TORPOR INDUCING TRANSFER HABITAT FOR HUMAN STASIS TO MARS

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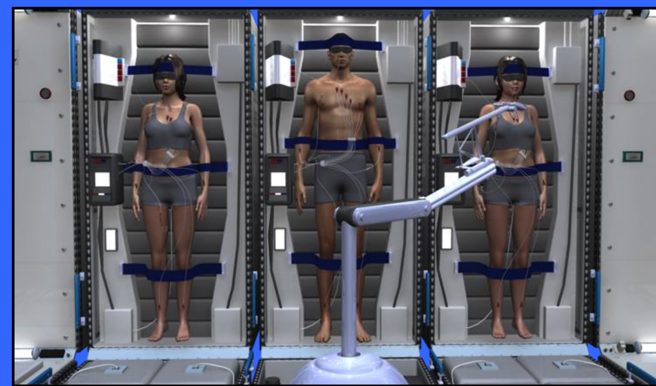

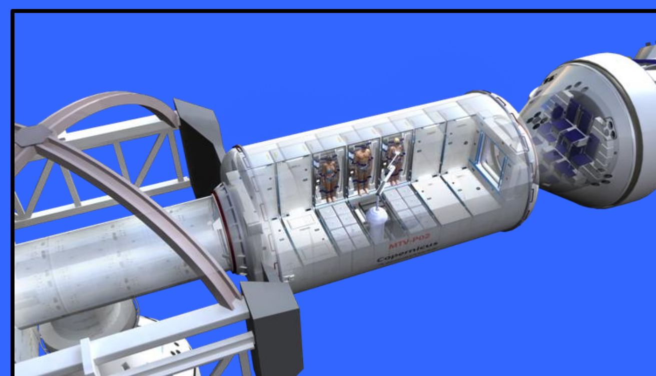

SpaceWorks®

NASA INNOVATIVE ADVANCED CONCEPTS (NIAC)
PHASE I
FINAL REPORT

TORPOR INDUCING TRANSFER HABITAT FOR HUMAN STASIS TO MARS

Grant Number: NNX13AP82G

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11 May 2014
Version 1.0

Prepared for

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Space Technology Mission Directorate (STMD)
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Washington, D.C. 20546-0001

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List of Acronyms

CTV	Crew Transfer Vehicle
DDT&E	Design, Development, Testing & Evaluation
DRA	Design Reference Architecture
ERV	Earth Return Vehicle
EVA	Extra-Vehicular Activity
H2S	Hydrogen Sulfide
HBE	Harris-Benedict Equation
ICP	Intracranial Pressure
IMLEO	Initial Mass in Low Earth Orbit
IV	Intravenous
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MOI	Mars Orbit Insertion
MTV	Mars Transfer Vehicle
NAFCOM	NASA-Air Force Cost Model
NASA	National Aeronautics and Space Administration
NIAC	NASA Institute for Advanced Concepts
NTR	Nuclear Thermal Rocket
SEI	SpaceWorks Enterprises, Inc.
SpaceX	Space Exploration Technologies, Inc.
STMD	Space Technology Mission Directorate
TEI	Trans-Earth Injection
TH	Therapeutic Hypothermia
TMI	Trans-Mars Injection
TPN	Total Parenteral Nutrition
TransHab	Transfer Habitat
TRL	Technology Readiness Level
VSH	Vision System Habitat

Foreword and Acknowledgements

Acknowledgment is given to the NASA Innovative Advanced Concepts (NIAC) program within the Space Technology Mission Directorate (STMD) for funding of this Phase I study that encompasses research addressed in this paper. Sincere appreciation is extended to NIAC Program Executive Dr. Jay Falker, NIAC Program Manager Mr. Jason Derleth, NIAC Outreach Manager Ms. Kathy Reilly, and NIAC Senior Science Advisor Dr. Ron Turner for providing material and collateral support on this project.

At SpaceWorks, insight into the system-level cost impacts and results were provided by Ms. Elizabeth Buchen. Mr. Mark Elwood generated all of the concept renders and illustrations contained herein.

For providing their time and medical expertise, we wish to thank Dr. Alejandro Rabinstein, M.D. Neurology at the Mayo Clinic, Dr. Robert Englert, Head of Neonatology at Portsmouth Naval Medical Center, and Dr. Richard Gist, Anesthesiologist and Critical Care Specialist.

For providing their time and expert opinions regarding their medical systems, the team also extends a thank you to Ms. Jessica Pitt, Product Director for Pinnacle at B. Braun Medical, Inc., to Mr. Fred Colen, President and CEO at BeneChill, Inc., Mr. Joe DeStefani, Research Director at BeneChill, Inc., Mr. Peter D’errico, Head Researcher for Koala at NovaMed, Inc., and Mr. Sam Privitera, V.P. of New Product Development at Bard Medical, Inc.

Executive Summary

SpaceWorks Enterprises, Inc. has performed an initial evaluation of an advanced habitat system designed to transport crews between the Earth and Mars. This new and innovative habitat design is capable of placing the crew in an inactive, torpor state for the duration of the in-space mission segments. This substantially reduces the mass and size of the habitat, which ultimately leads to significant reductions in the overall architecture size.

Our approach for achieving this is based on extending the current and evolving medical practice of Therapeutic Hypothermia (TH) – a proven and effective treatment for various traumatic injuries. TH is a medical treatment that lowers a patient's body temperature by just 5 to 10 degrees Fahrenheit causing their metabolism to reduce significantly and the body to enter an unconscious state. This method avoids the intractable challenges often associated with cell metabolic cessation through cryogenic freezing and other highly speculative approaches.

Figure 1. Torpor-Inducing Mars Transfer Habitats

TH is a proven treatment for traumatic injuries; however it has not been applied for non-critical care purposes due to current lack of purpose (i.e. no practical need). The opportunity exists to use TH in this capacity to enable and enhance our human spaceflight capability. With this concept, we have the potential to simultaneously solve multiple exploration challenges.

This concept is inherently multifaceted and introduces a number of wide-ranging questions that span medicine, physiology, psychology, and aerospace design. To summarize a few medical facts on what is currently known:

- Therapeutic Hypothermia (TH) is an emerging and rapidly evolving medical procedure that the medical community is still identifying the multiple benefits and uses to which it can be applied
- Human patients have been placed in a continuous torpor state using TH protocols for periods <u>up to 14-days</u>
- Humans have undergone multiple TH induction cycles with <u>no negative or detrimental effects reported</u> in either the near term recovery period or long term
- Testing in animals has shown that cancerous tumor growth and the effects of radiation are significantly reduced and slowed during the torpor-state (on par with metabolic rate reduction)
- While not currently recommended as a standard treatment for increased intracranial pressure (ICP) in any clinical setting, recent studies suggested that TH can lower ICP and may improve patient outcomes
- Human patients have regularly received sustenance for extended durations (>1 year) from an all-liquid solution, called Total Parenteral Nutrition (TPN), which can meet all hydration and nutritional needs

- Based on over a dozen studies with hundreds of patients, there was no evidence suggesting that TPN promotes bacterial overgrowth, impairs neutrophil functions, inhibits blood's bactericidal effect, causes villous atrophy, or increases the risk of death due to gastrointestinal complications

- All key hardware systems required are currently available in non- or semi-automated forms

While hard to assess quantitatively, through supposition it is reasonable to assume that the crew's mental well-being will be substantially improved by effectively eliminating the 400 days spent in transit to and from Mars. They will enter the torpor state upon Earth departure and awake in Mars orbit approximately 200 days later. This can avoid many of the challenges with crew compatibility, potential interpersonal conflicts, boredom, and depression. Upon successful completion of the mission at Mars, they will re-enter the torpor state for the journey home, awakening in cis-lunar space another 200 days later.

Specific results of the habitat design work performed to date have yielded the following:

- Compared to the current NASA reference TransHab design, the torpor-enabled habitats indicated mass reductions ranging from 52% to 68%, depending on the specific configuration, for the same mission requirements and non-torpor technologies

- Crew size sensitivity study results showed that the torpor-technology can be used to double the number of crew members for the same habitat mass, including crew and consumables

- The impact to the habitat of cycling the crew such that one crew member is conscious at all times during the transit phase was determined to be minimal

- Compared to the current NASA Mars reference architecture, IMLEO mass reductions ranging from 25% to 44% were achieved

- A torpor-enabled architecture using all-chemical propulsion can achieve the same IMLEO as a non-torpor, NTR-powered architecture

- The propulsion system performance on the non-torpor NTR-powered architecture would be required to increase by 22%, or an Isp increase of 200+ s, to achieve the same system-level mass reduction impacts obtained from a torpor-enabled habitat.

- An NTR-powered, Opposition-class mission becomes a viable option using torpor and can be accomplished with an IMLEO on par with a non-torpor, Conjunction-class NTR-powered architecture.

- Preliminary cost results indicate that a Mars mission campaign utilizing a torpor-enabled architecture can support almost twice as many crewed missions (6 vs. 3) compared to a non-torpor architecture

Based on this body of knowledge and numerous conversations with medical experts, we can make the following summary statements:

- To date, the team has found **no "show-stoppers"**, although more research and review is still required

- Results indicate **substantial habitat mass reduction** and **significant architecture improvements** are achievable even for conservative system designs

- In the cumulative experiences of the team, no other single technology has been found to have such a significant impact on a system element and across an architecture

Based on research and work conducted in Phase I, the SpaceWorks-team firmly believes there is strong evidence to justify the initiation of a rigorous development program if the merits of this approach continue to be justified.

1. Introduction and Rationale

The idea of suspended animation for interstellar human spaceflight has often been posited as a promising far-term solution for long-duration spaceflight. 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 (i.e. torpor) with significantly reduced metabolic rates in humans over extended periods of time. NASA should leverage these advancements for spaceflight as they can potentially eliminate a number of very challenging technical hurdles, reduce the IMLEO for the system, and ultimately enable feasible and sustainable missions to Mars.

Current estimates for Mars in-space habitats range from 20 t to as high as 50 t for crew sizes between 4 and 6 and habitat residence times of 360-400 days[1]. This is a sizeable hardware element that ultimately just serves to provide a place to contain the crew in a comfortable manner for transit periods to Mars. These habitats require advanced life support systems, heavy radiation shielding and SPE shelters, sleeping quarters, consumable preparation areas, exercise equipment, medical labs, and science stations. Additionally, any active mechanical systems require multiple levels of redundancy that further increase system mass and cost.

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. Some of the mass savings could then be used to enhance mission capability (e.g. reduce trip times) and improve safety (e.g. thicker radiation shielding). This can all be done with almost no detrimental impact to the scientific value or return from the mission.

Figure 2. Torpor Habitat Concept Overview Poster

SpaceWorks proposed the design of a torpor-inducing Mars transfer habitat and an architectural-level assessment to fully characterize the impact to Mars exploration. The habitat is envisioned as a very small, pressurized module that is docked around a central node/airlock permitting direct access to the Mars excursion vehicle and Earth return capsule by the crew.

The habitat primarily consists of sleep chambers that the crew would enter for stasis prior to Earth or Mars departure. These chambers would use a combination of body cooling systems and/or drugs to initiate and sustain the torpor state. Metabolic rates are expected to be reduced significantly over normal resting state, minimizing oxygen and nutrient requirements. The body's core temperature must be reduced 5^{o} to 10^{o}F to enable this. There are a number of ways to achieve this, all of which were investigated during Phase I. In stasis, body hydration and sustainment is provided through intravenous (IV) means. The ability to fully automate these systems is required (unless a decision is made to keep one member conscious during transit). The impact of inducing artificial gravity is also examined in Phase I.

Complete end-to-end Mars mission architectures were evaluated using the new habitat design. For comparison purposes, technology assumptions being used in other ongoing NASA studies were used. This human-stasis, or torpor-enabled, option were then compared with various Design Reference Architectures (DRAs) to quantify the impact and merits of the approach.

2. Background

2.1. Mars Exploration

Enabling the human exploration of Mars is arguably one of the most challenging problems whose achievement would represent one of the greatest feats 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.

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.

<u>Engineering</u>-

In order to safely send and return a crew from the surface of Mars, a massive system-of-systems architecture is required that will contains dozens of system elements, each with dozens of systems and subsystems within each of these. Ensuring that each architecture element is able to interface with the rest of the system is a massive coordination problem. Additionally, it is critical that each hardware piece (e.g. component, subsystem, etc.) meets the required mass, power, and volume budgets to make sure the combined system will work. Mass growth in one area can significantly increase the size of other elements due to the coupled nature of the systems.

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[3]. 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.

Round-trip Mars missions tend to be on the order of 2.5-years, with the biggest variation being in how long the surface stay/residence time is for the crew. All hardware systems and machines will need to be redundant and able to operate for the duration of the mission as only minimal spare parts and repairs will be possible. In addition to the need for highly robust systems, both the required level of redundancy and spare parts increase the total system mass.

<u>Affordability and Sustainability-</u>

A good first-order indicator of exploration mission costs, assuming similar technology levels, is the system's Initial Mass in Low Earth Orbit (IMLEO). The IMLEO for the crew stage of a typical Mars mission is often 300-500 tonnes (on par with the ISS), compared to ~120 tonnes for the Apollo-era lunar missions. Any approaches that can reduce the IMLEO are likely to have significant costs savings associated with them, assuming the technology development costs required to achieve the savings are not substantial.

Not only is IMLEO an indicator of the amount of mission hardware needed, but it indicates the Earth-to-orbit (ETO) payload lift capability needed to place all these elements and propellants into orbit. Even with a vehicle like NASA's SLS, a Mars-class mission could require half a dozen or more launches in just a few months' time for a single mission. Given that the current SLS launch manifest envisions 1-launch per year, this will put major demands on the operations infrastructure.

The affordability and more importantly, sustainability, of the architecture approach must be factored into the solution. If we are to accomplish more than a “flags and footprints” mission with lasting consequences we need to consider technologically innovative solutions that will have a long-term impact on the program.

Human Factors-

The introduction of the human crew to the architecture, compared to robotic exploration, has major consequences to the mission design. Time becomes of the essence as the human body is not naturally adapted and designed for survival in the space environment.

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 position of the planets. 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.

Physiologically, the human body experiences a number of detrimental effects in space. 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. Additionally, the extended exposure to high-levels of radiation can have near-term as well as permanent, long term mortality rate impacts. Other complications such as increased intracranial pressure (ICP), spinal elongation, and altered immune systems are also compounded with mission duration.

Psychologically, the 2+ year mission duration is 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 International Space Station (ISS) for missions of only 1-year in duration have shown a significant increase in recorded conflicts during the latter half of the mission[3]. 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[3].

2.2. Hibernation and Stasis

2.2.1. Types of Hibernation

There are three ways that organisms are known to hibernate in nature: obligate hibernation, facultative hibernation, and torpor.

Obligate hibernators spontaneously enter hibernation regardless of the ambient temperature or their access to food. In these creatures their core body temperature drops to environmental levels and heart/respiration rates will slow drastically. This form of hibernation is also characterized by periods of sleep with periodic arousals where the body temperature and heart rate return to normal levels to pass waste (e.g. marmots, arctic ground squirrel).

Facultative Hibernators only enter hibernation when they are either cold stressed, food deprived, or both for survival purposes (e.g. Prairie Dogs). In doing so these animals are able to awaken and eat during warmer days when food may be available.

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

2.2.2. Hibernation in Nature

Table 1 provides a listing of mammals that are known to hibernate or enter torpor states. Of particular interest is the black bear's ability to re-absorb nitrogen waste, contained in urine, internally and thus prevent muscle atrophy. The dwarf lemur is also significant as the only known primate hibernator. During hibernation periods lasting up to 5 months, it can reduce its metabolic rate to just 2% of its active state.

Table 1. Hibernating Animals[5]

Species	Duration [months]	Comments
Carnivora		
Black Bear	3 to 5	Minimal body temperature reduction Consumes 25-40% of body mass Nitrogen waste from body is recycled, preventing muscle atrophy
Rodentia		
Arctic Ground Squirrel	Up to 6	Experiences significant body temperature reductions
Marmot	4.5 to 8.5	Body temperature remains at ambient for days to weeks, followed by a brief return cycle (<24hr) to higher body temperature
Prairie Dog	4 to 5	Can spontaneously awaken to eat on warmer days
Groundhog	Up to 6	Moderate body temperature changes Heart-rate slows to approximately 4 beats per minute.
Primates		
Dwarf Lemur	4 to 5	Can reduce metabolic rate to 2% of "active" rate Only primate known to hibernate

2.2.3. Artificially Induced Hibernation

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 Univ. 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[6].

Inhaled Hydrogen Sulfide (H_2S) 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[7].

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[8,9].

Temperature-based cooling approaches have the largest body of medical data available for humans and is 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.

2.2.4. Latest Experimental Data

Chinese studies showed evidence of increased benefit from prolonged TH (up to 14-days) without increasing the risk of complication[10]. Recent studies confirm this data[11].

The goal of both of these studies study was to investigate the protective effects of long-term (3–14 days) mild hypothermia therapy (33–35 °C) on patients with severe traumatic brain injury (TBI). In half the patients in the mild hypothermia group, body temperatures were cooled to 33 to 35 °C for 3 to 14 days. Rewarming commenced when the individual patient's intracranial pressure (ICP) returned to the normal level. Body temperatures in 44 patients assigned to a normothermia group were maintained at 37 to 38 °C. Each patient's outcome was subsequently evaluated one year later. Approximately one year after TBI, the mortality rate and the rate of unfavorable outcome was significantly reduced in the mild hypothermia group. In the normothermia group, the mortality rate was 50% higher and the rate of favorable outcome was 40% lower. The data produced by these studies demonstrated that long-term mild hypothermia therapy significantly improved outcomes in patients with severe TBI[12,13].

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[16].

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[12,15].

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

2.2.5. Potential Evidence Supporting Ability and Recovery:

Real-world evidence offers encouragement that this process can be expanded from days to weeks or months once fully understood. Consider the well-publicized case of Mitsutaka Uchikoshi from Japan in 2006[17]. He was found after 24-days unconscious on a snowy slope in a hibernation state after a mountain hiking accident. His body temperature had dropped to 22 ^{o}C (71 ^{o}F) and his pulse was undetectable. Upon arrival at a hospital and his body experiencing warmer conditions, he woke up and has since made a full recovery.

In 1999, Dr. Anna Bagenholm, who at 29 years old, was revived after her heart was stopped for 3 hours after being submerged under the ice while skiing. Her body temperature quickly dropped to 14 ^{o}C and entered a torpor state, enabling her to survive the accident[18]. There is also the astounding case of Erika Norby, a one-year old, who in 2002 was revived after her heart stopped beating for over two hours. An accident left her exposed to -20 ^{o}C weather conditions and her core temperature had dropped to 17 ^{o}C[19,20].

More recently in the news was the miraculous survival of a 16-year old boy who stowed away in the wheel hub of a 747 travelling to Hawaii. He survived freezing temperatures and very low oxygen levels occurring at the 38,000-ft flight altitude for several hours and recovered with no medical complications. Doctors speculate that his body quickly entered a hibernative state due to the rapid temperature drop thus permitting him to survive at the minimal oxygen levels[21].

These cases are reminders of the resiliency of the human body and what it appears to be naturally capable of under certain conditions. Through medical science and technology, we can determine these exact conditions and recreate them as needed to induce similar effects for the purposes of achieving the human exploration of space.

3. Phase I Study Objectives

There were two primary objectives for the Phase I effort. The first objective is to identify any medical/physiological or technical hurdles that might prevent the proposed approach and system from being realized. As previously noted, the demonstrated state-of-the-art is a 14-day stasis period for humans. 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 assess the merits of this approach and quantify its overall value and system-level impacts. While there are always multiple solutions to solve a particular problem, the challenge is in identifying those that offer the greatest return with minimal cost and risk associated with their development and implementation. To this end, architecture-level studies based on current Mars exploration mission designs are conducted. While there are obvious unknowns associated with any technology that has yet to be fully developed, uncertainty is addressed through system-level trades and uncertainty analysis. For example, trades on crew-size, habitat mass growth margin, and mission type including Conjunction vs. Opposition-class and slow-transfer are examined.

4. Medical Perspective

4.1. Rationale and Goal

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.

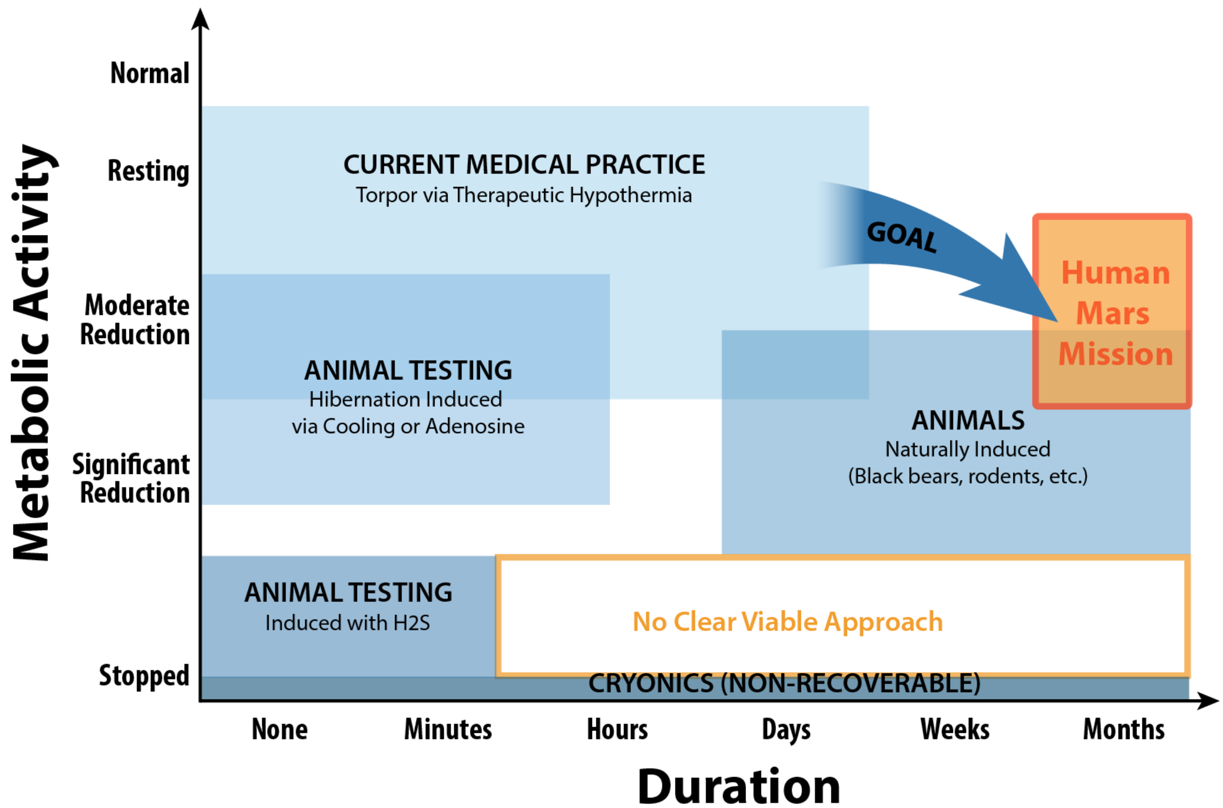


Figure 3. Medical Knowledge Spectrum

4.2. History

Body cooling as a therapy for traumatic injury has been theorized, and even tested, since antiquity. The Greek physician Hippocrates, arguably the world's first modern doctor, advocated the packing of wounded soldiers in snow and ice (400 BCE) for transport to army hospitals[22]. In 1810, Napoleonic surgeon Baron Dominique Jean Larrey tested this theory after noting that wounded officers who were kept closer to the fire survived less often than the minimally pampered infantrymen on the outskirts on the camp.

