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100-PERSON MARS TRANSFER VEHICLE USING TORPOR INDUCING HABITATS

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The idea of suspended animation for interstellar human spaceflight has often been posited as a promising far-term solution for long-duration voyages. A means of full cryo-preservation and restoration remains a long way off still. However, recent medical progress is quickly advancing our ability to induce deep sleep states (i.e. torpor) with significantly reduced metabolic rates for humans over extended periods of time. Since 2013 the authors have been investigating the feasibility and systems-level impact of applying this medical technology to human spaceflight, specifically for human missions to Mars. In a paper presented at IAC 2014 (IAC-14-A5.2.8), the authors presented the results of an initial study funded by the NASA Innovative Advanced Concepts (NIAC) program that considered the application of torpor-enabled habitats to near-term, exploration-class missions to Mars. Based on the promising results of that initial study, the authors have begun to consider the impact of torpor-enabled habitats to far term, settlement-class missions to Mars. This paper summarizes the results of a design study of a torpor-enabled 100-person deep space habitat for transporting a crew of long-term explorers to Mars. The Mars Transfer Habitat (MTH) is comprised of three habitats modules, a nuclear power-generation module, and several connection node modules. Two of the habitat modules are identical: habitation for 48 passengers each, kept in an unconscious torpor state for the duration of the transit from Earth to Mars orbit. The third module provides the living quarters for the active crew of 4 who serve as caretakers for the others. The total mass of the MTH is 200t, and it requires 300 kW of electrical power. Detailed engineering diagrams and mass breakdown statements for the habitat modules and overall transfer vehicle are provided.

I. INTRODUCTION

Background

Enabling the human exploration and settlement of another planet is a grand and challenging objective whose achievement would represent the greatest feat in human history. The challenges are extremely diverse and range from engineering, to affordability, sustainability, and human factors. Committing to such an endeavor will surely test our commitment and resolve to be a space faring species. However, success can ensure our long-term survival as a species against such threats as planetary-scale extinction events and ecological crisis.

In our solar system, Mars is the clear front-runner as the planetary body most suitable for colonization. Though the Moon is our nearest neighbor, it lacks many of the basic resources required for a permanent settlement. Compared to the Moon, Mars has large quantities of carbon, oxygen, and hydrogen between its carbon dioxide atmosphere and the water ice frozen as permafrost in its soil [1]. The other nearby planets, Venus and Mercury, are inhospitable for human life. Meanwhile, the limitations of today's propulsion technologies render human missions to the outer planets and their moons infeasible.

In the early 1990's, NASA developed a Design Reference Architecture (DRA) for a series of human exploration missions to Mars. As time has passed that DRA has been updated; the latest version, DRA 5.0, was released in 2009 [2]. This DRA outlines a set of three missions to the Martian surface, each with a crew of six. Despite decades of technology advancements, the technical feasibility of these missions continues to be extremely difficult. The single 6-crew in-space transfer habitat for this mission has a launch mass of 40t. Even using advanced nuclear thermal propulsion, the total transfer vehicle required to carry this habitat to Mars has a total mass of 350t, and requires four launches of a heavy-lift launch vehicle to assemble.

Current engineering solutions for near-term exploration missions do not scale well to long-term settlement missions, which will require crew sizes an order of magnitude larger than the NASA DRA missions. Looking at history, early European settlements in the Americas started with approximately 100 settlers. The first settlements at Plymouth Rock and Jamestown, for example, started with 102 and 104 settlers respectively [3,4]. Using habitats such as those described in NASA DRA 5.0, the total in-space habitat mass alone for a settlement-class mission would be on the order of 700t.

Human crews and the associated support items required to support them are major drivers on Mars mission mass and complexity. To enable settlement-class missions, we need a radical, out-of-the-box approach to transporting human crew.

Proposed Solution

Our proposed solution is to place the crew in an inactive state for the duration of the transit between Earth and Mars. If the crew is placed in an inactive state, many of the subsystems can be removed, psychological-social aspects eliminated, and the required habitable volume reduced.

The idea of suspended animation for interstellar human spaceflight has often been posited as a promising far-term solution for long-duration voyages. A means for full cryo-preservation and restoration remains a long way off still. However, recent medical progress is quickly advancing our ability to induce deep sleep states, also known as torpor, with significantly reduced metabolic rates in humans over extended periods of time.

Our solution combines two common and well-understood medical procedures to induce and maintain the crew in a torpor state. In medicine, torpor is induced in humans through Therapeutic Hypothermia (TH), a medical treatment in which a patient's body temperature is lowered to 32°C to 34°C (89°F to 93°F) in order to slow the body’s metabolism. While in the torpor state, the passengers can be fed intravenously by nutritional fluids delivered via a central venous catheter. This process is known as Total Parenteral Nutrition (TPN). By combining TH and TPN, a group of Martian settlers can be kept in torpor for the long durations required for Earth-to-Mars transit [5].

Study Objectives

There were two primary objectives for this effort. The first objective is to identify any medical/physiological or technical hurdles that might prevent the proposed approach and system from being realized. The demonstrated state-of-the-art is a 14-day stasis period for humans [6]. With the ultimate goal of extending this period to months, discussions with the medical community and research during the effort will help to reveal any potential issues and identify approaches to resolve them. The second objective is to develop an engineering design of a 100-person settlement-class habitat leveraging the torpor approach.

II. RATIONALE

A brief description of a few key exploration challenges will be provided next. The objective here is to emphasize the multifaceted nature (and magnitude) of this problem and not necessarily provide an exhaustive list of every challenge.

Challenges

The human body is not naturally adapted and designed for survival in the space environment. Microgravity, exposure to solar and galactic radiation, and long-term social isolation all present difficult challenges for the design of a settlement-class mission to Mars.

Due to the microgravity environment, significant bone demineralization and muscle atrophy occurs over time. These can seriously impact the performance and health of the astronauts [7]. Average bone loss rate on the Russian Mir Space Station was measured to be 1-2% per month [8]. During a Mars mission, crew members could lose up to 40% of muscle strength even with exercise [9]. In addition, prolonged exposure to microgravity can lead to elevated intracranial pressure (ICP), which can cause persistent vision issues both during and after spaceflight, in some cases for years after returning to Earth. Experiments on elevated ICP and its effects on vision are currently being researched on the International Space Station (ISS) as a part of the NASA Vision Impairment and Intracranial Pressure (VIIP) program [10].

Traveling in space away from the protective atmosphere and magnetic field of the Earth exposes astronauts to both Solar Particle Events (SPE) and Galactic Cosmic Radiation (GCR). Left unprotected, this radiation exposure can damage the central nervous system, skin, and body organs as well as ultimately increase an astronaut’s risk of cancer in the long term [11]. SPEs originate from the sun and occur intermittently. It is generally possible to receive notification of the event in advance and place the crew in small shielded compartment. GCR consists of a continuous, omnidirectional stream of very high-energy particles that originated from outside our solar system. For space travel, it is currently mass-prohibitive to provide adequate shielding against GCR, so alternative approaches and technologies must be used.

