Creating a Cambrian Explosion in Space Settlement

Kent Nebergall

May 29, 2022. ISDC Conference.

Abstract

This talk breaks down the root challenges of space settlement and space independence, including economic models for self-sustained growth. A series of space settlement architectures are proposed. First, a slight variant of SpaceX Starship that provides a foundation for large L5 habitats and surface bases for the moon, Mars, and asteroids. Second, an elegant and robust city on Mars that addresses every technical challenge at maximum difficulty yet generates top-tier revenue by addressing Earth's needs. Third, a beautiful system for para-terraforming canyons in multi-layered habitats, with the goal of maximizing species diversity and migration beyond our finite world. We not only preserve and diversify species across biomes but engineer new species for both artificial and exoplanetary habitats. This is an engine for creating technology and biological revolutions in sequence so that as each matures, a new generation is in place to keep driving expansion across the solar system and beyond. We also bring Astronomy, SETI, Exobiology, and Space Settlement sciences into a concise workflow.

Introduction

At the Mars Society, I've designed three generations of space settlement ecosystems, starting with Starship. We are basically going to speed-date our way through these three, plus some technology revolution planning.

So just for context, what was the Cambrian Explosion? It was a time 540 million years ago when life on Earth went from moss, sponges, and worms to nearly all phyla that still exist today. It's often used as a metaphor for the change from extremely slow progress to dramatic advances. So, are we finally there for Space settlement?

The Steelman Methodology

First, some Context. I'm using the steelman argument technique as a design guideline.
This philosophy assumes all challenges are extremely difficult to overcome. The benefit is that it forces you to overbuild and simplify your designs. Any solution that is overbuilt and still affordable is very likely to succeed. Overbuilt designs are easy to scale back.   Conversely, best guess designs will not survive contact with reality without expensive and delicate fixes. These designs are overbuilt on purpose. It's not paranoia, it's business.

Grand Challenges of Space Settlement (2004)

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 Power/ Propellant Production	Surface Mining and Extraction
	Psychology	Return Flight to Earth (speed, mass, etc.)	Hybrid Manufacturing
	Mechanical Entropy	Planetary Protection	Reproduction

In 2004, I created this "periodic table" as a checklist of what technologies we need to resolve for space settlement. Rows are sorted by urgency, and columns by isolation from Earth.

When I first started presenting this, the top left corner looked politically impossible. Government progress was already asymptotic in terms of heavy lift and affordability and had been since 1975. Then Starship was announced.

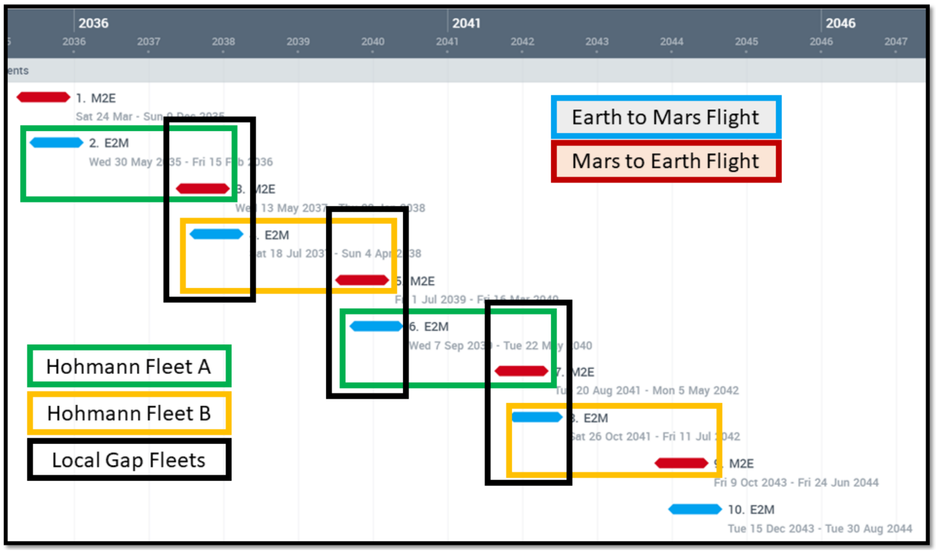
This NewSpace era is like the hydrogen from which all other the elements can come into being.

The next challenge is refilling on orbit. Specifically, doing so without orbital debris damaging the ships.

So let's start with the scale of the problem. How many Starships per Mars fleet do we have to refill?

Part 1: Outposts for Starships

At Least Four Starship Fleets Required for Mars



Elon Musk wants a thousand Starships to take a million tons to Mars. Let's start there. This timeline shows the Hohmann Transfer flight times from Earth to Mars in blue, and from Mars to Earth in red. Note that the return flight times from Mars to Earth overlap the departure flights from Earth to Mars. A ship cannot simultaneously be in both places at the same time.

With two Mars fleets, we alternate which is enroute to Mars and which to Earth. With this, each fleet can be refurbished and used locally on Mars or Earth for a year before the next sortie. We also want gap fleets that can be used locally for commerce, and on Mars for exploration. So, it's NOT a thousand starships flying to Mars at once. It's roughly a third of that. Does that still work?

Starship Production/ Flight Rates

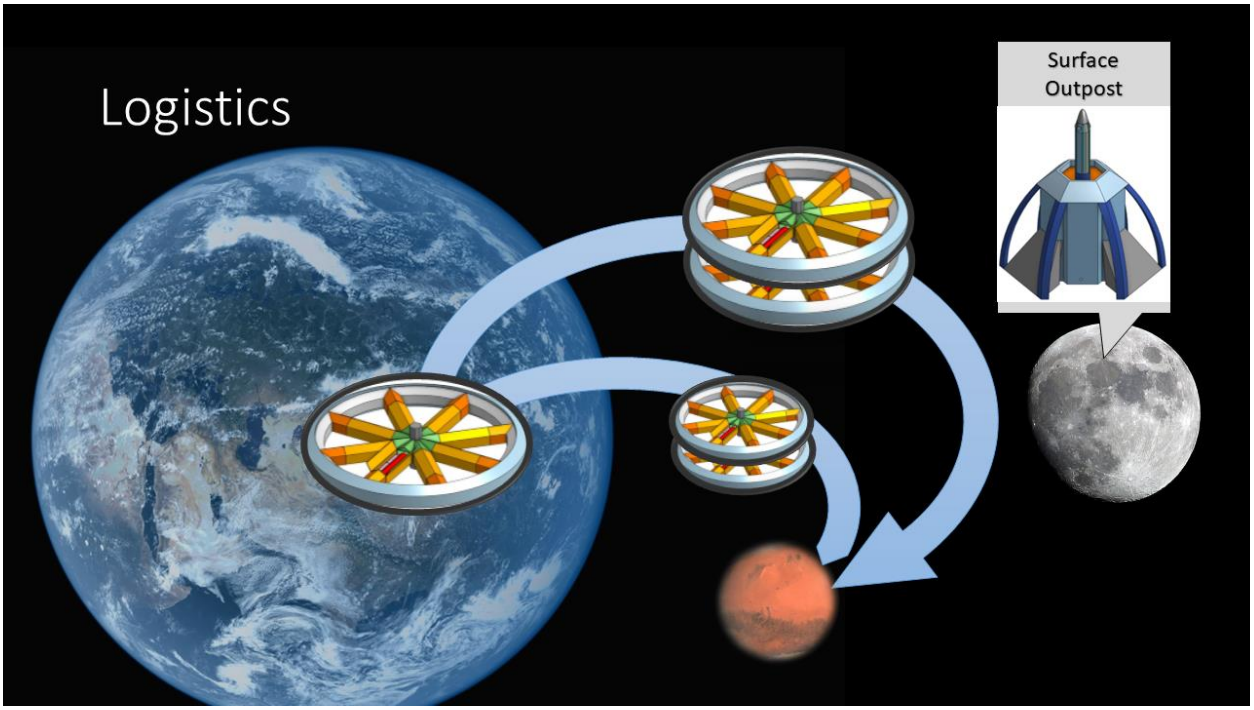
Earth to Mars	Return	Ships	Per ship	Per Sortie	Total Tonnes
11/15/2026	7/30/2027	3	100	300	300
1/3/2029	9/19/2029	5	100	500	800
2/22/2031	11/7/2031	12	140	1680	2,480
4/11/2033	12/26/2033	48	150	7200	9,680
5/30/2035	2/15/2036	96	150	14400	24,080
7/18/2037	4/4/2038	192	150	28800	52,880
9/7/2039	5/22/2040	288	150	43200	96,080
10/26/2041	7/11/2042	384	150	57600	153,680
12/15/2043	8/30/2044	384	150	57600	211,280
2/3/2046	10/18/2046	384	150	57600	268,880
3/22/2048	12/7/2048	384	150	57600	326,480
5/11/2050	1/26/2051	384	200	76800	403,280
6/30/2052	3/15/2053	384	200	76800	480,080
8/18/2054	5/3/2055	384	200	76800	556,880
10/7/2056	6/22/2057	384	200	76800	633,680
11/26/2058	8/11/2059	384	200	76800	710,480
1/14/2061	9/30/2061	384	200	76800	787,280
3/3/2063	11/18/2063	384	200	76800	864,080
4/22/2065	1/7/2066	384	200	76800	940,880
6/11/2067	2/26/2068	384	200	76800	1,017,680
7/29/2069	4/15/2070	384	200	76800	1,094,480
9/18/2071	6/3/2072	384	200	76800	1,171,280

Elon recently said the first crew could land as early as 2029.
On this chart, we have the first humans on the 60th anniversary of Apollo 11. We cross a million tons to Mars by the Apollo Centennial. This is with 384 ships per Mars fleet by the year 2041. So even if nothing improves after that, we still get a city on Mars four decades after first landing.

Ships versus Ports

Ports in space are required for real settlement. They lock in gains at each stage of the logistic train.

So 384 ships per launch window, working backwards… Let's start with the big picture.

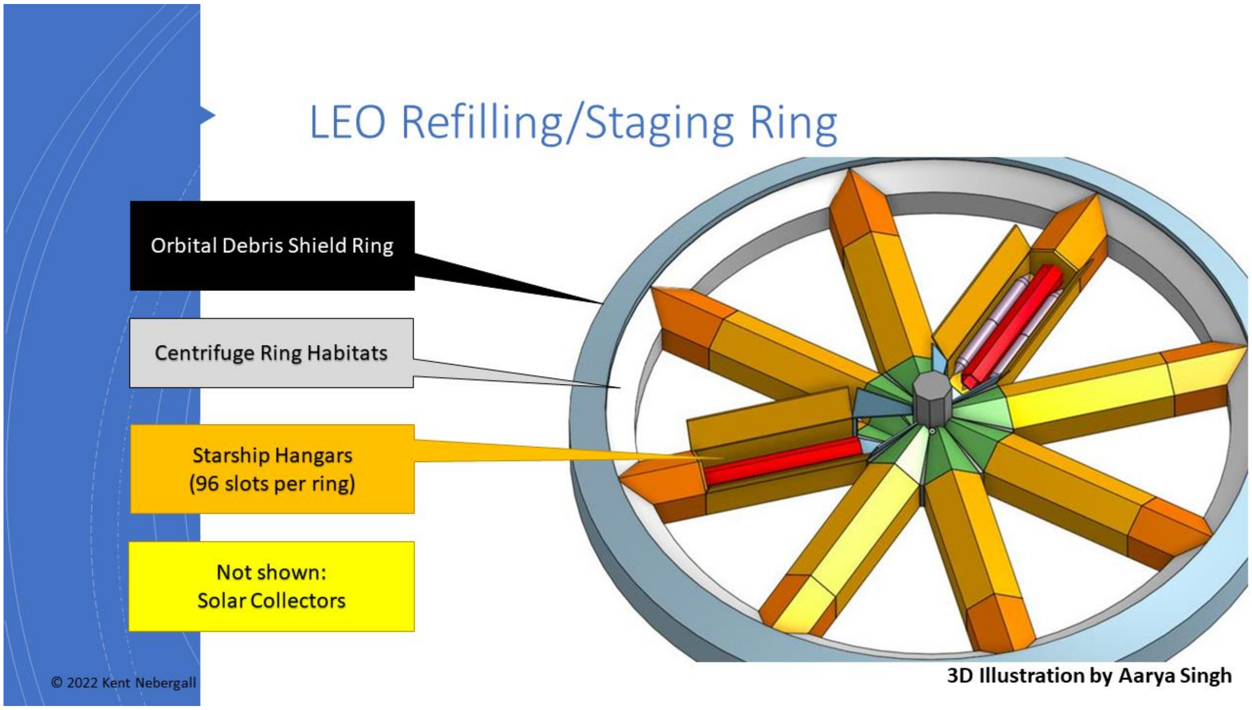


We have a refill station on orbit where we can stage small fleets with protection from orbital debris.

Then add four more rings at the Earth-Moon Lagrange points as a staging area away from orbital debris risk and much higher in the gravity well.

Having staging bases spun at Mars gravity three days away from Earth would let passengers get used to the idea of Mars settlement before committing to it. It would also give companies ready access to Mars gravity for system testing and tourism.

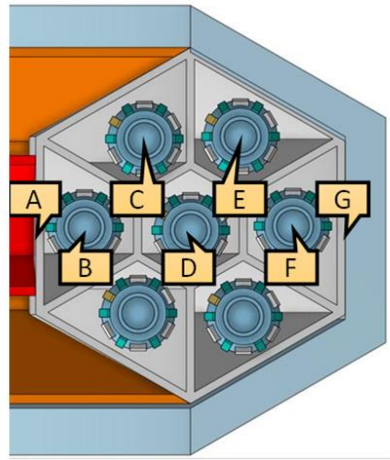
These rings are also deep space industrial outposts in the O'Neill tradition with a thousand inhabitants each. On the lunar and Martian surface, we simply take a slice of the ring architecture with starships inside as an outpost.



Since orbital debris tends to impact from the sides rather than above or below, the base has a ring shield around a set of hangars. This configuration accommodates 96 visiting starships. Since half these ships are tankers, we can service up to 48 deep spacecraft at a time.
The Orbital Debris Shield is made of bags of reenforced ice that are stronger than concrete and more resistant to ballistic damage.
We can also add a circular train of habitats within the debris shield.
The hangars are hexagonal and this scale to allow for both the current starship design and proposed 18-meter starship 2.0. As such, the sides of each hexagonal frame in these designs are 22 meters wide. This common modular framework is used throughout the rings, hangars, surface outposts, and so on. Anything involving ports should be scaled to allow for 100 years of ship improvements.

