ADVANCING TORPOR INDUCING TRANSFER HABITATS FOR HUMAN STASIS TO MARS

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List of Acronyms

BMR	basal metabolic rate
CTV	Crew Transfer Vehicle
CDRA	Carbon Dioxide Removal Assembly
CONOPS	concept of operations
CReA	Carbon Dioxide Reduction Assembly
CTB	cargo transfer bag
DDT&E	Design, Development, Testing & Evaluation
DRA	Design Reference Architecture
EMT	Emergency Medical Technicians
ERV	Earth Return Vehicle
EVA	Extra-Vehicular Activity
FDA	Federal Drug Administration
HBE	Harris-Benedict Equation
HIT	Hibernation Inducing Trigger
ICP	Intracranial Pressure
IMLEO	Initial Mass in Low Earth Orbit
IV	Intravenous
LCH4	Liquid Methane
LDRO	Lunar Distant Retrograde Orbit
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MAV	Mars Ascent Vehicle
MCPS	methane cryogenic propulsion stage
MDV	Mars Descent Vehicle
MOCET	Mission Operations Cost Estimation Tool
MOI	Mars Orbit Insertion
MTV	Mars Transfer Vehicle
NAFCOM	NASA-Air Force Cost Model
NASA	National Aeronautics and Space Administration
NG	Nasogastric
NIAC	NASA Institute for Advanced Concepts
NMES	Neuro Muscular Electrical Stimulation
NTR	Nuclear Thermal Rocket
OG	Orogastric
PEG	Percutaneous Endoscopic Gastrostomy
SEI	SpaceWorks Enterprises, Inc.
SEP	solar electric propulsion
SLS	Space Launch System
STMD	Space Technology Mission Directorate
TBI	traumatic brain injury
TCCS	Trace Contaminant Control Subsystem
TEI	Trans-Earth Injection
TH	Therapeutic Hypothermia
TMI	Trans-Mars Injection
TPN	Total Parenteral Nutrition
TRL	Technology Readiness Level
TTM	Targetted Temperature Management
VIIP	vision impairment and intracranial pressure
ΔV	delta-V (in km/s or fps)
C	Celsius
F	Fahrenheit
fps	feet per second
m	meters

Foreword and Acknowledgements

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For providing their valuable time, medical expertise, insights, and support, the SpaceWorks-team thanks Dr. Alejandro Rabinstein, M.D. Neurology at the Mayo Clinic, Dr. Matthew Kumar, at the Mayo Clinic, and Dr. Kelly Drew at the University of Alaska – Fairbanks and Be Cool Pharmaceutics, LLC. We also wish to thank astronaut Dr. Leroy Chiao for his contributions and insights in the area of human spaceflight.

1. Executive Summary

SpaceWorks Enterprises, Inc. (SEI) has conducted an evaluation of an advanced habitat system designed to transport crews between the Earth and Mars. This new and innovative habitat concept is capable of placing crew members in inactive, torpor states during transit phases of a deep space mission. 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 human metabolic rate to decrease 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.

The initial results obtained from the research and analysis conducted in the Phase I effort warranted further study of this concept and technology. The specific objectives of the continued work include:

1. Addressing critical medical aspects and risks for inducing torpor via Therapeutic Hypothermia and the approach for providing nutrition and hydration for the crew during torpor
2. Focusing on mitigation aspects and technology potential for solving key human spaceflight challenges
3. Addressing critical engineering aspects of the design that may impact the initial performance and cost results obtained in Phase I
4. Examining the broader extensibility and enabling capabilities of this concept through applicability to additional exploration missions beyond Mars
5. Establishing a technology development roadmap, addressing both medical and engineering aspects, that indicate a logical and scientifically achievable path forward for maturation of this technology

For this effort, four (4) key task areas were identified. These were structured and developed based on prior work to address key challenges/issues and to achieve the research objectives. Each element was designed to further explore and advance our knowledge of the concept. As shown in Figure 1, the focus areas and study task activities are:

(i) Medical Assessments and Evaluations
(ii) Mars Mission Habitat Design
(iii) Extensibility Beyond Mars
(iv) Technology Roadmap Development

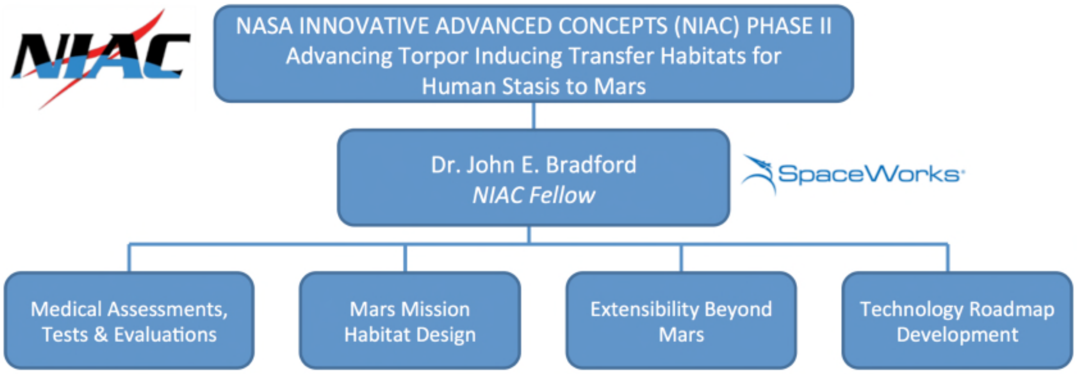


Figure 1. Study Organization and Key Research Areas

In addition to the experienced team of engineers from SpaceWorks, a diverse medical team that consists of expert practitioners and respected industry leaders in the fields of animal hibernation, therapeutic hypothermia, and advanced medicine were assembled. These experts supported further studies on the medical viability for this concept, identification of key risk and mitigation options, and assisted in creation of the technology roadmap.

The results of this effort provide NASA with the knowledge and information needed to understand the medical aspects, the engineering trades, and overall viability of this concept. This could potentially set NASA and the industry on a completely new path towards enabling exploration and make the prospects of humanity extending itself into deep space truly a reality.

This concept is multi-faceted and trans-disciplinary in nature. To fully realize its potential, it will require engineers from every discipline, hardware technicians, medical specialists in every aspect of human physiology, psychologists, psychiatrists, and human factors experts. For mission planners and designers, the effort will outline multiple options and paths forward to understand the best way to capitalize on the technology and maximize the benefits. It is expected that this broad look at the concept applicability will serve to foster further studies and innovation amongst the industry.

The ultimate goal of the team is to advance the concept from what is likely viewed as still very speculative based on the Phase I study to a viable option enabling human exploration at the conclusion of the Phase II effort (*albeit with much work still to do*). This study will likely encourage further investigations amongst the medical community that NASA can continue to leverage and use to the benefit of spaceflight. Similarly, NASA's interest and support in this field will likely help to maintain current research investments by NIH and DoD, potentially leading to spinoffs in the medical community in the form of new medical treatments, equipment, and applications.

To this end, SpaceWorks has compiled a developmental roadmap for this technology. As shown in Figure 1, research efforts for both the medical and engineering aspects are summarized and phased in time, including potential off-ramps as contingency for some key approaches.

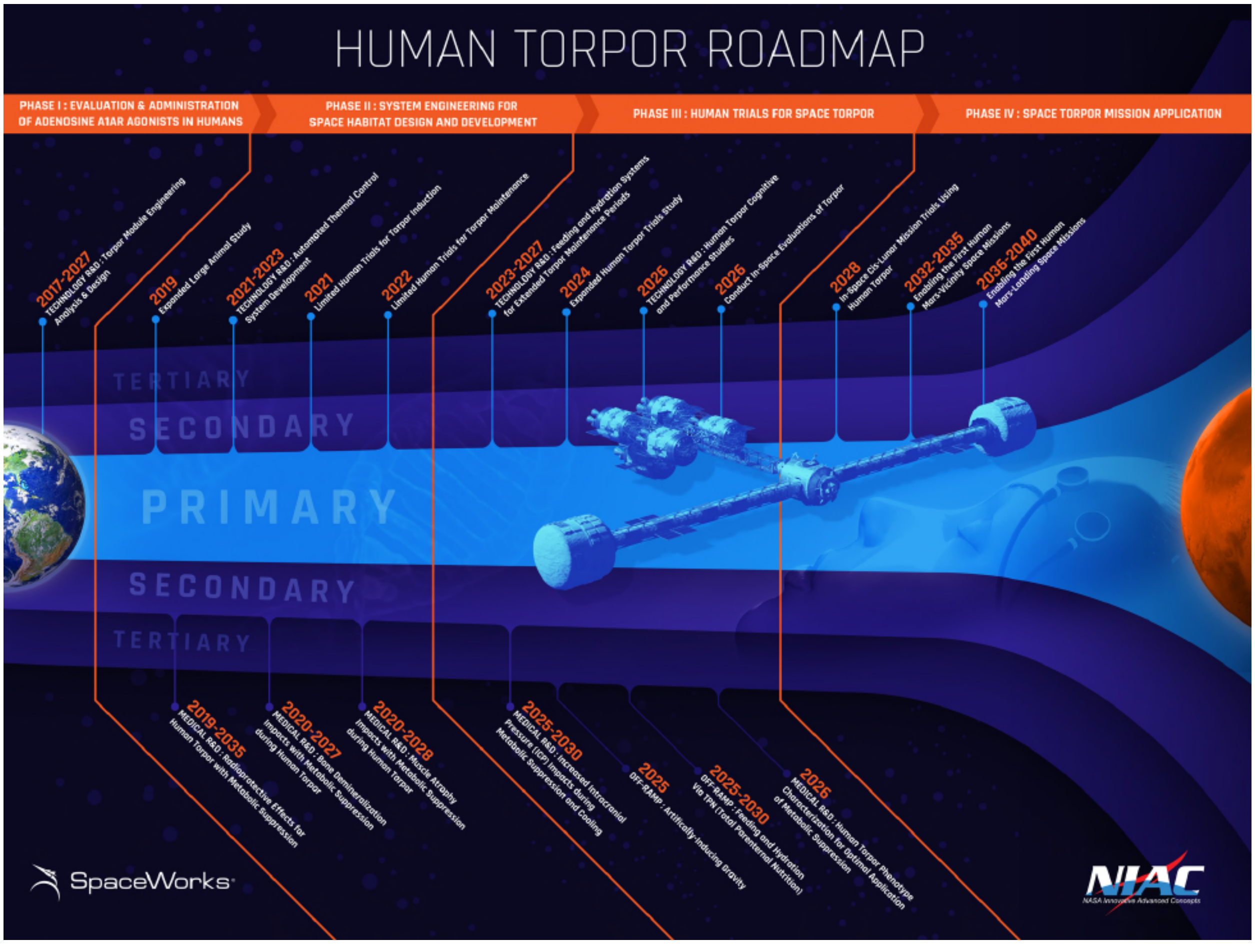


Figure 2. Space Torpor Development Roadmap

2. Introduction and Rationale

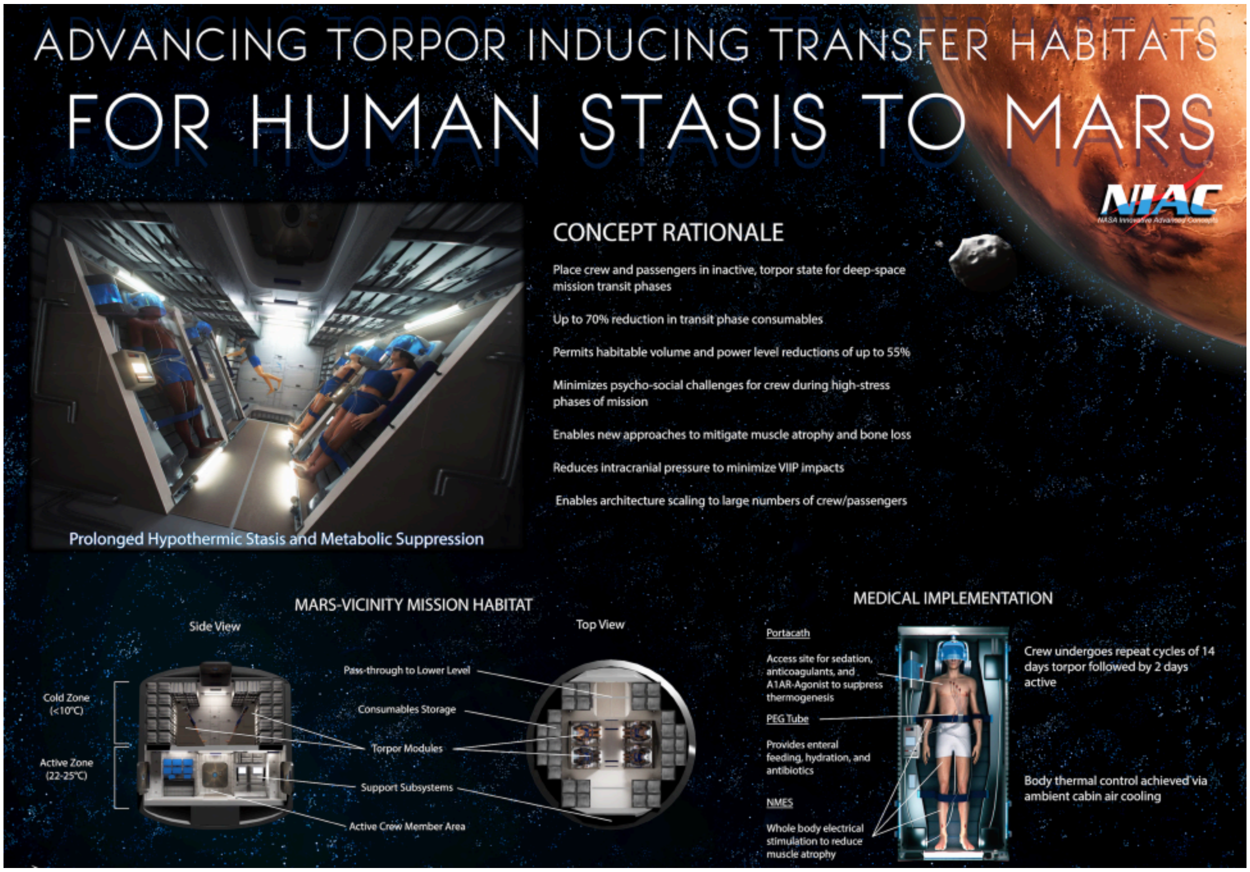
2.1. Introduction

Technology development for in-space habitats is often focused on improving the power generation system efficiency, lightweight structures, and environmental control and life support systems (ECLSS). Assuming these advanced technologies, estimates for Mars in-space habitats still range from 25 to 50 t for crew sizes between 4 and 6 [1,2]. With these habitat masses, advanced propulsion (SEP, NTR, etc.) and cryogenic transfer stages become mandatory architecture elements just to make the end-to-end system remotely feasible. We need affordable, game-changing technologies if we are to truly contemplate the prospects of humans pioneering to Mars and beyond.

SpaceWorks proposes the development of an advanced habitat system for transporting crews between the Earth and deep space destinations. This new and innovative habitat design is capable of cycling the crew through inactive, non-cryonic torpor sleep states for the duration of the in-space mission segments. While this idea of "suspended animation" for interstellar human exploration has often been shown in the realm of science fiction as the solution for long-duration spaceflight, recent medical advancements in Therapeutic Hypothermia (TH) have demonstrated our ability to induce deep sleep states (i.e. torpor) with significantly reduced metabolic rates for humans over extended periods of time with moderate reductions in core body temperature [4]. With currently foreseeable stasis periods of up to two weeks, this new approach to spaceflight can offer numerous benefits to the crew and mission [5]. Cycling the crew in and out of the torpor state further reduces the burden on fully autonomous systems, ensures crew cognitive abilities are maintained, and enables use by NASA on early Mars missions. Over time, it is reasonable to assume this capability can be further extended to periods of months to offer additional benefits.

The torpor habitat primarily consists of sleep chambers, or pods, that crewmembers would enter for stasis shortly after departure from Earth or after leaving their destination for Earth-return. The current approach envisions these pods using a combination of passive cooling systems, minimal dosage suppressive drugs, and an adenosine A1AR agonist pharmaceutical, to initiate and sustain the torpor state. As a result of this process, crew metabolic rates are subsequently and significantly reduced relative to standard basal metabolic rate (BMR), minimizing the oxygen demand and nutrient requirements. The body's core temperature need only be reduced to 89^o to 93^oF to enable this process. In stasis, body hydration and nutritional needs are then provided enterally via all-liquid solutions.

The baseline crew operations approach is referred to as a "sentry protocol". This protocol puts each crew member in a rotation sequence of being active for a brief period of a few days followed by a 10-14 days of an inactive, torpor phase. This approach is considered very reasonable based on current medical capabilities and emerging practices. At any time during transit, scheduling permits there to be at least one alert and active crew member on the mission with one other crew member either undergoing a cooling phase to enter torpor –or- a warming cycle to awaken. This schedule is repeated throughout the duration of the transit phase and has only minimal negative impact on the potential size of the habitat and mass savings that could be achieved compared to a full duration stasis period for the entire crew (e.g. 6 months of torpor).



ADVANCING TORPOR INDUCING TRANSFER HABITATS FOR HUMAN STASIS TO MARS

CONCEPT RATIONALE

- Place crew and passengers in inactive, torpor state for deep-space mission transit phases
- Up to 70% reduction in transit phase consumables
- Permits habitable volume and power level reductions of up to 55%
- Minimizes psycho-social challenges for crew during high-stress phases of mission
- Enables new approaches to mitigate muscle atrophy and bone loss
- Reduces intracranial pressure to minimize VIIP impacts
- Enables architecture scaling to large numbers of crew/passengers

Prolonged Hypothermic Stasis and Metabolic Suppression

MARS-VICINITY MISSION HABITAT

MEDICAL IMPLEMENTATION

Portacath: Access site for sedation, anticoagulants, and A1AR-Agonist to suppress thermogenesis

PEG Tube: Provides enteral feeding, hydration, and antibiotics

NMES: Whole body electrical stimulation to reduce muscle atrophy

Crew undergoes repeat cycles of 14 days torpor followed by 2 days active

Body thermal control achieved via ambient cabin air cooling

Figure 3. Torpor Inducing Habitat Concept Overview

With the mass savings achieved with torpor inducing transfer habitats compared to current industry habitat designs, a host of new options are available to enhance mission capability. This includes ability to expand launch windows, reduce trip times, reduce program costs (e.g. less hardware and complexity), and/or improve crew safety (e.g. thicker radiation shielding, greater redundancy). This can all be done with almost no detrimental impact to the scientific value or goals of the mission. This technology also uniquely offers a more sustainable approach to exploration, not merely from a cost perspective but also for system scalability. As humanity will ultimately desire and need to send ever increasing crew sizes into space, this technology is capable of supporting the demanding performance requirements for those missions.

2.2. Rationale

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.

The engineering analysis results under the 2013 Phase I study indicated the potential for substantial habitat mass reductions as well as significant architecture improvements [5]. In the cumulative experiences of the authors, no other single technology has been found to have such a significant impact on a system element and across a Mars exploration architecture as those achieved through the torpor concept. Based on the potential of this concept, further evaluation was certainly warranted. The innovative adaptation of TH to spaceflight is an opportunity to realize a game changing technology.

A brief description of a few key exploration challenges that torpor can address 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 and solution.

Engineering-
In order to safely send and return a crew from deep space, a massive system-of-systems architecture is required that will contain 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.

Space Environment-
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. 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.

Mission Duration-
Round-trip Mars missions tend to be on the order of 2.5-3 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. While additive manufacturing capabilities will surely offer some solutions for sparing, it is not a panacea. In addition to the need for highly robust systems, both the required levels of redundancy and spare parts increase the total system mass.

Affordability and Sustainability-
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, almost any delay 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. 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.

2.3. Technology

The torpor state is achieved by inducing a mild hypothermic state, a practice known as Therapeutic Hypothermia (TH). 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. Since 2003 TH 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 relatively inexpensive to implement and use. Standard protocols exist in most major medical centers throughout the world [6].

Large medical teams are generally required to provide care and treatment for the types of traumatic injuries that necessitate the use of TH in hospitals today. However, a single medical professional can perform the application and monitoring of the TH treatment component, as is currently demonstrated by Emergency Medical Technicians (EMTs) and first responders [7]. Thus, it is not unreasonable to assume that over the next decade or two, a healthy Mars-bound crew in torpor could be monitored by a single active crew member assisted by advanced robotic/AI systems and/or self-induce the process via automation.

While TH is a proven treatment for traumatic injuries, it has not been applied in non-critical care settings due to a current lack of medical need or purpose. 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 evolving procedure that the medical community is still identifying its multiple benefits and applications

- Human patients that have experienced traumatic injuries regularly undergo TH for periods of 24-48 hours (established treatment protocol). A recent Chinese study has indicated at least one patient successfully underwent TH for up to 14-days, although very little about their current condition(s) is known [4].

- A Percutaneous Endoscopic Gastrostomy (PEG) is a tube inserted through a small incision in the abdomen and into the stomach and is intended for long-term enteral nutrition (with a median use of 6 months, but with well documented extended use for over 4 years) [8].

- Conversations conducted with multiple medical practitioners, researchers, and experts have confirmed the medical plausibility of this concept and approach

As with any new concept or technology, there are potential risks or complications involved due to the lack of data and/or knowledge. This study effort has attempted to identify and mitigate any known or likely medical risks and challenges through revisions to the intial torpor approach that was postulated during the Phase I effort.

3. Background

3.1. Hibernation

Hibernation is a physiologic state that occurs in warm-blooded animals and is characterized by inactivity, reduced body temperature, slowed breathing and heart rate, and a decreased metabolic rate. Most often associated with low ambient temperatures and winter months, the primary function of hibernation is to allow an animal to conserve energy when resources are scarce. To enter this state, an animal decreases its metabolic rate, which in turn decreases its overall body temperature and other physiologic functions [2]. Hibernation can last from several days to several months depending on the species, the reason for hibernation, the ambient temperature, and the time of year.

The term hibernation can technically be subdivided into two distinct processes, obligate hibernation and facultative hibernation. While the mechanisms that initiate each type of hibernation are similar, the end result is markedly different [9]. Obligate hibernation is the process of spontaneous and annual hibernation that occurs regardless of the ambient temperature or an animal's access to food. This is the state most traditionally identified as "hibernation", where the animal's body temperature, heart rate, respiration rate, and metabolic activity level slows drastically. Facultative hibernation (also known as Torpor), on the other hand, only occurs when an animal is stressed by some environmental factor (i.e. extreme cold or food deprivation). A torpor state can last days to weeks, or even be episodic occurring at regular intervals in a 24-hour period (known as "daily torpor") [10]. There are dozens of warm-blooded species that are known to hibernate or undergo torpor, including four species of primates.

The actual step by step process that prepares an animal for hibernation and initiates its associated metabolic reduction is not currently known. This is likely due to the fact that hibernation is a complex physiological process regulated by multiple organ systems. At this time, the most accepted theory of hibernation induction is by a chemical called a "Hibernation Inducing Trigger" (HIT for short), which when released by the animal initiates the hibernation process. There is some research to support this theory. Early hibernation research in 1990s hinted at the ability to induce torpor in animals through the injection of blood taken from hibernating animals. While this research has not been duplicated, there is clinical evidence of substances in hibernator's blood that can lend protection to organs for possible transplant [11]. The leading candidates for the HIT chemical are either a selective delta opioid receptor agonist or an adenosine receptor agonist [12,13].

3.2. Therapeutic Hypothermia (TH)

Therapeutic hypothermia (TH), or the recently termed targeted temperature management (TTM), is a medical treatment that lowers and maintains a specific core body temperature in critically injured people in an effort to improve health outcomes. While the concept of hypothermia in medical applications has been theorized since the Greek physician Hippocrates, in-depth scientific research into its effectiveness and utilization started in the 1950s [14]. From this time, through the 1980s, multiple studies indicated the ability of mild hypothermia to assist in reducing blood loss during surgery, as well as its ability to act as a general neuroprotectant from incidents that resulted in reduced blood flow to the brain [15]. These animal studies were supported by two large human studies (conducted in Europe and Australia), that were published in the February 2002 issue of the New England Journal of Medicine demonstrating the positive effects of mild hypothermia utilized following cardiac arrest [16,17]. Since these landmark study findings hundreds of additional studies have been performed, resulting in the routine employment of TH/TTM in every major medical center throughout the world for multiple medical applications, including [18]:

1) Cardiac Arrest: Both the American Heart Association (2010) and the International Liaison Committee on Resuscitation (ILCOR) (2013) established guidelines supporting the use of TH (or TTM) as a treatment following resuscitation from cardiac arrest [19,20].
2) Neonatal Encephalopathy: In 2014 the American College of Obstetricians and Gynecologists (ACOG) and American Academy of Pediatrics (AAP) Task Force on Neonatal Encephalopathy recommended the routine use of TTM and established consensus-based guidelines for cases of suspected neonatal encephalopathy. In publishing their recommendations, they sited twelve studies showing the beneficial

effects of decreasing body temperature as a protective treatment during episodes of decreased fetal oxygen [21].

3) Increased Intracranial Pressure (Intracranial Hypertension): Studies support the use of TH as a safe and effective treatment option for refractory Intracranial Hypertension [22].
4) Ischemic Stroke: Multiple studies have shown the viability of TH as a protective treatment for the resuscitation of patients suffering from ischemic stroke [22,23].
5) Traumatic Brain or Spinal Cord Injury: A 2009 review of multiple TH studies supports the use of therapeutic hypothermia as a neuroprotectant during both traumatic brain and spinal cord injuries, although consensus on the optimal temperature and time of cooling has yet to be determined [24].

Current TH/TTMprotocols call for whole body or selective head cooling to 32–34 degrees Celsius, beginning within six hours of injury and continued for up to 72 hours [25]. A duration of 72 hours had been established as the maximum treatment period as no clinical benefit has been established at this time for continuing treatment beyond this period in large clinical trials [18]. However, several studies have been conducted that have noted a benefit of hypothermia when utilized for longer durations. Three independent studies were conducted in China between 2000 and 2009 [26 - 28]. In these studies patients were treated with mild hypothermia (31 to 34 degrees Celsius) ranging from a total of 2 to 14 days. These studies showed that compared with short-term mild hypothermia, long-term mild hypothermia significantly improved the outcome of severe traumatic brain injured (TBI) patients with cerebral contusion and intracranial hypertension without significant complications. Their data also suggested 5 days of cooling was more efficacious than 2 days of cooling when mild hypothermia was used to control refractory intracranial hypertension in patients with severe TBI [27]. In another joint study conducted in Europe, patients were grouped according to hypothermia initiation (early: days 1–2 and late: days 4–5 after admission) and hypothermia duration (short: 4–8 days and long: 9–15 days) [29]. This study noted a significant benefit of both hypothermia initiation and duration on the outcomes of patients with traumatic brain injury and increased intracranial pressure. Studies such as these listed above support the need for further research on the maximum duration and benefit of TH in the future.

3.3. Hypothermia

3.3.1. Method of Action

There are several ways that the cooling associated with TH results in therapeutic benefit. These range from decreases in cellular metabolic activity, the prevention of cellular death (apoptosis), the stabilization of cellular structures under stress, and protection from oxidative stress. At this time it is uncertain whether any of these effects are the primary factor behind TH's clinical benefits or if it is derived from all of the above noted physiological changes working in concert.

Early researchers theorized hypothermia's effectiveness as a neuroprotectant was due to the lower cellular metabolic rate that resulted from decreasing body temperature. Research shows that cellular metabolism slows by 5–7% for every one degree Celsius drop in body temperature [30]. This data supports the hypothesis that hypothermia prevents cellular damage by simply decreasing a cell's need for oxygen [31]. As a result, early studies primarily focused on the use of extreme hypothermia treatments in an attempt to directly correlate protective effects to the extent of temperature decline [32]. However, recent research suggests that there is equal benefit during cardiac arrest when cooling was performed at a near-normal temperature of 36 degrees Celsius compared to 33 degrees [33].

When addressing Neonatal Encephalopathy, the primary source of brain cell injury appears to be due to programmed apoptosis (automated cell death) caused by low oxygen supply. To be more specific, cell death is not directly caused by decreased oxygen levels, but is initiated indirectly by activating a cascade of intracellular events. The primary use of oxygen by cells is to create ATP. Cells use ATP to perform numerous functions, but its primary use is to fuel the import and export of ions to regulate intracellular ion levels. Thus, oxygen deprivation itself does not precipitate cell death, but the loss of intracellular homeostasis triggers the cell to initiate its own death as the cell cannot make the ATP it needs to regulate ion concentrations [31].

Research further shows that even a small drop in temperature encourages cell membrane stability during periods of oxygen deprivation. As a result, a decrease in cellular temperature makes the cell membrane less permeable, which in turn blocks the influx of unwanted ions during periods of low oxygen supply. By making the cell membrane more impermeable, hypothermia helps prevent the above noted apoptosis that is initiated by oxygen deprivation. This protective strengthening of cellular membranes is noted even with minimal decreases in body temperature [31].

TH may also prevent cellular damage by reducing reperfusion injury. Reperfusion injury is damage that is caused by the oxidative stress that occurs when the blood supply is restored to tissue after a period of ischemia. The primary mechanism of reperfusion injury is a series of inflammatory immune responses that affect cells that have been deprived of oxygen. In humans, the primary effect of these inflammatory responses is a marked increase in intracranial pressure and the introduction of free radicals, both of which lead to the injury and death of otherwise healthy tissue. Research shows that hypothermia is effective at reducing intracranial pressure, and therefore able to minimize this harmful effect [23]. The oxidation that results during tissue reperfusion also increases free radical production. During normal aerobic/anaerobic cellular activity, oxygen in the body is split into single atoms with unpaired electrons. As electrons like to be in pairs, these atoms, called free radicals, scavenge the body to seek out other electrons to pair with. This pairing causes damage to cellular structures, proteins and even DNA. Hypothermia has been shown to directly reduce free radical production, indicating another mechanism of action for hypothermia's therapeutic effect [34,35].

3.3.2. Methods of Cooling

There are a number of methods to induce hypothermia, with study data showing that there is no one method that is safer or more effective than the other [19,36]. No matter which method is employed, the same basic steps are performed. Core body temperature is measured (either directly via the esophagus, bladder, rectum, tunneled catheter, or wirelessly via an ingestible capsule) to monitor cooling rates and steady state cooling levels [19]. Prior to initiating TH, pharmacological agents (commonly used medications include buspirone, meperidine, dexmedetomidine, fentanyl, and propofol) are administered to both suppress the shivering response and help the patient tolerate the cooling process [37]. Patients are cooled at a rate of 1.5 to 2 degrees Celsius per hour and maintained at a target temperature of 32 to 36 degrees Celsius for 24 to 72 hours. In current hospital settings the rewarming process occurs slowly (at a rate of 0.5 degrees Celsius per hour) to avoid spikes in blood pressure and electrolyte shifts in the blood that are not well tolerated in critically ill patients [36].

Cooling catheters are closed loop intravenous lines that are inserted into the femoral or subclavian vein. Cooled saline solution is then circulated through the closed loop portion (commonly composed of either a metal coated tube or balloon) which uses convection cooling to lower the temperature of a patient’s blood. While the most invasive of the cooling techniques, multiple studies show that this method is both safe and effective, and allows for the tightest level of control over steady state temperature as well as cooling and rewarming rates [38,39]. However, unlike other non-invasive methods of cooling, the insertion of cooling catheters must be performed by a physician familiar with the procedure.

Nasopharyngeal evaporative cooling is a method of initiating TH that utilizes a cannula, placed into the patient’s nasal or oral cavity, to deliver a cooling gas. This gas usually consists of either dehumidified air plus nitric oxide gas or an inert perfluorocarbon coolant mixed with oxygen [40]. These gases pass directly underneath the brain and base of the skull, causing evaporative cooling of the blood passing through the cooling area, reducing core body temperature. This method is currently employed by emergency responders to easily and rapidly reduce a person's temperature while targeting the brain as the first area of cooling. Research has shown that this method of cooling is both simple to employ and results in very high cooling rates (average of 2.6 degrees Celsius) [41,42].

Cooling blankets also employ convection cooling, but with this method cold water is circulated through a blanket or torso vest and pelvic girdle. To use this method, approximately 70% of a person’s surface area should be exposed to the cooling surface. This method is the most commonly employed and the best studied means of controlling body temperature for TH. However, this method does possess several undesirable qualities. Cooling blankets are susceptible to leaking, which may represent an electrical hazard. In addition, The Food and Drug Administration has reported several cases of external cooling blankets causing significant burns to the skin. Other problems with this form of cooling include temperature overshoot (in up to 20% incidence) and increased induction time versus other methods [43].

The final clinic method for initiating TH (used primarily in infants suffering from Neonatal Encephalopathy and adults with head trauma) is through non-invasive head cooling systems [40]. There are a number of cooling caps and helmets currently available, all designed to target cooling of the brain while maintaining core temperature at near normal levels. These devices are typically constructed from a synthetic material such as neoprene, silicone, or polyurethane and filled with a cooling agent (such as ice or gel) that is cooled and pumped through the cooling cap. Heat from the head is transferred by conduction through the helmet wall and then removed by the circulating coolant. Theses systems have the benefit of being able to be tightly maintained at a constant temperature and have the facility for easy temperature adjustment [40].

There has been some recent initial research into other methods of hypothermia induction. In 2005, researchers were able to induce a suspended animation-like hypothermia state in mice through the inhalation of low dose hydrogen sulfide [44]. However, two 2008 studies failed to reproduce the effect in pigs or sheep, concluding that the effects seen in mice were not present in larger mammals [44]. The Future Technology Advisory Panel, under the European Space Agency's Directorate of Technical and Quality Management, has investigated other methods of hibernation induction, including both pharmacological and direct manipulation of the hypothalamus (research data pending). In addition, since 2010 numerous researchers, including Dr. Kelly Drew from the University of Alaska Fairbanks, have been conducting experiments with A1 adenosine receptor agonists to initiate hibernation in arctic ground squirrels and other members of the rodent family [13,45,46]. Updates on this research will be explored in later sections of this report.

4. Medical Approach

4.1. Overview

SpaceWorks proposed to leverage the well-studied application of therapeutic hypothermia (TH) to place long-duration spaceflight crews in an inactive, low-metabolic torpor state. Torpor would be initiated during the mission transit phases (e.g. after leaving Low Earth Orbit or a Lunar pre-stage orbit through arrival at Mars, and vice versa). This approach could simultaneously solve a myriad of medical and engineering challenges associated with human spaceflight, which would potentially make this capability the key enabling technology that will ultimately permit human exploration to Mars and beyond.

Current research supports the safe and effective use of TH for up to 15 days [26-29]. While the potential exists for even longer torpor durations, current study proven limits allow for the capability to place the crew in rotating and repeating torpor cycles lasting 14 days, referred to as a sentinel protocol. For a four-member crew, three crew members would be placed in a torpor state with the assistance of the fourth crew member. Through the duration of the 14-day cycle, alternating crew members would be woken approx. every 14 days with the assistance of the current sentinel crew member, and then assisted in the initiation of their own two-week torpor phase after a 2-3 day period of non-torpor activity.

The ultimate result of the sentinel protocol is that it allows for one member of the mission crew to be fully awake and active at all times, which provides multiple mission benefits. First, it allows for preventative and corrective maintenance of equipment and daily communication with mission control during the outbound and return phases of the mission. Second, it provides an onboard assistant to the medical team to assist with the monitoring and wakening of the other crew members thereby minimizing some of the dependency on automation systems. Finally, it allows for the capability of immediate corrective action during equipment malfunction or during a habitat or medical emergency. The main systems necessary to initiate, maintain, and recover from torpor are discussed in detail next.

4.2. Method of Induction

The baseline approach is to use the combination of an adenosine receptor agonist and cooling via convection with the ambient air. An alternative to this approach involves an active cooling system combined with sedatives. Details for both the baseline and alternative approach will be provided next.

Baseline Method of Induction

As discussed in the hibernation review above, the most accepted theory of hibernation induction in nature is through a chemical called a “Hibernating Inducing Trigger” (HIT for short), which when released by an animal initiates the hibernation process. One of the leading candidates for this agent is an adenosine receptor agonist [12,13]. Since 2010 numerous researchers, including Dr. Kelly Drew (a SpaceWorks hibernation consultant), have been conducting experiments with A_1 adenosine receptor (A_1AR) agonists to initiate hibernation in arctic ground squirrels and other members of the rodent family [13,45,46]. The synthetic adenosine receptor agonist used by Dr. Kelly Drew, N6-Cyclohexyl Adenosine (called CHA), is a pharmacological agent that has shown the ability to spontaneously initiate a torpor state with the associated decrease in metabolic rate in rats [54]. In addition, through the use of bolus and then continuous drip administration of CHA, Dr. Drew has been able to keep Arctic Ground squirrels and rats in a torpor state for over 24 hours [55].

In 2017, Dr. Kelly Drew, in conjunction with Dr. Matthew Kumar, Mayo Clinic (a member of the SpaceWorks Torpor Medical Team) performed an independently funded but collaborative research effort utilizing N6-Cyclohexyl Adenosine for torpor induction on a large animal model [56]. The results of this experiment are shown in Figure 4. After administering the CHA bolus, core body temperature of the test subjects remained steady state between 30-32 degrees C, without the assistance of evaporative gas, IV fluid, or conductive cooling. The presence of CHA in the blood stream resulted in lowering the animal’s core body temperature to 32 degrees Celsius. In addition, the subjects in this experiment exhibited no shivering response while body cooling occurred. Third, this compound appeared to be non-sedating. As demonstrated through oxygen consumption in Figure 5, twice during the process the animals started to wake. Two CHA boluses were given with only very short-term effect, resulting in the eventual need for a small dose of propofol to be administered to cause the subject to return to sleep.