Spaceflight introduces other health complications such as spinal elongation, disrupted circadian rhythm, and altered immune systems. All of these problems are compounded with mission duration.

Long duration spaceflight also introduces psycho-sociological issues. A mission lasting 2 or more years may be difficult both socially and emotionally for the crew members. At typical crew sizes of only 4-8 members, interpersonal conflicts are likely to amplify as the mission progresses. Data recorded by astronauts on the ISS for missions of only 1-year in duration have shown a significant increase in recorded conflicts during the latter half of the mission [9]. Results from the 2010-2011 Russian-ESA-Chinese Mars500 experiment with a 6-member "crew" held in isolation for 520-days also indicated interrupted sleeping patterns, depression, lethargy, and even willful isolationism [11].

NASA is currently studying the psycho-social impacts of long term isolation with their Hawaii Space Exploration Analog and Simulation (HI-SEAS) program. The most recent of these simulations, HI-SEAS IV, began on 28 August 2015 and will last one year [12].

On the medical side, there are challenges with simply providing treatment (e.g. open surgery) and having the necessary equipment and expertise on hand. To date, there has never been surgery conducted in space. Communications with the crew can also take anywhere from 4 to 24 minutes, depending on the relative position of Earth and Mars. In an emergency situation, this puts the crew in a position of having to make decisions with minimal or no input from remote support staff such as program managers, engineers, and medical teams.

Finally, a settlement-class human mission presents a significant logistical supply challenge. The consumable food, water, and oxygen needs of a 100-person crew will drive the size and complexity of the spacecraft and its environmental control and lift support systems. On a mission to Mars, the crew will be without ready access to replacement parts and spares as on the ISS; these must all be carried on the mission. A 100-person habitat would also need to provide sufficient habitable volume and crew accommodations for crew comfort.

Advantages of Torpor

Placing the crew in an inactive, hibernation state affords many advantages to a settlement-class mission. With the crew in hibernation, the total pressurized volume required for habitation and living quarters is significantly reduced. In addition, many ancillary crew accommodations (e.g. food galley, cooking and eating supplies, exercise equipment, entertainment, etc.) can be eliminated. Additionally, a person in torpor has reduced metabolic rates, and therefore requires less consumable food, water, and oxygen.

Applying torpor to his mission will also minimize psychological challenges for crew. After boarding the transfer vehicle in Earth orbit, the Martian settlers can simply sleep through the 6 to 9 month in-space transfer to Mars, and be woken once they have arrived in Mars orbit.

Having the crew inactive and stationary during the mission also provides some flexibility to habitat design that can help solve or mitigate a number of the health issues stemming from long-duration spaceflight. One approach to eliminating these risks is by rotating the habitat element to induce an acceleration field inside the crew cabin, thus simulating gravity. This concept of artificial gravity is not new – spinning habitats have been considered from the earliest days of human space exploration, and have been featured heavily in both engineering studies and works of science fiction. For an active crew, this often means creating a habitat in which the crew can "stand up" in the induced gravity field. Such a habitat must be large enough to not impart a significant acceleration gradient across a crew member, otherwise the crew can become disoriented or suffer other ill health effects. With a stationary crew, however, the crew can being "lying down" in the induced gravity field, significantly reducing the size requirements of the habitat and avoiding issues with gravity gradients.

The crew can also be better protected from radiation if they remain stationary for the duration of the mission. Rather than shielding the entire habitable volume from radiation, the habitat can be designed in a way to minimize radiation exposure in the exact locations where the crew will be located. This can be accomplished through the combination of consumables placement and additional radiation shielding as necessary [13].

There is also some evidence that TH may, itself, provide some health benefits to crews of a long-duration mission. For example, recent studies have shown that TH can be used to reduce elevated ICP [14].

III. MEDICAL PERSPECTIVE

Artificially Induced Hibernation

Torpor is defined as a deep sleep state that is induced by active metabolic suppression with minimal decrease in body temperature to save energy over the winter period. Black bears (Ursus americanus) are the most famous example of this type of hibernation. Due to the minor decrease in body temperature and physiologic function black bears have minimal systemic effects

Table 1. Current Cooling and Rewarming Target Temperatures and Inducement Times

Parameter	Cooling	Rewarming
Target Temperature	89 to 93 °F	97 to 98 °F
Rate of Change	1 °F per hour	1 to 4 °F per hour
Time Required	6 hours	2 to 8 hours

from hibernation and are able to fully arouse over a very short period of time

There are three (3) possible approaches for inducing a hibernation-like state in animals and humans that have been studied over recent years and are briefly summarized below:

1. Temperature-based. Torpor is achieved by lowering the body core temperature through either invasive cooling (infusing cooled IV fluids), or conductive cooling (e.g. gel pads placed on body or evaporative gases in the nasal and oral cavity).

2. Chemical/Drug-based. In 2011, Scientists at the University of Alaska successfully induced hibernation by activating adenosine receptors (5'-AMP) in arctic ground squirrels. More recent studies on rats have yielded similar results. While this "hibernation molecule" has had mixed experimental results when used on its own, when used in conjunction with temperature based induction it has yielded very promising results [3]. Inhaled Hydrogen Sulfide (H2S) has also been shown in recent studies to induce a deep hibernation state within mice by binding to cells and reducing their demand for oxygen [15]. This approach did not appear to work on larger animals.

3. Brain Synaptic-based. Current research shows significant decreases in the number of dendritic spines along the whole passage of apical dendrites in hibernating creatures. Whether this is an initiating factor for hibernation or a result of other metabolic processes is still being investigated [16,17].

Temperature-based cooling approaches have the largest body of medical data available for humans and are becoming a well-understood procedure. While our current assumed approach for inducing torpor uses this technique, it could easily be supplemented or enhanced with the other identified options with little or no impact to the overall habitat designs and architecture.

Therapeutic Hypothermia

Definition

Therapeutic Hypothermia (TH) is a medical treatment that lowers a patient's body temperature in order to help reduce the risk of ischemic injury to tissue following a period of insufficient blood flow.

In simple terms there are four aspects to the hypothermic process and stasis induction: initial body cooling, sedation, nutrition/hydration, and rewarming. Patients are actively cooled to a mild hypothermic state (defined as a core temperature between 32 to 34 °C (89 to 93 °F). While various cooling approaches exist, there is no evidence demonstrating the superiority of any one cooling method over another [18]. Shivering (a muscle activation response that tries to rewarm the body) is commonly suppressed with a very low-level infusion of propofol and fentanyl, with or without the intermittent treatment of benzodiazepines (e.g. midazolam). Patients are then maintained in this torpor like state until significant improvement is noted in their medical status. The patient is then rewarmed to normal body temperatures, with continued medical treatment as a standard critical care patient. Table 1 shows an example of a typical cooling and warming timeline.

