designed to be maintainable on Mars with 3D printing and so on, forgeries of historic items would be quite simple without a certification seal.

There is a potential conflict between the demand for the return of sponsored artifacts and the desire for settlers to keep hold of refined materials. A win-win option would put all the unique elements in a front-plate, including the certification seals, and possibly multiple seals to allow the returned identification plate to be split as a "limited-edition" series of artifacts (conceptual illustration, below). The equipment behind the plate could be reused on site or recycled into new equipment, with some parts returned with the ID plates for wear analysis and design improvements. Since the plates and parts would take less space/mass on return flights, more collectibles would be returned on each flight. They could also be returned while equipment is still in use, so the sponsorship returns on investment on both Earth and Mars simultaneously.



Investment Forum: The certificate/sponsorship system provides the financial foundation for getting the settlements profitable and democratizing production, investment, and base ownership far more quickly and dramatically than would otherwise develop. These contracts avoid ownership conflicts between settlers and remote institutions. Investing in settlement equipment would be like owning non-voting stock in Eureka's day-to-day operations. Once Eureka becomes profitable, twenty percent of that profit level is reserved for these pioneering suppliers above and beyond the other benefits. In addition to suppliers and equipment collectors, anyone could purchase a simple stock certificate/ flight certification seal combination in sponsorship of specific missions or equipment. These investor payments would help pay for non-returnable items such as reactor cores and foodstuffs. Many sponsors would keep returning to invest in blocks of missions to complete collections of seals and equipment related to some topic of interest. A collector may display seals for helping sponsor coffee shipments for Mars for an entire decade, with a special seal for sponsoring early coffee growth experiments included.

Since the end goal is space independence, the certificate of ownership would be non-voting and would have an "expiration date" in terms of the twenty percent profit sharing. This expiration date provides an investment that would trade like a stock option, but over years rather than days. The permanent value of the investment would be the flight certification seal itself, which would increase in historical value over time. Early contracts would be for longer periods due to how long they would have to wait for settlement profits and expire prior to settlement independence.

Minor Markets. Eureka could also sell sliced Mars rocks and surface meteors that would have the double rarity of being meteorites from the surface of Mars. An industry of making unique teas, coffees, and liquors on Mars for the Earth luxury market is also theoretically possible.

Import/Export Trade Balance

Our baseline assumption is that Earth to Mars transport costs $500/kg and exports to Earth are $200/kg. Raw imported material for onsite manufacturing such as chromium powder average $30/kg. Exports may average $100/kg (opportunity cost) to mine and collect in terms of extraction, packaging, and so on. Under a flat model, this would mean that exports would have to be marked up 830 percent to break even with imports. This model is unsustainable because the return on investment would take too long and grow too slowly for expansion and trade security. The LaunchFest model would help sponsor each import flight and raise the profit closer to the full $210 million per sortie. If twenty percent of the profit is a dividend for the sponsors, that gives $168 million to help operations and $42 million for the investors per flight. Investors in Eureka itself would also receive a comparable percentage on the intellectual and informational exports and research arrangements. The billions of dollars required to get Eureka built and expanded would be returnable in a reasonable time with far less effort, and a funding model is established for other deep space outposts that could become an ongoing tradition as humanity expands across deep space.

The Profitable Democratization Phase

This combination of investment methods would be enough to get Eureka past the early hype/chasm gaps and on to producing intellectual property, inventions, and commercialized and scientific research. The early enthusiasm and public engagement at this moment in history is embraced and democratized so that it may become distributed, normalized and permanent. Technology revolutions only fully mature when everyone has some mundane ownership of them. It may seem demeaning to break the grand challenges down in this way, but the alternative is to never advance at all. The pioneers of Mars are not priests; they are plumbers. By the time settlement hardware becomes too common for certificates to have high value, conventional investment in research will be self-supporting.

Once the city becomes profitable, the overall profit breakdown becomes twenty percent for the investors proportional to investment and the value of equipment sent, then twenty percent for onsite entrepreneurial start-ups, ten percent as a fund for earth-based entrepreneurial projects carried out on site, twenty percent for infrastructure capability expansion (things with no direct financial return but necessary, like better sewage disposal or mining techniques), and twenty percent base expansion. Ten percent would be for resilience improvements such as creating on-site systems to displace imported products, starting with the most massive and easiest ones. The twenty percent for onsite projects can be expanded by local settlers investing their own funds, and gaining commensurate increased returns. Research done for clients would be sponsored by those clients (pharmaceutical and agricultural organizations, universities, engineering firms, governments, or individuals on both Earth and Mars). This provides ample investment for growing trade and the domestic economy.

Mars-based Consumer Products

Common necessities such as basic foodstuffs, toiletries, and so on are produced in fixed batches based on demand. Conversely, complex products are imported from Earth. Production of limited run items such as furniture would be done in common maker spaces with contract labor or hobbyists. That leaves a middle zone that can be filled with Kickstarter-like operations that design new products, take pre-orders, and commit to building the items, along with spare parts. This avoids inventory and marketing issues. As in the age of sail, settlers will be used to pre-ordering complex items from their civilization of origin two years in advance of needing them. There are spares on site for replacements, but inventories are limited. Items designed for Mars can also be licensed and sold back on Earth with local production and royalty distribution.

