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ArmorHab: Design Reference Architecture (DRA) for human habitation in deep space

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ABSTRACT

ArmorHab architecture aims to develop long term habitats, constructed primarily (>50%) from in-situ resources of planetary bodies, using synthetic magnetospheres for shielding, providing protection for each type of habitat: transport, orbital, and surface habitats.

The ArmorHab architecture adapts to the challenges of extraterrestrial environments (extremes of temperature, pressure, radiation, etc.) using a combination of existing and new technologies. We maintain breathable air with redundant biological and mechanical systems, self-sealing walls which protect against micro-meteoroid punctures, and defense in-depth by using multiple sealed chambers with connecting airlocks. In low-gravity conditions, gravity is emulated through centrifugal force. Radiation shielding is provided by magnetosphere emulation using steady-state superconductive cables. Food production uses aeroponic and hydroponic industrial scale facilities, including lab-grown meats. The crew is busy with commercially productive mining, manufacturing, and base/station operations, including food production. Thermal isolation from the environment uses a combination of IR reflective films, thermal mass, and aerogel insulation. Structural components are built from in-situ materials using additive manufacturing and other advanced techniques. All of the components of the ArmorHab architecture serve multiple purposes: a layer of ice will provide self-sealing micrometeorite defense along with supplementary radiation shielding and water storage; structural reinforcement of the habitat will play a role in forming the artificial magnetosphere; algae bioreactors and radiation-resistant plants will scrub carbon dioxide and pollutants, produce biomass that will be utilized, and provide additional radiation protection.

KEYWORDS

transport habitat, orbital habitat, planetary habitat, magnetosphere emulation, gravity emulation

INTRODUCTION

In the late 1980's, engineers at Martin Marietta began a project which became “Mars Direct”, in 1996 inspired a book “The Case For Mars” (updated in 2011)[1], and spawned the Mars Society. Taking 1980s as the reference, we can also observe considerable advancements in the construction of space stations[2] but to date,, all of the stations from Salyut7 [108] to the International Space Station (ISS), were situated in Low Earth Orbit (LEO), using Earth's magnetosphere for shielding, were not producing commercial products in any serious quantity, and completely or almost completely relied on

Earth for supplies. NASA has long sought to counter these deficiencies. TransHab (1998)[3] was originally designed to transport crews to Mars, and evolved into the Bigelow Expandable Activity Module (BEAM)[4] recently attached to the ISS. The Vegetable Production System (Veggie)[5] demonstrated that food crops could be grown in microgravity. Manufacturing and recreation uses of space can expand with these technologies, using the commercial space fleet NASA is preparing to exploit the access to LEO.

Commercial technologies have also advanced, with Aerofarms[6] implementing aeroponics on an industrial scale. NASA originally developed ECLSS (Environmental Control and Life Support System) [7] with Boeing for the Space Shuttle, and extended those capabilities for the ISS. Bioregenerative Life Support Systems (BLSS)[8] using hydroponics derived technologies are ready to be implemented on a real-world scale.

Mars brings clarity to space projects that LEO does not – launch mass costs can quickly break even the budgets of billionaires, and if you don't bring it with you or can't build it there with In Situ Resource Utilization (ISRU), you may not survive. The Mars Society has contributed to this progress, with analogue Mars Desert Research Stations[9], also by including papers on related subjects over the past twenty years: 3D printing [57-58]; BLSS [59-72]; colonization [73-77]; construction [78-83]; geology/habitats[84-85]; ISRU[86-94]; mining[95-97]; power[98-101]; radiation protection[102]; stations[103] and water[104-107]. In this paper, we focus on new materials technology that can expand the trade space for launches.

BEYOND SPAM

Early spacecraft construction was aptly described by Chuck Yeager as “spam in a can.” Lockheed Martin's NextSTEP habitat[10] continues the tradition of round metal cans started by Skylab[2] in 1973. The Mars Base camp[11] they propose seems to be Son of Skylab, with additional round solar arrays. This redoubles the frequently heard complaint that we've had the technology to go to Mars for over twenty years, but have lacked the political will to do so. On NASA's current schedule and budget, at least another twenty years will pass before mankind lands on Mars[12]. For counterpoint, StarTrek canon (from “Voyager”[13]) says Mars was not colonized until 2103.

We refuse tosuccumb to this pessimistic viewpoint. We predict the full exploitation of ISRU can lower launch costs, and slay some famous dragons (such as radiation exposure)[49,50]. While MarsDirect was innovative and brilliant for an initial manned mission to Mars, it is not well factored as a long term solution. Buzz Aldrin has a practical alternative, the Cycler[14]. A fully developed Cycler model has EarthTrucks, MarsTrucks, and LunarTrucks, which provide transport to/from the surface. Trucks dock at Stations, the equivalent of airports. Cyclers transport passengers and cargo between Stations. Stations then use Trucks to transport passengers and cargo to Bases. The cycler model thus fits within the NASA “Proving Ground” and leads to the promised land of “Earth Independent”. Cycler models are better factored, since Cyclers never have to conduct atmospheric re-entry, Bases and Stations have no need of propulsion systems, etc. Extra complexity constitutes extra cost in both budget and mass, and is factored out by the metric of utility. Our cycler model is shown in Figure 1.

Launch costs from Earth are currently K$/kg, and radiation shielding is a necessity. We propose a transformative approach to building a resilient Mars habitat that maximizes the use of local materials for low mass launch costs, to provide redundant survivability, and to make all the components serve multiple purposes. Traditional construction results in buildings with masses of 980kg/m^2, while we target 90kg/m^2 for early stage habitats and 9kg/m^2 launch mass overall. During habitat construction, robotic bulldozers prep the site, and a robotic material handler positions components, such as doors and airlocks. The shell will use a combination of mylar inflated forms, wrapped in superconductive self-insulated cables. Aerogels such as Airloy^{tm} X60 [15] provide strength, insulation, and a protective shell. A layer of water ice provides thermal mass, radiation protection, and micrometeorite resistance. Another layer of aerogel insulates the water storage from the crew area, which is sealed and surfaced. Additional life support can be provided by an algae based bioreactor layer between the inner aerogel layer and the water ice. Figure 2 shows the basic wall model of the ArmorHab DRA. Additional layers can be added, for instance a layer of β-Ti_3Au (beta titanium-3-gold) for the metallic shell required for Skylab emulation, or large shell structures for bases can built by deploying a set of sagging and hogging cables and spraying a Martian soil concrete mix over them. Doors provide airlocks and separate areas, in addition to control and switching technology for air, water, power, sewage, and data. Thus the doors are the place for standardization, internal and external, just like the International Docking System Standard (IDSS) standardizes the interface between spacecraft[16].

Figure 3 shows the ArmorHab DRA TransportHab concept, also known as a cycler. Most of the features shown would be common to any interplanetary spacecraft design. The 15 cubic meter habitat on each end with magnetospheric emulation is a dramatic difference. We note that the only difference between a male and a female International Docking Adapter is which one has extended its petals for docking, any IDA can serve either role. We also provide simulated gravity, based upon an extension of the Mars Direct tether, where a structural member provides the ability to move between the habitats at either end without requiring a spacesuit. The Orion capsules can be clearly seen in Figures 3 and 4, which can be used as lifeboats, to remain in orbit and wait for rescue. Orion capsules can also re-enter and land if the emergency occurs in Earth orbit.

BASE CONSTRUCTION

"Human on Mars" is an expression mostly used to refer to sending humans in pioneer manned missions to Mars. These initiatives notably include *NASA Mars Design Reference Mission (DRM)*, *Russian Mars Piloted Orbital Station (MARPOST)*, and *The European Space Exploration Programme Aurora (ESA)*. Most of the concepts of those programs are focused on the immediate to near-future human exploration rather than long-term settlement. Colonization of Mars emerges to be the next logical step and an extending vision for the after landing stages. In this context, the Mars habitat has a few challenging constraints for human dwelling such as weak gravity, thin atmosphere and substantial harmful radiation, from x-rays up through galactic cosmic rays (GCR). Some of those challenges might be overcome by establishing suitable shelters made from Mars regolith, or buried underneath it.

