Conceptual Design of Self-Sustainable Inflatable Martian Habitat

ECLSS-IH Team, SSERD

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Abstract

A trip to Mars is a costly undertaking. But it is as exciting and as it is rewarding in the field of space exploration. With space agencies working towards colonizing Mars, it is clear that there is a need for long-term human sustenance due to the fact that frequent resupply missions to Mars are next to impossible. This is definitely not a reliable option. So this project deals with a Technology Demonstration Mission for a self-sustainable Martian habitat. It deals with Inflatable Habitat Technology and Life Support Systems required for the mission. The concept of an "Inflatable Habitat" is becoming an active and demanding area of research, as far as human space missions are considered. So this project is a conceptual design of such a mission, and is designed in par with SpaceX's Mars Mission. This also deals with all the necessary factors including detailed study of materials required, structural design and analysis and design of the Environment Control and Life Support System or ECLSS required. The ECLSS is what provides an Earth-like environment inside the habitat, making it suitable for the humans to live. The main aim of this mission is to achieve self-sustainability. Therefore, it would also serve a test-bed to test the possibility of growing plants inside the habitat to provide food for the astronauts. This project also caters to the power requirements and In-Situ Resource Management. This way, it is possible to achieve self-sustenance. With this, there is a strong hope that this project will open doors for future manned missions to Mars, eventually making Mars an established colony.

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1. Introduction

Space exploration has shown significant growth over the years. In the era of space exploration, a manned mission to Mars has far reaching implications both technologically, and for the growth of our country. Unlike missions to the ISS or the moon, a mission to mars is definitely a more challenging one especially since there is very little known about the planet.

All these days, we have continuously witnessed various unmanned missions to Mars to gather data of the environmental conditions on the planet, its topography, the composition of its surface and most importantly the possibility of the presence of water on the planet. Such unmanned missions include rovers like Curiosity, Spirit and Opportunity and the recently launched Perseverance Rover and Ingenuity Helicopter, and orbiters like Mars Orbiter Mission launched by ISRO, Maven Orbiter, Mars Reconnaissance Orbiter, Mars Odyssey Orbiter among many more. These missions have gathered valuable data for us while also paving the way for future missions.

If humans are to colonise Mars one day, an important step would be to solve the existing challenges. The technologies that would be developed on Earth need to be tested in actual Martian conditions, after testing them on Earth by simulating those conditions. For this, Technology Demonstration Missions would need to be carried out and habitats with self sustainable technology should be designed. Another important aspect of the mission would be to test the feasibility of growing selected crops in the habitat to meet the dietary requirements of the crew and public, once colonisation is successful. The inflatable habitat that we have designed takes into account all these requirements.

2. Objective

Developing the Conceptual Design of an Inflatable Martian Habitat as part of a Technology Demonstration Mission for a crew of four astronauts (for four months), taking into account its Structural Analysis and Material Requirements. The design also includes the development of self-sustainable In-Situ Resource Utilisation Systems, and the required Environment Control and Life Support Systems or ECLSS and Power Systems.

3. Habitat Location

Apart from the Voluminous volcanism revealed on early in Valles Marineris, Landslides, origin and evolution of the layered deposits, evidence for precipitation on Mars from dendritic valleys in the Valles Marineris area, mobility of large rock avalanches and some debates about the hydrated mineral stratigraphy of lus Chasma. Mars's Valles Marineris, is host to numerous preserved geologic features, modern atmospheric phenomena and potential subsurface aqueous activity favorable towards human habitation. Our Inflatable habitat proposal zone is centered atop the region due to its rich science and technology aspects and promising favorable environment conditions including high solar insolation and atmospheric pressure. As a future aspect, the key science interests in this region have always been search for biological signs and correlation with earth atmosphere for their survival. Valles Marineris stretches over 4,000 km across Mars in the east-west region below the equator and 7km deep, one of the largest canyons of the Solar System.

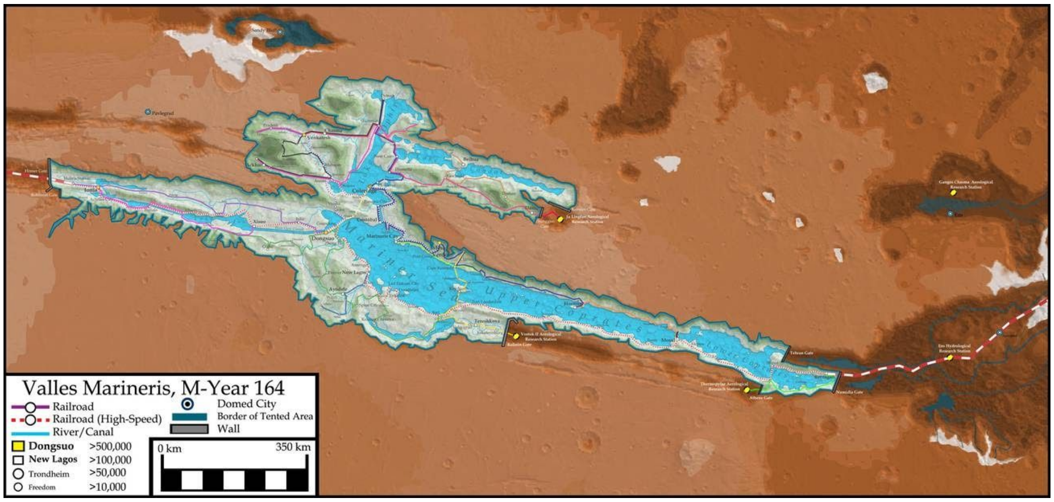


Figure 1: A topographic view of Valles Marineris

4. Design of the habitat

An Inflatable in general, is a structure that expands on being pressurized (typically like a balloon). This offers several advantages over a rigid-frame structure. The major advantage is that it offers high packing efficiency, thereby possessing less weight compared to a metal structure. So it can be deflated and packed in a small space in the rocket and carried, and later be inflated with air. This is also highly reliable due to payload constraints and also due to increasing research in the area of composite materials. NASA (along with Bigelow Aerospace) is already working on this technology, keeping in mind the requirements of the upcoming Moon and Mars missions. This would serve as the habitat for the Martian astronauts.

4.1 Design Requirements:

4.1.1 Mechanical Properties

Unlike on Earth, the habitat would be directly exposed to the harsh Martian environment and therefore must possess very good mechanical properties. To give an insight to the atmospheric conditions, the major factor to be considered is the temperature. The average surface temperature on Mars is -63degC, and it reaches a maximum of 20degC. So there is a vast temperature gradient. The next parameter to be considered is the dusty Martian storms, which reach speeds up to 30m/s. This poses a risk to the overall stability of the structure. In addition to these, Mars is highly prone to radiation and micrometeoroids. Therefore, all these have to be kept in mind while designing the habitat. To encounter these problems, the materials used should possess high impact tolerance, tensile strength, puncture resistance, creep life, temperature resistance, radiation-resistance and flex-resistance. This would require high space-grade materials that satisfy all these requirements, in addition to being light weight and cost-effective. Therefore, a detailed study on suitable materials is essential, which is provided subsequently.

4.1.2 Aerodynamic and Structural Stability

The structure as a whole should be able to withstand Martian storms. This demands it to be stable even during the worst dust storms. So the stability of the structure should be considered. This could be facilitated by avoiding tall vertical structures and instead going with horizontal and symmetrical structures.

4.1.3 Simulated Environment

The habitat should be able to house the astronauts in an Earth-like environment by providing the necessary pressure and temperature conditions and all other necessary ECLSS to ensure sustenance. The internal pressure would exert very high stresses on the inner walls of the structure due to the fact that the Martian atmosphere is extremely thin (about 1% dense as that of Earth). So the habitat should be designed in such a way that it withstands the stresses as well as supports human sustenance.

4.1.4 Volume

The structure should also be volumetrically efficient, thereby ensuring that sufficient usable volume is available for the astronauts to carry out all their activities. This also includes precise dimensions of the habitat, structural analysis, shielding requirements, mode of deployment and basic conceptual designs.

4.2 Structural Design and Analysis:

Keeping in mind all the aforementioned requirements, in order for the habitat to be habitable for the crew, and for it to provide enough space for all activities, a semi-hemispherical dome and four semi-cylindrical detachable modules have been conceptualised and designed. The dome is situated centrally and surrounded by the modules through isolatable airlock entries. Figure 1 shows a three-dimensional representation of the inflatable martian habitat after being deployed. It shows a central semi-rigid hemispherical wall with an inflatable half dome on top. The base of the central dome is made out of thermally insulated materials to ensure that the habitat has a safe and livable atmosphere at all times. The four modules are attached to the central dome through airlock entrances. In case of damage to any module, it can first be isolated from the rest of the habitat by sealing the airlock entrances, then deflated in order for the crew to carry out a repair operation. The cylindrical walls of the modules are inflatable and made of layered materials and their base is made out of a semi-rigid thermally insulated material to insulate the living space inside from the adverse temperatures of the martian surface. The airlocks are also made of rigid materials.