Current State of the Art

Since 2003 Therapeutic Hypothermia has become a staple of Critical Care for new-born infants suffering from fetal hypoxia and for adults suffering from head trauma, neurological injuries, stroke and cardiac arrest. Benefits of hypothermic therapy have been well proven, and it is inexpensive to implement and use. Standard protocols exist in most major medical centers throughout the world [19].

Hypothermic therapy is being used routinely and with broader application in hospitals to reduce the impact of traumatic body injuries. Therapeutic Hypothermia use can be divided into five primary treatment categories: neonatal encephalopathy, cardiac arrest, ischemic stroke, traumatic brain or spinal cord injury without fever, and neurogenic fever following brain trauma. Additionally, this type of cold therapy is the only known medical treatment to be clinically proven to prevent brain damage and improve mortality for newborns experiencing oxygen deprivation due to underdeveloped lungs.

Active Research

Chinese studies showed evidence of increased benefit from prolonged TH (up to 14-days) without increasing the risk of complication [6]. Recent studies confirm this data [20].

The U.S. military is also actively funding research in this area to support the warfighter, with the goal of being able to extend the time period to transfer an injured person to receive proper medical care. Additionally, the National Institute of Health (NIH) is funding research in this area in support of the same general objective [21].

Despite initial encouraging results with Hydrogen Sulfide on mice producing a brief hibernation-like/suspended animation state, more recent clinical trials were suspended after subsequent studies did not show this effect occurring in larger animals [22,23].

Unfortunately, none of the aforementioned efforts are focused on achieving extended durations or considering applicability to human space flight.

Mission Requirements

While Therapeutic Hypothermia is currently used as a short term medical treatment, an extrapolation from the current 14-day state-of-the-art to periods of weeks and months appears achievable over the next 10-20 years based on the rapid progress, understanding, and extension of this process over a relatively short period of time. Though longer-term stasis is not without its own difficulties and challenges, the current complications associated with hypothermia therapy may stem from the fact that this therapy is being used as a treatment for people with severe medical complications (e.g. shock, compromised immune systems, heart failure, traumatic injuries, etc.). Due to the current lack of need or rationale in medical treatments to maintain therapeutic hypothermia beyond 10-14 days, longer periods have not been attempted. While no medical procedure is without some risk, the known complication rates and the severity in which these complications occur should be significantly reduced when applied to healthy individuals.

Total Parenteral Nutrition (TPN)

All the nutrition and hydration needs for a person can be provided by a liquid solution and administered through an intravenous (IV) line directly into the body. This solution is known as 'Total Parenteral Nutrition' or TPN. This aqueous solution contains all nutrients that the body needs to maintain full physiologic function. The solution is fed slowly through a permanent IV line to the body over a period of hours and is routinely used in numerous post-surgery and oncological treatments where the individual has digestive issues or cannot process foods normally. Short-term TPN is used if a person's digestive system has shut down (for instance due to peritonitis), and they are at a low enough weight to cause concerns about nutrition during an extended hospital stay.

Long-term Total Parenteral Nutrition is often used to treat people suffering the extended consequences of an accident, surgery, or digestive disorder. Cancer patients and preterm infants are routinely on TPN for months at a time. While most patients usually recover enough to stop TPN use, there are circumstances where patients obtain all of their nutrition solely from TPN for years. Long-term parenteral nutrition requires a tunneled central venous catheter or a peripherally inserted central catheter (PICC). A tunneled catheter is preferable, since infections are more common among patients receiving parenteral nutrition at home through a PICC. Also, while single lumen central venous catheters should be dedicated solely for the infusion of parenteral nutrition, multiple lumen central venous catheters need only one port for this purpose [24].

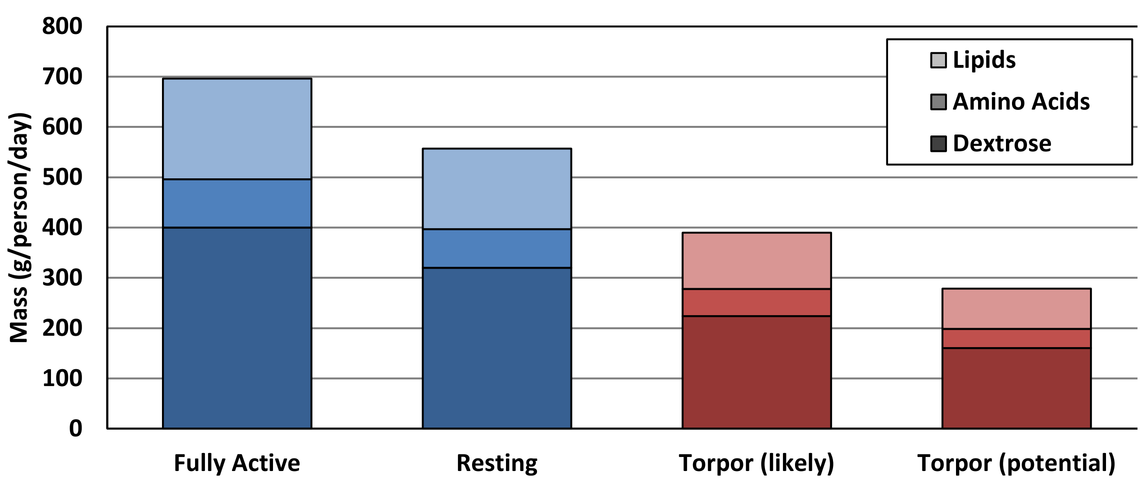

Figure 1. TPN Dosage Rate vs. Activity Level

The daily TPN requirement for the human body is a well understood science [25]. The standard protocol for calculating the dosage is to use the Harris-Benedict Equation (HBE) with additional adjustments for individual activity level (e.g. active, resting) and stress environment (e.g. recovering). The HBE estimates the basal metabolic rate and daily kilocalories needed and is a function of gender, body weight, and body height. The value obtained is designed to maintain the crew members' current body weight.

Figure 1 provides the required TPN mass per person per day based on a male crew member weighing approximately 80 kg. Female crew members TPN requirements are slightly lower. The values shown for a fully-active and resting-state are provided based on the HBE. The torpor values of "likely" and "potential" represent further reductions in daily TPN requirements from the resting rate due to the lower metabolic rate that is expected in the stasis condition.