Social/Cultural Structure

Constitution: Settlers must have independence with responsibility and property rights. The framework for this, in the near term, takes the form of employment and liability agreements. A 7-10 year labor contract can be entered to work in space, with the option to remain on Mars as a freelancer, employee, or entrepreneur when the contract ends, or return to Earth.

Employees still under contract may launch new businesses in their off-hours. To simplify this dynamic, rental offices, labs and maker spaces give shared resources for freelance or start-up operations until those enterprises can afford their own facilities, if appropriate. They may also start new manufacturing spaces and be the primary client, then rent out excess capacity when not needed. Those living on Mars must have enough freedom to experiment with local materials using jointly or privately-owned means of production. The outpost must be able to export local materials and market them on Earth directly without onerous trade restrictions or taxation. All businesses must respect the safety and property of the settlement and environs, and submit locally-extracted materials for scientific cataloging and analysis. While the materials of a space settlement may be privately owned, the base scientific knowledge of planetology is shared as a "common heritage of mankind" so long as mining rights and any security issues are respected (knowledge can be copied and shared; atoms cannot). For Mars, there is also a restriction requiring sterile mining equipment. On-site education would be a mix of first principles, classical, and practical work, and be continued online and in small study groups on a lifelong basis. Jobs would typically be done in seven-year contracts with a six-month transitional sabbatical to re-tool the mind for another career or return to the same roles, return to Earth or a tour on another outpost. One could see a lifetime of work in space being started in a lunar facility and going to Mars and the asteroid belt, with educational sabbaticals spent en route.

Sports would be tuned with rings and open domes in mind, with smaller courts, lighter balls to limit range, and allowances for gravity or centripetal effects. Robotics competitions are a local mirror image of LaunchFest, particularly where mining and manufacturing are concerned.

Political/Organizational Structure: Smaller organizational groups can function using less formal structure and more commonality of goods and services. A good breakdown point for an informal organization is Dunbar's Number, where organizations have 150 or fewer members. Breaking groups into organizations with 100-120 members reduce the risk of infractions and social isolation. Further, organizational units of this size are large enough for ambitious projects but small enough to form highly functional organizations with specialization.

Permanent and Guest Residents: There will be a complex mix of permanent residents and visiting specialists. Developing permanent tribal knowledge versus providing opportunities for shorter stays is another cultural complication. Visitors may over-prioritize their own research or business goals while sidelining local standards or the long-term well-being of the settlement. New residents would be required to have extensive training and stress testing prior to arrival. An ideal split between permanent and visiting populations is dependent on the culture and conditions, but there should be bias towards those who must live with the situation permanently rather than simply passing through in the name of career advancement.

Education and Sponsorship: Eureka has a "guild" style system based on the tasks required to keep the base operational, and additional guilds for research, engineering, and entrepreneurial projects. Guilds would sponsor new residents from Earth, train them (and eventually native-born residents), and provide a social safety net in terms of health and accident insurance. Guilds would be limited to Dunbar numbers, but contribute to common credit unions and insurance organizations. The guilds themselves are structured like a credit union for transparency and service. They would also sponsor infrastructure and quality of life improvements for the entire settlement. They provide the talent pool for institutional knowledge, and they would be represented like corporate departments within the settlement leadership. The second body of leadership is appointed based on local living area like an alderman. To prevent any group from amassing power or individuals from being given authority without responsibility, the representatives would only serve one six-month term. No one guild would provide too many necessary services so that they could not wield excessive political pressure. Development teams consist of workers from multiple guilds. Guild membership would typically be seven years, with people having the freedom to switch guilds periodically. This helps with knowledge transfer across professions such as biomimicry in engineering or sensor design in biological research. Guilds would not congregate in specific living areas to avoid "us-versus-them" issues with settlement political or social structure. By mixing people by proximity and profession, the cultural segregation and conflict intrinsic to human nature are minimized.

Further Work

As Elon Musk said during the Dear Moon discussion of the Starship/Raptor design, "The answer flowed once the question could be framed with precision. But framing [it] with precision was very difficult."[6] Eureka is focused on asking a broad spectrum of the hardest foundational questions, then giving the best possible answers from first and financial principles, to provide solid cornerstones for ongoing work. Any engineering or economic model must allow for the realities of physics, finance, and culture to disrupt those plans in the coming decades. Ongoing work focuses on designing the business plan, writing draft specifications for modular settlement systems, and developing concepts for certification seals. For further details, renderings, and updates on Eureka, visit https://macroinvent.com/mars-1000/.

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[1] Most of this paper is written in the present tense to save space. Eureka is named for the 2006-2012 US TV series about a hidden small town devoted to advanced science. 3D illustrations by Michel Lamontagne.

[2] Natural Transfer of Viable Microbes in Space from Planets in Extra-Solar Systems to a Planet in Our Solar System and Vice Versa. The Astrophysical Journal, Dec 1, 2009. https://iopscience.iop.org/article/10.1088/0004-637X/690/1/210/meta

[3] Kilopower (Official NASA website). https://www.nasa.gov/directorates/spacetech/kilopower

[4] CoLux is the inventor/leader in this field with very bright simulated sunlight, though there are other brands that are more like televisions. https://www.lightology.com/index.php?module=vend&vend_id=774

[5] This is a common architectural concept. https://www.architecturenow.co.nz/articles/longevity/

[6] YouTube Dear Moon announcement. https://youtu.be/zu7WJD8vpAQ?t=2806