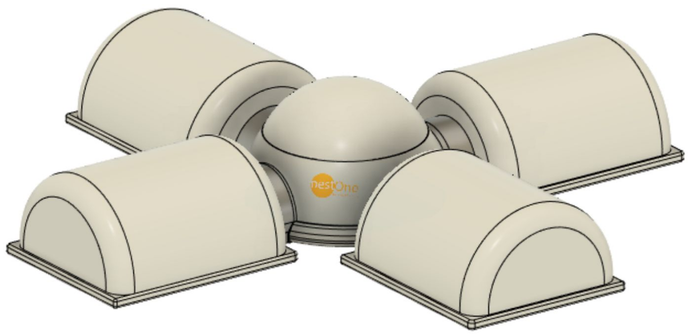
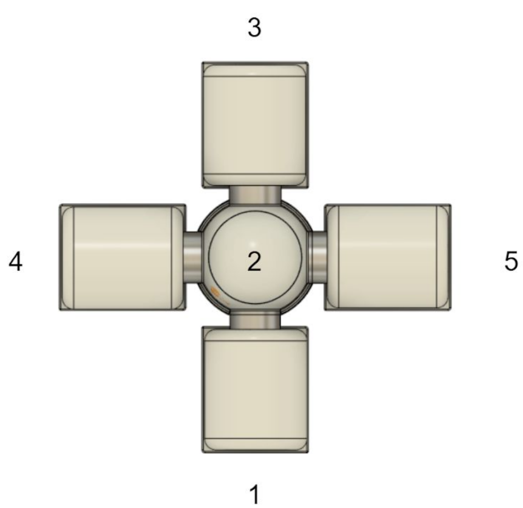


Figure 2: 3D representation of the inflated habitat

Figure 2. shows the functional organisation of the conceptual design of the Martian habitat. The central dome will serve as the Control Centre for the entire habitat. The modules attached to it will serve different purposes. The main entry bay will have an airlock system and will also act as the storage for spacesuits and other equipment. This structure is aerodynamically and structurally stable, making it reliable and convenient for the astronauts to use. This novel design will be very stable during the Martian storms too. All the modules are interconnected, ensuring efficient functioning of the entire habitat and easy monitoring from the control center.



1. Main entry bay with airlock system, storage unit
2. Command Centre
3. Crew Quarters: Kitchen, toilets, gym and recreation
4. Greenhouse
5. Scientific and experimental module

Figure 3: Diagram representing functional organisation

4.3 Internal Atmosphere of the Habitat

As the name suggests, internal pressure and temperature requirements have to be taken into account. This highly determines the overall functioning of the habitat. The standard sea-level atmospheric pressure on Earth is 101kPa. We can assume the same pressure to be maintained inside the habitat, but it poses a lot of challenges. The Martian atmosphere is very thin. The atmospheric pressure is around 0.6kPa (less than 1% of Earth's). This would induce very high tensile stress on the walls of the structure as there is no resistance offered by the external Martian atmosphere. Thus, the structure has to be designed in such a way that it is able to withstand the stresses due to internal pressure, as well as support human life. So, an average of 70-80kPa can be maintained inside the habitat. The International Space Station has the same pressure, and is similar to that of a standard Boeing Aircraft's cabin pressure. The habitat should thus have depressurization and pressurization systems to control the habitat's environment. This way, the safety of both the structure and human life is taken care of. Temperature is also another important factor. The average temperature on Mars is -63degC. So the internal temperature should also be chosen appropriately. Internal temperature of 20-30degC would suit the needs of the humans. Again, the average temperature inside the ISS is 24degC. And this will be taken care of by the temperature control and regulation systems, pertaining to the needs of the astronauts.

The inflation of the structure will take place after landing on the Martian surface. It can be done using air (mixture of O2, N2 and H2) which can be extracted from the atmosphere of Mars.

4.4 Dimensions and Volumetric Analysis:

The next logical step would be to find precise dimensions of the structure, as per the requirements. Taking inputs from the available references such as the International Space Station, Space Shuttle and Bigelow Aerospace's inflatable modules, and considering the volumetric requirements, the dimensions have been arrived at.

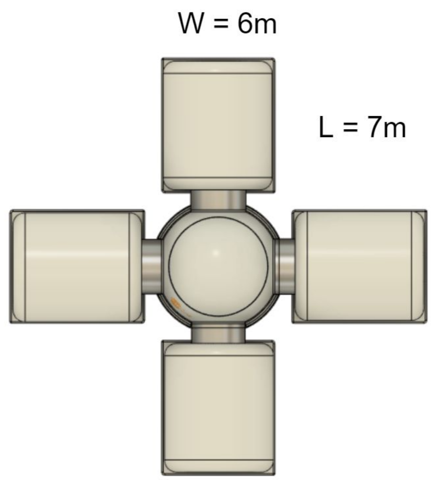


Figure 4: Top view of the habitat

4.4.1 Dimensions

For hemispherical dome,

Diameter = 6m, Height (radius) = 3m.

For semi-cylindrical module(s),

Diameter = 6m, Length = 7m, Height (radius) = 3m.

4.4.2 Volume Calculations

From the given values,

Volume of hemispherical dome,

$$(2/3)\ \Pi r^3 = 56.55 m^3.$$

Volume of semi-cylindrical modules,

$$4*[\Pi(r^2)h]/2 = 395.84 m^3.$$

Total volume = 452.39m^3.

The dimensions have been decided while catering to the needs of a crew of four extendable upto 6. The volumetric requirements are also based on the various sections like living quarters which consist of kitchen, toilet, gym and medical bay, greenhouse and scientific laboratory.

4.4.3 Stress Calculations

All the individual modules are essentially pressure vessels. So the internal pressure exerts tensile stresses on the inner walls of the structure. There are basically two types of stresses that would be induced - Longitudinal stress and Hoops (or circumferential stress). The design should be in such a way that the structure withstands these stresses, thereby ensuring safety. This will be discussed in detail in the Materials' section.