IV. CREW TORPOR SUPPORT SYSTEMS

Body Thermal Management Systems

Torpor is achieved by decreasing a crewmember's core temperature to approximately 34 °C (93 °F). There are several ways that this can be accomplished. Regardless of technique, all of the systems are low mass, low power, and can be automated. And as discussed above, multiple studies show that there is no evidence demonstrating the superiority of any one cooling method over another [26].

A new novel cooling approach that does not require access to a major vein or prolonged placement of cooling pads is called trans-nasal evaporative cooling. For this system, a cannula (small plastic tube) would be inserted into the crewmember's nasal cavity. This is used to deliver a spray of coolant mist that evaporates directly underneath the brain and base of the skull. As blood passes through the cooling area, it reduces the temperature throughout the rest of the body. The coolant mist is only used as needed to adjust the body temperature to within the target range. The RhinoChill™ system created by BeneChill, as shown in Figure 1, is an example of a trans-nasal evaporative system currently in use.

Hydration Fluids

Current space missions carry large stores of water onboard for multiple uses. Unfortunately, limitations of mass, volume, storage space, shelf-life, transportation, and local resources do restrict the availability of such important fluids. Potable water can be recycled from water waste produced on the space module with basic filtration systems, but medical grade fluids require a much higher level of processing.

In 2010, NASA successfully tested the IVGEN system, on an ISS Expeditions 23 and 24[27]. It is a handheld device that can convert regular drinking water to produce sterile, ultrapure water that meets the

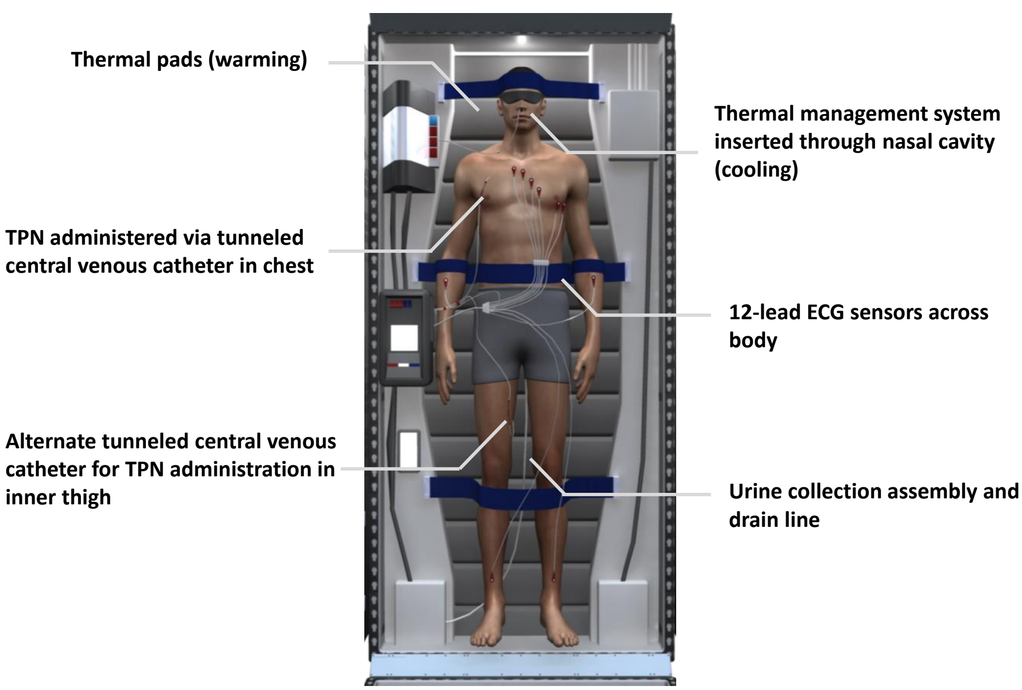

Figure 2. Implementation of Crew Support Systems

stringent quality standards of the United States Pharmacopeia for Water for Injection (Total Bacteria, Conductivity, Endotoxins, Total Organic Carbon). The device weighs 1 kg and is 2-cm long, 13-cm wide, and 7.5-cm high. One device can produce one liter of medical-grade water in 21 minutes. The device contained one battery powered electric mini-pump, although a manually powered pump can be attached and used. Operation of the device is easy and requires minimal training.

In addition to creating IV fluids, the device produces medical-grade water, which can be used for mixing with medications for injection, reconstituting freeze-dried blood products for injection, or for wound hydration or irrigation.

Implementation

The required crew support systems are identified and demonstrated in Figure 4. The basic features and systems required to support an individual would include:

1. A central monitoring station for evaluating heart function and vital signs (e.g. 12-lead ECG).

2. A tunneled catheter for IV hydration, TPN administration and lab draws. A second line could be placed as a reserve in case of infection or damage to the other line.

3. Nasal thermal management system for TH if evaporative approach is used. (A multi-lumen catheter could be used for both cooling and IV hydration if that method is preferred).

4. Urine collection assembly and drain line.

5. Thermal warming pads to act as an additional thermoregulator, and to provide emergency waking support if needed.

Additionally, some loose-fit straps and bindings are used to minimize any movement in the habitat and keep the crew member in their respective alcove.

V. TORPOR-ENABLED PASSENGER HABITAT MODULE DESIGN

Overview

The baseline torpor-enabled passenger habitat module is shown in Figure 3. The habitat module is a rigid pressurized cylinder with a diameter of 8.5m and length of 10.0m. At each end is a pressurized docking interface for passenger egress and ingress to other modules. The habitat is designed to carry 48 passengers in a torpor state for 1 year. This is sufficient time for a low-energy Earth-to-Mars transfer, plus time for loading and unloading in Earth and Mars orbit [28].

Each passenger is allocated an individual torpor compartment. In the baseline design, there are 3 levels / floors in the habitat, each with 16 torpor compartments along the wall, as shown in. The torpor compartments

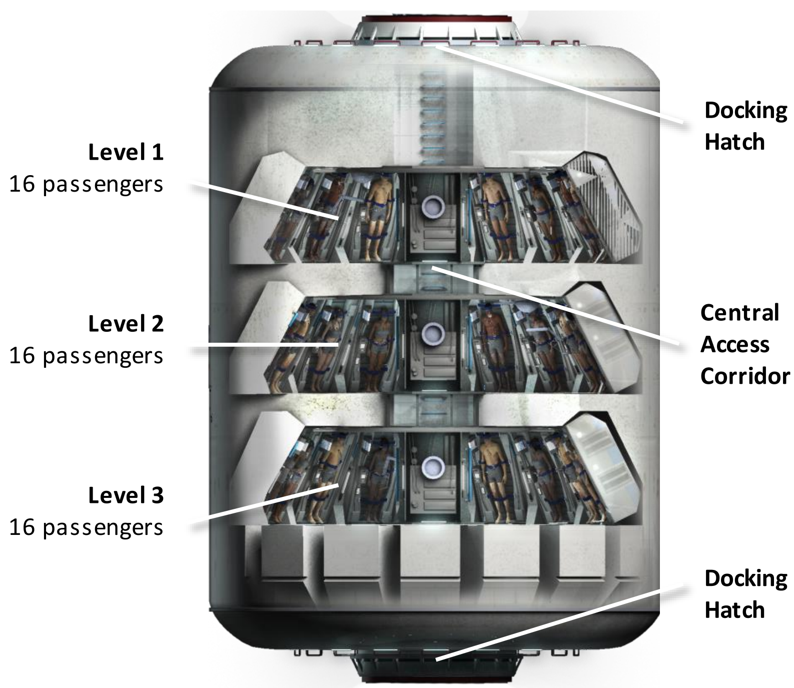

Figure 3. Torpor-Enabled Passenger Habitat Module (48 passengers)