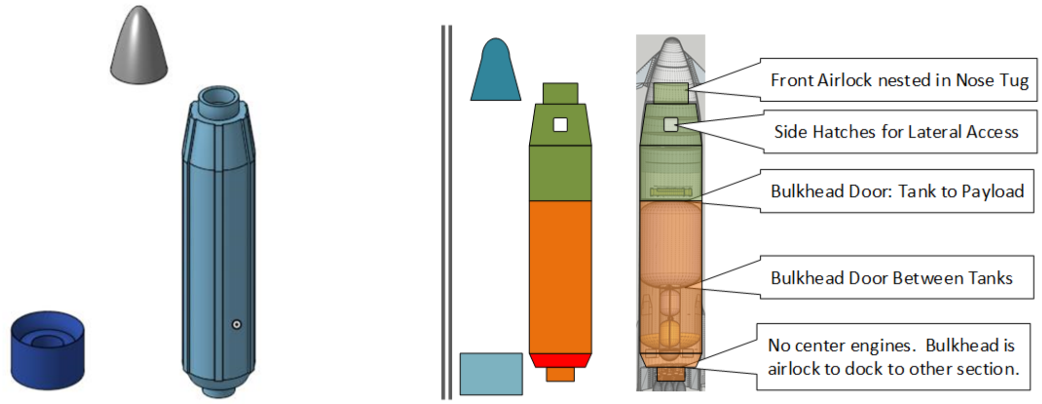
Ring Gravity (300m dia.)

Parameter	Lunar Surface	Mars Surface
Max gravity	0.775 Earth G Boost of 3.7x	1 Earth G
Ring Speed	113 kph/ 70 mph	102 kph/ 64 mph
Bank Angle	50.28 deg	44.43 deg
Rotation Rate	2 RPM	2 RPM
Baseline	D ring center	138 Full Cars, plus 4 Half Cars



So here is a ring cross section with seven tracks. The ice shield is 4 meters thick. This is sufficient to block almost all cosmic rays and allow for permanent deep space settlement. Inside the ring is essentially a passenger train with both ends connected. The train cars are converted starships.

We can fit 1000 people in six rings like this, with the seventh used for logistics. A 300-meter diameter ring in deep space can get to 60 percent Earth gravity. On the surface of Mars, it can be run at a banked angle and get to a full G. On the moon, we can get to almost 80 percent Earth gravity.

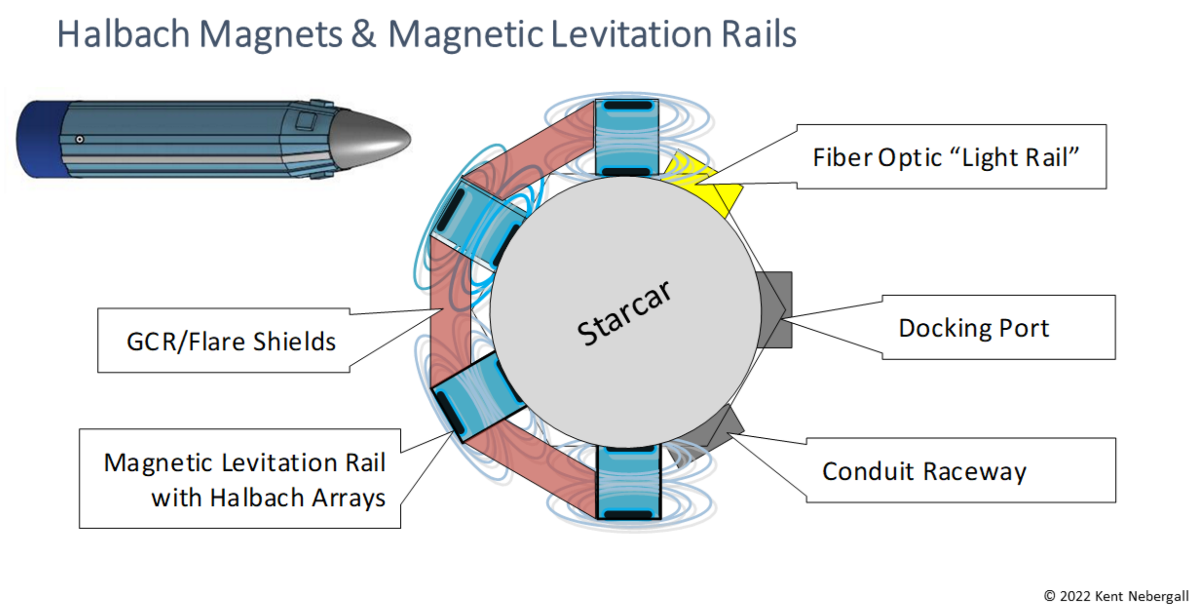


Starcar: Modular “Wet Lab” Habitat

The centrifuge rail cars are heavily modified Starships called StarCars.
It’s a starship converted to something much like a passenger train car with crew hatches from end to end. After it gets where it’s going, the propellent tanks are converted to crew space.
The nose and engine fairings are detachable, and the tanks are customized for future habitation.
One Starcar is twice the volume of the entire ISS. And it can be built on the same assembly lines as Starship. The interior would be three “stories” high when rotated on its side. While the downcomer pipe may block the last tank down the middle, it may either be removed as part of the conversion process or repurposed. Also, there is no reason not to off-set the hatches between modules other than allowing a clean central path through the habitats.
My population figures assume ten people living in the crew section, with the tanks used as an LED greenhouse. This provides up to 90 percent of the fresh food supply. If your greenhouses are elsewhere, you can double the living space and expand the menu. For a deep space habitat with constant sunlight, a fiber optic “rail” can be included on the ship exterior and set at the focus of a disc of concentrated sunlight within the ring structure. This would reduce transmission losses to the greenhouses within the habitats, as well as simplifying lighting and temperature management to something nearly passive.

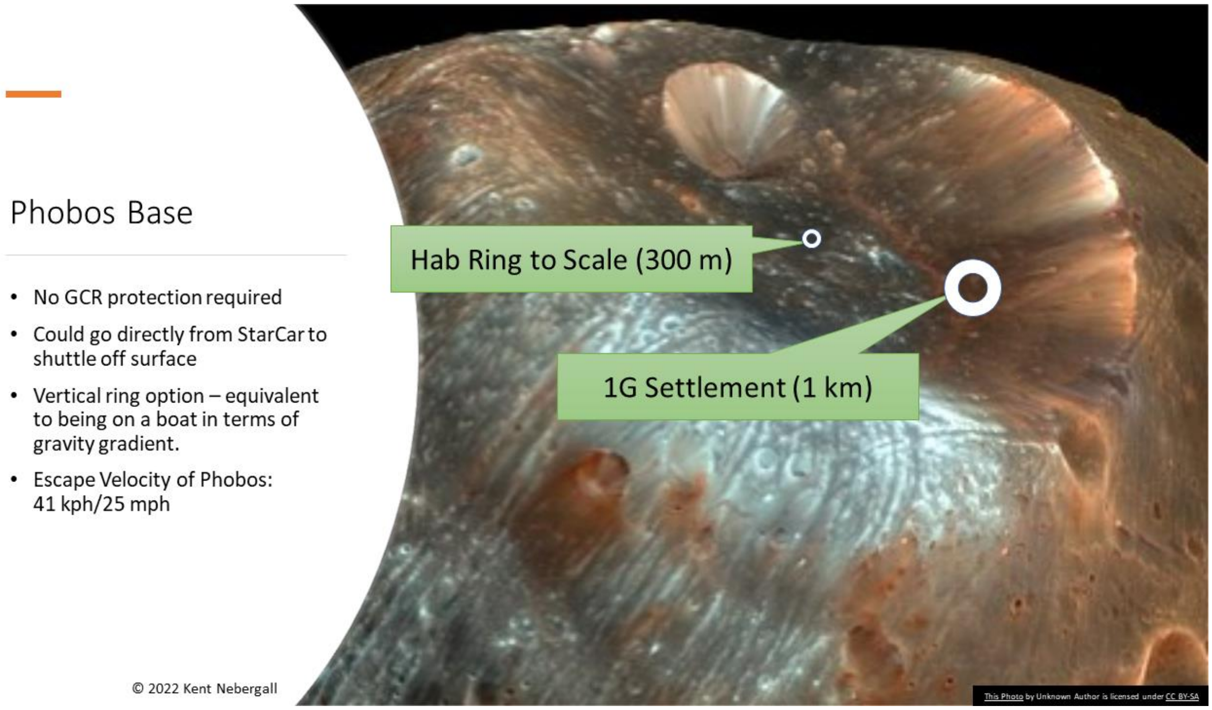
The nose and tail can be returned to Earth or used locally. There will presumably be no shortage of demand for spare Raptor engine assemblies in deep space with so many habitats.

I’m sure Elon Musk would appreciate that the perfect length for each StarCar is 42.69 meters. This means that a 300-meter ring can add another ring around the outside or inside by simply adding or subtracting one car. The lengths are within 13 centimeters of each other for several inscribing rings. Anything longer or shorter than 42.69 meters will increase this 13-centimeter margin, which would in turn require more complex adaptors between ring sizes. 13 centimeters could probably be allowed for in the common fore and aft hatch gaskets or simple universal adaptor rings. The hatches themselves are notionally 4 meters in diameter.

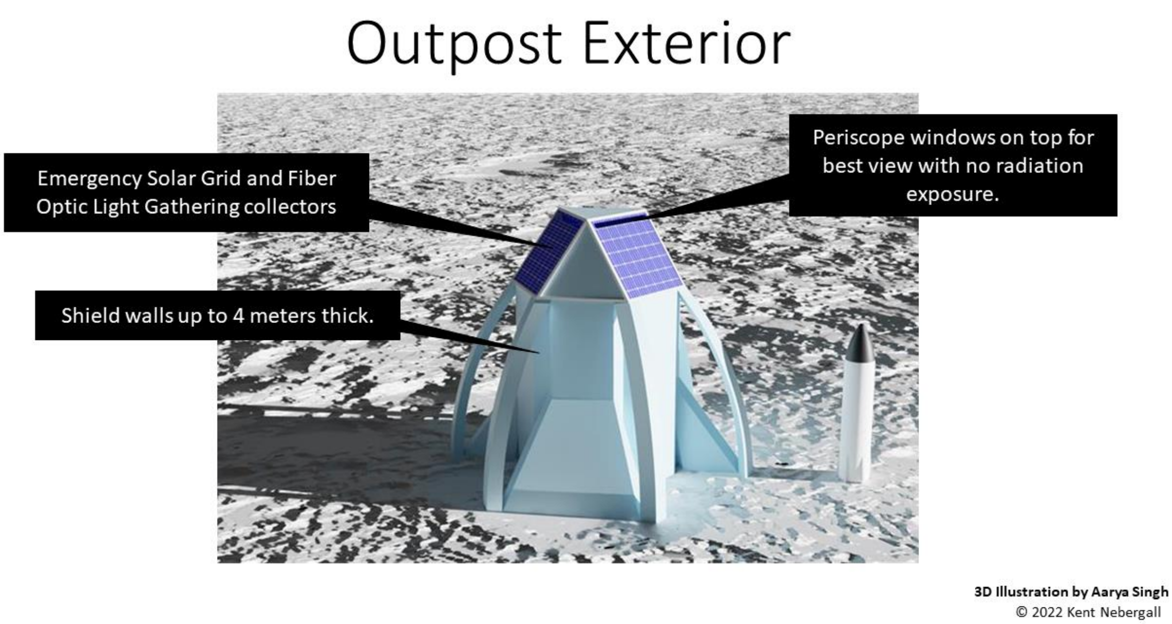


When StarCar is put on a magnetic train rail, the track uses Halbach magnet arrays, which turn the whole magnetic field in one direction. Having two such arrays facing each other for the rail maximizes performance while keeping the magnetic field away from the crew.

As a side benefit, the MagLev train track puts a lot of magnetic flux in a good position to protect the crew. Cosmic rays and flares are deflected to take a longer, curved path through the barrier shields, so a one meter shield is more like a meter and a half, because the charged particles can’t travel in a straight line. And that’s just the track, not the barrier wall.

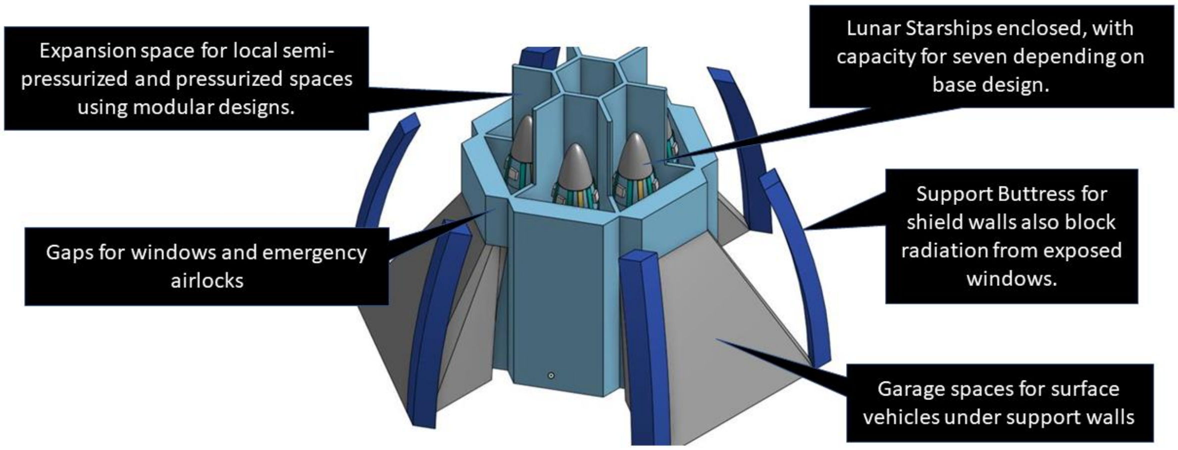


This shows the rings installed on the surface of Phobos in Stickney Crater. This spot is unique in that it's protected from cosmic rays by Mars almost filling the whole sky. The larger ring allows for 1 G acceleration. This gives engineers a head start on asteroid surface settlement methods.



So as noted, the hexagonal enclosure on the surface makes a nice little outpost.
This one is called Insight. I created it for a Moon Society paper last year.