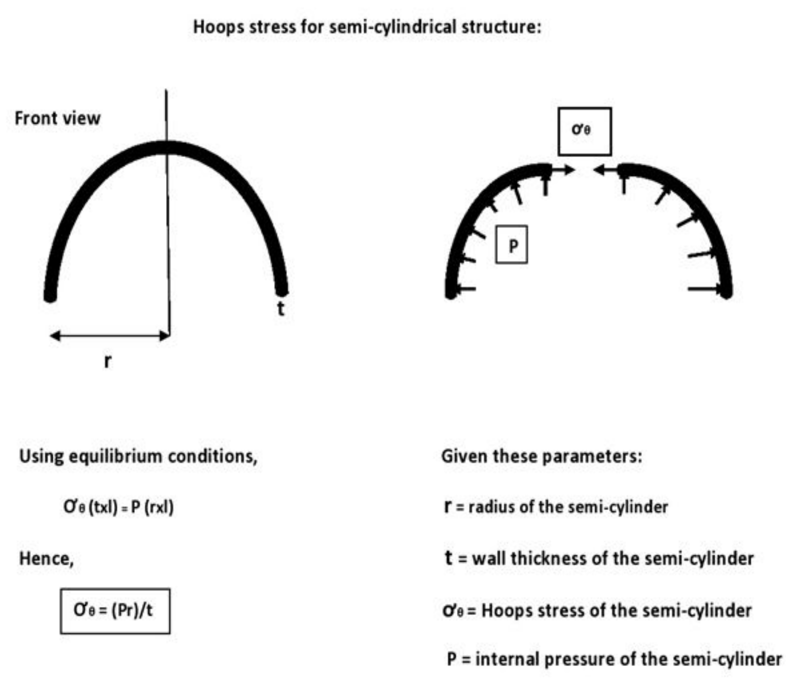


Figure 5: Hoops stress for semi cylindrical structure

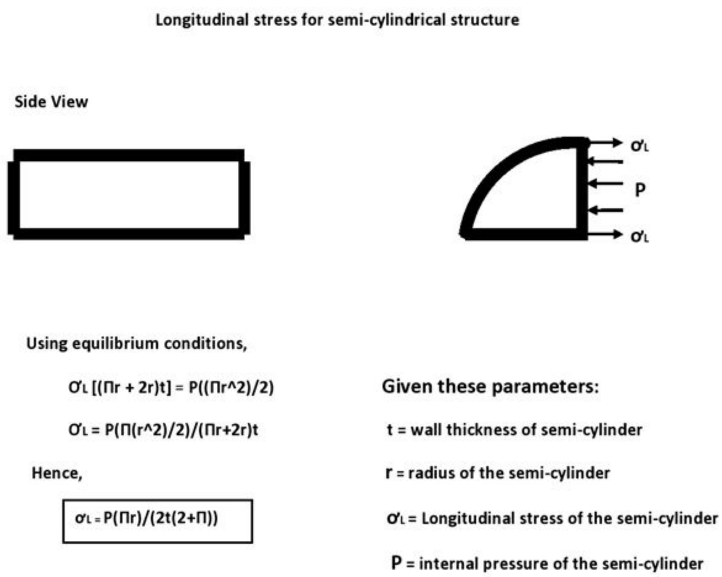


Figure 6: Longitudinal stress for half-cylinder

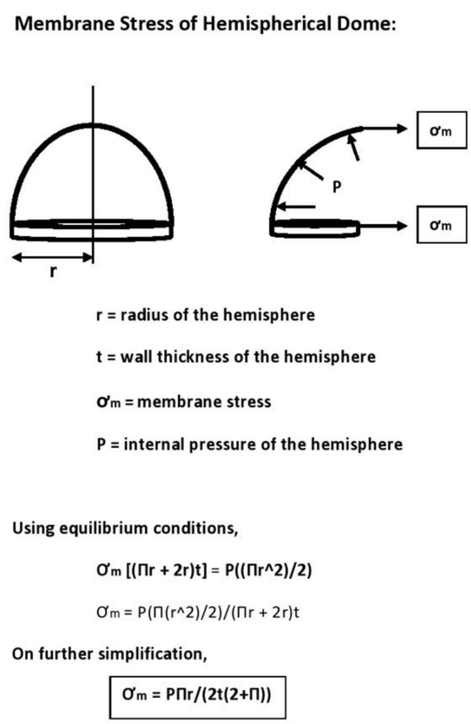


Figure 7: Membrane stress for hemisphere

Now to calculate the stresses, the value of wall thickness (t) should be known. So the thickness is taken to be 0.5m. This is in accordance with the references taken into consideration. One major reference is Bigelow Aerospace's B330 module, which is an inflatable space station under development. They are also working on building a Martian habitat, under similar design requirements. This value of thickness is therefore suitable for our project too. And since this structure is a thin-walled pressure vessel, this value is justifiable.

Assumed values: P = 80kPa, t = 0.5m, r = 3m.

Hoops stress for the semi-cylindrical structure,

$$\sigma_\theta = (Pr)/t = 480kPa.$$

Longitudinal stress for the semi-cylindrical structure,

$$\sigma_L = (P\Pi r)/(2t(2+\Pi)) = 146.63kPa.$$

Membrane stress for the hemispherical dome,

$$\sigma_m = (P\Pi r)/(2t(2+\Pi)) = 146.63kPa.$$

5. Materials

The Inflatable Habitat deals with Structures as well as Materials. The success of this entire mission relies heavily upon the grade of the materials used. These materials must be able to withstand the environment of Mars. As discussed earlier, such materials must exhibit very good mechanical properties. And for this mission, six candidate materials have been shortlisted (for any space mission in general) – Kevlar, Vectran, Dacron, Zylon, Technora and Spectra. All these materials exhibit very good properties. But –

Kevlar and Vectran prove to be the most promising ones. To understand this, one must know the shielding requirements for the habitat.

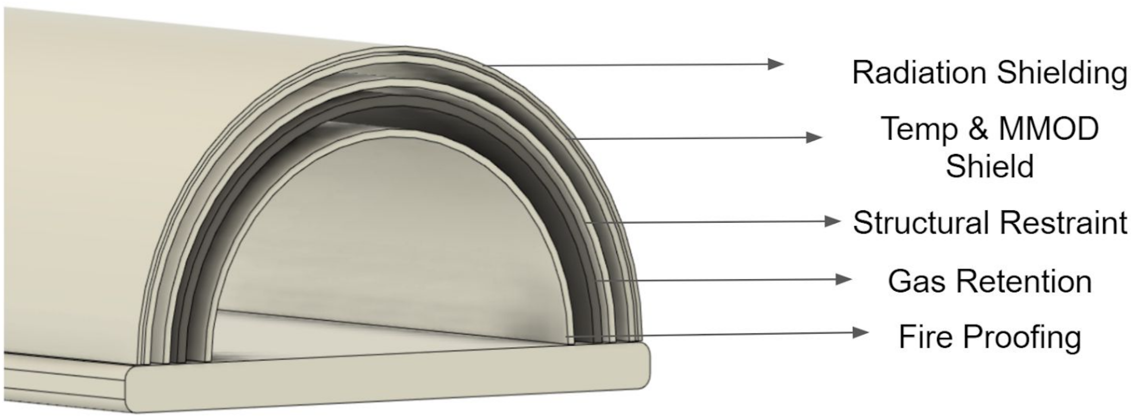


Figure 8: Cross-section of the habitat showing the different layers of shielding.

Out of these, Vectran is the most suitable material because of its unique combination of all required mechanical properties of the material. One major advantage of using Vectran is that its tensile strength is very high and it increases with decreasing temperature. Since the Martian temperature is very low (minus 63degC on an average), this material would be the best choice. It also has high creep resistance, impact tolerance, radiation resistance, flex/crack/abrasion resistance. It is used for ballistic applications like bullet-proof vests because it is capable of withstanding impacts created by particles of 2cm hitting it at 10km/sec, making it preferable for Micrometeoroid Shielding too. The strength of the structure can be enhanced by using a combination of Kevlar and Vectran to shield the habitat, with Kevlar being used for the structural restraint layer. This will act as a reinforcement for the structure, thus providing better resistance to internal pressure, higher puncture resistance and also facilitating gas retention.

The innermost layer will be made up of Vectran, that is fire-proof and directly takes the stresses. It has high flexibility, tensile strength and puncture resistance, making it highly preferable. So the inflation will be smooth. Next is a layer made of Kevlar. Now in between these Kevlar and Vectran layers, air is filled. This acts as an insulation to ensure that there is no heat exchange across the layers. This Kevlar layer also acts as a structural restraint, which enhances the overall strength of the structure. It also distributes the stresses equally and facilitates uniform inflation. The next is the outer layer again made up of Vectran. This layer is thick and is directly exposed to the Martian environment. This acts as the layer that provides shielding from radiation, temperature and micrometeoroids. Thus, this structure would be highly safe and stable for the operation of the habitat. In addition to the synthetic shielding layers, a layer of Martian regolith can also be used to provide enhanced shielding from radiation and micrometeoroids damage. This ensures longer operational life of the habitat.

6. Stowed Configuration for Vehicle Payload

An inflatable habitat designed for interplanetary missions needs to be carried from earth to that planet in a rocket in a very compact structure. The inflatable habitat is designed for SpaceX's Starship Super Heavy Lift Vehicle, which has fairing dimensions of 9m diameter and 15m height. The stowed payload is the compacted and deflated form of the habitat that fits in the vehicle fairing. Figure.7 shows the three-dimensional model of the stowed configuration of the inflatable habitat.

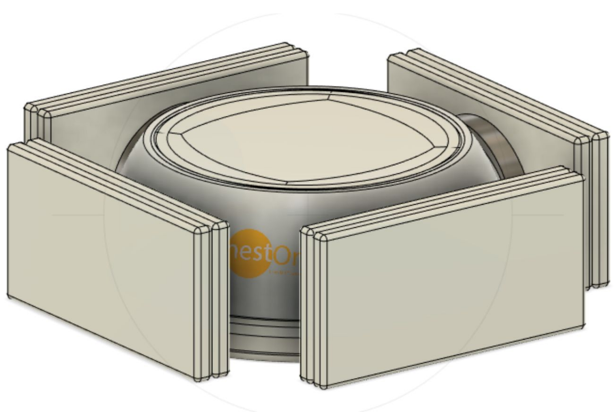
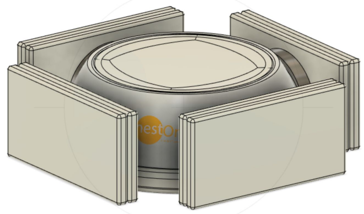


Figure 9: 3D representation of the stowed configuration

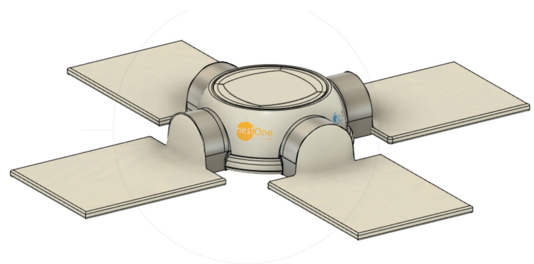
The stowed configuration has a central dome in two parts. The lower wall of the dome is a semi-rigid structure and the upper part, which is inflatable and made out of flexible materials along with layers for shielding. The solid airlocks are retracted to save space in the payload. The semi-rigid base of the uninflated semi-cylindrical modules is folded into half and attached through the inflatable material to the retracted airlock entrances. The payload also consists of cargo inside the semi-rigid dome that consists of essential ECLSS subsystems to prepare the deployed habitat autonomously in the pre-crew phase, gas cylinders, fuel cells to power the habitat, essential lighting, etc.