It has been suggested that a first dwelling habitat might be sent to Mars before sending humans. Such first dwelling might include prefabricated modular frames with pneumatic fabrics/materials that provide small size but protected shelters. Examples for such first dwelling was suggested in NASA's centennial challenge contest to design and build 3D printed habitat for deep space exploration. Some of the frontier idea included construction of a radiation-proof shelter from the abundant northern ocean permafrost ice on Mars. This proposal is further focused on the second/long-term dwelling habitat rather than first ones. In that sense, we suggest that such long-term dwelling shall be a resilient and sustainable habitat which can only be produced by utilizing Martian natural resources, materials, surface conditions and sub-surface features with technologies brought from Earth.

The first phase habitat will not have ball mills, smelters, cable drawing, and additive manufacturing capabilities required in addition to the robotic construction equipment, but will be built using inflated forms. As these advanced technologies arrive from Earth and are brought online, cables and prestressed concrete panels can be constructed. Extensions to the habitat core are 3D-printed using a Modular Assembly Structure (3D-MAS), extensively using large cables and prestressed technology in its construction. The cables will use locally-sourced metal (either iron or titanium, perhaps enhanced with carbon nanotubes), and will be robotically deployed to form a dual function layer of load-bearing shell structures and galactic radiation shielding. Steel cables exposed to the superconductive magnetic radiation shielding will become magnetized, providing additional passive protection.

We now explore the possibilities of construction possible with the full exploitation of ISRU made possible by additive manufacturing given the second phase equipment has arrived at the base. Here we propose the concept of a 3D-printed Modular Assembly Structure (3D-MAS) for long term Mars habitation. 3D-MAS will make use of large cables construction and prestressing technology assisted by 3D printing and automated robots. Prestressed concrete might be one of the most excellent alternatives for Martian Habitat. The reason is prestressed concrete is a type of concrete that is designed for no-cracking. This is an essential criterion we shall use to maximize radiation shielding and to ensure long service-life of our Martian structures. Prestressed concrete will also allow modular production of concrete on Mars. Prestressed concrete can be enabled by using Martian metal cables (mix of iron and titanium) from Mars. In the ArmorHab DRA, the concrete is the additional exterior layer (like the β-Ti_3Au skin of the TransportHab), or alternatively the interior layer (replacing the tile floor).

3D-printed Modular Assembly Structure (3D-MAS)

An interesting method to build on Mars is not to use the classical framing and concreting methods used on Earth, which are detail oriented, thus requiring human intervention, and very time consuming. We suggest combining prestressing and cable technologies for building large shell structures on Mars. Very large shell structures (with spans between 100-300 m) taking hyperparaboloid shape enables such development by establishing a set of sagging and hogging cables[17]. Such cables can be installed and positioned accurately using robots with a GPS system (provided by cubesats in orbit). An example geometry for those cables is shown in Figure 5.

We suggest developing precast prestressed regolith concrete panels that can be easily fabricated with an automated system inside shelters without much complexity. Robotic cranes can then drop infill prestressed regolith concrete panels in their location and a 3D printer is then used to fill the infill between the panels and seal the structure. The advantage of that system is it can be completely developed and installed using robots. Example panels dropped in location is shown in Figure 6. An example of such very large shell structures (about 44000 square meter area) that was constructed using sagging and hogging cable systems for fast construction of Calgary Saddledome in Canada for the 1988 Winter Olympics, shown in Figure 7.

Martian Concrete:

We suggest using the regolith, an abundant material on Mars, to build the Martian concrete. Regolith represents a combination of silica and iron and has no organic materials [18-19]. The proposed binder for the Martian concrete can be silica aerogel, sulfur [20] or a mix of low density polymer (e.g. polyurethane) and silica aerogel. Prior research on and investigation on using sulfur in lunarcrete will be reviewed [21]. We have recently developed a nano-modified sulfur concrete that might be suitable for Martian infrastructure [22]. Researchers have shown the most critical issue in the binder is to have high hydrogen content necessary to provide radiation shielding from x-rays up through galactic cosmic rays (GCR) [18-19]. Our research into Martian concrete will include developing and identifying the basic mechanical characteristics of Martian concrete with different binders including polymer and sulfur. We will also examine the long-term durability of Martian concrete under vacuum, radiation exposure and other Mars environmental conditions. We will also design and test an appropriate concrete mix to achieve required thixotropic characteristics to ensure successful 3D printing of Martian concrete. We will also examine the potential production of Martian shotcrete using similar mixtures and materials with different gradations. Our research will also examine methods to overcome the significance of 3D printing (specifically layering concerns) on Martian concrete characteristics and to examine some critical concrete characteristics such as creep and cracking that represent essential characteristics to enable producing prestressed Martian concrete.

Multi-function Martian Composites:

We suggest developing two multi-functional Martian composites to work as reinforcement for 3D printed concrete. The first Martian composite is made by isostatic pressing of a mix of aerogel and titanium producing composite mat of reinforcements. The suggested composite mat can be placed by 3D printing robots during 3D printing process as layers. The proposed reinforcement mat is fully based on native Mars materials and to provide necessary strength and deformability of Mars structures. Furthermore, Titanium based composites are recognized with excellent radiation shielding and improved impact resistance. We also suggest a new patented technology [23], based upon bandgap metamaterials, developing multifunctional reinforcement of Martian concrete that can enable superior GCR shielding, in effect creating a passive electromagnetic GCR Mirror. This patented technology [24] suggests Lincoln-Log Tungsten bars (or elements of higher atomic numbers), shown in work with Sandia National Lab (SNL) producing efficient bandgap structures [24-25], as internal reinforcement mats or prestressing cables for Martian concrete that can be placed during the 3D printing process. An example tungsten bandgap Lincoln-log is shown in Figure 8. We suggest producing bandgap reinforcement mats, perhaps made out of silica-titania sheets, that can be used as internal concrete reinforcement and provides superior GCR shielding. A schematic of the proposed use of Lincoln Log tungsten mats inside Martian concrete is shown in Figure 9. Our research will include design of the proposed reinforcement mat (i.e. defining number of layers, spacing and log dimension) using multiobjective optimization to achieve required structural strength and maximizing radiation shielding. Computational and experimental research will be integrated to achieve this design. Alternative shapes and media (e.g. air or silica aerogel) of photonic cells will be examined to create flexible multifunctional reinforcing/shielding mats that can be used as an external or internal surface shielding layer for Mars Habitat structures. The above multi-functional tungsten mat can also be fabricated using 3D printing technology making it an excellent addition to Martian concrete structures. Previous versions were manufactured using semiconductor etching techniques, but we suggest that 3D printing of such structures is now feasible.

Of specific interest to us is the design of the multifunctional reinforcement for Martian concrete is to enable reflection of energy in bandgaps in the range of 10^{10} eV and above as shown in the schematic of Figure 10 [26]. Special design of the bandgap mats to enable such protection is planned. The ability of the proposed reinforcement to enable heat dissipation is also of interest. The use of materials with low thermal transfer co-efficient should be considered. We suggest examining materials like palladium, platinum in addition to titanium for prototyping. The abundance of titanium on Moon and Mars might make it more attractive. The idea of burying the whole mat into aerogel Martian concrete as a multi-functional reinforcement provides another level of protection and construction efficiency never suggested before.

Our research into the above proposed Martian composites including multi-functional reinforcement will include computational design, synthesis, fabrication using 3D printing and testing. Mechanical testing will include testing under various stress and environmental conditions as well as testing as internal reinforcement and shielding of 3D printed concrete. Fabrication and testing will be conducted in our lab. Radiation shielding tests will be conducted through collaboration with Sandia National Laboratories.

3D Printing Concrete – progress and challenges

Researchers have predicted that 3D printed concrete will dominate the construction industry on earth in the next decade. Signs of worldwide interest has been reported by many countries worldwide since its inception a few years ago [27]. 3D printed concrete has been suggested as the main construction material for space exploration and in habitation [28]. Efforts have been reported worldwide on the possible use of 3D printing for large scale construction [29]. For instance, researchers in the Loughborough in UK developed computer controlled 3D printers for construction industry. Their 3D printers precisely deposit successive layers of high-performance concrete to form complex structural components such as curved cladding panels and architectural features that cannot be manufactured by conventional processes. The technique also facilitates the inclusion of increasingly complex building services infrastructure from the outset instead of time-consuming and costly on-site retrofitting. This state-of-the-art technology allows them to print up to 10 times faster and allows them to create architectural features, curved, geometrically complex, hollow and complex concrete designs [30]. Example shapes printed by the group in UK is shown in Figure 11. Similar efforts in the UK were reported by Bartlett School of Architecture in London [31]. In this technology, concrete is extruded layer-by-layer over a bed of granular support material, which allows the shapes to be more volumetric. The concrete is then pumped to a robot programmed to follow a linear fabrication tool path and deposited at a 1cm resolution. At each layer granular support material is deposited around the extruded concrete. A binder helps out by hardening specific parts to produce a multi-material piece. A dual material nozzle of concrete and binder is used to connect to an industrial robot. Similar technology can be used on Mars but would still have to be insulated and shielded for use in space as described above.