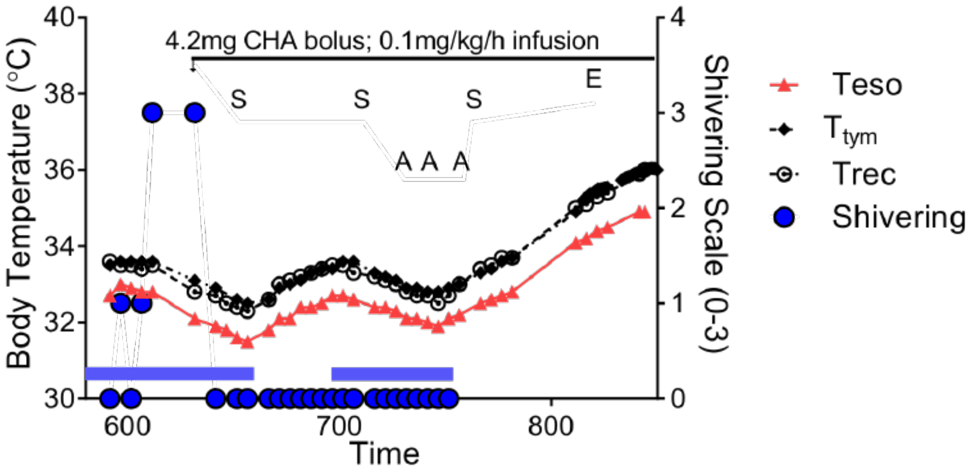


Figure 4. Administration of CHA A_1AR Agonist in Swine [Kelly,Kumar]

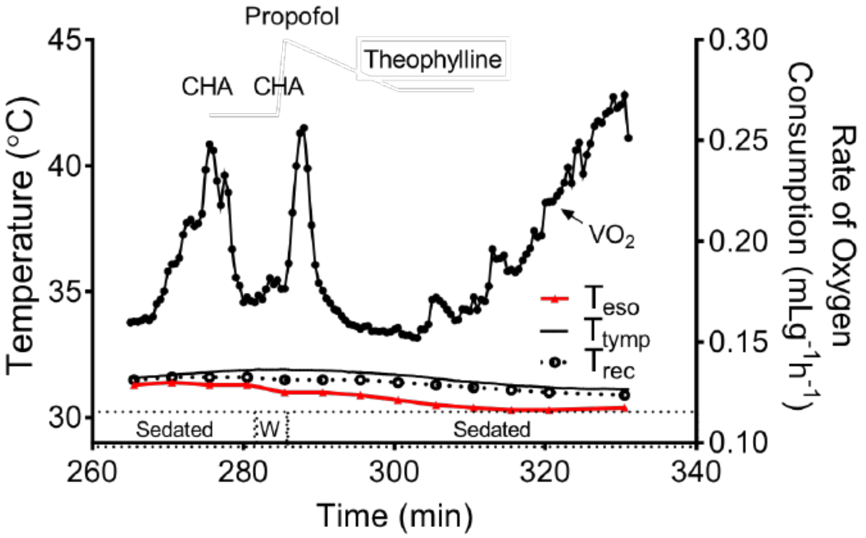


Figure 5. Oxygen Consumption in Swine During Administration of CHA [Kelly,Kumar]

Dr. Drew's research team has also been conducting experiments on another chemical compound, 8 – Sulphophenyl Theophylline (called 8-SPT). 8-SPT acts as A1AR Adenosine Receptor Antagonist, which means that it is a counter to the CHA discussed above. This medication has been used by her research team to counteract episodes of bradycardia (or a lowered heart rate), and hypotension (or low blood pressure) which can accompany induced hypothermia in rat studies [57]. This agent was also studied during the experimental trial conducted by Dr. Drew and Dr. Kumar, the results of which are shown in Figure 6.

As visualized on this chart, there is a significant effect on both heart rate and blood pressure of the test subjects when CHA is initially administered. However, a single dose of 8-SPT (time denoted as 'S') restored cardiovascular levels to normal without countering the CHA cooling process. This is because 8-SPT does not cross the blood-brain barrier, meaning it does not affect the brain or the hypothalamus, which is the thermoregulatory center for the body. As a result, a combination of CHA and 8-SPT could be used to set the core body temperature to torpor target levels while maintaining the cardiovascular system at a level that is within safe physiologic ranges.

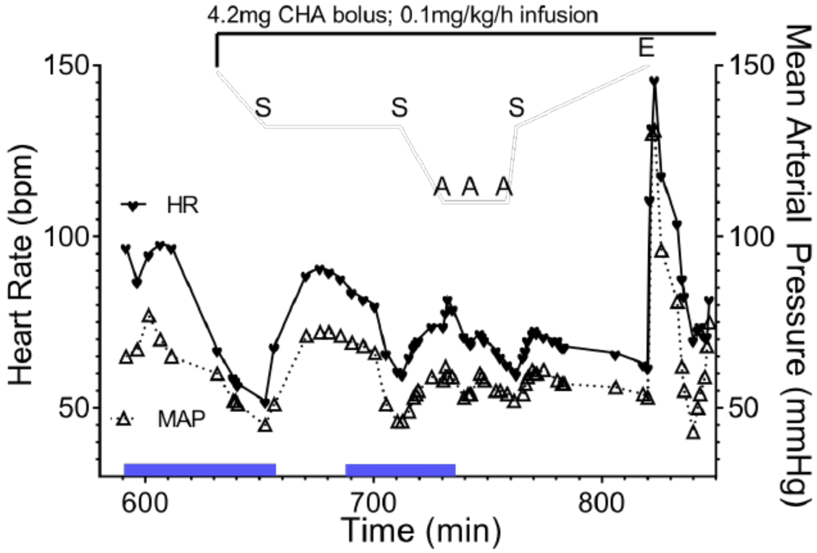


Figure 6. Administration of 8-SPT Adenosine Antagonist in Swine [Kelly, Kumar]

Most hospital TH protocols recommend a cooling rate of 1.5 to 2 degrees Celsius per hour until a target temperature of 32 to 34 degrees Celsius is achieved. As this is a well-established and studied cooling rate, the envisioned SpaceWorks Torpor protocol would utilize the same guidelines. Core body temperature would then be maintained at the target level (or oscillated between 32 to 34 degrees Celsius depending upon final crew availability requirements). In current hospital settings, rewarming occurs at a much slower rate (0.5 degrees Celsius per hour) to avoid spikes in blood pressure and electrolyte shifts in the blood that are not well tolerated in critically ill patients [36]. However, previous research has shown that much more rapid rates of warming (up to 1.5 degrees Celsius per hour) are possible without an associated increase in adverse risks [52]. Again, as 0.5 degrees Celsius is the well-established rewarming rate, the SpaceWorks Torpor protocol would utilize the same guidelines for normal torpor cycles. However, by employing the higher 1.5 degree Celsius rewarming rate crewmembers could be recalled from the torpor state rapidly and be available to provide assistance to the sentinel crew member during emergency situations.

While this is still early with limited research results available, initial experimental results are very encouraging. Further development and testing of these compounds could lead to a torpor induction protocol that does not require any active cooling, eliminates the need for pharmacological sedation to suppress shiver responses, and would counter any potential cardiovascular side effects associated with hypothermia and torpor induction. This would further reduce both the medical complexity and the equipment requirements for torpor utilization.

Ambient air cooling would be utilized during induction as needed to establish and/or maintain the target temperature profile for the torpor crew. Decreasing the ambient temperature of the habitat by simply radiating out more energy and increasing body surface area exposure, permits cooling to be achieved through direct convection from the skin to the surrounding air. Alternately, cooling could be limited to glabrous skin surfaces (namely the hands and feet), which account for 80% of human ambient heat loss [53]. This method would be similar to the cooling blanket and vest devices currently used by hospitals for targeted temperature management, which continues to be the most commonly employed and the most well studied means of controlling body temperature. This cooling method would alleviate potential complications associated with an active cooling system approach, decreasing overall system weight and volume requirements (as well as crew interfaces/contacts).

Alternate Method of Induction

If core body ambient air cooling and/or the A_1AR agonist approach does not prove to be effective (or safe), the current alternative approach is to utilize a nasopharyngeal evaporative cooling technique combined with sedation for torpor induction. This method of initiating TH utilizes a cannula that is placed into the crew member's nasal cavity to provide very precise temperature control during the cooling, warming, and maintenance phases. A gas is delivered directly underneath the brain and base of the skull, causing evaporative cooling of the blood passing through the cooling area resulting in a reduction in core body temperature. SpaceWorks favors dehumidified air plus nitric oxide gas for the cooling agent as it is easily recycled and does not require the added containment or collection systems that would be associated with the alternative perfluorocarbon coolant. Application of this cooling method would require a small, non-erosive cannula attached to an oxygen delivery system. This gas would be stored at the required cooling temperature or passed through a cooling system upon delivery. Feedback from core temperature monitoring would then allow for the adjustment of gas flow rate and temperature, maximizing thermoregulation. As this system only consists of the nasal canula, oxygen lines, and oxygen storage, maintenance and repair of the equipment would require little time and be simple enough for any active crew member to perform. Research has shown that this method of cooling is both simple to employ and can support very high cooling rates (average of 2.6 degrees Celsius) [41,42]. This method is also currently employed by emergency responders in the field to easily and rapidly reduce a person's temperature in a timely period prior to arrival at a hospital facility, and thus can be modified for utilization in the space environment with minor system alterations.

Crew members undergoing torpor first require the administration of a pharmacological agent to suppress the shivering response and help them tolerate the cooling process until core body temperature is reduced past the "shivering threshold" (approximately 35 °C or 95 °F) [47]. While there are multiple medications available for use (including magnesium sulfate, midazolam, fentanyl, remifentanil, and Propofol), our research team prefers dexmedetomidine [37,47]. Dexmedetomidine is an α2-adrenergic receptor agonist that has multiple uses including reducing anxiety, patient sedation, and pain management [48]. Dexmedetomidine is notable for its ability to provide sedation without risk of respiratory depression and neurocognitive dysfunction (unlike the other commonly used sedatives noted above) and can also provide cooperative and/or semi-arousable sedation [49,51]. The long-term use and effects of dexmedetomidine has not been characterized to date.

4.3. Intravenous (IV) Access

Whether utilizing torpor or not, safe and stable long-term IV access may be essential for both crew monitoring and healthcare during prolonged missions. First, long-term intravenous access allows for the simple collection and processing of laboratory testing to evaluate system electrolytes, basic body chemistry, red and white blood cell levels, and the presence and identification of any systemic body infection. Second, intravenous access allows for the administering of both IV fluids (the first and most common treatment during serious illness and trauma related injuries) and higher potency and more efficient medications. Finally, nutritional support can be provided through an IV to crew members that are in any state that does not allow for normal oral intake. While temporary IV placement can be useful, these access sites can be hard to place in a high stress environment and are only viable for a short period of time (a maximum of 72 hours) [58]. Presented below are the two of the most common forms of prolonged intravenous access: Peripherally Inserted Central Catheters, and port catheters.

A peripherally inserted central catheter (PICC or PIC line), is a form of intravenous access currently utilized in the hospital setting for chemotherapy regimens, extended antibiotic therapy, or total parenteral nutrition (TPN). PIC lines are inserted through the skin (percutaneously) at a peripheral site (usually the arm), then guided to the superior vena cava. PICCs can remain in place for extended periods of time, from seven days to up to 12 months in current studies [59]. PIC lines should be used regularly or undergo periodic flushing with normal saline and "locking" with Heparin or a normal saline solution when not in use. While these lines allow for higher volumes of fluids and nutrients to pass through them, they have a higher risk of failure and local infection or blood clot formation [60].

SpaceWorks proposes the use of an alternate form of long-term IV access, port catheters (shown Figure 7). Port catheters are small medical appliances that are surgically installed beneath the skin, usually in the upper chest just below the clavicle or collar bone. A catheter then connects the port to an underlying vein. Sitting directly under the skin, the port provides direct venous access via a septum through which medications and IV fluids can be administered and blood samples can be drawn. In medical settings, ports are commonly used to treat hematology and oncology patients, and are intended for long-term, outpatient use [61]. Once in place, these devices require no special maintenance or care, and usually do not limit any physical activities, including weightlifting and swimming. Ports can remain in place as long as required; however if used infrequently they it may be necessary to access the port, flush it with saline, and inject a saline or heparin lock similar to PIC line maintenance between uses [62]. Port access sites have lower fluid flow rates then PIC lines, but significantly reduced risk of failure, blood clot formation, and local infection [60].

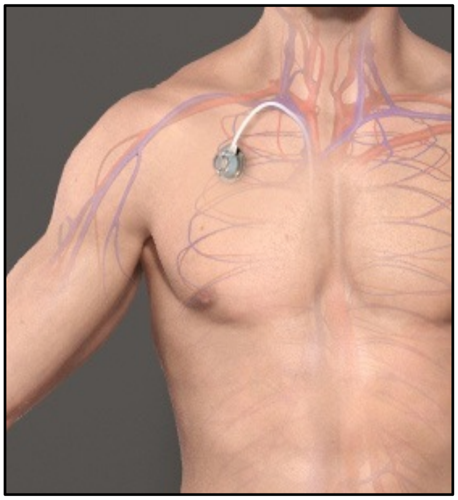


Figure 7. Port-A-Cath® Device for Central Vein Access (Credit: PM Solutions)

4.4. Nutritional Approach

There are two approaches for providing nutritional support during torpor cycles: Total Parenteral Nutrition (TPN), and enteral feeding via temporary nasogastric(NG)/orogastric(OG) feeding line or Percutaneous Endoscopic Gastrostomy (PEG) tube. Both of these methods rely on prepared solutions consisting of water and all the necessary nutrients, microelements and electrolytes necessary for healthy physiologic function. Both preparations contain approximately the same nutritional value (0.5 to 2 kcal/ml), so food stores for either method would occupy the same amount of habitat space [63]. Both preparations also have the same storage capabilities (2 years extended shelf life for unopened containers stored at room temperature) [63]. However, the actual method of nutritional delivery and the necessary support equipment involved with each nutritional method are markedly different.

Total parenteral nutrition (TPN) is the process of feeding of a person intravenously, bypassing the normal digestive system. In the medical setting, TPN is provided when the gastrointestinal tract is nonfunctional because of an interruption in its continuity, or due to impaired absorptive capacity. While TPN is typically a short-term therapy, there are approximately 40,000 people using long-term TPN at home in the United States each year [64]. Multiple delivery systems exist, including portable systems that allow for mobility and even the continuation of normal exercise. Solutions for TPN may be customized to individual personal requirements, or standardized solutions may be used. The use of standardized parenteral nutrition solutions is actually preferred as it is more cost effective and provides better control of serum electrolytes [65]. While the schedule of TPN administration is highly dependent on the medical condition of each patient, most receive TPN treatments three to five days a week. Possible complications associated with TPN include: infection or blood clot due to prolonged IV access, Fatty liver, Cholecystitis, and gut atrophy [66,67]. However, recent changes to TPN composition have helped to minimize or even potential eliminate some of these risks [68].

Enteral feeding involves a liquid based nutrient system similar to infant or geriatric supplements that are delivered via a temporary nasogastric (NG)/orogastric(OG) feeding line or permanent Percutaneous Endoscopic Gastrostomy (PEG) tube. Nasogastric and orogastric intubation systems are commonly used devises that are easy to place and maintain (with a 2013 study confirming the ability of people to safely insert and remove tubes themselves), although they are general used for short-term feeding indications [69,70]. NG tubes can have complications, although these are primarily limited to accidental removal of the tube and nasal irritation [69]. A Percutaneous Endoscopic Gastrostomy (PEG) is a tube inserted through a small incision in the abdomen and into the stomach. It is intended for long-term enteral nutrition (with a median use of 6 months, but with well documented extended use for over 4 years) [71]. Insertion of the tube is a simple surgical procedure that does not require general anesthesia; although mild sedation is typically needed. As the PEG is intended for long-term use, it requires minimal maintenance and care, and can be adjusted or even replaced at home with little training [72]. Complications of a PEG are rare after insertion, primarily consisting of cellulitis (infection of the skin) around the gastrostomy site, ulcer formation at either the site of the button or on the opposite wall of the stomach ("kissing ulcer"), or "Buried bumper syndrome" [73]. PEG administration of enteral feeds is the most commonly used method of nutritional support for patients in the home setting [69].

SpaceWorks supports the use of enteral feeding via NG/OG tube or PEG tube during torpor cycles, with a PEG tube as the baseline approach. First, it is now well documented that enteral feeding is the preferable nutritional route in long-term nutritional supplementation as it is less prone to complications and more closely maintains normal physiologic function [74,79]. Second, as previously noted, the initial placement of NG/OG or PEG tubes and the subsequent maintenance and replacement of enteral feeding equipment is significantly easier than parenteral (TPN based systems), requiring only minimal training. Third, the transition from normal oral nutritional intake to enteral feeding is a simple and seamless process, while the transition from IV to oral nutrition requires a systematic, step by step approach [80]. Utilizing an enteral feeding system could allow the active (sentinel) crew members to resume normal meals and hydration between torpor cycles, as well as during prolonged surface or orbital crew missions.

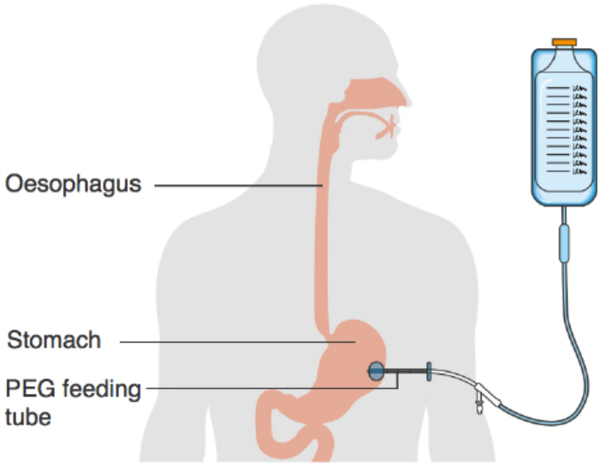


Figure 8. PEG Tube for Delivery of Liquid Nutrition and Hydration Fluids (Credit: Cancer Research UK)

The total caloric needs for crewmembers in Torpor will be approximately 25-35 kcal/kg/day, with a protein component of 1.2 – 2.0 gm/kg/day. No more than 20% of the calories will come from lipid emulsions, with fish oil fat emulsion like Omegaven® instead of egg-based formulas utilized as they help prevent/reverse liver disease and cholestasis [68]. Micronutrients will be adjusted as needed based on the type of solution utilized.

4.5. Waste Management

Whether enteral or parenteral nutrition is utilized, crew members undergoing torpor will require some method of urine collection. The most common indwelling bladder catheter is the Foley catheter, a flexible tube which a clinician passes through the urethra and into the bladder to drain urine. The catheter is secured in place with a balloon that is inflated with sterile water once inside the bladder. While most catheters are intended for short-term use (1-7 days), newer catheters created from PTFE, hydrogel or a silicon elastomer make catheters suitable for 28 days to three months indwelling duration [81]. As with enteral feeding tubes, Foley catheters are easy to insert, remove and maintain, with even children easily able to master the process with simple training [82]. Complications associated with prolonged catheter use include equipment failure and malfunction, irritation to the urethra, and bladder infection. However, the implementation of multifaceted intervention plans (i.e. sterile insertion, prophylactic antibiotics, and advanced materials) has reduced the risk of infection by 3-fold [83].

While the use of enteral feeding has significant advantages to Total Parenteral Feeding (TPN), it does introduce the need for fecal waste management during torpor cycles. There are multiple fecal collectors available, the newest of which are external collection systems that consist of a self-adhering skin barrier and attached pouch. These fecal collectors are a closed system and the pouch is entirely external and non-invasive, meaning patients using fecal collectors do not encounter the same risks to the internal anal sphincter and rectal mucosa that can accompany internal devices that pass through the anal sphincter and dwell in the rectum [84]. Fecal collectors are also classified as Class I medical devices (considered as presenting minimal potential for harm) [85]. In addition, with training a well-positioned and adhered fecal collector can provide up to 30 days of extended wear [86]. Possible complications associated with use include skin irritation caused by the adhesives on skin, leakage, and blockage [87]. Overall, fecal collectors are a user-friendly, cost-effective, efficient tool to contain solid waste for extended periods of time.

4.6. Monitoring and Evaluation

The evaluation of crew vital signs can continue to be adequately performed using current NASA approved monitoring systems. Systems like LifeGuard® and BioHarness® have been created and utilized to monitor the health of astronauts to ensure their safety during space flight and extravehicular activities and to monitor their physiology during exercise routines. NASA intends to further develop this technology to support medical emergency contingencies during long duration missions and address a number of the Bioastronautics Critical Path Roadmap risk areas [88]. These systems consist of button sensors that stick to the skin to take EKG and breathing rates. The device also uses an arm cuff to measure blood pressure and a sensor clipped or wrapped on an index finger to measure oxygen levels in the blood and pulse rate. These systems can also measure astronaut movements in three dimensions [89]. They are intended for long term use, have already been validated with research and on station testing, and would adequately provide all of the necessary vital signs monitoring required during torpor cycles. For core body temperature monitoring for torpor temperature regulation, SpaceWorks recommends the current medical practice of utilizing indwelling catheter bladder temperature monitors as they are easy to incorporate into Foley catheter systems and provide the most reliable temperature readings [90]. New wireless, indwelling temperature monitoring devices may also be viable option in the long term.

As discussed above, safe and stable long-term IV access will be essential for both crew monitoring and healthcare by providing access for the simple collection and processing of laboratory testing to evaluate system electrolytes, basic body chemistry, red and white blood cell levels, presence and identification of any systemic body infection, etc. SpaceWorks advocates the use of a port catheter system as they are unobtrusive to normal activity, easy to maintain and access, and have very low risk of failure or complication. Use of this port would allow awake crew members, with little training, to obtain periodic blood samples on torpor personnel [91]. However, newer systems are being tested that provide automated measurement of blood parameters for bedside monitoring of patient blood chemistry. These are programmable systems that can automatically draw blood samples at a suitable time frequency (or at predetermined times), and can automatically analyze the drawn blood samples and immediately measure and display blood parameters such as glucose levels, hematocrit levels, hemoglobin blood oxygen saturation, blood gases, lactate or other blood chemistry parameters [92]. By directly accessing the installed port catheter system, blood chemistry evaluation could then be accomplished remotely by observing medical personnel.

Direct visual examination of both torpor and sentinel crew members is another key component to evaluating and maintaining overall astronaut health. While basic evaluations can easily be performed by the sentinel crew member, SpaceWorks recommends a combination of remotely controlled and crew member-controlled video systems. This would allow both the crew and mission control medical team to perform scheduled visual examination of IV or port sites, areas touched by skin adhesives, and body pressure points as they often provide early indications of infection, equipment failure, or skin break down [93,94]. Visual inspection of crew support systems and habitats would also allow for recommendations and guidance during repair and preventative maintenance. Face to face communications between mission control and with active crew members could also provide insight on current fatigue and stress levels. Finally, the ability to observe the crew would allow for the direct assistance of terrestrial based medical providers during routine and emergency medical situations. While the effectiveness of direct communication would be reduced as distance increased the time delay of video and audio signals, regularly scheduled video recordings transmitted to mission control health teams would still provide an effective method of daily crew evaluation.

4.7. Potential Medical Challenges

With any new medical approach, pharmaceuticals, and/or adaptation, there will be potential areas of risk with challenges to address. This is particularly true in the space environment, given the additional uncertainties and limited human medical data available. A brief discussion of the key risk areas will be presented next.

Infection-
Infection is the most common complication associated with medical procedures. The Centers for Disease Control and Prevention estimates that 10% of patients per year become infected, with the most frequent type being urinary tract infections (36%), followed by surgical site infections (20%), and pneumonia (11%) [95]. In at least one study, the utilization of TH was shown to increase the overall risk of pneumonia [96].

However, the risk of infection associated with torpor is overall very low. Hospital infection rates are significantly impacted by the poor health of patients in the hospital setting. A study of patients utilizing central venous catheters for home based TPN showed an infection rate of only 1.47 per 1000 catheter days (or roughly 1 infection every 3 years) [97]. Infection rates with both OG/NG and PEG enteral feeding tubes and port catheter systems (the preferred SpaceWorks method of nutrition and IV access) are even lower, and are almost exclusively limited to the time period immediately after insertion when crew members would still be on Earth [98]. As discussed above, both the advent of new Foley catheter materials and advancements in the practices of catheter insertion and care have decreased the risk of urinary tract infections 3-fold (4.2 infections per 1000 catheter days) [83]. In addition, the use of low dose prophylactic antibiotics has been clinically proven to decrease the risk of catheter related bladder infections by another 50% [99]. Finally, recent studies show that the rates of pneumonia associated with TH treatment are equal to rates associated with intubated patients not undergoing torpor, indicating that the act of intubation and not hypothermia is the likely cause of pneumonia [100]. As the SpaceWorks torpor protocol does not require intubation this would significantly reduce the risk of lung-based infections.

Blood Clot Formation-
Blood clot formation, or thrombosis, is a medical complication that occurs when the human clotting cascade is activated resulting in the formation of a collection of platelets and other blood products in a superficial or deep vein. There are multiple risk factors for thrombosis, but two are associated with conditions experienced during TH; indwelling catheters and inactivity. In a recent study of 23,000 patients with PICC placement, there was a 4% overall incidence of vein thrombosis [101]. In the largest study available, the blood clot risk associated with the SpaceWorks preferred port catheter access was 1.8%, but this was a study conducted on patients undergoing port placement for cancer treatment, a known risk factor for blood clot formation [102]. Adjusting for those odds ratio numbers, the actual risk of blood clot formation with the port catheter IV system is closer to 0.6%. In addition, as discussed above, the use of intermittent heparin flushes has been proven to significantly reduce the risk of catheter blockage and blood clot formation [60].

Another significant factor in the prevention of blood clot formation is the direct affect TH itself has on the clotting cascade. Thrombin is an enzyme in the body that acts to convert fibrinogen to fibrin, a key component to binding platelets together to form blood clots. It also acts as a catalyst to many other coagulation-related reactions in initiating the clotting cascade. Numerous studies have noted that patients undergoing TH were at higher risk for bleeding, but not at increased risk for severe bleeding or complications from bleeding [103]. Recent studies indicate the cause, namely that dropping a human’s core temperature impairs thrombin generation [104]. As a result, healthy humans undergoing torpor would be less likely to generate an indwelling catheter or immobility induced blood clot due the decrease in clotting cascade activity achieved simply through the process of being cooled.

Electrolyte Imbalances-
Hypothermia can induce a process called "cold diuresis". This condition is thought to be caused by the constriction of peripheral blood vessels redirecting blood flow from the extremities to the body core [105]. The kidneys then sense this shift and increase urine production to excrete the perceived extra fluid in an attempt to stabilize core blood pressure [106]. This can lead to electrolyte abnormalities, specifically hypokalemia, hypomagnesaemia, and hypophosphatemia, as well as hypovolemia [107]. However, these changes are noted primarily during the cooling and rewarming phases and are easily mitigated by limiting cooling and heating rates [108]. In addition, the ability to directly measure and correct minor electrolyte abnormalities through a permanent port catheter and automated monitoring system would significantly counter this effect on a healthy, torpor induced crew.

Skin Pressure Ulceration-

Pressure ulcers (aka bedsores) are localized damage to the skin or underlying tissue that occur as a result of the constant pressure experienced by bedridden or mobility impaired patients. The most common sites for pressure ulcers are in the skin overlying the lower spine and the heels or the hips, but other sites such as the ankles, elbows, shoulders, or even the back of the head can be affected. Pressure ulcers occur due to a constant pressure being applied to the soft tissue, resulting in partial or complete obstructed blood flow. Outside of impaired immobility there are multiple other risk factors for developing pressure ulcers, including but not limited to: protein-calorie malnutrition, skin contamination, diseases that reduce blood flow or sensation in the skin, and age [109].

In a microgravity environment there would be little to no direct contact of astronaut pressure points to bedding to cause the compression force needed to make pressure ulcer formation a concern. However, if the torpor habitat was designed to utilize artificial gravity to potentially mitigate other complications of prolonged space travel (i.e. muscle atrophy and bone density loss), then preventative measures would be needed. The most important care for a person at risk for pressure ulcers is continuous movement and redistribution of pressure [110]. While this is generally accomplished by low cost alternatives (nurses or other hospital staff manually moving patients), more advanced technology does exist, such as single- or multi-compartment pressure ulcer prevention padding controlled by tactile sensory and temperature based sensors [111,113].

Interestingly, hypothermia may also be an effective preventative treatment for pressure ulcer formation. Previous animal studies have revealed that local skin cooling reduced the severity of ulceration in spinal cord injury patients. In addition, cooling is widely used in plastic surgery and organ transplants for tissue preservation. A human study from 2010 showed that, in patients at high risk for developing pressure ulcers, skin cooling to 25 C resulted in both decreased incidence and severity of pressure ulcer formation. These authors concluded that both metabolic and myogenic responses contributed to this protective effect. As a result, prolonged hypothermia may provide a protective benefit to skin degradation caused by prolonged immobility and pressure.

Medical Support Equipment Failures-

Equipment failure and repair are significant concerns for a prolonged space mission where both technical support and storage of spares is severely limited. Concerning torpor induction and maintenance equipment, continuing to employ NASA’s philosophy of simple, user friendly and universally compatible electronics and materials should be maintained. Luckily, most of the equipment that would be utilized for torpor induction and cycling is already manufactured with ease of use, field operability and integrated redundancy and durability in mind. However, little to none of the equipment that SpaceWorks proposes incorporating into the torpor protocol has been tested in the microgravity environment, so this type of equipment verification would need to be included in any proposal that plans to fully test the functionality of torpor for space applications.

No matter which form of hypothermia induction is utilized for torpor, each employs the premise of physically or pharmacologically lowering core body temperature below normal physiologic levels. In addition, active interventions (most likely in the form of medications) may be required to counteract the human body’s natural response to try and increase body temperature to normal levels. Because of this, failure of hypothermic inducing equipment would result in the loss of the artificial drive to decrease core temperature. In response, the crewmembers would begin to naturally increase core body temperature to normal levels and out of the torpor state. Therefore, the proposed SpaceWorks Torpor induction method would fail to “normal”, meaning that crew members would not be excessively cooled, or “locked” into a hypothermic state that could not be reversed if there was an equipment failure.

PICC line complications that involve intervention or removal tend to occur during the period immediately following insertion, and therefore would likely be identified and corrected before departing Earth. There are still some complications, including dislodgement, infection or clogging that would warrant removal during space missions. The use of the port catheter system has a significantly reduced risk of failure, blood clot formation, and local infection [60]. However, in the rare instance that a port catheter failed it could be removed by another crew member with minimal medical training and equipment. Removal of long-term IV access would result in the need for cyclic short-term peripheral IV placement or discontinuing torpor for the remainder of the mission.

Enteral feeding with a permanent PEG tube would require the use of a simple solution dispensary pump. If a rare long-term complication did occur, such as ulcer formation at either the site of the PEG or on the opposite wall of the stomach, then the tube would need to be removed, allowing the site to heal and close. At this point, torpor and enteral feeding could be continued using an NG/OG tube.

Concerning waste disposal, Foley catheters for urine collection are easy to insert, remove and maintain with simple training [82]. As these are collection and drain systems with no electronic and mechanical components, they have no true mechanical failure concerns other than anchor bulb leakage or tube degradation. Fecal collectors are also non-mechanical, closed loop systems. Possible complications associated with their use include skin irritation caused by skin adhesives, leakage, and blockage [87]. As with Foley catheters, fecal collectors are user-friendly, cost-effective, efficient tools which are easy for crew members to maintain and replace if needed.

Vital signs evaluation can continue to be adequately performed using current NASA approved monitoring systems. As these systems are currently in use all the necessary maintenance, repair and back-up protocols already exist [89]. Concerning core body temperature monitoring for torpor temperature regulation, current medical practice is to utilize an indwelling catheter bladder temperature monitor as they are easily incorporated into the Foley catheter system. If the core temperature sensor was to fail, the whole Foley system could simple be removed and replaced.

Medication Storage and Shelf-life-

The effects of microgravity and radiation exposure on the overall safety and effectiveness of medications during missions is a key concern to the NASA Human Research Program (HRP), so much so that it is included in 1 of their 33 identified key risks for prolonged space flight. Torpor specific medications and provisions, just like those currently used in space, will need to be adequately tested in a microgravity environment to verify their stability for multi-year missions. However, terrestrial based testing provides encouraging data towards the long-term stability of the proposed torpor medications and compounds. As discussed before, both TPN and enteral based nutrition formulas have a store capability of two years as currently constituted (for unopened containers stored at room temperature) [63]. Intravenous solutions and electrolyte supplements have an FDA approved shelf life of two to five years [114 - 116]. Most antibiotics maintain 90% of their effectiveness up to 66 months after they are manufactured, which would mean that they would be viable for the duration of any of the prolonged missions NASA currently has planned [117]. Heparin (used for long-term IV flushing) has a shelf life of 36 months (unopened bottles stored at room temperature) [118]. If N6-Cyclohexyl Adenosine (CHA) and 8 – Sulphophenyl Theophylline (8-SPT) were utilized for chemical torpor induction, shelf life effectiveness would need to be conducted. However, these chemicals are stored in powder form, and then reconstituted with injectable saline for use. Per Dr. Kelly Drew, the likely shelf-life of CHA and 8-SPT would be similar to other powder-based medications (2 to 5 years). Her team currently uses a shelf life of thirty days in the reconstituted, active form.

Cognitive Impairment-

The effect of hypothermia on the short-term and long-term cognitive function of crew members is a critical question to address before torpor can be utilized for space applications. Unfortunately, little to no study data exists on the cognitive effects of TH. This is because TH is currently performed on infants or critically injured or ill patients, situations that do not allow for obtaining pre-hypothermia controls or permit the differentiation of any adverse cognitive effects to hypothermia itself or to the medical condition that resulted in the application of TH. Key questions to address include:

1) How long does it take for a crew member to fully recover from a torpor cycle after the warming process?
2) What affect does torpor have on circadian rhythms and sleep quality?
3) Does prolonged torpor affect long-term or short-term memory?
4) If negative effects are noted, will they resolve or be compounded by repeat torpor cycles?

Concerning circadian rhythms and sleep quality, it is important to understand that hibernation and sleep are very different. Hibernation is a physiologic state. It results in a reduction of basal metabolic processes and basal core temperature in an attempt to slow an animal's utilization of energy stores, allowing them to survive during periods of extreme cold temperatures or food shortages. There are physiological changes during sleep that are similar to hibernation (reduced heart and breathing rate, slightly lower basal temperature and metabolic rate), but these changes are very slight compared to extremes we see during hibernation [119]. Sleep is primarily a mental state, characterized by changes in brain activity. However, studies show that the brain waves of hibernating animals more closely resemble waking brain wave patterns [120]. It is also known that during long periods of hibernation many animals (including bears, hamsters and dwarf lemurs) exit their hibernation state to allow for short periods of sleep. This is important, because many animals that are awaked from hibernation exhibit some signs of sleep deprivation and often need to sleep to recover [121]. Sleep, on the other hand, is much easier to reverse. Animals go from deep sleep to fully awake within a matter of seconds if the right stimulus is supplied.

Studies of animal brainwave activity during hibernation show that they continuously cycle through states of electrophysiologically defined wakefulness and non-rapid-eye-movement (NREM) sleep [122]. Unlike REM sleep, NREM sleep is associated with little or no eye movement or dreaming. They are the result of two different brain generators, which explains the differences seen in REM and NREM mental activity [123]. The mental activity that takes place during NREM sleep is more thought-like in appearance, whereas REM sleep is more hallucinatory [123]. Even though we spend the majority of our time in NREM sleep, REM sleep is believed to be essential for restfulness [119]. This is why hibernating animals, even though they cycle through NREM sleep, often need days or even weeks of normal sleep to completely recover from long hibernation periods.

Humans in altered states of consciousness (i.e. comatose or “vegetate states”) can also provide some insight into the mind of an astronaut undergoing torpor. Consciousness still remains a mysterious phenomenon. Scientists still don't know exactly how brain activity gives rise to consciousness, but they have been able to find some similarities between a conscious brain and an unconscious one. It now appears that comatose patients may be aware of their surroundings even though they can't visibly communicate with others. Like hibernating animals, their brains cycle through states of wakefulness and non-rapid-eye-movement (NREM) sleep [124]. Some comatose patients show brain wave patterns and levels of awareness similar and to that of fully awake, healthy individuals. For example, although the patients did not perform any physical movements in response to commands, brain imaging showed that when comatose patients were told to imagine doing a physical activity the area of the brain responsible for controlling that movement was activated. Similar responses have been observed in asking a comatose patient to picture an image in their head or upon the mentioning of the name of a loved one. And like hibernating animals, humans often need a period of normal sleep to completely recover after awaking from a comatose state.

Given this data, an astronaut in a state of torpor would most likely cycle through episodes of mental wakefulness (without awareness), and non-REM sleep. They would receive the physiologic advantages of hibernation (decreased need for food and water, potentially decreases in bone density loss and muscle mass reductions), while the only mental deficits they would experience would be those similar to sleep deprivation. A short period of sleep recovery could potentially be all that is needed to transition from sleeping passenger to active explorer.

Response to Injury/Emergent Situations-

With all but one crew member in torpor during the outbound and return stages of a long duration mission, concern exists regarding the ability to provide adequate and appropriate assistance to that individual during an injury or emergent situation. As discussed in detail above, most hospital TH protocols recommend a maintained, fixed target temperature of 32 to 34 degrees Celsius. As this is a well-established and thoroughly studied process, the SpaceWorks torpor protocol would utilize the same guidelines. However, core body temperature could be oscillated between 32 to 34 degrees Celsius and still provide significant metabolic reductions and protective benefit. In addition, while current hospital settings recommend rewarming rates of 0.5 degrees Celsius per hour, previous research has shown that much more rapid rates of warming (up to 1.5 degrees Celsius per hour) are possible without an associated increase in adverse risks [52]. Again, as 0.5 degrees Celsius is the well-established rewarming rate, the SpaceWorks torpor protocol would utilize the same guidelines for normal torpor cycles. However, by employing both an oscillating core temperature and the higher 1.5-degree Celsius rewarming rate crewmembers could be recovered from torpor much more rapidly and be available to aid the sentinel crew member during emergency situations at an accelerated rate.

Fortunately, the likelihood of an emergency situation arising during a mission appears to be low. The NASA Human Research Program has performed an extensive summary on the risk of injury and illness on both astronauts and those personnel who work in astronaut analog fields [125]. This report addressed the incidence of behavior and psychiatric conditions, the risk of inability to adequately treat an ill or injured crew member and provided a detailed list of all historical astronaut fatalities and injuries during space flight to date.

Concerning the occurrence of behavioral and psychiatric conditions, the incidence rate onboard shuttle missions was one per every 2.86 person-year, with the most commonly reported symptoms being anxiety and annoyance [126]. The incidence rates of these conditions on the Russian Mir station from 1995 -1998 was 0.77 per person year [127]. Anxiety symptoms during space flight occurred once every 1.2 years, and signs and symptoms of depression occurred once every 7.2 years [128]. To date, no behavioral emergencies have occurred before or during any U.S. space flight mission. In examining Antarctica crews, the overall incidence rate for depression that required pharmacological intervention was 2.03% (or one case of depression every 1.1 years) [129]. For submariners, the incidence of psychiatric disorders that were severe enough to result in either the loss of a workday or the need to be medically evacuated ranged between 0.44 and 2.8 per person-year [130]. It should be noted that sleep disruption, monotony and boredom are the most frequent complaints of individuals in an integrated collaboration environment such as space flight, with the combination of monotonous work with requirements for high degrees of alertness and penalties for errors seen as especially stressful [131,132].