7. Deployment

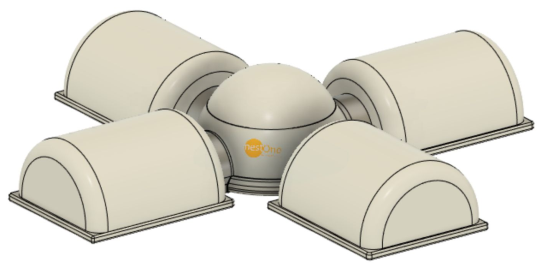
Once the stowed configuration of the habitat has landed on the surface of Mars, it needs to deploy, inflate, and prepare the cabin atmosphere and other necessities into a functional habitat for crew arrival. The deployment of an inflatable habitat is comparatively less complex than a mechanised system. During the deployment phase, the first step is the extension of the retracted airlock frame. Then, the semi-rigid base of each of the side modules extends outwards till it becomes horizontal on the surface of Mars. Once the base of the modules has been set in place, the airflow pumps are activated and the walls of the semi-cylindrical modules, and the upper half of the dome are inflated. The primary airlock entrance is deployed in the entrance module, and the system powers up the ECLSS subsystems to prepare the cabin atmosphere, the In-Situ Resource Processing system (ISRPS), and the Water Reclamation System (WRS).



(a)



(b)



(c)

Figure 10: Deployment stages (a) Stowed configuration (b) Half deployment with module bases extended (c) Fully deployed habitat

8. Power Source

In order to power the Martian habitat, many sources of power have been identified and theorized by scientists and NASA, SpaceX and other space research organizations and institutes. Some of the sources of power that have been used to power rovers in previous NASA space missions include:

8.1 Solar Energy

Solar panels have an area of approximately 10 square meters (107.6 square feet) and contain 3,744 individual solar cells. The solar cells are able to convert more than 26% of the Sun's energy directly into electricity so that the power they produce is 32 volts, the voltage that most devices on the spacecraft need to operate properly. At Mars, the two panels together produce 1,000 watts of power.

8.2 Nickel Hydrogen Batteries

Nickel-hydrogen rechargeable batteries can be used to power the habitat's power systems, each with an energy storage capacity of 50 ampere-hours -- at 32 volts that's 1,600 watts for one hour. However, to ensure there is no power failure, only a maximum of 40% of the battery can be utilized at a time.

8.3 Fuel Cells

Fuel cells are one of the most sought after inventions because it converts chemical energy from hydrocarbon fuels directly into water and electricity causing little to no pollution. The water produced from fuel cells can also directly be sent to the Water Reclamation System, which after purification can be utilized by the astronauts in the habitat itself.

This report will take into account Solar Cells and Nickel-Hydrogen Batteries as power sources as well as fuel cells which have been explained.

9. In-Situ Resource Utilisation

In-Situ Resource Utilization (ISRU) is a means of harvesting essential commodities like power, food, oxygen and other necessary gases to support long-term human and robotic exploration efforts on Mars. The Martian atmosphere contains many useful resources that can be utilized for exploration efforts, including carbon dioxide that can be used to produce oxygen, methane, and water.

The Martian atmosphere consists of about 95.5% CO2, 2.7% N2, 1.6% Ar, 0.13% O2 and 0.07% of other gases. CO2 from the atmosphere can be extracted using various techniques such as CO2 freezing, use of membranes, acid-base chemistry, chromatography and molecular sieves. After extraction, CO_2 has to be refined from trace chemicals and can be used as a valuable resource in the following manner:

1. Reforming CO_2 and trace amount of CH_4 to produce fuel gas using Fischer Tropsch process so as to power the habitat and the ECLSS..
2. Using CO_2, on biohybrids with the presence of water and sunlight to create organic molecules and oxygen.
3. Control the O_2 level in the greenhouse module by addition of CO_2.
4. Utilize Martian CO_2 to produce O_2 that can be utilized in the atmospheric control system for Astronauts.

N_2 and Ar present in the Martian atmosphere can also be collected so as to be used for buffer purposes. The scope of this report deals only with the utilization of CO_2 for the production of lower hydrocarbon fuels such as methane, ethane and methanol as well as the utilization of these fuels in a fuel cell that can be used to power the ECLSS subsystems.

9.1 Fuel production from a Martian atmosphere

Synthetic fuel can be produced by the Electro-Chemical Reduction (ECR) of CO_2, which can be a viable way of powering the ECLSS system. The flow of the system will be as follows: CO_2 captured from the atmosphere will be reduced electrolytically to CO. The electricity will be obtained from solar cells which store energy using the solar concentrators located on top of the habitat. The reduced CO will be separated from the unreacted CO_2. The unreacted CO_2 can be recycled while the separated CO will continue to the Fischer Tropsch or FT. In the FT, H_2 released from the hydrolysis of water to produce O_2 can be used to be combined with CO and produce synthetic fuel gas.

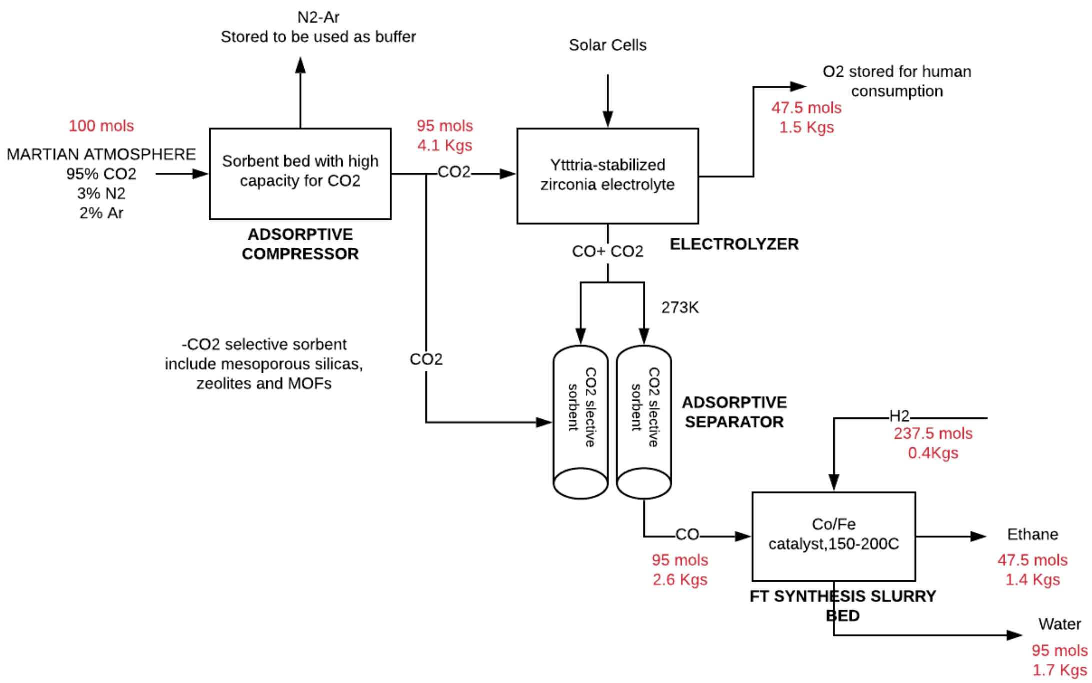


Figure 11: Ethane fuel from CO_2 block diagram

9.1.1 Adsorptive Compressor

In the above process, we are separating CO_2 from the remaining gases by the use of an adsorptive compressor having a sorbent bed with a high affinity for CO_2. Usually, CO2 selective sorbents include mesoporous silicas, zeolites and metal oxide frameworks(MOFs). The sorbent bed absorbs CO_2, and vents out N_2 and Ar which can be stored and used as a buffer. CO_2 is absorbed till maximum capacity after which it is heated to raise the internal pressure of the compressor to 1 bar. Carbon dioxide gets desorbed and is vented out to the electrolyzer. Meanwhile, the compressor cools down until reaching environmental pressure.

Suggested sorbent: Lewatit VP OC 1065 (Ion Exchange Resin)

9.1.2 Solid Oxide Electrolyzer

The vented CO_2 enters the electrolyzer, where it undergoes electrocatalysis and/or thermal dissociation produces O_2 at the anode. The CO formed at the cathode, as well as unreacted CO_2 are sent to a separation chamber. The electrolyzer requires DC voltage which can be obtained from solar powered batteries. The electrolyte used is a Yttria-Stabilized Zirconia (YSZ) electrolyte. Water from frozen Martian water is sent to an electrolyzer. Oxygen produced at the anode is sent to AMS for human consumption.