Furthermore, an innovative research and development company called “G.tecz” has developed printable pure water and cement based concrete in collaboration with Voxeljet (manufacturer of industrial 3D printing systems) and University of Kassel, in Germany. While the printed volume was not very large, 60x40x40 cm, the details of printing and the possible parallel printing enables significant time savings in construction [32]. A team of engineers at Technical University of Dresden (TU Dresden) in Germany aimed at producing 3D printed concrete structures on a large scale using specially controlled robotic arms. The technology is designed to directly apply concrete to the building site without additional formworks through an additive manufacturing, or layer-by-layer system. A special mix of fast setting concrete will be extruded through print head nozzle guided with geometric precision of the large scale robotic system [33]. An example of that system is shown in Figure 12.

Similar efforts have been happening at home. Researchers at UC Berkeley recently developed new powder-based concrete 3D printing technique. The new polymer-fiber-based concrete was relatively strong and lightweight. A concrete structure that is 2.7 m height with a 3.6 x 3.6 m foot print was printed with the above concrete. The structure is connected to steel. Although the structure was decorative but it shows the possible use of large number of 3D printer (11 printers) to finish a major structure in 28 days [34]. Conversely, a single such 3D printer could complete the same structure in less than a year, perfectly tuned to the 26 month schedule of launches to Mars. Researchers at the University of Southern California (USC) are also testing a giant 3D printer that could be used to build an entire house in under 24 hours, well suited to building one of our bases. The technology, known as Contour Crafting (a fabrication process by which large-scale parts can be fabricated quickly in a layer-by-layer fashion) aims to replace construction workers with a giant robot [35] is shown in Figure 13.

Finally, industrial firms worldwide have also examined the use of 3D-printed concrete [36-38]. Reports on successful 3D printing concrete efforts from China, Sweden and the US are available in the public domain. Chinese materials firm Yingchuang New Materials has reportedly produced 10 3D-printed buildings in 24 hours, using a custom-built machine that outputs layers of construction waste mixed with cement. The Suzhou-based company spent 20 million yuan (£2 million) and 12 years developing its specialized additive manufacturing device, which can be used to 3D print self-supporting architectural structures [36]. The company demonstrated the technology earlier this year by producing 10 stand-alone houses in the space of a day, which will be used as offices at an industrial park in Shanghai [37]. It is important to note that China has produced and used more concrete in 2011-2014 than the United States has in the past 100 years. Finally, Rudenko’s 3D printing company has successfully validated its functionality and ability by 3D printing in concrete an assortment of trial structures, including world's first 3D-printed concrete castle in United States and the 3D-printed Concrete Hotel for Lewis Grand in Philippines and in the US [38]. Example 3D printed concrete structures and components are shown in Figure 14.

The above reports show interest and significant progress in 3D printed concrete. Significant challenges lie ahead in producing resilient concrete structures with necessary performance necessary for space habitats [39-40]. Some of the challenges related to the production and others to characteristics. For instance, 3D printing of concrete requires concrete with specific control of its fresh properties as well as setting time and characteristics. Research on concrete thixotropy and its need in 3D printed concrete is still in its infancy [40]. This is a very critical aspect for the need for concrete to stand its own weight in the layers during casting without forms. The use of nanomaterials, such as nanoclay to control shear flow in polymer composites and therefore polymer concrete can be of significant interest and value [41]. Another significant challenge in 3D printed concrete is the layered structure of concrete which can result in weak shear transfer between concrete layers results in reducing strength and producing planes of weakness [42]. The use of fiber reinforcement during 3D printing has been recently examined [43]. We also suggest that ultra-high performance concrete (UHPC) developed by the end of the last century with specific strength and flowability criteria might be an excellent candidate for 3D printing [44]. We intend to examine the mechanical and durability (long-term) characteristics of 3D printed Martian concrete we described above. The possible inclusion of polymers specifically powder polymers will also be examined.

BREATHING IN SPACE

It is expected that the habitat and (its systems) will operate under a permanent threat of massive unpredictable external damage. To mitigate such a threat, we will embed the enhanced ability to withstand such damage (or survivability) at the early stage of the layout/systems designs, and will explicitly account for habitat material properties (individual and combined into multilayer, multipurpose shells). This will maximize the habitat's operability until repair/patching of the damaged sections is completed. We will assess efficiency of other damage mitigation strategies such as control, wide-area protection, reconfiguration, and intentional islanding. In no system are these principles more important than life support.

Since the amount of atmosphere we can take with us is bounded, we must build a shell. Since temperatures can cause the atmosphere to liquify, we must control it. Since punctures can cause the atmosphere to escape, we must seal them. But humans are even pickier than this, they require low radiation, moderate gravity environments to function properly for long periods of time. The first organisms in our biota were microorganisms, and we can use them to make our space environments more comfortable. Indeed, we use all the surfaces of our spacecraft, transport habitats, stations, and bases to recycle our exhaled carbon dioxide into breathable oxygen. But the potential of our symbiosis only begins there.

The Martian atmosphere is about 100 times thinner than Earth's but rich in CO2 (~95%), and its crust contains most of the elements needed for photosynthesis[45]. Nitrogen may be a key limiting component (~2.7% atmospheric content) although nitrogen salts are predicted in the Martian regolith, crust[46]. Cyanobacteria have attracted considerable interest as pioneer organisms that produce O2 and convert CO2 into foods, fuels, and polymers for habitable Martian ecosystems[47]. We will investigate and engineer solar-radiation and salt-tolerant cyanobacteria for efficient utilization of Martian resources for O2 and bioproduct production. Bio-products such as terpenes that are continuously excreted from cells are of particular interest, as terpenes are major biosynthetic building blocks. We will develop bioreactors that can be fabricated from Martian resources and that can incorporate immobilized cyanobacteria into Martian habitat structures. The immobilized cultures will be stable for extended periods, require less water, and will serve as microbial biofactories for Mars. Ultimately we will integrate the bioreactor products into the production process for habitat materials, e.g., serving as coatings, adhesives, and binders.

Large scale bioreactors on bases will augment the BLSS capability implemented by aeroponic and hydroponic gardens which perform dual service reducing carbon poisoning and also providing food, or purifying water and producing food. Since these are closed loop systems, they are perfect for long term space voyages. The ECLSS provides a monitoring component and defense in depth backup to the BLSS. Figure 15 shows a large scale biofuel facility and a small scale bioreactor. These systems are used to provide the equivalent of the full hydrocarbon chain that petrochemical industries provide on Earth.

Dehydrated foods must also be supplied. While the fresh food of the BLSS is important, it must not become a single point of failure, either for atmosphere recycling, or for food supply. Likewise, advances in meat production using “lab grown meats” can provide protein to supplement the BLSS vegetarian sources.

ROBOTICS

The Aerofarms aeroponics are highly automated, but until there is a habitat shell to install them within, they cannot provide the BLSS services we desire. Figure 22 shows a Navy EOD robot which could be modified to suit our needs to plug in the water pipes, sewer pipes, power cables and data cables of the base (BCAP robot). Figure 23 shows a SPHERES robot modified to do the same essential functions for transport habitats and stations (SCAP robot). This same robot can be used as a material handler during in-space assembly.

The walls of the habitat must be constructed somehow, so for the first station, we position the premanufactured station core with IDA compatible docking ports where it is connected to the station. The spars of the rotating wheels are attached to an emergency airlock by magnetic strips and inflated. Figure 24 shows the base version of of the Internal Spraying and Sealing robot (BISAS), where Figure 25 shows the station version (SISAS). Layers of β-Ti_3Au, aerogel, water ice, encapsulated algae, aerogel, and silica / tile surfacing follow with a nice NASA white sealant. The torus quadrants can be added the same way, then the magnetic bearings and electromotors of the artificial gravity system started. The SCAP robot(s) can begin connecting up the station systems, and “spare” ISS human labor can be provided to work out issues with the robots. The goal of the first station is to learn how to completely automate the assembly of the station.