In-flight illness incidence rates are summarized in Table 1 through Table 3 [133]. It should be noted that a majority of these conditions are not true medical emergencies and could be adequately treated by taking medications carried on board. Astronauts routinely take medication during missions for non-emergency conditions (motion sickness, headache, sleeplessness, and back pain). More important is the potential for medical emergencies during space flight. Among these conditions, only arrhythmias, renal colic, and infections have been noted. The documented arrhythmias were mostly mild abnormalities, such as occasional premature atrial contractions (PACs) and premature ventricular contractions (PVCs), which were present in 30% of astronauts at some point during periods of strenuous activity. There is one noted case of ventricular bigeminy, as well as one case of ventricular ectopy that was reported on Skylab and a 14-beat run of ventricular tachycardia experienced by one Russian astronaut onboard MIR [134]. Other medical emergencies that have been observed in space include cases of urological and dental emergencies [135,136]. Of concern are noted episodes of renal colic and arrhythmia that have required that crew members be brought back to Earth for evaluation [137].

Table 1. In-flight Medical Events for U.S. Astronauts During Space Shuttle Program (STS-1 to STS-89)

Medical Event or System by ICD9* Category	Number of Events	% of Total
Space adaptation syndrome	788	42.2
Nervous system and sense organs	318	17.0
Digestive system	163	8.7
Skin and subcutaneous tissue	151	8.1
Injuries or trauma	141	7.6
Musculoskeletal system and connective tissue	132	7.1
Respiratory system	83	4.4
Behavioral signs and symptoms	34	1.8
Infectious diseases	26	1.4
Genitourinary system	23	1.2
Circulatory system	6	0.3
Endocrine, nutritional, metabolic, and immunity disorders	2	0.1

**International Classification of Diseases, 9th Ed*.

Table 2. Medical Events Among Astronauts on MIR (3/1995 – 6/1998)

Event	Number of Events	% of Total
Musculoskeletal	7	25
Skin	6	21
Nasal Congestion, irritation	4	14
Bruise	2	7
Eyes	2	7
Gastrointestinal	2	7
Psychiatric	2	7
Hemorrhoids	1	4
Headaches	1	4
Sleep disorders	1	4

Risk of injury due to equipment failure or malfunction is also a concern during prolonged space missions, especially in the setting of torpor where only one crew member would be active for a majority of the habitat transit time. Of all non-fatal spaceflight accidents reported, only one involved the loss of consciousness of a crew member, and there were no incidents that involved any major injury. In addition, all but one of the injuries occurred during a high-risk event (EVA mission, corrective maintenance, payload release, etc). By having astronauts avoid these types of activities while serving as the sentinel crew member would ensure that one or more of the crew would be available to aid during an accident or medical emergency.

Table 3. Medical Events and Recurrences Among Astronauts of All Nationalities on Mir (3/1995-6/1998)

Event	Number of Events	% of Total
Superficial injury	43	24
Arrhythmia	32	18
Musculoskeletal	29	16
Headache	17	9
Fatigue	17	9
Sleeplessness	13	7
Contact dermatitis	5	3
Surface burn	5	3
Conjunctivitis	4	2
Acute respiratory infection	3	2
Asthenia	3	2
Ocular foreign body	3	2
Globe contusion	2	1
Dental	2	1
Constipation	1	1

4.8. Proposed Induction Protocol

The current SpaceWorks proposal for torpor induction and maintenance is outlined below in Figure 9, and is divided into five stages: Pre-Flight, Preparation, Initiation, Maintenance, and Reversal. The current protocol utilizes adenosine receptor agonist compounds with minimal sedation combined with ambient air cooling (vs active cooling). Long-term IV access would be provided through a preplaced Port catheter. Nutrition would be provided through enteral feeding via a preplaced PEG tube during torpor cycles, with an option for normal oral hydration and nutrition while active. Waste collection during torpor would be accomplished through Foley catheter and fecal waste collection systems.

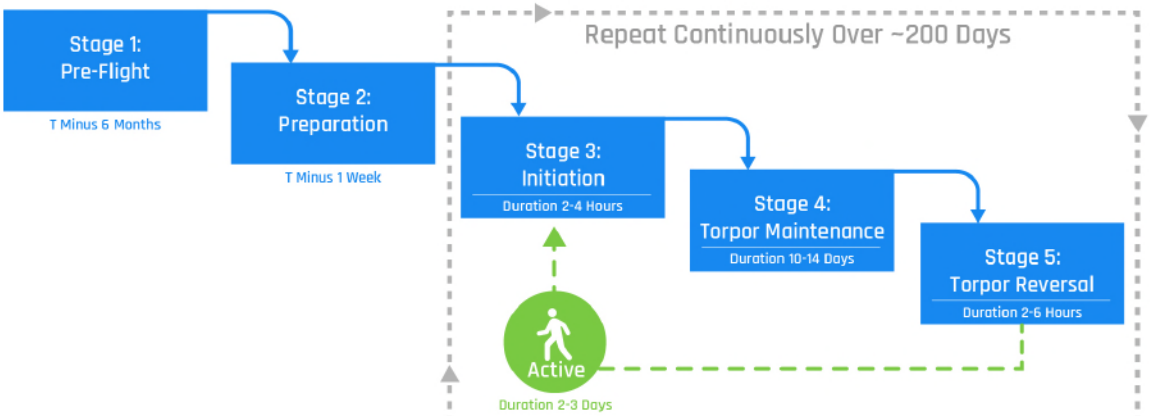


Figure 9. Overview of Key Torpor Induction Steps

A description of the activities associated with and required for each stage of the process are provided next.

4.8.1. Stage 1: Pre-Flight

Beginning approximately six (6) months before the crew mission is launched:

4.8.1.1. Training

Training on catheterization of the bladder, application and removal of fecal collection systems and competency in venous access, including access and maintenance of Porta Cath® will be mastered. Crew members will also become familiar with the inspection, maintenance, and use of the PEG tube and alternate NG/OG tubes.

Basic interpretation of altered vital signs including level of consciousness, heart rate, blood pressure, respiratory rate, urine output, and end-tidal carbon dioxide output must be learned to assist with medical staff evaluation of torpor induced crew members. Finally, the crew must familiarize themselves with the operation and maintenance of basic life support monitoring systems (e.g. EKG, pulse oximeter, automatic blood pressure device, and end-tidal carbon dioxide capnography) as well as torpor specific systems (e.g. gas delivery, nutritional support).

4.8.1.2. Exposure to Torpor Cycles

Crew members will undergo short duration (24-48 hour) cycles of torpor. This will allow the crew to experience and prepare for the physical and psychological effects associated with the torpor initiation and waking process. Crew members can also assist the medical team in torpor initiation and recovery steps, increasing their knowledge and application of induction protocols to allow them to assist with mission torpor cycles. Finally, exposing each crewmember to short torpor cycles will help identify which members of the crew best tolerate the temperature and pharmacological aspects of torpor.

4.8.1.3. Establish Permanent IV and Nutritional Access

Approximately 12 weeks prior to the flight, a central venous catheter, 9 Fr single lumen silicone catheter with Titanium portal (Porta Cath®) will be inserted in the left subclavian vein for right handed subjects and in the right subclavian vein for left handed subjects.

A Percutaneous Endoscopic Gastrostomy (PEG) tube will also be surgical placed via a combined laparoscopic and endoscopic approach. This will allow adequate time for surgical recovery and to identify postsurgical complications. Procedures on the safe access, discontinuation, flushing, and maintenance of these portals must be practiced and mastered.

4.8.2. Stage 2: Crew Preparation

Beginning approximately one (1) week before torpor induction (likely post-Earth departure):

4.8.2.1. Skin Preparation

Crew members will apply Mupirocin 2% ointment to each nostril twice a day for 7 days prior to induction of torpor. Three days prior to induction, the skin will be cleaned with chlorhexidine gluconate (CHG) alcohol wipes, twice a day, paying attention to axillae, groin, and rectal regions. Most nosocomial infections in prolonged bedridden patients are from the patients' own endogenous flora found in the skin, mucus membrane, respiratory tract, and gastrointestinal tract. Reducing the surface bacterial flora appears to mitigate the risk of local and post-site skin infection [138,139]. Once torpor cycling has been initiated, this procedure will be repeated daily during any active, non-torpor periods for the crew members until the last torpor cycle.

4.8.2.2. Bowel Preparation

With enteral feeding through PEG or NG/OG tube: Two days prior to torpor crew members will start a clear liquid diet. Twelve hours prior to torpor astronauts should take two bisacodyl tablets (common stool softener). They will continue to consume oral liquids until two hours prior to the induction of torpor. As bowel movements, passage of flatus, and defecation are decreased under moderate sedation and hypothermia, this will transition waste to a more mobile form that is more conducive to the proposed waste collection systems.

4.8.2.3. Perform Systems Test on Torpor Induction Systems

One day prior to torpor induction the crew, in conjunction with mission control support teams, shall perform operational tests on all torpor-based electronics and mechanical equipment systems.

4.8.2.4. Test Access to Port-a-Cath and PEG Tube:

Prior to induction of torpor, the crew shall access the Porta Cath and initiate maintenance infusion of Lactated Ringers 40 ml/hr. The PEG tube line will be flushed with 100-200 ml of sterile water or saline to ensure patency.

4.8.3. Stage 3: Initiation

4.8.3.1. Torpor Habitat

Crew members will maximize skin exposure to facilitate heat transfer from the body. If glabrous skin surface cooling is utilized, then hand and feet heat-exchange garments will be donned. If heat exchange through ambient cooling is utilized, then crew torpor habitat cooling will be commenced at this time and cabin temperature reduced to <10 degrees Celsius.

4.8.3.2. Place Foley Catheter, Fecal Collection system, and OG/NG Tube

At this time fecal collection system placement is required if enteral feeding is selected, and OG/NG tube placement would be required if a PEG tube is not utilized. Urination continues whether TPN or enteral feeding is utilized. Foley collection systems therefore must be placed as the drainage of the bladder is necessary to maintain renal function and measure the adequacy of tissue perfusion. The bladder temperature obtained through Foley catheter will also provide a measure of core body temperature.

4.8.3.3. Apply Monitors

Crew will apply the following monitors: Bispectral Index (BISTM) monitor, non-invasive blood pressure, EKG, pulse oximeter, and end-tidal CO2 monitor. Core body temperature will be recorded from bladder temperature measured through Foley catheter.

4.8.3.4. Induce Moderate Sedation

Moderate sedation will be induced and maintained for the duration of the torpor using a balanced anesthetic technique. A combination of intravenous medication will be used to achieve hypnosis, analgesia, and depression of the nervous system to suppress the shivering response and help the crew tolerate the cooling process until core body temperature is reduced past the “shivering threshold” (approximately 35 °C/ 95 °F) [47].

Dexmedetomidine is the current preferred sedation medication as discussed above [37,47]. The objective is to provide analgesia, amnesia, and abolish spontaneous movements. At the same time the crewmembers should be able to maintain a patent airway, adequate minute ventilation, and satisfactory hemodynamic parameters. The level of sedation should be such that the crew will not respond to verbal commands but should respond to noxious stimuli. The need for sedation would be reduced and may potentially be avoided with CHA torpor induction as CHA not only resets thermogenesis threshold but also suppresses the shivering response.

4.8.3.5. Induction of Hypothermia

Ambient cooling of the torpor habitat would be continued, resulting in hypothermia through direct conduction and convection from the skin to the surrounding air. Alternately, cooling could be limited to glabrous skin surfaces (namely the hands and feet). Core temperature would be regulated by either further cooling the ambient environment, or through active warming by convection air or through a heating pad or blanket (commonly used in operating rooms to prevent hypothermia during surgical cases) [49].

Adenosine Receptor Agonist: CHA and 8-SPT torpor induction would be initiated through IV infusion through the Port-a-Cath per research study verified weight-based calculations. Current estimates are 4.2 mg bolus with a 0.1 mg/kg/h maintenance infusion rate for CHA, with 8-SPT administered per research study verified weight-based calculations as needed to maintain normal blood pressure.

4.8.4. Stage 4: Torpor Maintenance

4.8.4.1. Evaluation of Vital Signs and Blood chemistry

Continuous vital signs evaluation would be performed using current NASA approved monitoring systems. The collection and processing of laboratory testing to evaluate system electrolytes, basic body chemistry, red and white blood cell levels, and the presence and identification of any systemic body infection can be conducted by programmable automated systems or by sentinel crew member [92]. Laboratory testing, including urinalysis from Foley catheter samples, would be conducted at scheduled intervals and as per crew member vital signs or physical symptoms dictate.

4.8.4.2. Nutrition

Enteral feeding via temporary NG/OG feeding line or PEG tube would be initiated through gravity drainage or lower pressure pump assistance. Prepared solutions consisting of water and all the necessary nutrients, microelements and electrolytes necessary for healthy physiologic function would be administered in a single feeding of 2 kcal/ml nutrient solution.

4.8.4.3. Infection Control

To minimize the risk of infections, broad spectrum antibiotics (Ciprofloxacin at ~400 mg every 12 hours) will be started and continued for the duration of hypothermic torpor. Broad spectrum antibiotic ointment should be instilled in both eyes, with lids closed. The inside of the mouth and gum lines should be periodically swiped with chlorhexidine gel swabs. Porta Cath access should also be inspected and cleaned with Betadine swabs. Both urethral orifice and catheter surfaces should be inspected for signs of infection or biofilm formation. If necessary, the Foley catheter should be replaced with a sterile new catheter.

4.8.4.4. Thrombosis Prevention

Systemic intravenous anticoagulation will be started and continued for the duration of the hypothermic torpor. Periodic Heparin line flushes with Lepirudin or Rivaroxaban (once daily through enteral feeding tube) are the preferred medications for preventing blood clot formation. Mechanical pulsatile compression devices will also be utilized as well as automated pressure point modification systems.

4.8.4.5. Monitoring and Periodic Care

Each crew member in torpor should be monitored daily for signs of infection, development of deep venous thrombosis, or formation of pressure ulcers. Exams should be performed in a systematic fashion from head to toe, looking for injury or infection of any kind. Routine care such as changing the position of crewmembers, dental care, monitoring and cleaning of IV and nutritional access sites, Foley catheter and fecal collection system inspection and replacement, and auscultation of heart and lungs will also be performed. Many of these activities can occur via automated systems with robotic manipulators. Periodic crew member inspections will be video recorded and sent to mission control based medical teams for further review and care recommendations.

4.8.5. Stage 5: Torpor Reversal

4.8.5.1. Rewarming

The ambient temperature in the hibernation pod will be increased, allowing passive rewarming to occur until core temperature has reached 36°C, at which point the infusion of CHA will be stopped.

4.8.5.2. Wakening

Once the core body temperature has reached 36°C, the infusion of sedatives will be stopped (if utilized) and the crewmember will be allowed to gradually wake up.

4.8.5.3. Discontinue Monitoring, Antibiotics and Anticoagulation

Monitoring should be maintained until all physiological functions have returned to normal levels. If necessary, serum chemistry, including glucose, acid-base, and electrolytes should be check prior to discontinuing the EKG. Once torpor has been reversed antibiotics can be stopped. Anticoagulation should be stopped after the crewmember has resumed spontaneous and voluntary movements in the limbs.

4.8.5.4. Resume Normal Diet (if available)

Crewmembers may start on an oral liquid diet and then advance gradually to a normal solid diet. Once oral nutrient intake is adequate the temporary NG/OG tube can be removed (it utilized).

4.8.5.5. Resume Normal Activity

Crewmembers will gradually increase physical and mental activities. Minor muscle weakness, joint stiffness, and clouding of consciousness may need to be reversed through increased physical and mental activities immediately after wakening. Structured exercises to increase muscle strength and tone, such as those already instituted on current NASA missions, should be continued. Range of motion exercises may need to be added to existing exercise regimes. Complete elimination of sedatives and other pharmaceutical agents from the body will occur naturally shortly after waking, allowing for the return of normal wellbeing.

5. Impact on NASA's Human Research Program (HRP)

In order to consider the full potential impact of torpor towards supporting future human spaceflight, the medical team reviewed all of the NASA Human Research Program (HRP) Identified Spaceflight Risks. Each team member independently considered each risk and provided a score on its potential to positively or negatively impact each risk. Additionally, each member provided not only their personal rationale but also supporting clinical research whenever possible. Some of the risks that were identified are poorly understood and have not been evaluated by any large, formal studies at this time. This overall results from the research team indicated that torpor could positively benefit at least 11 different HRP spaceflight risks, which are represented in Table 4. Note that for brevity, the risks determined to have minimal or no impact on HRP risks due to torpor were not included.

Table 4. NASA HRP Risk Rankings based on SpaceWorks' Team Qualitative Torpor Impact Assessment

Torpor Impact Rankings	HRP Risk ID #	NASA HRP Risk Title
1	33	Risk of Spaceflight-Induced Intracranial Hypertension/Vision Alterations
2	21	Risk of Inadequate Nutrition
3	5	Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders
4	26	Risk of Performance and Behavioral Health Decrements Due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation within a Team
5	28	Risk of Performance Decrements and Adverse Health Outcomes Resulting from Sleep Loss, Circadian Desynchronization, and Work Overload
6	3	Risk of Acute (In-flight) and Late Central Nervous System Effects from Radiation Exposure
7	16	Risk of Impaired Control of Spacecraft/Associated Systems and Decreased Mobility Due to Vestibular/Sensorimotor Alterations Associated with Spaceflight
8	4	Risk of Acute Radiation Syndromes Due to Solar Particle Events (SPEs)
9	13	Risk of Cardiovascular Disease and Other Degenerative Tissue Effects from Radiation Exposure
10	27	Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System
11	17	Risk of Impaired Performance Due to Reduced Muscle Mass, Strength & Endurance

While SpaceWorks is not proclaiming torpor as a solution to these risks, our team feels strongly that this technology may provide a roadmap for potential research and study to address these issues in the future. Details on some potential risk benefits will be provided.

5.1. Short-term and Long-term Effects of Radiation Exposure and SPEs

HRP Identified Spaceflight Risks #3, #4 and #13 all address the concerns of the detrimental effects of radiation exposure on astronauts during prolonged space missions. There are 23 significant studies on hibernation, hypothermia and radio-resistance ranging from 1961 – 2017 [140-162]. These studies included research on a variety of mammals (including mice, rats, hamsters, and ground squirrels) as well as cell and tissue samples collected from similar mammals and humans. In each case, the studies observed some radio-protective affect associated with hypothermia, with some studies showing significant increases in the mean survival time and the overall survival rates of the hypothermic groups. There are multiple theories of how hibernation provides radio-resistance, but given the limited number of studies none of them have been verified. Also, there has been renewed interest in hibernation and its radioprotective effects. For example, Isaac Bailey, Pharmacologist and Organic Chemist, University of Alaska Fairbanks, was recently awarded research funds from the Alaska Space Grant Program to study the impact of metabolic reduction on bone density loss and radioprotection (April 2017).

Radiation and chemotherapy are an essential component of the treatment of cancer. Cancer patients can be exposed to high-doses of radiation during these treatments, but these levels are still limited by tissue toxicity, which limits the maximum radiation and chemotherapy dose that can be used on the tumor. When exceeded, tissue toxicity results in damage to other vital organs and serious side effects to the patient. Oncologists are currently exploring if hypothermia could allow patients to be treated with radiation and chemotherapy at doses that would not be acceptable in normal conditions because of organ dose limits. In addition, researchers are interested in determining if hypothermia could prevent or mitigate the more serious complications caused by these treatments. These studies are also still in early stages and limited data currently exists.

5.2. Spaceflight-Induced Intracranial Hypertension/Vision Alterations

Multiple large studies have found that TH was effective at lowering intracranial pressure resulting from traumatic brain injury [163-171]. As a result, there is now support for the use of TH as a safe and effective treatment option for refractory intracranial hypertension [22]. The primary mechanism of action is that TH minimizes cerebral fluid shifts due to changes in central and peripheral blood pressure and blood electrolyte changes due to cellular death. This same mechanism of action is likely to minimize the microgravity induced effects of increased intracranial pressure on vision changes as well as vestibular/motosensory alterations. In addition, placing a crew in a torpor state may provide a more efficient engineering model to allow for induced gravity in the crew habitat, also mitigating microgravity affects.

5.3. Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders, and the Risk of Performance and Behavioral Health Decrements

As discussed above, little to no study data exists on the cognitive effects of TH. Given what we know about the mental state of hibernating animals, an astronaut in a state of torpor would likely cycle through episodes of mental wakefulness (without awareness), and non-REM sleep. Therefore, the only mental deficits they would experience would be those similar to sleep deprivation, with a short period of sleep recovery potentially all that is needed to transition from sleeping passenger to active explorer.

Sleep disruption, monotony and boredom are the most frequent complaints of individuals in an integrated collaboration environment such as space flight, with the combination of monotonous work with requirements for high degrees of alertness and penalties for errors seen as especially stressful [131,132]. Given this fact, utilizing torpor would not only provide significant engineering benefits but would very likely reduce the amount of emotional and psychological stress, monotony, boredom, and sleep disruption experienced by crew members during a prolonged mission. When coupled with the reduction in the length and frequency of crew interaction and conflict, as well as greater opportunity for privacy and independence, is likely to significantly reduce the incidence of intrapersonal conflict and relationship-based stress.

5.4. Adverse Outcomes Due to Sleep Loss, Circadian Desynchronization, and Work Overload

Studies on medication usage rates showed that 45% of all medications used by Space Shuttle crew members were sleep aids, and that 71% of all astronauts onboard the ISS have reported using sleep aids at least once during a mission [172,173]. Use of sleep onset medications not only affects the level of wakefulness and alertness of the crew members but can also have long-term medical complications including liver damage and withdrawal affects [174]. Prolonged sleep cycles of seven days and beyond could significantly reduce the use of sleep onset medication and eliminate astronaut work overload. The crew would spend a majority of the transit time during deep space missions in a torpor state. This will mitigate most of the emotional and psychological stress associated with crew interactions, isolation, lack of sleep and the physical discomforts of space travel. The result would be reduced incidences of depression, anxiety, sleep disruption and interpersonal conflicts during the portion of the mission where the crew has minimal mission tasks that engage their attention and promote teamwork.

As discussed above, with what we know about the mental state of hibernating animals, an astronaut in a state of torpor would likely cycle through episodes of mental wakefulness (without awareness), and non-REM sleep. Therefore, astronauts do have the potential to experience some level of sleep deprivation while in torpor. However, the level of sleep disruption is not likely to exceed current levels experienced by crews on current missions, with a short period of sleep recovery potentially all that would be needed to transition from torpor to fully active.

5.5. Risk of Impaired Performance Due to Reduced Muscle Mass, Strength & Endurance

Significant muscle atrophy can be observed in human muscles after only 5 days in space, but an overall time course and plateau for atrophy has not been established [175]. While generally not a concern during missions, these changes in the musculoskeletal system contribute significantly to the impaired function and risk of reloading injury experienced in the post-flight period [176]. As in bone density loss, humans on bed rest exhibit similar levels of muscle atrophy to those seen by astronauts in a zero-g environment. Bed rest studies show a notable level of muscle atrophy in as little as four days with significant increases continuing until two weeks, with larger losses noted in younger verses older patients [177].

Once again, hibernating animals do not exhibit the same levels of muscle atrophy during inactive hibernation periods. Studies routinely show that there is relative stability of fiber type percentage and size, fiber size to body mass ratio, myosin heavy chain isoform content, shortening velocity, power output and elevated specific tension in hibernating animals between summer and winter months [178-180]. Torpor may provide similarly benefits to muscle atrophy prevention and the follow-on risk of reloading injury.

Additionally, placing the crew in a torpor state may again provide a more efficient engineering model for inducing gravity in the crew habitat, mitigating microgravity affects. Outside of that, the reduced state of consciousness associated with torpor will allow for more prolonged and aggressive use of known preventative mechanisms, such as Neuromuscular Electrical Stimulation (NMES). While thoroughly studied and clinically proven to significantly impact muscle atrophy in both the hospital and microgravity environments, the repeated and prolonged use of NMES on large muscle groups is difficult to achieve due to the level of physical and mental discomfort it causes [181-184]. With crew members in a deep sleep like state, higher levels of muscle protection could be achieved with NMES by allowing for longer, more frequent, and more intense therapy sessions on large muscle groups.

5.6. Risk of Inadequate Nutrition and Effects on Crew Performance and Crew Illness

Inadequate nutrition has been a concern since the dawn of exploration. For NASA missions in particular, the NASA HRP Identified Spaceflight Risks #21 and #27 address concerns of inadequate nutrition and its effect on crew performance and risk of illness. Beyond the obvious concerns of malnutrition (fatigue, weight loss, muscle and bone density loss), poor nutritional intake is also directly associated with decreased immune function, impaired memory and cognitive function, and even decreased mental wellbeing [185-187]. Scientists have long known that rehydrated foods (such as those currently used on long-term space missions) lose nutritional value though the dehydration/preparatory process and during storage [188]. Enteral based nutrition formulas, such as those proposed for SpaceWorks' torpor protocol, have a proven nutritional stability and store capability of two years as currently constituted (for unopened containers stored at room temperature) [63]. Given the ease of use and the prolonged bioavailability and storage life, nutritional supplementation during torpor should meet all recommended nutritional requirements and adequately protect from malnutrition and its associated detrimental effects.

5.7. Adverse Risk of Bone Fracture and Spaceflight-induced Changes to Bone

Spaceflight-induced changes to bone leading to early onset osteoporosis and the subsequent increased risk of both long bone fracture and intervertebral disc damage (NASA HRP Identified Spaceflight Risks #2, #11, and #15) have long been known as significant medical concerns associated with long-term space missions. Data collected from Skylab and Mir astronauts have shown bone density losses of nearly 8 percent in the calcaneus (heel bone) over 84 days and 19 percent over 140s days [189]. It is estimated that a three-year Mars mission could result in a loss of bone density mineralization of 50 percent or more [190]. Bone density loss in humans on bed rest is surprisingly similar to those seen by astronauts in a zero-g environment. One study on the effects of 100 days of bed rest treatment for T8 spine compression fractures revealed a 19% reduction in lumbar spine bone mineral density and a 6% reduction in total hip density [191].

While the overall torpor impact for these risk areas were generally not scored high by the team, it is worth noting that hibernating animals (even though they can be inactive for time periods equal to or longer than those of astronauts or bedridden patients), do not exhibit the same bone density losses discussed above. Studies involving arctic ground squirrels and bears showed: 1) Cortical bone geometrical properties (i.e., thickness, cross-sectional area, and moment of inertia) at the midshaft of the femur were not different in animals sampled over the hibernation and active seasons; 2) That while femoral ultimate stress tended to be lower in hibernators than in summer animals, bone toughness was not affected by hibernation, 3) And that the area of osteocyte lacunae was not different between active and hibernating animals [192,193]. In addition, there were no differences in bone structure, mineral content, or mechanical properties between fall and spring bears, and bone geometrical properties differed by less than 5% and bone mechanical properties differed by less than 10% [193]. These studies show that hibernating animals are able to preserve many bone properties during hibernation despite being physically inactive for up to 8 months.

It is plausible that torpor may be able to provide similarly significant bone protection in unloaded environments (i.e. microgravity or bed-rest), resulting in a decreased risk of vertebral disc and large bone fracture or reloading injury. At a minimum, placing the crew in a torpor state appears to provide a more efficient engineering model for inducing gravity in the crew habitat, which can be used to mitigate these effects of microgravity.

6. Engineering Analysis and Modeling

6.1. Mission Architecture Closure Model

To support the planned mission-level architecture assessments, SpaceWorks integrated several proprietary, conceptual design tools into an Integrated Design Framework (IDF) using Phoenix Integration's ModelCenter© software (see Figure 10). The input parameters for each tool were anchored to data gathered based on a NASA EMC Reference architecture. The IDF was then used to assess hundreds of thousands of architecture options in order to properly size and understand the impact of various technologies and/or system assumptions.

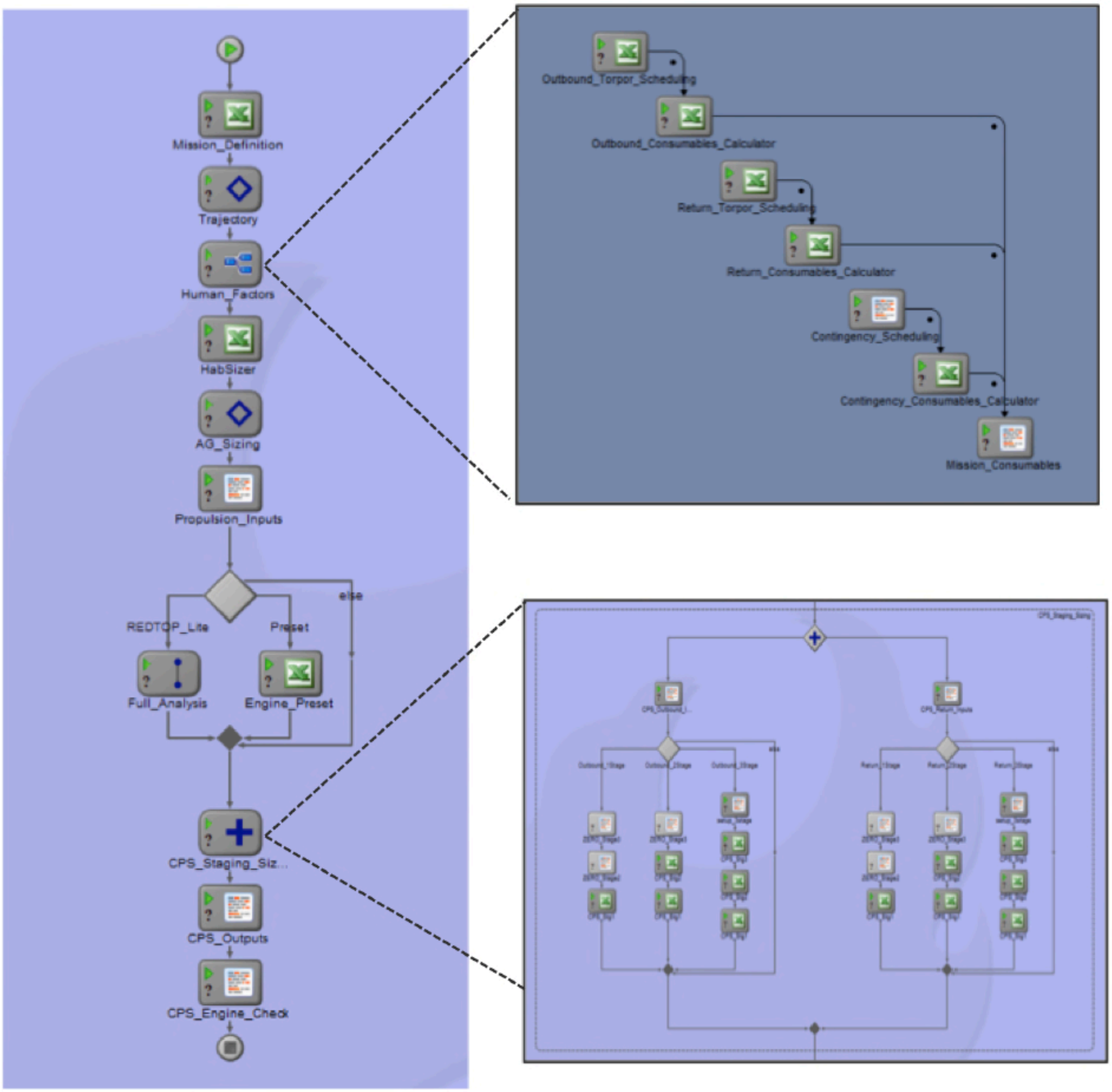


Figure 10. Mission Architecture Integrated Design Framework (IDF)

Table 2 provides a listing of the engineering tools used to support the architecture modeling. Bullseye is an in-space, high-thrust trajectory simulation tool developed by SpaceWorks [194]. The software minimizes the mission energy requirements (i.e. C_3 or ΔV) for a user-specified transit phase(s) and/or destination stay time, utilizing two-body patched conic approximations. The Bio-Simulator is an enhanced version of an initial, Excel-based model for optimizing the crew schedule using the sentinel protocol (see Section 6.1.2). REDTOP-Lite is a performance analysis routine for liquid rocket engines and is capable of sizing an engine to a required thrust level and predicting the specific impulse (Isp) and weight for the engine based on the selected cycle type (e.g. expander, staged-combustion) [195].

Table 5. Engineering Analysis and Design Tools

Domain	Tool Name	Modeling Framework/Language
Mission Variant Generator	-	Python
Trajectory and Mission Design	Bullseye	Java
Torpor Schedule Optimization	Bio-Simulator	C++
Rocket Engine Sizing	REDTOP-Lite	C++
Propulsive Stage Mass Properties	StageSizer	Excel
Habitat Mass Properties	HabSizer	Excel
Artificial Gravity System Sizing	AG-Sizer	Excel
Crew Metabolism	*Custom Excel Spreadsheet*	*Custom Excel Spreadsheet*

6.1.1. Parametric Propulsive Stage Sizing

Reducing the mass of the habitat will enable reductions in propulsive stage mass, reduce the total number of stages, or/and reduce the engine count per stage for equivalent ΔV requirements. To evaluate the potential performance savings obtained with the use of torpor, SpaceWorks sized and estimated the mass of the stages using *StageSizer*, a parametric sizing tool for liquid propellant propulsive stages. StageSizer can perform a detailed analysis and sizing of approximately 15 different subsystems required for a launch system or in-space propulsive stage. This includes tank structures, interstage adapters, power generation, power management & distribution (PMAD), thrust structure, communications, thermal control, pressurization system, attitude control system (ACS), etc.

StageSizer was initially anchored to a NASA EMC reference propulsive stage mass statement and dimensions; as detailed in Reference 198. Using this reference model as a point of departure, SpaceWorks was able to generate propulsive stage concepts for each new payload mass and mission opportunity by varying the key stage design parameters of maximum diameter, length, engine vacuum thrust level, and engine quantity.

6.1.2. Bio-Simulator Tool

SpaceWorks created a dynamic software tool to optimize the crew schedule by maximizing the total inactive/torpor period for the specified mission segment subject to a minimum number of active crew members, a maximum and minimum torpor cycle duration, minimum active period, the number of crew teams, mission duration, mission time to first induction cycle, etc. The schedule is optimized at the resolution of hours and can be performed for any number of crewmembers. Additionally, torpor-specific parameters such as the minimum and maximum core body temperature (e.g. 32 to 34 degrees C), rate of cooling (e.g. 2.0 degrees/hour), and rewarming rate (e.g. 0.5 degrees/hour) are used to generate crew metabolic profiles over time for the mission duration.

The Bio-Simulator tool performs an exhaustive, full-factorial assessment by discretizing the design space and generating a crew schedule for each combination of design parameters. One scheduling complexity arises out of the need to phase the induction period for the crew members to permit generating scenarios where all crew members are not in synch to be active or inactive simultaneously. To handle this, the tool includes an induction offset parameter as an internal parameter that adds the additional degree of freedom necessary to meet the user-specified constraints.

Table 6 provides the results from the Bio-Simulator for two reference mission scenarios. The first is for a crew size of 4 and the second is for a crew size of 8. For both cases, the minimum number of active crew members was required to be at least 1. For the 4-crew scenario, while the maximum permissible torpor duration was 14 days, the allowable duration was limited to 9 days given the design constraints and requirement to have at least one active member. The

8-crew scenario gives the crew a lot more schedule flexibility and the allowable torpor duration is permitted to reach the maximum value of 14 days. This results in an increase in the overall torpor utilization rate (i.e. total time in torpor/total mission time) from ~71% to ~82%.

Table 6. Comparison of Torpor Sentinel Protocol Results for Crew Size of 4 versus 8 (from Bio-Simulator)

Parameters	4 Crew Results	8 Crew Results
Mission Duration	200 days	200 days
Maximum Torpor Cycle Duration	14 days	14 days
Initial Induction Delay	7 days	7 days
Minimum Number Active Crew	1	1
Maximum Number Inactive	3	7
Minimum Number Active	1	1
Total Crew Active Hours	5,520	6,984
Total Transition Hours	261	389
Total Crew Inactive Hours	13,419	31,027
Ideal Torpor Cycle Duration / Active Period	9 days / 3 days	14 days / 2 days
Initial Crew Offset	72 hours	48 hours
Torpor Utilization % for Mission	**70.85%**	**81.63%**

Figure 11 graphs the core body temperature over time for the first 30-days with a crew size of 4. For this scenario, the target core temperature during torpor was desired to be held at a constant 32-degrees C. During periods of activity, the core temperature for each member is at the nominal value of 37-degrees C. Note that there was an initial 7-day delay (or 168 hours) after the start of the mission before initiating any crew members into torpor. Per the specified constraint, it is also easy to see that there is always at least one crew member that is active. Figure 12 provides a similar view, but in this scenario the core temperature is oscillated between 32 and 34-degrees C. One of the reasons for doing this is to potentially minimize the wake time for additional crew members in the event of an emergency. The 2-degree delta may reduce the required rewarming time by 1-2 hours.