Overall Reaction,

$$CO_2 \rightarrow O_2 + CO$$

Suitable Temperature Range,

700-900 degC

Voltage Required: At 25 °C, ΔG_f is 257 kJ mol^{-1}, which corresponds to a reversible voltage of 1.33 V. At 800 °C, ΔG_f is only 189 kJ mol^{-1} or 0.97 V

9.1.3 Adsorptive Separation

The CO and CO_2 mixture passes through a sorbent bed containing CO_2 selective material. The feed enters the sorbent bed at 273 K, and CO passes through the bed while the CO_2 gets absorbed until full capacity. At this point, the CO_2 is desorbed from the bed by heating it to 373 K and recycling the CO_2 into the electrolyzer. The bed is then cooled back to 273 K and the flow is started again. CO is sent to a FT synthesis slurry bed.

9.1.4 FT synthesis slurry bed

The CO and H2 enter the Fischer Tropsch synthesis slurry bed. The Fischer-Tropsch process is a catalytic chemical reaction in which carbon monoxide (CO) and hydrogen (H2) in the syngas are converted into hydrocarbons of various molecular weights according to the following equation:

$$(2n+1)H_2 + nCO \rightarrow C_nH_{(2n+2)} + nH_2O \qquad \Delta H= -165KJ/mol$$

Fe or Co metal catalysts are suitable for FT synthesis. Fe is a better catalyst at higher temperatures and reduces methane formation. Co is a good alternative to Fe, but operates at lower temperatures and promotes methane formation. It has a longer lifetime. The reaction takes place at 200 – 300 °C and 10 bars.

Other general reactions are,

$$2H_2+CO\rightarrow(CH_2)+H_2O$$

$$(2n)H_2+nCO\rightarrow C_nH_{2n}+nH_2O$$

Since the reaction is exothermic, a cooling system is required to maintain the temperatures at a required heat range.

Catalyst suggested: Fe-K/ZSM-5

10. Life Support System

The Environmental Control and Life Support System or ECLSS is hardware technology based on principles of regeneration from waste matter, to support and sustain a healthy lifestyle for the crew in the habitat. The primary role of the ECLSS is atmospheric control, waste management and water regeneration. The ECLSS also plays an important role in linking the output of the ISRPS with the appropriate subsystem.

10.1 Waste Management System (WMS)

The whole waste from the habitat can be broadly divided into two classes namely recyclable and non-recyclable. Storage buffers are required throughout the ECLSS to accommodate nominal variations in production and consumption and to accommodate and recover from contingency conditions (e.g. unplanned repair activities).

The human metabolic waste and food waste can be classified into recyclable waste. The medical and the other waste (which includes the waste from plants etc.) can be classified into non-recyclable waste as shown in the hierarchy chart (figure1).

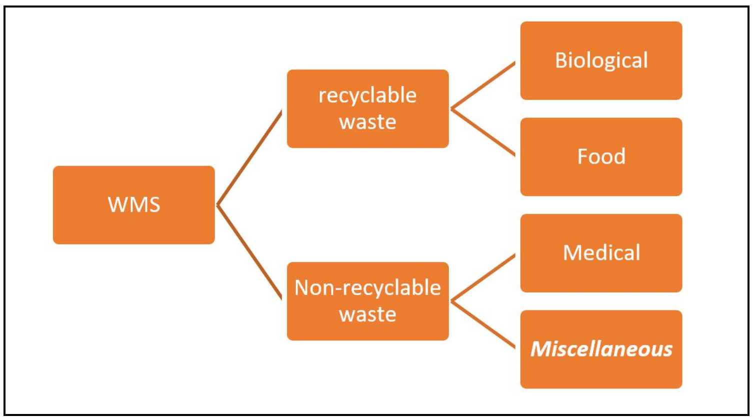


Figure 12: Hierarchy chart of WMS

The representative life support inputs and outputs for a typical human being are shown in figure 2. The WMS has to be designed based on the values.

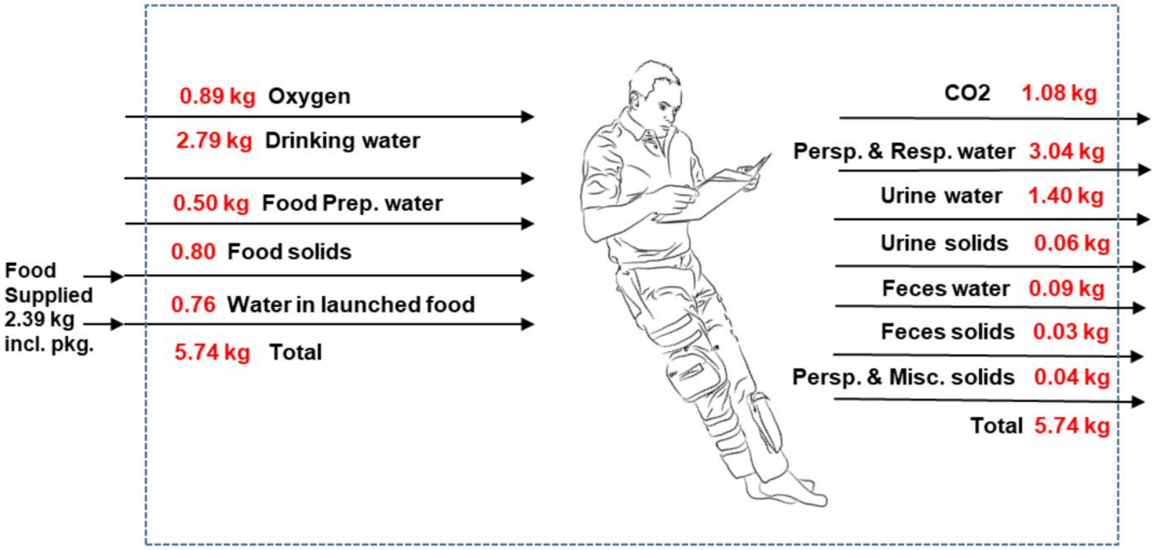


Figure 13: Output waste quantities of a person per day

10.1.1 Human metabolic waste-collection and storage.

The human metabolic waste consists of solid and liquid waste, the two waste are collected separately in the toilets and stored in the aluminum storage containers which can accommodate 0.13kg/per human being/per day of solid waste and 4.53kg/per human being/per day liquid waste.

10.1.2 Food waste- collection and storage.

The food waste consists of two classes of waste one of them are containers (non-recyclable) and the other being leftover food. The two classes of waste are to be collected in separate aluminum containers and stored.

10.1.3 Non-recyclable waste management system.

The non- recyclable waste should not contaminate the Martian surface so it has to be sealed in the air tight container and buried into the Martian soil with disinfecting systems.

10.1.4 Medical waste collection and storage

All the medical waste is to be collected in an aluminum container.

10.1.5 Miscellaneous waste

This contains the waste of plant waste, human grooming waste, e-waste. These are to be collected into aluminum containers.

10.2 Water Reclamation System

The Water Reclamation System (WRS) mainly focuses on the objective on recycling used water in habitat. The WRS consists of various treatment processes for generating treated pure water, and potable water. The Potable water is used by the crew for hydration and cooking. It also consists of storage tanks and sensor controlled valves to control the flow of pure water to other subsystems where it is required, and to the cabin. The system gets water from the ISRPS, cabin humidity, hydration system and moisture from Extra Vehicular Activity suits, and from transpiration of plants in the greenhouse module, and from the waste recycling.
The water which is recovered must meet stringent purity standards before it can be used in various ways.

10.2.1 Reusable Waste Processing Assembly (RWPA)

The Reusable waste processing assembly (RWPA), takes the inputs from biological payloads, plants waste and produces manure, methane, carbon dioxide and small amounts of water as the output.

The manure preparation requires the correct mixture of soil and the degradable biomass, the regulators attached to each collection and storage system extracts the predetermined ratio of biomass and sends it to the Reusable waste processing assembly (RWPA). The soil extracted from the Martian surface has to be screened and only fine powered sand is to be pumped into the pit. The processing pit undergoes the conversion process for 50 days and produces the manure and by-products. The manure is sent to the greenhouse and the methane and carbon dioxide is sent to the fuel generation system. The water generated from RWPA is sent to the water processor assembly (WPA) which can be processed and used for the biological payloads. The block diagram in figure 12 shows the processes involved in the RWPA.