Outpost Interior



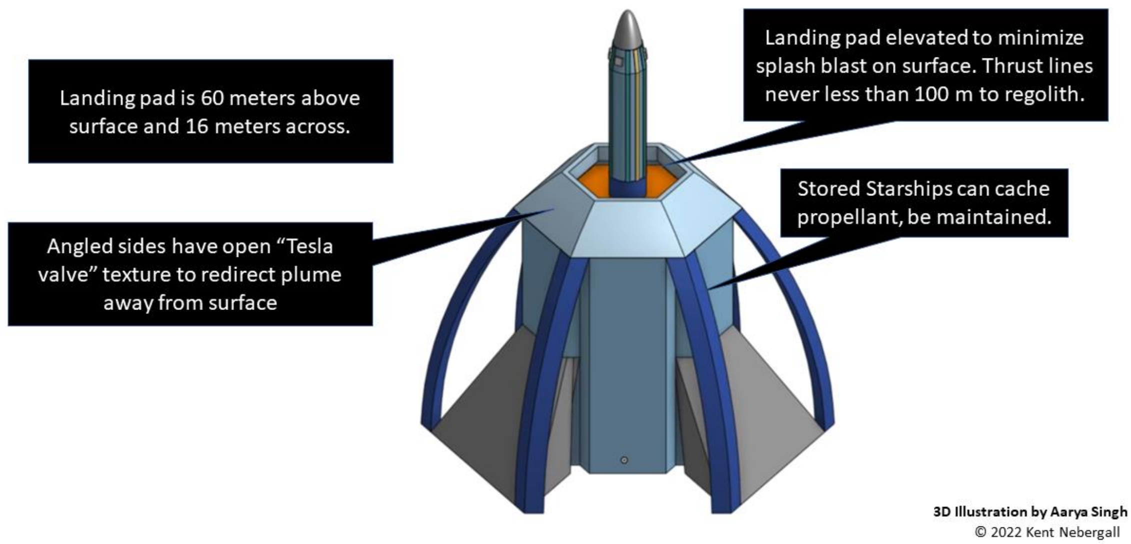
3D Illustration by Aarya Singh

We park four Lunar Starships on a foundation, then build a frame around them. The walls are filled with interlocked regolith sand-bags which are allowed to settle, then sintered with microwaves to lock them in place.

Settlers would use the extended tower workspace like an unfinished basement. They will determine how much pressure it can hold, and extend living spaces into it. Even if they are confined to the starships, this tower can house 40 people. This is a good baby step approach to Lunar construction.

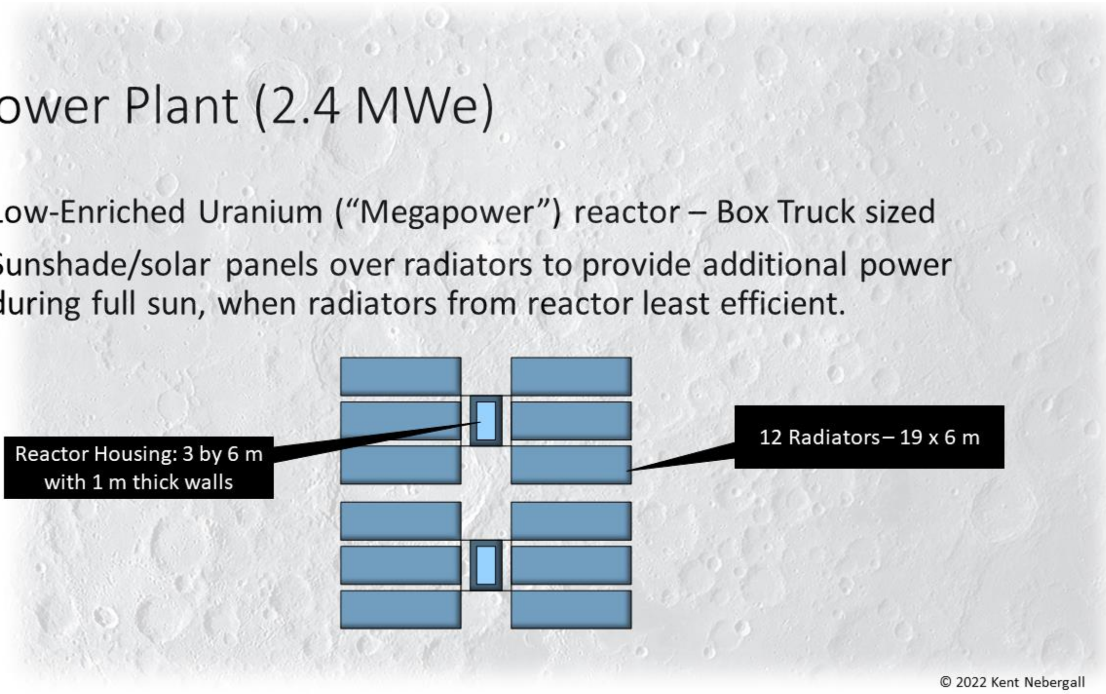
The top of the structure has periscope windows. Using periscopes like this gives the settlers at any level of the habitat a top-floor view.

Spaceport Engineering

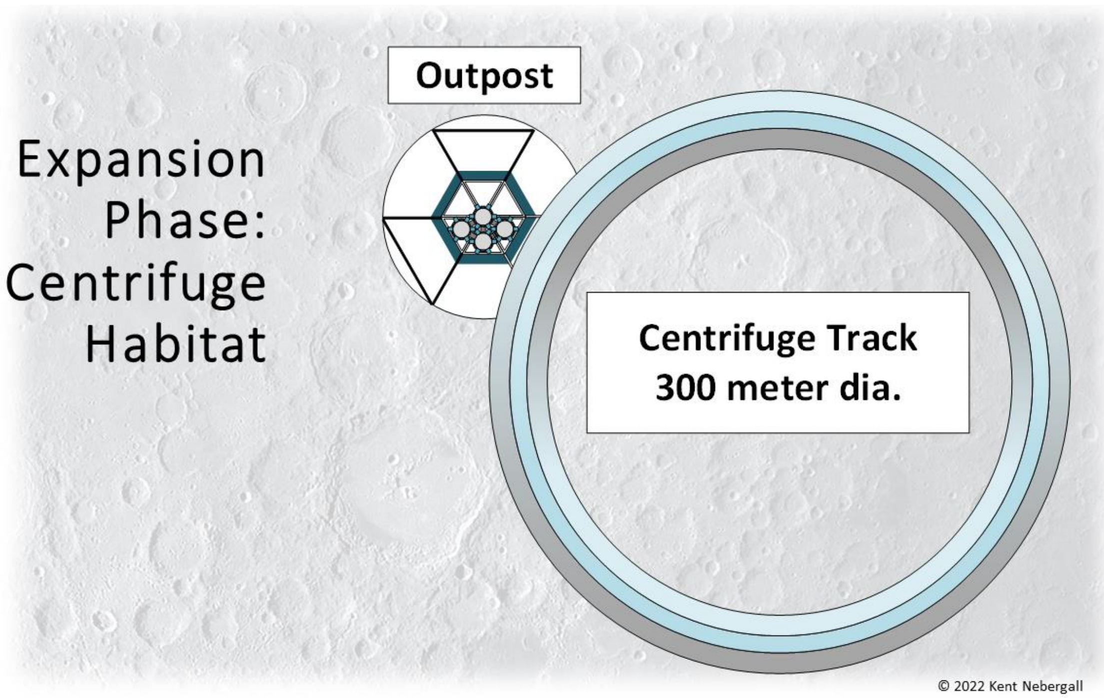


The surface spaceport has a similar design. The goal is to keep the exhaust plumes off the surface to avoid splash damage. This roof elevator approach keeps the plumes 100 meters off the surface. A tower with vehicle catch arms can be added.

Up to seven starships could be hangered inside. Some internal starships are for propellant manufacturing and storage. Note that this is a compromise in that the propellant is stored in an enclosure away from debris damage risks from meteors or vehicle accidents. However, in a real design we would want to separate the methane from the oxygen tank storage locations for safety purposes. In much the same way, any welding shop separates the compressed oxygen and acetylene tanks into different rooms to avoid creating a much more serious explosive hazard. Arriving ships would be drained of propellant while being stored and serviced, and probably only filled with liquids once "outside". This would also reduce stress on the elevator, since it would be in a locked position prior to fueling and launch.



The nuclear power plant is designed to be affordable, long lasting, and low maintenance. Low enriched uranium is much easier to work with and lasts longer, even though it doesn't make quite as much heat as conventional reactors. The radiators are not as efficient during lunar daytime, so we would shade them with solar panels to close the power gap. Each radiator here is the same size as the new solar arrays being added to ISS.



In the long term, we can use the outpost as a construction shack and access point for a centrifuge habitat. With greenhouses moved to surface towers, a population of two thousand can be housed here.

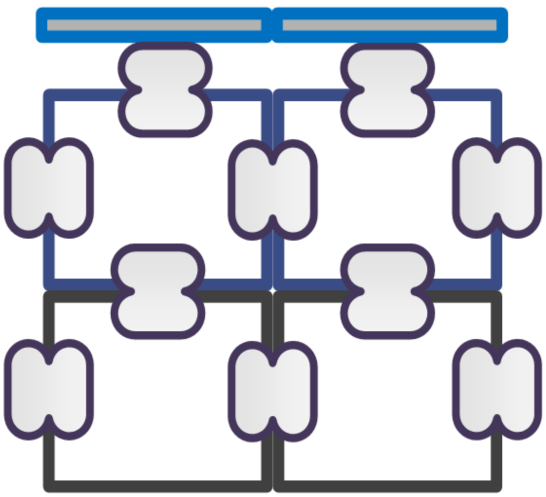
Let’s get deeper into wall construction for a minute. There are two concepts here, with three applications.

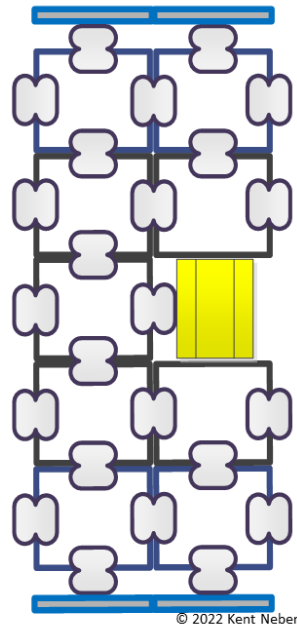
- Insulated, reenforced ice blocks (LEO, deep space, and Mars surface)
- A similar bag filled with spun regolith (basically Rockwool insulation) and moondust, packed in place and sintered with microwaves into solid bricks. (On Mars, some form of locally-sourced concrete may be used where temperatures are permanently warmer next to a habitat.)

Both types of “bag bricks” are beta cloth or something similar brought from Earth initially, but able to be built from local materials in the long term.

The bricks have dovetail joints between them. To avoid making the interlocks permanent, the dovetails themselves are locked in place with key gaskets with soft sides as shown below. The core material is probably water that is frozen in place in the case of any outpost not on the moon or another hot surface. Lunar gaskets may be pressurized with water that is allowed to freeze but is not required to stay frozen – it is simply there to pressurize the core of the gasket and lock it in place. The gaskets in the illustration below are made much too large compared to the bricks to better illustrate the structure. If the ice blocks shrink or grow, the seals get tighter either way.

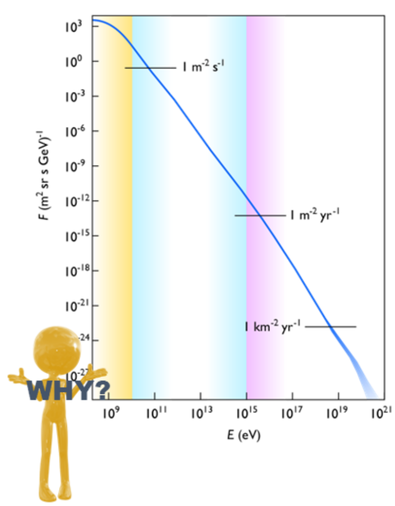
Modular Pykrete Construction

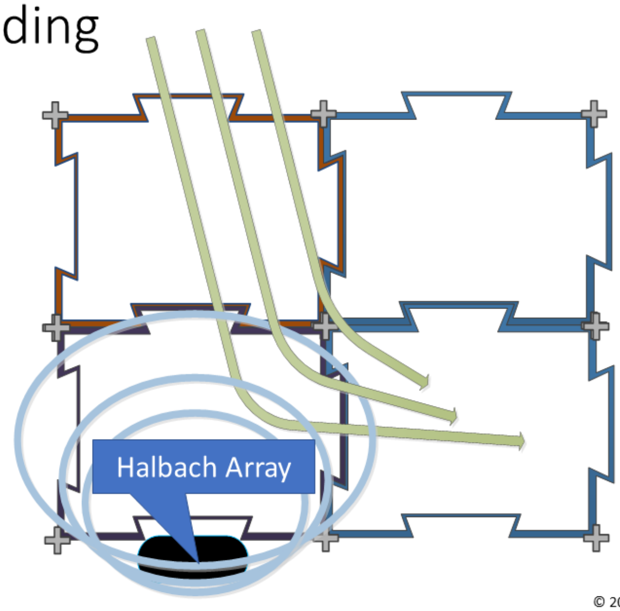




Gaps in the block matrix are used for raceways. If an ice block is damaged, just microwave the contents until they melt, drain the bag, and replace it. Reenforced ice, known as pykrete, is stronger than concrete, resistant to melting, and resists ballistic damage.

Cosmic Ray Shielding





As with the rails, we can make the walls thinner by adding Holbach array magnets to the inside wall. This would force cosmic rays to take a longer path through the shielding material before reaching the interior. Low energy cosmic rays are much more plentiful than high energy ones. So Halbach Arrays and Ice are a dramatic force multiplier for radiation shielding.