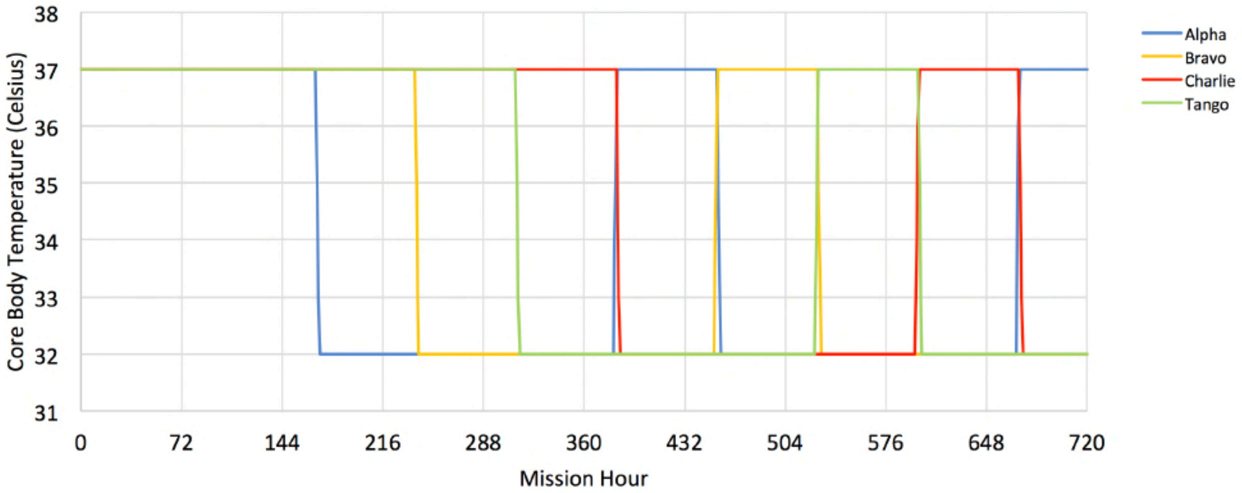


Figure 11. Bio-Simulator Results: 4-Crew with Constant Core Temperature

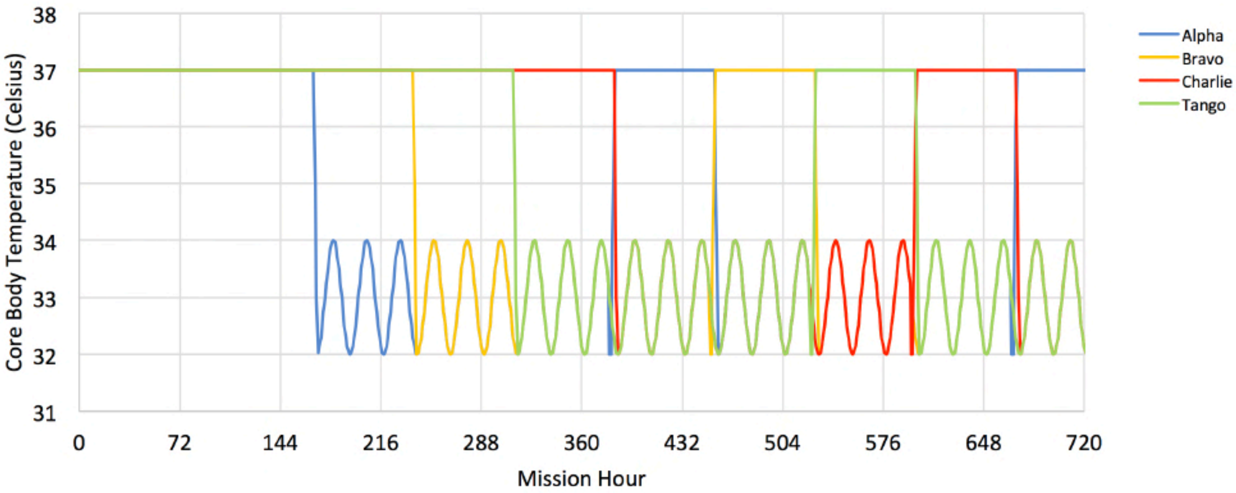


Figure 12. Bio-Simulator Results: 4-Crew with Variable Core Temperature

6.1.3. Modeling Crew Consumables and Metabolism

Reducing the total mass of the required crew consumables is one of the primary advantages of the torpor-inducing habitat. SpaceWorks calculated changes in the total mass of crew consumables by calculating new totals as a function of crew biological profile, transit duration, and torpor metabolism reductions.

The baseline crew model consists of four astronauts with uniform nutrition and hydration requirements. Individual basal metabolic rate (BMR) is calculated with a variant of the Harris-Benedict Equation modified by Mifflin. Activity level effects are captured by multiplying the calculated BMR by an activity level multiplier. Table 7 lists the assumptions regarding reference crew physiology and nutrition. With these parameters, the total food intake rate for each crew member is approximately 1.95 kg/day.

Inducing torpor reduces the mass of required crew consumables in two ways. First, astronauts in torpor can be sustained with liquid, enteral feeding instead of 'normal' solid food. Enteral nutrition supplements have a higher caloric density by design, are able to be stored more efficiently with less packaging waste materials, and the water content of the nutrients can be recaptured in a closed-loop life support system. As a result, simply switching from 'normal' solid food to a liquid enteral supplement leads to a large reduction in total crew consumables. Assumptions for the enteral nutrition model are given in
Table 8. With enteral nutrition and a normal metabolism, the total food intake rate for each crew member is 0.762 kg/day.

Table 7. Reference Crew Member Physiological Assumptions for Sizing Case

Name	Value	Units
Gender	Male	-
Weight	73.25	kg
Height	75	in
Age	40	years
Carbohydrates % of Total Caloric Intake	55	%
Fat % of Total Caloric Intake	25	%
Protein % of Total Caloric Intake	20	%
Food Fluid Fraction	30	%
Nutrition Dosage	26.0	g/day/kg-mass

Table 8. Torpor Crew Physiological Assumptions for Sizing Case

Name	Value	Units
Gender	Male	-
Weight	73.25	kg
Height	75	in
Age	40	years
Enteral Nutrition Dosage	8.663	g/day/kg-mass

Torpor induction also reduces metabolic rate, which leads to an even lower daily nutritional requirement. The exact savings depends on the degree of metabolic reduction, which is a function of the core body temperature.

For each mission, the total food mass required to sustain the crew is calculated for the parameters given in Table 7 and
Table 8. Mission-specific inputs include the active and torpor cycle durations and 'crew-days' from the Torpor Cycle Scheduler. Outputs from this analysis are the active, transition, and torpor nutrient rate (kg/person/day) and the total food mass required for the mission.

6.1.4. Integrated Design Framework (IDF)

To support rapid design space exploration and trade studies, SpaceWorks integrated all parametric design tools into an Integrated Design Framework (IDF). The IDF automates the data flow and execution of each model in the following sequence of analyses:

1. Define mission destination and departure year
2. Determine the minimum characteristic energy (C_3) trajectory and compute time of flight and ΔV requirements for each segment of the trajectory using Bullseye
3. Optimize crew torpor schedule if evaluating a torpor-enabled mission using the Bio-Simulator
4. Estimate nominal and contingency crew consumables mass based on the mission duration and nutrition type selected
5. Parametrically estimate the habitat mass based on mission duration and total consumables mass
6. Generate engine design for selected nominal thrust level (assuming high-performance expander cycle design using LOX/CH4 propellants)
7. Size each stage in the transfer vehicle propulsive stack
8. Sum total mass of all transfer stages required for both outbound and return segments

6.2. Cost Modeling

SpaceWorks estimated the overall architecture-level costs for the crew transit elements based on the published Evolvable Mars Campaign (EMC) documentation and results generated from the parametric models for both architecture configurations (EMC Reference Habitat and the SpaceWorks Torpor Habitat). The overall architecture level cost model includes recurring (production) and non-recurring (research, development, testing, and evaluation) costs for the in-space propulsive stages and transit habitat(s), as well as mission operations and launch costs. Mass inputs were used from the Habitat and Propulsive Stage sizing models, as well as component application inputs from the design team, and programmatic inputs consummate with NASA standard modeling approaches. A combination of parametric and analogous cost tools was used to model various components of the architecture-level costs. The primary industry cost tools utilized for this effort are shown in Table 9. Note that technology development costs for torpor were not included in the cost estimates. Consistent with all other subsystem development efforts and standard cost estimating practices, maturation costs up to TRL 6 are not accounted for.

Table 9. System Cost Modeling Tools

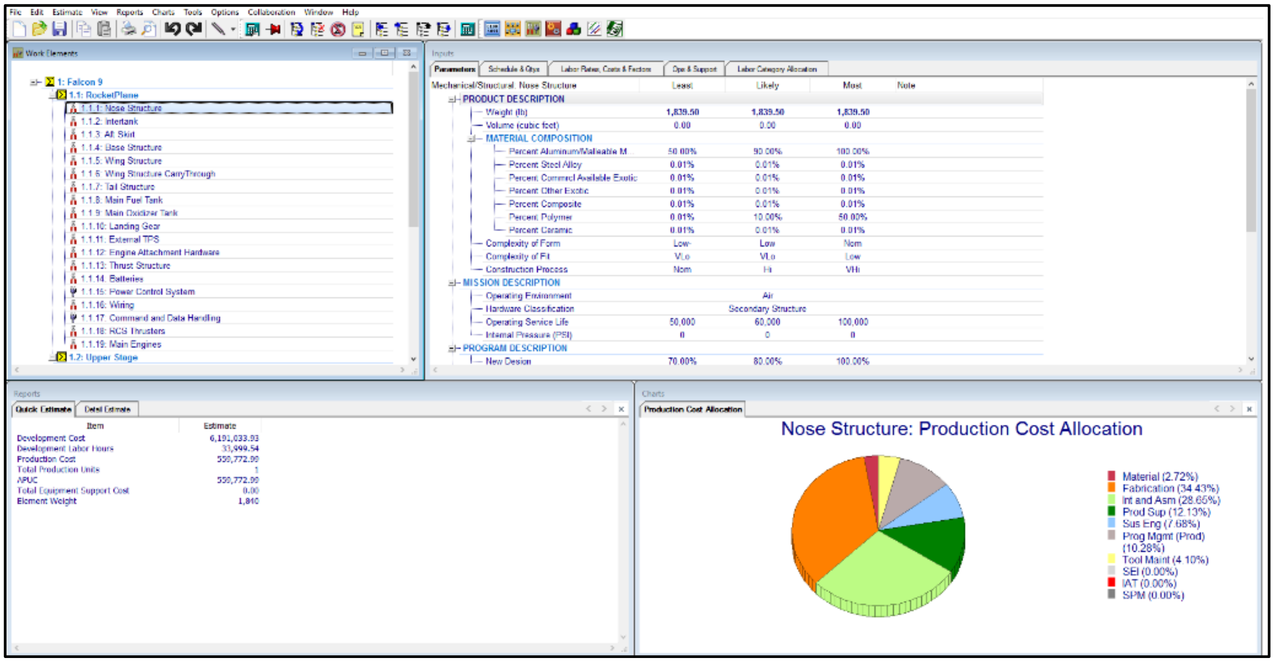
Tool Name	Developer	Used For
SEER-H	Galorath, Inc.	Recurring and Non-Recurring Costs
PCEC	NASA	Recurring and Non-Recurring Costs
MOCET	Aerospace Corporation	Operations Costs

6.2.1. SEER-H Costing Tool

SEER-H is a parametric cost-analysis tool developed and distributed for the last 20 years by Galorath, Inc. (see Figure 13) [199]. It is used in numerous industries, including aerospace and defense. The tool consists of internal knowledge bases with cost estimating relationships (CERs) that are applied to both organization and project-specific factors. Principal inputs include:

- Mass
- Application
- Acquisition process
- Complexity
- Material properties
- Heritage design percentage
- Labor rates
- Learning effects
- Production standard
- Platform category

Outputs from SEER-H consist of subsystem development and production costs based on a user-input work breakdown structure. System level costs are disseminated into integration, assembly and checkout (IACO), system test operations (STO), system support equipment (SSE), system engineering and integration (SE&I), and program management (PM) costs.



- 1: Falcon 9
  - 1.1: RocketPlane
    - 1.1.1: Nose Structure
    - 1.1.2: Intertank
    - 1.1.3: Aft Skirt
    - 1.1.4: Base Structure
    - 1.1.5: Wing Structure
    - 1.1.6: Wing Structure CarryThrough
    - 1.1.7: Tail Structure
    - 1.1.8: Main Fuel Tank
    - 1.1.9: Main Oxidizer Tank
    - 1.1.10: Landing Gear
    - 1.1.11: External TPS
    - 1.1.12: Engine Attachment Hardware
    - 1.1.13: Thrust Structure
    - 1.1.14: Batteries
    - 1.1.15: Power Control System
    - 1.1.16: Wiring
    - 1.1.17: Command and Data Handling
    - 1.1.18: RCS Thrusters
    - 1.1.19: Main Engines
  - 1.2: Upper Stage

Mechanical/Structural: Nose Structure	Least	Likely	Most	Note
PRODUCT DESCRIPTION				
Weight (lb)	1,839.50	1,839.50	1,839.50	
Volume (cubic feet)	0.00	0.00	0.00	
MATERIAL COMPOSITION				
Percent Aluminum/Malleable M...	50.00%	90.00%	100.00%	
Percent Steel Alloy	0.01%	0.01%	0.01%	
Percent Commrcl Available Exotic	0.01%	0.01%	0.01%	
Percent Other Exotic	0.01%	0.01%	0.01%	
Percent Composite	0.01%	0.01%	0.01%	
Percent Polymer	0.01%	10.00%	50.00%	
Percent Ceramic	0.01%	0.01%	0.01%	
Complexity of Form	Low-	Low	Nom	
Complexity of Fit	VLo	VLo	Low	
Construction Process	Nom	Hi	VHi	
MISSION DESCRIPTION				
Operating Environment		Air		
Hardware Classification		Secondary Structure		
Operating Service Life	50,000	60,000	100,000	
Internal Pressure (PSI)	0	0	0	
PROGRAM DESCRIPTION				
New Design	70.00%	80.00%	100.00%	

Item	Estimate
Development Cost	6,191,033.93
Development Labor Hours	33,999.54
Production Cost	559,772.99
Total Production Units	1
APUC	559,772.99
Total Equipment Support Cost	0.00
Element Weight	1,840

Figure 13. SEER-H Cost Estimation Tool Interface from Galorath, Inc.

6.2.2. PCEC Costing Tool

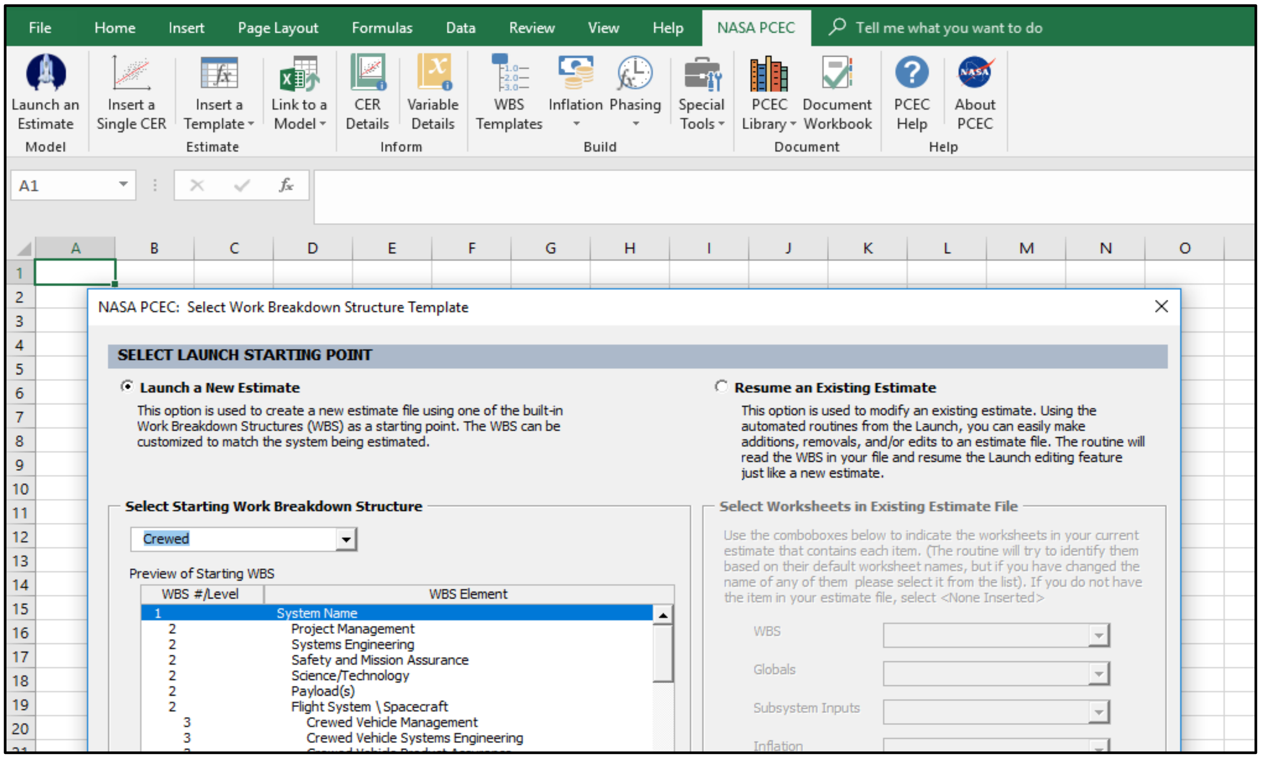
The Project Cost Estimating Capability (PCEC) tool is a parametric cost-analysis tool produced and maintained by the NASA Engineering Cost Office at Marshall Spaceflight Center (see Figure 14) [200]. Building on the wide-spread acclaim of its predecessor, NAFCOM, PCEC integrates over 150 NASA and Air Force spaceflight hardware projects to provide CERs and cost modeling frameworks for establishing probabilistic cost estimates. PCEC allows for simple weight-based estimates, as well as complex, multi-input estimates. Tool outputs consist of subsystem design and development, as well as production costs.

There are two primary cost estimating methodologies available within PCEC:

- Multi-variable estimating is data driven, statistically based and allows users to document estimating assumptions rather than using complexity factors – supportable, repeatable, and verifiable.

- Weight-based estimating is valuable early in the estimating process when an analyst may only have a WBS and mass statement – also useful if estimating hardware very analogous to a mission in the historical database

For this analysis, weight-based estimating was used due to the early stage of the design concepts. Additionally, the relatively high-level master-equipment-list (MEL) available for the purposes of cost estimating was insufficient to properly assess complexity factors and specific assumptions.



NASA PCEC: Select Work Breakdown Structure Template

SELECT LAUNCH STARTING POINT

● **Launch a New Estimate**

This option is used to create a new estimate file using one of the built-in Work Breakdown Structures (WBS) as a starting point. The WBS can be customized to match the system being estimated.

○ **Resume an Existing Estimate**

This option is used to modify an existing estimate. Using the automated routines from the Launch, you can easily make additions, removals, and/or edits to an estimate file. The routine will read the WBS in your file and resume the Launch editing feature just like a new estimate.

Select Starting Work Breakdown Structure

Crewed

Preview of Starting WBS

WBS #/Level	WBS Element
1	System Name
2	Project Management
2	Systems Engineering
2	Safety and Mission Assurance
2	Science/Technology
2	Payload(s)
2	Flight System \ Spacecraft
3	Crewed Vehicle Management
3	Crewed Vehicle Systems Engineering

Select Worksheets in Existing Estimate File

Use the comboboxes below to indicate the worksheets in your current estimate that contains each item. (The routine will try to identify them based on their default worksheet names, but if you have changed the name of any of them please select it from the list). If you do not have the item in your estimate file, select <None Inserted>

WBS

Globals

Subsystem Inputs

Inflation

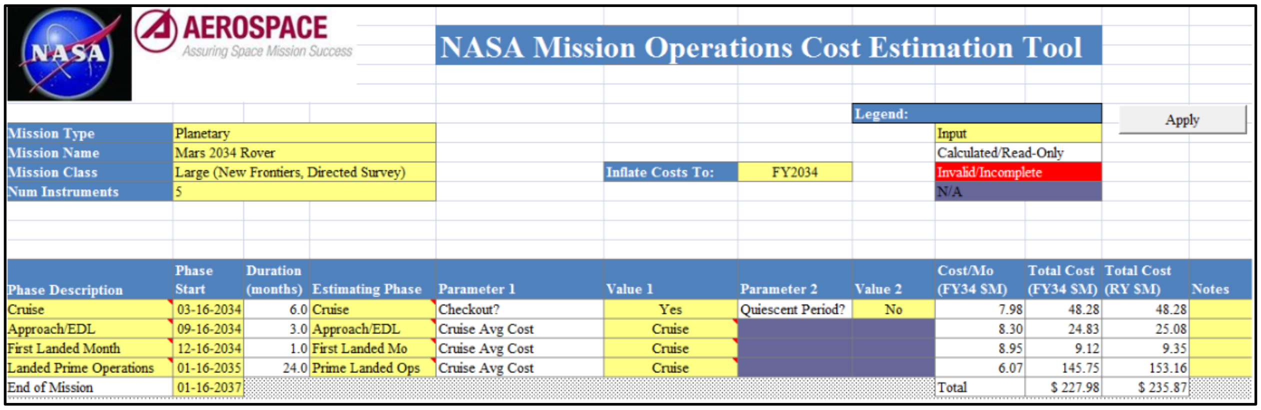
Figure 14. PCEC Parametric RDT&E and TFU Cost Estimation Tool Interface from NASA

PCEC was used as an alternative estimating tool for habitat WBS items that were either too broad to be accurately estimated at the component level using SEER, or that had relatively small knowledge bases in SEER (i.e., exclusively human exploration-related WBS items). In each instance where PCEC was used, both the development and production costs were modeled as a direct throughput cost in the overall SEER model. PCEC was used for the following WBS items:

- Crew Visual Displays & Controls
- Environmental Control & Life Support
- Crew Accommodations
- EVA Equipment
- Airlock Equipment
- Mechanisms & Other

6.2.3. MOCET Costing Tool

The Mission Operations Cost Estimating Tool (MOCET) is a model developed by the Aerospace Corporation in partnership with NASA's Science Office for Mission Assessment (SOMA) [201]. As seen in Figure 15, MOCET provides a new capability to generate cost estimates for the operational portion of NASA science missions. The overall MOCET development effort drew upon nearly 50 individual earth orbiting and planetary science missions to develop CERs for mission operations.



NASA Mission Operations Cost Estimation Tool

Mission Type	Planetary
Mission Name	Mars 2034 Rover
Mission Class	Large (New Frontiers, Directed Survey)
Num Instruments	5

Inflate Costs To: FY2034

Legend:
🟨 Input
Calculated/Read-Only
🟥 Invalid/Incomplete
N/A

Phase Description	Phase Start	Duration (months)	Estimating Phase	Parameter 1	Value 1	Parameter 2	Value 2	Cost/Mo (FY34 $M)	Total Cost (FY34 $M)	Total Cost (RY $M)	Notes
Cruise	03-16-2034	6.0	Cruise	Checkout?	Yes	Quiescent Period?	No	7.98	48.28	48.28	
Approach/EDL	09-16-2034	3.0	Approach/EDL	Cruise Avg Cost	Cruise			8.30	24.83	25.08	
First Landed Month	12-16-2034	1.0	First Landed Mo	Cruise Avg Cost	Cruise			8.95	9.12	9.35	
Landed Prime Operations	01-16-2035	24.0	Prime Landed Ops	Cruise Avg Cost	Cruise			6.07	145.75	153.16	
End of Mission	01-16-2037							Total	$ 227.98	$ 235.87	

Figure 15. MOCET Mission Cost Estimation Tool Interface from NASA and Aerospace Corporation

Within the tool, each segment of the mission is separated out into one of 18 different phases, each with a length of time (in months), as well as unique, phase-specific input factors. The resulting output is both a cost by phase, as well as a total mission cost. For each manned Mars mission in the EMC Reference Architecture, the following phase structure was used:

Table 10. MOCET Mission Phases Used for Manned Mars Missions

Phase Description	MOCET Phase Type
Mars Transfer Vehicle Assembly & Check-out	Checkout
Earth Departure/TIM Burn	Cruise
Entry into Mars 1-SOL Orbit	Orbit Insertion
Orbiting in Mars 1-SOL Orbit	Orbital Operations
Rendezvous with Pre-Position Hardware	Orbital Operations
Pre-Position Hardware Checkout	Checkout
Surface Operations (Dormant Habitat)	Cruise
Rendezvous with Habitat	Orbital Operations
Return Vehicle Checkout	Checkout
Mars Departure/TEI Burn	Orbit Insertion
Mars to Earth Flight	Cruise
Lunar Retrograde Orbit Insertion/DRLOI Burn	Orbit Insertion
Rendezvous	Orbital Operations

The MOCET tool is primarily intended for use with NASA science missions, and not crewed exploration missions. Due to the lack of a suitable alternative for estimating mission operations costs, SpaceWorks elected to use the MOCET tool as a baseline, while augmenting the MOCET outputs with additional analogous cost estimates based on the 2013 ISS operations budget. To avoid over-proportioning ISS operations costs, SpaceWorks used only a subset of the operations budget that included only those cost centers expected to be incurred in a similar capacity during a manned Mars mission. Table 10 identifies the selected mission phases to be included. These costs were escalated to FY2018 dollars and scaled based on the expected mission duration. The additional human exploration-related expenses included in operations cost estimates are shown in Table 11.

Table 11. MOCET Mission Cost Categories and Monthly Cost

Cost Category	Average Monthly Cost ($M, FY2013)
Labor	$ 328
Operation & Maintenance of Equipment	$ 238
Advisory & Assistance Services	$ 106
Operations & Maintenance Services	$ 102
Other Services	$ 94
Other Purchases	$ 44
Suppliers & Materials	$ 22
Travel	$ 12
Land & Structures	$ 8

7. Advanced Habitat Designs

7.1. Habitat Design Assumptions

7.1.1. General Assumptions

The crew habitat is designed to support a complement of 4 during the transit phases of missions to Mars and/or the Martian moons of Phobos and Deimos. The habitat is sized for 1100 days of crewed duration during the Mars mission, plus additional uncrewed time at a lunar Distant Retrograde Orbit (LDRO) for outfitting and checkout. The transit habitat will be reused over several missions and is assumed to last for 15 years.

The habitat is designed to fit within the 8.4 meter diameter shroud for Space Launch System (SLS) which corresponds to a 7.5 meter diameter usable envelope that limits the habitat diameter to less than 7.5 meters when stowed. This diameter maintains flexibility to use the 8.4 or 10 meter diameter SLS shrouds. The habitat length limit is set by the 8.4 meter diameter shroud usable envelope when co-manifested with a hybrid propulsive stage (HPS) for LDRO insertion. The transit habitat is launched with the HPS, with the habitat on the top of the propulsion stage. These launch vehicles are packaged with adaptors such that neither payload carries the loads of the other.

The habitat structure is sized to provide sufficient load bearing interfaces for integration with propulsion stages or other elements above or below the habitat in the launch-vehicle stack. A factor of safety of 2.0 on ultimate loads was selected to comply with JSC 65828 "Structural Design Requirements and Factors of Safety for Spaceflight Hardware". The habitat provides 3 docking mechanisms with hatches, which is driven by aggregation operations requiring simultaneous docking with the Gateway habitat, logistics delivery modules, and Orion crew vehicle.

Micrometeoroid Orbital Debris (MMOD) protection is sized to be sufficient for the 15-year lifetime in a deep space environment. The transit habitat does not carry dedicated GCR and SPE protection beyond that provided by the habitat structure, internal subsystems, and consumables. Internal layout of consumables is therefore driven by the desire to maximize passive GCR and SPE protection.

The habitat does not contain any power generation systems. Instead, it receives power generation located on the propulsive element(s) of the combined transfer vehicle stack. The habitat does include internal power management and distribution systems and batteries to provide 72-hours of power in emergency scenarios.

The habitat internal atmosphere is a 101.3 kPa (14.7 psia), with 21% O_2 nominal atmosphere. The habitat contains a fully closed-loop water recycling and oxygen generation life support systems, with a 30-day open-loop consumable backup for water, oxygen generation, and carbon dioxide removal. The habitat also carries logistics, spares, and maintenance for the full crew during the entire 1100-day mission duration.

7.1.2. Life Support Systems

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

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

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

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

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

For torpor-enabled habitats, the required crew support systems and body interfaces are identified in Figure 16. When torpor is utilized, the maximum duration is nominally 14 days. The crew schedule, generated by the Bio-Simulator tool, is set such that there is always at least one active crew member. This yields active periods between cycles of 2-3 days, depending on the total number of crew members.

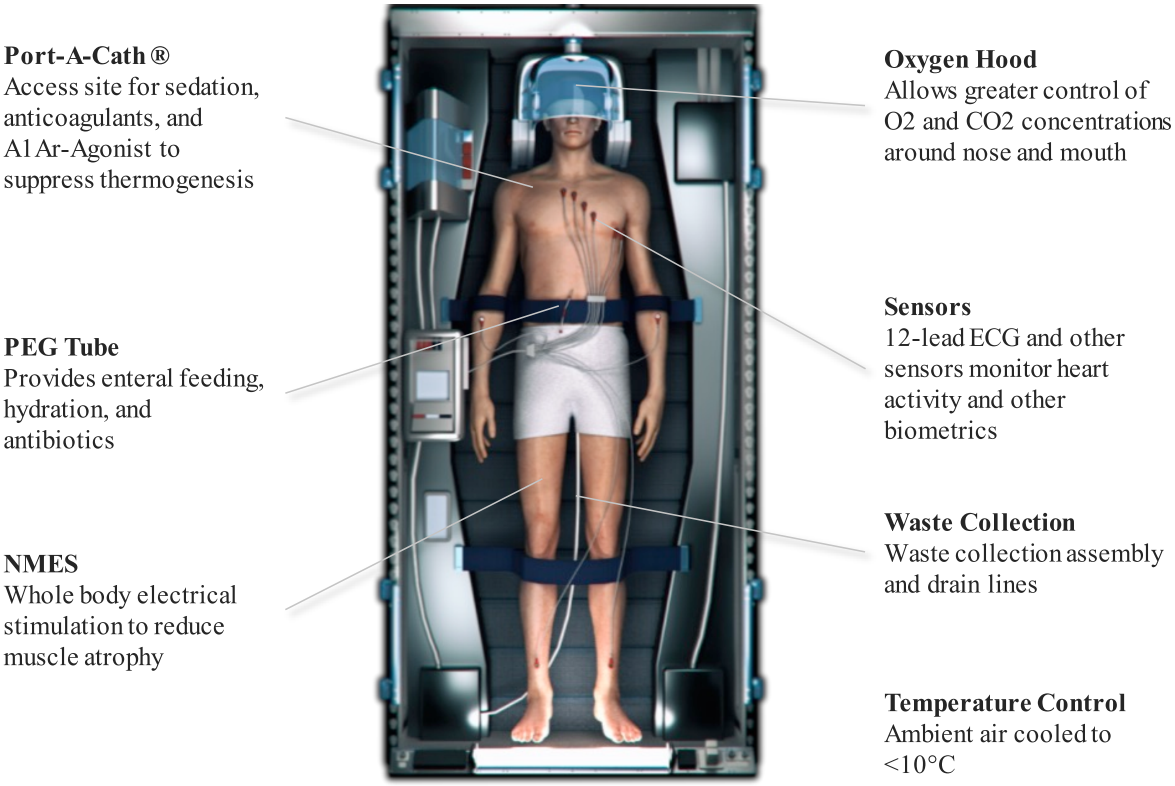


Figure 16. Torpor Pod and Crew System Implementation

7.2. NASA Reference EMC Habitat Design

7.2.1. Habitat Design

Summary metrics for the EMC Reference transit habitat are shown in Table 12. For a crew of four, the habitat provides 25 m^3 of habitable volume per person.

Table 12. NASA EMC Reference Habitat Summary Metrics

Metric	Value
Empty Mass	21.0 t
Loaded Mass	45.5 t
Length	7.5 m
Diameter	7.2 m
Habitable Volume	100 m^3
Pressurized Volume	300 m^3
Power Required	20 kW

The NASA EMC Reference habitat geometry is shown in Figure 17 and Figure 18. The habitat is divided into two levels. The lower level serves as the crew living area and workspace. The upper level houses consumables and spares, as well as crew sleeping quarters. Life support subsystems are housed in the deck beneath the lower level.

Figure 17. NASA EMC Reference Habitat Concept Views (4 Crew)

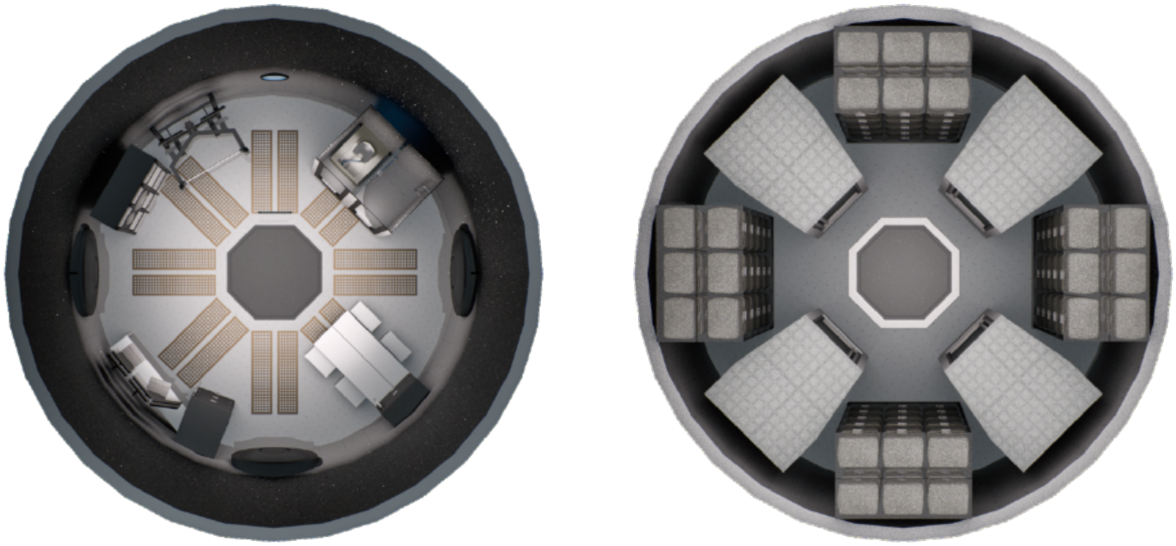


Figure 18. NASA EMC Reference Habitat Lower Level (left) and Upper Level (right) Overhead Views

The lower level is divided into four quadrants as shown in Figure 18. The upper left quadrant contains crew exercise equipment, medical equipment, and storage for medical supplies. The upper right quadrant contains the toilet, shower, and storage for crew hygiene supplies. The lower right quadrant is the galley, which includes food rehydration and warming stations, a foldable table and chairs for mealtimes, and storage for habitat cleaning supplies. The lower left quadrant is the command station with interfaces and displays for the onboard computer systems.

The upper level has four private crew quarters for sleeping and relaxation, one for each crewmember. The sleeping quarters are surrounded on all sides by ISS-style cargo transfer bags (CTBs) containing all of the life support system consumables: 1100 days of food; 30 days of emergency water, oxygen, and lithium hydroxide canisters; and contingency oxygen and nitrogen to re-pressurize the cabin in case of depressurization. Equipment spares are also carried in CTBs.

The radiation protection provided by the consumables allows the crew quarters to also serve as a storm shelter during SPEs. Crew total GCR exposure is also reduced because the crew spends 7-8 hours a day resting in the protected sleeping quarters.

The two levels are connected by a central hatch. Three of the four docking hatches are located in the lower level along the walls. The fourth docking hatch is location in the upper level in the center of the ceiling.

A full mass breakdown statement for the NASA EMC Reference Habitat is shown in Table 13.

Table 13. NASA EMC Reference Habitat Mass Breakdown Statement

Subsystem	Mass (kg)	Descriptions/Notes
Structures	7,361	Pressure vessel, windows, hatches, internal walls & floors
Docking & Launch Support	1,305	Docking and berthing mechanisms, launch support hardware
MMOD Protection	680	
Power Distribution	1,231	Batteries, power distribution units, switches, converters, harness
Electronics	450	Command and data handling, communications, crew displays and controls
Thermal Management	1,811	Internal and external active TCS fluid loops, radiators, MLI
Environmental Control	1,078	Atmosphere revitalization and oxygen generation
Crew Habitation & Support	2,284	Water processing system, food preparation, waste collection, exercise equipment, medical equipment, crew hygiene
EVA Support	1,134	Airlocks, suits, suit charging stations
Maintenance & Repair	393	Robotic support equipment and charging stations
Payload Provisions	3,251	Multipurpose workstation with payload manipulation and storage equipment
Empty Mass	20,978	
Habitat Outfitting	4,258	Crew mission kits and stowed items, habitat ECS consumables
Maintenance, Repair, & Spares	4,694	Equipment spares, tools
Payloads & Research	2,023	Scientific research experiments
Habitation Consumables	4,975	Water, oxygen, waste collection canisters, health care, hygiene
Food Consumables	8,524	Dehydrated food
Outfitting & Consumables	24,475	Pressure vessel, windows, hatches, internal walls & floors
Total	**45,452**	

7.2.2. Cost Assessment – Single Production Unit

For the NASA EMC Reference Habitat (with 4-Crew), the cost results shown in Table 14 reflect the cost of RDT&E, prototypes, and one production unit. This estimate does not reflect any margin or contractor fees, as this was calculated at the architecture-level.

Table 14. NASA EMC Reference Habitat Cost by Element

Work Element	Development ($M,FY2018)	Production – 1 Unit ($M,FY2018)	Total*** ($M,FY2018)
Body Structures	$ 1,304	$ 149	$ 1,453
Natural & Induced Environmental Protection	$ 29	$ 2	$ 31
Power Systems	$ 521	$ 133	$ 654
Command & Data Handling Systems	$ 84	$ 8	$ 92
Guidance, Navigation, & Control Systems	$ 26	$ 2	$ 28
Communications & Tracking Systems	$ 91	$ 37	$ 128
Crew Displays & Controls	$ 28	$ 5	$ 33
Environmental Control Systems	$ 319	$ 63	$ 381
Crew/Habitation Support Systems	$ 252	$ 46	$ 298
Extravehicular Activity Support Systems	$ 163	$ 22	$ 184
Maintenance & Repair Systems	$ 155	$ 26	$ 182
Connection & Separation Systems	$ 97	$ 15	$ 112
Launch Support Equipment	$ 36	$ 8	$ 44
System Integration, Test, & Evaluation	$ 901	$ 148	$ 1,049
Total*	**$ 4,004**	**$ 664**	**$ 4,668**

* Cost differences between sum of elements and total are due to rounding

** Margin and fee not included

7.2.3. Cost Assessment – Two Production Units

For the NASA EMC Reference Habitat, the incremental cost of producing a subsequent unit was examined and the results are provided in Table 15. The additional production unit is necessary to allow a mission using the NASA EMC design to accommodate eight (8) crew members vs. the nominal four. For this analysis, it was assumed these habitats would not be produced in a single batch, but rather in sequential order allow for learning to take place. These estimates include production learning curve effects ranging from 85% to 93% depending on the component type/application. This estimate does not reflect margin or contractor fees, as this was calculated at the architecture-level.