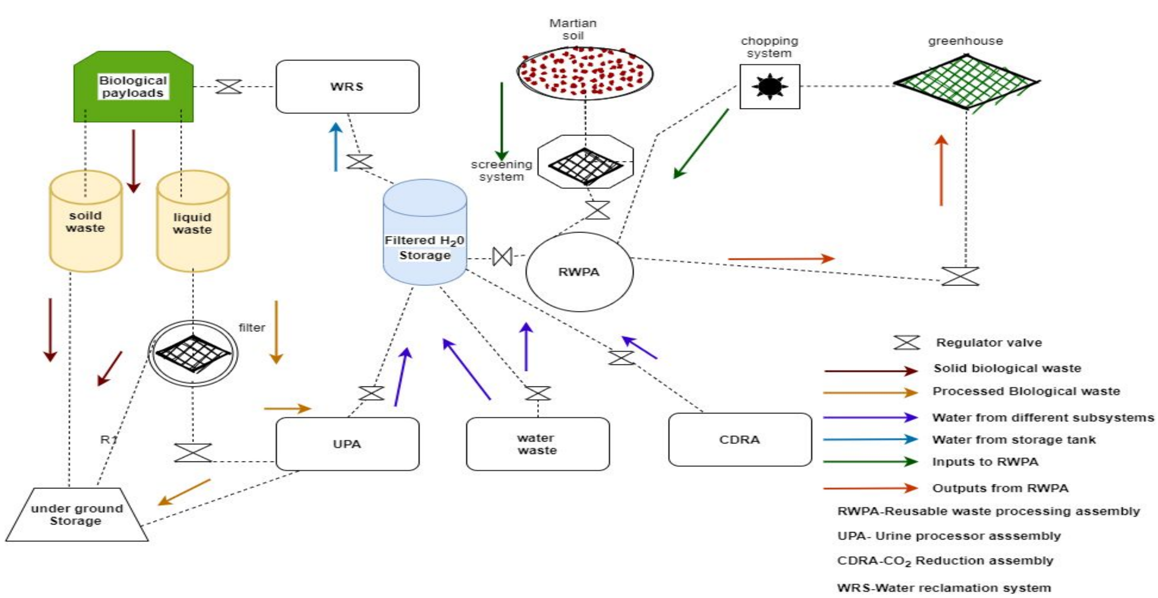


Figure 14: Block diagram of Waste Management System.

10.2.2 Urine Processor Assembly (UPA)

A simplified schematic of the Urine Processor Assembly (UPA) is shown in figure 13. Urine is delivered to the UPA from the liquid waste container of biological payloads as shown in figure 3. The urine is temporarily stored in the Waste water Storage Tank Assembly (WSTA) until it reaches a setpoint to begin processing. The Fluids Control and Pump Assembly (FCPA) is a four-tube peristaltic pump which moves urine into the Distillation Assembly (DA), concentrated waste from the DA into the Recycle Filter Tank Assembly (RFTA), and product water to the interface with the WRS. The DA is the heart of the UPA, and consists of a rotating centrifuge where water is evaporated from the waste urine stream at very low pressure. A rotary lobe compressor provides the driving force for the evaporation and compression of water vapor. Waste brine resulting from the distillation process is concentrated in the RFTA. The Pressure Control and Pump Assembly (PCPA) is another fourth tube peristaltic pump, which removes non-condensable gases and water vapor from the DA. These gases are pumped to the Separator Plumbing Assembly (SPA), which recovers and returns water from the purge gases to the product water stream. A Firmware Controller Assembly (FCA) provides the command control, excitation, monitoring, and data downlink for UPA sensors and effectors.

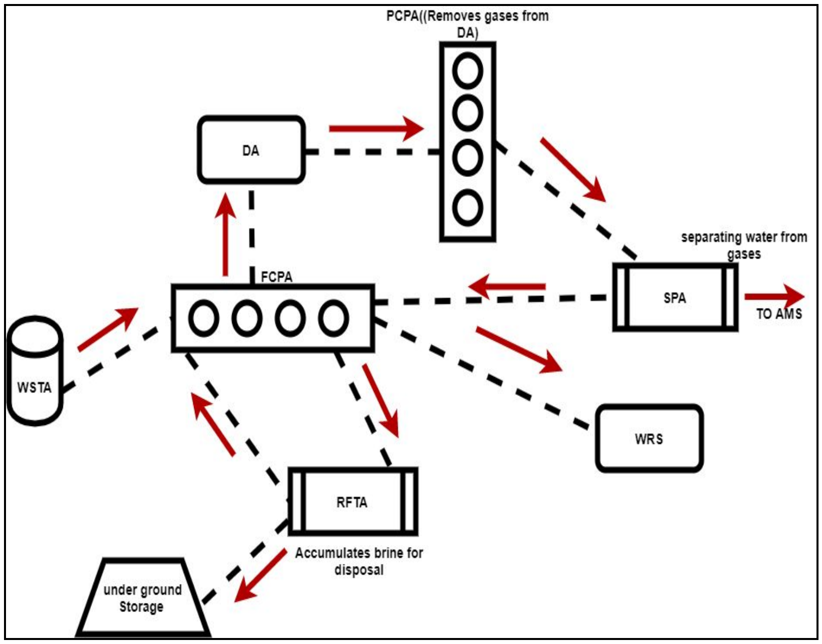


Figure 15: Block diagram representation of UPA

10.2.3 Distillation Assembly (DA)

The Distillation Assembly (DA) is the primary component in the UPA. The processes in DA are of two phases. The first phase of the process is done under vacuum and the second phase is done under microgravity. At a maximum load, the UPA[2] can process 13.6 kg (30 Ibs.) of wastewater over an 18-hour period per day. It operates in a Batch mode, consuming 424 W power when processing, and 108 W during standby. And recovers a minimum of 85% of the water content in the specified wastewater stream.

Urine is pumped into the DA from the FCPA. It enters the rotating evaporator through the feed tube (Figure 5). The urine is spread onto the evaporator wall in a thin film that travels the length of the evaporator until it is collected in the urine/brine trough and pumped out by the FCPA through the evaporator pickup tube. As it travels down the wall of the evaporator, water is evaporated from the urine. The steam that is generated is pumped through the centre of the hollow stationary shaft and compressed in the condenser by the compressor. Once the steam's pressure is raised, it begins to condense and give up its latent heat to the evaporator. This latent heat plus the waste heat generated from the compressor and motor are what provide the energy for the evaporation of water from the urine. The steam then condenses and, due to centrifugal force, collects on the outer wall of the condenser and travels to the product water trough. There it is pumped out of the condenser by the FCPA through the product water pickup tube. This entire process is done under vacuum. The vacuum is contained by the stationary bowl which surrounds the rotating still and compressor.

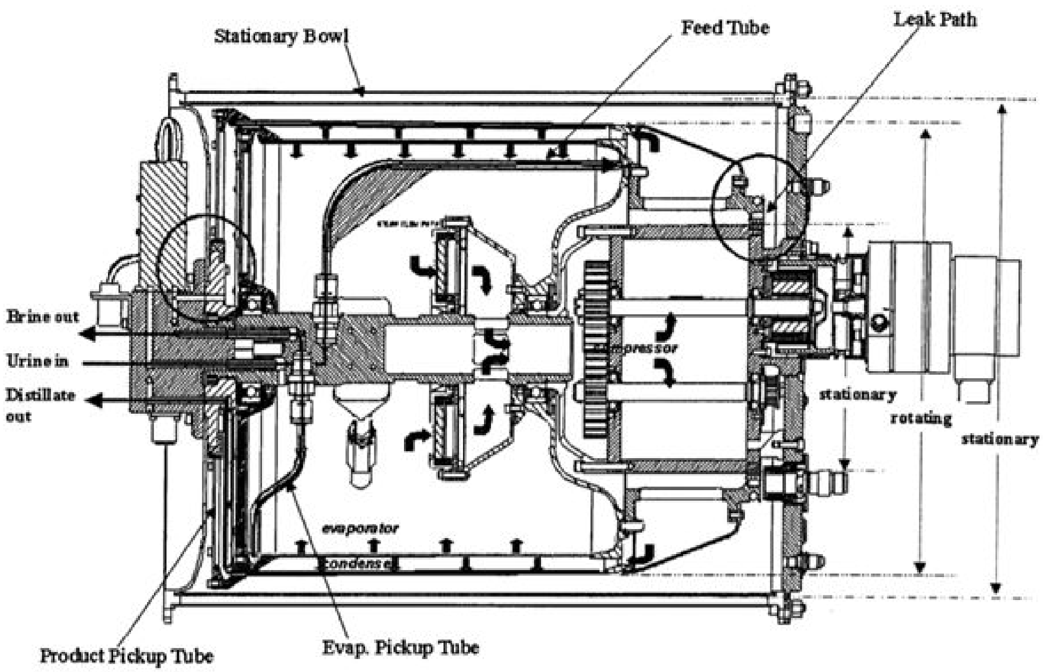


Figure 16: Cross-section of Distillation Assembly

The two-phase operation is controlled in microgravity by the centrifugal force of the rotating still. This allows the DA to control the location of liquid and steam in the DA so that the evaporation and condensation process can take place and the liquids can be pumped into and removed from the DA.