The first base faces issues with foundations and access that the space stations do not. Something equivalent to a bulldozer (more formally called a skid steer or track loader in the construction trade) which can plow the ground flat and pour a runway (or for VTVL craft, a landing pad). The equivalent

Caterpillar D6N Base Track Loader (BTL) is shown in Figure 26, as modified for the off-world environment. We remove the engine, replace it with batteries, replace the crew compartment with electronics and solar panels. The body is replaced with β-Ti_3Au for heavy duty components and aerogel structural or CFRP for other components to reduce launch mass. Tanks in the back can spray the runway or landing pad. The material handler is shown in Figure 27, with similar modifications, performing the services of a crane, primarily positioning airlocks or doors, but eventually the ball mills, smelters, additive manufacturing and subtractive manufacturing equipment. Figure 28 shows one such ball mill, which can process regolith for input to the concrete manufacturing or smelting. Figure 29 show a ball mill specifically adapted for the concrete industry.

Figure 30 shows how much infrastructure we use on Earth to transform raw ore into wire cable, and even this picture ignores the transportation and processing steps involved. NASA and MIT have been working over the past few years to simplify the smelting process for ISRU, as shown in Figure 31. We suggest that additive manufacturing simplifies the overall process further, by using robots (BTL) to feed regolith into ball mills, take the output from the ball mills (BCAP) into concrete preparation and smelters, then take the smelted/refined output (BCAP) to ball mills to provide powder input to the additive manufacturing. The products of this design start with concrete mix, oxygen, silicon for aerogel and solar panels, calcium and sodium, magnesium, manganese, chromium and the primary three metals (iron, titanium and aluminum). In combination with the algae hydrocarbon chain, the generic manufacturing system will be more limited by the CAD/CAM files provided than anything else.

POWER

Spacecraft have the potential to be solar powered, within the orbit of Jupiter. Energy harvesting from the heliosphere, and magnetospheres of planets is also possible. Stations can optimize their energy production due to their fixed orientation, as can bases. Backup power generation can also be used for short term requirements.

But power exists to be used. Whether stored in batteries to last through a cold winter night, or used to power a smelter to extract oxygen, iron, and silica from regolith. Transport habitats need less power than stations and bases. Robots must recharge to be useful, and biological systems may need artificial lighting. Nuclear reactors and wind power are also alternatives.

ONE EXAMPLE COLONIZATION ORDER

We propose a replacement for the ISS which we call Johnson Prime, to sit in Geosynchronous orbit above Houston, as shown in Figure 16. Such a station would simulate gravity to avoid the long term complications of microgravity exposure, using two counter-rotating wheels. Such a station could be assembled at the ISS and then towed to GEO.

Next we build a Lunar base, which we call Luna-1, to sit on the edge of a Mare, to be able to exploit both the Iron/Ilmenite ore, and the aluminum (lunar bauxite) ore, as shown in Figure 17. Such a base would be able to complete all three phases of base construction. The third phase of base construction requires a combination of additive (AM) and subtractive (SM) manufacturing techniques in a highly automated system to provide a generic manufacturing capability. We designate this capability as Lights Out Windowless Generic Manufacturing (LOW-GM), as shown in Figures 18-21. Such a LOW-GM system could manufacture everything from lawn chairs to robots, vehicles to spacecraft. With the biofuel capability from the algae ponds, and a refinery, a full economically viable foundation for a self supporting civilization exists.

Next we build a pair of cyclers at the ISS, beginning routine transport from Earth to Moon and vice versa. This fully qualifies the Cycler system for , as we build the Luna Prime station. The development of a LunarTruck to provide surface to station transport will demonstrate systems necessary to build the first Mars Truck. More Cyclers are built.

During the next Opposition, Ares Prime is taken to Mars orbit, and the Mars Truck is robotically qualified, as the Mars-1 base is built.

During the next Opposition, Mars is colonized.

CONCLUSIONS

Three launches may be required to assemble a TransportHab (aka Cycler), providing 44000 cu.ft. of habitat. Five or six launches may be required to assemble a station or surface base, each providing 65,000 sq.ft. of long term self sustaining habitat. Our research is designed to unify the best of all technology for the colonization of Mars, in an open interdisciplinary framework, in an open, multi-institutional effort. Transport habitation which is not well factored will not get us to Mars as efficiently as we can using a cycler system, provided we intend to do more than just plant the flag. To do that, we must implement a manufacturing infrastructure, which given the cost of creating it in the first place, must not just be thrown away once the habitats are constructed. Given that the lowest cost solution requires creating a transport infrastructure, we insist on using it to implement an economic infrastructure. Given the Earth-Moon-Mars system, using the Moon as a proving ground, we can choose to visit Mars, or to colonize Mars, either partially or completely. We prefer complete colonization. ArmorHab does what is required, for the least cost per component. It also lets us live there, long term.