4.2.1. Modern Usage

The "modern" era of Therapeutic Hypothermia was initiated by the U.S. Military during World War II. The table below shows a timeline of the most significant events in the formation of current TH protocols.

Table 2. Milestones in Development of Therapeutic Hypothermia[23]

Year	Description
1945	First medical articles concerning use of hypothermia published
1955	Division of Medical Sciences, NRC symposium on the Physiology of Induced Hypothermia, sponsored by U.S. Army, Navy, and Air Force
1980	Animal studies prove that mild hypothermia acts as a general neuro-protectant following a blockage of blood flow to the brain
2002	Two landmark human studies published simultaneously by the New England Journal of Medicine
2003	American Heart Association endorses the use of TH following cardiac arrest
2005	Protocols for use of TH for prenatal infants established
2009	RhinoChill® IntraNasal cooling system enters clinical trials

The first medical article concerning hypothermia was published in 1945. In the 1950s hypothermia was employed during intracerebal aneurysm surgery to help create a bloodless field. Because most of the early research on TH focused on placing patients in a deep hypothermia (body temperature between 20–25 °C/68–77 °F), numerous serious and life threatening side effects were noted, and hypothermia was viewed as impractical in most clinical situations.

By the 1980s animal studies were showing the ability of mild hypothermia to act as a neuroprotectant. As noted above, the 1999 skiing accident of Anna Bågenholm's (her heart stopped for three hours and her body temperature dropped to 13.7 ^{o}C prior to being resuscitated without any adverse effects) kick-started a new interest in TH. By 2002 two landmark human studies were published by the New England Journal of Medicine that showed the positive effects of mild hypothermia following cardiac arrest [23]. Currently, almost every major hospital around the world includes hypothermic therapies in their care for critically ill patients. There are even some researchers that argue that hypothermia provides better neuroprotection than any drug treatment[24]. By 2005 multiple studies had also shown that hypothermia is a highly effective treatment for preterm and newborn infants suffering from birth asphyxia, significantly increasing the chance of survival without brain damage[25].

4.3. Therapeutic Hypothermia (TH)

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. Initial use on a limited basis started in 1980's, but since 2003 Therapeutic Hypothermia has become a **staple of Critical Care** for newborn 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[26].

4.3.1. State-of-the-Art Usage

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.

Notable cases reported involving the use of TH in the news include:

- N.Y. Times (2013) - Michael Schumacher at critical stage in treatment for head injury. Doctors treating ex-F1 champion are keeping him in an induced, hypothermic comatose state to cool his brain and reduce swelling

- Boston Globe (2013) – Small Lily Harvey's life saved five times by staff at Southampton General Hospital's PICU by keeping her in hypothermic state

- Los Angeles Times (2013) - Burbank marathoner thanks medical pros who saved him after finish-line heart attack

- Associated Press (2013) - 28-Year-Old Cardiac Arrest Survivor Meets EMS Personnel Who Helped Save Him

- Associated Press (2013) - Brave toddler born with major heart complications defies odds to take part in 10k walk in aid of hospital that saved her.

Figure 4. Recent Individuals Receiving Therapeutic Hypothermia (TH) Treatment

4.3.2. Medical Procedure

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 [27]. 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 3 below shows an example of a typical cooling and warming timeline.

Table 3. 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

4.3.3. Temperature and Vital Signs Monitoring

Core body temperature should be monitored continuously during therapeutic hypothermia (TH). The most common method of measurement is via central venous temperature, but several other options are available, including esophageal, bladder, or rectal probes. Esophageal temperature is the most accurate surrogate method[24].

Basic vital sign monitoring is required during therapeutic hypothermia. This normal includes a 12 lead ECG to monitor cardiac activity, a central line monitor and measure systemic blood pressure and an indwelling catheter or urine collection system to monitor urine output to measure for dehydration.

4.4. Body Thermal Management Systems

Torpor is achieved by decreasing a crewmember's core temperature to approximately 34 ^{o}C (93 ^{o}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[27].

4.4.1. Invasive

Invasive techniques involve the insertion of a double lumen catheter into a major vascular structure. In most cases this cooling catheter would be inserted into the crew's femoral vein. A cooled saline solution is then circulated through either a metal coated tube or a balloon located in the catheter body. The saline cools the patient's whole body by lowering the temperature of a patient's blood through conduction cooling. No cooled fluid actually enters the patient's blood stream. The CoolGard 300R™ with IcyT Catheter by ZOLL Medical, as shown in Figure 5, is an example of an invasive system currently in use. While these systems are very effective at controlling body temperature, they are typically used for shorter term stasis periods or with infants and not desirable for longer induction periods.

Figure 5. CoolGard 3000R^{TM} with IcyT Catheter by ZOLL Medical

4.4.2. Non-Invasive

An alternative to the aforementioned invasive procedure is a non-invasive technique that involves circulating cold water through a blanket or body pads. This method lowers the core temperature exclusively by cooling a crewmember's skin, requiring no clinician performed invasive procedures. Although this technique of temperature management dates back to the 1950s, it still remains in use today. The treatment also represents the most well studied means of controlling body temperature. The ArcticSun 5000™ by Medivance, Inc. is an example of an approved and widely used non-invasive system. The primary drawback of this system is the need for long term contact of the blankets and pads with the skin which could cause surface erosion. These pads also need to be changed every seven days per manufacture recommendations.

4.4.3. Trans Nasal Evaporative Cooling

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 6, is an example of a trans nasal evaporative system currently in use.

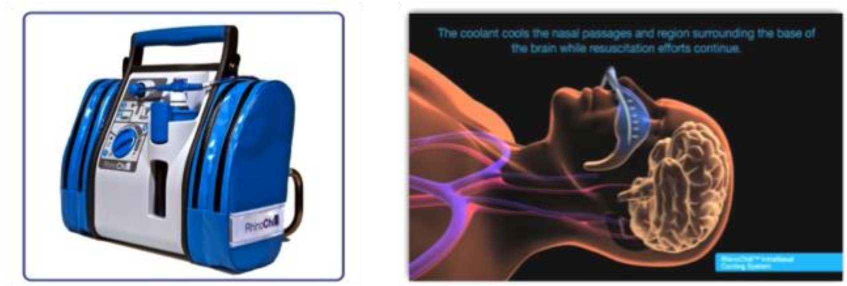


Figure 6. RhinoChill™ System by BeneChill, Inc.

4.4.4. Environmental

The unique cold environment of space would allow cooling the astronauts core temperature by lowering the temperature of the entire habitat. Temperature stability could then be achieved through conductive warming through bedding pads with embedded heating elements, similar to the KOALA System™ produced by NovaMed Inc. (see Figure 7).

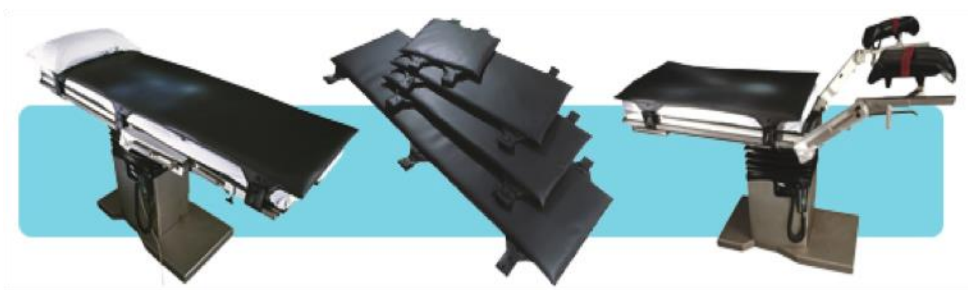


Figure 7. KOALA System™ by NovaMed Inc.

4.5. 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[28].

4.5.1. Contents

A typical or normal TPN mixture contains five different substances[29]: They are:

1. Dextrose: Dextrose-containing stock solutions are available in a variety of concentrations and provide a majority of the caloric contribution of total parenteral nutrition.
2. Amino acids and electrolytes: Amino acid solutions contain most essential and nonessential amino acids. Electrolytes are contained in the buffer solution that is used to help administer the TPN. Most electrolytes are given with maintenance fluids and are not given with the TPN dose.
3. Lipids: Lipids are provided as an emulsion that is added to the mixture (three-in-one mixture).
4. Vitamins and trace elements: Multiple studies have been conducted evaluating the benefit of adding vitamins and trace minerals to TPN. These studies have not conclusively noted any benefit. However, given their safety, it seems reasonable to provide vitamins and trace elements to astronauts that would be undergoing prolonged TPN reliance of all nutrition needs. The optimal mixture of vitamins and trace elements is yet to be determined.
5. Glutamine: Glutamine is a precursor for DNA synthesis and is an important fuel source for rapidly dividing cells.

The exact concentration of each fluids in the TPN mixture can vary based on daily measurements of a person's vitals and blood to provide the ideal nutritional requirement.

4.5.2. Dosing

The daily TPN requirement for the human body is a well understood science[29]. 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 8 provides the required TPN mass per person per day based on a male crew member weighing approximately 175-lbm. 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.

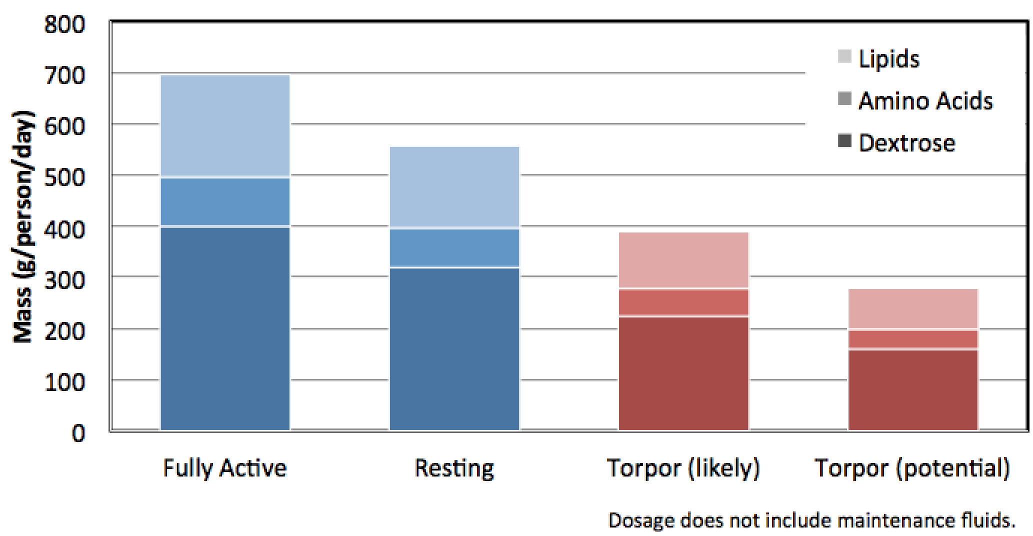


Figure 8. TPN Dosage Rate vs. Activity Level

4.5.3. Administration

Total Parenteral Nutrition (TPN) can be administered by continuous infusion over 24 hours or cyclic infusion over 12-14 hours. Cyclic infusion is used with a tapering-up period at the beginning and a tapering-down period at the end to avoid electrolyte and blood sugar complications. Infusion occurs via pump using either peripheral or central venous line[29].

While historically medical personnel have mixed TPN solutions manually, hardware has recently been developed to automate this process. These automated systems contain a nutrient bank that is used to mix daily doses of TPN based on weight, activity and lab analysis parameters.

The Pinnacle system, shown in Figure 9, is an automated TPN delivery system created by B. Braun Medical, Inc. It is a manually inputted and activated system that runs on a 115 VAC, 60 Hz, 5.0 Amp electrical system. Control panel dimensions are height: 14.76 inches, width: 11.77 inches x depth: 1.93 inches with a weight of 10.78 lbs. Pump dimensions are height: 28 inches, width: 19.4 inches x depth: 11.8 inches with a weight of 30 lbs. Each nutrient reservoir contains a 2 Litre course container for mixing the final TPN solution. Discussions with Jessica Pitt, Product Director for Pinnacle, have shown that the system could be modified to include battery back-up and remote operation and control, as well as an increase in the nutrient source reservoir to any size desired. Little modifications would need to be made for this product to be space ready.

Figure 9. Pinnacle System^{TM} for Automated TPN Dispensing

4.5.4. Monitoring

Routine monitoring of total parenteral nutrition includes measurement of fluid inputs and output and periodic laboratory studies. In the hospital environment patients have serum electrolytes, glucose, calcium, magnesium, and phosphate labs performed daily until they are stable. Once stable these labs are typically decreased to a weekly basis[29]. On a space mission, it is expected that more rigorous monitoring will be conducted with daily measurements taken.

4.6. 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, as shown in Figure 10, on an actual space mission[30]. It is a handheld device that can convert regular drinking water to produce sterile, ultrapure water that meets the 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 litre 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.

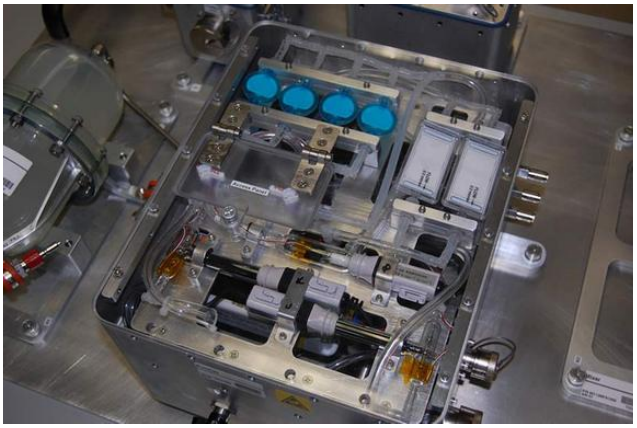


Figure 10. IVGEN System for Production of IV-grade Fluids (credit: NASA)

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.

4.7. Discussions with Medical Researchers and Practitioners

While Therapeutic Hypothermia and Total Parenteral Nutrition are well studied and often practiced medical procedures in every major medical center in the world, their use on healthy individuals over a long period of time in the space environment would be completely innovative. As no data exists at this time that we can use to answer some of the more pressing questions about long-term TPN and TH use, information can be extrapolated based on our current knowledge of these technologies. To address some of these issues SpaceWorks has consulted with several medical experts in multiple medical specialties to access the feasibility of long term use and overcoming the long-term medical complications that can occur.

Questions posed to clinical experts:

1. **What effects would long-term TH have on cognitive function? When the astronauts awaken would they have a recovery period they were fully mission ready?**

It is hard to determine if there are any direct effects of Therapeutic Hypothermia on cognitive function. Every patient that is currently placed into TH would already be suffering from impaired or decreased cognitive function due to their injuries, so it is not feasible to test the effects of TH alone on function without placing healthy individuals under TH with the specific goal to evaluate that effect. However, our clinical experts do not see any reason why TH should have significant effects on the cognitive function of the crew members.

2. **What are your concerns about the long-term use (greater than 10-14 days) of Therapeutic Hypothermia and Total Parenteral Nutrition?**

Electrolyte abnormalities caused by both TPN and TH were the consensus primary concern. However, all subspecialists agreed that this could be easily controlled by daily adjustments to TPN and maintenance fluids. The other primary concern was that, as a general rule currently, the longer that someone is under TH the slower and longer the rewarming process is. A majority of the risk associated with Therapeutic Hypothermia is not with initiation or maintenance of the TH state, but the rewarming process and the subsequent physiological effects that occur. Most experts agree at this time that shorter, repeat cycles of TH would be safer than single, long-term cycle.

3. What concerns exist about repeat cycles of Therapeutic Hypothermia?

None of our experts had any concerns with shorter, repeat cycles. Everyone thought that they would be tolerated well and, as discussed above, would prefer this method to longer cycles.

4. Would placing an astronaut provide any Psychological Advantages?

The Neurologist consulted by SpaceWorks feels that the mild sedation associated TH would not only provide psychological advantages but also suggested that placing the astronauts in a Torpor state could be "mentally protective", meaning that it would put the brain in a sleep/standby mood that would not require constant stimulation for good brain health.

5. How would healthy individuals tolerate Therapeutic Hypothermia compared to current TH patients?

Our consultants feel that healthy individuals would tolerate TH much better than the current patient population. Without the confounders of medical complications, they feel that crewmembers would have less chance of bleeding and infection (such as pneumonia due to decreased effects on cilia function), could tolerate longer periods of TH, would be easier and safer to wake, and would recover from the torpor state more quickly.

6. Would some crewmembers be better suited than others for Torpor missions?

There is a lot of medical evidence that shows that some people have less of a shivering response and physically handle both TH and the medications associated with its use better than others. There is obviously a genetic component to it, but our experts feel that this tolerance to cooling may be programmable. This would mean that you could test astronauts beforehand to see which ones better tolerate TH. You could also expose them to short periods of TH before the mission. This would "prime" them for Torpor and allow their bodies to become accustomed to the physiologic effects of TH. It would also prepare the crewmembers for the actual Torpor process, mentally decreasing their anxiety about the procedure.

Further work with the expert team of subspecialists assembled will enable us to address more questions and concerns like the ones above, as well as help guide research in the areas of prolonged TPN and TH in the space environment.

7. Can current Therapeutic Hypothermia and TPN equipment be used for this mission?

The RhinoChill™ system is an evaporative cooling system created by BeneChill, Inc. It uses a Hexan fluid compound and a nasal cavity cannula to deliver a spray of coolant mist that evaporates directly underneath the brain and base of the skull. It is a manually activated system (but automatically adjusts to regulate body temperature) that runs on a 115 VAC, 60 Hz, 6.0 Amp electrical system or a 4-hour battery pack. Total weight of the system is 10 lbs. Dimensions are height: 47-cm, width: 47-cm, depth: 18-cm. Discussions with Fred Colen, President and CEO of BeneChill, have shown that the system could be modified to include longer battery back-up and remote operation and control. Little modifications would need to be made for this product to be space ready.

The Koala System™ is a conductive warming system currently used for warming patients during surgical operations NovaMed, Inc. It is a manually activated system (but automatically adjusts to regulate body temperature) that runs on a 115 VAC, 60 Hz, 10.0 Amp electrical system. Weight for normal pad and control panel is approximately 7 lbs. In discussion with Peter Derrico, Head Researcher for Koala, indicated in a discussion that the system could be modified to include battery back-up and remote operation and control. In addition, due to the unique nature of the material the Koala warming pads could be modified to any shape, not limited to bedding, padding or even uniforms. Little modifications would need to be made for this product to be space ready.

The ArcticSun 5000™ is a non-invasive cooling system produced by Bard Medical Inc. It is an automated system that runs on a 230 VAC, 50 Hz, 5.5 Amp (115 VAC, 60 Hz, 11.0 Amp Nominal) electrical system. Total weight of the operating console, coolant (3-4L of normal saline), and attachments is 47 kg (103 lbm). Dimensions are height: 89-cm), width: 36-cm, depth: 47-cm. In discussions with Sam Privitera, V.P. of New Product Development, indicated in a discussion that the system could be modified to include battery backup and remote operation and control. The system as currently constructed is not space ready at this time though due to the fact the console must remain upright to prevent coolant leakage.

8. Can Therapeutic Hypothermia help minimize the adverse effects associated with placing the crew in a rotating environment to induce artificial gravity?

Again, specific testing would be need to be conducted to determine what affects the sedative state of Therapeutic Hypothermia would have on increasing the level to which the crew would tolerate artificial gravity. However, our clinical experts expect that the disorientation caused by spinning would not physiologically affect an astronaut that was in a Torpor state. This would allow for the induction of an artificial gravity in space, potentially minimizing both muscle atrophy and bone density loss on the long mission to and from Mars.

4.8. Crew Support Systems

The required crew support systems are identified and demonstrated in Figure 11 below.

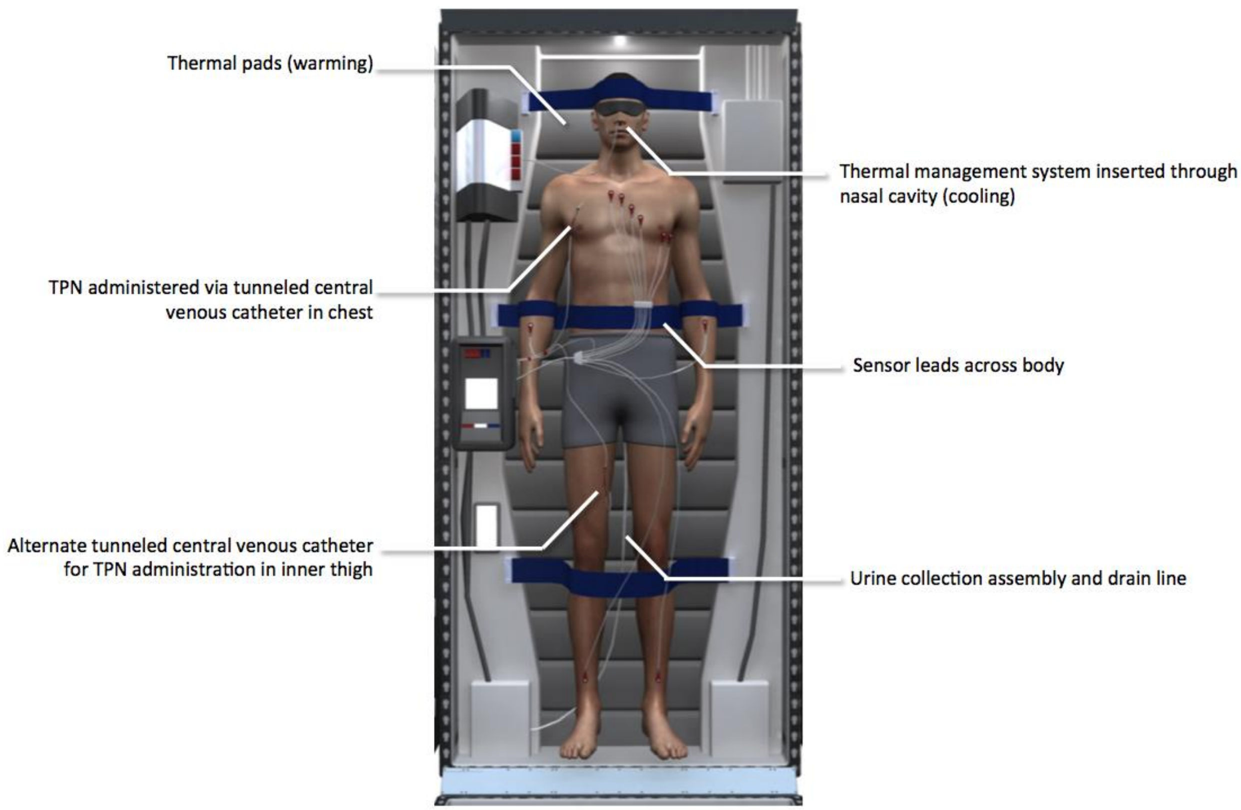


Figure 11. Implementation of Crew Support Systems

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 EKG).
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.