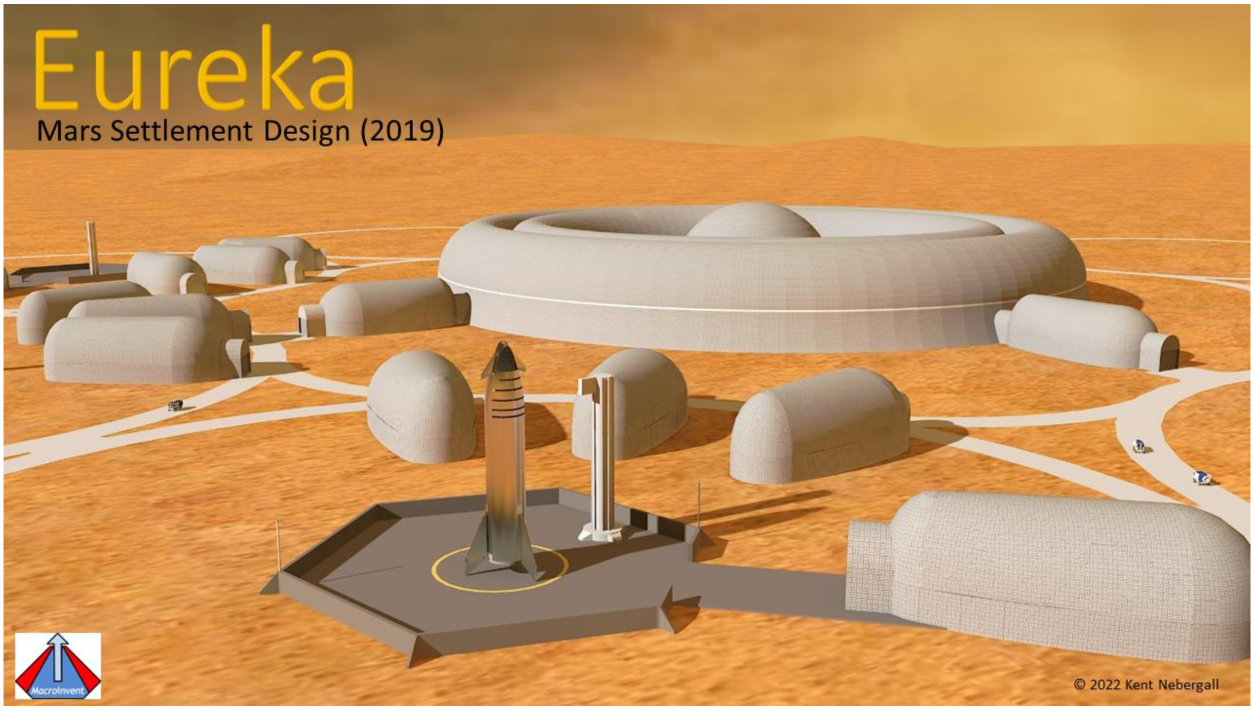
Revisiting the Grand Challenge Table

Grand Challenges (Deep Space Coves)

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 Power/ Propellant Production	Surface Mining and Extraction
	Psychology	Return Flight to Earth (speed, mass, etc.)	Hybrid Manufacturing
	Mechanical Entropy	Planetary Protection	Reproduction

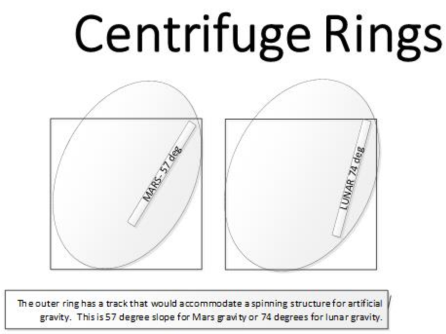
So if you are keeping score, we now have all these issues in green addressed at maximum difficulty. Not bad so far. Let's give our future settlers something even better to dream of.

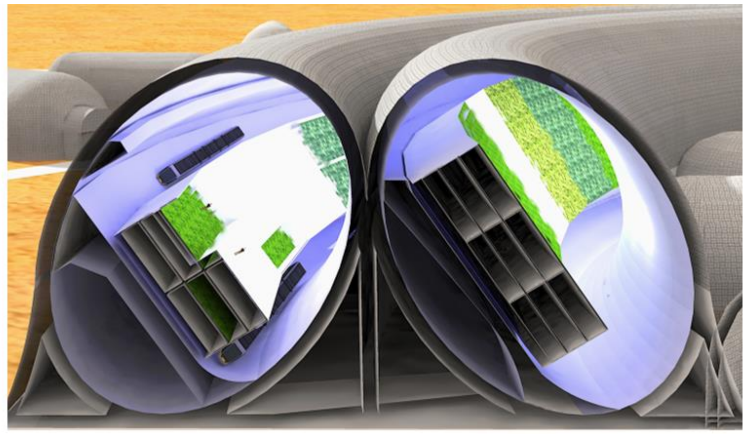
Part 2: Eureka

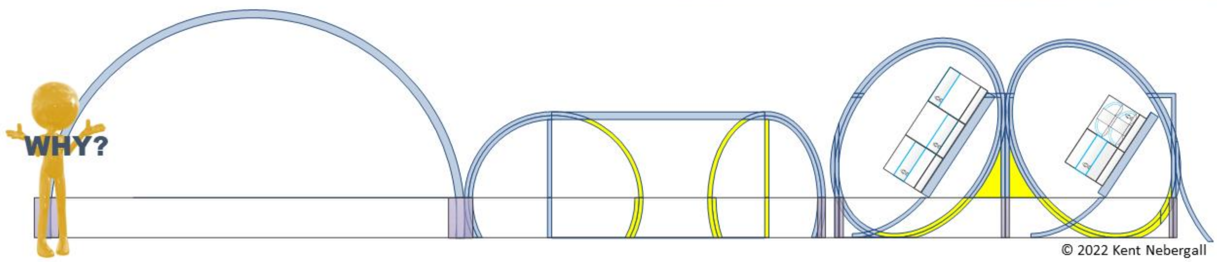


This is Eureka. It's a thousand-person settlement on Mars built for a Space Settlement Design competition from The Mars Society. At the time, I decided to take the entire matrix of grand challenges, crank the difficulty all the way up, and solve them anyway. I invented several interesting technologies like an economic model and flexible airlocks. It was basically my Mona Lisa, as I saw it at the time – my grand work that would address and overwhelm all obstacles to space settlement in a way that had never been done before. Unfortunately, while it did make the top ten of over a hundred competitor designs submitted, it did not make the top five. I think it was demonstrably better than all but the top two, and debatably better than those as well. However, I was Steering Committee Chair of the organization running the competition, so it may have been bad for the organization had I won. Either that, or Robert didn't like steelman approach, since he'd spent decades pushing a more optimistic model of the challenges of space settlement in general and Mars in particular.

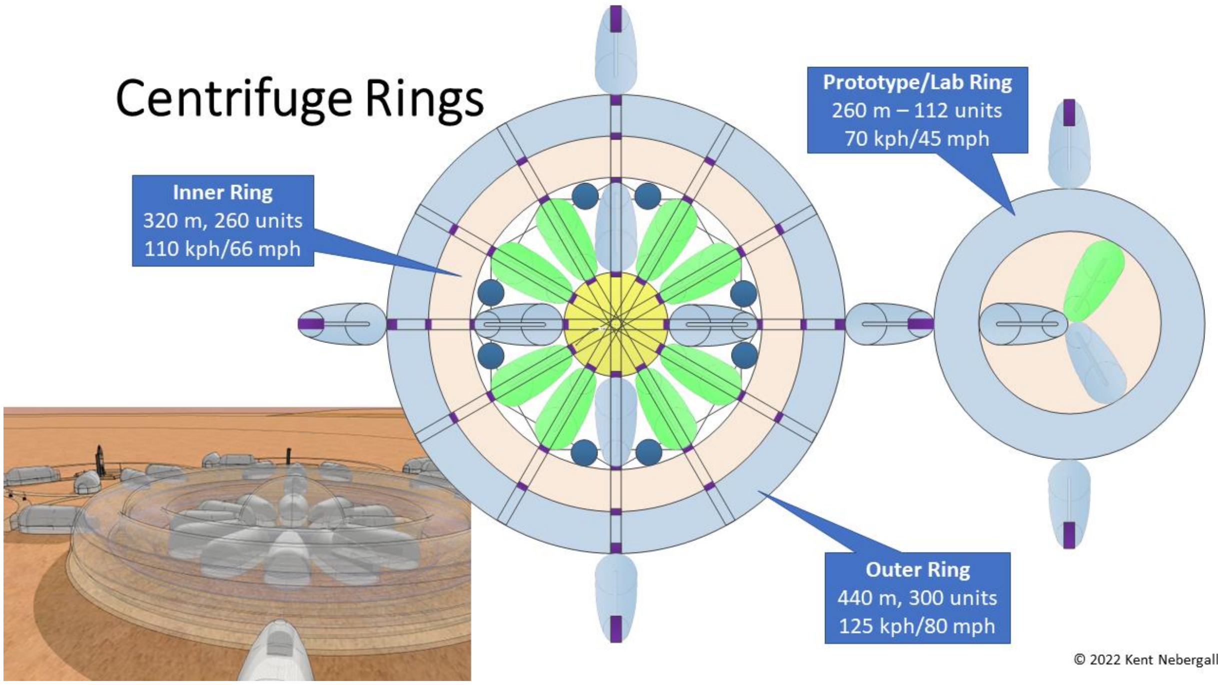
It's chapter six of a book from The Mars Society a couple years ago that Robert Zubrin handed to Elon Musk. Maybe he's seen it. That's really my only consolation in all this. That, and I was able to address my own doubts about the whole enterprise of coming up with space settlement ideas, upon which I'd already spent the last 14 years of my life at that point. Anyone who has poured a decade or two of their life into a failed career or relationship with absolutely nothing to show for it in the end can empathize with wanting to know the truth before investing my years and attentions any further. The concepts you've read prior to this point are prequels to Eureka, and the space settlement canyon later is a sequel. The economic model is also from this concept, although a bit expanded around the edges.







This takes that "Earth gravity required" steelman concept to the city level. Can you make a thousand-person city on tracks? Yes. It's a bit M C Escher to be honest, but it works.
We can increase the bank to 74 degrees for lunar use, or 90 in the asteroid belt. Cities in the outer solar system can be built like this. So, it's overkill for Mars, but perfect for Pluto. That also means city hardware is standardized early and everywhere for rapid expansion across the entire solar system.



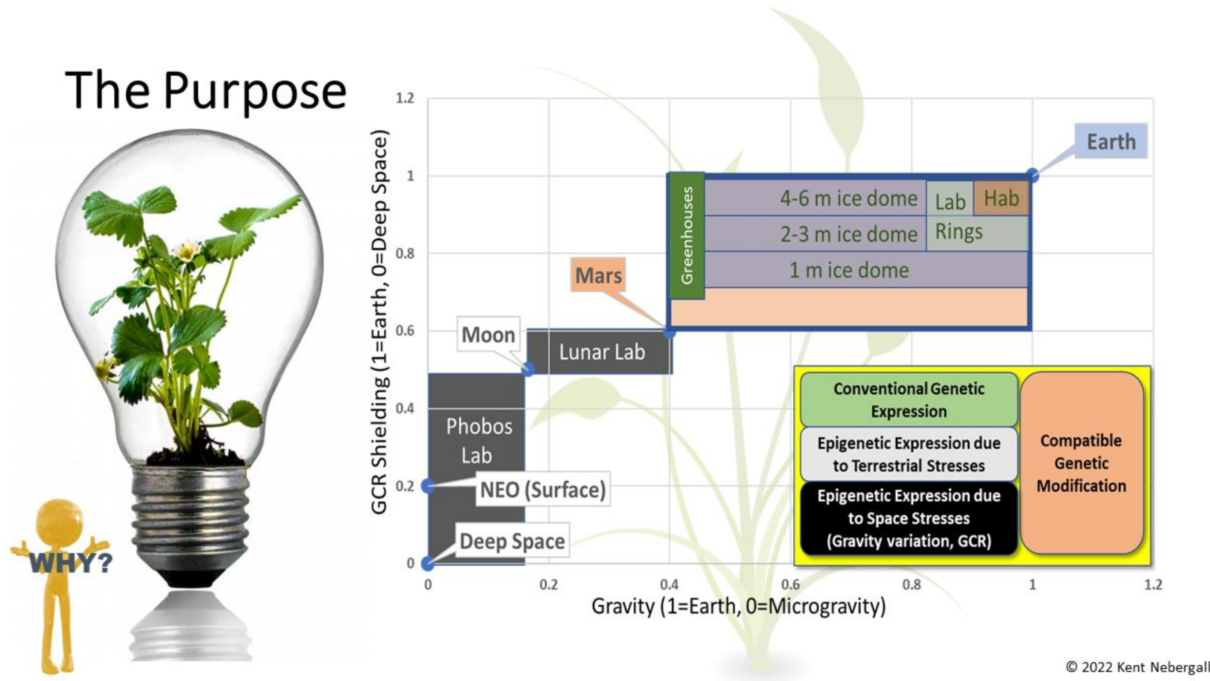
With larger pressure shells made of pykrete on the outside and a concrete on the inside, we can make large shells for multi-story buildings. Within the rings are three levels of living space with home gardens on the roofs. The dual rings lean against each other for improved buttressing of the stem walls. Anyone designing domes for Mars will rapidly hit the issue with stem walls (ring foundations connecting them to the surface) being the weak link. Buttressing them against other rings and making the dome walls very heavy makes the dome easier to create from an engineering perspective. On Earth, the biggest issue with a dome is the weight of the dome. On Mars, the biggest problem is containing the internal pressure, which is a hundred times greater than the ambient atmosphere outside. The bigger the dome, the greater the stress. However, when your other goal is having a heavy shell to block radiation and other damage risks such as meteors, you can play the two problems against each other and simply make very thick, heavy domes to overcome the vertical stresses. Having thick, buttressed stem walls helps overcome the hoop and other horizontal stresses on the domes and rings. Practically every dome in this structure is counterbalanced by another dome structure all the way to the outside ring. And even that uses the airlock dual-dome structures as a form of buttressing.

A prototype ring is built first. Once the construction is worked out, the main city is built with two concentric rings. The prototype can then be used at variable speeds for any gravity level between Mars and Earth.

For food, we have the rooftop gardens, plus other LED greenhouses at Mars gravity levels. We also have a hundred-meter central dome as a park for residents. This dome is also will be a surface gravity biome prototype.

All grains on Mars could be grown in greenhouses on the surface. Even a crop failure due to dust storms every decade or so could be compensated for with grain surpluses in good years. LED greenhouses would be for garden vegetables with shorter shelf life.