ACKNOWLEDGEMENTS

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Terms and Acronyms

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APPENDICES

FIGURES

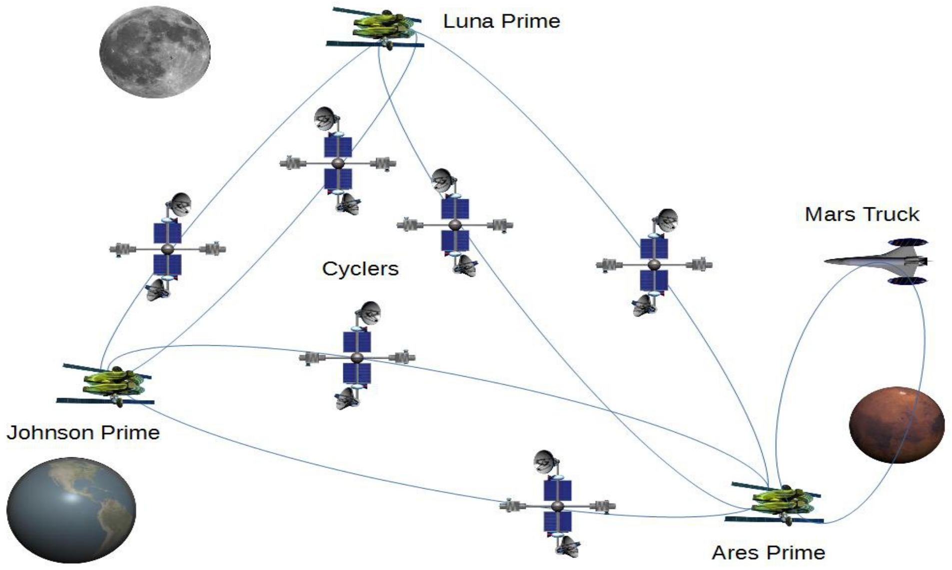

Figure 1: Cycler model showing Mars Truck, six TransportHabs and three Stations

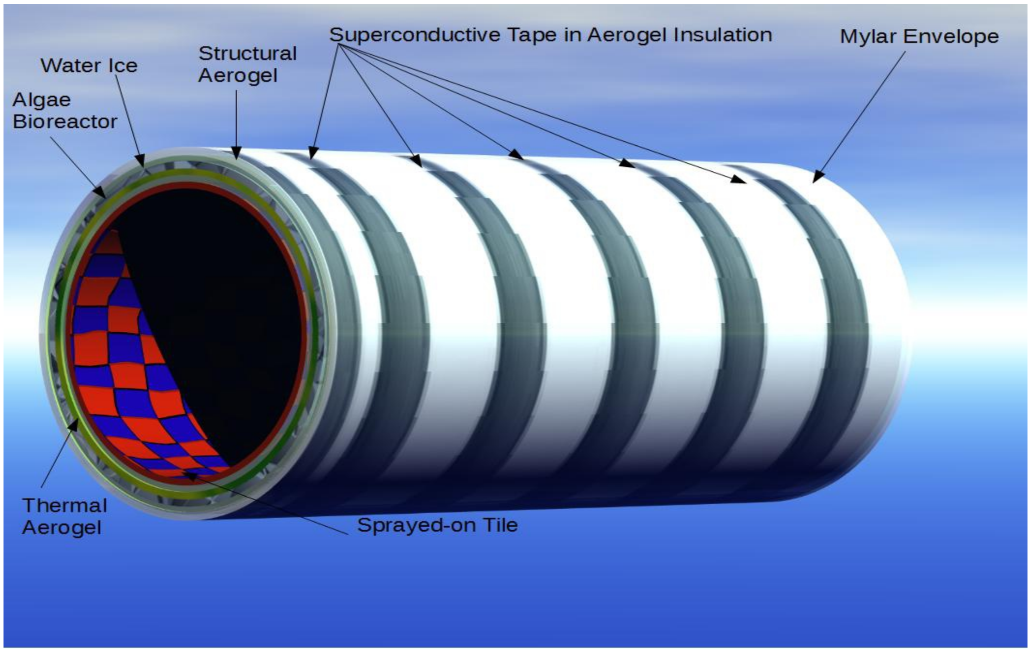

Figure 2: ArmorHab Wall design

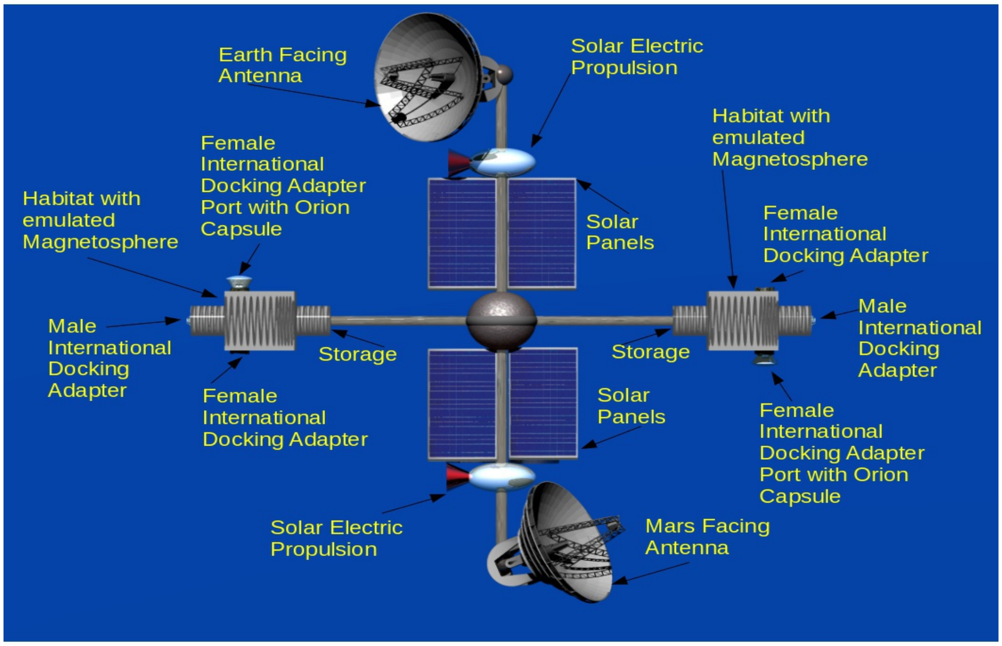

Figure 3: ArmorHab TransportHab Top View

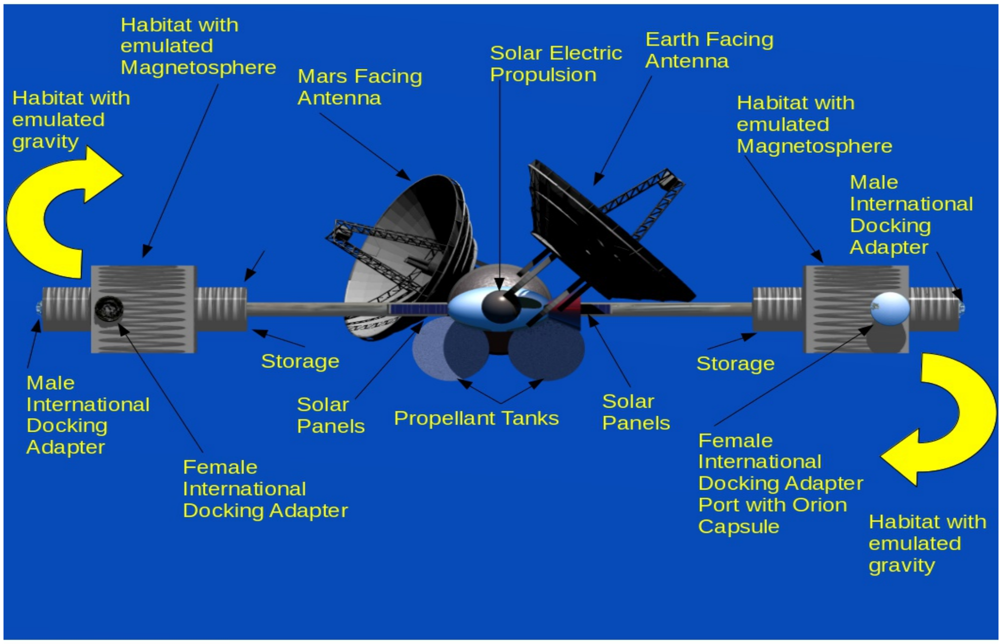

Figure 4: ArmorHab TransportHab Side View

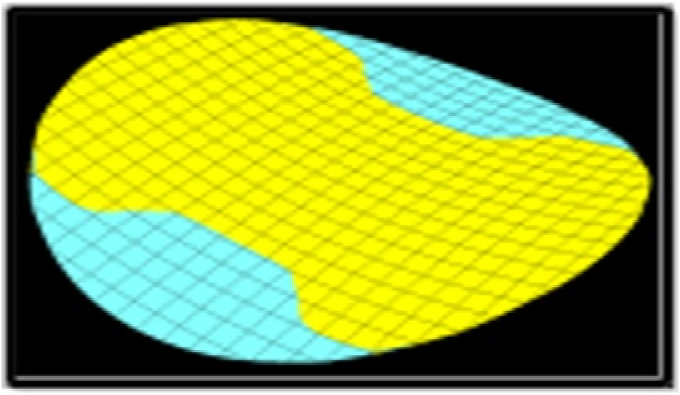

Figure 5: Graphical simulation of hogging and sagging cables making a hyperparaboloid shell structure [17]

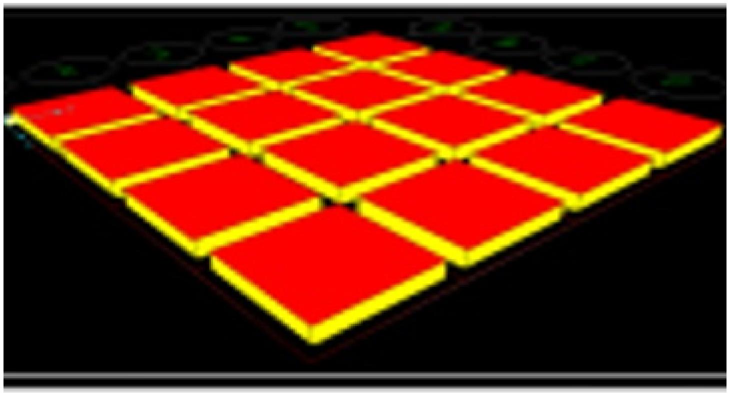

Figure 6: Graphical presentation of precast drop panels showing panels and links to be filled [17]

Figure 7: Example very large structure built using the proposed concept in Calgary, Canada [17]

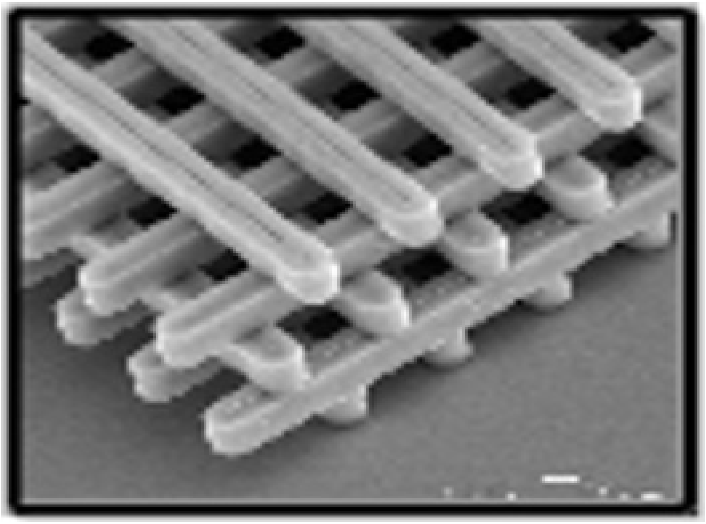

Figure 8: A snapshot of tungsten Lincoln log proposed for combined reinforcement and GCR shielding [24]