4.9. Potential Medical Challenges

The key medical challenges to be researched and mitigated for extended Torpor periods with the use of TPN are listed in Table 4 below. The issue area, initiator or cause, and comment on the issue or identification of the solution is provided. Note that while there are a number of potential challenges associated with torpor, there are a number of general human spaceflight challenges that are not unique to torpor. Each of the torpor-specific issues will be briefly discussed next.

Table 4. Summary of Concept Medical Challenges

Issue	Initiator	Solution/Comments
Torpor-Specific		
Thromboembolism (Blood Clotting)	Prolonged sleep status and indwelling IVs	Periodic heparin flushes to dissolve clots, Clotting is generally reduced in TH state, Minimize IV access
Bleeding	Decrease in coagulation factor activity	Not a significant concern outside of trauma May decrease risk of thromboembolism
Infection	Temperature reduction in white blood cell activity	Minimize IV access, improved sterile techniques, use of tunneled catheters and antibiotic-infused catheters
Electrolyte Imbalances	Decreased cellular metabolism	Close monitoring and IV stabilization with TPN
Fatty Liver and Liver Failure	Long term TPN usage	Can alternate source of lipids to reduce risk
Other Complications (hypo/hyper glycemia, bile stasis, etc.)	TPN and reduced metabolic rate	Augment TPN with insulin, exogenous CCK, etc. Avoid abrupt termination of TPN
General Crewed Spaceflight		
Bone Demineralization and Density Loss	Prolonged zero-G environment	Pharmaceuticals (e.g. bisphosphonates) Artificially-induced gravity
Muscle Atrophy	Disuse	Automated physical therapy tools Neuromuscular electrical stimulation (NMES)

4.9.1. Thromboembolism

Thromboembolism, or the formation of blood clots in the blood stream, can occur with any prolonged IV access. Peripheral IVs are particularly associated with blood clots, which is why a tunneled IV line is preferred. Prevention of clot formation includes good sterile practices, using centrally placed long-term IV lines, and utilizing new technology for such as anti-coagulation impregnated IV equipment. Treatment for thromboembolism is done with heparin flushes through the line to dissolve any formed clots[30]. In addition, a known side effect of Therapeutic Hypothermia is a general decrease in clotting factor activity[32]. (This would provide protection from the formation of a thromboembolism as well.

4.9.2. Bleeding

As described above a known side effect of Therapeutic Hypothermia is a general decrease in clotting factor activity. There is no documented evidence of any bleeding requiring the stopping of TH in patients that were not trauma patients already suffering from significant internal or external bleeding at the initiation of treatment[32].

4.9.3. Infection

TPN requires long-term IV access for the solution to run through, and the most common complication is infection of this catheter[33]. Therapeutic hypothermia does not incur a risk of overall infection, but can increase the risk of pneumonia and sepsis if infection occurs[34]. Prevention of IV line infection includes good sterile practices, using centrally placed long-term IV lines, and utilizing new technology for such as antibiotic impregnated IV equipment[35]. New studies show that in the case of infection the IV line need not be removed as previously thought. Treatment for central line infection includes IV administered antibiotics and rewarming and waking from the Torpor state.

4.9.4. Electrolyte and Glucose Imbalances

As addressed multiple times above, Therapeutic Hypothermia can be associated with electrolyte imbalances in patients. The use of TPN and the associated laboratory testing and solution preparation would mitigate this complication.

4.9.5. Fatty Liver Disease

Fatty liver is usually a rare and more long term complication of TPN. The main cause of this is common use of linoleic acid (an omega-6 fatty acid component of soybean oil) as the major source of lipids. Research is currently underway that shows that alternate sources of lipids have a much lower risk of this complication. Fatty liver disease is usually benign in nature and can be corrected with adjustments in diet and exercise[36].

5. Torpor Habitat Overviews

5.1. NASA Reference Habitat Design

The NASA DRA 5.0 in-space habitat is the TransHab inflatable module, a design concept originally proposed in the late 1990s as crew quarters for the International Space Station (ISS). The DRA 5.0 habitat is an evolved version of the TransHab designs developed for NASA DRM 3.0 and 4.0. It can support a crew of 6 in deep space for up to 400 days nominally and up to 900 days in a contingency. A number of advanced technologies are assumed including fully-closed regenerative life-support, inflatable structures, and composites. [37]

The TransHab is a hybrid structure that combines a rigid load-bearing core with an inflatable outer section. The TransHab central core is made from lightweight carbon-fiber composite materials and is comprised of two major sections. The center passageway is a tunnel that runs the length of the module and provides access to all levels. The outer shell interface provides three floors and dividers between compartments. Each end of the center passageway leads to a pressurized docking interface for crew egress and ingress to other vehicles.

Summary metrics for the DRA 5.0 TransHab vehicle are shown in Table 5 and an exterior view is shown in Figure 12.

Table 5. Summary Metrics for NASA Mars DRA 5.0 TransHab

Parameter	TransHab
Mission Configuration	Mars Conjunction-class Avg. 200-days(out), 500-days(surface), 200-days(return)
Crew Complement	6
Dry Mass	27.5 t
Consumables with Contingency	13.1 t
Total Volume	500 m^3
Habitable Volume	350 m^3
Length	9.0 m
Maximum Diameter	8.2 m

TransHab's inflatable shell consists of two-dozen layers of blanket insulation, micrometeoroid and orbital debris protection, and redundant pressurized bladders. The protective layers include Nextel space between open cell foam, and a layer of superstrong woven Kevlar to hold the module shell. The pressurized bladders are composed of Combitherm. The innermost layer, which forms the inside wall of the habitat module, is fireproof Nomex cloth[38].

For radiation protection, the sleeping location is heavily shielded with 19 g/cm^3 of protection. The remaining TransHab living space is only lightly shielded from the passive structure and equipment[37].

The Environmental Control and Life Support System (ECLSS) on the TransHab maintains habitable conditions in the pressurized cabin by providing oxygen to and removing carbon dioxide from the cabin atmosphere, filtering particulates and removing volatile organic trace gases from the air, and maintaining cabin pressure, temperature and humidity levels. The ECLSS is also responsible providing potable water for consumption, food preparation, and crew hygiene. Both the oxygen generation and water production loops are closed, meaning waste products are recycled and reused within the habitat. Though not specifically described in the reference DRA 5.0 documents, it is assumed that the DRA 5.0 TransHab would use ISS-heritage ECLSS components wherever possible.

On ISS, carbon dioxide is converted into oxygen using a three step process. First, carbon dioxide is removed from the cabin atmosphere with the Carbon Dioxide Removal Assembly (CDRA). The CDRA uses a regenerative 4-bed molecular sieve system that cycles between absorbing and venting carbon dioxide from the air. Second, the carbon dioxide is vented into the Carbon Dioxide Reduction Assembly (CReA) and combined with hydrogen gas. The

CReA uses the Sabatier reaction to convert the carbon dioxide and hydrogen gas into water and methane. The methane is vented into space as a waste product of the reaction, while the water is passed on to the Oxygen Generation Assembly (OGA) for the final step of the conversation process. The OGA uses electrolysis to break the water molecules apart into oxygen and hydrogen gas. The oxygen gas is returned to the cabin atmosphere, while the hydrogen gas is sent back to the CReA to support the Sabatier reaction. Additional tanked hydrogen gas provides the remaining hydrogen required for the CReA.

Figure 12. NASA Reference TransHab Design (credit: NASA)

The ISS water recovery system provides clean water by reclaiming all wastewater including water from crewmember urine and cabin humidity condensate. Crew urine is treated in the Urine Processor Assembly (UPA), which uses a low pressure vacuum distillation process to recover water. The UPA product water is combined with other cabin wastewater in the Water Processor Assembly (WPA). The WPA removes free gas and solid materials (hair, dust, etc.) before passing the water through a series of multifiltration beds. Finally the filtered water is passed through a high-temperature catalytic reactor assembly to purify the water of organic contaminants and micro-organisms. This process is repeated until the water is sufficiently clean[39].

The TransHab is outfitted with a number of crew accommodations. The galley includes a refrigerator-freezer, microwave oven, water dispenser, and food preparation equipment. The crew quarters contain personal compartments for each crew members with sleeping bag, sleeping restraints, personal item stowage, and a computer entertainment center. The crew health area contains a full-body cleansing compartment, changing area, exercise equipment, and a medical suite[38].

Electrical power is provided to the TransHab through four 125-m^2 rectangular photovoltaic solar arrays. Each array is capable of providing 12.5-kWe of electrical power, for 50-kWe total power production. The crew habitat itself only requires an average of 30-kWe; the remaining power is used by the zero boil-off cryocoolers (~15-kWe) and high data-rate communications systems (~5-kWe)[37].

To perform analysis work for this study, a parametric sizing tool was developed by SpaceWorks to generate mass estimates for different habitat configurations. This parametric sizing tool was first anchored to the baseline TransHab concept.

5.2. Torpor-Enabled Habitat Design for Zero-G Mars Mission

5.2.1. Overview

The baseline torpor-enabled habitat is shown in Figure 13. Its overall design is evolved from the ISS crew modules, particularly the Destiny module. The habitat is a rigid pressurized cylinder with 4.3-m diameter and 7.5-m length. At each end is a pressurized docking interface for crew egress and ingress to other vehicles. Like the DRA 5.0 habitat, the baseline torpor-enabled habitat can support a crew of 6 in deep space for up to 400 days nominally and up to 900 days in a contingency. Though designed for nominal crew-sleep conditions, there is sufficient livable volume to support the crew in the event of an emergency crew-awake scenario.

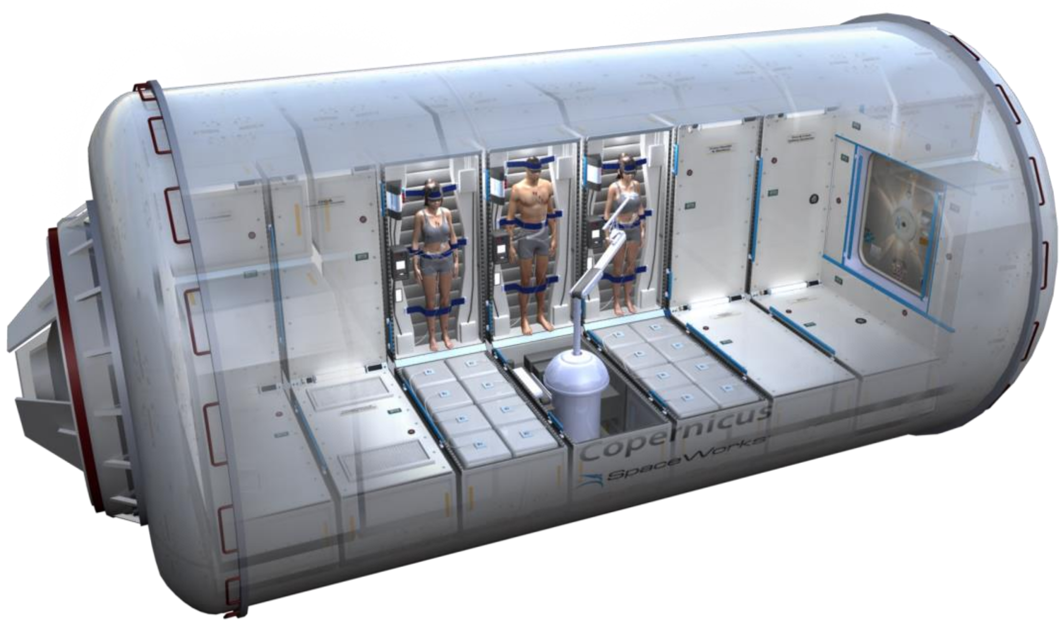


Figure 13. Baseline Torpor-Enabled Habitat Design : Internal View

Each crew member is allocated an individual torpor compartment. In the baseline design, there are three torpor compartments along each the port and starboard walls, aligned in the center of the module as shown Figure 13. The torpor compartments each contain all of the subsystems required to support the crew during the mission, including:

- Intravenous lines for the administering of TPN for crew 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 crew 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

The torpor compartments can also be partially radiation shielded, to provide the crew with comparable radiation protection as assumed in DRA 5.0.

The torpor habitat contains two robotic manipulator arms, one overhead and one in the deck, centrally located in the habitat to provide reach to all six crew members. The manipulator arms are used to manage and manipulated the crew lines, leads, and restraints during the mission. The arms are redundant; a single arm can access all six crew members.

The torpor habitat shares many ECLSS technology assumptions with the DRA 5.0 habitat. It uses a similar closed-loop oxygen production system with the CDRA, CReA, and OGA and closed-loop water recovery system. 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 TransHab counterparts.

The crew accommodations requirements for the torpor habitat are much less than those of the TransHab. All crew 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 crew will spend the majority of the mission in an inactive torpor state, no exercise equipment or individual crew quarters are provided.

Because there are much fewer crew accommodations systems in the torpor habitat, its power requirements for are significantly reduced from the DRA 5.0 TransHab. Furthermore, many of the atmospheric control systems are much smaller; though both carry the same number of crew, the total pressurized volume of the torpor habitat is significantly less than that of the TransHab. The average power required for the torpor habitat was estimated at 17-kWe, compared to 30-kWe for the TransHab.

5.2.2. Size and Mass Comparison with NASA DRA 5.0 TransHab

The torpor-enabled habitat is significantly smaller in size compared to the voluminous DRA 5 habitat required to support the crew of 6. Figure 14 provides a scale comparison of the two habitats along with key geometry dimensions.

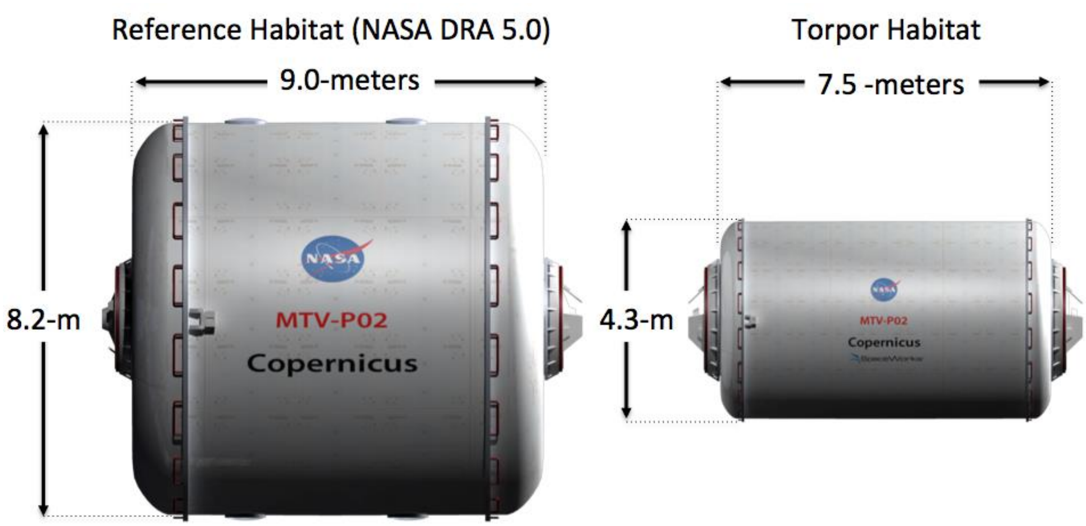


Figure 14. Size Comparison for DRA 5.0 TransHab vs. Baseline Torpor-Enabled Habitat

Summary statistics for the baseline torpor-enabled habitat are shown in Table 6; a full mass breakdown statement is shown in Table 7.

Table 6. Baseline Torpor-Enabled Habitat Summary Metrics

Parameter	DRA 5.0 Reference	Baseline Torpor Habitat
Mission Configuration	Mars Conjunction-class Avg. 200-days(out), 500-days(surface), 200-days(return)	
Crew Complement	6	6
Dry Mass	27.5 t	15.5 t
Consumables with Contingency	13.1 t	3.9 t
Total Volume	500 m^3	100 m^3
Habitable Volume	350 m^3	30 m^3
Length	9.0 m	7.5 m
Diameter (rigid)	4.3 m	4.3 m
Diameter (inflated)	8.2 m	-

Table 7. Mass Estimates for Baseline Torpor-Enabled Habitat Design

Item	DRA 5.0 Reference (kg)	Baseline Torpor Habitat (kg)	Delta (%)
Power System	5,840	3,350	-43%
Avionics	290	290	-3%
Environmental Control & Life Support	3,950	2,250	-43%
Thermal Management System	1,260	820	-35%
Crew Accommodations	4,210	1,480	-65%
EVA Systems	870	840	-3%
Structure	2,020	1,220	-40%
Mass Growth Allowance (30%)	4,920	2,850	-42%
Additional Spares	4,180	2,330	-44%
Habitat Dry Mass	**27,540**	**15,420**	**-44%**
Crew	560	560	-
Total Consumables	13,080	3,870	-71%
Total Mass	**41,340**	**19,850**	**-52%**

Many elements show appreciable mass reduction from the DRA 5.0 TransHab reference habitat. The factors driving these reductions are described in Table 8.

Table 8. Driving Factors for Mass Reductions

Element	Driving Factors
Power System	Total power level is reduced through elimination of crew accommodations systems and reduction of ECLSS system
Environmental Control & Life Support	Significant reduction in pressurized volume / cabin size
Thermal Management System	Scales with both pressurized volume and total power level required; both are reduced in the torpor-enabled habitat
Crew Accommodations	Elimination of a number of systems not required in the torpor-enabled habitat (galley, crew quarters, etc.)
Structure	Reduction in habitat diameter and length dimensions
Consumables	Reduced metabolic rate of crew and processed, raw-nutrients TPN is significantly more mass efficient than solid foods, and requires very little packaging mass

5.2.3. Configuration Layout

The subsystem packaging and layout for the torpor habitat is shown in Figure 15. The view is a top-down view. Each box represents the equivalent volume of a single ISS Standard Payload Rack. The row of boxes across the top and bottom represent the overhead and deck compartments respectively.

At the center of the habitat are the six torpor compartments. Immediately above and below the crew are the required crew consumables and robotic arm assembles. The aft third of the habitat is devoted to the ECLSS oxygen generation and water production facilities. The forward third of the habitat is devoted to the other supporting subsystems. Components that feed into one another (e.g. CDRA to CReA to OGA, UPA to WPA, etc.) are placed either adjacent or near to one another to minimize plumbing, ventilation, and power cabling.

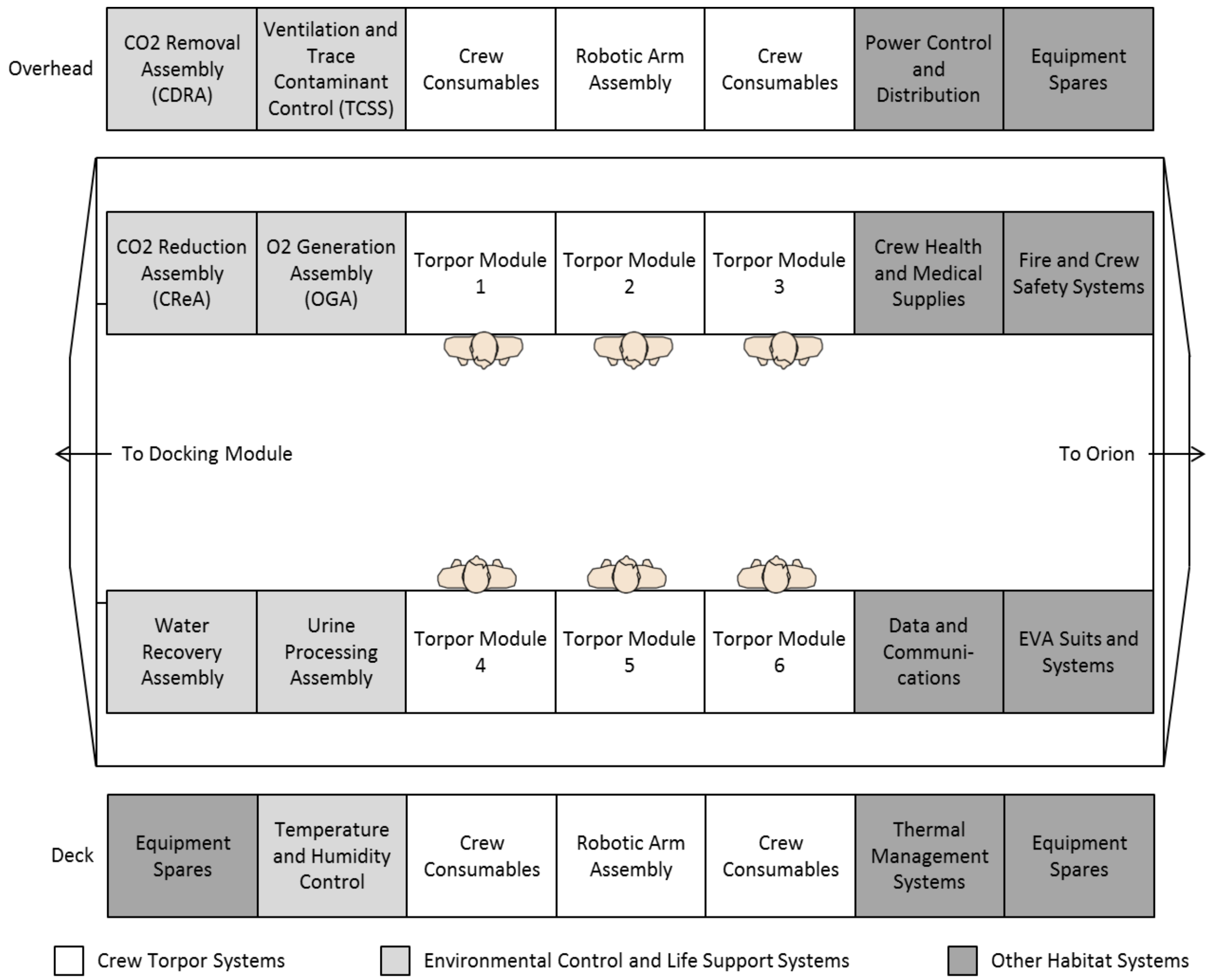


Figure 15. Baseline Torpor-Enabled Habitat Subsystem Packaging

5.3. "Vision System" Habitat Design for Mars Missions

5.3.1. Overview

The baseline torpor habitat was designed to be a direct evolution from the ISS crew modules, to give the crew sufficient habitable volume in a contingency situation, and to give the crew direct access to the subsystems for maintenance and repairs. The baseline habitat also carries sufficient contingency TPN consumables directly within the habitat, should the crew be unable to access the Surface Habitat and be required to live in the in-space habitat in Mars orbit. All of these design choices increase the overall mass of the habitat.