10.2.4 Pre-treatment of liquid waste in WSTA

There are two methods employed for pretreatment one followed by NASA and other by Roscosmos there are detailed in the table below. The table also contains Total organic Carbon (TOC) ,Total Inorganic Carbon(TIC), pH and Conductivity.

Parameter	**U.S Pre-treated Urine Distillate**	**Russian Pre-treated Urine Distillate**
Pre-treatment Chemicals	Oxone/sulfuric Acid/potassium benzoate	Chromium Trioxide/Sulfuric Acid
TOC	150 mg/liter	55 mg/liter
TIC	-	1.1 mg/liter
pH	3.2	3.15
Conductivity	137 umhos/cm	150 umhos/cm

Table 1: Water quality data, indicating that the Russian pre-treatment may actually improve water quality.

10.3 Atmospheric Management System (AMS)

The Atmospheric Management System or AMS mainly deals with the Carbon Dioxide control, Oxygen Production, Atmospheric Circulation, Atmosphere Particulate Control, Trace Contaminant Control, Fire Detection and Notification, Post-Fire Atmospheric Recovery, Atmosphere Temperature and Humidity Control. Maintaining the proper pressure is required for crew comfort and survivability as well as habitat structural limits. AMS shall revitalize and maintain a safe, breathable and comfortable atmosphere for the crew and equipment within the habitat. Maintaining proper O2, CO2, trace contaminant concentration, humidity and air circulation through the habitat ensures crew comfort. Ventilation is needed for thermal control and air circulation. Proper cabin atmosphere maintenance is also necessary for the proper functioning of other subsystems designed for that particular condition inside the habitat.

10.3.1 Atmosphere circulation

Variable speed fans circulate the habitat air to provide homogeneous air mixture, heat transport and movement of air through the various units that revitalize the air. Habitat fans are nominally controlled by the master computer and only switched off during contingency operations like fire to stop the spread of harmful chemicals till the system contains them.

10.3.2 Atmosphere Particulate Control

High-efficiency particulate absorbing filters (HEPA)[6] will be attached to the fans and air intake in the habitat. These filters can remove particles of 0.3 micrometer diameter and make air safe to breath.

10.3.3 Trace Contaminant Control

Trace Contaminant Control System (TCCS) removes most hazardous contaminants from the habitat using a carbon bed, but some must be destroyed in high temperature catalytic oxidizers. TCCS should be designed to maintain the level of trace contaminants in the atmosphere of habitat below the allowable concentration. Over 214 particles[18] have now been identified, including the the alcohols, aldehydes, aromatics, ethers, ester, halocarbons, fluorosilanes, hydrocarbon, kittens, silicones, sulphides, and inorganic compounds such as carbon monoxide. Majority of the contaminants are removed from the atmosphere by charcoal beds and others are removed by the water revitalization system. however, highly volatile low molecular weight compounds such as light hydrocarbons (Methane, acetylene, ethylene and ethane), carbon monoxide, light hydrocarbons (chloromethane, dichloromethane, and freon 22) and sulphur compounds like hydrogen sulphide have little affinity for activated carbon, and must be catalytically oxidised.

Cabin air enters the activated carbon bed at roughly 250 litres[18] per minute the activated carbon readily absorbs most contaminants including a variety of compounds that contain sulphur, nitrogen and halogens that would poison the catalyst in addition the carbon bed is impregnated with phosphoric acid to absorb ammonia before it reaches the oxidizer. A small portion (70 litre per minute) of the air leaving the activated charcoal bed is sent to a high temperature catalytic oxidizer. The air entering the oxidizer is heated to 400 degree Celsius by the regenerative heat exchanger and resistance heater. The catalyst oxidises the Organics to carbon dioxide and water and converts the inorganic compounds to acidic gases such as HCL, HF and SO2. The air leaving the catalyst bed is cooled in the regenerative heat exchanger and passed through a little hydroxide array, Bade that is removed in acid by products produced during the oxidation process. Thus TCC from the cabin air is removed with activated carbon and high temperature catalytic oxidation assembly[18].

10.3.4 Fire detection and notification

Fire detection consists of dedicated carbon monoxide sensors as well as particulate smoke detectors throughout the habitat that continuously monitor habitat air circulating through the habitat along with the additional carbon monoxide measurements provided by the atmosphere quality monitoring system. The habitat master computer is notified of any fire event. Portable fire extinguishers (PFE) will be used for fire suppression . The implementation would be similar to that of the CO2 portable Fire extinguisher currently employed on the ISS. The PFE would be designed to be refilled by crew. We will not depressurise the habitat in any fire event instead the habitat compartment will be automatically separated from habitat by air lock to reduce further damage of habitat.

10.3.5 Post-fire Atmosphere Recovery

Recovering the atmosphere after the fire event and making it suitable and breathable for crew will be done by a post fire atmospheric recovery system. The post fire atmosphere recovery provides for the removal of harmful post combustion products such as particulate, traces, organic compounds, carbon monoxide and carbon dioxide without the need of depressurization of the atmosphere and the pressurization with stored gas. The subsystem utilizes the existing HEPA filters to remove 99.97% of airborne particulates 0.3 microns or greater in particle diameter. A cartridge inserted in the ARS air stream by the crew following a fire event utilizes granulated media to remove organic compounds and converts CO to CO2. Generated CO2 is removed by CO2 removal assembly.

10.3.6 O2 Generation System

The Oxygen Generation System produces oxygen for the crew to breathe. The system consists of the oxygen generation assembly and the carbon dioxide reduction assembly. The oxygen generation assembly is composed of the cell stack, which electrolyzes water provided by the WRS, yielding oxygen and hydrogen as byproducts. The oxygen is delivered to the cabin atmosphere while the hydrogen is stored to be used by other subsystems. The assembly uses that hydrogen along with carbon dioxide exhaled by the crew in a Sabatier reactor. The byproducts of that process are methane and water for storage in the WRS.

Another backup system that makes oxygen through chemical reactions. The system is called the Solid fuel oxygen generator (SFOG) and is located in the station's service module (Zvezda). The SFOG, which is also called oxygen candles or chlorate candles, has canisters that contain a mixture of powdered sodium chlorate ($NaClO_3$) and iron (Fe) powder. When the SFOG is ignited, the iron "burns" at 1112 degrees F (600 degrees C), which supplies the heat energy required for the reaction. The sodium chlorate breaks down into sodium chloride (table salt- NaCl) and oxygen gas (O_2). Some of the oxygen combines with iron to form iron oxide (FeO) at 600°C

$$NaClO_3\ (s) + Fe\ (s) \rightarrow 3O_2\ (g) + NaCl\ (s) + FeO\ (s)$$

The SFOG supplies 6.5 man-hours of oxygen per kilogram of the mixture[3].

10.3.7 Atmospheric Humidity and Temperature Control

Warm humid habitat is circulated across a condensing heat exchanger to cool the air and condense the water vapour into liquid. The flow of active thermal control system (ATCS) supplied chilled coolant through a liquid gas heat exchanger is regulated by a bypass valve to affect the required air temperature control. The non-potable condensed water is collated and transferred to the WRS for further processing. The cool dry air is returned to the habitat atmosphere.

10.3.8 Carbon Dioxide Removal System

The block diagram depicts the Carbon Dioxide Removal Assembly(CDRA), the Oxygen Generation Assembly(OGA), and the Carbon Dioxide Reduction Assembly(CRA). The CDRA collects and concentrate carbon dioxide and feeds its to the CRA. The OGA electrolyzes the water for oxygen and feeds the byproduct hydrogen to the CRA. The CRA reacts hydrogen and carbon dioxide to form methane and water. The water is returned to the OGA, thus partially closing the oxygen loop. The CMS includes the mechanical compressor and accumulator. As of now, with existing improved technology, the previous 4 bed molecular sieve CDRA has been updated.