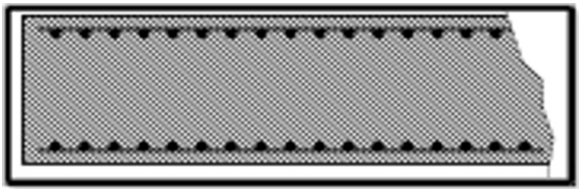

Figure 9: A schematic of suggested use of tungsten bandgap as reinforcement mat of Martian concrete [23]

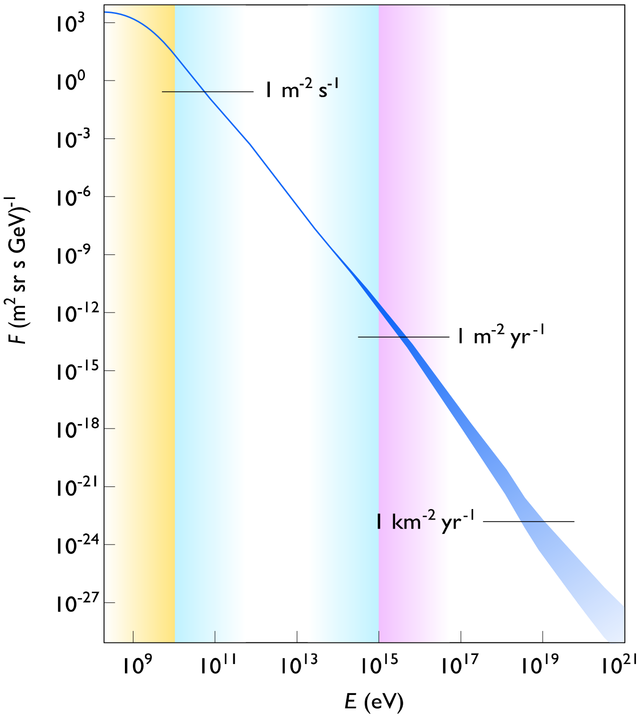

Figure 10: GCR spectrograph and energy ranges where proposed multifunctional reinforcement of Martian concrete will be used to protect Mars habitat against GCR [26]

Figure 11: Example complex shapes for 3D printed concrete recently finished in UK [30]

Figure 12: Example 3D printing layer-by-layer concrete system with robot guided extrusion [33]

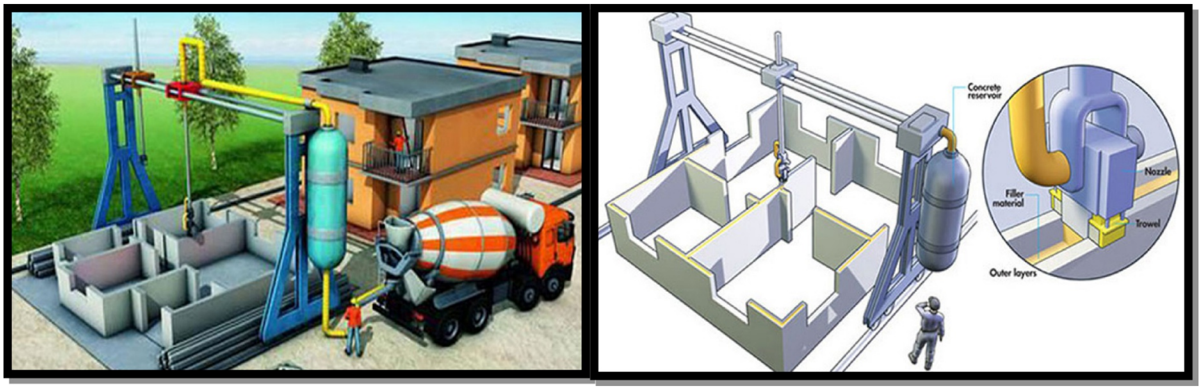

Figure 13: Contour crafting technology developed at USC with potential use to produce Martian bases [35]

Figure 14: Example 3D printed concrete structure by industries worldwide [36,38]

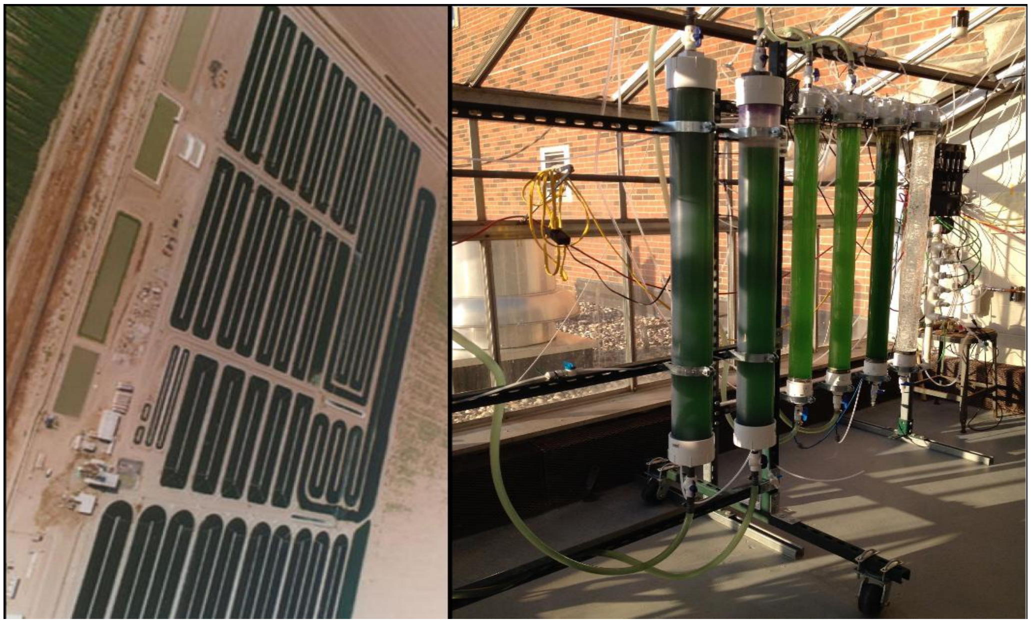

Figure 15: Algae ponds in New Mexico, Bioreactor in Algoma Algal Biotechnology Lab