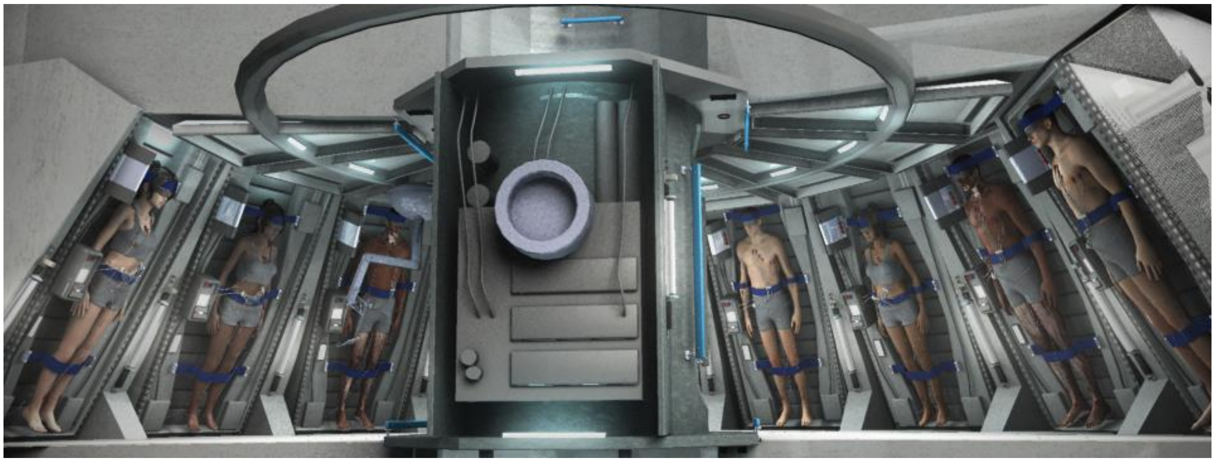

Figure 4. Single Level of Passenger Module (16 passengers)

each contain all of the subsystems required to support the passengers during the mission, including:

- Intravenous lines for the administering of TPN for passenger nutrition with active monitoring and feedback
- Intranasal cooling and warming lines for body thermal management
- Heating pads for additional body thermal management
- 12-lead ECG system for passenger health monitoring
- Neuromuscular Electrical Stimulation (NMES) leads for muscle activation, through very low-level electrical impulse administration, to prevent muscular atrophy to key muscle groups
- Zero-g restraints

Each level of the torpor habitat contains two robotic arms, placed on rails so as to be able to maneuver and reach all 16 passengers. The manipulator arms are used to manage and manipulate the passenger lines, leads, and restraints during the mission. The arms are redundant; a single arm can access all 16 crew members.

All passenger nutrition in the torpor habitat is provided intravenously as TPN, so the torpor habitat does not need a galley; food storage and preparation equipment is not included. Furthermore, because the passengers will spend the vast majority of the mission in an inactive torpor state, no exercise equipment or individual passenger quarters are provided.

Artificial Gravity

During the transit between Earth and Mars, the torpor habitat module will rotate to induce an artificial gravity field. In this configuration, the passengers will be accelerated into the padding on the torpor compartment; the sensed acceleration will be as if lying down in a gravity field. The passengers are inclined slightly such that with respect to the gravity field, the head is slightly above the feet.

The acceleration field gradient is typically a concern in traditional artificial gravity habitat designs; the human body cannot tolerate a large acceleration gradient well. However, because the passengers are stationary in the torpor-enabled habitat, the passengers can be placed nearly perpendicular to the acceleration vector, significantly reducing the acceleration gradient across the body. This allows the torpor-enabled habitat to have a much shorter rotation radius than a traditional habitat, thus reducing the total size and mass requirements.

The induced artificial gravity parameters for the torpor-enabled habitat are shown in Table 2. It is unknown at this time what the artificial gravity requirements will be to mitigate the medical risks associated with long-term microgravity exposure; the required rotation speeds to induce Lunar, Martian, and Earth gravity are shown Table 2.

Table 2. Induced Artificial Gravity Parameters for Torpor-Enabled Habitat

Planetary Analogy	Induced Earth Gs	Rotation Rate
Moon Surface	0.16	7.1 rpm
Mars Surface	0.38	11.5 rpm
Earth Surface	1.00	17.6 rpm

Closed-loop ECLSS

The Environmental Control and Life Support System (ECLSS) for the torpor habitat module is its most important subsystem. Where possible, existing and near-term technologies used on the ISS were selected in the design of this system to minimize risk associated with development. In order to support the large number of passengers for a 1 year mission time, the ECLSS for the torpor habitat uses a Water Processing System (WPS) to recycle water, and the Atmosphere Revitalization System (ARS) and Oxygen Generation System (OGS) to recycle oxygen.

In the WPS, water is collected from the atmospheric humidity (driven by passenger breathing and sweat) using the Temperature and Humidity Control (THC) subsystem, and collected from passenger urine in the Urine Processor Assembly; a vacuum distillation process is used to recover water from urine. All water collected is sent to a Water Processor for treatment [29].

In the ARS, the first step of the oxygen recovery process is to remove the carbon dioxide from the cabin atmosphere using a Carbon Dioxide Removal Assembly (CDRA). The ARS also includes a Trace Contaminant Control Subsystem (TCCS) to filter particulates and remove volatile organic trace gases from the air [29].

Once collected the carbon dioxide is passed OPS, specifically to the Carbon Dioxide Reduction Assembly (CReA) for processing. The CReA uses a Sabatier reaction to convert carbon dioxide and hydrogen into methane and water. The water is sent on to the final step of this process, the Oxygen Generation Assembly (OGA). The OGA uses electrolysis to break the water into hydrogen and oxygen gas. The oxygen is fed back into the cabin atmosphere, while the hydrogen is sent back into the CReA to support the Sabatier reaction.