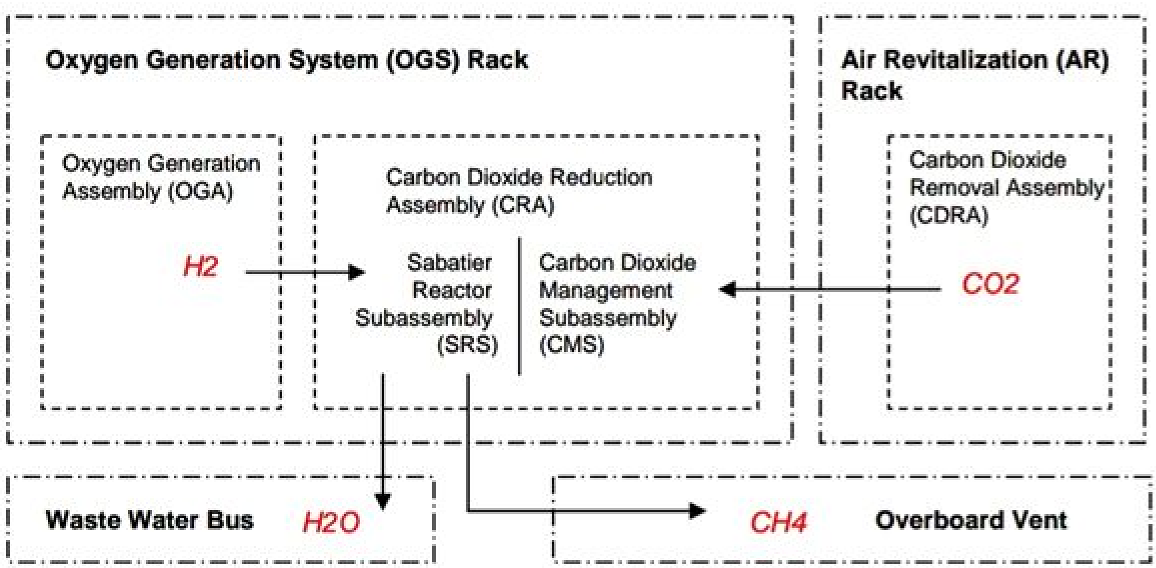


Figure 17: Block diagram representation of the AMS

10.3.9 4 – Bed Molecular Sieve (4BMS) Carbon Dioxide Removal Assembly (CDRA)

Four bed molecular sieve process consists of two desiccant beds and two carbon dioxide sorbent beds. Additionally, it includes blower, air-save pump, heat exchanger, values and sensors. Cabin air is monitored and drawn towards one of the desiccant beds to remove the moisture and then passes through the sorbent bed to remove carbon dioxide. Processed air is thereby sent through the second, heated desiccant bed to re-humidify the stream before returning the air back to the cabin. At the same time, the second sorbent bed, which is loaded with carbon dioxide, is heated and evacuated to desorb the carbon dioxide. The vacuum circuit runs from the desorbing bed check value to space vacuum (represented as yellow line).

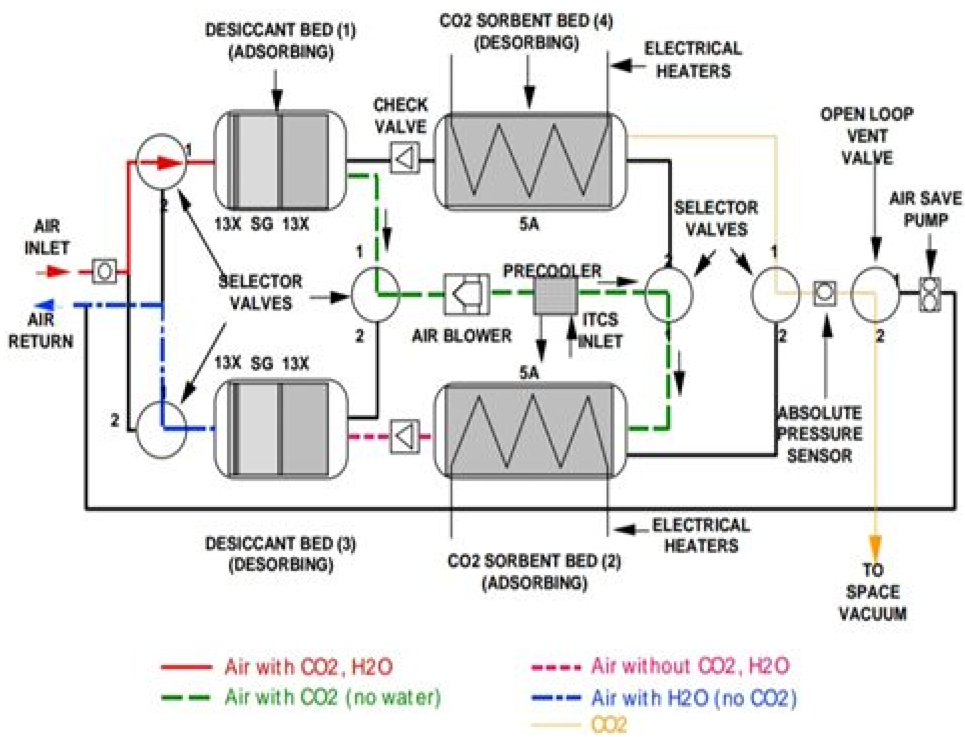


Figure 18: Block diagram representation of CDRA

In half the cycle, one bed is doing all the carbon dioxide removal functions. At the next half cycle, all beds switch to opposite mode and cabin air flow swings to the other set of adsorbent beds, the alternate bed then performs the carbon dioxide removal function. CDRA followed by compressor are used for compression of carbon dioxide for efficient storage and controlled delivery to the Sabatier. The compressor is designed out for oil free so that no oil contamination is introduced to the Sabatier reactor. Accumulators are used for buffering capacity to integrate 4BMS and Sabatier when using a mechanical compressor. Due to space limitation within the OGA rack where the CRA hardware would be located, the total accumulator volume is achieved by hanging several small vessels together.

10.3.2 Sabatier CRA

Sabatier consists of Sabatier reactor, a condensing heat exchanger, a phase separator, and necessary valves and sensors. Carbon dioxide from CDRA and hydrogen from OGA combines to produce methane and water. Water is sent to the Waste Management System for processing it to potable water. Methane is used as a fuel source. Reaction in a catalyst reactor is reversible, highly exothermic. Ruthenium and nickel are found to be appreciably more active catalysts for promoting the Sabatier reaction. But Nickel causes slow deterioration over the period and carbon deposition is reported at 650-700°F. A hydrogen cylinder and a flow controller are used to simulate the delivery of H_2 from an OGA. Water vapor in the product stream is condensed in an air-cooled heat exchanger. The methane gas and liquid water are separated in a rotary drum phase separator.

$$4H_2(g) + CO_2(g) \rightleftharpoons 2H_2O(g) + CH_4(g)$$

Sabatier CRA has two primary modes of operation: Process and Standby. In Process mode, inlet gases flow through the system and methane and water are produced. In Standby mode, supply gases and the system is isolated, coolant air is stopped. Low temperatures favor high conversions. At 700°F and a feed ratio

(H_2:CO_2) of 3.5:1 the equilibrium conversion of H_2 is only 90%, while at 400°F it is about 99%. As the feed ratio falls below 3.5:1, carbon becomes thermodynamically stable at higher temperatures. Carbon monoxide formation is thermodynamically possible above 700°F.

$$CO_2 + H_2 \rightleftharpoons CO + H_2O$$

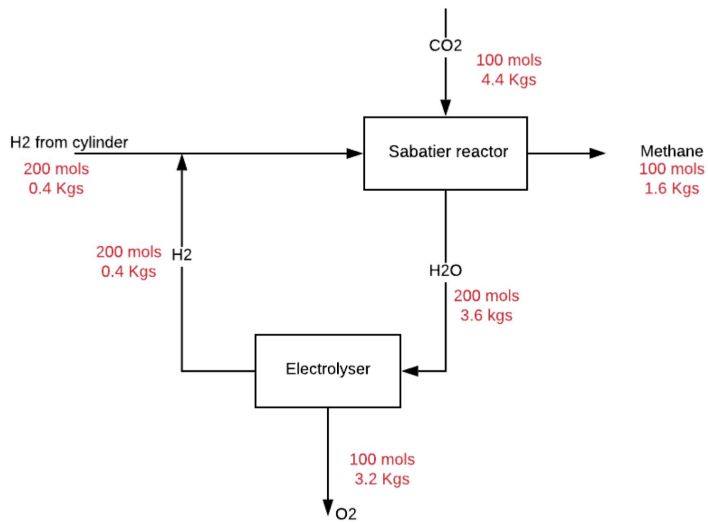


Figure 19: Block diagram of the Sabatier and OGS showing the quantities of materials

11. Results and Conclusions

A conceptual inflatable habitat was designed. A structure for the habitat was finalised after considering different configurations like Habitat Designs for Lunar and Martian Missions, and Inflatable Space Station Modules. Stress and Volumetric Analyses were performed for the structure of the habitat. A 3D model was developed for the habitat, and its stowed configuration and deployment were conceptualised. Environmental factors that would affect the habitat and materials to be used in each layer of the inflatable habitat were studied. The entire habitat was divided into sections which would house specified activities. ECLSS was designed for the habitat for a crew size of 4 (expandable upto 6), for a duration of 4 months. In addition to these, various technologies were studied to utilise the resources present on the planet and make the habitat self-sustainable.

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