Table 15. Incremental Cost for Additional NASA EMC Reference Habitat

Work Element	First Unit ($M, FY2018)	Additional Unit ($M, FY2018)	Total for Two*** ($M, FY2018)
Body Structures	$ 149	$ 119	$ 268
Natural & Induced Environmental Protection	$ 2	$ 2	$ 4
Power Systems	$ 133	$ 108	$ 241
Command & Data Handling Systems	$ 8	$ 7	$ 15
Guidance, Navigation, & Control Systems	$ 2	$ 2	$ 4
Communications & Tracking Systems	$ 37	$ 33	$ 70
Crew Displays & Controls	$ 5	$ 4	$ 9
Environmental Control Systems	$ 63	$ 52	$ 115
Crew/Habitation Support Systems	$ 46	$ 43	$ 89
Extravehicular Activity Support Systems	$ 22	**$ 19**	**$ 51**
Maintenance & Repair Systems	$ 26	$ 23	$ 49
Connection & Separation Systems	$ 15	$ 12	$ 27
Launch Support Equipment	$ 8	$ 7	$ 15
System Integration, Test, & Evaluation	$ 148	$ 100	$ 248
Total*	**$ 664**	**$541**	**$1,205**

* Cost differences between sum of elements and total are due to rounding
** Margin and fee not included

7.3. NASA EMC Habitat Concept Using Torpor

7.3.1. Methodology

The motivation for this design effort was to characterize the impact of implementing torpor into an existing transit habitat design. In the creation of this habitat design, only those systems directly impacted by the inclusion of the torpor concept of operations and supporting subsystems were changed.

In this concept, the majority of the standard dehydrated space food is replaced with liquid enteral nutrition formula. The crew is also provided with two weeks of solid (normal) food stores for each period of transition into and out of torpor operations, or eight weeks' worth in total. The replacement of solid food with liquid nutrition formula yields significant reduction in total food mass because of the mass-efficiency of the formula relative to solid food. The quantity of housekeeping and other habitat consumables was also reduced to capture the impact of reduced crew activity on habitat outfitting requirements.

Because the crew spends the majority of the transit phase in torpor, the scientific payloads and payload provisions were removed. The on-duty crewmembers will spend the majority of their time tending to those crewmembers in torpor and maintaining spacecraft operations. Payload storage is still available for sample return to Earth.

7.3.2. Habitat Design

Summary metrics for the NASA EMC habitat using torpor are shown in Table 16, along with the reduction in value from the reference habitat.

Table 16. NASA EMC Habitat Using Torpor Summary Metrics

Metric	Value	Reduction	Percent Reduction
Empty Mass	17.0 t	4.0 t	19%
Loaded Mass	32.3 t	13.1 t	29%
Length	7.5 m	-	-
Diameter	7.2 m	-	-
Habitable Volume	100 m^3	-	-
Pressurized Volume	300 m^3	-	-
Power Required	20 kW	-	-

The geometry and configuration of the habitat are unchanged from the reference EMC habitat. It is assumed that the torpor support subsystems are integrated directly into the existing crew quarters.

A full mass breakdown statement for the EMC Reference Habitat is shown in Table 17, along with the reduction in mass from the reference habitat.

Table 17. NASA EMC Reference Habitat Mass Breakdown Statement

Subsystem	Mass (kg)	Reduction (kg)
Structures	7,361	0
Docking & Launch Support	1,181	124
MMOD Protection	680	0
Power Distribution	1,231	0
Electronics	450	0
Thermal Management	1,811	0
Environmental Control	1,078	0
Crew Habitation & Support	1,688	595
EVA Support	1,134	0
Maintenance & Repair	393	0
Payload Provisions	0	3,251
Empty Mass	17,008	3,970
Habitat Outfitting	4,102	156
Maintenance, Repair, & Spares	4,379	315
Payloads & Research	0	2,023
Habitation Consumables	3,114	1,861
Food Consumables	3,660	4,864
Outfitting & Consumables	15,255	9,219
Total	**32,263**	**13,189**

7.4. SpaceWorks Torpor-Enabled Habitat Designs

7.4.1. Methodology

The motivation for this design was to fully characterize the impact of implementing torpor in a new habitat design, primarily by taking advantage of the reduced consumables and supplies storage volume, and to reduce the quantity of equipment spares required based on lower ECLSS demands during torpor period.

As with the previous concept, the majority of the standard dehydrated space food is replaced with dehydrated enteral nutrition formula. The crew is provided with two weeks of solid food for each period of transition into and out of torpor operations, or eight weeks' worth in total. As before, the replacement of solid food with nutrition formula yields significant reduction in total food mass because of the mass-efficiency of the formula relative to solid food. Compared to the reference habitat, the quantity of housekeeping and other habitat consumables was also reduced to capture the impact of reduced crew activity on habitat outfitting requirements. This reduced food and consumables mass translates to reduced consumables volume.

Similarly, because the crew spends the majority of the transit phase in torpor, the scientific payloads and payload provisions are not included. The on-duty crewmembers will spend the majority of their time tending to those crewmembers in torpor and maintaining spacecraft operations. Payload storage is still available for sample return to Earth.

A new habitat layout was conceived to take full advantage of the reduced consumables and supplies volumes. It was decided that, because only one crewmember is active for the majority of the mission, the habitable volume per crewmember can be reduced below 25 m^3. This allowed for a significant reduction in overall habitat size. Subsystems, equipment, and accommodations were repackaged into the smaller volume. This allowed the pressure vessel, structures, and MMOD protection masses to be reduced based on the smaller habitat geometry.

The reduced habitable volume can also be propagated into the sizing of the ECLSS systems. With smaller ECLSS systems, the power requirements of the habitat are also reduced, thus reducing the mass of the power distribution and thermal management systems.

7.4.2. Habitat Design

Summary metrics for the SpaceWorks torpor-enabled habitat are shown in Table 18, along with the reduction in value from the NASA EMC Reference habitat.

Table 18. SpaceWorks Torpor-Enabled Habitat Summary Metrics

Metric	Value	Reduction	Percent Reduction
Empty Mass	12.5 t	8.5 t	40%
Loaded Mass	25.5 t	20.0 t	44%
Length	6.5 m	1.0 m	13%
Diameter	6.0 m	1.2 m	16%
Habitable Volume	50 m^3	50 m^3	50%
Pressurized Volume	180 m^3	120 m^3	40%
Power Required	15 kW	5 kW	25%

The SpaceWorks torpor-enabled habitat geometry is shown in Figure 19 and Figure 20. Similar to the EMC Reference design, the habitat is divided into two levels. The lower level serves as the crew living area and workspace. The upper level houses consumables and spares, as well as crew torpor modules. Life support subsystems are housed in the deck beneath the lower level.

The lower level is divided into five areas as shown in Figure 20. The top area contains storage for medical supplies and habitat cleaning supplies. The upper left area is the command station with interfaces and displays for the onboard computer systems. The upper right area contains crew exercise equipment and medical equipment. The lower left area contains the shower and hygiene station. The lower right area contains the toilet and storage for crew hygiene supplies. The bottom area is the galley, which includes food rehydration and warming stations, and a foldable table and chairs for mealtimes.

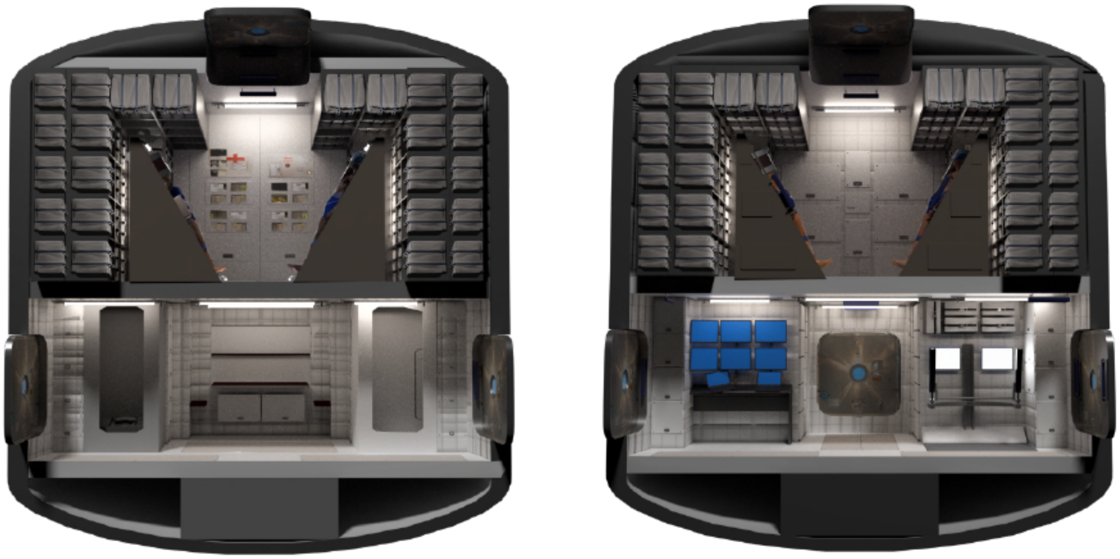


Figure 19. SpaceWorks Torpor Habitat Concept Views (4 Crew)

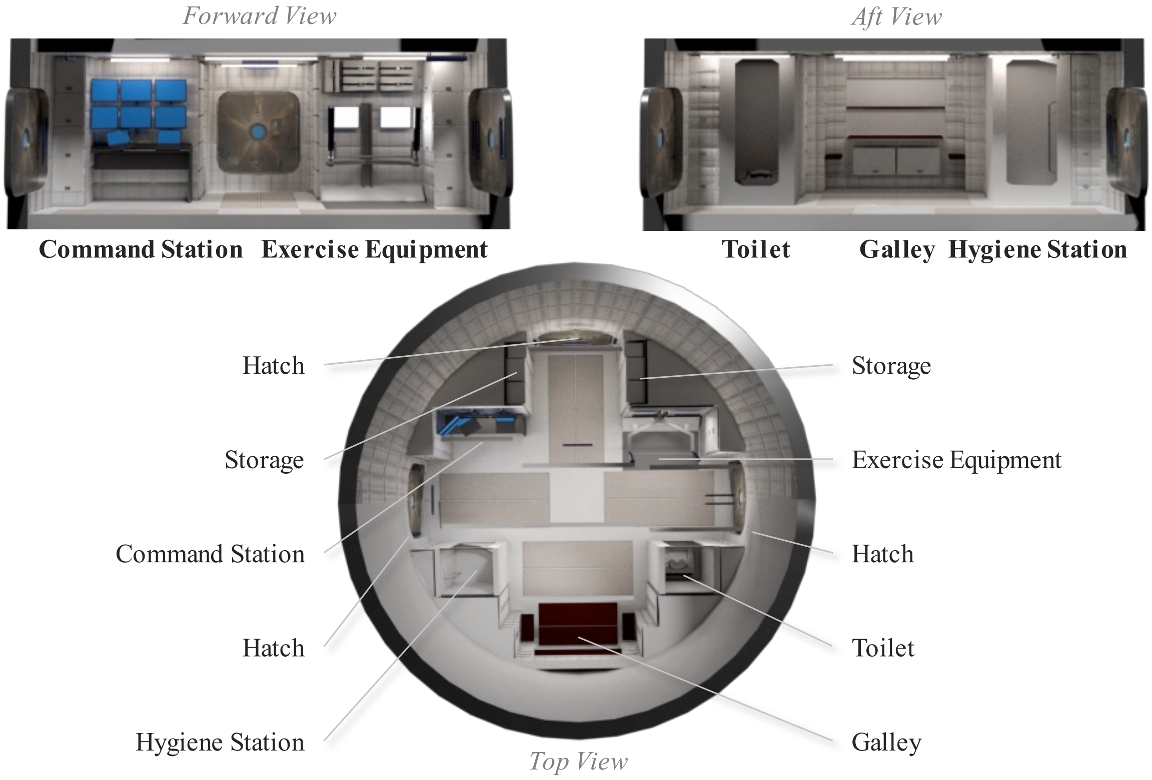


Figure 20. SpaceWorks Torpor Habitat Concept Lower Level Design (4 Crew)

The upper level, as shown in Figure 21, has four torpor modules containing all of the torpor support subsystems, one for each crewmember. The torpor modules are surrounded on all sides by ISS-style cargo transfer bags (CTBs) containing all of the life support system consumables: 60 days of food and 1100 days of enteral nutrition; 30 days of emergency water, oxygen, and lithium hydroxide canisters; and contingency oxygen and nitrogen to re-pressurize the cabin in case of depressurization. Equipment spares are also carried in CTBs.

The radiation protection provided by the consumables allows this area to also serve as a storm shelter during SPEs. Crew total GCR exposure is significantly reduced because the crew spends the majority of the mission in torpor within this protected area.

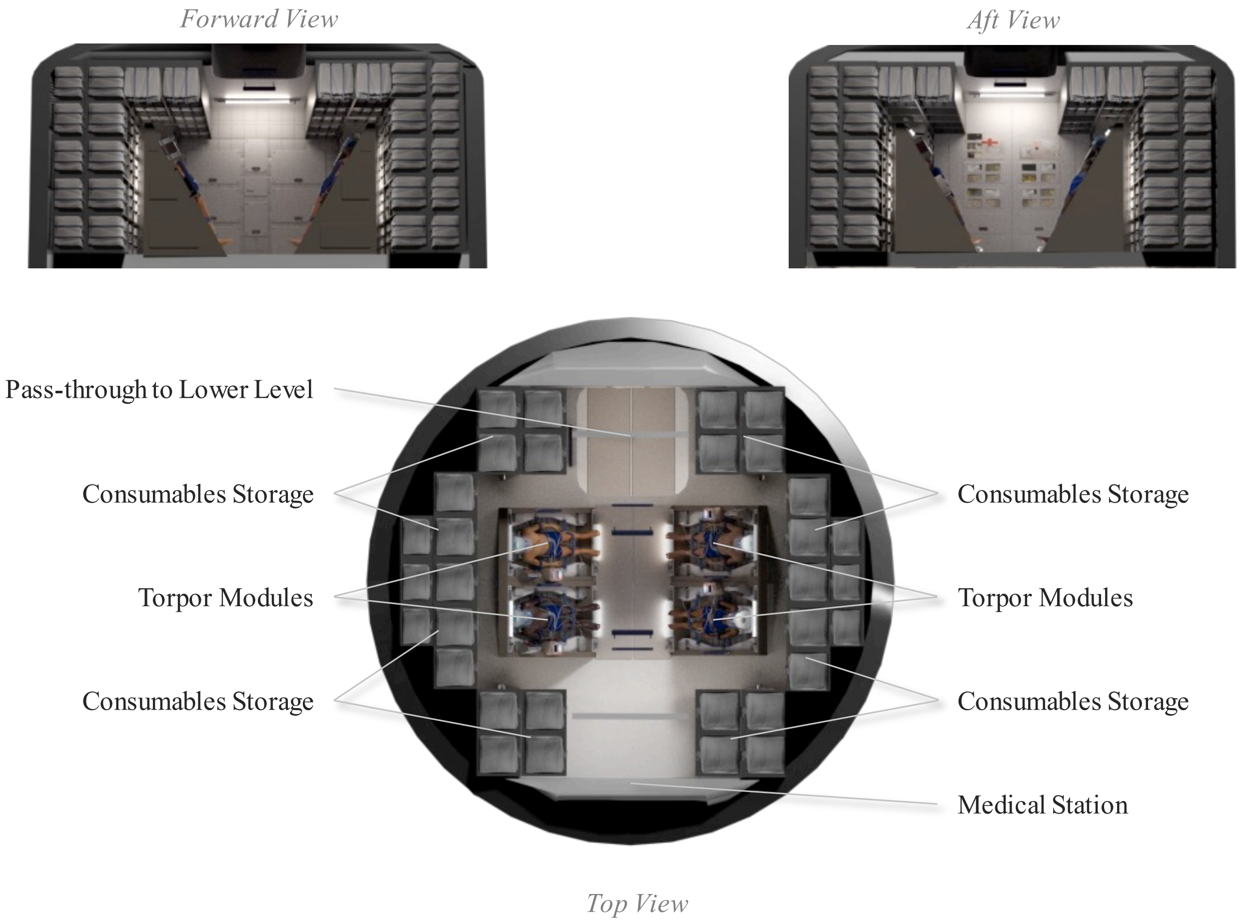


Figure 21. SpaceWorks Torpor Habitat Concept Upper Level Design (4 Crew)

The two levels are connected by a central hatch. Three of the four docking hatches are located in the lower level along the walls. The fourth docking hatch is location in the upper level in the center of the ceiling.

A full mass breakdown statement for the SpaceWorks torpor-enabled habitat is shown in Table 19, along with the reduction in mass from the reference habitat.

Table 19. SpaceWorks Torpor-Enabled Habitat Mass Breakdown Statement

Subsystem	Mass (kg)	Reduction (kg)	Description/Notes
Structures	4,101	3,260	Pressure vessel, windows, hatches, internal walls & floors
Docking & Launch Support	1,040	264	Docking and berthing mechanisms, launch support hardware
MMOD Protection	474	206	
Power Distribution	923	308	Batteries, power distribution units, switches, converters, harness
Electronics	450	-	Command and data handling, communications, crew displays and controls
Thermal Management	1,459	352	Internal and external active TCS fluid loops, radiators, MLI
Environmental Control	896	182	Atmosphere revitalization and oxygen generation
Crew Habitation & Support	1,650	633	Torpor support subsystems, water processing system, food preparation, waste collection, exercise equipment, medical equipment, crew hygiene
EVA Support	1,134	-	Airlocks, suits, suit charging stations
Maintenance & Repair	393	-	Robotic support equipment and charging stations
Payload Provisions	-	3,251	
Empty Mass	12,522	8,455	
Habitat Outfitting	3,872	386	Crew mission kits and stowed items, habitat ECS consumables
Maintenance, Repair, & Spares	2,386	2,308	Equipment spares, tools
Payloads & Research	-	2,023	
Habitation Consumables	3,114	1,861	Water, oxygen, waste collection canisters, health care, hygiene
Food Consumables	3,660	4,864	Dehydrated food and enteral nutrition formula
Outfitting & Consumables	13,033	11,442	
Total	**25,555**	**19,897**	

A graphic showing the mass reduction in the SpaceWorks torpor-enabled habitat compared to the NASA EMC reference habitat is shown in Figure 22.

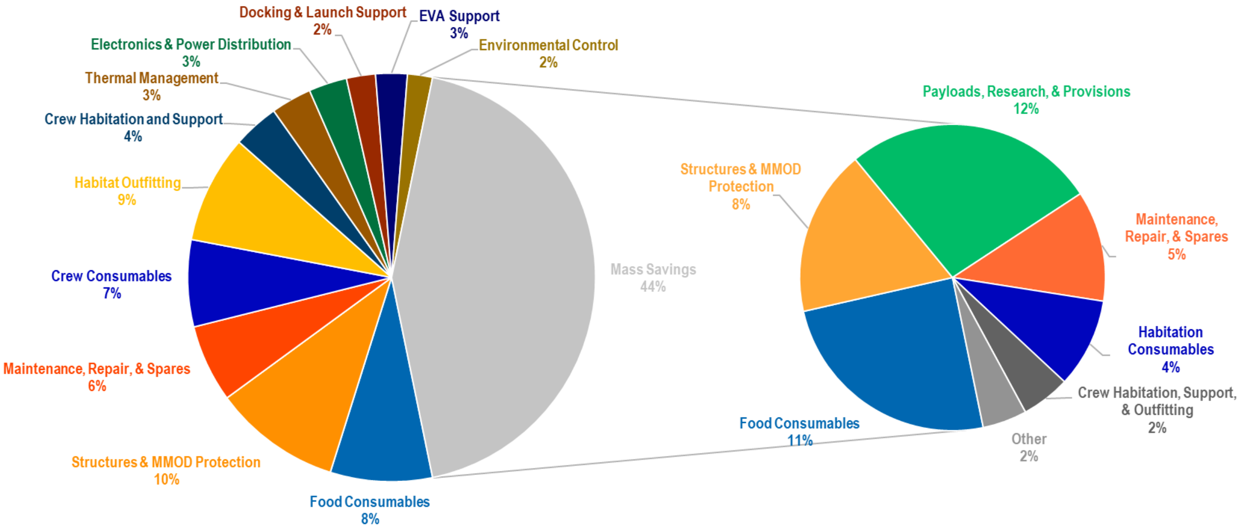


Figure 22. SpaceWorks Torpor Habitat Mass Savings and Subsystem Impact Distribution

7.4.3. Cost Assessment – Single Production Unit

For the SpaceWorks Torpor Habitat (4-Crew System), the cost results in Table 20 reflect the cost of RDT&E, prototypes, and one production unit. This estimate does not reflect margin or contractor fees, as this was calculated at the architecture-level.

Table 20. SpaceWorks Torpor Habitat Cost By Element (4 Crew)

Work Element	Development ($M, FY2018)	Production -1 Unit ($M, FY2018)	Total*** ($M, FY2018)
Body Structures	$ 800	$ 88	$ 888
Natural & Induced Environmental Protection	$ 21	$ 2	$ 23
Power Systems	$ 379	$ 95	$ 474
Command & Data Handling Systems	$ 84	$ 8	$ 92
Guidance, Navigation, & Control Systems	$ 26	$ 2	$ 28
Communications & Tracking Systems	$ 91	$ 37	$ 128
Crew Displays & Controls	$ 28	$ 5	$ 33
Environmental Control Systems	$ 288	$ 57	$ 345
Crew/Habitation Support Systems	$ 185	$ 28	$ 212
Extravehicular Activity Support Systems	$ 163	$ 22	$ 185
Maintenance & Repair Systems	$ 153	$ 26	$ 179
Connection & Separation Systems	$ 97	$ 15	$ 112
Launch Support Equipment	$ 23	$ 5	$ 28
System Integration, Test, & Evaluation	$ 629	$ 120	$ 749
Total*	**$ 2,965**	**$ 511**	**$ 3,476**

* Cost differences between sum of elements and total are due to rounding, ** Margin and fee not included

7.4.4. Cost Assessment – Two Production Units

The cost of producing an additional torpor habitat was examined and the results are provided in Table 21. The additional production unit is necessary to allow a mission architecture that can accommodate eight crew members vs. the nominal four. For this analysis it was assumed these habitats would not be produced in a single batch, but rather in sequential order allow for learning to take place. These estimates include production learning curve effects ranging from 85% to 93% depending on the component type/application. This estimate does not reflect margin or contractor fee, as this was calculated at the architecture-level.

Table 21. Incremental Cost for Additional SpaceWorks Torpor Habitat

Work Element	First Unit ($M, FY2018)	Additional Unit ($M, FY2018)	Total for Two ($M,FY2018)**
Body Structures	$ 88	$ 71	$ 159
Natural & Induced Environmental Protection	$ 2	$ 1	$ 3
Power Systems	$ 95	$ 78	$ 173
Command & Data Handling Systems	$ 8	$ 7	$ 15
Guidance, Navigation, & Control Systems	$ 2	$ 2	$ 4
Communications & Tracking Systems	$ 37	$ 33	$ 70
Crew Displays & Controls	$ 5	$ 4	$ 9
Environmental Control Systems	$ 57	$ 48	$ 105
Crew/Habitation Support Systems	$ 28	$ 26	$ 54
Extravehicular Activity Support Systems	$ 22	$ 20	$ 41
Maintenance & Repair Systems	$ 26	$ 22	$ 48
Connection & Separation Systems	$ 15	$ 12	$ 27
Launch Support Equipment	$ 5	$ 4	$ 9
System Integration, Test, & Evaluation	$ 120	$ 81	$ 201
Total*	**$ 511**	**$ 409**	**$ 918**

* Cost differences between sum of elements and total are due to rounding, ** Margin and fee not included

7.5. Cost Comparisons for System Designs

The cost savings for the SpaceWorks Torpor Habitat are primarily driven by eight individual WBS items. The areas of greatest impact are provided in Table 22.

Table 22. Torpor Habitat Primary Cost Saving Drivers

Work Element	EMC Reference Habitat Total Cost*** ($M, FY2018)	Torpor Habitat Total Cost*** ($M, FY2018)	Cost Delta
Body Structures	$ 1,453	$ 888	- 39%
Natural & Induced Environmental Protection	$ 31	$ 23	- 27%
Power Systems	$ 654	$ 474	- 28%
Crew/Habitation Support Systems	$ 298	$ 212	- 29%
Launch Support Equipment	$ 44	$ 28	- 37%
System Integration, Test, & Evaluation	$ 1,049	$ 749	- 29%

* Cost differences between sum of elements and total are due to rounding
** Margin and fee not included

The over dollar-figure difference between the two systems is estimated to be approximately $1.2B, representing an approximately 26% cost reduction when using the SpaceWorks Torpor Habitat (4-Crew System) vs. the EMC Reference Habitat (4-Crew System).

7.6. Alternate Eight-Crew Torpor Habitat System Design

7.6.1. Methodology

The motivation for this design study was create an alternate torpor-enabled habitat design to support a crew of 8 rather than a crew of 4 (or 8 via 2 identical habitats). For a crewed surface mission to Mars, a larger crew complement is desired compared to precursor Mars-vicinity missions. This design leverages the design elements of the 4-crew torpor-enabled design, with necessary changes made in habitable volume, subsystems design, and consumables quantity to support the increased crew size. In this concept of operations, there will be two crew members on duty at all times, with the remainder of the crew being in torpor. It would be possible to alter the 4-crew member schedule such that there is still only 1 active crew member at any time, leaving 7 in the torpor state. However, while this would increase the overall effectiveness of torpor (higher inactive/active ratio), it would also increase the workload and burden on the active crew member.

As with the 4-person concept, the majority of food consumables is provided as liquid enteral nutrition formula. The crew is provided with two weeks of solid food for each period of transition into and out of torpor operations, or sixteen weeks' worth in total. The quantity of housekeeping and other habitat consumables is also doubled.

A new habitat layout was conceived provided sufficient habitable and total volume for the increased crew size. Subsystems, equipment, and accommodations were repackaged into the new volume. The pressure vessel, structures, and MMOD protection masses were recalculated based on the new habitat geometry.

The increased number of crew has a significant impact on the sizing of the ECLSS systems. With larger ECLSS systems, the power requirements of the habitat are also increased, thus increasing the mass of the power distribution and thermal management systems.

7.6.2. Habitat Design

Summary metrics for the SpaceWorks 8-crew torpor-enabled habitat are shown in Table 23, along with comparative specifications from the 4-crew torpor habitat design. As anticipated, there is a design efficiency in that doubling the crew size does not double the habitat mass. The diameter of the habitat is still below the target limit established for incorporation within the smaller 8.4 meter diameter SLS payload fairing.

Table 23. SpaceWorks Torpor-Enabled Habitat 8-Crew vs 4-Crew Summary Metrics

Metric	8-Crew Design	4-Crew Design
Empty Mass	19.5 t	12.5 t
Loaded Mass	42.3 t	25.5 t
Length	8.75 m	6.50 m
Diameter	7.25 m	6.00 m
Habitable Volume	100 m^3	50 m^3
Pressurized Volume	360 m^3	180 m^3
Power Required	30 kW	15 kW

The SpaceWorks torpor-enabled habitat geometry is shown in Figure 23. The habitat is divided into three levels. The upper level houses consumables and spares, as well as crew torpor modules. The middle level serves as the primary crew living area and workspace. The lower level houses the hygiene areas and life support subsystems.

Figure 23. Alternate SpaceWorks Torpor Habitat Concept Views (8 Crew)

The mid-level deck is divided into three areas. The first area is the galley, which includes food rehydration and warming stations, and a foldable table and chairs for mealtimes. The second area contains crew exercise equipment and medical equipment. The third area is the command station with interfaces and displays for the onboard computer systems.

The lower level contains two hygiene stations, two toilets, and storage for housekeeping supplies. It also contains the majority of the habitat life support systems.

The upper level has four torpor modules containing all of the torpor support subsystems, one for each crewmember. The torpor modules are surrounded on all sides by ISS-style cargo transfer bags (CTBs) containing all of the life support system consumables: 60 days of food and 1100 days of enteral nutrition; 30 days of emergency water, oxygen, and lithium hydroxide canisters; and contingency oxygen and nitrogen to re-pressurize the cabin in case of depressurization. Equipment spares are also carried in CTBs.

The radiation protection provided by the consumables allows this area to also serve as a storm shelter during SPEs. Crew total GCR exposure is significantly reduced because the crew spends the majority of the mission in torpor within this protected area.

The three levels are connected by a central hatch. Three of the four docking hatches are located in the middle level along the walls. The fourth docking hatch is location in the upper level in the center of the ceiling.

A full mass breakdown statement for the SpaceWorks 8-crew torpor-enabled habitat is shown in Table 24, compared against the mass of the 4-crew habitat design.

Table 24. SpaceWorks 8-Crew vs 4-Crew Torpor-Enabled Habitat Mass Breakdown Statement

Subsystem	8-crew Design (kg)	4-crew Design (kg)
Structures	6,683	4,101
Docking & Launch Support	1,258	1,040
MMOD Protection	760	474
Power Distribution	1,846	923
Electronics	526	450
Thermal Management	2,514	1,459
Environmental Control	1,798	896
Crew Habitation & Support	2,586	1,650
EVA Support	1,134	1,134
Maintenance & Repair	393	393
Payload Provisions	0	-
Empty Mass	19,500	12,522
Habitat Outfitting	5,867	3,872
Maintenance, Repair, & Spares	3,416	2,386
Payloads & Research	0	-
Habitation Consumables	6,153	3,114
Food Consumables	7,320	3,660
Outfitting & Consumables	22,757	13,033
Total	**42,257**	**25,555**

7.7. Cost Comparisons for 8-Crew Torpor Habitat System Design

It is worth examining and comparing the cost results of developing a single 8-crew habitat design compared to producing two smaller 4-crew habitats. The RDT&E and production costs estimates indicated a total cost of ~\$3B when using 2 smaller habitats of ~\$4B for a single, larger habitat. The smaller habitat designs benefits from a lower initial development cost and learning rate improvements for the 2nd habitat. The ECLSS experienced the largest cost increase due to the complexity of this system and increased size. Not that while the 2-habitat option benefits on the basis of cost, its mass is ~20% larger than the single 8-crew habitat design. This will result in larger propulsion stages for the 2-habitat solution that may ultimately offset the initial cost savings that were obtained for the habitats alone.

Table 25. SpaceWorks Torpor Habitats Cost Comparison

Work Element	2x4-Crew Torpor Habitat Total Cost ** ($M, FY2018)	8-Crew Torpor Habitat ** Total Cost ($M, FY2018)	Cost Difference
Body Structures	$ 959	$ 1,328	38%
Natural & Induced Environmental Protection	$ 24	$ 34	42%
Power Systems	$ 553	$ 659	19%
Environmental Control Systems	$ 394	$ 628	60%
Crew/Habitation Support Systems	$ 238	$ 313	31%
Launch Support Equipment	$ 32	$ 41	28%
System Integration, Test, & Evaluation	$ 831	$ 1,025	23%
Total*	**$ 3,031**	**$ 4,029**	**$ 998**

* Cost differences between sum of elements and total are due to rounding, ** Margin and fee not included

8. Mars Exploration Mission Analysis

8.1. Introduction

As indicated in the previous sections and analysis results, incorporating torpor into the in-space transportation system will significantly reduce the mass of the crew habitat and provide both physical and psychological benefits to the crew. These benefits directly impact the full Mars Mission architecture by reducing propulsive stage mass and quantity, reducing the number of SLS launches required, and by providing health benefits to the crew such as reduced radiation damage (potentially) and psychological strain. The following sections outline a series of architecture trades that quantify the mission-level improvements enabled by the torpor concept.

8.2. NASA EMC Mars Architecture Overview

8.2.1. Overview

During the Phase I Effort, SpaceWorks selected the NASA DRM 5.0 (circa. 2009) mission and architecture as a point of departure [1]. Since that time, NASA has invested significant effort into a new series of Mars mission studies referred to collectively as the Evolvable Mars Campaign (EMC). This collection of architecture and technology studies is intended to guide the agency’s efforts to sustainably extend human presence from Low-Earth Orbit (LEO) into deep space.

There are several important distinctions between the various EMC scenarios and the older DRM 5.0 architecture. First, the EMC scenarios lay out a campaign of several missions that leverage existing investments to progressively prove-out systems and reduce the effective overhead for each individual mission. Next, the EMC incorporates proposals from private industry to supplement government assets. Finally, the EMC assumes the operation of a 'lunar gateway' which will serve as the primary base of operations for aggregation of mission assets, on-orbit assembly, and system checkout. To appropriately capture these ambitious capabilities and trade-offs, the authors have selected the EMC's "Mars vicinity and Phobos followed by mission to Mars' surface" scenario as the baseline architecture for performing architecture-level assessments. Specific architecture details and requirements for this scenario are described in the next section.

8.2.2. The “EMC Baseline” Mission Architecture

SpaceWorks selected a specific subset of the various NASA-published EMC studies to use a reference point of departure for use in specific architecture performance comparisons. For the purposes of this study, the EMC Baseline refers to a campaign that includes a single manned mission to Phobos in 2033, followed by two subsequent missions to the surface of Mars in 2039 and 2043. All missions are supported by robotic precursor and supply missions and assume the reuse of a single habitat module and several re-used propulsive stages. In this architecture, robotic missions use high efficiency Solar Electric Propulsion (SEP) for minimum launch cost while manned missions used advanced Methane Cryogenic Propulsive Stages (MCPS) to minimize time of flight and radiation exposure. EMC studies and reports from 2016-2017 form the baseline point of departure from which to evaluate the torpor crew transport vehicle. References [196] and [197] are the primary sources of all EMC baseline design parameters and reference values.

The EMC Baseline Architecture makes the following assumptions:

- Humans will travel to the Mars System by mid-2030s.
- The International Space Station (ISS) will operate through at least 2024 – until a regular cadence of Space Launch System (SLS)/Orion missions to cis-lunar space is established. The Mars-class life support and related habitation systems will be tested first on ISS.
- The SLS Block 2 launch vehicle will be available (4 x RS-25 engines on Core + Exploration Upper Stage (EUS) + Evolved Boosters + 8.4 m or 10 m fairing) for Mars missions.
- The Orion spacecraft will be available.

- The SLS/Orion launch rate of one per year is sustainable in the Proving Ground Phase 1 and will increase to one cargo and one crew launch per year in preparation for the Mars mission system validation.
- In-space propulsion technology will utilize solar electric propulsion systems; augmented with chemical systems when necessary to reduce trip times.
- Mars vehicle checkout and aggregation will be conducted in cis-lunar space to leverage infrastructure established during Proving Ground missions in the 2020s.
- Crew vehicle and transportation systems will be reused for sustainability and potential cost advantages when reasonable.

8.2.3. Baseline Concept of Operations

Each of the three missions will have unique profiles and trajectories, but the overall concept of operations for each mission, shown for the Phobos mission in Figure 24, remains very similar. The overall in-space crew transportation architecture is designed to be the same for each of the three missions in order to reduce risk and development costs.

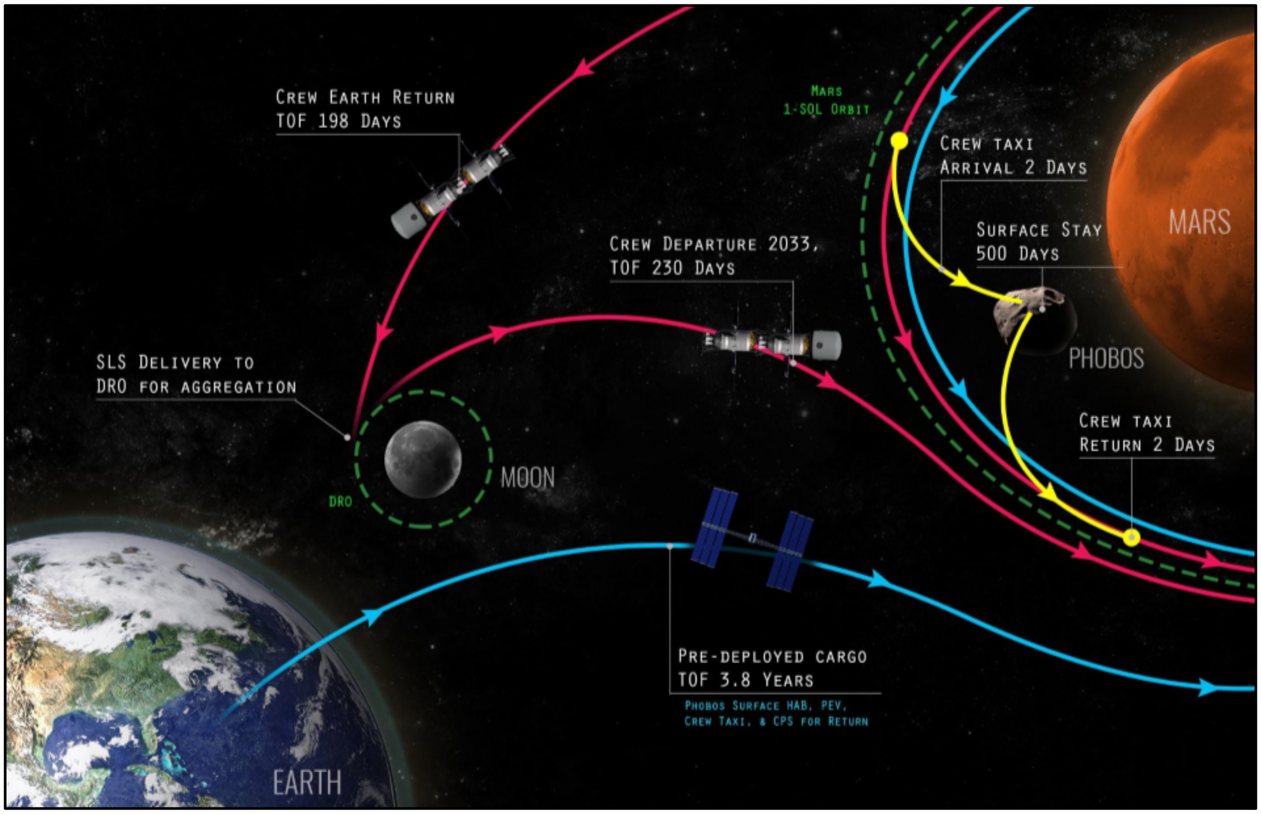


Figure 24. Representative Mars Campaign Mission CONOPS for Phobos Mission

During pre-supply transit, the Crew Transportation Vehicle (CTV) goes through assembly and checkout in a Distant Lunar Retrograde Orbit (DLRO) near a future Deep Space Gateway (DSG). Following successful pre-deployment and CTV checkout, the crew launches on a dedicated launch vehicle to a lunar-distance, highly elliptical orbit (LDHEO) to rendezvous with the CTV. After successful rendezvous, the CTV performs a Trans-Mars Injection (TMI) maneuver and departs for Mars. Using chemical propulsion, the total mission time from TMI to Earth Orbit Injection (EOI) is approximately 1100 days for each of the three crewed mission opportunities in 2033, 2039 and 2043. This cadence allows for alternating crew and pre-supply mission departures. According to reference [197], the total change in velocity (ΔV) for each individual mission ranges from 2,800 m/s to 3,400 m/s.