In an attempt to capture the full potential of the torpor technology, a second Vision System habitat was conceived, designed specifically to minimize total habitat size and mass. The exterior and interior views of the Vision Habitat are shown in Figure 16 and Figure 17 respectively. The habitat is a rigid pressurized cylinder with 4.3-m diameter and 5.0-m length. It contains a single docking interface for crew egress and ingress.

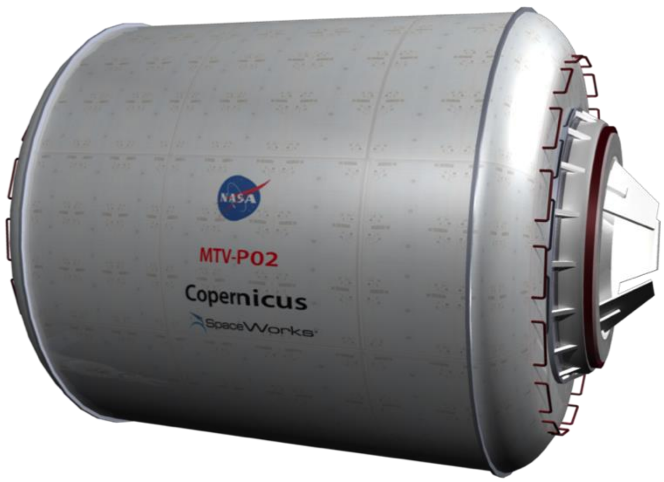


Figure 16. Vision System Habitat Design : External View

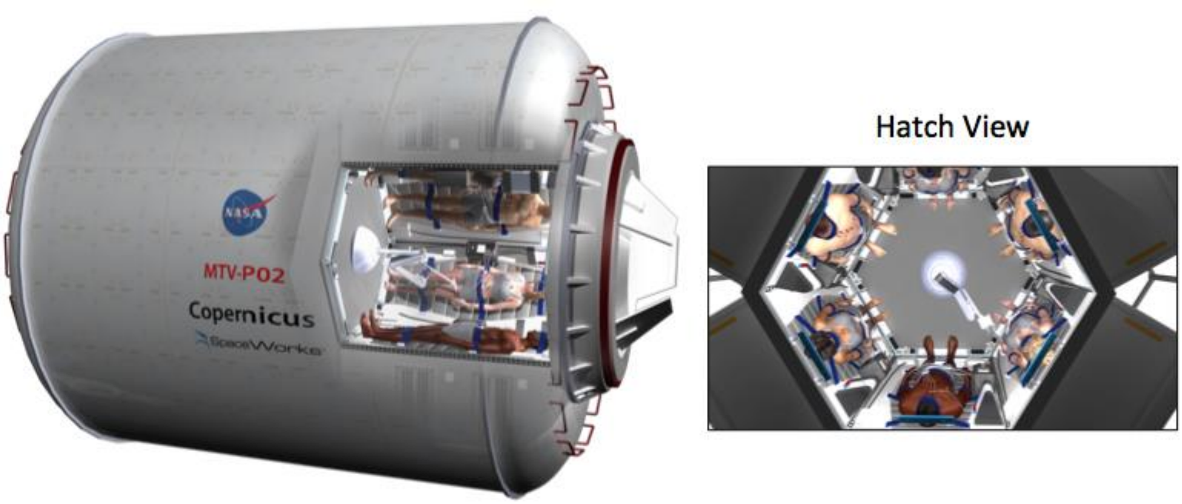


Figure 17. Vision System Habitat Design : Internal Views

As seen in Figure 17, the size of the crew compartment has been minimized; it is designed solely to support the crew in a torpor state, not to serve as contingency habitable volume. It also only carries consumables for the outbound and return flights, not for the on-orbit contingency stay at Mars.

As with the baseline habitat configuration, each crew member is allocated an individual torpor compartment, which each contain all of the subsystems required to support the crew during the mission. The vision habitat contains a single robotic manipulator arm in the deck that can reach to all six crew members.

The Vision Habitat shares all of the ECLSS technology assumptions with baseline torpor habitat, using a closed-loop oxygen production system and closed-loop water recovery system. As with the baseline torpor-enabled habitat, crew nutrition is provided intravenously as TPN, so there is no need for a galley.

Though significantly smaller in size, the vision torpor-enabled habitat has similar power requirements as the baseline because it carries all of the same crew-specific subsystems. The Vision Habitat requires 15-kWe average power, compared to 17-kWe for the baseline habitat.

5.3.2. Size and Mass Comparison with NASA DRA 5.0 TransHab

The Vision Habitat is significantly smaller in size compared to the voluminous DRA 5.0 habitat required to support the active crew of 6. Figure 18 provides a scale comparison of the two habitats along with key geometry dimensions.

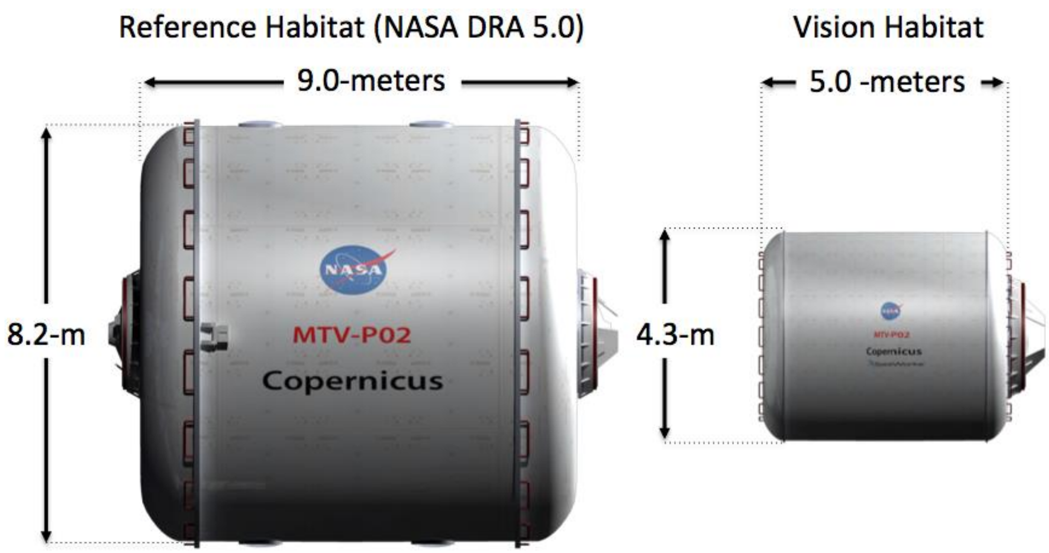


Figure 18. Size Comparison for DR5 5 TransHab vs. Vision Habitat

Summary statistics for the baseline torpor-enabled habitat are shown in Table 9; a full mass breakdown statement is shown in Table 10.

Table 9. Vision Torpor Habitat Summary Metrics

Parameter	DRA 5.0 Reference	Vision Torpor Habitat
Mission Configuration	Mars Conjunction-class Avg. 200-days(out), 500-days(surface), 200-days(return)	
Crew Complement	6	6
Dry Mass	27.5 t	11.1 t
Consumables with Contingency	13.1 t	1.6 t
Total Volume	500 m^3	75 m^3
Habitable Volume	350 m^3	8 m^3
Length	9.0 m	5.0 m
Diameter (rigid)	4.3 m	4.3 m
Diameter (inflated)	8.2 m	-

Table 10. Mass Estimates for Vision Torpor Habitat Design

Item	DRA 5.0 Reference (kg)	Vision Torpor Habitat (kg)	Delta (%)
Power System	5,840	2,870	-51%
Avionics	290	280	-3%
Environmental Control & Life Support	3,950	2,040	-48%
Thermal Management System	1,260	770	-39%
Crew Accommodations	4,210	790	-81%
EVA Systems	870	0	-100%
Structure	2,020	840	-59%
Mass Growth Allowance (30%)	4,920	2,160	-56%
Additional Spares	4,180	1,330	-68%
Habitat Dry Mass	**27,540**	**11,080**	**-60%**
Crew	560	560	-
Total Consumables	13,080	1,620	-88%
Total Mass	**41,340**	**13,260**	**-68%**

6. Architecture-Level Assessment

6.1. Introduction

The previous section outlined the mass savings predicted by incorporating torpor in the in-space transfer habitat for Mars missions. Reductions in habitat mass will directly impact Mars mission architectures by reducing the size of the propulsive stage(s) required for that habitat. In order to quantify these impacts, a full mission architecture analysis was performed.

The NASA Design Reference Architecture 5.0 (DRA 5.0) is a 2009 study for a campaign of human space missions to the Martian surface in the 2030s. It is NASA's latest design reference architecture for Mars missions, having evolved from earlier versions 1.0 through 4.0. Because of its public release and general visibility in the aerospace industry, the authors have selected DRA 5.0 as the baseline architecture for performing architecture-level assessments of the torpor-enabled habitat.

In order to perform these assessments, parametric sizing models for the propulsive elements of the architecture were created, and anchored to the baseline DRA 5.0 architecture. The models allow the propulsive elements to be resized based on changes to the architecture payload masses, and predict the total IMLEO required to accomplish the mission.

The baseline DRA 5.0 architecture is described in the next section; the results of the architecture assessment are discussed in subsequent sections. For each architecture assessment, the DRA 5.0 TransHab was replaced by a torpor-enabled habitat, and the propulsive elements were resized. In the case of the Vision Habitat, several other vehicle-level changes were enabled and incorporated.

6.2. NASA DRA 5.0 Mars Architecture Overview (*Non-Torpor*)

6.2.1. Overview

The architecture involves the assembly of three separate in-space vehicles in Low Earth Orbit (LEO), two cargo Mars Transfer Vehicles and one crew Mars Transfer Vehicle (MTV). The payloads for these vehicles are shown in Table 11.

Table 11. Mars Transfer Vehicle Payloads for DRA 5.0

Mars Transfer Vehicle	Payload
Cargo 1	• In-Situ Resource Utilization (ISRU) System • Mars Ascent Vehicle
Cargo 2	• Surface Habitat •
Crew	• TransHab • Orion • Docking Module

The concept of operations for DRA 5.0 is shown in Figure 19. Though not shown in the figure, each vehicle requires several heavy lift launches in order to deploy its propulsive and payload elements.

The two cargo missions are shown in blue in Figure 19. The first cargo mission deploys the ISRU production system and Mars Ascent Vehicle directly to the Martian surface through aerobraking, aerocapture, and direct Entry, Descent, and Landing (EDL). The second cargo mission deploys the Surface Habitat and Pressurized Rover into

Mars orbit. For the purposes of this study, it is assumed that the cargo missions are unaffected by the inclusion of a torpor-enabled habitat, and are shown only for reference.

The crew mission is shown in red in Figure 19. Once the crewed MTV is assembled in LEO, the crew is launched into LEO on a dedicated launch vehicle and rendezvouses with the MTV. The MTV departs directly from LEO and transfers the crew from Earth to Mars, where it enters Mars orbit for a rendezvous with the Surface Habitat. The crew uses the Surface Habitat to access the Martian surface, and uses this habitat as the primary surface base for the surface mission. At the end of the surface mission, the crew returns to Mars orbit using the Mars Ascent Vehicle, and transfers back to the TransHab on the crew MTV. The MTV departs Mars orbit and transfers the crew back to Earth. The crew uses the Orion vehicle to perform a direct entry into the Earth atmosphere.

The baseline DRA 5.0 architecture assumed Nuclear Thermal Rocket (NTR) powered propulsive stages using liquid hydrogen (LH2) propellant. An alternative architecture with all-chemical propulsive stages using LH2 and liquid oxygen (LOX) propellants is also included in DRA 5.0 (Figure 19. shows the baseline NTR vehicles).

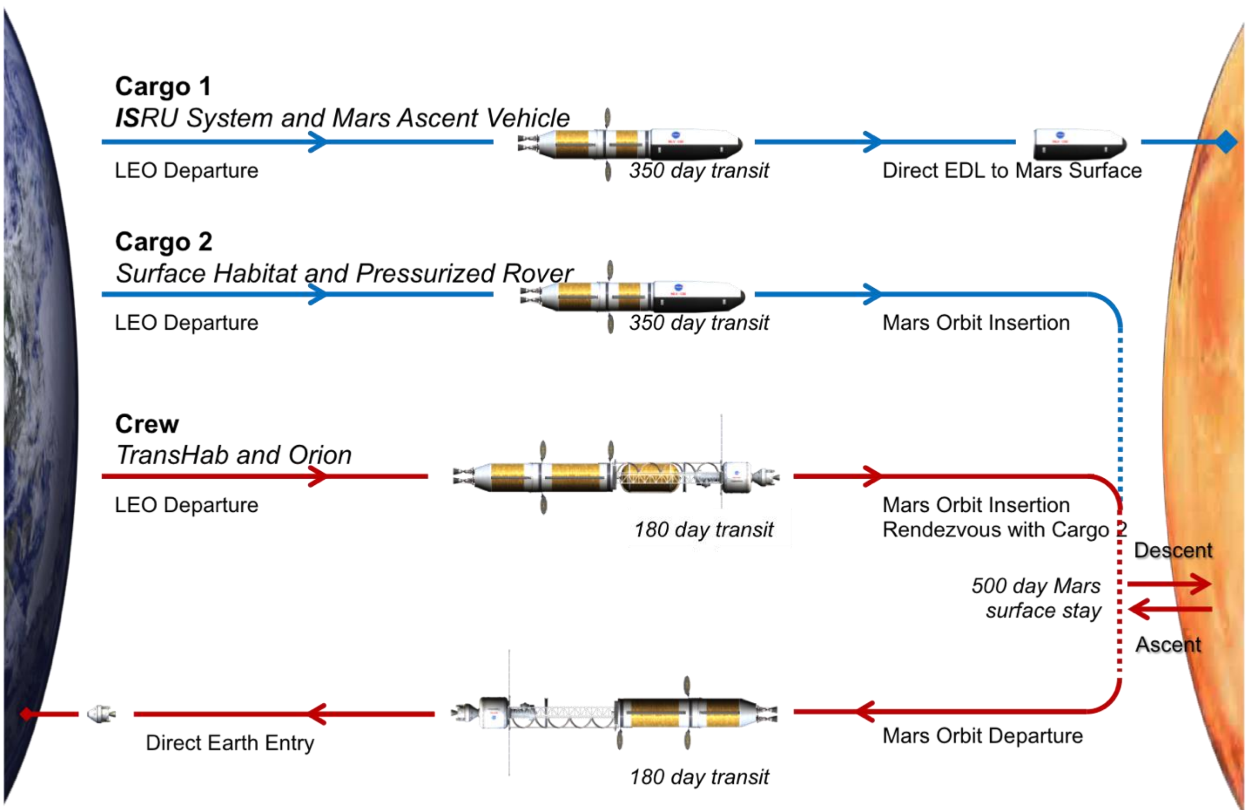


Figure 19. DRA 5.0 Mission CONOPS Overview

6.2.2. Mission Performance Verification

To perform the required mission-level architecture assessments, SpaceWorks first independently verified the interplanetary trajectory analysis published in DRA 5.0. The missions assumed in DRA 5.0 are conjunction-class or long-stay missions, which involve a ~ 200 day Earth-to-Mars outbound flight, ~500 day stay at Mars, and ~200 day Mars-to-Earth return flight. The missions have three primary propulsive maneuvers: Trans-Mars Injection (TMI) at Earth departure, Mars Orbit Insertion (MOI) at Mars arrival, and Trans-Earth Injection (TEI) at Mars departure.

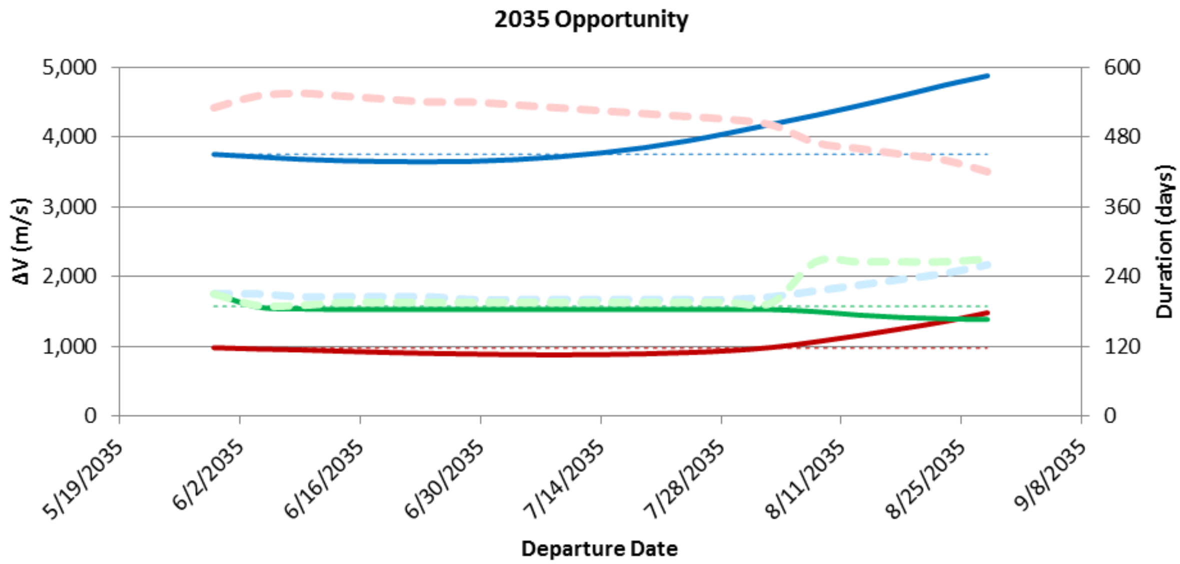
Eight opportunities for conjunction-class missions occur between 2030 and 2046; the required propulsive change in velocity (ΔV) for the TMI, MOI, and TEI maneuvers for each opportunity is presented in DRA 5.0. The authors selected the 2035 and 2037 mission opportunities for independent assessment.

Example trajectories during the 2035 and 2037 mission opportunities are shown in Figure 20. These trajectories were generated using the SpaceWorks Software Bullseye™ interplanetary trajectory simulation. The flight times, surface stay times, and arrival/departure dates for the example trajectory are all presented in the figure.

Figure 20. Typical Mars Conjunction-class Mission Opportunities

These example trajectories each represent a single mission solution of Earth and Mars arrival and departure dates; many such solutions exist within the given opportunities. In order to verify the required propulsive ΔVs, all of the different solutions were calculated. For each Earth departure date, the minimum total ΔV solution (i.e. combination of Mars arrival, Mars departure, and Earth arrival dates) was determined. The results of this analysis are shown in Figure 21.

The solid colored lines represent the calculated ΔV results using Bullseye; the thin dashed lines represented the ΔV results published in DRA 5.0. The thick dashed lines represent the associated mission times for the given mission solution. For the 2035 opportunity, the calculated TMI, MOI, and TEI ΔVs match very well with the published results. For the 2037 opportunity, the TMI and MOI ΔVs match well, while the calculated TEI ΔVs were lower than the published values. It is likely that the DRA 5.0 used a more conservative set of assumptions for this mission.



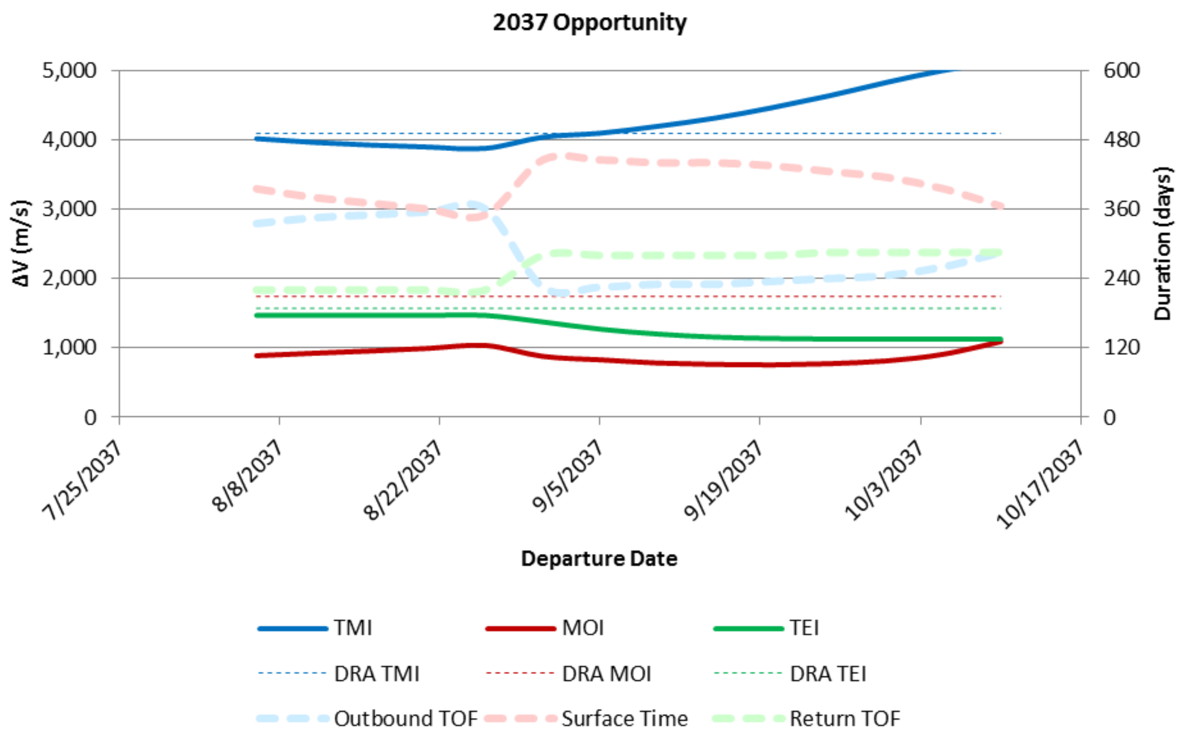


Figure 21. Mission Delta-Vs and Durations for Typical Mars Opportunities

6.3. Torpor-Enabled DRA 5.0 Mars Architecture with Baseline Habitat

6.3.1. NTR-Propulsion

The results of the mission architecture assessment using the baseline torpor habitat in place of the TransHab on the NTR-powered MTV are shown in Table 12. By using the baseline torpor habitat, the IMLEO is reduced by 90 t compared to the TransHab, or approximately a 25% mass savings. This translates into a reduction of an entire SLS launch, from 4 launches to 3 launches, in order to assemble the crew MTV.