The additional hydrogen required to maintain the CReA is recovered from its methane exhaust. Excess oxygen in the system, introduced from the TPN dextrose molecules and recovered via the OGA, is reacted with the methane exhaust to produce carbon dioxide and water. The water is sent to the OGA for electrolysis, while the carbon dioxide and remaining methane are vented from the habitat. A small amount of hydrogen gas is included in the system outfitting to initiate this process.

Mass and geometry results

A mass breakdown statement for a single torpor inducing habitat module is shown in Table 3. The dry mass represents the lowest possible launch mass; outfitting and consumables can be brought on board after launch. A 20% mass growth allowance is carried on all system dry masses. Masses for all systems were estimating using mass estimating relationships derived from physics-based models, empirical data and historical records [30,31,32].

Table 3. Mass Breakdown Statement for Torpor-Enabled Passenger Habitat Module (per Module)

Item	Mass (t)
Structures and Interfaces	4.2
Power Generation & Distribution	4.8
Thermal Management	5.6
Avionics	0.8
Environmental Control & Life Support	13.1
Crew Systems and Accommodations	5.3
Mass Growth Allowance (20%)	10.1
Dry Mass	**43.9**
Outfitting	0.5
Spares	7.2
Outfitted Mass	**51.6**
ECLSS Consumables and Storage	2.3
TPN Consumables and Storage	13.1
Loaded Mass	**67.1**
Passengers (48)	4.3
Gross Mass	**71.4**

VI. SUPPORTING MODULE DESIGN

In addition to the primary torpor-enabled passenger habitat modules, several other modules are required to support the fully-integrated Mars Transfer Habitat (MTH). By design, the vehicle will carry 96 passengers in an inactive torpor state, along with a crew of 4 caretakers to maintain operations on the vehicle during the long transit to Mars. A separate habitat module, analogous to the TransHab carried in the NASA DRA 5.0 mission, is included to house this active crew. For crew access to and from the MTH, several node modules with multiple hatches are included. Finally, power is provided to the entire spacecraft by a nuclear reactor electric power module.

Active Crew Habitat Module

The active crew habitat module is a rigid pressurized cylinder with the same structural design as the torpor habitat. It has a diameter of 8.5m and length of 10.0m. At each end is a pressurized docking interface for crew egress and ingress to other modules. The crew habitat module is designed to house 4 active crew members for one year.

The crew habitat module uses a similar ECLSS setup as the torpor-enabled passenger habitat module. It uses a closed-loop oxygen production system with a CDRA, CReA, and OGA. Crewmember urine and cabin humidity condensate is collected and processed through the UPA and WPA. Systems for filtering particulates and removing volatile organic trace gases from the air, and maintaining cabin pressure, temperature and humidity levels are also similar to their torpor habitat counterparts. Unlike the passengers in torpor, the active crew will not receive nutrients through TPN. Instead, dehydrated food is carried in the habitat; it is hydrated before consumption, and the water is recycled using the WPA. Food storage and preparation equipment is provided in the crew galley.

The crew habitat module does not provide artificial gravity. It therefore includes aerobatic and resistive exercise equipment to combat muscle atrophy and bone demineralization caused by the microgravity environment. For hygiene, the habitat includes a toilet and microgravity shower similar to those designed for the ISS. Each crew member is also provided a private crew quarters for sleeping and relaxation. In case exterior repairs to the transfer vehicle are required, the DSH also includes an airlock and four space suits for the active crew.

A mass breakdown statement for the crew habitat module for active crew is shown in Table 4. A 20% mass growth allowance is carried on all system dry masses. Masses for all systems were estimating using mass estimating relationships derived from physics-based models, empirical data and historical records [30,31,32].

Table 4. Mass Breakdown Statement for Crew Habitat Module

Item	Mass (t)
Structures and Interfaces	2.5
Power Generation & Distribution	1.7
Thermal Management	1.4
Avionics	0.3
Environmental Control & Life Support	2.4
Crew Systems and Accommodations	2.5
Extra-Vehicular Activity (EVA)	0.7
Mass Growth Allowance (20%)	3.4
Dry Mass	**14.9**
Outfitting	0.4
Spares	2.8
Outfitted Mass	**18.1**
ECLSS Consumables and Storage	1.2
Food Consumables and Storage	3.7
Loaded Mass	**23.0**
Crew (4)	0.4
Gross Mass	**23.4**

Power Generation

Power is generated for the entire MTH from a single power module. The power module uses a heatpipe-operated nuclear fission reactor to produce electrical power. Its design is based on those of the proposed Heatpipe-Operated Mars Exploration Reactor (HOMER) [33] and Safe Affordable Fission Reactor (SAFE) [34]. As described by these programs, the heatpipe-operated reactor affords several advantages over both other nuclear fission reactor concepts, and other power generation systems such as solar arrays. Advantages include a lower development time and cost; increased safety, reliability, and lifetime; and improved thermal, nuclear, and mechanical performance [33].

To protect the MSH from radiation, a 5.0 m diameter radiation shield is placed between the reactor and the spacecraft. The radiation shield consists of 18 cm of Beryllium, 5 cm of Tungsten, and 5 cm of Lithium Hydroxide [35].

For conversion of thermal energy to electric, as with the HOMER study, a Stirling cycle engine with a 20% efficiency was chosen [33]. The module produces 300 kWe of electrical power from 1,500 kWt of thermal power. The module uses a series of deployed radiator panels to remove excess thermal energy.

A mass breakdown statement for the power generation module is shown in Table 5. A 20% mass growth allowance is carried on all system dry masses. Masses for all systems were estimating using mass estimating relationships derived from physics-based models, empirical data and historical records [30,31,32,33,35].

Table 5. Mass Breakdown Statement for Power Generation Module

Item	Mass (t)
Core/Reflector/Heatpipes	1.7
Component Shielding	0.8
Instrumentation and Control	0.2
Power Conversion and Management	4.1
Radiator Assembly	2.1
External Shield	2.6
Structures	4.0
Mass Growth Allowance (20%)	3.1
Gross Mass	**18.6**

Crew Access and Support

Crew access to the transfer vehicle is provided through the access node modules. The access node modules are based on the Unity module of the ISS. It has six hatches; one top, one bottom, and four outward around the center. The top and bottom hatches dock to different modules of transfer vehicle (e.g. torpor habitat, DSH). The four central hatches are used for crew ingress / egress to and from the Mars transfer vehicle at the beginning and end of the mission. Other vehicles, such as crew capsules at Earth or surface landers at Mars, can dock at these central hatches.

A mass breakdown statement for a single node module is shown in Table 6. A 20% mass growth allowance is carried on all system dry masses. Masses for all systems were estimating using mass estimating relationships derived from physics-based models, empirical data and historical records [30,31,32].