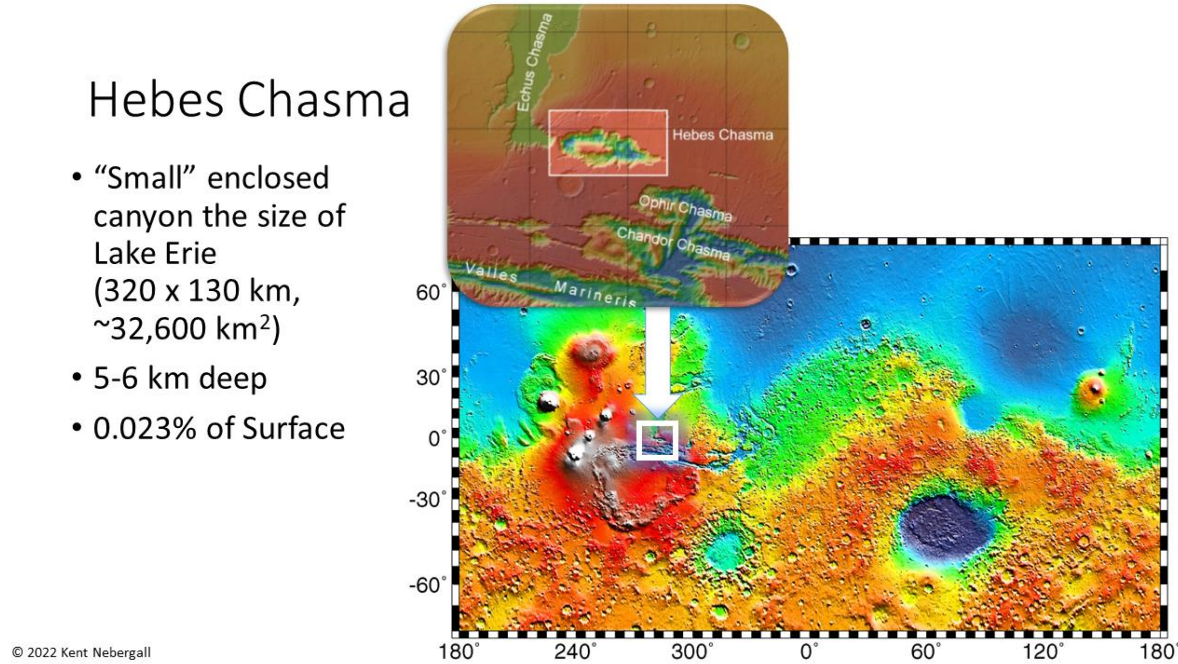
For factory space, we have more elliptical domes and smaller 25-meter utility domes.



So why all the centrifuges? Let's examine this a bit.
The chart shows "1" as being Earth surface conditions and deep space being zero, with the vertical axis for radiation and the other for gravity.
The dots for the moon and Mars show what intermediate conditions we can experience.
We know any species will have a range of gravity and radiation exposure that they can tolerate.
We know this will vary from species to species.
We can experiment to determine which species adapt quickly, which can adapt but require countermeasures, and which cannot be readily adapted.
All life, particularly plants, have many silent genes that carry traits that are only activated under stresses such as drought. The behavior of the plant is altered even if the genetic code is not. Some of these stresses are brought out in microgravity on the International Space Station. These have been found useful in making crops that are not gene spliced with other species as with current GMO plants. They are simply activating genes that were there to begin with. This has the beginnings of an agricultural revolution that avoids the controversies of GMOs.

With this, we can dramatically expand the ways to make food, clothing, and construction materials everywhere, including Earth.

Part 3: Para-Terraforming Hebes Chasma

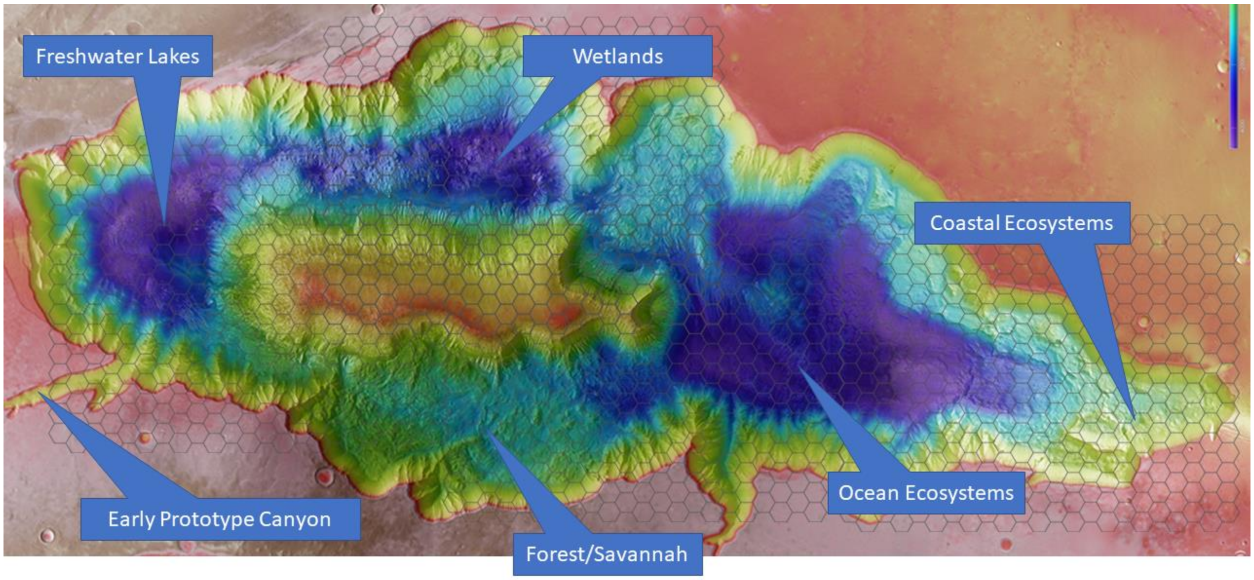


Which brings us to para-terraforming.

Hebes Chasma is a canyon the size of Lake Erie just north of Valles Marineris. It has the advantages of being directly on the equator and being closed on both ends.

There are indications that Mars may lack enough volatiles to terraform the entire planet. Some reports have it that the entire planet's surface would have to be mined and recycled down to release enough materials to achieve an earth-like atmosphere. Other reports are more optimistic. The bottom line is that we don't know the actual number. There is also the matter that a lightweight ecosystem could be produced with a much thinner atmosphere and humans in oxygen masks. This would resemble life on Mount Everest, but at least you wouldn't need a pressure suit.

So back to the steelman methodology. If we cannot terraform 100 percent of Mars, what about a valley is only 0.023 percent of the total surface? That would be trivial in comparison. It's the equivalent to being asked for a thousand dollars versus being asked for a quarter.



The plateau in the middle is also handy for placing a central city and spaceports at the same height as the canyon rim. It would take about a month to casually hike from one end to the other on foot. The call-outs in this picture give an idea of the ecosystems that could be collected here.

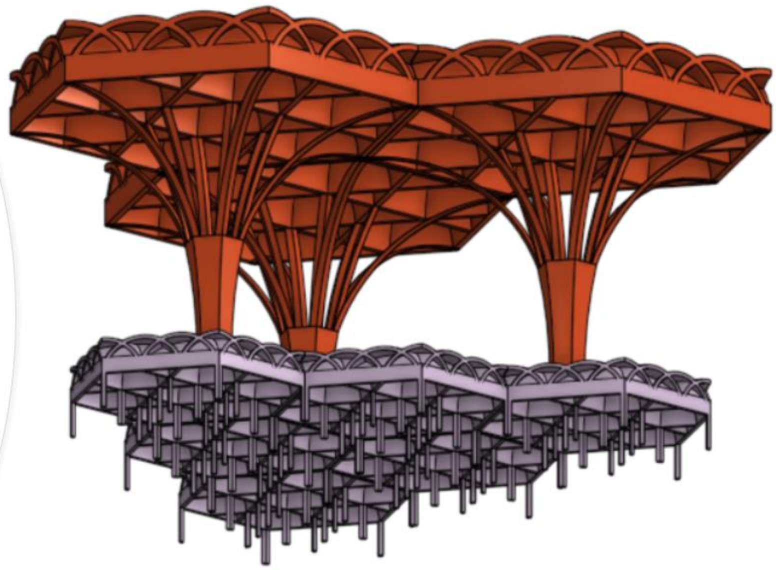
Hebes Chasma can keep us busy for a few centuries. We can also duplicate this success in other canyons and craters as we see fit.

We would first mine anything useful from the canyon floor and level it. We build a series of hexagonal domes 500 meters across as a sort of basement across the surface. Each one of these hex domes can house a Eureka-sized centrifuge. Air pressure would help support the roof. These are shown in gray, below.

Base View

- View up into ceiling fairly open
- Roof can be a kilometer or more high.
- Sub-layer can step up or down to match bedrock
- Enclosure is zoned with drop-curtains to prevent blow-out if meteor strikes roof
- Roof blocks GCR to Earth-like levels
- Rain is mostly simulated, but roof high enough for clouds to form.

3D Illustration by Aarya Singh

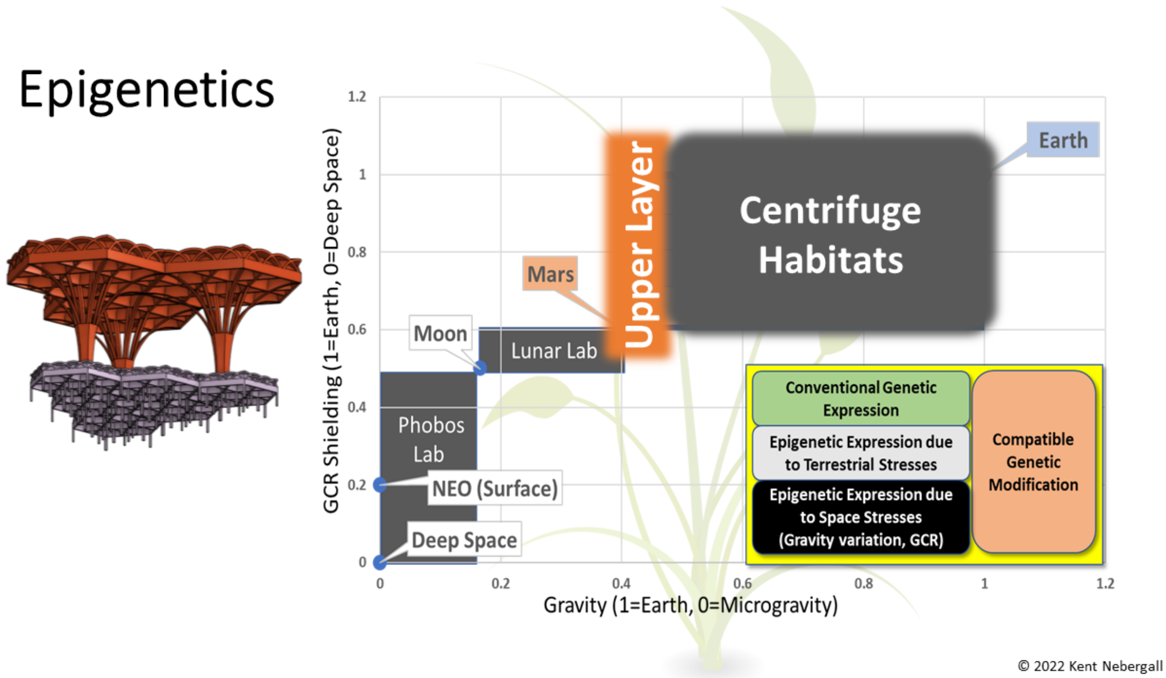


Once that is complete, we build a second layer of even larger, kilometer scale arches that reach to the top of the canyon rim. This would enclose enough atmosphere to contain weather. We run lighting systems through the roof to simulate daylight.

The basement gray section then becomes the space for heating, transport, power generation, and so on. We landscape terrain both on top of and underneath the basement layer. Heat from power generation at that layer keeps the system warm. It can also power any artificial light needed.

We can even set spark gaps in the tree structures to fix nitrogen they same way thunderstorms do on Earth. We can reenforce the basement to keep the roof up.

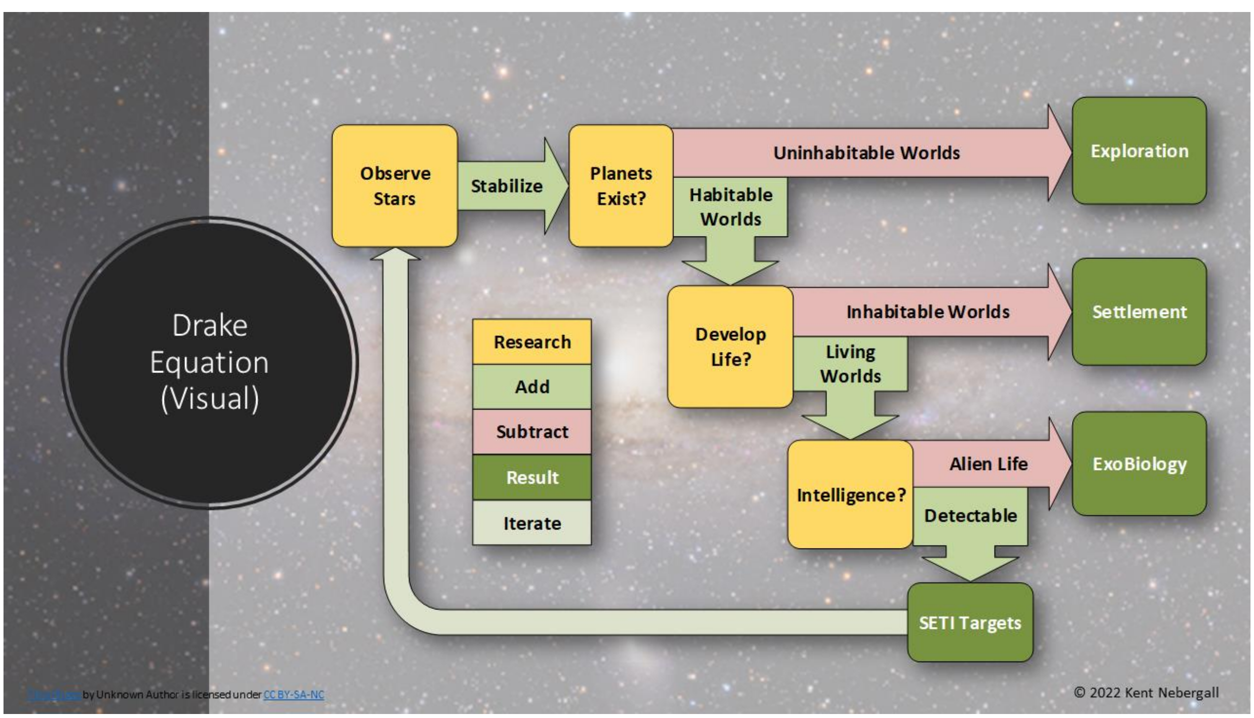
The view from below would be magnificent. Picture these domes at the height of clouds on a typical summer day.