Table 12. Summary Metrics for DRA 5 vs. Baseline Torpor-Enabled NTR-Powered MTV

Parameter	DRA 5.0	Torpor-Enabled
IMLEO	360 t	270 t
Total Length	105 meters	94 meters
Maximum Diameter	8.5 meters	8.5 meters
Number Required SLS Launches	4	3

A size comparison of the NTR-powered DRA 5.0 crew MTV and baseline torpor-enabled crew MTV is shown in Figure 22. The overall vehicle length is reduced from 105-m to 94-m.

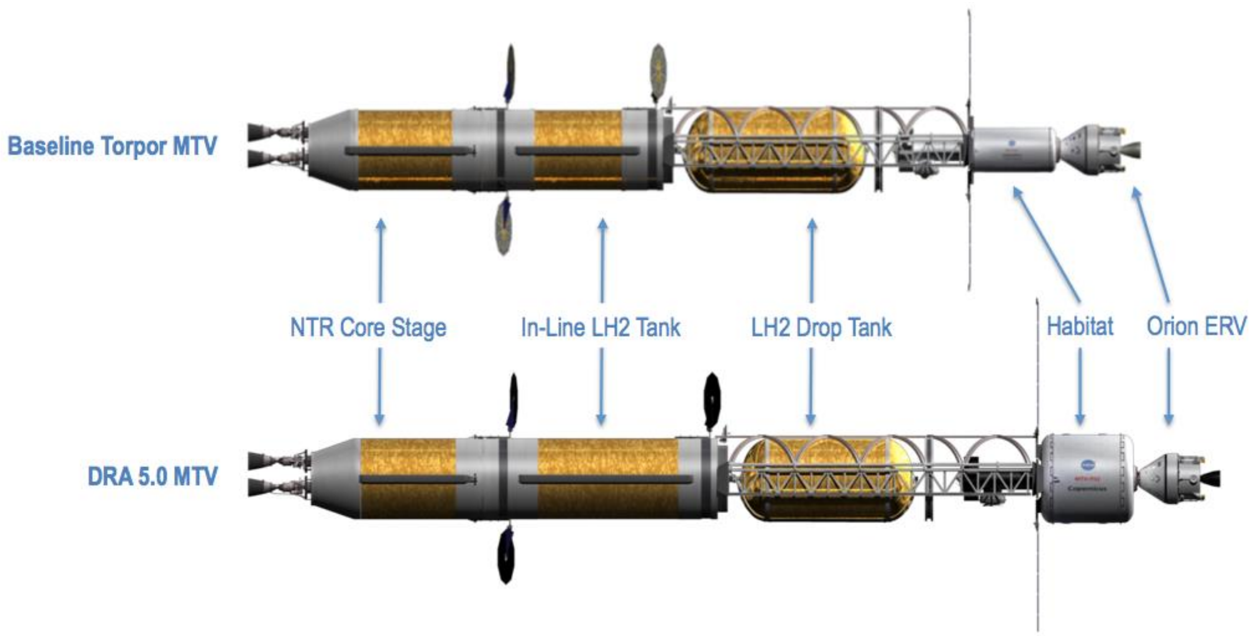


Figure 22. DRA 5 vs. Baseline Torpor-Enabled NTR-Powered MTV

6.3.2. All-Chemical, LOX/LH2 Propulsion

The results of the mission architecture assessment using the baseline torpor habitat in place of the TransHab on the all-chemical MTV are shown in Table 13. By using the baseline torpor habitat, the mission IMLEO is reduced by 150 t compared to the TransHab or approximately 31% mass savings. This translates into a reduction of an entire SLS launch, from 5 launches to 4 launches, in order to assemble the crew MTV.

Table 13. Summary Metrics for DRA 5 vs. Baseline Torpor-Enabled All-Chemical MTV

Parameter	DRA 5.0	Torpor-Enabled
IMLEO	490 t	340 t
Total Length	50 meters	40 meters
Maximum Diameter	5.0 meters	5.0 meters
Number Required SLS Launches	5	4

A size comparison of the all-chemical DRA 5.0 crew MTV and baseline torpor-enabled crew MTV is shown in Figure 23. The reduced habitat mass allows for the elimination of an entire propulsive stage for this concept; the MOI and TEI stages, separate in the DRA 5.0 baseline architecture, can be combined. Furthermore, the reduction in overall stage mass allows the propulsive stages to be designed with four, rather than five, RL-10 B-2 engines each. All of these impacts will reduce overall mission cost and improve the viability of using an all-chemical architecture.

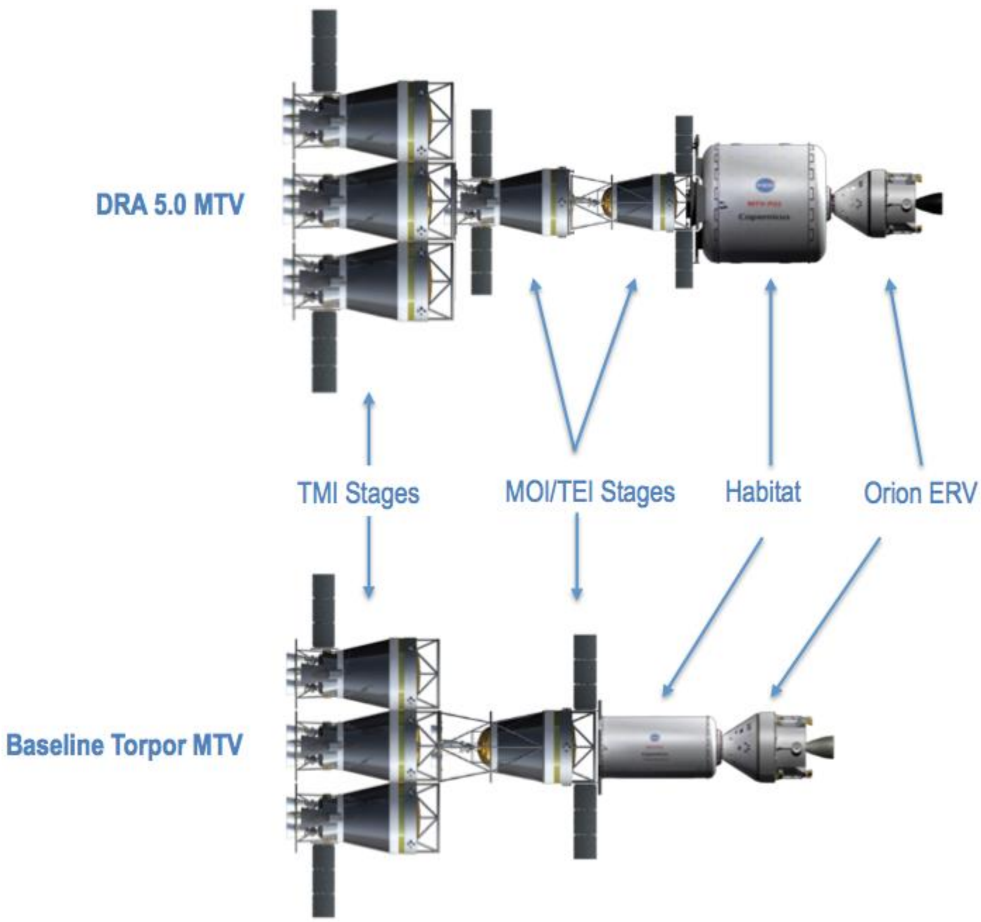


Figure 23. DRA 5 vs. Torpor-Enabled All-Chemical MTV

6.4. Torpor-Enabled Mars Architecture with Vision System Habitat

The results of the mission architecture assessment using the Vision Habitat in place of the TransHab on the NTR-powered MTV are shown in Table 14. By using the Vision Habitat, the mission IMLEO is reduced by 160 t compared to the TransHab. This is an incredible 44% mass savings which ultimately translates into a reduction of 2 entire SLS launches, from 4 launches to only 2 launches, in order to assemble the crew MTV.

Table 14. Summary Metrics for DRA 5 vs. Vision System Habitat and NTR-Powered Mars Transfer Vehicle

Parameter	DRA 5.0	Vision Torpor
IMLEO	360 t	200 t
Total Length	105 meters	75 meters
Maximum Diameter	8.5 meters	8.5 meters
Number SLS Launches	4	2

A size comparison of the NTR-powered DRA 5.0 crew MTV and vision system torpor-enabled crew MTV is shown in Figure 24. The reduced habitat mass allows for the elimination of the drop tank in this configuration; the TMI maneuver can be performed from a single tank, either as a single or multiple burns. This further reduces MTV mass by removing the saddle truss required to house the drop tank. The MTV was reconfigured, placing the docking module between the crew habitat and Orion vehicle, in order to accommodate the removal of the saddle truss.

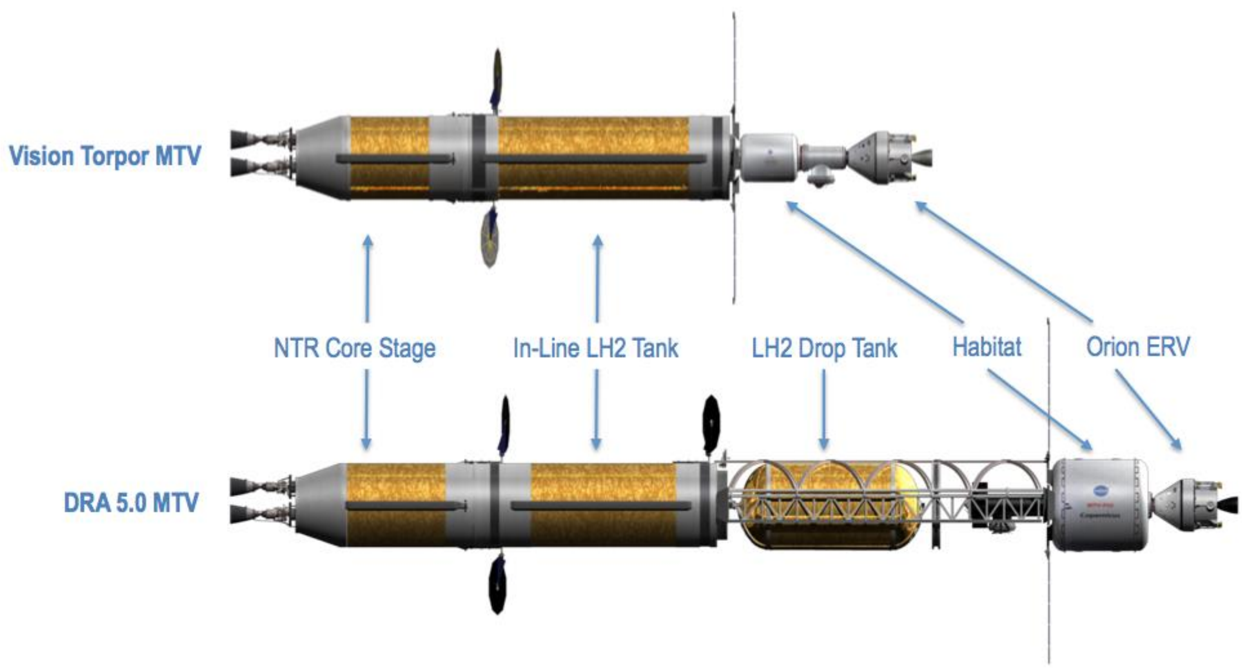


Figure 24. DRA 5 vs. Vision Torpor Habitat and NTR-Powered Mars Transfer Vehicle

6.5. Architecture Cost Assessment

A human Mars campaign is often estimated to cost a few hundred billions of dollars, with the least expensive options still ranging in the tens of billions of dollars. With the current, and likely future, budget-constrained human exploration environment, assessing the affordability of a torpor-enabled architecture is critical. In order to determine the economic impacts of a torpor-enabled design, the non-recurring development and recurring production costs were estimated for the DRA 5.0 and torpor crewed mission architectures (chemical and NTR versions of each), as well as the Vision Habitat architecture. A summary of the elements included in one crewed mission of each of the five architectures is shown in Table 15.

The original DRA 5.0 architecture assumed the use of the former NASA Ares V heavy-lift launch vehicle and the Ares I for crew delivery. The Ares V has been replaced with the SLS heavy-lift launch system and the Ares I program was cancelled. Consequently, the final delivery of the Mars crew to orbit has been assumed to occur using the SpaceX DragonRider (in lieu of an Orion capsule) delivered to orbit on the Falcon 9.

Table 15. Mars Crewed Mission Architecture Element Summary

	Quantity*				
Element / *Propulsion* / *Habitat*	**NTR DRA 5.0**	**NTR Torpor-Enabled**	**NTR Vision System**	**Chemical DRA 5.0**	**Chemical Torpor-Enabled**
Transportation					
NASA SLS	4	3	2	5	4
SpaceX Falcon 9	1	1	1	1	1
Propulsive Stages					
Core NTR Module	1	1	1	-	-
In-line LH2 Tank	1	1	1	-	-
Saddle Truss + Drop Tank	1	1	-	-	-
TMI Stage	-	-	-	3	2
MOI Stage	-	-	-	1	-
Combined MOI/TEI Stage	-	-	-	-	1
TEI Stage	-	-	-	1	-
Crewed Systems					
Transit Habitat	1	1	1	1	1
DragonRider	1	1	1	1	1
Orion ERV	1	1	1	1	1

* Quantities reflect those required for one crewed Mars mission.

A combination of the NASA/Air Force Cost Model (NAFCOM) and publicly available and internal cost sources were used to produce the crewed mission architecture estimates. The estimates assume the program is conducted as a customary government acquisition program via contracting to a traditional aerospace prime contractor. All vehicle technologies are or were assumed to be at technology readiness level (TRL) 6 or greater, thus technology maturation costs for anything below TRL 6 were not included in the cost results. Industry standard programmatic wraps reflective of a standard government program were applied to the base costs, as necessary.

Based on traditional cost estimating definitions, the crewed mission architecture design, development, test and evaluation (DDT&E) costs include the development, testing, and integration of each of the relevant subsystems for all architecture elements, and the effort to integrate the subsystems together for each element. The production costs include the acquisition, manufacturing, and integration of all subsystems, as well as system level integration. Modest learning curves were applied when calculating the total production costs of multiple identical elements.

Figure 25 compares the total cost of the DRA 5.0 and the Vision System with NTR architectures for a varied number of crewed Mars missions. This total includes the DDT&E and production costs of all elements listed in Table 15. As noted in the figure, the baseline DRA 5.0 architecture assumes three crewed missions and the Vision System cost savings percentages were derived relative to this baseline. While achieving multiple human missions to Mars is undoubtedly and inevitably expensive regardless of the approach, for the same cost as three NTR-based DRA 5.0 crewed missions, a Torpor architecture enables *nearly twice the number of missions*. Six missions, instead of three, allows NASA to obtain a greater return on their investment in the form of sustained human presence on Mars, as well as maximized scientific return. It is noteworthy that similar trends and improvements are obtained for the all-chemical architectures (not included for brevity).

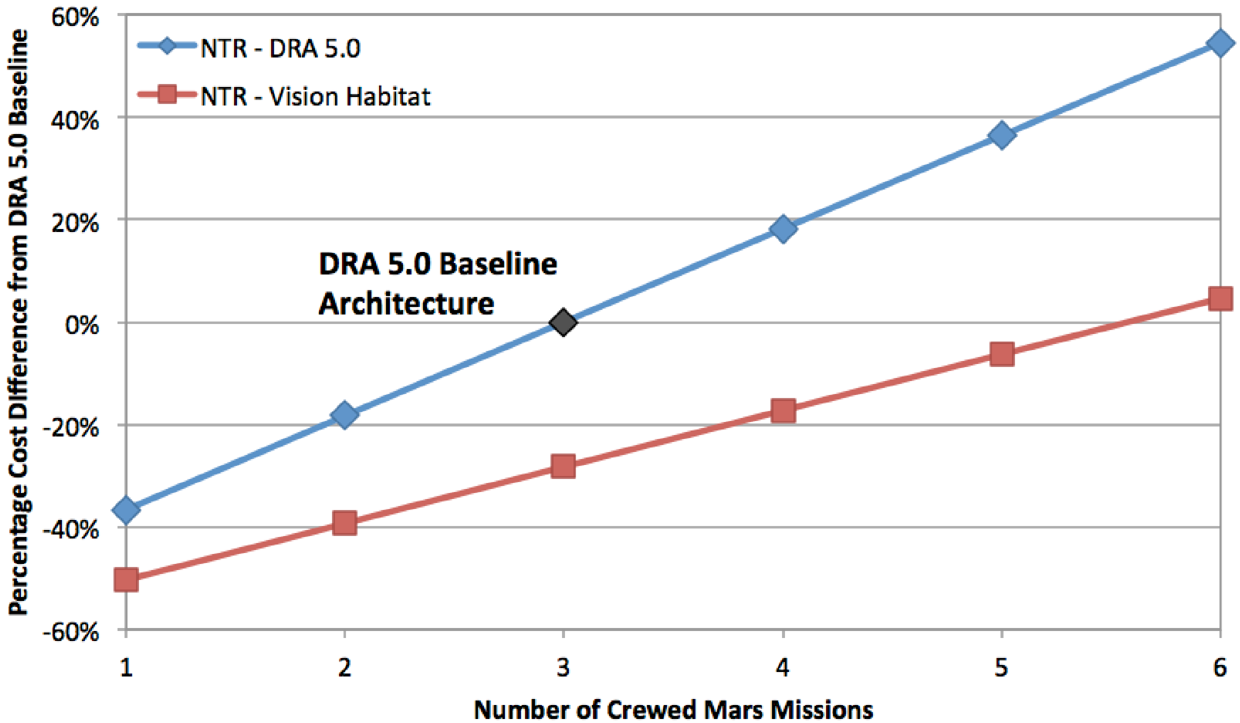


Figure 25. Mars Mission NTR Architecture Cost Comparison vs. Number of Missions

7. Trade Studies and Investigations

A number of trade-studies were performed during the course of this effort to further understand the concept and its potential. Results of various investigations noted in the original proposal are provided next.

7.1. Artificial-Gravity Inducing Habitat Configuration

7.1.1. Motivation

The negative effects on the human body of long duration exposure to microgravity are a major risk area for human space exploration. Major areas of concern include bone decalcification, muscle atrophy, and fluid shifts. Though NASA is working towards mitigating or reducing these risks through ongoing research on board the ISS, it is likely that the microgravity environment will continue to pose a medical challenge for initial human missions to Mars. [40]

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.

7.1.2. Design

The design of the torpor-enabled artificial gravity habitat is shown in Figure 26 and Figure 27. The pressurized volume is a rigid cylinder 4.0-m in height and 8.0-m in diameter. The entire pressurized volume rotates around fixed end caps, which contain the docking ports and hatches to access other crew vehicles and elements. Power and data are transmitted wirelessly across the interface between the rotating and fixed ends of the habitat; all of the internal habitat subsystems are rotated inside the pressurized volume.

In this configuration, the crew will be accelerated into the padding on the torpor compartment; the sensed acceleration will be as if lying down in a gravity field. 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 crew is stationary in the torpor-enabled habitat, the crew can be placed 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.

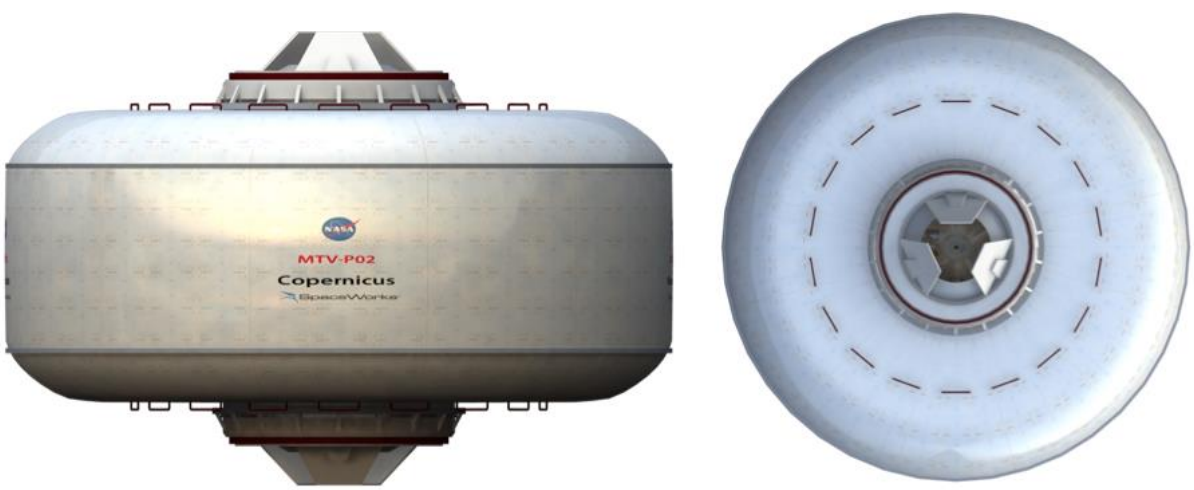


Figure 26. Torpor-Enabled Habitat with Artificial Gravity : External Views

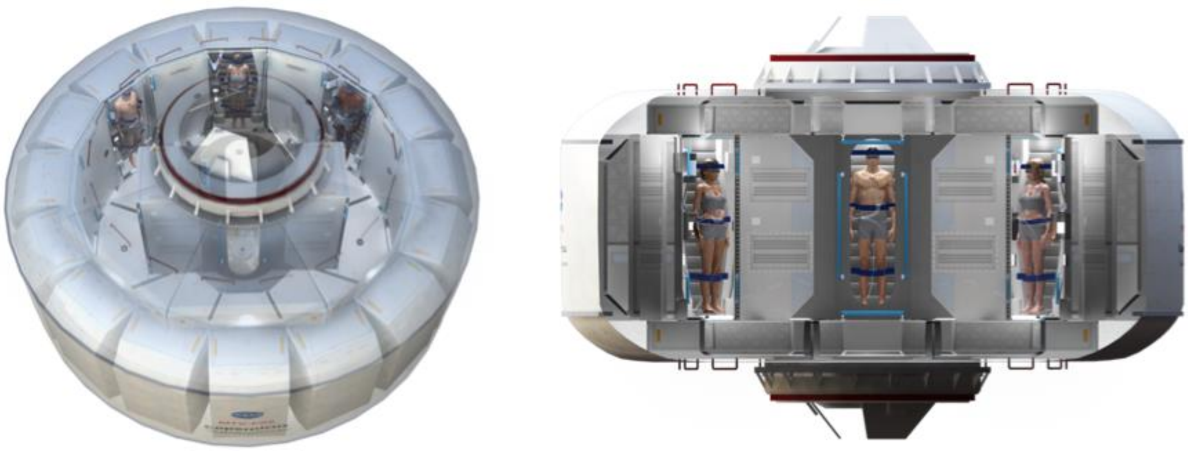


Figure 27. Torpor-Enabled Habitat Design with Artificial Gravity : Internal Views

The induced artificial gravity parameters for the torpor-enabled habitat are shown in Table 16. 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 16.