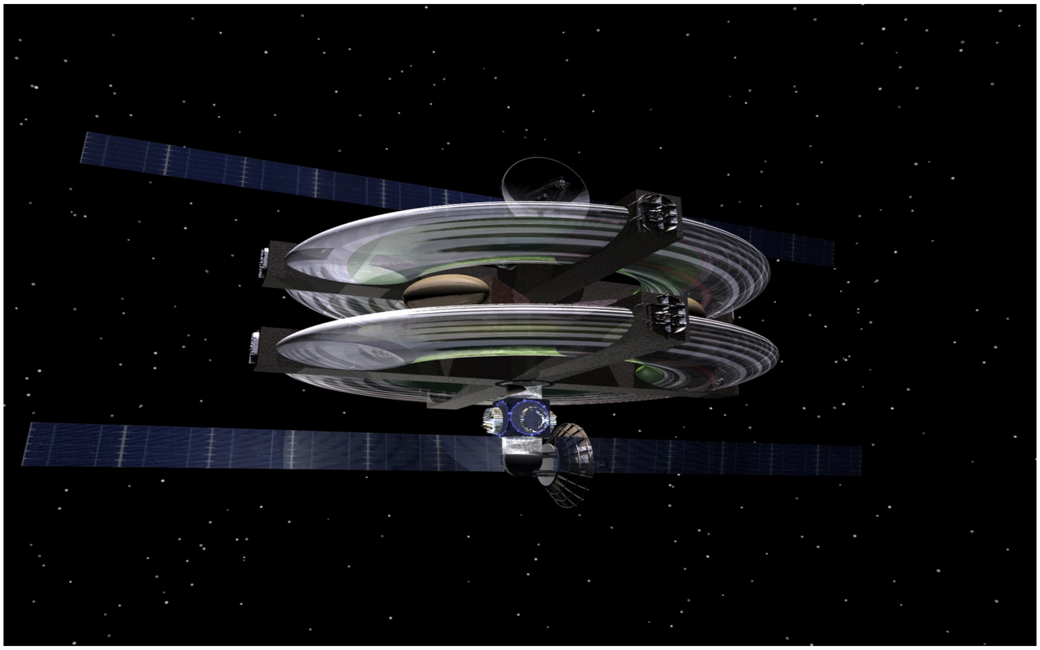

Figure 16: Orbital Space Station Johnson Prime in GEO

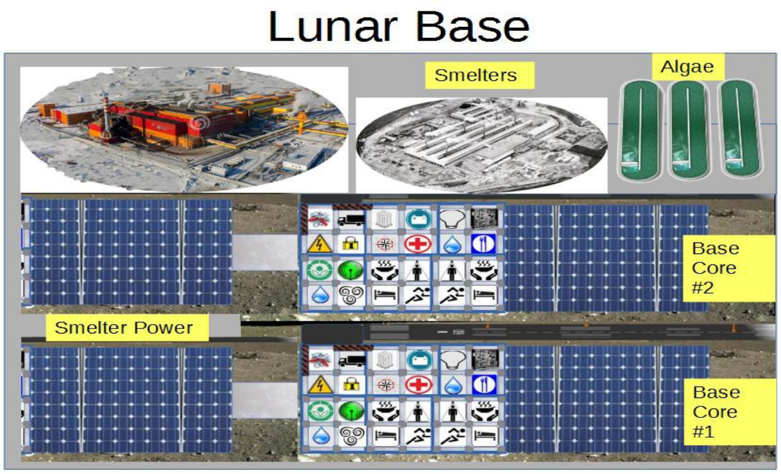

Figure 17: Luna-1 Base prepared to implement LOW-GM

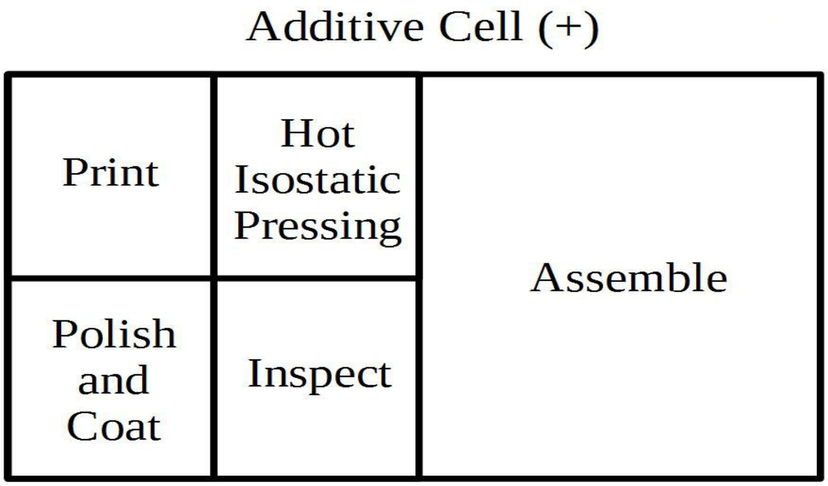

Figure 18: Additive Manufacturing Cell

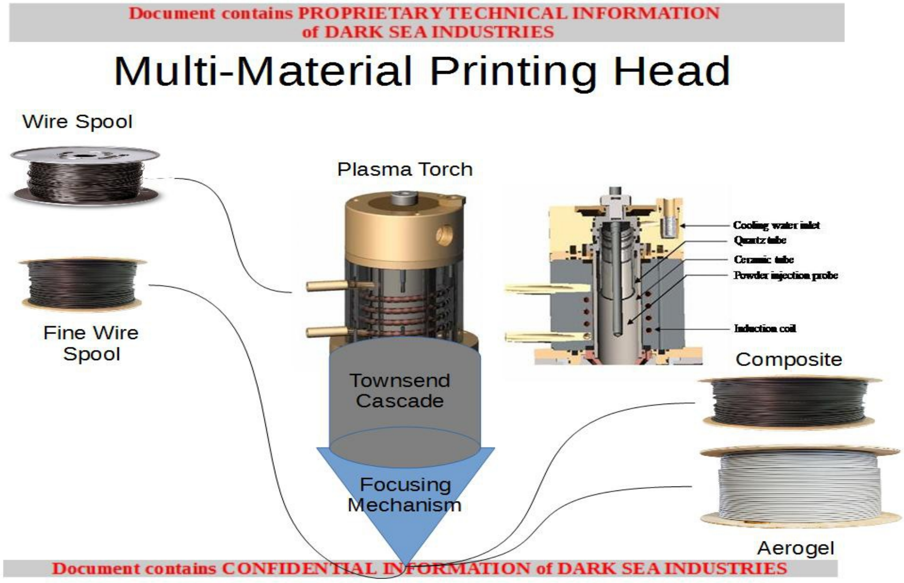

Figure 19: Multi-Material 3d print head

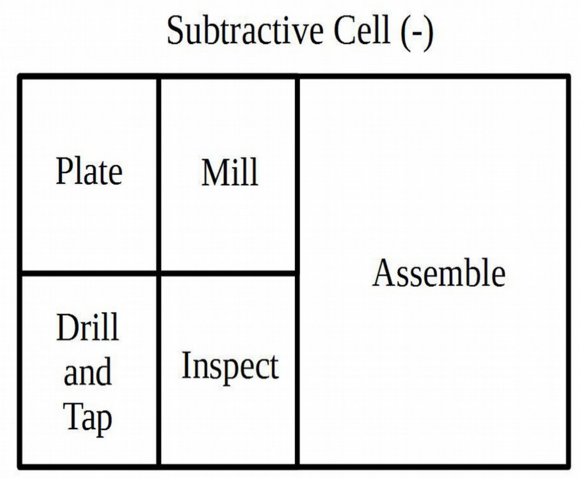

Figure 20: Subtractive Manufacturing Cell

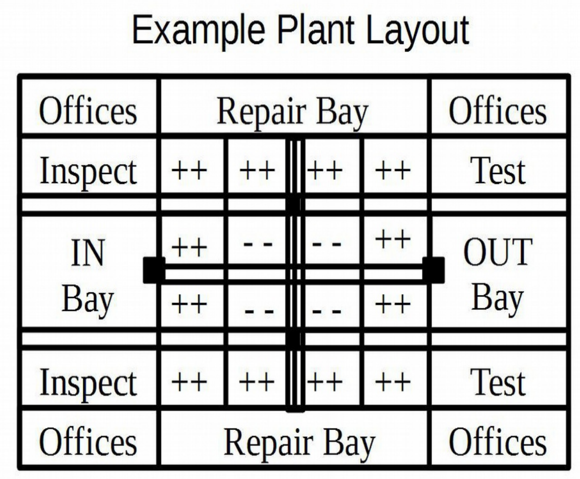

Figure 21: Lights Out Windowless Generic Manufacturing (LOW-GM)

Figure 22: Navy EOD Robot which can be used as prototype for Base Cable and Piping (BCAP) Robot [51]

Figure 23: ISS SPHERES Robot which can be used as prototype for Stations Cable and Piping (SCAP) Robot[52]

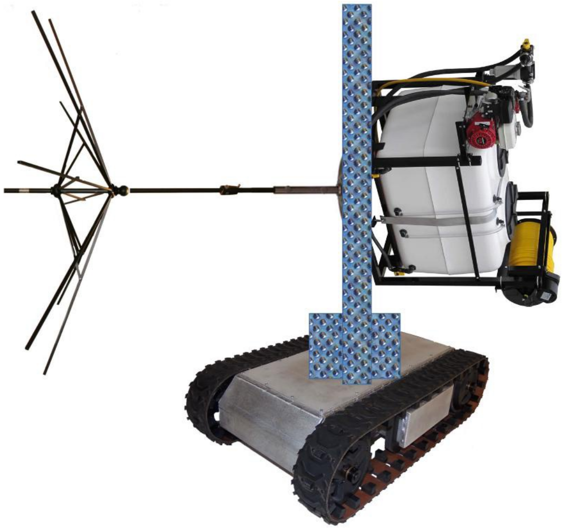

Figure 24: Prototype for Base Internal Spraying and Sealing (BISAS) Robot

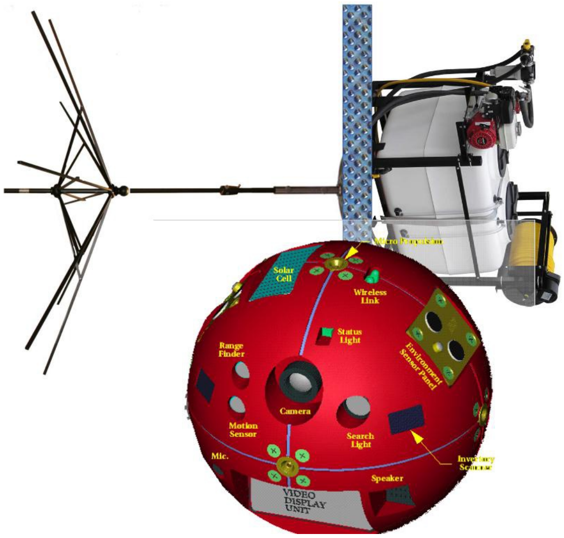

Figure 25: ISS SPHERES Robot used as prototype for Station Internal Spraying and Sealing (SISAS) Robot[52]