Upon arrival at Mars, the CTV performs a Mars Orbit Injection (MOI) burn to enter a 1-Sol parking orbit at Mars. Next, depending on the mission, the crew descends to the surface of either Phobos or Mars to rendezvous with predeployed assets and being their surface mission phase. Upon completing their mission, the crew returns to the CTV and departs for Earth via a Trans-Earth Injection (TMI) burn. Finally, the CTV arrives in Earth's vicinity and performs the EOI burn to capture back into LDHEO where astronauts transfer to a reentry vehicle and return home to Earth. Both the EOI propulsive stage and the crew habitat return to LDRO for inspection and reuse.

8.2.1.Reference Crew Habitat Design

See Section 7.2.1 for a full description of the crew habitat design for the EMC Baseline architecture.

8.2.2. Reference Crew Transport Propulsive Stage

As detailed in reference [198], the selected EMC architecture assumes a modular crew transit system (CTS) to maximize 'reuse of elements and commonly applied technologies'. Each CTS 'stack' consists of the crew habitat, two propulsive stages, integration structure, and large solar arrays for power generation. Using a modular stack allows for the effective payload mass at each propulsive maneuver to minimized, while still enabling reuse of both the habitat and some of the propulsive stage elements.

NASA has investigated several different primary propulsion systems under the auspices of the EMC study including high-power Solar Electric Propulsion (SEP), Nuclear Thermal Propulsion (NTP), and a Methane Cryogenic Propulsion Stage (MCPS). As note previously, a liquid oxygen - liquid methane propulsion is viewed as a key, enabling technology because it is compatible with future envisioned in-situ propellant production capabilities, and because it can be leveraged for multiple vehicles including the Mars Descent Vehicle (MDV), the Mars Ascent Vehicle (MAV), and the CTS. Due to low TRL and the inability to share propulsive elements with both the MDV and MAV, the NTP option was not considered for the present study. SpaceWorks ultimately selected the MCPS option for use in crew transportation architecture sizing because it enables high-thrust, interplanetary trajectories that significantly reduce the in-space travel time and radiation exposure levels for the crew (compared to the low-thrust SEP variant).

The baseline MCPS is a self-contained propulsive stage with independent propellant storage, power generation and management, communications, reaction control thrusters, and main propulsion. Figure 25 provides a notional image of the MCPS.

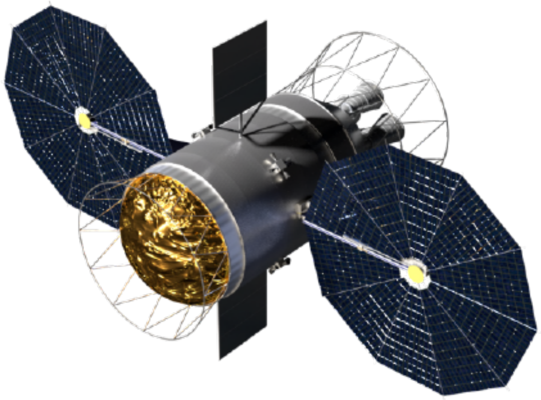


Figure 25. Notional MCPS Propulsive Stage

The baseline MCPS is designed for modularity and resiliency under several driving requirements. First, the MCPS is designed for production in quantity. Sharing the propulsive stage design over multiple missions reduces the total number of propulsion system design programs and leads to reduced program cost and risk. To further embrace these optimizations, a single, modular engine design is used to power all EMC propulsive stages including the interplanetary CTV, the MDV and the MAV. The baseline MCPS is assumed to contain three of these modular engines with a thrust level of 22,500-lbf each. For propellant, this main propulsive system relies on two in-line, aluminum tanks with a diameter of 4 meters.

Each MCPS must support independent, and in some cases autonomous operation, to enable remote rendezvous and docking maneuvers. As a result, the MCPS is a fully self-contained unit with power, thermal, communications, and attitude control systems. The baseline point of departure design for the MCPS requires 4.4kW at peak load and draws this power from a pair of deployed ATK Ultraflex solar arrays. Each array has a diameter of 4.4 meters and a mass of 46.8 kg. General thermal control is accomplished using an ammonia coolant loop with deployable radiators. Cryogenic propellant thermal management is accomplished by a single 90k reverse turbo-Brayton cryocooler. The reference mass of the MCPS is 45,320-kg [197] .

8.3. Parametric Mission Design Approach

To ensure appropriate comparisons, SpaceWorks sized each baseline mission and torpor analog using the same assumptions, constraints, and system closure model. As detailed in Section 6.1, all domain-level analysis tools were integrated into the IDF to enable rapid design optimizations and trade studies. SpaceWorks used the IDF to evaluate hundreds of thousands of design variants for each mission type. This optimization was accomplished by using the IDF to run a full-factorial design of experiments with the parameters given in Table 26. Note that the values chosen for this effort (and variables of interest) could easily be further expanded - at the expense of increased analysis time. Additionally, the time of flight and propulsive ΔV estimates that were generated for each architecture is held constant across all variants for the full factorial assessment.

Table 26. Phobos Mission DOE Parameters

Parameter	Values	Units
Outbound Stage Count	1, 2, 3	#
Return Stage Count	1, 2, 3	#
Engine Design Thrust	20.0, 22,5, 25.0	Klbf
MCPS Stage Diameter	9.0, 10.0, 11.0, 12.0, or 13.0	feet
Outbound Stage #1 Engine Count	1, 2, 3, or 4	#
Outbound Stage #2 Engine Count	1, 2, 3, or 4	#
Return Stage #1 Engine Count	1, 2, 3, or 4	#
Return Stage #2 Engine Count	1, 2, 3, or 4	#

This design space exploration process was used to determine a minimum mass architecture designs for each of the study cases, subject to launch mass and initial thrust-to-weight constraints. Figure 26 captures the results of this process by plotting the total mass of the return CTS stack versus the total mass of the outbound CTS stack. Design points generally segmented themselves into groups for each combination of outbound and return stage count. Results for lower stage counts (i.e. 1 out, 1 return) coalesced in the bottom left while higher stage counts (i.e. 3 out, 3 return) were represented in the upper right corner. The *total mission mass* color scale and primary metric of interest for each variant is the sum of the respective crew habitat, outbound propulsive stages, and return propulsive stages.

Two primary constraints impacted the number of feasible cases considerably. First, the total launch mass of an individual stage is limited to 45 metric tons to ensure that it can be launched to DLRO by an SLS Block 2 vehicle. Second, the initial thrust-to-weight for each propulsive stack is required to be at least 0.3 to maintain the ‘near instantaneous ΔV assumption’ required for the trajectory model. For cases were the specified constraints are not met or violated, the architecture becomes denoted in gray. Note that while these values represent the nominal constraints, alternative relaxed constraints are discussed in later sections.

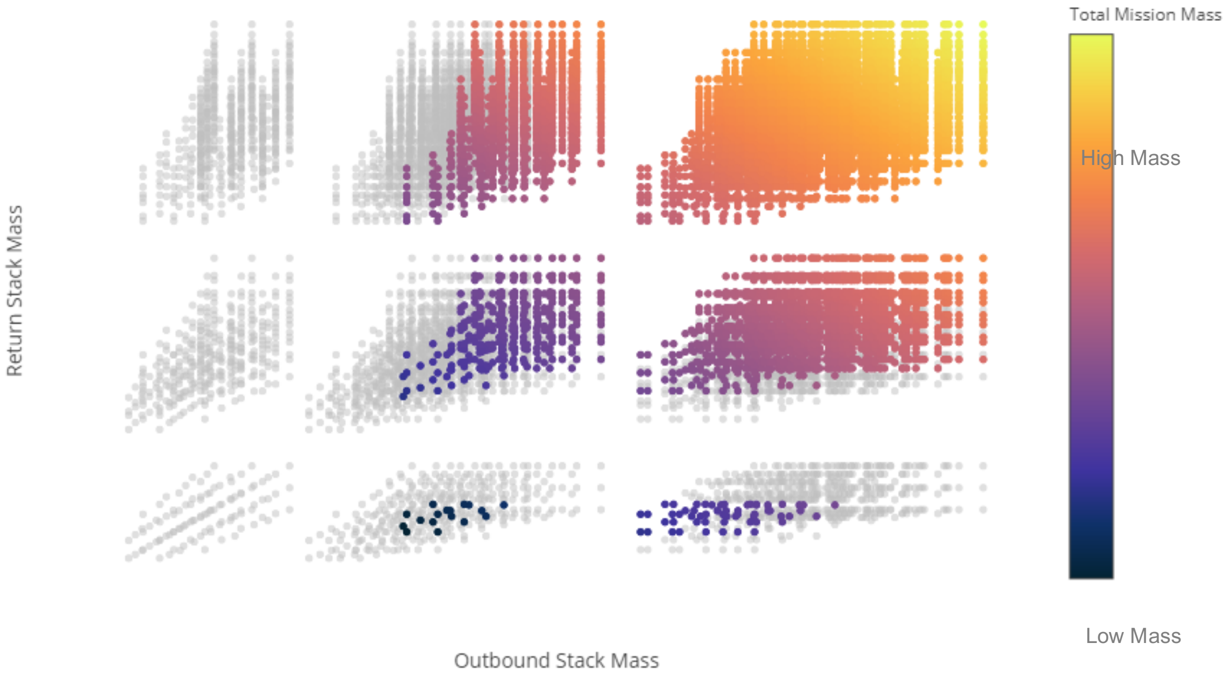


Figure 26. Mission Mass Results using NASA EMC Habitat for 4-Crew Mission to Phobos (40,000 Cases)

In all evaluated cases, the minimum total mass case corresponded to the case with the fewest total number of propulsive stages, engines, and the lowest total thrust that still met all constraints.

8.4. Mars Phobos-Deimos Missions with Torpor and 4-Crew Members

8.4.1. Re-Optimized Reference Mission Design

Campaign Mission #1 of the EMC Baseline is a manned expedition to Mars' orbit and the surface of Phobos with four crew members. The reference mission departs for Mars in 2033 and returns in 2035 with an outbound time of flight of 230 days and a return time of flight of 198 days.

To ensure a consistent comparison, SpaceWorks re-sized the reference mission to minimize the total mission mass and the total number of propulsive stages. First, SpaceWorks re-optimized the outbound and return trajectories to minimize mission total C3. These trajectories assume a total of four, approximately 300-second duration burns with one each at TMI, MOI, TEI, and EOI. The parking orbits at Earth and Mars are described in Table 27. In the reference mission, the crew departs from High-Earth Orbit (HEO), travels to a '1-sol parking orbit' at Mars, then returns to HEO. Specific periapsis and apoapsis altitudes are derived from the NASA DRM 5.0 report.

Table 27. Assumed Terminal Orbits for Transfers Between Earth and Mars

Orbit	Periapsis Altitude (km)	Apoapsis Altitude (km)
HEO	400.0	326,400
Mars 1-Sol	250.0	33,793

The trajectories were optimized via a full-factorial search for all dates in the year 2033 and for time of flights ranging from 150 to 275 days. The new optimized trajectories for the 2033 opportunity are described in Table 28.

Table 28. Minimum C3 Trajectories for 2033 Mission to Mars Orbit

Parameter	Outbound Trajectory	Return Trajectory
Departure Date	4/16/2033	5/6/2035
Arrival Date	11/2/2033	11/22/2035
ΔV1 (km/s)	0.53	1.06
ΔV2 (km/s)	1.25	0.53
Time of Flight (days)	200	200
Total C3 (km^2/s^2)	20.078	17.947

Using these new optimal trajectories, SpaceWorks used the IDF in concert with the design space exploration process described in Section 8.3 to establish a new 'Reference Optimized' architecture. The new propulsive stage designs are described in Table 29. This architecture analysis, conducted using SpaceWorks methods and analysis tools, will provide a fairer point of comparison when weighing against torpor-enabled architectures. Note that the search yielded a solution with one fewer propulsive stage by sizing the return propulsive stage to accomplish both the TEI and EOI burns. The re-optimized EMC mission for a crew of four departing in 2033 has a total crew transportation mass of 145.7t. All stages utilize a combination of common LOX/CH4 engines, each with a vacuum thrust of 20,000-lbf.

Table 29. Mass-Optimized EMC Baseline Mission with 4-Crew Departing in 2033

Parameter	Outbound Trajectory		Return Trajectory
Propulsive State Burns	*MOI*	*TMI*	*TEI-EOI*
Inert Mass (t)	7.13	7.27	8.44
Usable Propellants (t)	24.16	18.01	35.41
Payload(s) (t)	45.27	MOI Stage	43.72
Gross Weight (t)	76.57	101.85	87.57
Stage Length (feet)	33.4	29.7	40.4
Stage Diameter (feet)	10.0	10.0	10.0
Number Engines	3	4	3
Engine Vacuum Thrust, each (Klbf)	20	20	20

8.4.2. SpaceWorks Torpor-Enabled Mission Design

For the same trajectories and mission duration, replacing the EMC Reference habitat with the SpaceWorks Torpor habitat leads to a 62.3-ton (42.7%) mass reduction for the crew transportation system. This mass reduction is achieved by using a less massive habitat (25.5t vs. 45.5t), reducing crew consumables and total propellant loads. These impacts enable a vehicle design that can meet all design constraints while utilizing one less propulsive stage. Figure 27 shows the allocation and magnitude of mass reductions for the major components. Note that the outbound stage #2 (or 'OutStg2') mass reduction, along with the outbound stage #1 (or 'OutStg1') mass increase are the result of dropping the second, outbound propulsive stage in favor of a single larger stage.

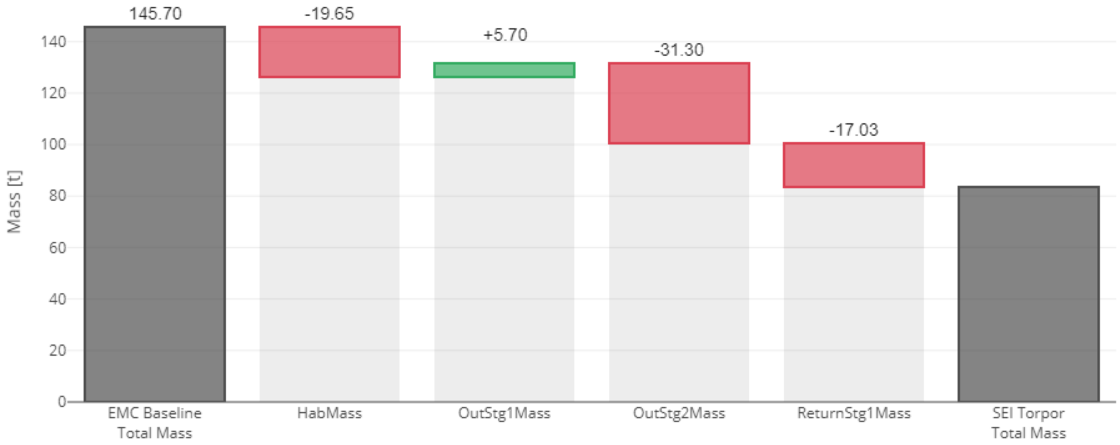


Figure 27. Impact of Torpor on Overall Mission Mass to Phobos Relative to Optimized NASA EMC Baseline

Optimal propulsive staging for the Phobos mission using the SpaceWorks Torpor habitat is given in Table 30. Note that the mass savings derived from the SpaceWorks Torpor habitat led to a reduction in the total number of propulsive stages by combing the MOI and TMI burns into in a single stage.

Table 30. Mass-Optimized SpaceWorks Torpor Mission Departing in 2033 (4 Crew Members)

Parameter	Outbound Trajectory	Return Trajectory
Propulsive Stage Burns	MOI-TMI	TEI-EOI
Inert Mass (t)	6.73	6.26
Usable Propellants (t)	26.95	23.12
Payload(s) (t)	28.22	27.79
Gross Weight (t)	61.90	57.18
Stage Length (feet)	38.2	35.3
Stage Diameter (feet)	9	9
Number Engines	2	2
Engine Vacuum Thrust, each (Klbf)	20	20

SpaceWorks Torpor-enabled mission architectures can offer significant crew health improvements and over a 40% reduction to 83.4t in the total mass of the crew system. In addition, the total number of LOX/CH4 engines to be produced drops from 10 to 4, and the total number of SLS launches required drops from 7 to 5. The effects of these changes on campaign cost are detailed in Section 9.

8.5. Mars Surface Landing Missions with Torpor and 8-Crew Members

8.5.1. Study Motivation

NASA's Evolvable Mars Campaign (EMC) studies emphasize the efficiency and achievements that can be made by developing a series of missions that feature "incremental investments in capabilities to enable a cadence of incrementally more complex missions" [2,196,196,197]. Pursuant to this goal, SpaceWorks has investigated a follow-on to the 2033 Phobos mission that features 8 crew members to showcase the mission-enabling mass savings achievable with a torpor-enabled crew system. Other than the number of crew, this mission follows the same NASA EMC assumptions and ground rules laid out in Section 8.2. Robotic pre-supply missions depart for Mars in 2035 and 2037. Following successful pre-supply checkout, the crew embarks on a Conjunction-class mission in 2039. After an extended stay on the surface of Mars, the crew returns to Earth in 2041. SpaceWorks generated a minimum characteristic energy trajectory using the Bullseye trajectory tool assuming four ~300-second propulsive burns with the destination orbits and burn locations the same as the 2033 mission. Parameters for the optimal trajectory are presented in Table 31.

Table 31. Minimum C_3 Trajectories for 2039 Mission to Mars

Parameter	Outbound Trajectory	Return Trajectory
Departure Date	10/08/2039	08/13/2041
Arrival Date	06/09/2040	05/15/2042
$\Delta V1$ (km/s)	1.05	1.08
$\Delta V2$ (km/s)	1.00	0.59
Time of Flight (days)	245	275
Total C3 (km^2/s^2)	48.731	17.947

The Martian surface stay time is 430 days and the total mission time from Earth-orbit departure to Earth-orbit return is 950 days. Although the in-space transportation time is longer for this mission than the 2033 mission, the total expected mission duration is the same. With these new trajectories as inputs, SpaceWorks used the IDF to explore alternative architecture designs via a full-factorial DOE with the independent variables described in Table 26.

8.5.2. NASA EMC Baseline with 8 Crew

To size a reference 8 crew mission with the baseline NASA EMC stages, SpaceWorks developed a CTS model that houses 8 crew members by stacking two independent EMC Baseline habitats. All 4-crew missions outlined in Section 8.4 can be completed with four or less propulsive stages while still meeting the mass and thrust-to-weight constraints of 45 tons and 0.3 respectively. For the 8-crew mission however, the total crew habitat mass increased by a sufficient amount that it was no longer possible to use a single propulsive stage for each ΔV burn while still meeting these constraints. As a result, the IDF full-factorial search also included variants where either the first or second burn was split between two stages. After performing the full-factorial search with up to three propulsive stages in either direction, however, there were still no variants of the propulsion stage architecture that could transport eight crew members to Mars using the EMC baseline habitats.

To find feasible designs, the constraints on the EMC Baseline case's propulsive stages would have to be relaxed to a maximum 50-ton launch mass and an initial thrust-to-weight minimum of 0.24. Even with these relaxed constraints, Figure 28 shows that only a small set of cases, all with three stages in either direction, are feasible. As before, architecture scenarios that could not meet the constraints are identified in grey.

The minimum mass EMC Baseline variant with 8 crew has a total CTS mass of 332 tons. This design requires 9 total propulsive stages (3 out and 3 return) and 24 engines to support both outbound and return transits. Table 32 provides the propulsive stage details.

It should be mentioned that it would be possible to simply send two completely independent crew "trains", each with a single habitat sized for a crew of four. Based on the preceding results, this would yield a value of 291.4 t for our primary metric of 'total mission mass'. Notably there are both performance (e.g. safety, reliability, redundancy, etc.) and non-performance factors (e.g. crew interaction, complexity, emergency options, etc.) worth considering for placing the 8 crew members together during the mission. Assuming a feasible architecture design can be obtained in either case, it is not immediately obvious which approach is better. However, this examination was beyond the scope of this effort.

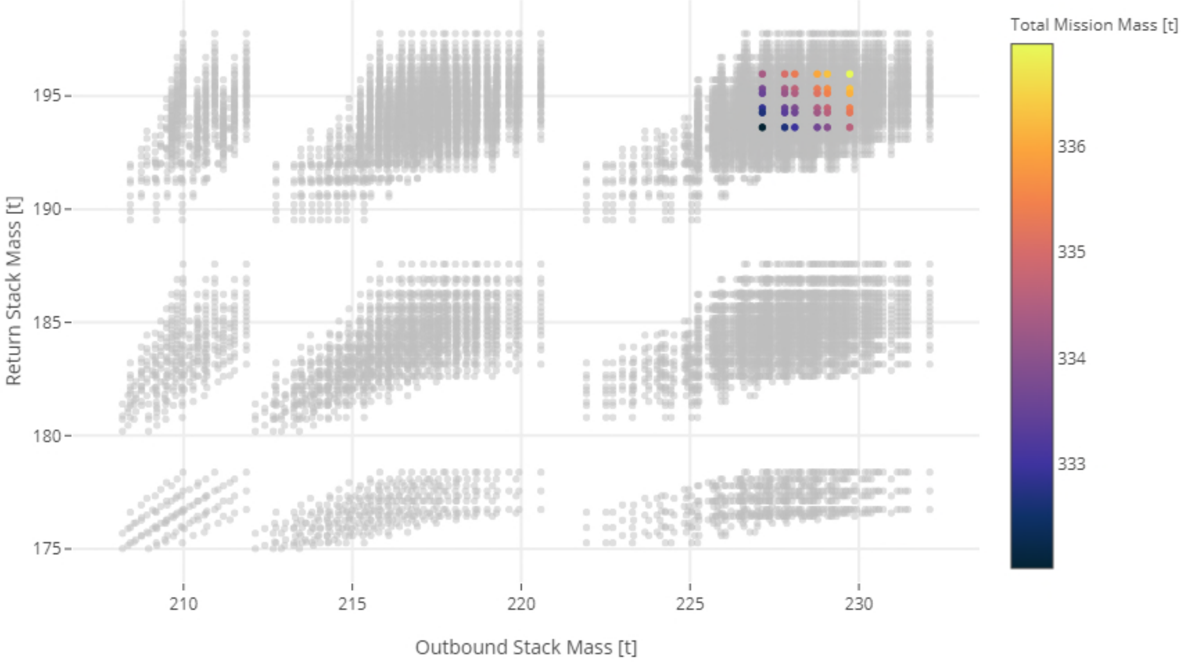


Figure 28. Results for 8-Crew Mission to Phobos using EMC Reference Habitat

Table 32. Propulsive Stage Sizing for Minimum Mass, 8-Crew EMC Baseline Mission

	Outbound			Return		
Propulsive Burn	MOI	TMI-2	TMI-1	EOI	TEI-2	TEI-1
Percent of Burn	100%	50%	50%	100%	50%	50%
Inert Mass (t)	10.36	10.42	12.52	8.37	9.36	11.26
Usable Propellants (t)	37.09	28.25	35.91	23.06	23.30	29.52
Payload(s) (t)	92.58	140.03	178.70	88.73	120.16	152.83
Gross Weight (t)	140.03	178.70	227.14	120.16	152.83	193.61
Stage Length (feet)	34.8	32.7	34.5	31.9	31.9	32.9
Stage Diameter (feet)	13.0	13.0	13.0	13.0	13.0	13.0
Number Engines	3	4	5	3	4	5
Engine Vacuum Thrust, each (Klbf)	25	25	25	25	25	25

8.5.3. SpaceWorks Torpor Architecture with 8 Crew

SpaceWorks also examined a torpor-enabled, 8-crew mission to Mars that supports 8 crew by stacking two independent SpaceWorks Torpor habitats together, as detailed in Section 7.4. The IDF was used to run a full factorial design sweep with the original constraints on maximum launch weight (45t) and minimum thrust-to-weight (0.3) applied. Unlike the EMC baseline, the SpaceWorks Torpor architecture can still meet these original constraints when sized for a crew of 8. The results of this design space sweep with the original constraints are shown in Figure 29.

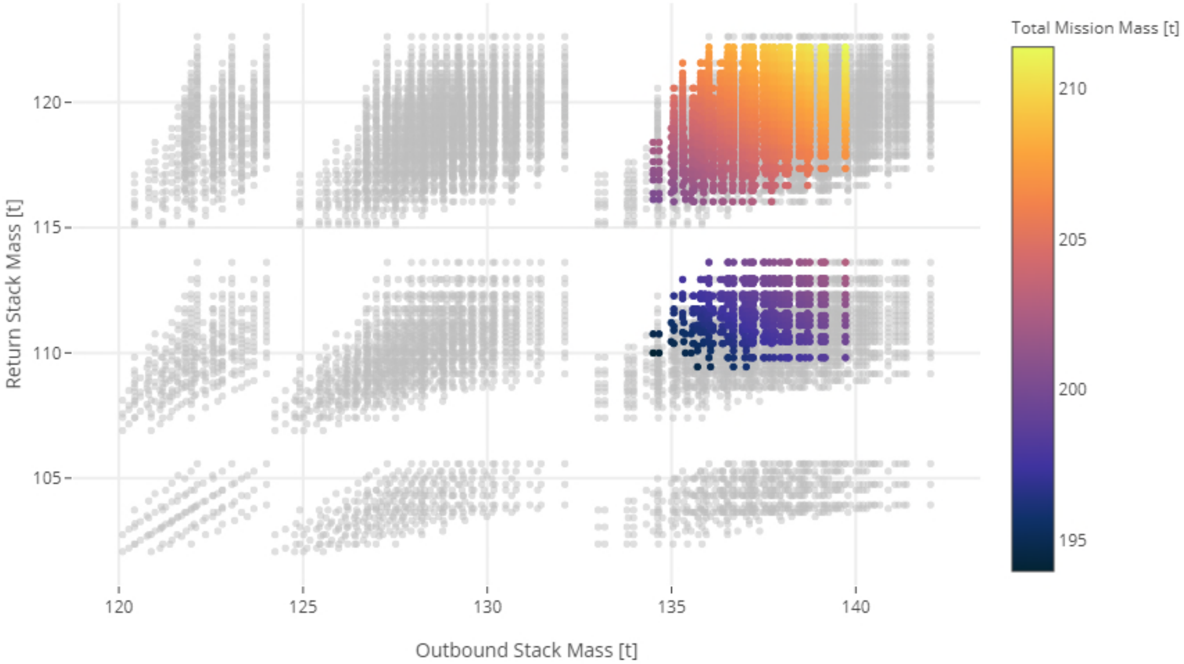


Figure 29. Results of Torpor for 8-Crew Mission to Phobos with Original Constraints

When the relaxed constraints on maximum launch weight (50t) and minimum thrust-to-weight (0.24) are applied, the SpaceWorks Torpor mission architecture makes it possible to send 8 crew with only two propulsive stages in either direction. The feasible cases under the relaxed constraints are shown in Figure 30.

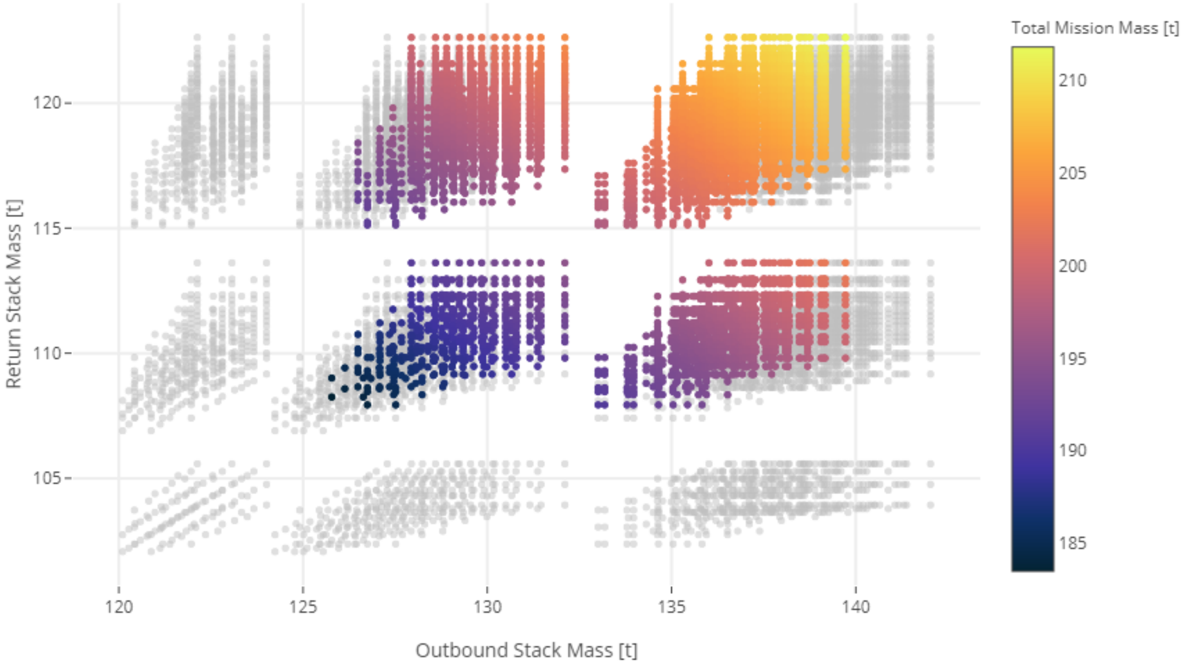


Figure 30. Results for Torpor 8-Crew Mission to Phobos with Relaxed Constraints

Under the relaxed constraints, the optimal architecture requires a total of four propulsive stages, 14 LOX/CH4 engines, and has a total mass of 187.4 metric tons. See Table 33 for propulsive stage mass details.

Table 33. Propulsion Stage Sizing for Minimum Mass, 8-Crew SpaceWorks Torpor Architecture

	Outbound		Return	
Propulsive Stage Burns	MOI	TMI	EOI	TEI
Inert Mass (t)	7.22	9.97	6.05	9.06
Usable Propellants (t)	21.40	37.18	13.44	30.93
Payload(s) (t)	52.17	80.79	50.53	70.01
Gross Weight (t)	80.79	127.93	70.01	109.99
Stage Length (feet)	30.6	38.4	28.4	35.2
Stage Diameter (feet)	11.0	11.0	11.0	11.0
Number Engines	3	4	3	4
Engine Vacuum Thrust, each (Klbf)	22.5	22.5	22.5	22.5

For the same trajectories and mission duration, the SpaceWorks Torpor habitat leads to a 144.6-ton (43.6%) mass reduction for the crew transit system. This mass reduction is achieved due to the less massive habitat that ultimately enables elimination of two entire propulsive stages. Figure 31 shows the allocation and magnitude of mass reductions for major components. Note that both the Outbound Stage #3 and Return Stage #3 mass savings are realized by eliminating those stages from the vehicle.

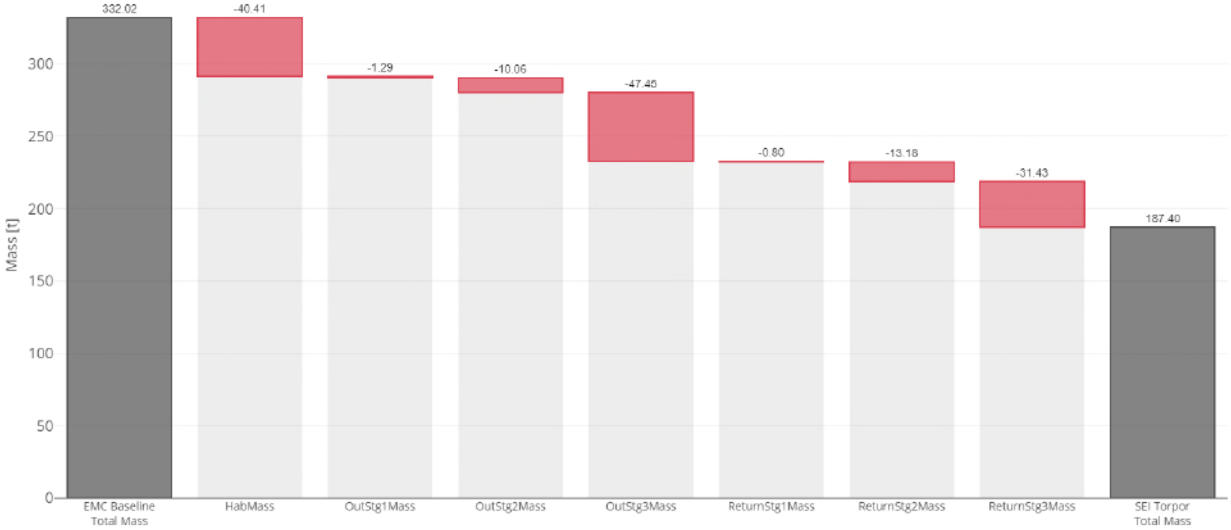


Figure 31. Impact of Torpor on Mission Mass

8.5.4. SpaceWorks Torpor-enabled Mission with 8-Crew Habitat

Further mass reductions can be realized by combining the two 4-crew SpaceWorks Torpor habitats into a single 8-crew habitat. This approach greatly increases the packing efficiency of the habitat and reduces the mass of the habitat by nearly 9 tons, as detailed in Section 7.6. SpaceWorks again characterized the design space for this variant by running a full-factorial search with the IDF. This search showed that even under the original propulsive stage constraints on max launch weight (45t) and minimum thrust-to-weight (0.3), a unified, 8-crew habitat further reduces the total CTS mass to 151.82 tons; a reduction of over 35 tons (18.9%). Furthermore, the 8-crew habitat enables a mission architecture that requires one fewer propulsive stage than the SpaceWorks Torpor mission with 2x4-crew habitats, and 3 fewer propulsive stages than the EMC Baseline case. Propulsive Stage details for the torpor-enabled architecture with an 8-crew habitat are given in Table 34.

Table 34. Propulsive Stage Sizing Results for Minimum Mass, Single 8-Crew SpaceWorks Torpor Habitat Architecture

Parameter	Outbound Trajectory		Return Trajectory
Propulsive State Burns	*MOI*	*TMI*	*TEI-EOI*
Inert Mass (t)	6.15	8.54	8.74
Usable Propellants (t)	17.82	31.06	36.20
Payload(s) (t)	43.31	67.28	41.67
Gross Weight (t)	67.28	106.89	86.80
Stage Length (feet)	29.5	37.7	40.9
Stage Diameter (feet)	10.0	10.0	10.0
Number Engines	2	3	3
Engine Vacuum Thrust, each (Klbf)	25	25	25

9. Mars Architecture Campaign Cost

A human Mars campaign is often estimated to cost in the hundreds of billions of dollars, with the least expensive options still ranging in the tens of billions of dollars. Despite recent increases in NASA's human exploration budget, minimizing overall mission architecture costs are critical. Assessing the affordability of a torpor-enabled architecture is critical in validating that this technology could be successfully integrated into the agency's Evolvable Mars Campaign (EMC). To determine the economic impacts of a torpor-enable design, the non-recurring (NRE) development and recurring production costs were estimated for the EMC Baseline architecture, as well as for torpor-crewed mission architectures.

When evaluating Mars architecture campaign costs, definitions surrounding what elements should be included vary widely. Architecture studies may cover everything from SLS/Orion, to the Lunar-orbiting Gateway, to astronaut deep space habitat training. For the purposes of this analysis, SpaceWorks focused on a specific subset of activities within the overall EMC for comparison and that are of most relevance when assessing the impact of torpor enabled systems. An exact description of what elements are and are not included in this analysis is shown below in Table 35

Table 35. Mars Architecture Campaign Cost Analysis Scope

Work Element	Element Included	Launch Included
ISS Utilization	-	-
Commercial Crew	-	-
Commercial Cargo	-	-
SLS/Orion/Crew Rendezvous	-	-
Lunar Orbiting Gateway	-	-
Crew Training	-	-
Crew Transportation	-	O
Crew Supplies	-	O
Deep Space Habitat	O	O
In-space Propulsive Stages	O	O
Habitat/Propulsive Stage Assembly	O	-
Spacecraft/Habitat Operations	O	-
Mars Surface Habitat	-	-
Mars Surface Operations	-	-

The above included activities have been roughly categorized as the "in-space transportation" phase of the campaign. This phase nominally begins at the assembly of the crew habitats with the propulsive stages, includes the duration of the astronaut phase leading up to the departure of the crew for the Martian (or Martian moon) surface, and the entirety of the return journey, ending at the rendezvous point in lunar orbit. Additionally, included is the "dormant habitat" operations while the crew is on the surface. The overall Mars architecture cost analysis considered a three-part exploration campaign consisting of a 4-person mission to Phobos/Deimos, and two 8-person missions to the Martian surface. This analysis considered a nominal surface stay duration for each mission of approximately 400 days.

A combination of parametric cost tools results, publicly available cost estimates, and internal cost sources were used to produce the crew 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 system 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 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. For the purposes of the architecture-level cost analysis, a 10% vendor fee was applied to the habitat and propulsive stages, as well as a 20% margin was applied to all cost centers. A detailed description of all cost tools and methodologies used for this effort can be found in Section 6.2 Cost Modeling.

9.1. NASA Reference EMC Baseline Architecture Cost

SpaceWorks' independent cost assessment for an approximately 10-year, multi-mission Mars campaign using the NASA EMC Baseline architecture indicates an in-space transportation cost of approximately $41B, broken out across four categories: Launch, Habitat, Propulsive Stage, and Operations.

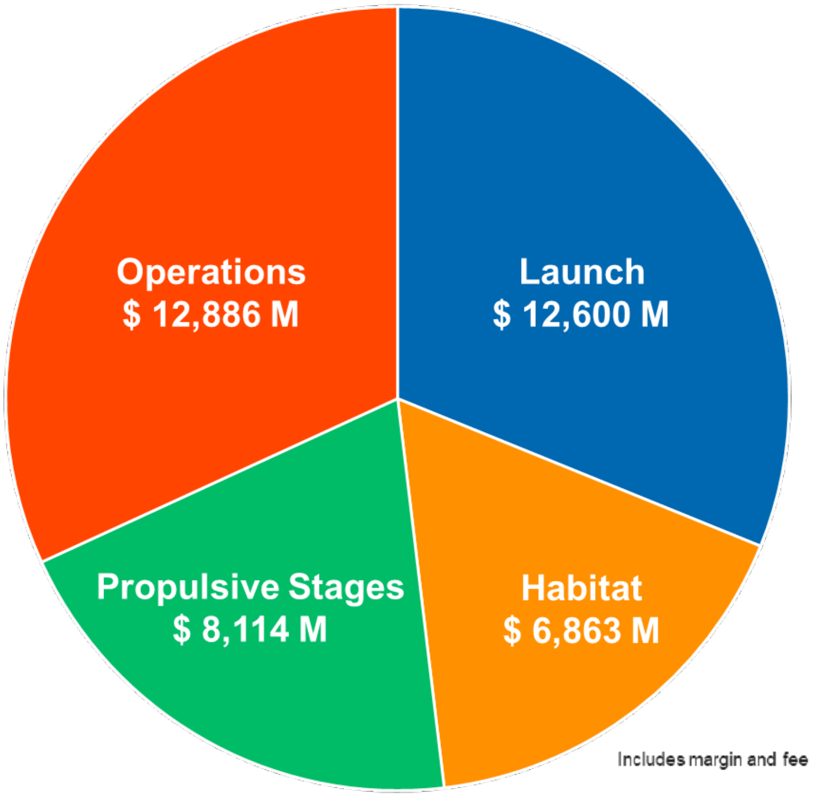


Figure 32. NASA EMC Baseline Architecture Cost Breakdown (FY2018)

9.1.1. NASA EMC Baseline Architecture Launch Cost

SpaceWorks assumed an SLS per-launch cost of $500M for this analysis, with a total of 21 launches being required across all three missions. This results in the launch costs being the second most significant cost driver for the in-space transportation phase, encompassing nearly $13B (~31%) of the entire architecture-level cost. A breakdown of launches can be found below in Table 36.