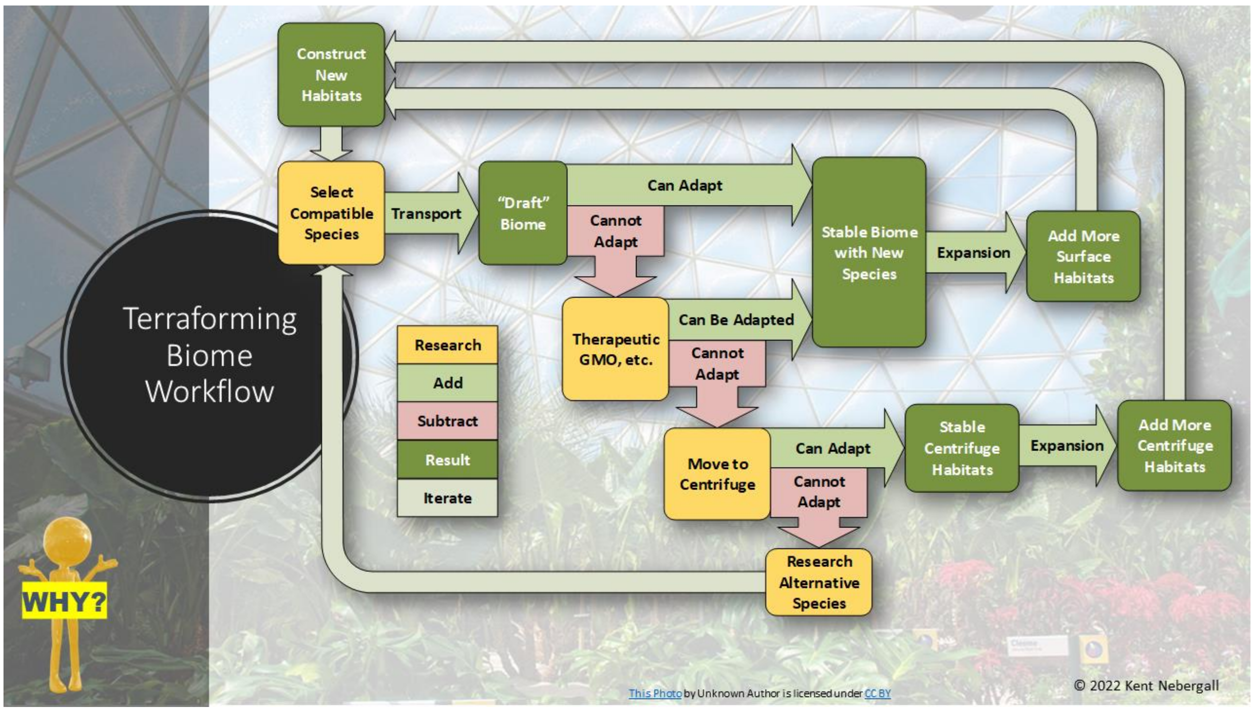
So the upper habitat at Mars normal gravity is filled with species that acclimate to it easily, with the basement habitats supporting additional species. The canyon is then a dual layer ecosystem representing a broad range of environments.

We can follow the elevations of the canyon to create lakes, forests, wetlands, and a miniature ocean habitat about 100 kilometers across.

Not all areas would be multi-layered. Determining how much of what environment is needed based on species adaptation is the core goal of the system.



So, think of the Drake equation for finding extraterrestrial life and intelligence.
If we structure it as a flowchart, it looks like this, with each variable set as a yes or no.
The gateway questions determine if the studied world is subject to exploration, settlement, exobiology, or SETI.
During one presentation, someone said, “I’ve never seen the Drake Equation expressed this way before!” I responded, “Because I came up with this diagram as an analogy to explain the next slide.”



We have a similar flowchart here for adapting Earth species to space settlement, with similar logic gates. Some species will adapt easily and some will be stressed. It would be a work in progress for many generations. Ones that cannot adapt to surface gravity can move to the centrifuges. That said, there may be species like migrating birds that cannot adapt to either.

This down-selection will narrow the biodiversity from what we have on Earth.
But different environments and the stresses of those environments will bring adaptations.
We will see what the silent genes have hidden much sooner than mutation brings new species via evolution. In the end, there should be more Exo-species than those on Earth.

Data Lakes for Biome Management

Earth Species Parameters	
Territory	Enclosure type
	Territory Area
	Ecosystem Depth
Climate	Temperature Range
	Humidity Range
Interdependence	Required Species
	Reliant Species
	Accepted Species
	Excluded Species
	Minerals and water
	Oxygen/etc. needs
Waste Parameters	Biological output
	Microbiome notes

Artificial Biome	
Environment	Volume Available
	Gravity Level
	Radiation Level Range
	Pressure Range
	Temperature Range
Habitat	Day/Night/Brightness
	Mineral Resources
	Soil Types/ Chemistry
	Other Species
	Microbiome
	Water Chemistry

Stress Impacts	
Health Stress	Direct Impact on Species
	Impact on Required Species
Genetic Stress	Epigenetic Impacts
	Gestation Impact
	Generational Impact
Behavioral Impacts	Feeding/Hunting/Evading/Play
	Biological Functions

Observation Scale	
Granularity - Population	Per Individual
	Per Generational Unit
	Per Self-Sustaining Population
Granularity - Time	As Observed (Real Time)
	Daily
	Per Life Cycle Phase
	Yearly (Earth Imposed)
	Yearly (Mars Adapted)
	Generational

While this seems far off, creating a database of life parameters on Earth can start now. From there, future space settlers can select species with the highest chance of success and work their way down the list until they hit the limit of technology for that generation.

Active Countermeasures

Remediation Method	Description
Natural Selection	Percentage of poorly-adapting creatures that do not breed in the ecosystem naturally.
Artificial Selection	Active farming of generations to promote most beneficial traits for the artificial ecosystem.
Genetic Modification	Can the species be modified and can the traits be passed to future generations?
Food Chain Modification	Can GMO foods be engineered to overcome issues and can those species be added to the ecosystem over generations?
Nutrient Modification	Can the environment itself be supplemented with higher oxygen levels, more calcium in soil, etc. to offset ill effects of artificial system? Will these resources need to be replaced periodically from outside or are they recycled in the food chain?
Habitat Modification	Can new artificial habitats be built that offset the effects and the species be transplanted there?
Replacement	Find another species from Earth (or another habitat) that adapts to this niche better and test.

This is our toolbox for adapting any species to be multi-planetary.

There are a lot of tools one can use without resorting to genetic engineering. Most of these would be the food-chain and gravity modification versions of what is done on the ISS to keep crews healthy with diet, medication, and exercise.

Biology Conclusions

Area	Description
Apex Additions	As habitats expand, more plants, bigger herbivores, and more apex predators can be supported by the environment.
Mars is Not Earth	The mix of species that work together on Mars may be from unexpected combinations of environments from Earth, mixing continents and ecosystems.
Epigenetics and Exo-Species	Plants and animals will use the lower gravity as an opportunity to find new survival strategies. This will happen fastest in smaller animals with fast generations.
Exo-habitats	Experimental Habitats with higher oxygen, etc, may cause interesting effects.
Biodiversity	Population will grow in species that adapt and shrink in ones that cannot adapt naturally or be modified to survive. This will settle into equilibrium.
Limits	How much Mars territory to terraform is limited by the needs of species that can adapt to Mars, plus the Exo-habitat variations of Mars. This increases over time as more species become exo-species.

Even considering this as a thought experiment, we come to some conclusions. We will have a huge challenge with apex predators and migratory species. We will probably have hybrid environments where species from different terrestrial ecosystems are brought together into a mash-up ecosystem. We can customize oxygen levels and other evolutionary drivers to reinvent ancient earth, and possibly the species of ancient earth. The real question is how much of this requires a few canyons and space cylinders and how much requires an entire planet?

Part 4: Business Models for Technology Revolutions

So here is our last stop. Switching from “How?” to “”How Much?”
We need a technology revolution to build the Funding models for all this.

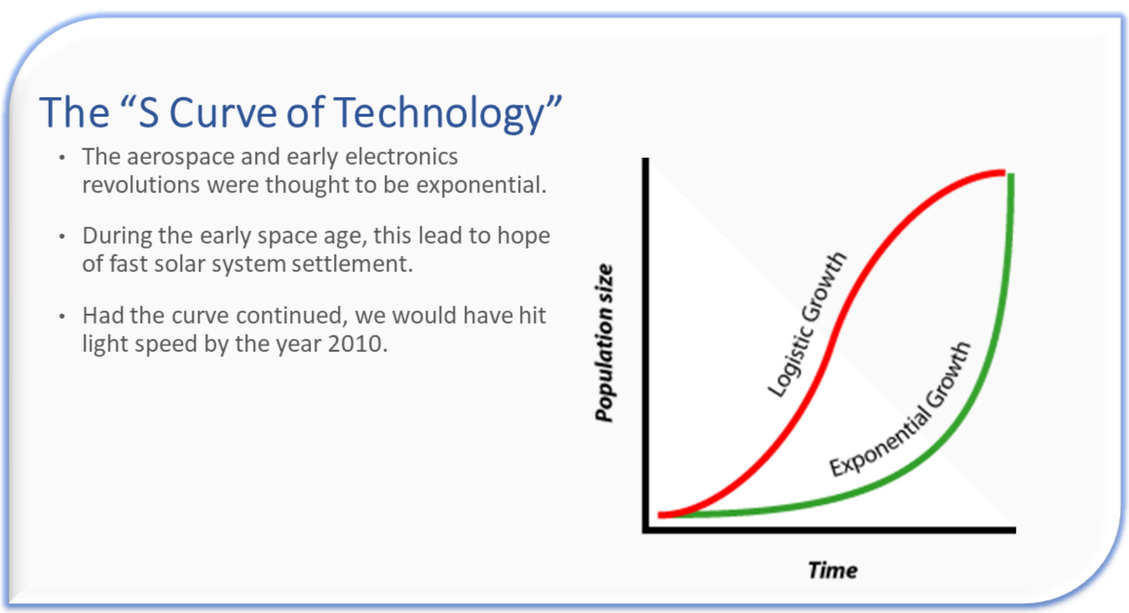
Energy Density, Invention, Information

Energy System	Utilization Inventions	Information
Human Power	Hunting, Gathering, Migration, Villages, Basic Farming, Textiles	Language
Fire	Metallurgy, Sterilization/Cooking, Light, Heat	Engineering
Animal Power	Farming, Roads, Cities, Travel, Mass Warfare, Writing, Trade	Math
Wind Power	Ocean going vessels, Navigation	Celestial Navigation
Steam (Wood)	Fast transport on rail/oceans. Paddle-wheels/wood boats.	Telegraph
Steam (Coal)	Ironclad ships with screw propellers. Steel and other alloys.	Fast News
Petroleum (Kerosene)	Indoor lighting, advanced industrial chemistry of petroleum.	[Radio]
Electricity	Indoor lighting, Distributed mechanical/heat power.	Telephone
Petroleum (Gasoline)	Internal combustion, Cars, Aircraft, early rockets.	[Television]
Chemical Rockets	Moon landings, Solar system exploration, etc.	Satellites
Nuclear Power	Nuclear power plant, Submarines/Aircraft carriers, NERVA.	[Computers]

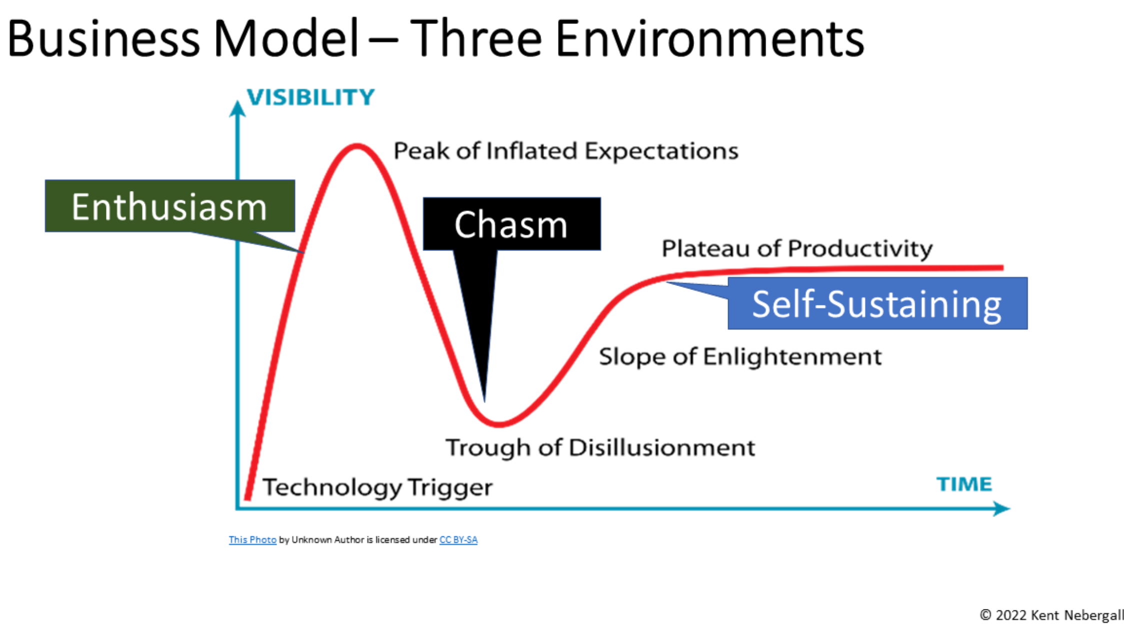
Here is a map of human history in terms of energy, invention, and information.

Each of these converged to make new foundations. They eventually became the baseline for the next technology age.