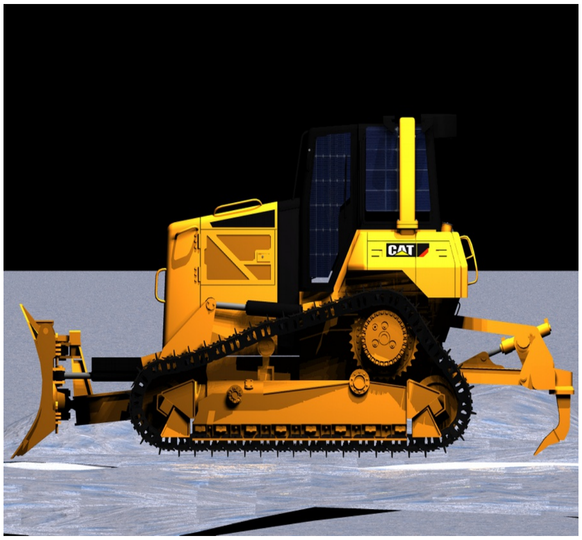

Figure 26: Prototype for Base Track Loader (BTL) Robot based upon Caterpillar D6N_LGP with solar panels and EV technology

Figure 27: Prototype for Base Material Handler (BMH) Robot based upon Caterpillar 330D-MH with solar panels and EV technology

Figure 28: PATTERSON® 3'0" dia X 4'0" long batch type "DJ" Jacketed 304 Stainless Steel Ball Mill, with 10 HP Integral Gear Motor for dry grinding. This Mill has a special polished inside finish for a pharmaceutical application. Drive side view.[53]

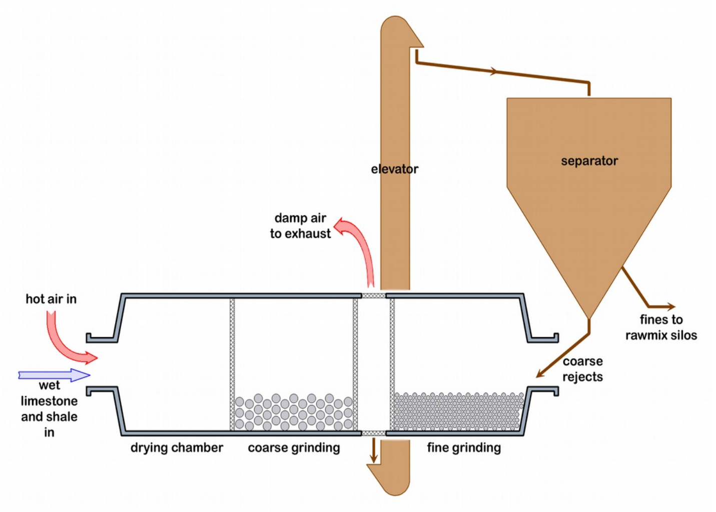

Figure 29: Traditional dual ball mill design for cement kilns from United Kingdom.[54]

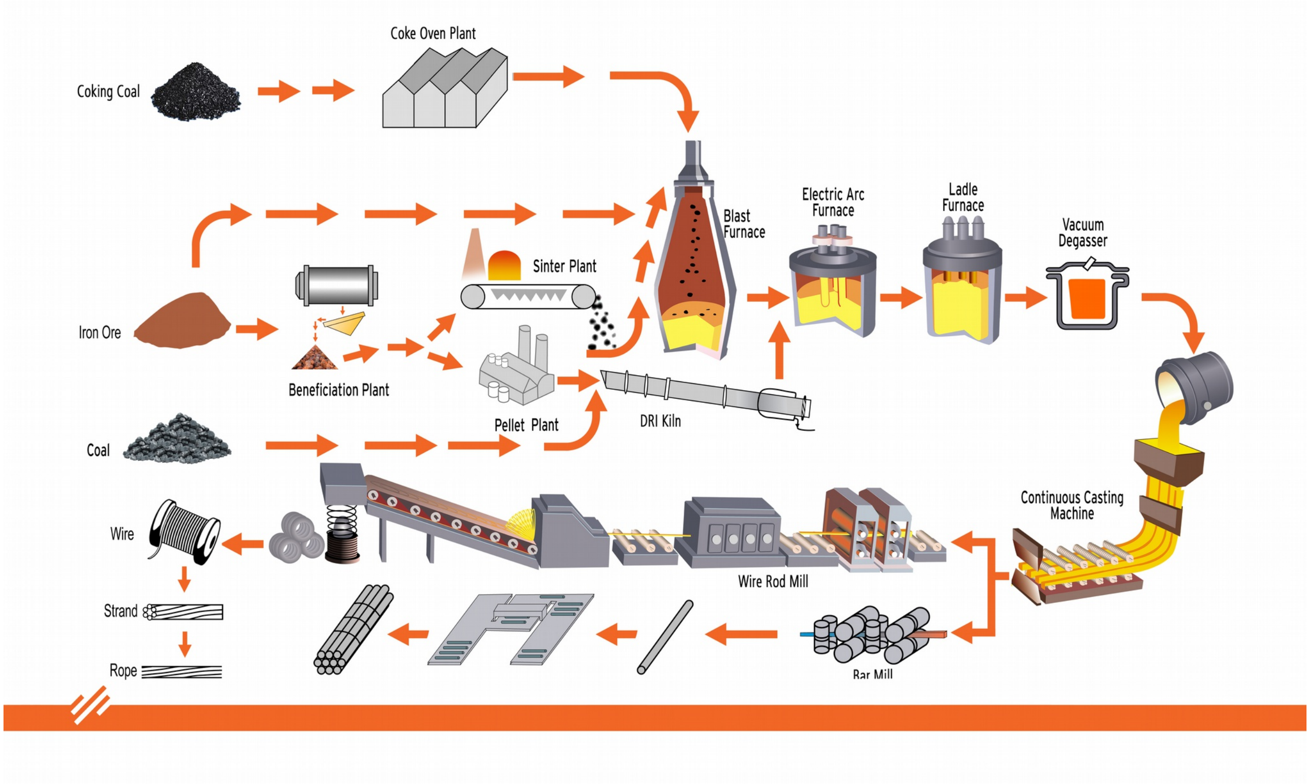

Figure 30: Overview of the traditional process to transform raw materials into wire rope.[55]

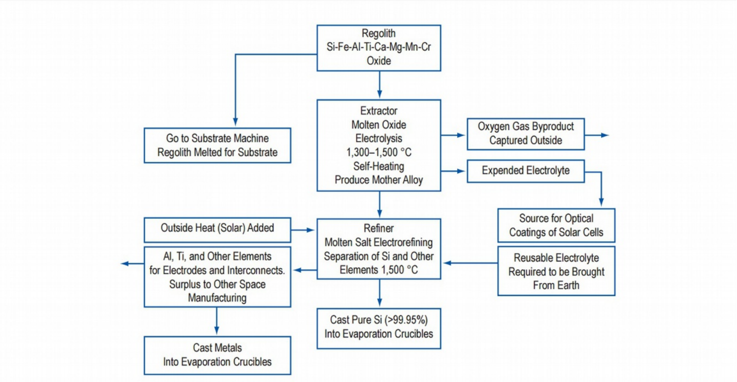

Figure 31: Overview of the NASA/MIT process to transform raw materials into metals.[56]