Table 36. NASA EMC Baseline Architecture Required Heavy Lift Launches

Mission	Cargo/Propulsive Stage Launches	Habitat Launches	Crew Launches	Total
Phobos/Deimos Mission	4	1	1	6
Mars Surface Mission #1	6	1	1	8
Mars Surface Mission #2	6	0*	1	7
Total	**16**	**2**	**3**	**21**

* Prior mission habitats are recovered to DLRO and reused

9.1.2. NASA EMC Baseline Architecture Habitat Cost

While the crew habitat is the single most expensive hardware element, it is the smallest cost driver for the in-space transportation phase due to the lower quantity. It is also an important driver of other individual cost centers. Based on the independent cost assessment for the NASA EMC Baseline Habitat design (see Section 7.2), habitat costs at the architecture level (including margin) are estimated to be approximately $7B (17%). This estimate includes Research, Development, Testing, & Evaluation (RDT&E), as well as production costs for two NASA EMC Baseline Habitats (4-Crew System). In this configuration, SpaceWorks assumed that the initial habitat produced for the Phobos/Deimos mission would be re-used for the subsequent missions and that only one additional habitat would need to be produced for the two Mars surface missions. Table 37 details the architecture-level breakdown of habitat costs for the NASA EMC Baseline architecture.

Table 37. NASA EMC Baseline Architecture Habitat Costs

Work Element	RDT&E Cost** ($M, FY2018)	First Production Unit ($M, FY2018)	Second Unit ($M, FY2018)	Total*** ($M, FY2018)
Habitat	$ 4,004	$ 664	$541	$ 5,209

* Cost differences between sum of elements and total are due to rounding, ** Margin and fee not included

9.1.3. NASA EMC Baseline Architecture Propulsive Stage Cost

Propulsive stage costs for the NASA EMC Baseline are estimated to be approximately $9B (21%) at the architecture level (including margin). This estimate includes Research, Development, Testing & Evaluation (RDT&E), as well as production costs for each propulsive stage. Based on inputs from the engineer design team, each propulsive stage was assumed to be different enough that it would require its own development effort, which drive the Propulsive Stage costs up significantly. For each of the propulsive stages used for the Phobos/Deimos mission, a production quantity of one was used, while propulsive stages for the Mars surface missions used a quantity of two (to reflect two missions) – it was assumed these stages would not be produced in batches, and thus learning curve effects consummate with industry standard rates were used. The final Return Stage (Return Stage #3) is the exception to this rule, as it was assumed this stage could be reused for the second mission after returning to Earth, and a production quantity of one was used.

Table 38. NASA EMC Baseline Architecture Propulsive Stage Costs

Work Element	RDT&E Cost ($M, FY2018)	Production Cost ($M, FY2018)	Total*** ($M, FY2018)
Phobos/Deimos Outbound Stage #1	$ 574	$ 66	$ 640
Phobos/Deimos Outbound Stage #2	$ 463	$ 59	$ 522
Phobos/Deimos Return Stage #1	$ 485	$ 61	$ 545
Mars Surface Outbound Stage #1	$ 789	$ 160	$ 1,042
Mars Surface Outbound Stage #2	$ 597	$ 138	$ 788
Mars Surface Outbound Stage #3	$ 572	$ 125	$ 756
Mars Surface Return Stage #1	$ 626	$ 151	$ 826
Mars Surface Return Stage #2	$ 561	$ 133	$ 741
Mars Surface Return Stage #3	$ 521	$ 66	$ 688
Total*	**$ 5,188**	**$ 959**	**$ 6,547**

* Cost differences between sum of elements and total are due to rounding, ** Margin and fee not included

9.1.4. NASA EMC Baseline Architecture Operations Cost

Mission operations costs for the NASA EMC Baseline architecture are the largest cost driver for the overall architecture and are estimated to be nearly $13B (including margin) over the entire campaign. This estimate is based on the cost of spacecraft operations, scientific payload operations, and human exploration-related operations over the 10-year campaign. As outlined in Section 6.2.3, operations costs were estimated using the MOCET tool produced by the Aerospace Corporation and augmented with analogous figures from NASA 2013 ISS operations budget. SpaceWorks recognizes this cost approach leaves room for improvement, but believe it provides a reasonable baseline for exploring the tradeoffs between the EMC Baseline and SpaceWorks Torpor architectures at the present design-fidelity.

Table 39. NASA EMC Baseline Architecture Operations Costs

Work Element	Total Cost ($M, FY2018) ***
Phobos/Deimos Operations	$ 3,659
Mars Surface Mission #1 Operations	$ 4,614
Mars Surface Mission #2 Operations	$ 4,614
Total	**$ 10,739**

* Cost differences between sum of elements and total are due to rounding, ** Margin and fee not included

9.2. SpaceWorks Torpor Baseline Architecture Cost

A similar cost assessment was conducted for the minimum-mass SpaceWorks Torpor architecture identified in Table 30 and Table 33. The results indicate an in-space transportation cost of approximately $26B, broken out across four categories as: Launch, Habitat, Propulsive Stage, and Operations. Figure 35 provides the relative cost contributions for each of these categories.

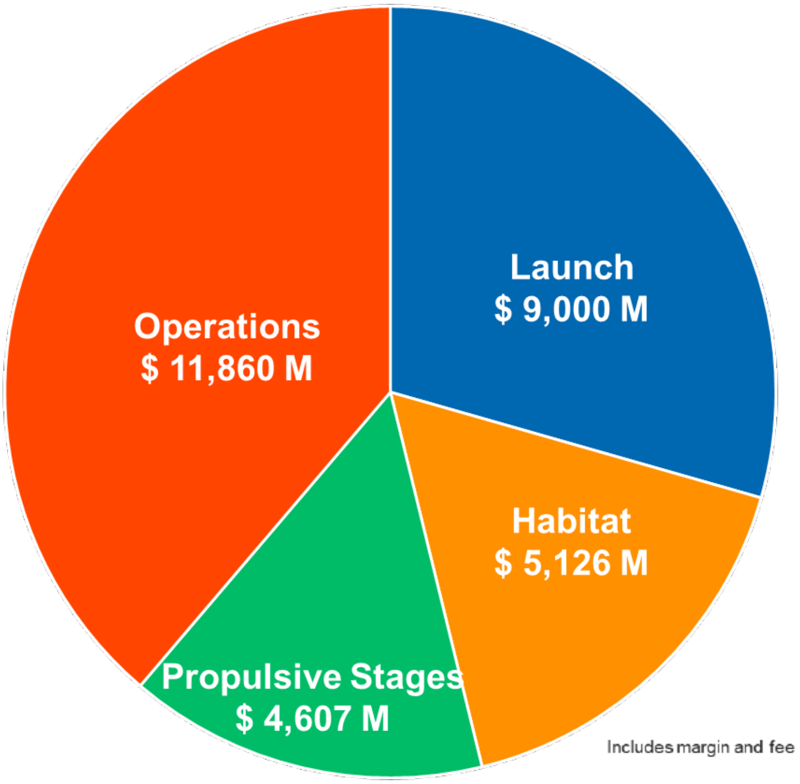


Figure 33. SpaceWorks Torpor-Optimized Architecture Cost Breakdown (FY2018)

9.2.1. SpaceWorks Torpor Architecture Launch Cost

Launch is the second most significant cost driver for the in-space transportation phase, encompassing $9B (~29%) of the entire architecture-level cost. SpaceWorks assumed an SLS per-launch cost of $500M for this analysis, with a total of 15 launches being required across all three missions. A breakdown of launches can be found below in Table 40. Relative to the optimized, non-torpor NASA EMC campaign requiring 21 launches, a net savings of $3B is already achieved using torpor.

Table 40. SpaceWorks Torpor Architecture Required Heavy Lift Launches

Mission	Cargo/Propulsive Stage Launches	Habitat Launches	Crew Launches	Total
Phobos/Deimos Mission	2	1	1	4
Mars Surface Mission #1	4	1	1	6
Mars Surface Mission #2	4	0	1	5
Total	**10**	**2**	**3**	**15**

9.2.2. SpaceWorks Torpor Architecture Habitat Cost

The habitat is the smallest cost driver for the in-space transportation phase but is an important driver of the other individual cost centers. Based on the cost assessment for the SpaceWorks Torpor Habitat design (see Section 0), habitat costs at the architecture level are estimated to be approximately $5B (17%). This estimate includes Research, Development, Testing, & Evaluation (RDT&E), as well as production costs for two SpaceWorks Torpor Habitats (4-Crew System). In this configuration, SpaceWorks assumed that the initial habitat produced for the Phobos/Deimos mission would be re-used for the subsequent missions and that only one additional habitat would need to be produced for the two Mars surface missions. Table 41 details the architecture-level breakdown of habitat costs for the NASA EMC Baseline architecture.

Table 41. SpaceWorks Torpor Architecture Habitat Costs

Work Element	RDT&E Cost ($M, FY2018)	First Production Unit ($M, FY2018)	Second Unit ($M, FY2018)	Total*** ($M, FY2018)
Habitat	$ 2,965	$ 511	$ 409	$ 3,885

* Cost differences between sum of elements and total are due to rounding, ** Margin and fee not included

9.2.3. SpaceWorks Torpor Architecture Propulsive Stage Cost

Propulsive stage costs for the SpaceWorks Torpor architecture are estimated to be approximately $5B (16%) at the architecture level (including margin). This estimate includes Research, Development, Testing & Evaluation (RDT&E), as well as production costs for each propulsive stage. Based on inputs from the engineer design team, each propulsive stage was assumed to be different enough that it would require its own development effort, which drive the Propulsive Stage costs up significantly. For each of the propulsive stages used for the Phobos/Deimos mission, a production quantity of one was used, while propulsive stages for the Mars surface missions used a quantity of two (to reflect two missions) – it was assumed these stages would not be produced in batches, and thus learning curve effects consummate with industry standard rates were used. The final Return Stage (Return Stage #2) is the exception to this rule, as it was assumed this stage could be reused for the second mission after returning to Earth, and a production quantity of one was used.

Table 42. SpaceWorks Torpor Architecture Propulsive Stage Costs

Work Element	RDT&E Cost ($M, FY2018)	Production Cost ($M, FY2018)	Total*** ($M, FY2018)
Phobos/Deimos Out Stage 1	$ 485	$ 53	$ 538
Phobos/Deimos Return Stage 1	$ 409	$ 128	$ 537
Mars Surface Out Stage 1	$ 583	$ 128	$ 711
Mars Surface Out Stage 2	$ 468	$ 108	$ 576
Mars Surface Return Stage 1	$ 517	$ 122	$ 638
Mars Surface Return Stage 2	$ 433	$ 58	$ 491
Total*	**$ 2,894**	**$ 596**	**$ 3,490**

* Cost differences between sum of elements and total are due to rounding, ** Margin and fee not included

9.2.4. SpaceWorks Torpor Architecture Operations Cost

Mission operations costs for the NASA EMC Baseline architecture are the second largest cost driver for the overall architecture and are estimated to be nearly $12B (39%) over the entire campaign (including margin). This estimate is based on the cost of spacecraft operations, scientific payload operations, and human exploration-related operations. As outlined in Section 6.2.3, operations costs were estimated using the MOCET tool produced by the Aerospace Corporation and augmented with analogous figures from NASA 2013 ISS operations budget. This analysis did not specifically account for any inflation or deflation factors to account for differences in operations management for a crew under the impact of torpor, as there is no current basis for quantifying these impacts. Cost differences were based on already established CERs set out in the MOCET tool. Further exploration into the operations impact of torpor could yield substantial changes in the operations cost modeling of the SpaceWorks Torpor architecture operations costs. SpaceWorks recognizes this costing approach leaves room for improvement, but believes it provides a reasonable baseline for exploring the tradeoffs between the architectures at the present design-fidelity.

Table 43. SpaceWorks Torpor Architecture Operations Costs

Work Element	Total Cost ($M, FY2018)***
Phobos/Deimos Operations	$ 2,780
Mars Surface Mission #1 Operations	$ 3,552
Mars Surface Mission #2 Operations	$ 3,552
Total	**$ 9,884**

* Cost differences between sum of elements and total are due to rounding, ** Margin and fee not included

9.3. SpaceWorks Torpor vs. NASA EMC Baseline Architecture Cost Comparison

The SpaceWorks Torpor architecture demonstrates a significantly lower cost than the NASA EMC Baseline architecture, yielding a total savings in excess of $10B. Cost savings of the torpor-enabled campaign were driven heavily by a lower overall habitat size, which in turn significantly reduced the number of required launches and propulsive stages. Operations costs were less impacted by the reduced habitat size; however, the mission operations impact of torpor have not yet been fully explored and future potential savings may be unveiled as additional research progresses.

This analysis suggests that the SpaceWorks Torpor architecture is not only cost competitive with the NASA EMC Baseline architecture, but actually significantly cheaper. Overall, the SpaceWorks Torpor-enabled architecture is estimated to reduce the in-space transportation phase of an EMC architecture by approximately 24%.

Table 44. SpaceWorks Torpor Architecture Costs vs. EMC Baseline Architecture Costs

Work Element	EMC Baseline Architecture Cost ($M, FY2018)***	SpaceWorks Torpor Architecture Cost ($M, FY2018)***	Cost Delta
Launch	$ 12,600	$ 9,000	29%
Habitat	$ 6,863	$ 5,126	25%
Propulsive Stages	$ 8,114	$ 4,607	43%
Operations	$ 12,886	$ 11,860	8%
Total	**$ 40,462**	**$ 30,593**	**24%**

* Cost differences between sum of elements and total are due to rounding, ** Margin and fee included

10. Exploration Missions Beyond Mars

10.1. Introduction

To further examine the potential of torpor, SpaceWorks performed the systems analysis for a future human mission beyond Mars to the main asteroid belt, with a goal of visiting Ceres. From a brief literature search and review, there were very few published architecture designs for human missions to Ceres. However, Ceres is one of the more interesting and compelling destinations beyond Mars orbit.

As it is highly unlikely that a mission to Ceres would occur prior to any human mission to Mars, mission opportunities were evaluated in 2040+ timeframe and nominal scenario selected. A crew complement of three (3) was assumed to be the minimum number acceptable that would not compromise any science goals and/or safety of the crew.

10.2. Destination: Ceres

Ceres is the largest object in the asteroid belt, comprising approximately 1/3 of the total mass of all asteroid belt objects. Due to its synodic period with the Earth of 1.28 years compared to 2.14 years for Mars, mission opportunities are much more frequent. However, the required mission propulsive ΔVs are much more demanding relative to Mars. Table 45 provides some orbital parameters and features for Ceres.

Table 45. Specifications for Asteroid Belt Object Ceres

Parameter	Value
Distance from Sun	2.55 – 2.98 AU
Orbital Period	4.6 years
Mean Radius	474 km
Orbital Inclination (ecliptic)	10.6 degrees
Escape Velocity	0.51 km/s
Surface Gravity	0.03 Gs

Figure 34 provides the envision CONOPS for the Ceres mission. An initial pre-deployment of various assets to vicinity and surface of Ceres is assumed. A short-stay surface habitat, exploration vehicle, and return propulsive stages are all sent in advance of the crew. The current architecture is also predicated and enabled with ISRU to produce hydrogen from frozen, subsurface ice at Ceres and provide the return fuel for the NTR stages.

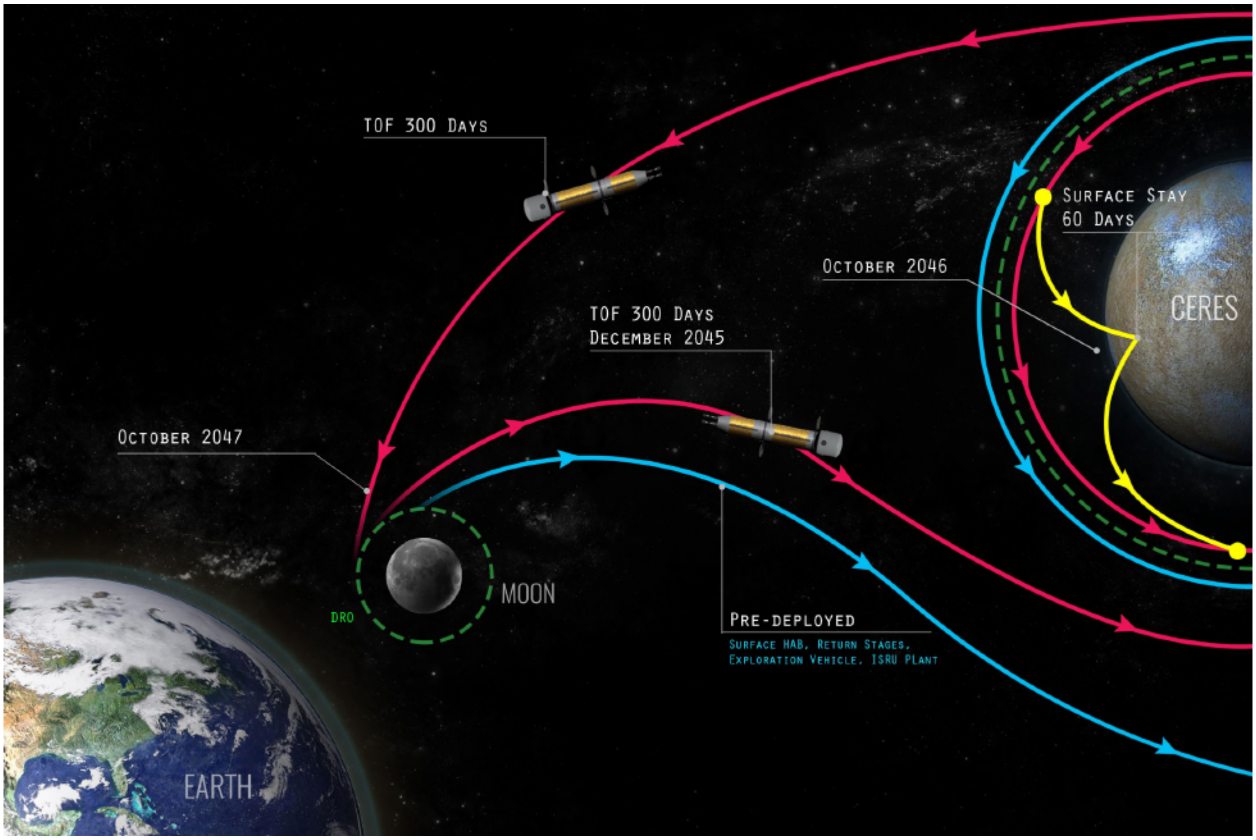


Figure 34. CONOPS for Human Mission to Ceres

10.3. Architecture Analysis

To establish the mission propulsive requirements, Bullseye was used for the in-space trajectory analysis. It was decided that the transit time should be constrained to be less than 300 days, with a minimum surface stay time of at least 60 days. The optimal ΔVs for this scenario is shown in Table 46, along with the corresponding crew time of flight in Table 47. Note that some small ΔV savings could be achieved with longer transit times and/or shorter surface stay times.

Table 46. Propulsive ΔV Requirements for Ceres Mission

Propulsive Maneuver	Delta-V (km/s)
Trans-Ceres Insertion (from LDRO)	3.7
Ceres Rendezvous Insertion	7.2
Trans-Earth/Lunar Insertion	10.2
DLRO Insertion	3.2
Total Mission DV	**24.3**

Table 47. Crew Time of Flight for Ceres Mission

Mission Phase	Time of Flight (days)
Outbound (from DLRO)	300
Ceres Vicinity	60
Return (to DLRO)	300
Total Crew Mission Duration	**660**

Due to significant reduction in solar flux as the crew moves beyond Mars coupled with the demanding mission ΔVs required, it was decided that the stages will all use hydrogen-fueled Nuclear Thermal Rocket (NTR) for propulsion instead of attempting to use traditional chemical propellants or SEP. The NTRs were assumed to have a vacuum Isp of a ~900 seconds and a vacuum thrust level of 25,000-lbf (per engine).

SpaceWorks then used the torpor habitat sizing model to establish a new design with capabilities to support a mission to Ceres. For this mission and design, a crew complement of 3 was assumed. The fully outfitted SpaceWorks Torpor habitat mass was estimated at 18.5 tons for the 660-day mission duration. Table 48 provides some additional specifications for the habitat.

Table 48. Ceres Mission Crew Habitat Specifications

Metric	Value
Crew Complement	3
Empty Mass	12.3 t
Loaded Mass	18.5 t
Habitable Volume	40 m3
Pressurized Volume	140 m3
Power Required	12 kW
Total Consumables (nutrition, water, atm. Gas, medical, etc.)	2.5 t
Nominal Consumables Outfitting	360 days
Length	6.0 meters
Diameter	5.5 meters

10.4. Mission Analysis Results

Since this was a very preliminary effort and examination, an extensive architecture search using the IDF was not conducted for this part of the study. A local optimization was conducted assuming 3 outbound NTR propulsive stages and 2 return NTR propulsive stages. Due to the use of hydrogen fuel, large propellant tanks were going to be required. Therefore, the stage diameters were all set at the maximum value permitted within an SLS fairing (~7.3 meters) and their lengths were allowed to vary to achieve the necessary ΔV.

The results of the stage sizing are provided in Table 49. While the gross weight of the stack for the return phase was almost 500t, note that it is assumed that ISRU from Ceres will be used to provide the ~300t of fuel. An assessment of the practicality and logistics for this has not been conducted at this time.

While the mission analysis generally did not encounter any issues achieving the necessary ΔVs, the resultant length of the stages exceeding 50-meters was excessive and will be problematic as the system is currently envisioned. Alternate design solutions that involve increasing the number of stages or reusing the tank(s) of a future heavy-lift launch system, or manufacturing of the tanks in orbit are all possible remedies.

Table 49. Ceres Mission Propulsive Stage Sizing Results

	Outbound			Return	
Propulsive Maneuver	COI	TCI	EOI	TEI-1	TEI-1
Inert Mass (t)	30.43	80.1	15.22	60.45	96.48
Usable Propellants (t)	40.04	146.8	14.39	102.2	191.73
Payload(s) (t)	17.84	COI Stack	17.84	EOI Stack	TEI-1 Stack
Gross Weight (t)	88.31	315.12	47.45	210.1	498.3
Stage Length (m)	20.4	57.0	11.3	42.4	66.5
Stage Diameter (m)	7.3	7.3	7.3	7.3	7.3
Number NTR Engines	2	4	1	3	4

11. Trade Studies

11.1. Parasitic Radiation Shielding

In space there are two predominant types of harmful radiation: Solar Particle Events (SPE) and Galactic Cosmic Rays (GCR). While SPE can be very dangerous and harmful to the crew, it is relatively easy to shield against compared to GCR radiation. The effectiveness of two materials, aluminum and polyethylene for radiation shielding is shown in Figure 35.

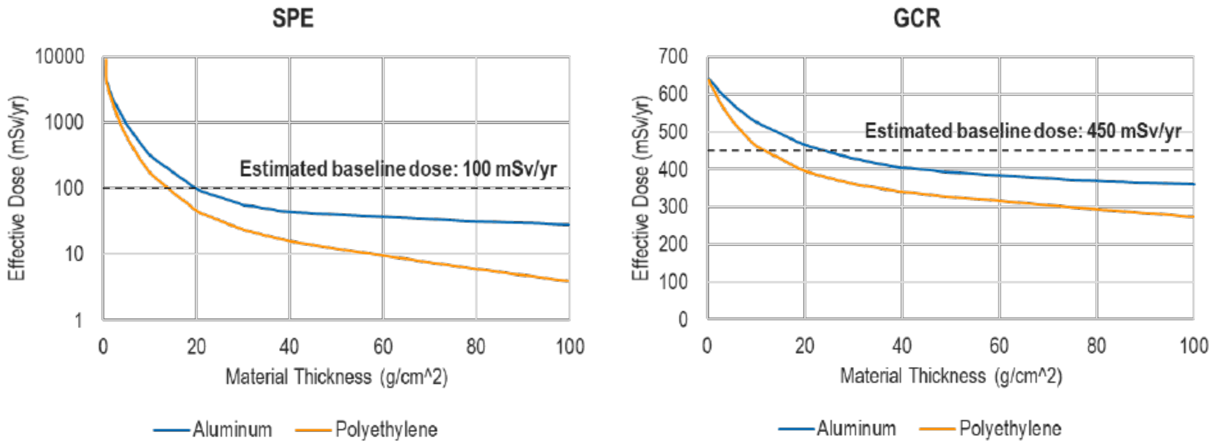


Figure 35. Radiation Shielding for Two Different Material Options and Varying Thickness

To examine the potential to reduce the crew's radiation exposure, both the EMC Reference habitat and SpaceWorks Torpor habitat were examined using two different approaches to apply and integrate parasitic radiation shielding materials. For the EMC habitat, the first scenario considered covering the exterior structure completely. The second scenario examined the EMC habitat with only the crew quarters region of the habitat covered. For the SpaceWorks Torpor habitat, a full coverage scenario was examined in addition to only placing shielding around the crew torpor modules/pods.

The radiation effects for this analysis were only considered for the space segment of the mission, with 600 total days in space. During this time, a crew member is expected to spend 67% of that time in torpor. This last metric matters when additional shielding is considered on the torpor pods.

In order to understand how the mass of shielding affected the radiation dosage, different shielding schemes needed to be considered. The two materials used were aluminum, to represent the structure, and polyethylene to represent the consumables on board. The three different benchmark cases used for each were 5-cm of aluminum with 5-cm of polyethylene; 5-cm of aluminum with 10-cm of polyethylene; and 5-cm of aluminum with 15-cm of polyethylene. From this an empirical formula was developed to determine the thickness required in order to achieve the desired radiation dosage (or reduction).

As specific radiation exposure requirements for a Mars mission have not been identified yet, the reduction range of interest was varied from 20% to 30%. Additional mission radiation dosage reductions are achievable but undesirable due to diminishing returns on radiation protection. This is partially due to the general ineffectiveness of shielding against GCR radiation. Figure 36 presents the results of the radiation study.

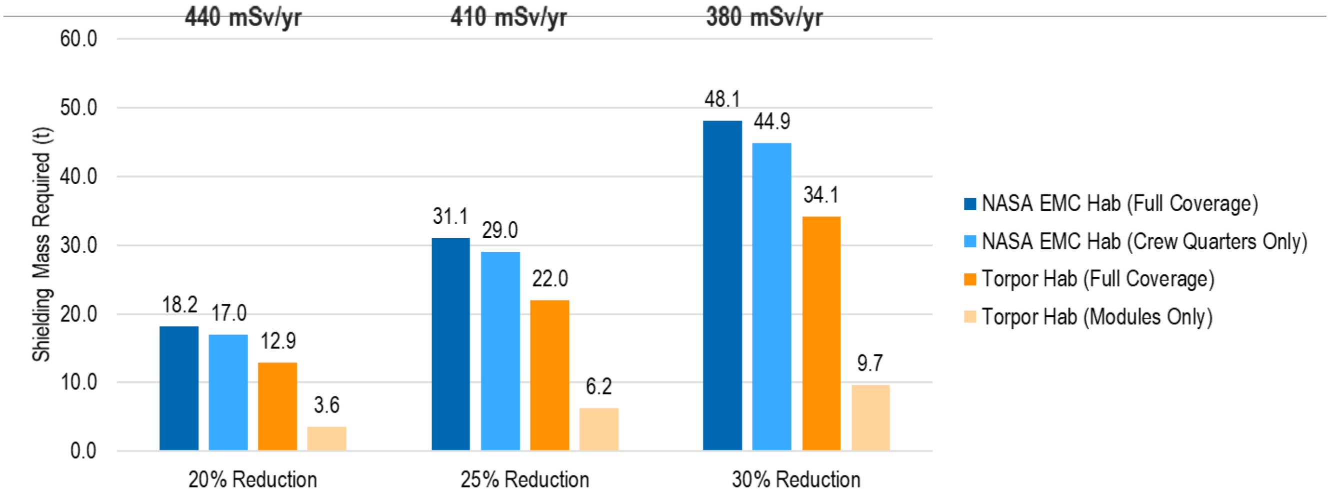


Figure 36. Shielding Mass Impact vs. Radiation Exposure Reduction for Various Implementation Concepts

The two most demanding mass requirements resulted for both scenarios of the EMC Reference habitat. This is primarily due to the larger size of the habitat, though the surface area of the habitat module and the torpor modules is roughly comparable. The second lightest option is the torpor habitat fully shielded. This habitat has a smaller surface area than the EMC design, resulting in less mass for the same percentage of radiation reduction.

The most interesting option however is applying additional radiation protection over the torpor modules/pod areas only. Since crew members spend a significant portion of their time in torpor and the significantly lower surface area to cover means that there is a much lower mass penalty associated with reducing their radiation exposure. Additionally, not only was this shielding approach the lowest mass, but the actual magnitude of the mass penalty is the only one likely to be acceptable from a mission sizing/performance perspective.

While the benefits of torpor are typically demonstrated in terms of mass reductions for the entire system via reduced habitat and propulsion stage size(s), an alternate approach is to reinvest those savings back into the habitat in order to improve overall safety (e.g. added redundancy) and/or improve crew health (e.g. reduce radiation exposure).

11.2. Reduced Mars Transit Duration

The duration of the interplanetary crew transfer mission phase is an important factor to be considered when managing environmental and psychological risks to the crew. Any reduction in the total amount of time that the crew spends drifting through interplanetary space can result in huge dividends through reduced radiation exposure, reduced bone and muscle loss, and less cumulative psychological strain. Reductions in transit time can also increase the amount of productive surface time for a given mission.

For all of these reasons, mission designers generally try to minimize the total amount of time the crew spends in transit. This is part of the rationale for using lower performing (but high thrust) chemical propulsion systems. While solar-electric propulsion can offer lower overall system mass through higher performance, the resultant transit times increase significantly due to the lower thrust levels. This is generally detrimental to the crew health in a number of ways.

As demonstrated previously, using a torpor-enabled architecture offers significant advantages over a traditional system in the domains of crew health, total system mass, and total mission cost. However, some of these advantages can be traded for alternative advantages by increasing the mass and thrust of the propulsive stages to reduce the duration of the in-space transit time.

To evaluate this approach, SpaceWorks generated a short-duration transit trajectory for the 2033 Phobos mission and then re-evaluated the optimal system design using the process outlined in Section 8.3. To size the short duration trajectory, SpaceWorks maintained the same terminal orbits and 4-burn structure as the original mission but fixed the transit duration to be 150 days for both outbound and return flight. Under these constraints, the new minimum-mass trajectories are described in Table 50.

Table 50. Mission C3 Trajectories for "Fast" 2033 Crewed Mission to Mars Vicinity

Parameter	Outbound Trajectory	Return Trajectory
Departure Date	4/26/2033	6/20/2035
Arrival Date	9/23/2033	11/17/2035
ΔV1	0.686 km/s	1.528 km/s
ΔV2	1.928 km/s	0.635 km/s
Transit Time of Flight	150 days	150 days
Total C3	32.06 km^2/s^2	25.82 km^2/s^2)

Achieving the 150-day transit trajectory requires the propulsive stages to provide 42% more ΔV (+1.406 km/s). SpaceWorks explored this new trade space using the IDF for the fast transit mission approach and, as expected, the total mass of the system is increased significantly.

Figure 37 includes the results of the new, 150-day transit (upper right) and previous slower transit time cases of 200 days.

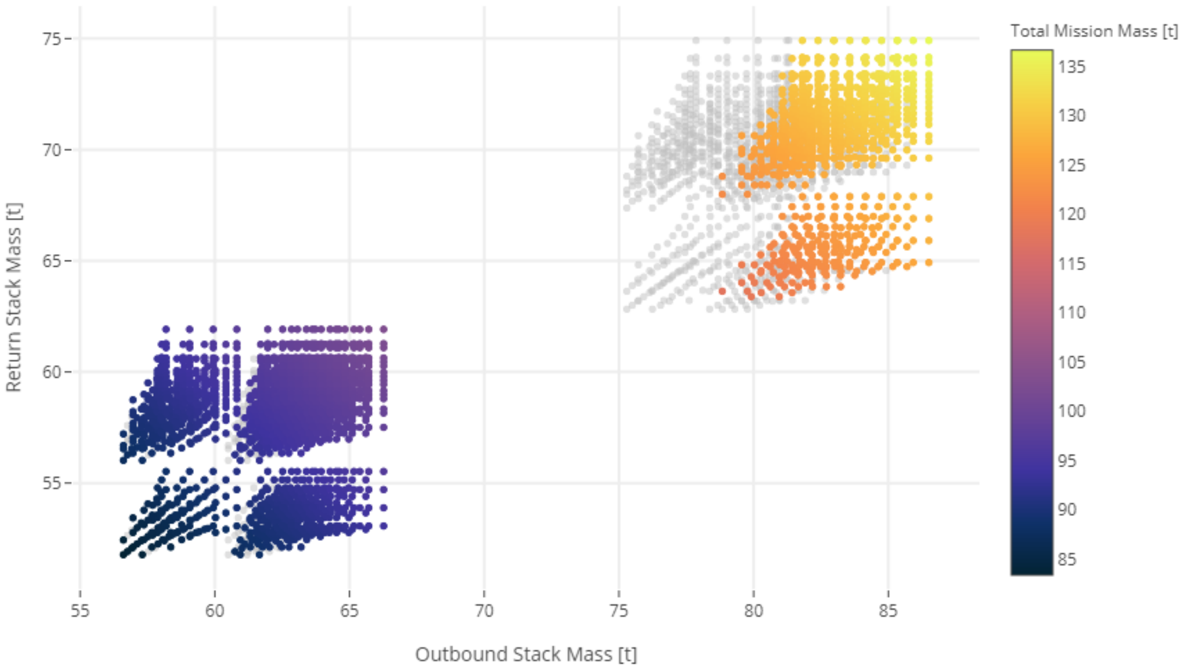


Figure 37. Impacts on Total System Mass for SpaceWorks Torpor Habitat with 150-day Transits (upper right) versus 200-day Transits to Phobos in 2033 (bottom left)

Reducing the interplanetary transit time leads to significant increases in total system mass and requires an additional propulsive stage when compared to the mass-optimal solution for the baseline 200 day transit. Summary results are provided in Table 51.

Table 51. Comparison of CTS for the Nominal and Short-Duration Mission

Parameter	Baseline 200 Day Transit	Short 150 Day Transit	Delta
Total System Mass	83.42 t	117.71 t	+ 34.29 t
Total Propulsive Stages	2	3	+ 1
Total # Engines	4	8	+ 4
Total ΔV	3.37 km/s	4.78 km/s	+ 1.41 km/s
One-Way Time of Flight	200 days	150 days	- 50 days
Total Mission Duration	950 days	935 days	- 15 days

This short-duration mission architecture shows the most promise when compared to the EMC Baseline architecture. Even while providing 40% more ΔV, the short-duration SpaceWorks Torpor architecture still weighs 28 tons less than the EMC Reference case. This study shows that the SpaceWorks Torpor-enabled habitat can enable crewed Mars mission with less time in space, less risk to the crew from transit hazards, and still deliver mass savings compared to the non-torpor EMC Reference case.

11.3. Artificial-Gravity Concepts

11.3.1. Motivation

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

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

11.3.2. Designs

SpaceWorks has evaluated two alternative concepts for inducing artificial gravity onboard a Mars Crew Transportation System (CTS). Both concepts feature a modular design with multiple propulsive stages arranged along a truss structure and connected to a pair of rotating habitats. However, the habitat truss structure and axis of rotation varies between the two concepts.

The first concept (AG1) places the habitats at opposite ends of a long truss with a central docking node at the center. The entire truss rotates about the central docking node where it is attached to the propulsive stage assembly. This concept is shown in Figure 38 and the masses required for each of the AG system components is given in Table 52.

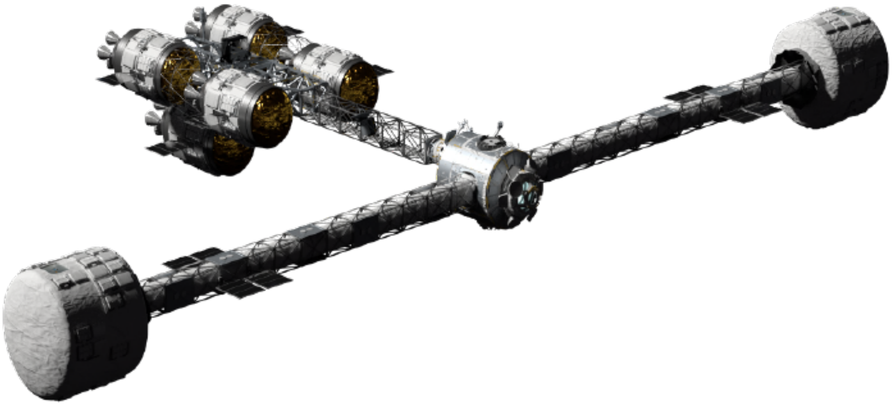


Figure 38. Notional AG1 "Traditional" Concept Configuration for Torpor and Non-Torpor Habitats

Table 52. AG1 Component Masses and Descriptions

Component	Mass [t]	Length [m]	Diameter [m]
Rotating Truss	12.0	60.0	2.0
Central Docking Node	11.6	-	4.2
Cupola	1.8	-	3.0
CMGs	5.0	-	-
Total	**30.4**		

Compared to a non-AG CTS design, the AG1 requires an additional 30.4 tons of hardware, plus the additional propellant mass required to rotate the system and that depends on the total mass moment of inertia.

The second concept (AG2) leverages the crew's stationary state in torpor to dramatically reduce the radius of rotation. AG2, shown in Figure 39, shrinks the distance to the habitat from the central docking node, and places the axis of rotation along the center axis of each habitat. The habitats rotate in opposite direction to balance the imparted rotational moments.