Table 16. Induced Artificial Gravity Parameters for Torpor-Enabled Habitat

Parameter		
Rotation Radius		**2.4 meters**
Induced Gravity	**RPM**	**Tangential Velocity**
1.0 Earth	19.3	4.9 m/s
1.0 Mars	11.8	3.0 m/s
1.0 Lunar	7.8	2.0 m/s

The artificial gravity habitat shares the same closed-loop oxygen production and water recovery ECLSS systems, and crew torpor compartments, as the baseline torpor-enable habitat, though these systems will need to be designed to operate in both microgravity and artificial gravity setting. All other subsystems are assumed to be identical to the baseline torpor-enabled habitat design. Redundant motor systems built into the fixed habitat end caps drive the rotation of the pressurized cabin.

Summary metrics for the torpor-enabled habitat with artificial gravity are shown in Table 17.

Table 17. Summary Metrics for Torpor-Enabled Habitat with Artificial Gravity Capability

Parameter	Torpor Habitat
Mission Configuration	Mars Conjunction-class Avg. 200-days(out), 500-days(surface), 200-days(return)
Crew Complement	6
Dry Mass	18.8 t
Consumables with Contingency	3.9 t
Total Volume	200 m^3
Habitable Volume	50 m^3
Length	4.0 m
Diameter	8.0 m

The subsystem packaging and layout for the artificial gravity torpor habitat is shown in Figure 28. The view is a top-down view. Each box represents the equivalent volume of a single ISS Standard Payload Rack. The row of boxes across the top and bottom represent the overhead and deck compartments respectively.

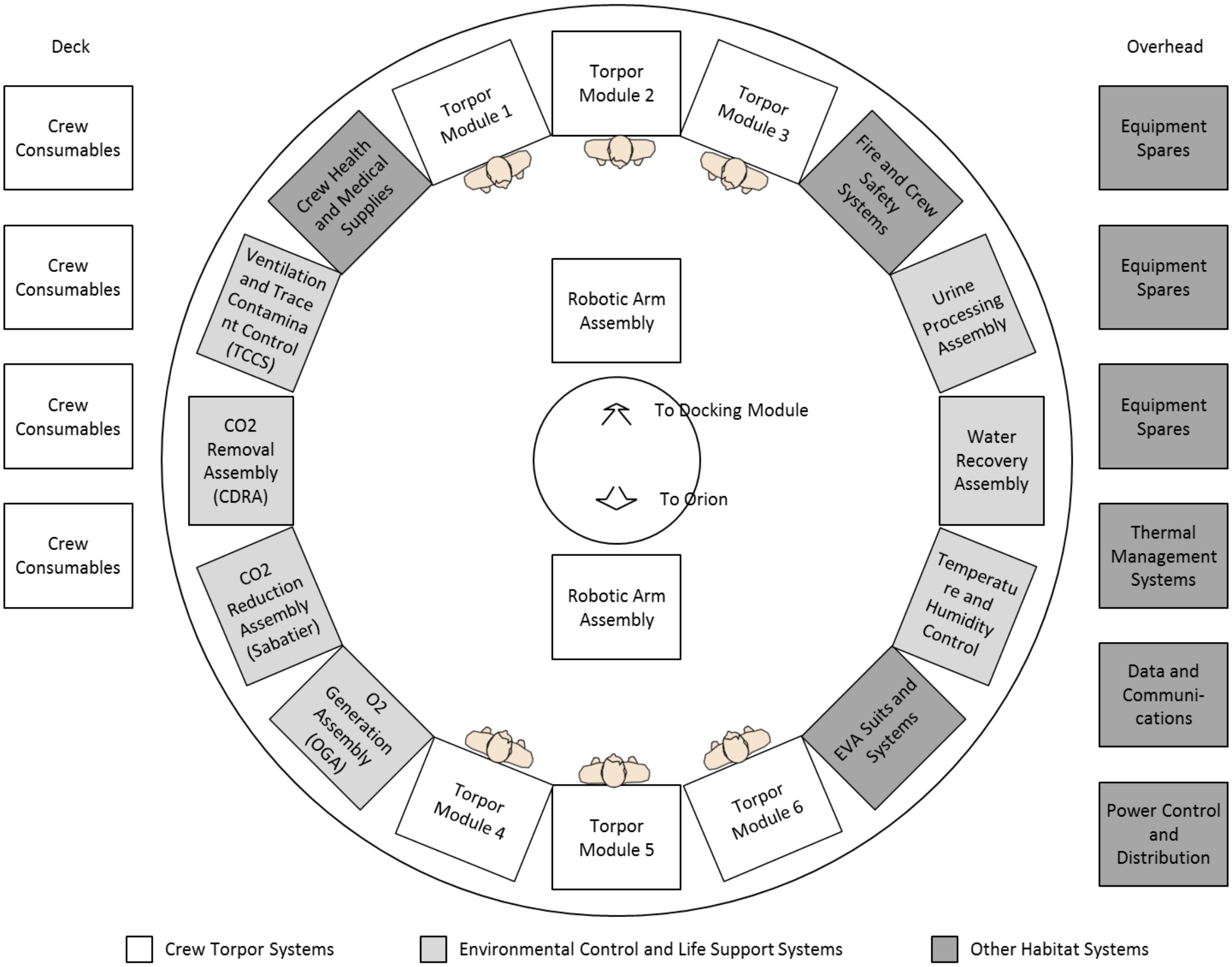


Figure 28. Torpor-Enabled Habitat with Artificial Gravity Subsystem Packaging

Three torpor compartments are placed at each the forward and aft sections of the habitat, each managed by a single robotic arm assembly. The closed-loop oxygen generation and water recovery systems are placed between the two torpor compartment clusters. Other supporting subsystems and equipment spares are stored in the remaining spaces and overhead areas, while the crew consumables are stored under the deck. Components that feed into one another (e.g. CDRA to CReA to OGA, UPA to WPA, etc.) are placed either adjacent or near to one another to minimize plumbing, ventilation, and power cabling.

A central shaft running through the pressurized cabin provides crew access to the Orion crew vehicle and docking modules.

7.2. Impact of Conscious Crewmember

While the nominal and most beneficial mission results are obtained by placing the entire crew in a torpor-state for the entirety of the Mars mission transit phases, there are obvious mission-level safety advantages associated with having a conscious crew member onboard. It is undesirable to have the same crew member conscious and alone while the remaining members are in torpor for the 6-month transit. Therefore, a protocol has been developed that puts each crew in a rotation sequence of being active for a brief period of a few days followed by an 8-10 day torpor phase. At any time, there will be at least one alert and active crew member on the mission and one other crew members either undergoing a cooling phase to enter torpor –or- a warming cycle to awaken. A representative schedule for this protocol for a 6-member crew over a 21-day period is shown in Figure 29. This schedule would be repeated for the duration of the transit phase.

It is noteworthy that the maximum duration of the torpor phases in this scenario is within the currently demonstrated treatment periods for TH (i.e. maximum of 14-days). While the number of consecutive torpor-cycles experienced by any one crew member would be on the order of 15 during a transit and exceeds the current medical record of five TH cycles, medical researchers have indicated a higher confidence level in our near-term ability to achieve more cycles without any detriment impact to the crew compared to achieving longer durations. In the longer term, achieving torpor cycles of greater duration still appear medically feasible however and remain the ultimate goal.

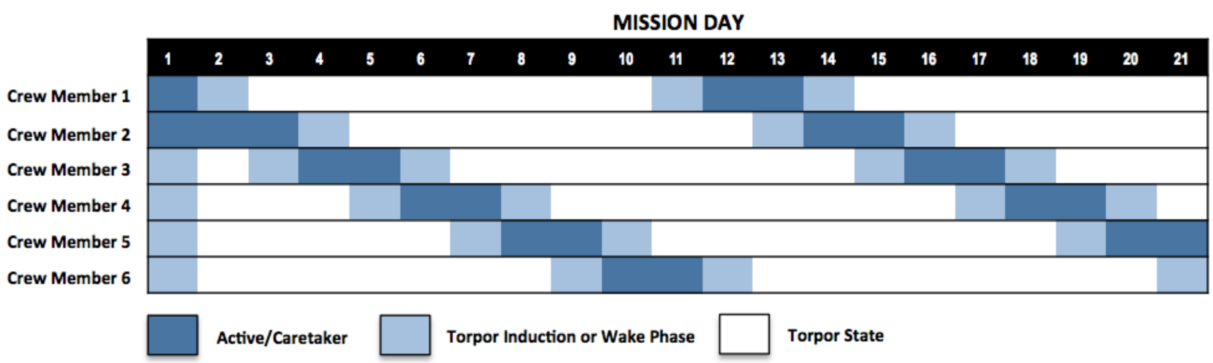


Figure 29. "Sentinel Protocol" Crew Rotation Schedule

For the baseline torpor-enabled habitats, both zero-G and artifcial-gravity capable designs, the total consumables budget and habitat mass would be unaffected if using the “Sentinel Protocol” as shown in Figure 29. For more than one conscious crew member or for longer active periods (i.e. >2 days), the habitable volume (and consequently mass) would increase.

For the Vision System habitat design, the crew consumables mass would need to increase by 17% (~0.2 t) to support a Sentinel protocol approach. Note that the available crew volume is significantly reduced in the Blk-2 design, thus the conscious crew member would likely need to access the additional volume available in the ERV and docking port.

7.3. Opposition vs. Conjunction Class Missions

The orbital mechanics of the Earth-Mars system are such that round trip mission trajectories fall into two general categories, conjunction-class and opposition-class. Conjunction-class missions are characterized by long stay times at Mars (> 1 year), and medium, roughly equal transfer times for the outbound and return mission segments (~6 months). Opposition-class missions are characterized by short stay times (~1 month), with one medium (~6 month) and one long (> 1 year) transfer; typically the outbound segment is the shorter of the two.

Conjunction-class missions are longer overall, but require less time in space and offer more time at Mars. Opposition-class missions are shorter overall, but limit the amount of mission time at Mars. Conjunction-class missions require less propulsive ΔV than opposition-class missions.

Mission parameters for conjunction-class and opposition-class missions are shown in Table 18.

Table 18. Conjunction vs. Opposition-class Mission Parameters

	Conjunction-class Mission	Opposition-class Mission
Propulsive Delta-Vs Required		
TMI ΔV	3,760 – 4,125 m/s	3,600 – 4,950 m/s
MOI ΔV	980 – 1,800 m/s	920 – 2,850 m/s
TEI ΔV	1,560 – 1,580 m/s	1,170 – 3,440 m/s
DSM ΔV	n/a	0 – 4,290 m/s
Total ΔV	**6,300 – 7,500 m/s**	**7,800 – 11,000 m/s**
Typical Mission Times		
Outbound Transit	200 days	220 days
Surface Stay	500 days	30 days
Inbound Transit	200 days	400 days
Total	**900 days**	**650 days**

Though the conjunction-class mission was selected as the baseline configuration for the DRA 5.0 architecture and for this study, the opposition-class mission was considered as an alternative. In order to assess the opposition-class mission approach, mission propulsive ΔVs were determined based on the analysis performed in the DRA 5.0 addendum. [37] These propulsive ΔVs were then used in the existing parametric sizing models to resize the propulsive stages required for the torpor-enabled habitat. The resulting crew MTV masses are shown in Figure 30.

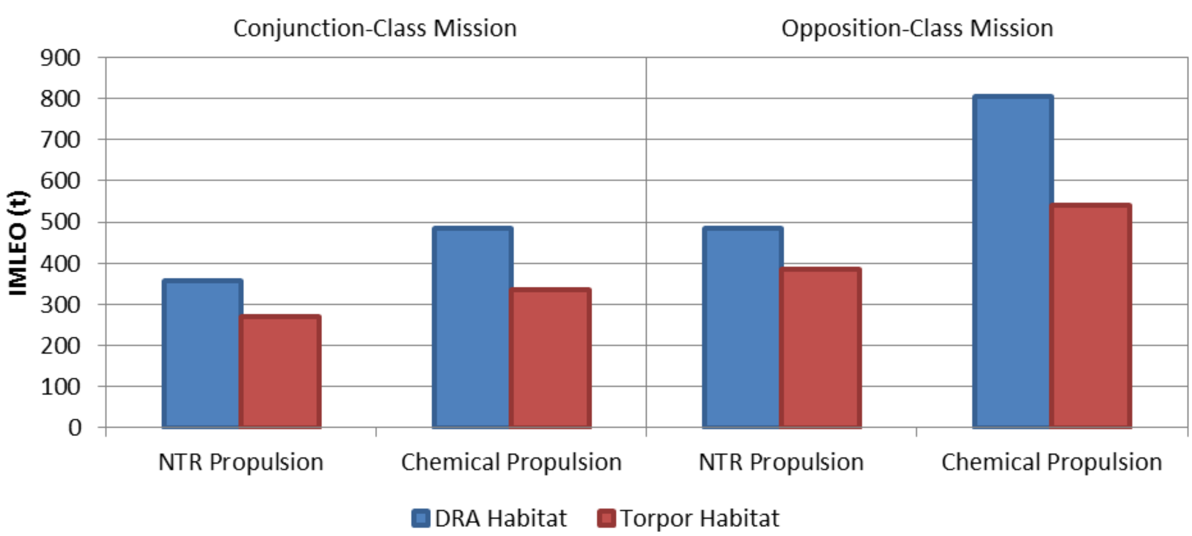


Figure 30. IMLEO for Conjunction vs. Opposition Class Mars Missions

Several observations can be made from the results in Figure 30. First, an opposition-class NTR-powered crew MTV with a torpor-enabled habitat is only slightly more massive than the conjunction-class NTR-powered mission crew MTV with the TransHab. Second, the opposition-class NTR-powered crew MTVs are roughly equivalent to the conjunction-class all-chemical crew MTVs. Finally, opposition-class all-chemical crew MTV with a torpor-enabled habitat is only slightly more massive than the conjunction-class all-chemical crew MTV with the TransHab.

7.4. Dry Mass Growth Sensitivity

A study of the sensitivity of the crew MTV mass to habitat mass was performed for both the DRA 5.0 vehicle and the baseline torpor-enabled vehicle. The results of the study are shown in Figure 31. For each case, the mass of the habitat was changed by a fixed percentage; consumables mass was not changed. The crew MTV was then reclosed with the new habitat mass.

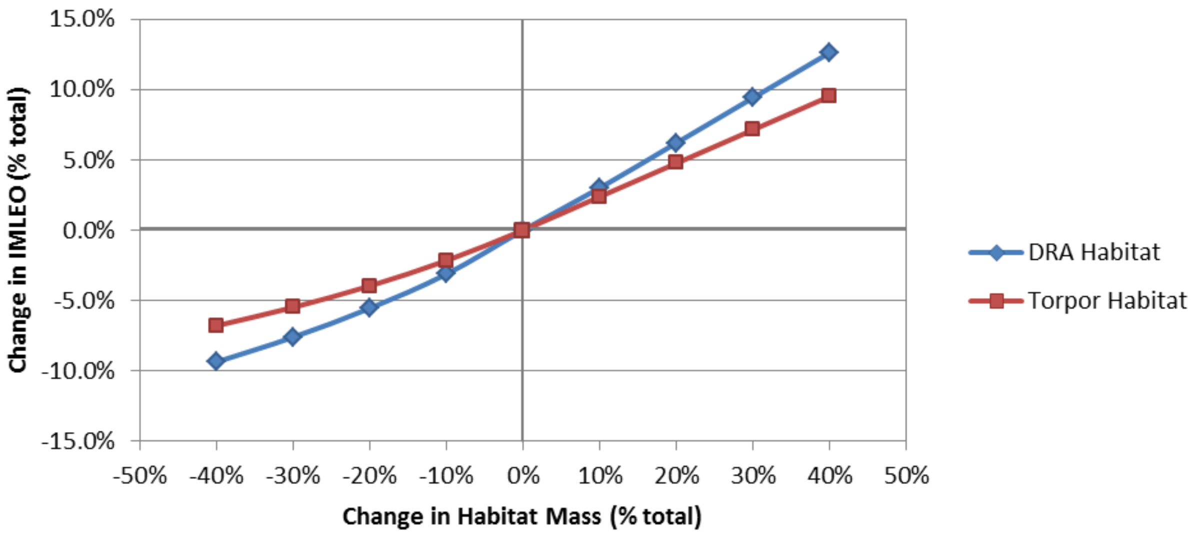


Figure 31. Habitat Mass Growth Sensitivity

The DRA 5.0 crew MTV is slightly more sensitivity to changes in habitat mass than the torpor-enabled crew MTV. At the high end, increasing the habitat mass by 40% yields an increase in crew MTV IMLEO of 13% for the DRA 5.0 vehicle and 10% for the torpor-enabled vehicle. Conversely, reducing the habitat mass by 40% decreases the IMLEO by 10% for the DRA 5.0 vehicle and 7% for the torpor-enabled vehicle.

7.5. Crew Size Sensitivity

Crew size is a major mission and architecture-level decision. Larger crew sizes are generally beneficial for personal interactions, minimizing conflict potential, and greater skillsets and capabilities. However, all the hardware (e.g. habitat volume, power generation requirements, etc.) and consumable systems increase with crew size. Thus, it is a significant consideration that must balance the engineering and program costs with the overall well-being and scientific return capability of the crew.

The impact of crew size on the habitat was investigated to understand the mass growth sensitivity. The parametric habitat models that were created for both the DRA 5 TransHab and torpor-enabled, zero-G habitat were used to support this assessment. While the nominal crew size is 6, habitats capable of supporting 4 and 8 crew members were examined.

Figure 32 presents the results of the crew size sensitivity. Both the mass of the hardware and consumables for the respective habitats are provided. As expected, larger crew sizes result in larger habitat masses. What is truly noteworthy is that the torpor-enabled habitat mass for a crew size of 8 is still less than the NASA non-torpor habitat for a crew size of only 4. Thus, the **torpor technology enables more than twice as many crew members** on a given mission.

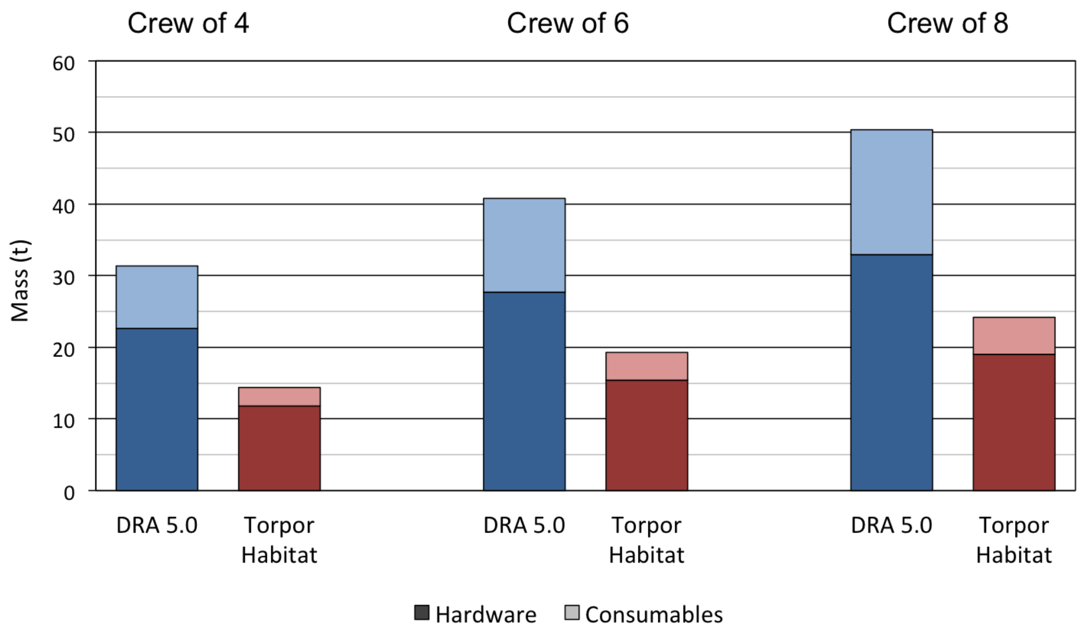


Figure 32. Habitat Crew-Size Sensitivity

7.6. Emergency Wake Scenario

In certain circumstances or situations, it may be desirable (or necessary) to wake an inactive crew member in an expeditious manner. With current TH protocols, the fastest wake cycle would require about 2 hours. This is based on a 4 ^{o}F temperature change per hour and warming occurring from 90 ^{o}F to 98.6 ^{o}F. While not to discount the challenges associated with rapid warming, after discussions with medical personnel the following considerations should be noted:

- These protocols are established for patients that have suffered from and are being awaken after sustaining traumatic injuries. They are designed to minimize any risk of compounding the injuries. It is therefore plausible that for application to healthy and uninjured crew members, the warming protocols could allow for a more timely response.

- For reference, the warming process is typically conducted in fixed steps, with the actual temperature change occurring over a short period, ~15-minutes, which is followed by an body equilibrium and acclimation period for the remainder of the hour. While maintaining the lowest body temperature possible minimizes metabolic rate and thus consumables, it is possible to continuously vary the crew members body cyclically over the temperature range that still maintains the torpor state, typically from 89 to 93 ^{o}F. In this manner, it could be structured such that there could always be one or more crew members near the high end of the temperature range. In an emergency scenario, these crew members would then have a shorter wake cycle and could act as first responders.

- Lastly, it may be possible to augment the warming process with active thermal systems, like the KOALA thermal pads, as well as with drugs, like adenosine. This is another area of research that currently lacks a compelling clinical reason to explore, but application to spaceflight would justify. For instance, doctors will almost always warm patients at the minimum suggested rate of 1 °F per hour despite protocols permitting warming at four times that rate.