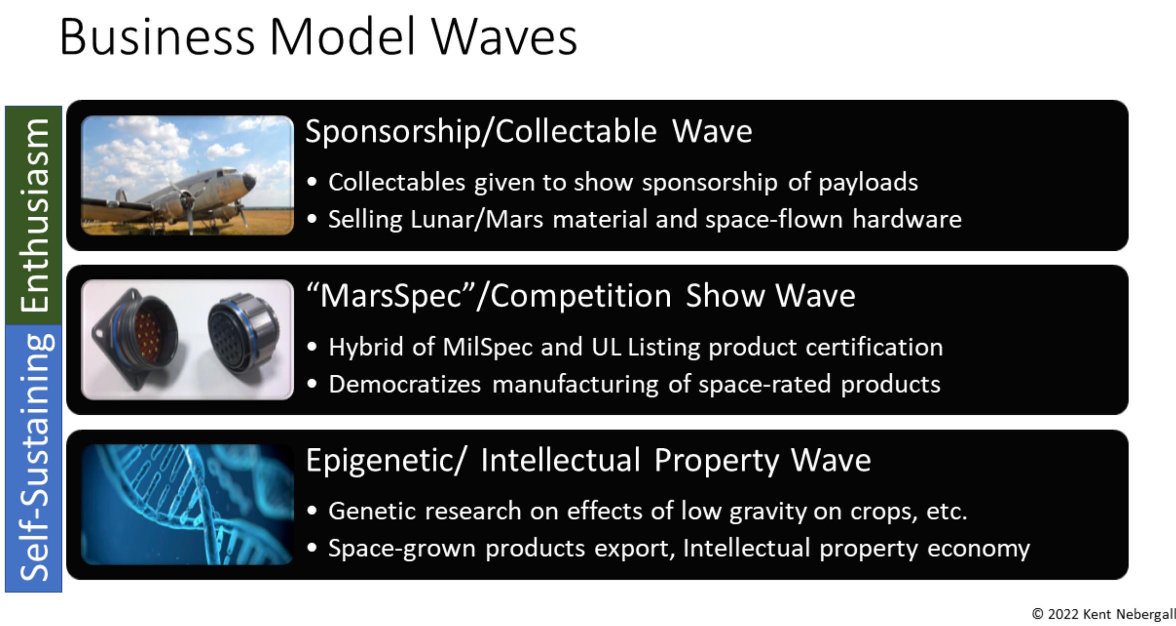
Energy, invention, and Information are the material components of technology revolutions. But broader acceptance depends on affordability and excitement. Getting many people doing many experiments at once generates dramatic growth and convergence. These are the mass times velocity that drive further innovation. They are the Cambrian Explosion.



This chart shows exponential growth versus Logistic growth. During the early phases, Logistic growth looks a lot like exponential growth, with no end in sight. This helps fuel optimism in the case of technology.
But we always hit a saturation point and the curve bends down, for a variety of reasons.
When a technology hits both market saturation and manufacturing optimization, it tends to stagnate. It remains asymptotic until a new technology comes along that works in the same solution space. Typically, these new technologies are driven by a new energy or information source, or a convergence with an unrelated technology.



In reality, however, there is a gap between simply being able to DO something and being able to profit from it. This gap is called The Chasm.
This chart is the Gartner Hype Cycle of technology acceptance. Remember how Apollo made everything seem possible? And then shortly after Apollo, not even Apollo was possible? After fifty years in the Chasm, we finally have renewed invention and innovation in human spaceflight.
A good business model anticipates all three phases of growth up front and has an independent business plan for each phase. The phases are very different worlds.
The goal then is to make enough money in the first phase to build the infrastructure to survive the chasm and get to the productive Future.
As each wave becomes mundane, the next wave takes over to rebuild excitement.

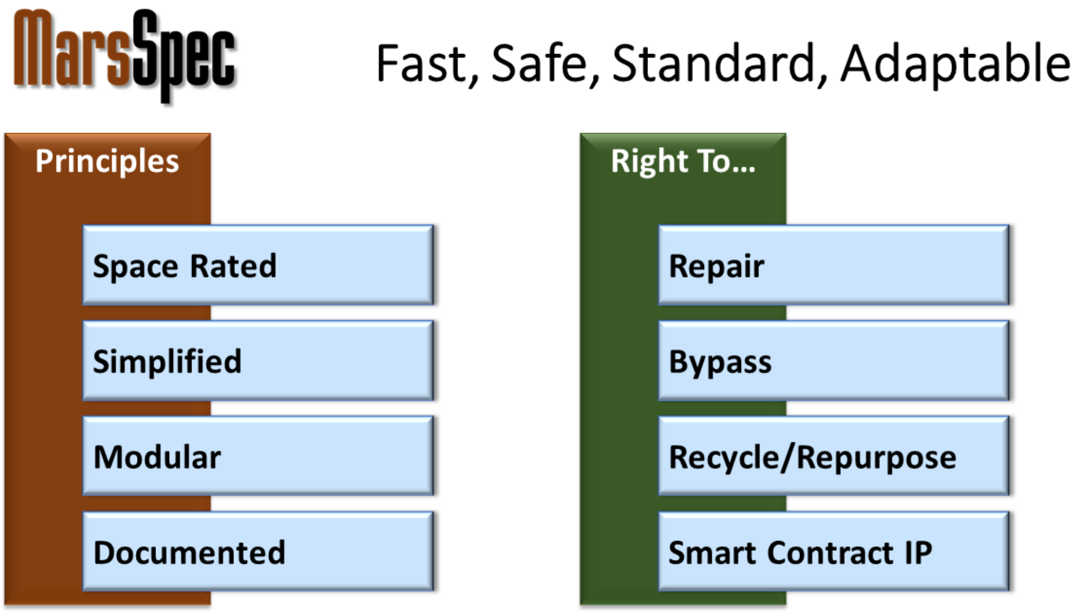


For example, the first wave would sponsor payloads and return collectables. While the first Mars rock may cost governments billions to return, the millionth mars rock will be used as a bookend in a basement bar.

We must build up the industrial base for space rated hardware and software, so that what used to cost millions will be commonplace. You should be able to order a desk for use on Mars from Ikea, not Lockheed.

Eventually, we have enough infrastructure in space to unleash the epigenetic research wave to optimize agriculture and medicine. We also have an intellectual property wave to optimize everything else.

MarsSpec



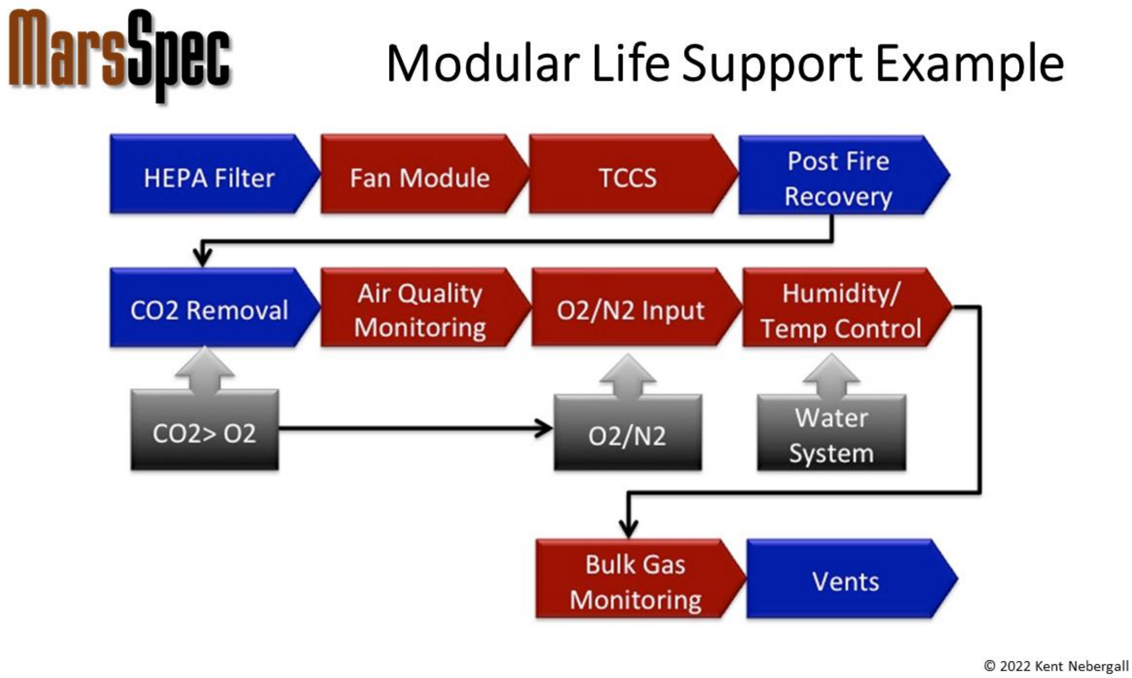
MarsSpec is the minimum standard for use in space settlement in terms of reliability and maintainability. It forms a common design language across industries that would supply these outposts.

Metaphorically, it’s like MilSpec or Aerospace grade to identify quality products. Being MarsSpec would improve sales and profit margins by differentiating competitors. With most manufacturers already UL Listed and using Lean Six Sigma, a new differentiator is desirable.

From here we can build a Smart Contract Innovation Model. This allows intellectual property from across the solar system to become a Catalog of innovations.

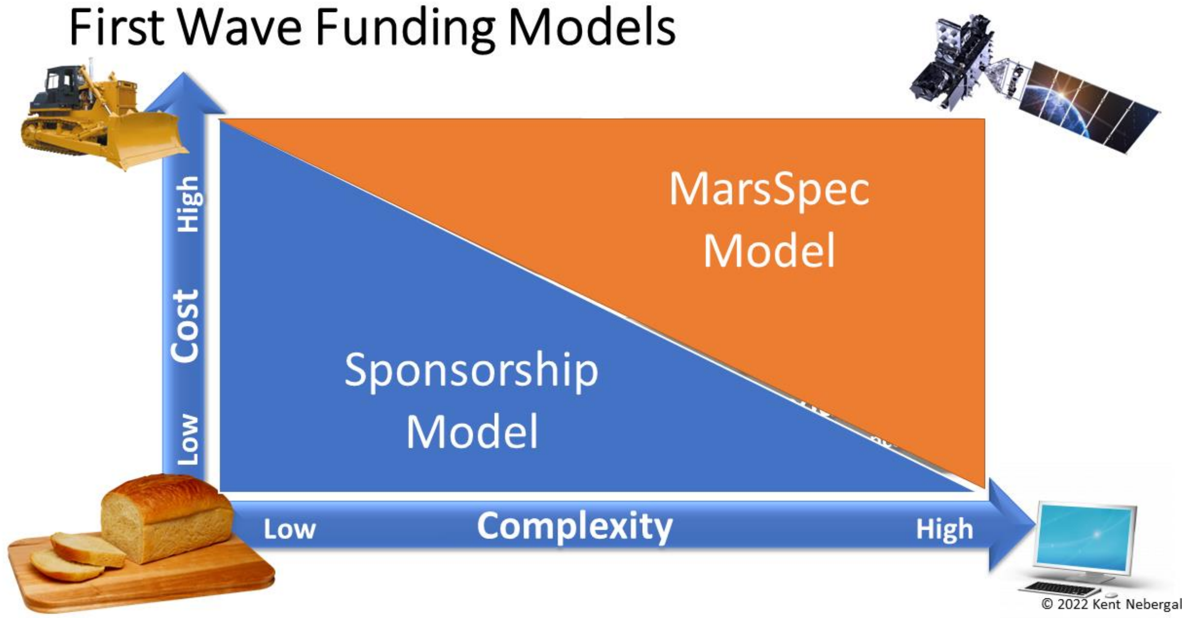
It will do to patents what streaming services did to record stores.

We mostly want things simple and modular. The best part is no part. And modularity lets you adapt to the unexpected.

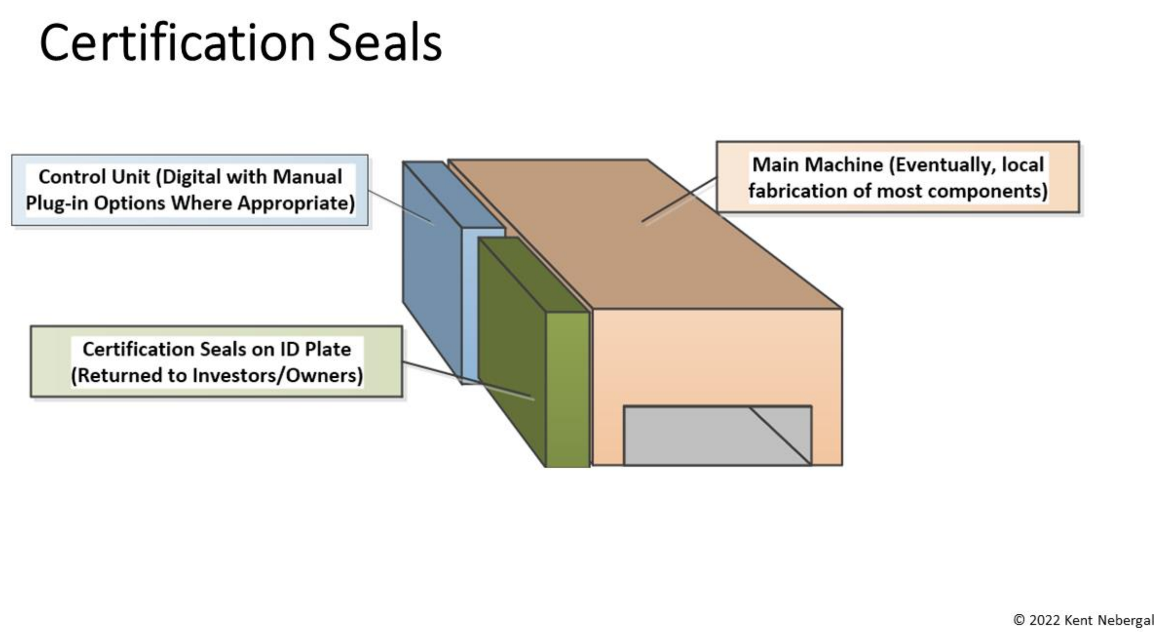


Here is a small Life Support system broken into smaller chunks like Legos that could be reconfigured in flight as needed. This provides a robust system since spare parts can be stacked into system to add capacity. Part vendors also face smaller challenges because they can build to their strengths in motors or filters, as opposed to only a few players on the market who can build entire life support systems. We lower costs, increase reliability, and can bypass or replace systems at the component level quickly if they fail.