Table 6. Mass Breakdown Statement for Access Node Module (per Module)

Item	Mass (t)
Structures and Interfaces	1.7
Power Generation & Distribution	0.1
Thermal Management	0.5
Environmental Control & Life Support	0.6
Crew Systems and Accommodations	0.1
Mass Growth Allowance	0.9
Dry Mass	**4.0**
Spares	0.3
Consumables	0.2
Gross Mass	**4.4**

The transfer vehicle also includes a cupola module for observation and experiments, similar to the cupola module on the ISS. The cupola module is docked to the front of the crew habitat module and has seven windows. It has a total mass of 1.9t [36].

VII. MARS TRANSFER HABITAT SUMMARY

A diagram of the fully-assembled Mars Transfer Habitat (MTH) is shown in Figure 5. The assembled vehicle is 80m in length and 22m in width and height. It contains one crew habitat module, two identical torpor passenger habitat modules, one power generation module, and three access node modules. Fully assembled, the MTH has 13 external access points across the three node modules.

The power module radiation shield shadows the radiator assembly and all crewed elements from the nuclear fission reactor.

A mass breakdown statement for the MTH is shown in Table 7. The power requirements for the MTH are shown in Table 8. The MTH has a total mass of 200 t and power generation requirement of 300 kWe.

Table 7. Mass Breakdown Statement for Mars Transfer Habitat

Element	Mass (t)
Crew Habitat Module	23.4
Torpor Passenger Habitat Module 1	71.4
Torpor Passenger Habitat Module 2	71.4
Access Node Modules	8.9
Cupola Module	1.9
Power Generation Module	18.7
Total	**195.7**

Table 8. Power Requirements for Mars Transfer Habitat

Element	Power (kWe)
Crew Habitat Module	27
Torpor Passenger Habitat Module 1	101
Torpor Passenger Habitat Module 2	101
Access Nodes	3
Power Generation Module	15
Margin (20%)	49
Total	**297**

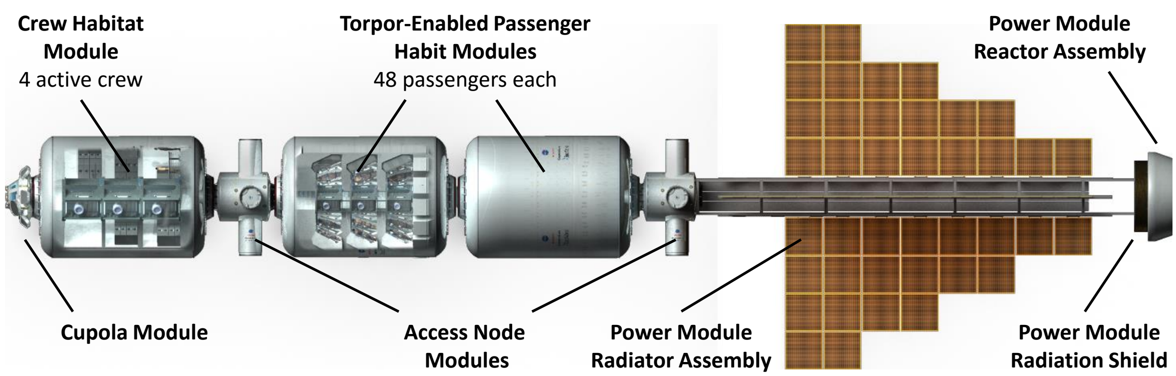

Figure 5. Assembled 100-Person Mars Transfer Habitat (MTH)

VIII. CONCLUSIONS

There were two primary objectives for this effort. The first objective was to identify any medical/physiological or technical hurdles that might prevent the proposed approach and system for inducing long-duration torpor for humans from being realized. The second objective was to develop an engineering design of a 100-crew settlement-class habitat leveraging the torpor approach. This study serves as a continuation of efforts by the authors to investigate the use of these technologies for human spaceflight [39].

Regarding the medical feasibility and assessment of this concept, the results are promising. Human patients have been placed in a continuous torpor state using TH protocols for periods of up to 14-days already with no adverse effects. While this duration is still significantly short of the desired 6-month+ stasis period desired, we believe our goal is medically plausible and that with continued advancements we can ultimately achieve these extended torpor periods.

Additionally, humans have undergone multiple TH induction cycles with no negative or detrimental effects reported in either the near term recovery period or long term. Human patients have regularly received sustenance for extended durations (>1 year) TPN, which can meet all hydration and nutritional needs for this settlement-class mission. The administration of TPN is a well understood science within the medical community and is used at every major hospital. All key hardware systems required (i.e. body cooling systems, TPN mixing and dispensing, space-based IV-grade solution generation, etc.) are currently available in non- or semi-automated forms. Conversations to date with medical system R&D divisions did not identify any immediate concerns or challenges with fully automating their hardware.

A torpor-enabled habitat solution also shows a number of benefits with respect to the medical challenges of human spaceflight. By incorporating induced gravity, the microgravity impact on bones and muscles can be mitigated. The combination of induced gravity and TH also may reduce the risk of elevated ICP. By keeping the passengers in a torpor state, disruption of circadian rhythm, as well as the psycho-sociological issues relating to long-term isolation, can be avoided. A torpor-enabled habitat can also be better designed to protect the passengers from space radiation, both SPE and GCR.

The final Mars Transfer Habitat, as designed, has a total mass of 200 t and power generation requirement of 300 kWe. This represents a significant improvement in mass and power requirements, for a total crew size of 100, when compared to scaling current architectures for human exploration of Mars. The reduced metabolic rates that are achieved through torpor relax the mission requirements on consumable food and water, and positively impact the design of the habitat environmental control and life support systems.

Overall, the application of long-duration torpor for humans to space exploration missions appears to be both medically and technically feasible, and shows great promise as a means to enable settlement of the solar system.

IX. REFERENCES

1. Zubrin, R., Wagner, W., “Preface,” *The Case for Mars*, 1st ed.,Touchstone, New York, 1996 p. xv.

2. Drake, et al., “Human Exploration of Mars, Design Reference Architecture 5.0”, Mars Architecture Steering Group - NASA Headquarters, NASA SP-2009-566, July 2009.

3. Caleb H. Johnson, *The Mayflower and Her Passengers*, Xlibris Corp., Indiana, 2006, p. 33.

4. Congressional Record (1975). "Congressional Record 1975". Congressional Record 121. Retrieved Oct 2014.

5. Schaffer, M., Bradford, J., Talk, D., “Torpor Inducing Transfer Habitat for Human Stasis to Mars”, IAC-14-A5.2.8, 65th International Astronautical Congress, Toronto, Canada, Sept 29 – Oct 3, 2014.