7.7. Slow Transfer Mars Mission

A torpor-enabled crew habitat, particularly one that can induce artificial gravity, may allow the crew to remain in microgravity on an in-space mission segment for longer than in a traditional habitat. Lifting the constraint on in-space time may allow the crew to transfer to Mars on a lower propulsive ΔV, longer duration transfer trajectory, similar to those used for the cargo MTVs.

To investigate the impact of a longer transfer trajectory, two trajectory trades were performed. In the first trade, the outbound flight duration was not constrained, but the Mars arrival MOI propulsive ΔV was constrained. In the second trade, neither the outbound flight duration nor the arrival ΔV were constrained (i.e. non-propulsive aero-capture used to enter Mars orbit). The results of these trades are shown in Figure 33.

In both the MOI-constrained and MOI-unconstrained cases, the TMI propulsive ΔV required is lower than the reference DRA 5.0 value. For the first half of the opportunity dates, the TMI ΔV values are the same. However, roughly at the end of January 2031, the MOI constraint appears to become active, forcing a shorter time-of-flight solution for the outbound trajectory; this change is apparent in the time-of-flight results. Without the MOI constraint, the TMI solutions trend towards even lower ΔV required.

Overall, it appears that lengthening the in-space segment may yield lower propulsive ΔV requirements for the mission. This, in turn, would further reduce the total IMLEO required of the Mars mission.

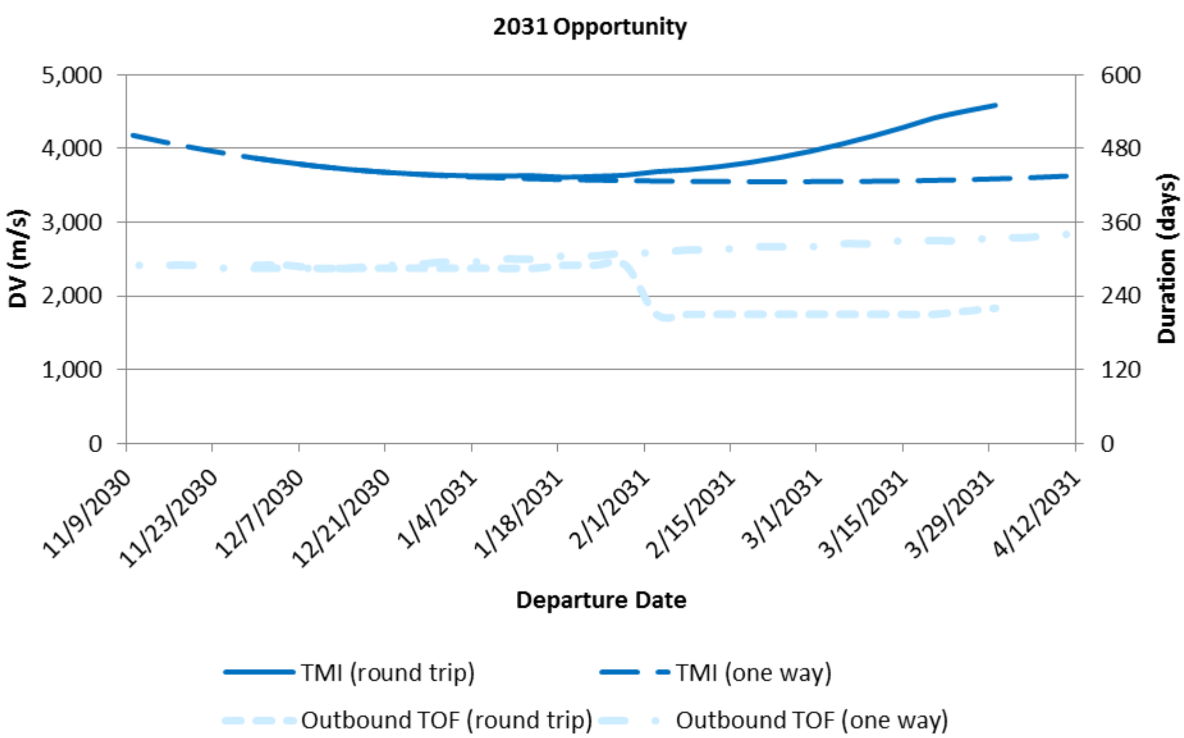


Figure 33. Long Duration Outbound Trajectory for 2031 Mars Mission Opportunities

8. Summary and Recommendations

8.1. Phase I Study Results

Regarding the medical feasibility and assessment of this concept, a number of findings were made. Specifically,

- Human patients have been placed in a continuous torpor state using TH protocols for periods up to 14-days. Prior to the start of the study, the team was only aware of TH being applied for up to 7-days. This longer duration is important because it makes viable approaches like the sentinel protocol with an active caretaker.

- Humans have undergone multiple TH induction cycles with no negative or detrimental effects reported in either the near term recovery period or long term. The most notable case study is a young child that underwent five cycles of TH.

- Reports from a symposium sponsored by the U.S. Army and facilitated by the National Academy of Sciences in the 1950's presented reports of testing on animals that showed reductions in cancerous tumor growth and the effects of radiation during while in the torpor-state. The tumor growth and cell-damaging effects of the radiation were seen to resume upon warming of the animals.

- While not currently recommended as a standard treatment for increased intracranial pressure (ICP) in any clinical setting, recent studies suggested that TH can lower ICP and may improve patient outcomes. ICP has been cited on NASA's Human Research Program (HRP) and Risk Roadmap as a major concern for which there is no current solution to protect a conscious crew member against.

- Human patients have regularly received sustenance for extended durations (>1 year) from an all-liquid solution, called Total Parenteral Nutrition (TPN), which can meet all hydration and nutritional needs. The administration of TPN is a well understood science within the medical community and is used at every major hospital.

- Contrary to some opinions and concerns, based on over a dozen studies with hundreds of patients, there was no evidence suggesting that TPN promotes bacterial overgrowth, impairs neutrophil functions, inhibits blood's bactericidal effect, causes villous atrophy, or increases the risk of death due to gastrointestinal complications

- 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 with medical system R&D divisions did not identify any immediate concerns or challenges with fully automating their hardware.

Specific results of the habitat design work performed have yielded the following:

- Compared to the current NASA reference TransHab design, the torpor-enabled habitats indicated mass reductions ranging from 52% to 68%, depending on the specific configuration, for the same mission requirements and non-torpor technologies.

- Crew size sensitivity study results showed that the torpor-technology can be used to double the number of crew members for the same habitat mass, including crew and consumables. This is potentially very important as we eventually transition from the exploration to the colonization on Mars. We will ultimately need to be able to transport larger numbers of people and there is currently no practical means to achieve this without torpor.

- For an initial mission, it may be desirable to have at least one crew member awake during the transit phases to monitor the MTV systems and inactive crew members. The impact to the habitat and mission of cycling the crew such that one crew member is conscious at all times during the transit phase was determined to be minimal for the baseline habitat design. For the Vision Torpor Habitat, the impact would still be manageable but somewhat larger due to the need to increase the habitable volume.

- The mission-level impact of the habitat for both the NTR-powered transfer vehicle and the All-Chemical propulsion transfer vehicles from NASA DRA 5.0 were examined. Compared to the current NASA Mars reference architecture, IMLEO mass reductions ranging from 25% (NTR) to 44% (All-Chemical) were obtained. In addition to reducing the launch mass requirement (i.e. SLS launches), these mass reductions also resulted in the elimination of significant pieces of hardware (e.g. tanks, stages, engines).

- The propulsion system performance on the non-torpor NTR-powered architecture would be required to increase by 22%, an Isp increase of 200+ seconds, to achieve the same system-level mass reduction impacts obtained from a torpor-enabled habitat. For NTR propulsion, this is not likely to be a feasible goal.

- An NTR-powered, Opposition-class mission becomes a viable option using torpor and can be accomplished with an IMLEO on par with a non-torpor, Conjunction-class NTR-powered architecture.

- Preliminary cost results indicate that a Mars mission campaign utilizing a torpor-enabled architecture can support almost twice as many crewed missions (6 vs. 3) compared to a non-torpor architecture for the same cost. Given the substantial investment required to enable human missions to Mars, any program will need to be able to offer more than a single mission or a “flags and footprints” approach. The torpor-enabled systems provide that opportunity for NASA.

8.2. Recommendations for Future Work

Based on the promising results and assessment from the Phase I activity, the SpaceWorks team would make the following recommendations for the continuation of this work:

1) Activities in the medical community regarding the use of TH and new case studies should continue to be monitored. In addition to the refining of current techniques and protocols by the medical community, the types of scenarios for which TH is applied continues to expand. Further applicability to human spaceflight may occur if in clinical environments longer durations are attempted and/or the simultaneous administration of TPN is used.

2) The medical team needs to be expanded to facilitate an multidisciplinary dialogue among medical experts. This team should include both researchers and practitioners from various fields and specialties. Specific specialists desired include a neurologist, critical care specialist, pulmonologist, cardiologist, physical therapist, anesthesiologist, and an endocrinologist.

3) The engineering aspects of the system should continue to be examined. Various habitat configuration and design options should be developed in light of uncertainty. This will help to establish requirements that could be used to influence or support future technology maturation work.

4) Assessment of the concept at the system-level via mission architecture analysis and trade studies/sensitivities should continue. As additional knowledge and details on how various aspects of the approach will work is obtained, the impact of this concept on the Mars architecture is likely to change. Maintaining a rigorous technology evaluation program will ensure future investments are justified.

9. Media and Public Relations Efforts

During the course of the Phase I effort, SpaceWorks provided project and concept information through a variety of public venues. These efforts helped increase awareness of the project and NIAC program to both the technical community and the public in general. While not a formal aspect or actual work item under the grant, the team has supported a number of telephone and email interviews with different sources.

Notable interviews included:

"Incredible Technology: How Astronauts Could Hibernate On Mars Voyage"
Author: Senior Writer Mike Wall at SPACE.com
This story was subsequently voted as "Story of the Week" and received 200+ tweets and 1,000+ facebook posts.

"Space Travel's Efficient, Cheaper Future: Sleeping Your Way To Mars In A Stasis Habitat",
Author: Reporter Michael Venables for Forbes Tech

"Sleeping to Mars: Travel to Mars is Probably Achievable if We Hibernate on the Way"
Author: Author Caroline Kraaijvanger for Scientias.nl in the Netherlands.

"2014: The Year Science Will Blow Your Mind : NASA's Craziest Ideas"
Author: Science Writer Will Gater for Focus Magazine (UK)

In addition to previously noted press articles, an interview was conducted with writer Fabrice Nicot for the youth-oriented French science magazine called 'Science & Vie Junior'.

A project blog maintained by NIAC Fellow, Dr. John Bradford, is available at: http://spacetorpor.blogspot.com.

Additional speaking engagements that were supported (or scheduled) include:

2014 NIAC Symposium at Stanford University, California on February 4th-6th, 2014
Georgia Tech AIAA Student Division on February 13th
65th International Astronautical Congress in Toronto Canada, September 29th-October 3th, 2014

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Appendix B: Organization and Personnel

DESCRIPTION OF ORGANIZATION

SpaceWorks Enterprises, Inc. (SEI) is an aerospace engineering concept design and systems analysis firm focusing on next-generation space transportation systems, future technologies, human and robotic exploration of space, and emerging space markets and applications. SEI's advanced concept design and development work helps our customers envision the impact of future technologies, understand the feasibility of proposed space missions, and make strategic decisions regarding future markets.

Our experienced team uses the latest multidisciplinary design techniques to combine a range of technical and economic assessments into an integrated capability. In-house capabilities include performance assessment, aerodynamic analysis, propulsion systems analysis, mission design, cost assessment, reliability and safety analysis, reusable launch vehicle operations simulation, business case assessment, artwork, and custom computer animation and renders. Design work can be performed probabilistically or deterministically, depending on customer needs and requirements.

Our customers include NASA, the U.S. Air Force, DARPA, traditional aerospace primes and emerging space entrepreneurs and their companies. Since our founding in 2000, SEI has served a variety of customers on space projects and contracts ranging from large to small, and from long to short duration. Our capabilities include single-discipline support for a client’s design team to complete end-to-end space concept analysis that includes performance, weight estimates, cost, and technology sensitivities.

SEI engineers are also engaged in advanced research and outreach activities on topics that resonate with the world community. Our internal research projects include mission studies of concepts that might be used to deflect potentially dangerous asteroids, applications of space-based solar power for strategic energy independence, and promotion of market-driven space development activities such as space tourism and space resource utilization.

In 2004, SpaceWorks received the NASA Group Achievement Award for the ATLAS Advanced Technology Lifecycle Analysis System management decision-support modeling tool as well as the NASA TGIR Turning Goals into Realities Award for Outstanding Contributions to the NGLT Systems Analysis Project Team (Mission Risk Analysis). SpaceWorks has also received the Orbital Sciences Corporation (OSC) Team Appreciation Award and is a recipient of the Inc. 500/5000 Award where it is listed as one of the fastest growing businesses in the United States. SpaceWorks is featured on the 2011 Inc. 500/5000 list as the second fastest growing engineering firm in Georgia and number 39 in the Engineering category overall based on 2010 revenues.

SEI is a privately held S-corporation based in Atlanta, GA. SEI is also a corporate partner in the Georgia Space Grant Consortium.

DR. JOHN E. BRADFORD, NIAC FELLOW

Dr. John E. Bradford is President of SpaceWorks Engineering in Atlanta, Georgia. SpaceWorks is an aerospace engineering concept design and systems analysis firm focusing on next-generation space transportation systems, future technologies, human and robotic exploration of space, and emerging space markets and applications. SEI's advanced concept design and development work helps our customers envision the impact of future technologies, understand the feasibility of proposed space missions, and make strategic decisions regarding future markets.

Dr. Bradford's expertise is in systems integration, multidisciplinary optimization, and the design and assessment of future space systems. As President, Dr. Bradford oversees the day-to-day operations of the office, manages the engineering staff and task assignments, and performs bid and proposal work for new efforts. He is the primary interface for all business with the Department of Defense and the corporate Facility Security Officer (FSO).

As a Principal Engineer, his recent projects at SpaceWorks have included assessing heavy-lift configuration options for NASA's SLS, technology road-mapping and prioritization for AFRL hypersonic systems, programmatic support to the Air Force's Reusable Booster System (RBS) Pathfinder flight demonstrator program and independent concept analysis for the NASA-AFRL Joint Systems Study (JSS).

Prior to joining SpaceWorks, Dr. Bradford worked at both NASA Marshall Space Flight Center (MSFC) in Huntsville, AL and Aerojet in Sacramento, CA. His specific area of interest is in computational analysis and design of future systems using collaborative, automated engineering frameworks. Dr. Bradford has developed both disciplinary analysis tools as well as end-to-end concept simulation models spanning performance assessment through life-cycle cost.

Dr. Bradford received his Doctorate and Master's Degree in Aerospace Engineering from the Georgia Institute of Technology. At Georgia Tech, he was the recipient of a NASA Graduate Student Researchers Program (GSRP) Fellowship. He also holds a Bachelor of Science degree in Aerospace Engineering and a Minor in Computer Programming from North Carolina State University. He is a Senior Member of the American Institute of Aeronautics and Astronautics (AIAA), a NASA Academy (NAAA) alumnus, on the Steering Committee and a judge for NASA's RASC-AL student design competition, an alumni member of the AIAA High Speed Air-Breathing Propulsion Technical Committee, an Adjunct Professor at the Georgia Institute of Technology, and regularly a guest speaker at science fiction conventions.

Dr. Bradford is a native of California and resides in Atlanta, Georgia with his wife and two children.

MR. MARK SCHAFFER, SENIOR PROJECT ENGINEER

Mark Schaffer is a Senior Aerospace Engineer in the Engineering division of SpaceWorks Enterprises, Inc. (SEI). Mr. Schaffer's disciplinary focuses include conceptual design of space access and space exploration architectures, performance and closure analysis of architecture elements, trajectory determination for Earth-to-orbit and deep space missions, and technology impact evaluation.

Mr. Schaffer is member of SpaceWorks' Advanced Concepts Group and is the company lead for human space exploration. In this role, he led a study sponsored by ULA to investigate cryogenic propulsive stages for human missions to the Moon, asteroids, and Mars. He has supported NASA lunar architecture studies for crew habitation and surface infrastructure design, and performed the habitat designs for a SpaceWorks study of manned Mars missions. In addition, Mr. Schaffer served as the team leader and lead engineer for SEI's Foresight proposal, a concept for a radio tagging mission to the asteroid Apophis. This proposal won first prize in the 2007-2008 Planetary Society Apophis Mission Design Competition.

Mr. Schaffer also supports SpaceWorks' space launch systems and hypersonic flight focus areas. He recently participated in the joint NASA-DARPA Horizontal Launch Study as a member of the analysis team, focusing on meta-model development and integration for closure and performance metrics models, and technology impact evaluation on the concept vehicles. He also led a study through the Joint Systems Study to investigate the impact of technologies on NASA's TBCC launch system.

Mr. Schaffer received his Bachelor of Science degree in Aerospace Engineering from the University of Illinois at Urbana-Champaign in 2006.

DR. DOUGLAS TALK, MEDICAL LIASION

Dr. Douglas W. Talk completed medical school at Eastern Virginia Medical School in Norfolk Virginia and performed his residency at the Naval Medical Center Portsmouth in Virginia. Dr. Talk holds a Master's in Public Health and Epidemiology from Eastern Virginia Medical School. Dr. Talk is a native of North Carolina who earned his bachelor's degrees in Biology and Biochemistry at North Carolina State University. He continues to be stationed at Naval Medical Center Portsmouth. He has headed several research studies and presented at both the Armed Forces District and American College of Obstetrics and Gynecology national meetings.

During his four years on service as an OB/GYN resident and Chief resident his duties have included the care of both non-emergent and emergent obstetrics and gynecology patients. Dr. Talk has both clinical, surgical and intensive care unit privileges and works regularly with the Critical Care, Neonatology and Oncology departments in the treatment of cancer patients, obstetrical trauma and maternal/neonatal resuscitation, and acute medical care. Routine duties include diagnostic testing and evaluation of patients, medical and surgical management of illness and ICU care (including sedation, hypothermic therapy and nutritional recovery with TPN).

Dr. Talk has an extensive military background. He attended the Naval Nuclear Power Training Program and served as both a nuclear chemist and nuclear plant technician aboard the USS Cavalla (SSN 684). After obtaining his bachelors' degrees he served on board the USS Wadsworth (FFG 9) and USS Curts (FFG 38) acting as the Auxiliary Officer and Navigational Officer as well as performing duties as Officer of the Deck and Combat Information Center Officer. Dr. Talk has also served as the Congressional Liaison Officer for the United States Fleet Forces Command Public Affairs Office. During his service he has earned multiple honors including the Navy Achievement Medal twice, the Navy Commendation Medal, several Admirals' Letters of Accommodation, and was award the OB/GYN Intern of the year and later the Teaching Resident of the year at Naval Medical Center Portsmouth.

Dr. Talk currently lives in Norfolk, Virginia with his wife of 12 years and his three children.

Appendix C: Frequently Asked Questions (FAQ)

FREQUENTLY ASKED QUESTIONS (FAQ)
TORPOR INDUCING TRANSFER HABITAT FOR HUMAN STASIS TO MARS
April 2014

Questions on the Concept and Motivation

[C.1] Could you explain a little bit about how you came to work on this project?

SpaceWorks has evaluated a number of Mars mission architectures over the years, from both a performance and cost perspective. Mars exploration is a tough problem that will require a lot of technology development work to get to a feasible system in the foreseeable future. Traditionally, the technology focus is on the propulsion system, as there are a lot of gains to be made there. However, propulsion technology tends to be a very expensive investment area. We wanted to focus on a different aspect of the mission that may be equally advantageous and could be synergistic with any advances in propulsion capability. This naturally led to a focus on the crew and associated systems, with a goal of trying to reduce their 'footprint,' or mass contribution to the system.

[C.2] What is the purpose of this project?

In short, we are studying the feasibility of putting a Mars-bound crew in a deep-sleep stasis during the 6 to 9-month transfer periods between the Earth and Mars. Currently, we are not performing any actual experiments or clinical trials. Our medical team is examining the existing body of data and case studies for the application of Therapeutic Hypothermia (TH), our baseline approach. For this initial 9-month phase being funded by the NASA Innovative Advanced Concepts (NIAC) program under the Space Technology Mission Directorate (STMD), we are focused on addressing the question of feasibility, evaluating engineering solutions, and exploring the implications for human exploration of Mars.

NIAC

Website: http://www.nasa.gov/directorates/spacetech/niac/

[C.3] Why put the crew to sleep?

With the crew in a torpor state, we believe we can significantly reduce the mass and volume of the in-space habitat during the outbound and return segments of the mission. This ultimately reduces the entire launch mass for the system. The habitat itself will be a very small module, nominally containing 4 to 6 crewmembers each in their own sleep chamber. By contrast, a typical habitat for an active crew is required to have space for food preparation/eating, exercise, science stations, bathrooms, sleeping quarters, entertainment, etc.

Many of the psychological-social challenges of prolonged space flight can be eliminated with this system. On a Mars mission, it is typically assumed that a small crew will be confined to a very small space for an extended period of time. The crew is under a lot of stress, a long way from home, and has no way to abort if there is a problem. This environment creates a lot of requirements and constraints pertaining to crew selection, increases the burden on the medical teams to monitor mental well-being, and consequently adds uncertainty to the mission. A lot of these issues are solved if the crew is asleep during peak periods of stress and likely boredom. Ultimately, we think it will be the preferred way to travel! We are eliminating the most mundane portion of the mission. Just imagine going to sleep and waking up on Mars 6 months later, no worse for the wear!

[C.4] Isn't this science fiction?

Absolutely not! While it has certainly been inspired by sci-fi, we are taking a much more practical approach. We have volumes of medical research and case studies involving humans that gives credence to and bolsters our claims that this approach is achievable. We are adapting and extending ongoing efforts in medical practice and science.

[C.5] Has anyone ever done this before?

Good question! No – only various aspects of the approach have been performed here on Earth. Scientists are actively looking at inducing hibernation states in non-hibernating animals. Both the Department of Defense (DOD) and National Institute of Health (NIH) have sponsored work aimed at putting humans in a preservation state in order to extend the time period under which critical care could be administered.

[C.6] Is this technology real?