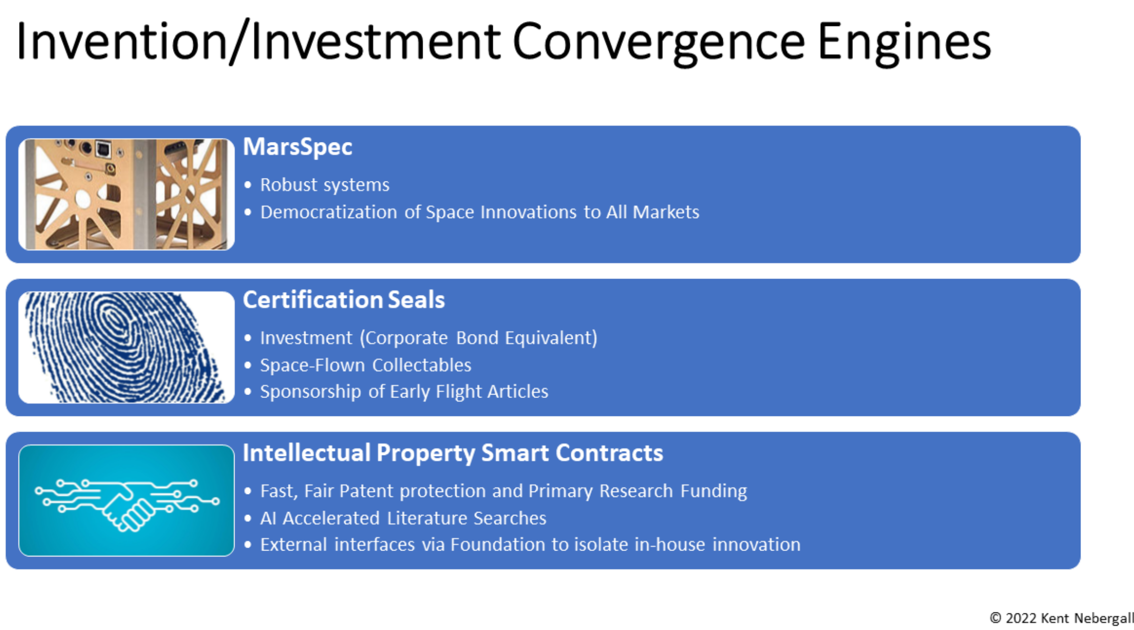
Picture a modular system like that above that can be broken down into smaller pieces to support a spacesuit onboard an unpressurized rover or other vehicle. It could be tripled in size with stacking and parallel systems to operate in a small spacecraft. It could be adapted for small outpost bases by being repeated in every large room. If any one of these systems broke down, others could be cannibalized to extend the life of the system until rescue or evacuation were possible.



Not all things bound for space are equal. Mars needs bread as well as bulldozers.
So, we have different models for different needs.
The Sponsorship model is for simple cheap things like food and other commodities
The MarsSpec model is for upgrading common manufactured products to space-rated quality levels.



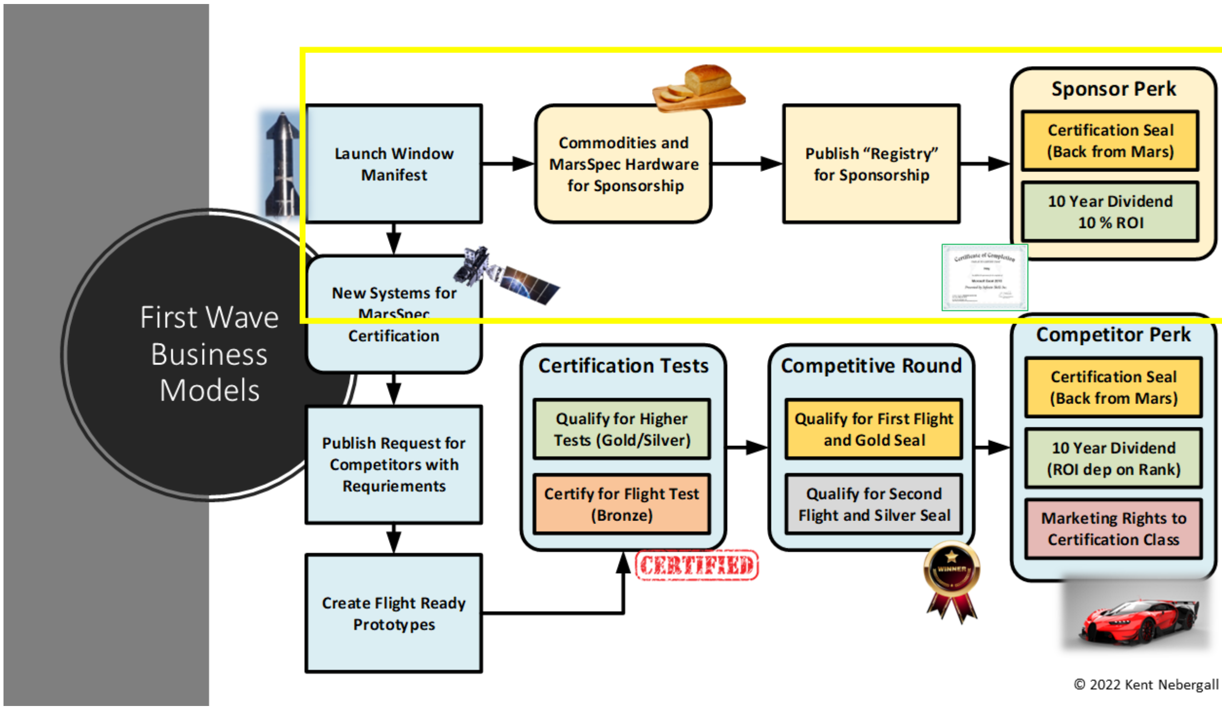
Since the Equipment is Modular, and Controls are Modular, why not the Collectability of spaceflown artifacts as well? We equip each item flown to Mars with a Certification seal of who sponsored it.
Certification Seals must be impossible to counterfeit, Easy to identify, and linked to a blockchain. I've already prototyped this concept.



As we saw at the history overview, any Technology Revolution has a corresponding boost in communications.

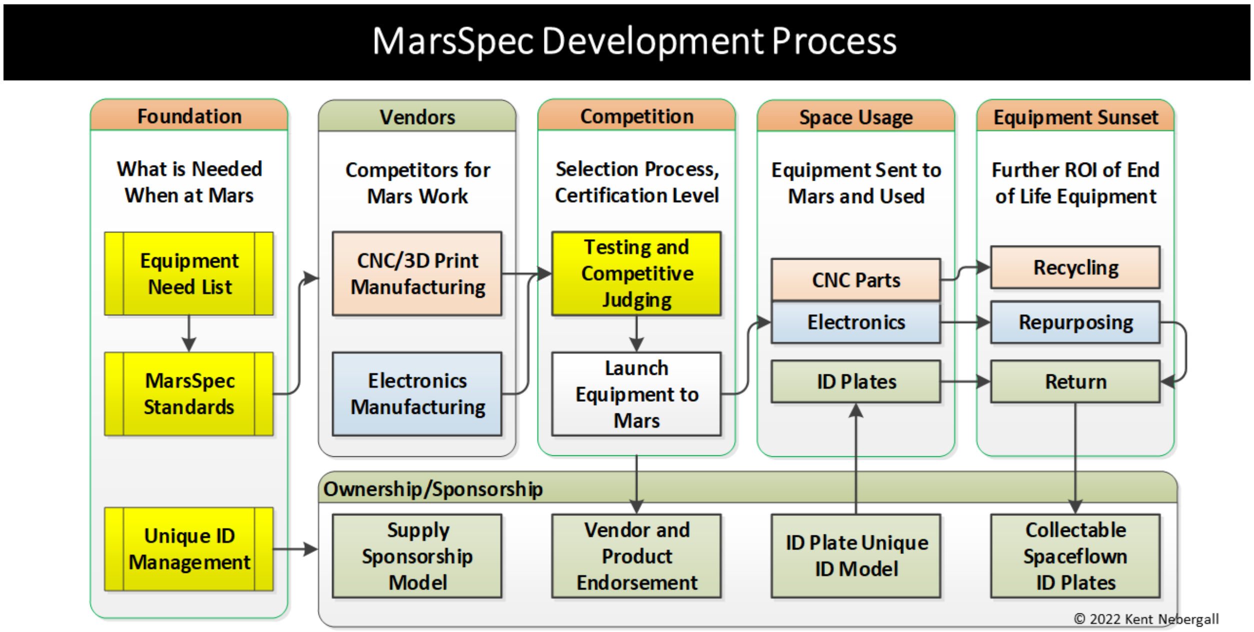
- MarsSpec provides a new Design Language.
- Certification Seals provide a new Investment Language.
- And a Catalog of Innovations with Smart Contracts gives an Invention Language.

Design, Invention, and Investment are converged into a very efficient and democratized engine for the Mars Age.



So how does this work?
First, we create the shipping manifest for the next launch window.
For simple commodities, the sponsorship model is a bit like a wedding registry. Sponsors can then pay for those items and, in return, get a certification seal that has been flown to Mars and back. A fractional benefit for that supply is calculated. The sponsor also gets ten percent of that benefit as a dividend over ten years.
Thus participation and benefits are democratized immediately.
Early mission seals will grow in historic value over time as well, much as space flown artifacts from the Apollo Era have done.

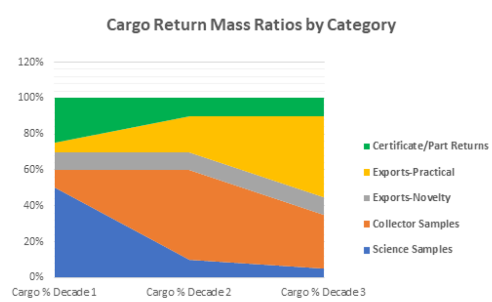
For more complex systems that require improvement to be ready for spaceflight, we have the MarsSpec route. This is a bit like Formula One sponsorship to show what car makers have the best engineers for marketing and recruitment.
We publish the requirements and open it to industrial competition. Competitors send in their hardware for certification.
If it meets the minimums, it gets bronze certified and can be sponsored for flight in future launches, but not the current one. They also can advertise they are minimally qualified to customers.
For the best ones, they enter competition to be the first to Mars. Winners also get higher ten-year dividends depending on quality and field lifespan.

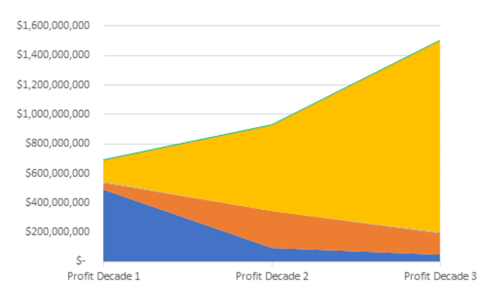


We can then use these three elements together with a foundation to get resupply and expansion flights equipped.
The Space Settlement Foundation would decide manifests and administer MarsSpec.
The equipment and supplies go to Mars with the certification seals. On the next flight, the seals come back to the sponsors and manufacturers as space-flown artifacts. Equipment and supplies are left on Mars for ongoing use and repurposing.

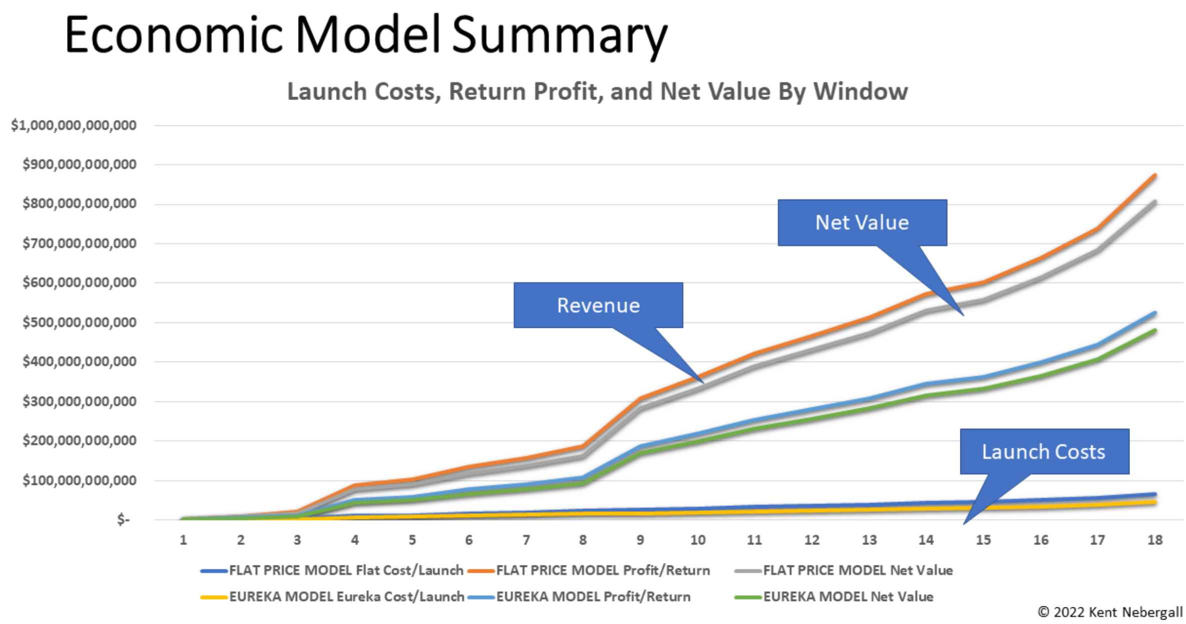
Growth and Market Shift

Date	Year	E2M Sorties	M2E Sorties	Population
2039	0	7	4	60
2041	2	16	14	100
2043	4	36	30	300
2046	6	100	95	800
2048	8	115	110	1200
2050	10	150	145	2500
2052	12	175	170	3500
2054	15	205	200	4200
2056	17	235	205	10,000
2058	19	266	240	15,000
2061	21	300	280	18,000
2063	23	325	310	20,000
2065	25	360	340	22,000
2067	27	390	380	24,000
2069	30	420	400	26,000
2071	32	450	440	28,000
2073	34	500	490	30,000
2075	36	600	580	36,000





This is a 30-year timeline of launch windows for a Mars settlement, starting in 2039.
The model allows for market saturation over time as the things that were novel become normal.
This business model allows for each excitement phase to die out in roughly a decade.



After the third launch window, the profitability explodes. So we only need to maintain novelty for six years to get the economy to be self-sustaining.
We progress from Settlements to Cities, and then exo-cultures. Note that this becomes an enterprise on the scale of Microsoft or Apple and in roughly the same amount of time.