6. “Hypothermia Protocols,” Center for Resusitation Science, Perelman School of Medicine, University of Pennsylvania, https://www.med.upenn.edu/resuscitation/hypothermia/protocols.shtml, Retrieved September 24, 2015

7. "The Body in Space," Discoveries for Space and Earth, Nation Space Biomedical Research Institute, http://www.nsbri.org/DISCOVERIES-FOR-SPACE-and-EARTH/The-Body-in-Space/, Retrieved May 2014

8. LeBlanc, A., et al., "Bone mineral and lean tissue loss after long duration space flight", Journal of Musculoskeletal and Neuronal Interactions, 1(2), 2000, pp. 157-160.

9. Fitts, R., et al., "Effect of Prolonged Space Flight on Human Skeletal Muscle", http://www.nasa.gov/mission_pages/station/research/experiments/245.html, NASA, July 2015. Retrieved Sept 2015.

10. Polk, J., et al., "Vision Impairment and Intracraniel Pressure, http://www.nasa.gov/mission_pages/station/research/ex

periments/1038.html, NASA, May 2015. Retrieved Sept 2015.

11. Shelhamer, M. “Critical Risks for Extending Human Spaceflight”, Briefing to the Future In-Space Operations (FISO) Working Group, April 2, 2014.

12. "Hawaii Space Exploration Analog and Simulation", http://hi-seas.org. Retrieved Sept 2015.

13. Bailey, L., "Radiation Studies for a Long Duration Deep Space Transit Habitat", NASA Johnson Space Center, presented to Future In-Space Operations (FISO) Telecon Colloquium, Oct 2012.

14. Flynn Liam M.C., Rhodes Jonathan, and Andrews Peter J.D., "Therapeutic Hypothermia Reduces Intracranial Pressure and Partial Brain Oxygen Tension in Patients with Severe Traumatic Brain Injury: Preliminary Data from the Eurotherm3235 Trial", Journal of Therapeutic Hypothermia and Temperature Management. September 2015, 5(3): 143-151.

15. Mark B. Roth and Todd Nystul. “Buying Time in Suspended Animation”. Scientific American, 1 June 2005

16. Ignat'ev DA, Gordon RIa, Patrushev IV, Popov VI. “The functional brain state of hibernators and nonhibernators at different animals temperatures”. Usp Fiziol Nauk. 2012 Jan-Mar;43(1):48-74. Review. Russian.

17. Popov VI, Medvedev NI, Patrushev IV, Ignat'ev DA, Morenkov ED, Stewart MG. “Reversible reduction in dendritic spines in CA1 of rat and ground squirrel subjected to hypothermia-normothermia in vivo: A three-dimensional electron microscope study. Neuroscience. 2007 Nov 9;149(3):549-60. Epub 2007 Sep 11. Erratum in: Neuroscience. 2008 Apr 9;152(4):1145. “

18. Therapeutic hypothermia and controlled normothermia in the intensive care unit: Practical considerations, side effects, and cooling methods. Polderman, Kees H. MD, PhD; Herold, Ingeborg MD. Critical Care Medicine March 2009. Volume 37, pg 1101-1120

19. Ji-Yao Jiang, Ming-Kun Yu, Cheng Zhu. “Effect of long-term mild hypothermia therapy in patients with severe traumtic brain injury.” 2000 J. Neurosurg 93:546-529

20. Mild Prolonged Hypothermia for large intracerebral hemorrhage. Stykov D, Wagnwe I, Volbers B, Doerfler A, Schwab S. Neurocrit Care, April 2013(2): 178-183

21. “Federal Research is Exploring Potential for ‘Human Hibernation’”, CNSNews Article, published 5/19/2009, http://cnsnews.com/news/article/federal-research-exploring-potential-human-hibernation/, Last visited: May 8, 2014.

22. Ji-Yao Jiang, Ming-Kun Yu, Cheng Zhu. “Effect of long-term mild hypothermia therapy in patients with severe traumatic brain injury.” 2000 J. Neurosurg 93:546-529

23. Haouzi P, Notet V, Chenuel B, Chalon B, Sponne I, Ogier V et al. (2008). "H2S induced hypometabolism in mice is missing in sedated sheep". Respir Physiol Neurobiol 2008. 160 (1): 109–15.

24. Mirtallo J, Canada T, Johnson D, et al, "Safe Practices for Parenteral Nutrition," JPEN J Parenter Enteral Nutr, 2004, 28(6):S39-70. [PubMed 15568296]

25. ASPEN Board of Directors and the Clinical Guidelines Task Force, "Guidelines for the Use of Parenteral and Enteral Nutrition in Adult and Pediatric Patients," JPEN J Parenter Enteral Nutr, 2002, 26(1 Suppl):1-138

26. Therapeutic hypothermia and controlled normothermia in the intensive care unit: Practical considerations, side effects, and cooling methods. Polderman, Kees H. MD, PhD; Herold, Ingeborg MD. Critical Care Medicine March 2009. Volume 37, pg 1101-1120

27. McQuillen, J.B., et. al., “Final Report for Intravenous Fluid Generation (IVGEN) Spaceflight Experiment”, NASA, TM-2011-217033, July 2011.

28. St. Germain, B., et al., "Utilizing Lunar Architecture Transportation Elements for Mars Exploration," AIAA-2007-6136, Space 2007, Long Beach, California, Sept 18-20, 2007.

29. "International Space Station Environmental Control and Life Support System", NASA Facts FS–2008–05–83–MSFC. Retrieved Sept 2007.

30. Wertz, J. R., Everett., D. F., Puschell, J. J., *Space Mission Engineering: The new SMAD*, Microcosm Press, 2011.

31. Larson, W. J. and Pranke, L. K., *Human Spaceflight Mission Analysis and Design*, Space Technology Series, The McGraw-Hill Companies, Inc., 1999.

32. Eckart, P., *Spacecraft Life Support and Biospherics*, Space Technology Series, Microcosm, Inc., El Segundo, CA, and Kluwer Academic Publishers, Dordrecht, The Netherlands, 1996.

33. Poston, D., "The Heatpipe-Oerated Mars Exploration Reactor (HOMER)", Los Alamos National Laboratory, Oct 2000.

34. Martin, J., Reid, R., "Sodium Based Heat Pipe Modules for Space Reactor Concepts: Stainless Steel SAFE-100 Core", Paper 4275 ICAPP 2004, Pittsburgh, PA, June 13-17, 2004

35. Humble, R. W., Henry, G. N., Larson, W. J., *Space Propulsion Analysis and Design*, Space Technology Series, Learning Solutions, 2007.

36. "International Space Station Cupola Observation Module", European Space Agency, http://www.esa.int/Our_Activities/Human_Spaceflight/International_Space_Station/Cupola, Retrieved Sept. 2015.