Yes. Both the use of Therapeutic Hypothermia (TH) and Total Parenteral Nutrition (TPN) used in our approach are proven medically. For example, people are routinely fed using TPN for durations lasting over a year here on Earth. So we know that solution works well and is understood. We have a small set of data for people undergoing hypothermia therapy for periods of up to 14-days. We have considerably more data for people undergoing TH for shorter periods of 2 to 4 days. We also have instances of individuals undergoing multiple/repeated TH cycles. In all these cases, there have been no reported complications with the patients associated with the TH.

[C.7] At the end of this study phase, what do you hope to have achieved?

We expect to have a baseline approach from a medical standpoint of how induced torpor for a space crew can be achieved. We hope to have some solid data that our system can significantly impact the design of the Mars architecture. We believe we can show benefits that can be applied to the near-term feasibility of going to Mars, possibly with this technology being the key enabler. We also think we can show benefits for exploration in the longer term, so this is not a capability that would be phased out after a few initial missions.

[C.8] What other spin off benefits do you anticipate?

Medically, the alternate uses of therapeutic hypothermia and sustaining a reduced metabolic condition are still being determined. Research has shown some benefits such as significantly reducing the growth rate of tumors (growth currently resumes upon rewarming) and lowering internal cranial pressure (ICP).

The U.S. military is already very interested in the ability to slow down human metabolism in order to increase the time available to provide critically wounded soldiers with proper care. Our proposed approach is obviously synergistic with those goals.

Similar to the military's goal, this capability could be used on non-Torpor Mars missions in the event of a serious injury. After putting the injured crewmember in stasis, the rest of the crew would have more time to communicate with doctors on Earth to evaluate the situation and recommend the best solution. This is especially important given the signal time delay between Earth and Mars that can range from 4 to 21 minutes.

[C.9] How can I learn more?

You can view an overview briefing on the project here:
 http: www.sei.aero/eng/papers/uploads/archive/NIAC-Torpor-Habitat-for-Human-Stasis-2-28-2014.pdf
You can get periodic updates via the Space Torpor blog at:
 http://spacetorpor.blogspot.com
You can also get more information from the NASA NIAC project page at:
 http://www.nasa.gov/content/torpor-inducing-transfer-habitat-for-human-stasis-to-mars

Questions on the Medical Aspects

[M.1] How does this idea work?

Torpor (or Hibernation) is a state of inactivity characterized by low body temperature, slow breathing and heart rate, and low metabolic rate. Many animals in nature hibernate to conserve energy during periods when sufficient food supplies are unavailable. To achieve this, hibernators will decrease their metabolic rate, which then results in a decreased body temperature. Hibernation may last several days, weeks, or months depending on the species, ambient temperature, time of year, and individual's body condition.

Doctors in patient care for extreme trauma are currently applying this idea. Medically induced Torpor (called Therapeutic Hypothermia) is a medical treatment that lowers a patient's body temperature in order to help reduce the risk of the injury to tissue during a period of poor blood flow. Examples include patients that suffer from cardiac arrest, stroke, trauma and brain injuries, as well as infants that are premature or had a complicated delivery. Lowering the patient's temperature by even a couple of degrees (to 34^{o}C or 93^{o}F) can produce the same effects that are seen in animals, including slowed breathing and heart rate, and a decreased metabolic rate. This reduced metabolic rate means a lower need for oxygen by cells in the human body, protecting them from damage during the medical emergencies listed above.

[M.2] Won't the crew get hungry?

Crew members that are in a Torpor state will get their nutrition through a process called Total Parenteral Nutrition (TPN). With TPN the crew member will obtain all nutrients (such as glucose, amino acids, lipids, added vitamins and dietary minerals) through an intravenous (IV) line, bypassing the usual process of eating and digestion. TPN is a well-known and often used medical process for the long-term care of preterm infants and adults that are suffering from medical conditions that do not allow them eat.

The physical sensation of hunger is related to contractions of the stomach muscles. These contractions, sometimes called hunger pangs, are believed to be triggered by high concentrations of the hormones (Ghrelin is the most common) that is released if a person's blood sugar levels get low.

[M.3] Are they breathing?

Yes! Astronauts that are in Torpor are in a deep sleep similar to that of bears and other hibernating animals. Because their body is at a decreased temperature they will experience a decrease in metabolism. This will result in a decrease in their respiratory rate, heart rate, and blood pressure. However, crewmembers in Torpor will continue to have normal physiologic processes.

[M.4] What kind of special equipment does this take?

Torpor is achieved by decreasing a crewmember's core temperature to approximately 34^{o}C (93^{o}F). There are several techniques that can be used to accomplish this. Some are invasive, involving injecting a cooled saline solution into the femoral vein, while others are non-invasive, such as circulating cold water through a blanket or body pads. Our preferred solution is called Trans Nasal Evaporative Cooling. With this approach, a small plastic tube is inserted into a 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 current terrestrial variant of this system is called RhinoChill® by BeneChill, Inc.

Administering nutrition and hydration via Total Parenteral Nutrition (TPN) requires use of an intravenous (IV) line and no additional equipment.

Crewmembers will also have monitoring equipment similar to those seen in a normal hospital setting to monitor their vital signs while in the Torpor state.

[M.5] Will humans that are hibernating age?

There is no direct evidence on what effect Torpor will have on aging. This is primarily due to the fact that current uses for Torpor in the medical community are limited to several days or weeks. However, there is evidence from multiple animal studies that show that hibernating animals do live longer than non-hibernating animals. It is physiologically possible that since torpor decreases a crewmember's metabolism it would cause cells to age and die at a slower rate, slowing the "aging" process.

[M.6] Will all the senses be working (seeing, hearing)?

Yes, human senses continue to work while we are sleeping. Similarly crewmembers in a Torpor state will continue to be able to feel, hear, and see bright lights in their sleep state. However, typically humans require a very small amount of a mild sedative to suppress the body's natural shiver response that occurs while undergoing Torpor. This sedative would prevent normal sensory stimulation from affecting the astronauts while in hibernation.

[M.7] What is known about the effect of therapeutic hypothermia or torpor on the mental state and cognitive function of the patient? My concern is that upon waking up after ~180 days of sleep, some or all of the crew might not be prepared to function at a high level in a demanding environment.

Currently there is no data available on the effects of long-term Torpor on mental, physical or cognitive function. Therapeutic Hypothermia (TH) is only used by the medical community on critically injured or ill patients. These patients have baseline mental, physical and/or cognitive function impairment due to these injuries, making isolating the long-term effects of Torpor hard to predict.

However, hibernating animals like the black bear can be aroused and fully functional in a very short period of time to protect themselves while in torpor. This would suggest it is plausible that humans may be able to awaken from prolonged torpor with minimal affect to mental, physical or cognitive function. Researchers around the world are actively studying this process in animals to understand exactly how and why it works. This is also something we can conduct human trials for here on Earth before attempting it in a space environment.

[M.8] What does the lack of gravity affect in terms of muscle, bone and blood?
Changes to the musculoskeletal system and the cardiovascular system are a well-known complication of prolonged space travel.

Skylab and Russian Space data shows us that astronauts lose approximately 8% bone mineral density after 84 days in space. This increases to 19% by 140 days. Theoretically, an astronaut could lose up to 50% or more of their bone mineral density over a 3-year space mission.

Significant atrophy of skeletal muscle starts after only 5 days in space, and there is no idea if and when a plateau of atrophy would be reached. Most of these changes appear to be due to deconditioning and not any particular microgravity pathology. However, cycling and treadmill activity do not appear to affect muscle density loss but do prevent biophysical changes (gait changes, foot drop) that worsen density loss and recovery.

There are some changes in the cardiovascular system (decreased fluid volume, decrease in stroke volume and cardiac output by about 15%) with prolonged space travel. However, there are no noted changes in heart rate or function so these changes do not appear to be a health risk at this time.

NASA has extensively worked to identify therapeutic and preventive measures to combat these issues.

[M.9] Won't the intranasal cooling system and gas dry out the crew's nasal cavity – is this viable in long run?

Many studies have been performed on Trans Nasal Evaporative Cooling systems. Studies have shown that for the methods used currently it does <u>not</u> occlude the nostrils and <u>no erosion</u> of the nasal mucosa was seen, although care and lubrication was required when inserting the nasal catheters to avoid causing nosebleeds. There was no evidence of sinusitis, tympanic membrane injury or olfactory dysfunction. We would also note that the flow rate of the gas is very low and that it is not always being released. It is only used when the body temperature starts to rise and exceed the target temperature range.

Many researchers have noted that the procedure may cause an oppressive feeling due to the high volume of circulating air and that it is only suitable in sedated patients. With high flow systems the large amount of dry air was noted to cause stinging and dryness of the nasal mucosa during initiation, but this was temporary and counteracted by either moisturized air or lubricant when placing the tubes.

[M.10] How do you prevent corneal stenosis?

Corneal stenosis is a disorder of the eyes characterized by damage or erosion to the outermost layer of cells of the eye. The condition is excruciatingly painful because the loss of these cells results in the exposure of sensitive corneal nerves. Corneal stenosis can occur in medical patients that are in a coma or other prolonged sleep state as the cornea tends to dry out the longer the eyelids are closed. Prevention of this condition includes ensuring that the air is humidified rather than dry, maintaining general hydration levels with adequate fluid intake, applying long-lasting eye ointments before starting the sleep cycle, and applying artificial tear drops under the inner corner of the eyelids before opening eyes upon waking.

[M.11] Will the crew develop pressure sores due to lack of movement?

Pressure ulcers (also known as decubitus ulcers or bedsores) are injuries to the skin or underlying tissue. They occur due to pressure applied to the tissue resulting in partial or complete blood flow blockage of the blood supply to soft tissue. Pressure ulcers most commonly develop in persons who are not able to move on their own. Fortunately these injuries are easily preventable and treatable if detected early. Primary prevention is to redistribute pressure by turning the patient regularly. In addition to turning and re-positioning, eating a balanced diet with adequate protein and keeping the skin free from exposure to contaminants is also helpful.

In a microgravity environment crewmembers would have minimal pressure applied to the skin and soft tissue, which would greatly reduce the incidence and severity of pressure ulcers during a torpor state

[M.12] Have any animals ever been tested?

As noted above, Therapeutic Hypothermia and Total Parenteral Nutrition are medical procedures that are used in every major medical center in the United States. They have been well studied in both animal and human investigative trials. Current human studies have shown the safety and medical benefit of Torpor for as long as 14 days straight and as many as 5 repeat cycles. Prolonged Therapeutic Hypothermia resulting in Torpor greater than that has not been studied at this point and would need to be investigated further.

[M.13] What about the increase in intracranial pressure?

Microgravity-Induced Visual Impairment/Intracranial Pressure (VIIP) is of recent concern at NASA regarding long-duration space missions. Although its exact cause is not known at this time, it is suspected that the low gravity space environment causes a fluid shift to the brain. This causes an increase in the crewmember's intracranial pressure (ICP) resulting in optic disc edema and globe eye flattening that can cause mild but persistent changes vision. NASA is currently looking at how to address this medical concern.

Medically therapeutic hypothermia has remained a controversial issue in the debate concerning the management of elevated intracranial hypertension. It is not currently recommended as a standard treatment for increased intracranial pressure in any clinical setting. However, recent studies suggest that hypothermia can lower ICP and may improve patient outcomes. Hypothermia also appeared to be effective in lowering ICP after other therapies have failed.

[M.14] Is there a way to predict or prevent the medical side effects from occurring (while the crewmembers are in Torpor)?

Patients that undergo Therapeutic Hypothermia do not all respond in the same physiologic manner. Some patients have a very strong shiver response that requires multiple large doses of sedation medications to control while others have only mild or no shivering response at all. Similarly, the effects on patient heart rate, blood pressure, coagulation factors, white blood cells and blood sugar are all widely variable. This would indicate that some patients are just better suited to handle the physiologic effects of TH than others. In addition, there is some evidence from patients that have undergone repeat cycles of Therapeutic Hypothermia that the body becomes accustomed to the physical changes that occur, resulting in decreased physiologic complications.

Because of this it would be feasible to place all available astronauts from the mission pool under short test cycles of TH and identify which ones are least likely to have complications. In addition, crew members that were mission critical or had moderate to mild complications may be able to be conditioned for the Torpor state by undergoing short repeat cycles.

Questions on the Mars Architecture

[A.1] What if something goes wrong?

We are considering emergency-wake procedures for the crew. The best rewarming process for TH patients is an ongoing area of research and study. Generally, a slower warming process that is on the order of a few hours is preferred. But, this dataset is based on patients that have experienced some traumatic injury. A combination of approaches including cessation of the cooling process, active warming, and injection of adenosine, for example, could permit acceleration of the emergency-wake procedure.

Alternatively, we have evaluated an operational protocol that would have at least one crew member awake at all times and the remaining crew members on a 14-day torpor cycle. The impact to our baseline habitat mass for this approach is minimal to support this approach.

[A.2] How do those in torpor respond to the short warnings on incoming radiation?

Ultimately, we would plan to have the crew stasis pods shielding to be on par with a storm shelter. Since the surface area of these pods is fairly low, the parasitic shielding mass is tolerable.

We are also looking at the option to surround the habitat with the liquid hydrogen being used for the trans-Earth injection (TEI) propulsive burn upon Mars departure. With this, the crew would have additional protection during the outbound trip to Mars and in the event of an aborted surface mission that leaves them in orbit. During the return segment, the shielding level would be reduced, however.

With the mass savings provided by our approach, we can offer and afford radiation shielding levels that would otherwise be prohibitive for an ‘active’ habitat design.

[A.3] What medical problems with torpor have been noted on Earth and how do we mediate them with the limited resources carried into space?

There are several potential complications associated with Torpor. The most significant risks are increased risk of bleeding and increased risk of infection. In addition, TH can adversely affect several other physiologic processes. It should be noted that all of the complications listed below are rare, and can be completely corrected through autonomous systems and monitoring of crewmembers if needed.

1. Torpor induces a mild coagulopathy (increased risk of bleeding). With body temperatures below 35ºC, clotting factors operate more slowly and platelets function less effectively. As a result, some bleeding is seen in up to 20% of patients treated with TH, although bleeding that needs to be treated with medication is rarely seen even in trauma patients and blood transfusions are rarely required.

No treatment is required for mild coagulopathy. Even mild bleeding from the nose and IV sites will still stop without treatment. The treatment for heavy bleeding associated with trauma would be the addition of clotting factors through the IV line and increasing the crew member's blood volume with both IV fluids and blood products. Since the crewmembers will already have an IV line the process would require someone to just defrost and hook-up the needed product. Clotting factors and blood can be frozen for as long as 10 years. After thawing blood products are only usable for 42 days.

2. Torpor can impair white blood cell function. The incidence of significant infections is likely to increase if hypothermia is maintained longer than 24 hours. While an increase in infection rates has been noted in several studies, these infections have not been associated with any increased mortality (risk of death) and are usually easily treated.

Preventing the infection from occurring is the best and easiest method. This includes using improved sterile techniques for IV placement and care and for utilizing improving technology in antimicrobial IV equipment. IV antibiotics antibiotic are used if an infection does occur, and are easily administered in space.

3. Hypothermia slows heart conduction and can cause irregular heart beat patterns called arrhythmias, including bradycardia and QT interval prolongation. A heart rate in the 40's is common at 33ºC, but does not require intervention if the blood pressure is in the normal range. Multiple studies show that TH is not associated with an increased need for medications to increase blood pressure. This would indicate that most cases of hypotension (low blood pressure) in TH patients are due to either injuries or shock and <u>not</u> Torpor itself.

Treatments for hypotension include increasing IV fluids to increase blood volume and the use of medications called "pressors" to artificially increase blood pressure, both of which can be performed easily in space.

4. Hyperglycemia (high blood sugar) due to insulin resistance has been noted during TH. IV Insulin may be needed in severely hyperglycemic patients.

5. Hypothermia leads to a "cold diuresis," which in turn can cause hypovolemia (low blood volume), hypokalemia (low potassium), hypomagnesaemia (low magnesium), and hypophosphatemia (low phosphates). In addition, temperature fluctuations during the induction of TH and rewarming can cause potassium to move between the extracellular and intracellular compartments. Therefore, careful monitoring of volume status and measurement of basic electrolytes approximately every three to four hours during temperature manipulation should be done. This can easily be corrected with IV fluids.

[A.4] Does torpor help or hurt with respect to the degeneration of the body in extended weightlessness?

This is a question we are attempting to address but it will be some time still before it can be answered fully. While there appear to be potential benefits with torpor, we are also considering different options enabled by the use of torpor for addressing common spaceflight physiological issues. For instance, with the crew in an unconscious state, we can induce artificial gravity at higher rotation rates and lower radii without concern for discomforting Coriolis effects and gravity-gradients. Similarly, to reduce muscle atrophy, we can routinely apply electrical neuromuscular stimulation to the crew - something that would not be possible with an active crew. They may actually arrive at Mars in better physical shape than when they left Earth!

[A.5] Is the mission architecture predicated on the use of torpor for transit both to and from Mars?

Yes, to obtain the most benefit from our approach, the crew would ideally be in stasis for both outbound and return phases. If medical technology is capable of supporting the extended torpor period, current medical evidence shows there is no detrimental impact to undergoing repeat cycles.

Questions on the Concept Overview Presentation

In reference to:

www.sei.aero/eng/papers/uploads/archive/NIAC-Torpor-Habitat-for-Human-Stasis-2-28-2014.pdf

[P.1] Chart #31 indicates that the use of induced torpor would result in a savings of 70% in total consumables mass (total food mass, really). However, on slide #22, the savings offered by torpor in terms of nutrition mass/crew/day is no more than 59% (more likely 27-42%). What am I missing here?

The bar chart on slide #22 shows dosage rates for TPN-based nutrition only. For a fully-active person, this is about 0.7 kg/day of the aqueous dextrose/amino acid/lipid solution. By comparison, the typical mass allocation with traditional solid/partially-hydrated food used by astronauts, based on spaceflight experience and the ISS, and is over 2 kg/day.

For our baseline habitat, we used the "resting-level" TPN dosage rate (0.55 kg/day) to determine our food stores. This is a conservative approach since we did not take any further reductions for the Torpor-state. This handles our contingency case if the crew were to awake and remain in a conscious state.

So, we don't think you are missing anything here, just using the wrong basis number for comparison!

[P.2] Is the on-orbit assembly of the transfer "stack" assumed to be performed robotically? If not, does the human assembly crew have to live in the torpor-optimized habitat during assembly operations?

Yes, the baseline architecture calls for robotic, on-orbit assembly. Note though either way, between the crew transfer vehicle (e.g. Orion), the habitat, the pressurized docking node, and the Earth Return Vehicle (ERV), there is still a lot of habitable volume available.

[P.3] What happens if a crewmember wakes up halfway to Mars? Does that affect energy/mass budget? What if they all wake up halfway there?

For our baseline habitat, the consumables for both the transit phases as well as the contingency stores are based on the required TPN dosage for a resting state. We did not take further reductions to account for the lower metabolic state associated with cooling. Thus, the habitat is designed for the off-nominal situation of a conscious crew.

See response P.1 for additional, related information on this subject.

[P.4] Is the 85-ton saving a round trip or one-way?

The 85-ton IMLEO mass savings is in comparison to the baseline NTR-powered DRA 5.0 architecture. This is a Conjunction-class (180-day out, 500-day surface stay, 180-day return), round trip mission to Mars with a crew complement of 6.

[P.5] What happens if there is a catastrophic failure – meteor impact, failure in the system?

We think a catastrophic system failure is unlikely since we have a number of redundant systems. The torpor-specific hardware consists of fairly simple systems and would all fail benignly. For example, a failure with the thermal control cooling system would merely cause the crew to awake from stasis due to the warming. In the event of a shut down with the TPN distribution system, the crew member(s) would be awoken to correct it. They could actually survive for 3-4 days without hydration or TPN injection, so plenty of time to correct any issue and/or awaken crew.

The non-torpor hardware (e.g. ECLSS, power, etc.) is identical to NASA's planned system designs and has their own margins and redundancies.

For a major external event like a meteor impact, we are considering emergency-wake procedures for the crew. The best rewarming process for TH patients is an ongoing area of research. Generally, a slower process that is on the order of a few hours is preferred. But, this dataset is based on patients that have experienced some traumatic injury. A combination of approaches like cessation of the cooling, active warming, and injection of adenosine, for example, could permit acceleration of this process.

Alternatively, we have evaluated an operational protocol that would have at least one crew member awake at all times. The remaining crew members would be on 14-day torpor cycles. For this case, the impact to our baseline habitat mass is minimal to support this approach.

[P.6] What do we know about the human digestive system not working for that long of a time?

There are many groups of medical patients, including preterm infants, coma patients, and cancer patients that undergo long periods of TPN use as their only source of nutrition. As a result, doctors have long had concerns over the affects of TPN and its long term affect on the human digestive system. Thirteen different studies have been conducted on over 400 infants and children between the ages approximately 4 months to 17 years old, and almost 100 healthy adults control subjects to identify complications such as gastrointestinal bacterial overgrowth and sepsis, impaired immune functions, overall mortality including bowel or stomach perforation, intestinal villous atrophy, and the effects of TPN on gut mobility. Based on this literature there is no evidence suggesting that TPN promotes bacterial overgrowth, impairs neutrophil functions, inhibits blood's bactericidal effect, causes villous atrophy, or increases the risk of death due to gastrointestinal complications. The hypothesis of a negative effect of TPN, while commonly cited by many doctors, was also unproven in these studies.

The most common complication that can occur in adults from prolonged TPN use is a complication after returning to normal food called "refeeding syndrome". "Refeeding syndrome" is a complication in patients that have gone without food for a long period time (usually greater than 5 days). When food is reintroduced to the patient they can have rapid disturbances in their electrolyte levels, causing complications with their body chemistry. This is a rare complication with TPN and can be easily prevented with the proper re-introduction of oral food and the proper monitoring and correction of the person's electrolytes.

[P.7] What are you doing for Galactic Cosmic Ray (GCR) shielding and providing a 'safe place' for the crew?

The NASA DRA 5.0 architecture design does not include a dedicated storm shelter or any parasitic radiation protection shielding for the crew. To enable a direct comparison of the torpor-system, we have made similar assumptions with our baseline design.

However, with the significant mass savings we are obtaining, we have the system mass margin to now include additional shielding for the crew. Not only can we add additional shielding, we only have to protect a smaller volume inhabited by the crew. Thus, we can increase safety and wellness for the crew and still reduce the IMLEO for the architecture.

[P.8] Are you considering the use of any artificial gravity?

Yes. While DRA 5.0 baseline was a zero-G architecture, we have developed a habitat configuration that would easily permit inducing an artificial gravity field. While the radius of rotation in this habitat is fairly small, less than 3-meters, with the crew in an unconscious state we do not have to be concerned with the typical issues of uncomfortable gravity gradients or Coriolis effects. If we are going to have an active crew member, we would need a slightly more complex design that would have a larger radius.

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