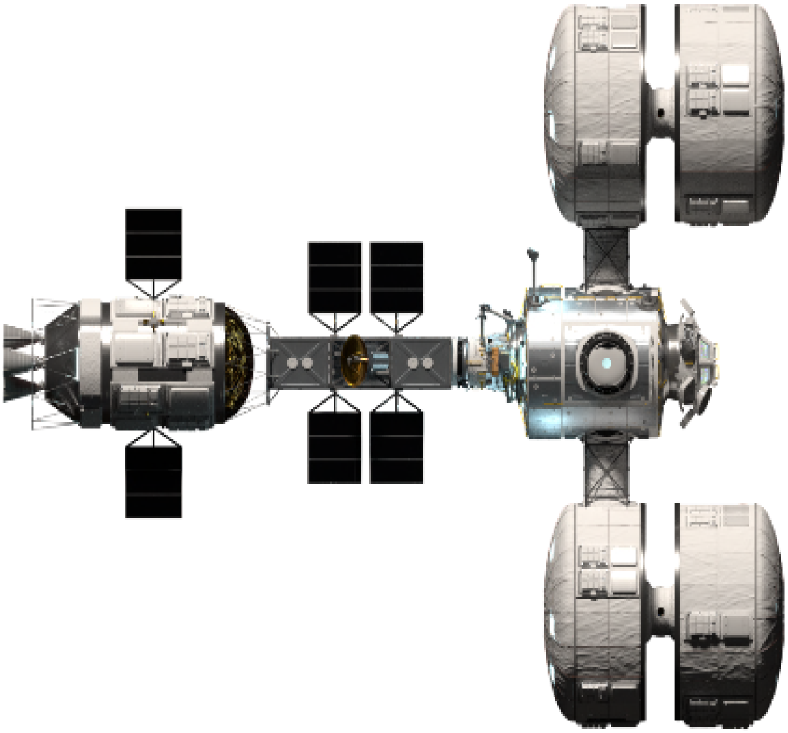


Figure 39. Notional AG2 Configuration

The reduction in truss length reduces the total mass of the AG system hardware for AG2 to 21.4 tons. See Table 53 for details.

Table 53. AG2 Component Mass Estimates and Descriptions

Component	Mass [t]	Length [m]	Diameter [m]
Rotating Truss	3.0	15.0	2.0
Central Docking Node	11.6	-	4.2
Cupola/CMGs	5.8	-	3.0
Total	**21.4**		

11.3.3. Impact on Crew Transportation Architecture

Each of these artificial gravity concepts offer crew-health benefits at the cost of additional mass. To characterize the optimal configuration for each AG concept, SpaceWorks evaluated over 40,000 alternative designs. This study uses the same ground rules and assumptions laid out for 8-crew missions to Mars in Section 8.5. All mission ΔV estimates are based on the same mass-optimal trajectory that departs during the 2039 opportunity.

Table 54 enumerates the parameter values that were explored in the design space sweep.

Table 54. Full-Factorial Trade Space Parameters for Artificially Induced Gravity Configurations

Parameter	Values	Units
Outbound Stage Count	1, 2, 3	#
Return Stage Count	1, 2, 3	#
Engine Design Thrust	20.0, 22,5, 25.0	Klbf
Propulsion Stage Diameter	9.0, 10.0, 11.0, 12.0, or 13.0	feet
Outbound Stage #1 Engine Count	1, 2, 3, or 4	#
Outbound Stage #2 Engine Count	1, 2, 3, or 4	#
Return Stage #1 Engine Count	1, 2, 3, or 4	#
Return Stage #2 Engine Count	1, 2, 3, or 4	#

First, SpaceWorks characterized the impact of the AG1 concept on the crew transportation system (CTS) for an 8-crew mission to Mars departing in 2039. All crew, environmental, and propulsion assumptions for this study match the assumptions given in Sections 8.2 and 8.5. Table 55 provides the propulsive ΔVs, assuming four ~300 second burns at TMI, MOI, TEI and EOI, with a departure in 2039.

Table 55. Minimum C_3 Trajectories for 2039 Mission to Mars

Parameter	Outbound Trajectory	Return Trajectory
Departure Date	10/08/2039	08/13/2041
Arrival Date	06/09/2040	05/15/2042
ΔV1	1.05 km/s	1.079 km/s
ΔV2	1.00 km/s	0.593 km/s
Time of Flight	245 days	275 days
Total C3	48.731 km^2/s^2	17.947 km^2/s^2

To appropriately characterize the feasible results from the design space exploration, SpaceWorks applied constraints on the total wet mass and initial thrust-to-weight (T/W) of each propulsive stage. The total wet mass was constrained to 50 tons, the SLS Block II launch capacity to DRO, and the stage initial T/W was constrained to 0.24. Under these constraints, AG1 with the SpaceWorks Torpor habitat is feasible with a total of six propulsive stages. However, sizing the AG1 CTS with the EMC Reference habitat yields no viable variants under these constraints. For the sake of comparison, these constraints were relaxed to a maximum propulsive stage mass of 65 tones (30% increase of SLS Blk-2 capabilities) and a minimum stage initial T/W of 0.18. Under the relaxed constraints, the AG1 system with EMC Reference habitats requires a total of 6 propulsive stages, each with a wet mass between 45 and 65 tons.

The results of the design space sweep for this configuration is shown in Figure 40. Note that each of the nine groupings of points represents a different quantity of outbound and return propulsive stages. Points colored in gray represent infeasible points based on the specific maximum stage mass and minimum stage initial T/W.

Under the relaxed constraints, the minimum CTS mass for the AG1 concept with the EMC Reference habitat is 450.47 tons. A basic mass breakdown and comparison is given in Table 56.

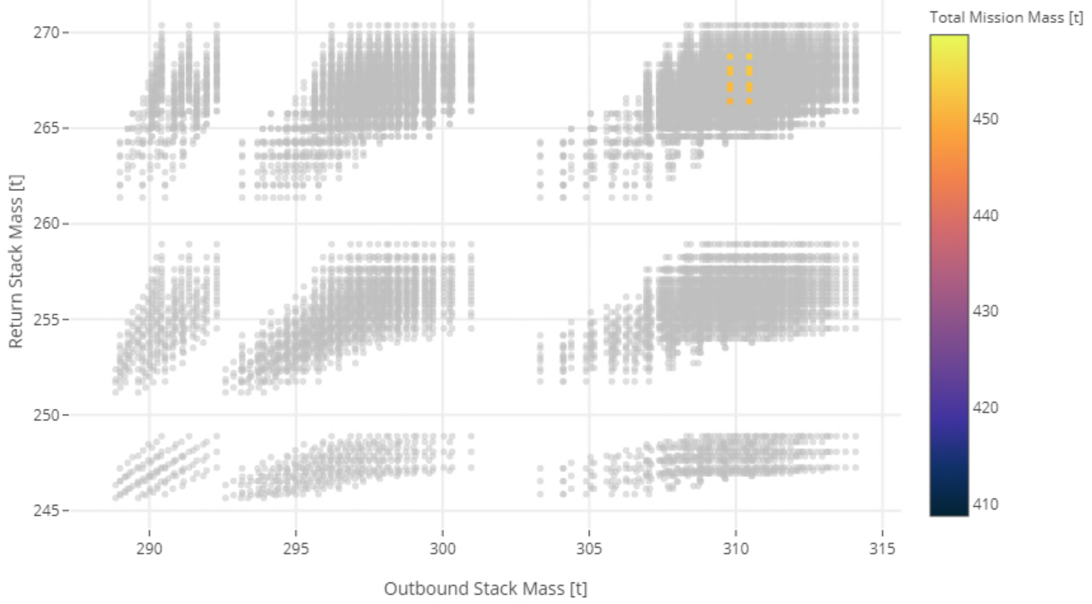


Figure 40. Total Mission Mass Sizing Results for AG1 Configuration and 2 EMC Reference Habitat for Mission to Mars Surface in 2039 (8 Crew)

Subsequently sizing the AG1 concept with the SpaceWorks Torpor habitat for 8 crew members yields far more options due to the reduced torpor habitat mass of ~44%. This mass reduction leads to reduced propellant requirements, smaller propulsive stage sizes, and enables numerous options for minimum mass systems that have one less propulsive stage, as shown in Figure 41.

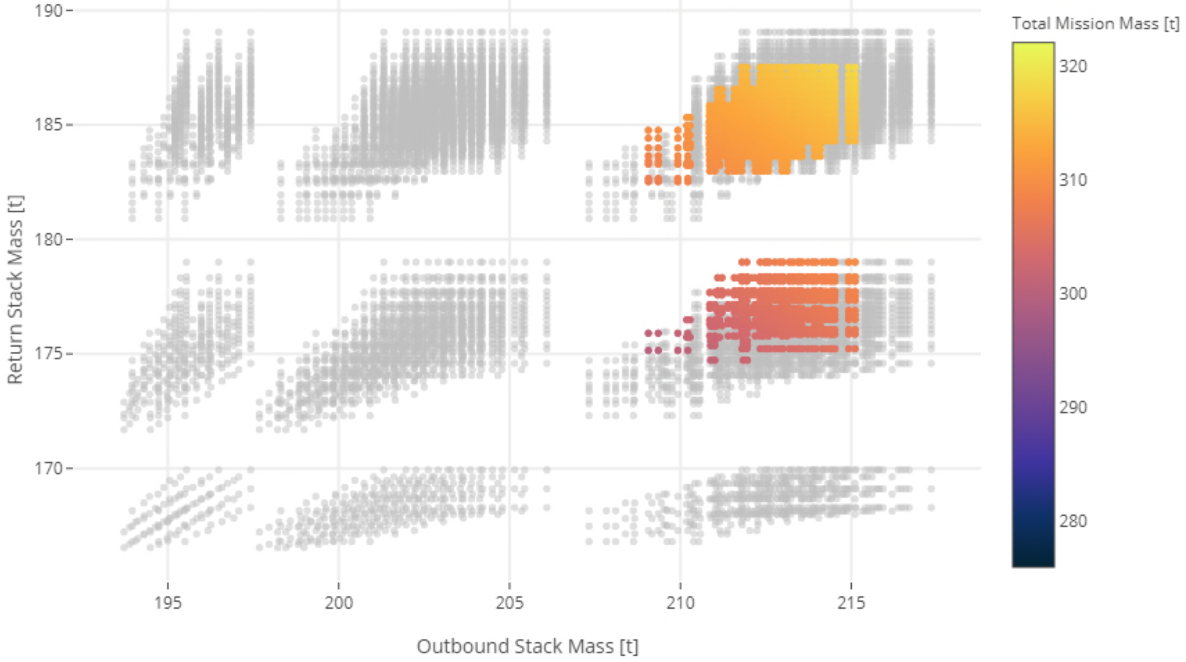


Figure 41. Total Mission Mass Sizing Results for AG1 Configuration and 2 SpaceWorks Torpor Habitats for Mission to Mars Surface in 2039 (8 Crew)

Finally, SpaceWorks performed the same design space sweep described in Table 54 to characterize and compare the AG2 concept relative to the AG1 concept. Note that the AG2 concept design using a small radius of rotation is only feasible with the SpaceWorks Torpor habitat and inactive crew members.

The AG2 concept reduces the mass of the AG hardware systems from 30.4 tons to 20.4 tons (a 9t savings), and significantly reduces the propellant mass necessary to provide the same level of artificial gravity. These mass savings are passed downstream to the propellant and inert masses of the propulsive stages to enable the lowest total system mass of any of the AG concepts. All evaluated configurations from the design space sweep are displayed in Figure 42. The total system mass for the best AG2 configuration was 251.78 tons and consisted of 2 outbound stages and 2 return stages.

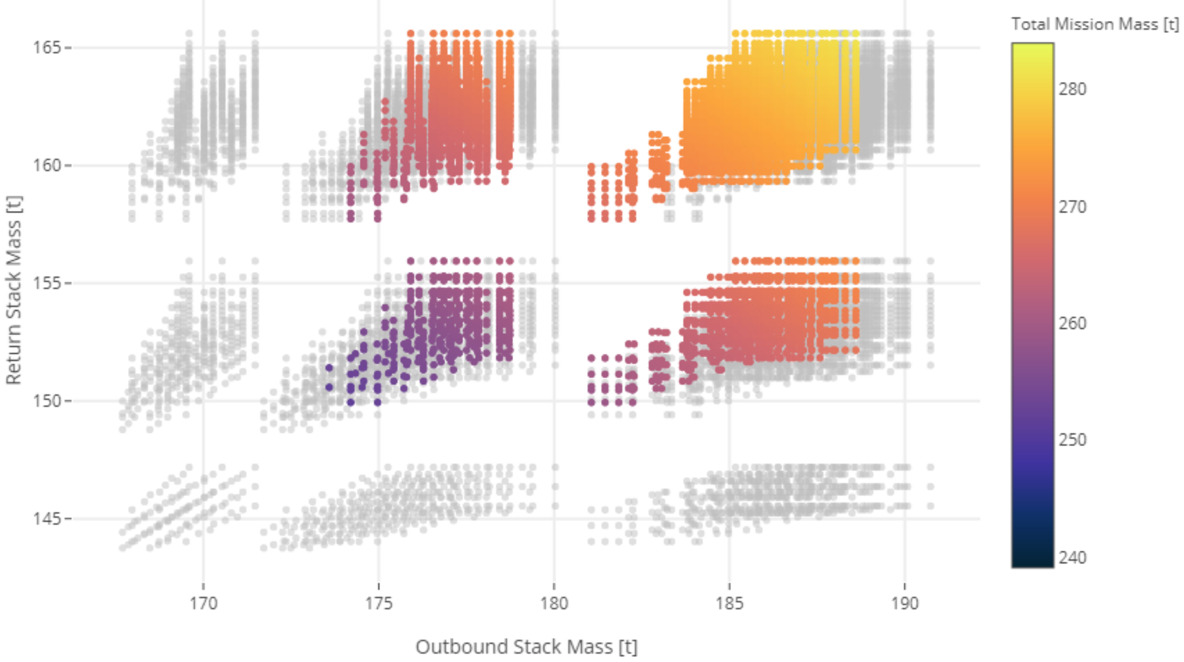


Figure 42. Total Mission Mass Sizing Results for AG2 Configuration and 2 SpaceWorks Torpor Habitats for Mission to Mars Surface in 2039 (8 Crew)

11.3.4. Summary

The addition of an artificial gravity system to a Mars mission architecture results in a significant increase in total system mass but may be required if numerous human spaceflight challenges cannot be solved through other means. Compared to the non-AG systems with 8 crew and the EMC Reference habitat, inclusion of the AG1 system led to a 35% increase in total system mass and was unable to meet the original constraints on maximum propulsive stage mass and minimum propulsive stage T/W. Under the original constraints, the torpor-enabled habitat becomes a required and enabling technology to fly a Mars mission with the AG1 system. Furthermore, the torpor-enabled habitat leads to even greater mass savings by enabling the AG2 concept. The minimum system mass and mass breakdown for each of the three cases studied in this section are given in Table 56.

While the architecture costs were not estimated for this initial examination, it is anticipated that one of the most significant mission cost reductions will be due to reductions in the number of propulsion stages. While the lower system mass is beneficial, the elimination of actual hardware elements and engines from the architecture as well as in-space automated rendezvous and docking (AR&D) maneuvers are expected to be more impactful.

Table 56. Mass Breakdown for the Minimum-Mass Solutions of Each AG Concept Case

Component	AG1 with EMC Reference Habitat	AG1 with Torpor Habitat	AG2 with Torpor Habitat
Habitat Mass (x2)	92.58 t	52.17 t	51.17 t
AG System Total Mass	37.0 t	33.7 t	21.8 t
Total Crew System Mass	450.48 t	299.9 t	251.8 t
Number of Propulsive Stages	6	5	4
Number of Engines	25	18	12

12. Developmental Roadmap

12.1. Technology Development Roadmap

The team developed a high-level timeline and roadmap of the activities, studies, and research efforts necessary to mature and advance the torpor technology and concept from both a medical and engineering perspective. This roadmap is designed and coordinated to support human exploration missions to deep space starting in the 2030s timeframe, consistent with the mission architecture analysis.

The roadmap identifies 14 key research and development activities. Activities are identified as being either: Primary, Secondary, or Tertiary. Primary activities are critical to development and implementation of the technology. Secondary activities are generally capability enhancements to the system and/or technology. Tertiary activities are primarily contingency off-ramps for the baseline approach.

Element	Timeframe/ Duration	Type	Preceeding Elements	Title	Description
1.0		**PRIMARY**	**-**	**EVALUATION AND ADMINISTRATION OF ADENOSINE A1AR AGONISTS IN HUMANS**	
1.1	Jan-2019	Sub-Element	-	Expanded Large Animal Study	*Porcine evaluations to confirm physiological response to administration of A1AR agonists*
1.1.1	*3 months*	*Activity*	-	*Large Animal Study for Torpor Induction*	*Short/minimal duration evaluations examining induction process and response using A1AR agonists*
1.1.2	*3 months*	*Activity*	1.1.1	*Large Animal Study for Torpor Maintenance*	*Longer duration evaluations examining the induction process followed by brief maintenance periods to assess sustained torpor when using A1AR agonists*
1.1.3	*6 months*	*Activity*	1.1.2	*Large Animal Study for Prolonged Torpor*	*Extended duration evaluations refining the induction process followed by long maintenance periods*
1.1.4	*12 months*	*Activity*	1.1.3	*Large Animal Study with Repeat Torpor Cycles*	*Studies to evaluate impact of multiple, repeat extended duration torpor cycles*
1.2	Jan-2021	Sub-Element	1.1	Limited Human Trials for Torpor Induction	Testing on 4-6 healthy, human volunteers using CHA/8-SPT and spontaneous rewarming. Mix of men and women, with nominal ages in mid-20s and mid-40s. Cooling will be via cold saline injection and application of external gel pads. Nutrition will not be provided.
1.2.1	*3 months*	*Activity*	-	*Feasibility of Torpor Induction in Healthy Humans*	*Achieve core body target temperatures after administration of torpor induction medication, starting at 35degC, 34degC, 33degC, 32degC*
1.2.2	*6 months*	*Activity*	*1.2.1*	*Safety of Torpor Induction in Healthy Humans*	*Assess any side effects due to chemical induction of torpor, including limited airway patency, adequacy of spontaneous ventilation, shivering, and hemodynamic stability*
1.2.3	*6 months*	*Activity*	*1.2.2*	*Optimal Weight-Based Dosage for Safe Induction of Torpor*	*Evaluate various doses of torpor induction medication to reach target temperature with minimal side effects*

1.2.4	*3 months*	*Activity*	*1.2.3*	*Tolerability of Induction without Sedation*	*Evaluate volunteer physical and mental response to induction without use of sedatives. Examine cold sensitivity based on cooling rate to target core temperature and target temperature.*
1.3	Jul-2022	Sub-Element	1.2, 1.1.2	Limited Human Trials for Torpor Maintenance	Testing on 4-6 healthy, human volunteers using CHA/8-SPT and controlled rewarming. Target maintenance period will be 24-hours. Mix of men and women, with nominal ages in mid-20s and mid-40s. Use of sedation during induction will be dependent on outcomes from 1.2.4 activity. All cooling will be via cold saline injection and application of external gel pads. Nutrition will not be provided.
1.3.1	*6 months*	*Activity*	*-*	*Feasibility of Torpor Maintenance in Healthy Humans*	*Maintain target temperature after induction and achieving target temperature*
1.3.2	*6 months*	*Activity*	*1.3.1*	*Safety of Torpor Maintenance in Healthy Humans*	*Assess any side effects during chemical maintenance of torpor, including limited airway patency, adequacy of spontaneous ventilation, shivering, and hemodynamic stability*
1.3.3	*3 months*	*Activity*	*1.3.2*	*Optimal Weight-Based Dosage for Safe Maintenance of Torpor*	*Evaluate various doses of torpor induction medication to maintain target temperature with minimal side effects.*
1.3.4	*3 months*	*Activity*	*1.3.2*	*Tolerability of Maintenance without Sedation*	*Evaluate volunteer's physical and mental response to torpor maintenance without use of sedatives. Induction period may or may not use sedation pending outcome of 1.2.4.*
2.0		**PRIMARY**		**HUMAN TRIALS FOR SPACE TORPOR**	
2.1	Jan-2024	Sub-Element	1.3	Expanded Human Torpor Trials Study	Significantly expand number of human volunteers. All will use continuous infusion of CHA/8-SPT and controlled rewarming. Target maintenance periods will range from 72-336 hours. Mix of men and women, with nominal ages in 20s and 50s, and of various body mass. Cooling during induction will be via cold saline injection and ambient air during maintenance. Enteral feeding will be supplied using via gastrointestinal tube.
2.1.1	*3 months*	*Activity*	*-*	*Feasibility and Safety with 3-Days Torpor for Healthy Humans*	*Conduct torpor induction and maintenance evaluations with 3-day maintenance periods for all volunteers.*
2.1.2	*2.5 years*	*Activity*	*-*	*Characterization of Metabolic Rate Reductions and Consumables Demand during Torpor*	*Measure impact of torpor on metabolic rate reductions via oxygen demand, CO2 production testing, etc. Assess caloric demands to provide and maintain adequate nutrition with extended duration torpor periods.*
2.1.3	*6 months*	*Activity*	*2.1.1*	*Feasibility and Safety with 7 Days Torpor for Healthy Humans*	*Conduct torpor induction and maintenance evaluations with 7-day maintenance periods for all volunteers.*
2.1.4	*12 months*	*Activity*	*2.1.2*	*Feasibility and Safety with 2 Weeks Torpor for Healthy Humans*	*Conduct torpor induction and maintenance evaluations with 14-day maintenance periods on subjects*

					exhibiting greatest tolerance during induction, health/stability during maintenance, and fastest recovery.
2.1.5	*12 months*	*Activity*	*2.1.3*	*Feasibility and Safety of Repeat Torpor Cycles in Humans*	*Conduct torpor induction and maintenance evaluations with repeat torpor cycles. Initial evaluation would focus on 3-day torpor cycles with a 7-day recovery period. This would be expanded to 14-day torpor cycles with a 14-day recovery period. Maximum number of repeat cycles would be dependent on physiologic, mental and emotional tolerance of volunteers.*
2.2	Oct-2026	Sub-Element	2.1	Conduct In-Space Evaluations of Torpor	
2.2.1	*6 months*	*Activity*	-	*LEO ISS Environment Torpor Test of Human Induction*	*Repeat of previous protocols from 1.3 and 2.0 in a LEO gravity free environment. These will be Human-tended procedures, with minimal automation*
2.2.2	*6 months*	*Activity*	2.2.1	*LEO ISS Environment Torpor Test of Human Induction/Maintenance*	*Repeat of previous protocols from 1.3 and 2.0 in a LEO gravity free environment. These will be Human-tended procedures, with minimal automation*
2.2.3	*6 months*	*Activity*	2.2.2	*Examining the Optimal Dosage for In-space Application/Administration of Torpor*	*Repeat of previous protocols from 1.3 and 2.0 in a LEO gravity free environment. These will be Human-tended procedures, with minimal automation*
2.2.4	*6 months*	*Activity*	-	*Body Thermal Management System Testing*	*Evaluation of current terrestrial torpor thermal management systems intended for use during prolonged torpor cycles in a gravity free environment. Any noted engineering changes required for proper function would be noted and equipment modifications performed at this time.*
2.2.5	*12 months*	*Activity*	-	*Evaluation of Automated Torpor Support Systems*	*Evaluation of current terrestrial torpor automated support systems intended for use during prolonged torpor cycles in a gravity free environment. Any noted engineering changes required for proper function would be noted and equipment modifications performed at this time.*
3.0		**PRIMARY**		**SPACE TORPOR MISSION APPLICATION**	
3.1	Oct-2028	Sub-Element	2.2.2, 2.2.4, 2.2.5	In-Space Cis-Lunar Mission Trials Using Human Torpor	
3.1.1	*1 year*	*Activity*	-	*Deep Space Mission Protocols for Torpor*	*Verification and test simulated "deep space" mission protocols under nominal conditions*
3.1.2	*1 year*	*Activity*	3.1.1	*Use of Torpor During Emergency Conditions in Deep Space*	*Evaluate and test emergency response protocols in simulated "deep space" conditions*
3.1.3	*1 year*	*Activity*	3.1.3	*Torpor-Enabled Cis-Lunar Checkout Flight*	*Conduct extended mission in cis-lunar space or Gateway using torpor with multiple cycles.* *30-90 day mission with total crew complement of 4; 2 crew members*

					undergoing torpor cycles during mission
3.2	2032-2035	Sub-Element	3.1	Enabling the First Human Mars-Vicinity Space Missions	*Mission to Mars moons Phobos/Deimos, with crew complement of 4. Up to two weeks of torpor and repeat cycles during transit phases, with minimum of 1 active caretaker.*
3.3	2036-2040	Sub-Element	3.1	Enabling the First Human Mars-Landing Space Missions	*Mission to Mars surface, with crew complement of 4. Up to two weeks of torpor and repeat cycles during transit phases, with minimum of 1 active caretaker. Utilizing NMES and/or artificial gravity for muscle atrophy and bone loss.*
4.0		**SECONDARY**		**RADIOPROTECTIVE EFFECTS FOR HUMAN TORPOR WITH METABOLIC SUPPRESSION**	
4.1	Jan-2019	Sub-Element	-	Identification of Mechanisms for Human Radioprotective Effects During Torpor	Develop theories on possible mechanisms for radioprotective effects in humans
4.2	Jan-2023	Sub-Element	4.1	Animal Evaluations for Radiation Shielding Mechanisms	
4.2.1	*3 years*	*Activity*	-	*Exposure Evaluation of Hibernating vs. Non-Hibernating Species at NASA Space Radiation Lab (NSRL), Brookhaven*	*Examine radiation exposure impacts between hibernating and non-hibernating species*
4.2.2	*3 years*	*Activity*	*4.2.1*	*Exposure Evaluation for Large Animals at NASA Space Radiation Lab (NSRL), Brookhaven*	*Conduct porcine study to assess any potential mechanisms that reduce radiation exposure impacts*
4.3	Jan-2030	Sub-Element	3.1.3, 4.2	Evaluation of Humans During Cis-Lunar Space Missions Utilizing Long-Duration Torpor	Obtain baseline radiation exposure levels between torpor and non-torpor crew members
4.3.1	*1 year*	*Activity*		*Crew monitoring during mission, with non-torpor control group vs. torpor test group*	
4.4	2032-2035	Sub-Element	3.1, 4.3	Evaluation of Human Radiation Exposure Impacts During Deep Space Missions	Compare radiation exposure levels for crew with shielded torpor pods vs. unshielded
4.4.1	*4 years*	*Activity*		*Crew monitoring during mission*	
5.0		**SECONDARY**		**MUSCLE ATROPHY IMPACTS WITH METABOLIC SUPPRESSION DURING HUMAN TORPOR**	
5.1	Jan-2020	Sub-Element	1.1.3	Quantifying Muscle Atrophy Rates in Non-Hibernating Animals with Metabolic Suppression	Large animal model testing using post torpor muscle strength testing and needle biopsy of muscular tissues to identify impacts of torpor on gravity based muscle atrophy
5.2	Oct-2024	Sub-Element	5.1, 2.1.2	Quantifying Muscle Atrophy Rates in Humans Undergoing Metabolic Suppression	Large human model testing using post torpor muscle strength testing and needle biopsy of muscular tissues to identify impacts of torpor on gravity-based muscle atrophy

5.3	Oct-2025	Sub-Element	5.2	Terrestrial NMES Effectiveness Studies	Large human model testing using patient populations at risk for muscle atrophy (i.e. coma, paralysis, elderly) to evaluate the effectiveness of whole-body NMES for muscle atrophy prevention. Study will utilize post therapy muscle strength testing and needle biopsy of muscular tissue to identify impacts after extended and extensive use of NMES on muscle atrophy
5.4	Oct-2028	Sub-Element	2.2.2, 5.3	Space-Based NMES Effectiveness Studies	Human model testing using ISS/LEO based crew members to evaluate the effectiveness of NMES for muscle atrophy prevention. Study will utilize post therapy muscle strength testing and needle biopsy of muscular tissue to identify impact of NMES on gravity-based muscle atrophy
6.0		**SECONDARY**		**BONE DEMINERALIZATION IMPACTS WITH METABOLIC SUPPRESSION DURING HUMAN TORPOR**	
6.1	Jan-2020	Sub-Element	1.1.3	Quantifying Bone Demineralization Rates in Non-Hibernating Animals with Metabolic Suppression	Large animal model testing using post torpor DEXA scans and core biopsies of bone tissue to identify impact of torpor on gravity-based bone demineralization
6.2	Oct-2024	Sub-Element	5.1, 2.1.2	Quantifying Bone Demineralization Rates in Humans with Metabolic Suppression	Large human model testing using post-torpor DEXA scans and core biopsies of bone tissue to identify impact of torpor on non-use bone demineralization
6.3	Oct-2027	Sub-Element	2.2.2, 6.2	Space-Based Bone Demineralization Studies	Human model testing using ISS/LEO based crew members to evaluate the effectiveness torpor for the prevention of bone demineralization. Study will utilize post-torpor DEXA scans and core biopsies of bone tissue to identify impact of torpor on gravity-based bone demineralization
7.0		**SECONDARY**		**INCREASED INTRACRANIAL PRESSURE (ICP) IMPACTS DURING METABOLIC SUPPRESSION AND COOLING**	
7.1	Oct-2025	Sub-Element	2.1.3	Terrestrial Head Tilt Studies During Application of Torpor in Healthy Humans	Large human model testing using Head Tilt Studies during torpor cycles to identify the impact of torpor Space Adaptation Syndrome and potential gravity induced increased ICP.
7.2	Oct-2027	Sub-Element	7.1, 2.2.2	Space-Based Measurements of Astronaut Cranial Pressure During Torpor	Human model testing using ISS/LEO based crew members to evaluate the short-term impact of torpor Space Adaptation Syndrome and potential gravity induced increased ICP.

7.3	Oct-2030	Sub-Element	2.2.2, 3.1.2	Assessment of VIIP Impact During Extended Space Mission	Human model testing using ISS/LEO based crew members to evaluate the long-term impact of torpor Space Adaptation Syndrome and potential gravity induced increased ICP.
8.0		**TERTIARY**		**HUMAN TORPOR PHENOTYPE CHARACTERIZATION FOR OPTIMAL APPLICATION OF METABOLIC SUPPRESSION**	
8.1	Oct-2026	Sub-Element	2.1	Conduct human studies to establish optimal application/administration of torpor as well as any unique human tolerance/adaptations based on phenotype (height, gender, metabolism, etc.)	Conduct torpor induction and maintenance evaluations with repeat torpor cycles. Focus of this study would be to validate any data collected from 2.1.4 that would indicate unique physiologic (i.e. weight, height, race, gender) or genetic tolerance of torpor by certain crew members
9.0		**PRIMARY**		**HUMAN TORPOR COGNITIVE AND PERFORMANCE STUDIES**	
9.1	Oct-2026	Sub-Element	2.1	Mental Capabilities	Conduct torpor induction and maintenance evaluations with repeat torpor cycles with pre-cycle and post-cycle cognitive function, memory and psychological evaluation scores.
9.2	Oct-2026	Sub-Element	2.1	Physical Capabilities	Conduct torpor induction and maintenance evaluations with repeat torpor cycles with pre-cycle and post-cycle physical performance and dexterity evaluations.
10.0		**PRIMARY**		**FEEDING AND HYDRATION SYSTEMS FOR EXTENDED TORPOR MAINTENANCE PERIODS**	
10.1	Jul-2023	Sub-Element	-	Design of Automated Control Systems for Monitoring, Measuring, Delivery, and Waste Management of Enteral Nutrition and Hydrating Fluids	Adjustments to systems based on findings from 2.2.4 and 2.2.5
10.2	Jul-2025	Sub-Element	10.1	Short-Duration Testing of ACS-MMDWM Nutrition/Hydration via PEG Tube in Healthy Humans Undergoing Torpor	Conduct torpor induction and maintenance evaluations with repeat torpor cycles to evaluate the effectiveness and potential short-term side effects and complications of PEG enteral feeding and waste collection.
10.3	Jul-2027	Sub-Element	10.2	Long-Duration Testing of ACS-MMDWM Nutrition/Hydration via PEG Tube in Healthy Humans Undergoing Torpor	Conduct torpor induction and maintenance evaluations with repeat torpor cycles to evaluate the effectiveness and potential long-term side effects and complications of PEG enteral feeding and waste collection.
11.0		**PRIMARY**		**AUTOMATED THERMAL CONTROL SYSTEM DEVELOPMENT**	
11.1	Oct-2021	Sub-Element	-	Space-Qualified Sensor Development for Core Temperature Monitoring	Primarily terrestrial evaluations. Develop and test medical devices for use in space environment for monitoring temperature of core and

					extremities. Devices must be suitable for long-term use, reliable, highly accurate, and non-invasive.
11.2	Oct-2022	Sub-Element	11.1	Cooling Management and Effectiveness Studies	Look at various approaches and techniques for highly-controlled decrease in body and core temperature. Including ambient air cooling, periodic application of gel pads, esophageal cooling devices (ECD), trans-nasal cooling systems, etc.
11.3	Oct-2023	Sub-Element	11.1	Warming Management and Effectiveness Studies	Look at various approaches and techniques for highly-controlled increase in body and core temperature. Including ambient air rewarming, thermal blankets, heat pads, etc.
12.0		**TERTIARY**		**OFF-RAMP : ARTIFICIALLY-INDUCING GRAVITY**	
12.1	Jan-2025	Sub-Element	5.3, 6.2	Mitigation of Bone Loss and Muscle Atrophy Using Artificial Gravity via Small Radii Rotational Systems	Large human model testing while in induced torpor state using ground centrifuge testing to identify feasibility of torpor and the physiologic tolerance of humans to small radii rotation.
12.1	*18 months*	*Activity*		*Ground Centrifuge Testing in Torpor State (examine RPM and radius impacts, assess crew comfort, operations impact - safety)*	
12.2	*18 months*	*Activity*	*12.1*	*Full-scale Ground Prototype Development*	
12.3	*2 years*	*Activity*	*12.2*	*Unmanned, In-Space System Testing*	
13.0		**PRIMARY**		**TORPOR MODULE ENGINEERING ANALYSIS & DESIGN**	
13.1	Jan-2017	Sub-Element	-	Concept Design Review (CoDR)	*Completed in NIAC Phase-2 Study*
13.2	Jan-2019	Sub-Element	13.1	System Requirements Assessment (leading to SRR)	Establish functional requirements, with threshold and objective goals
13.3	Jul-2019	Sub-Element	13.2	Construct full-scale system mockup	Establish functional layout and design for demonstration purposes
13.4	Jul-2020	Sub-Element	13.2, 13.3	Subsystem RDT&E	
13.5	Jan-2026	Sub-Element	13.4	Ground Prototyping and Integrated Demonstration	
13.6	Jan-2027	Sub-Element	13.5	Flight-Qualified Prototype Development	
14.0		**PRIMARY**		**SYSTEM ENGINEERING FOR SPACE HABITAT DESIGN AND DEVELOPMENT**	
14.1	Jan-2017	Sub-Element	-	Concept Design Review (CoDR)	Design update will be pending outcome on effectiveness of torpor in mitigating microgravity effects on bone/muscle in 6.0 and 12.0.

14.1.1	*2 years*	*Activity*		*Completed in NIAC Phase-2 Study*	
14.2	Jan-2019	Sub-Element	14.1	System Requirement Review (SRR)	Establish functional requirements, with threshold and objective goals
14.3	Jan-2020	Sub-Element	14.2, 13.4, 13.3	Preliminary Design Development (leading to PDR)	Detailed design of critical subsystems
14.4	Jan-2022	Sub-Element	14.3, 13.5	System RDT&E Phase (leading to CDR)	
14.5	Jan-2026	Sub-Element	14.4	Full-Scale Ground Prototype	
14.5	Jan-2027	Sub-Element	14.5, 13.5	Production of Space-Qualified Block-1 Unit	
14.6	Jan-2029	Sub-Element	14.5, 3.1.2	Cis-Lunar Flight Demonstrations	
14.7	Oct-2031	Sub-Element	14.6	Production of Deep Space Habitat Block-2 Unit	
15.0		**TERTIARY**		**OFF-RAMP : NUTRITION AND FEEDING VIA TPN**	
15.1	Jan-2026	Sub-Element	10.2	Design of Automated Control Systems for Monitoring, Measuring, Delivery, and Waste Management of Total Parenteral Nutrition and Hydrating Fluids	
15.2	Jul-2027	Sub-Element	15.1	Human Testing of ACS-MMDWM Nutrition/Hydration via PEG Tube in Healthy Humans Undergoing Torpor	

12.2. Technology Maturation Challenges

The team identified a number of key challenges and obstacles that must be solved and/or overcome in order to see this capability come to fruition. While not an exhaustive list, some notable items will be discussed briefly.

12.2.1. Receipt of FDA Drug Approvals

The proposed A_1AR agonist, CHA, and antagonist, 8-SPT, used as an alternative, improved means to induce a low metabolic state in humans has not actually been tested in humans to date. FDA approval will be necessary before trials and further evaluation of the CHA/8-SPT compounds can begin on humans.

While there have been numerous successful evaluations of these drugs on small animals, and limited studies on large animals, at least one large animal study involving numerous additional subjects (and a successful outcome) will likely be required before proceeding to human trials.

12.2.2. Minimizing Sedation Levels

With current clinical applications in critical care scenarios, heavy sedation is used to minimize movement, suppress the shivering reflex during cooling, reduce pain, and provide for the overall comfort of the patient. For a healthy crew, the primary concerns are to suppress the shivering reflex and provide for overall comfort. However, receiving high sedation levels over long periods of time will significantly increase the recovery period after a torpor cycle, possibly require the need to intubate the crew member, and is likely to have detrimental health effects.

The ability and need to minimize the sedation levels is of the upmost importance. The use of A_1AR agonists may suppress the shivering reflex and therefore significantly reduce the necessary sedation levels. A light sedative such as dexmedetomidine is a promising candidate for use during torpor. This non-opioid drug can sedate without the respiratory depression often encountered with many sedatives (e.g. Propofol, fentanyl, diazepam) and can even permit communication with the crew member in a semi aroused state. However, the impacts of long-term use of dexmedetomidine have not been evaluated and thus it is not currently recommended for use in clinical settings beyond short periods.

12.2.3. Torpor Testing in the Spaceflight Environment

Once successful terrestrial-based torpor testing has occurred and advanced sufficiently, testing will need to be conducted in the space environment. Initially, this is likely to be performed on a platform such as the International Space Station (ISS) or a future cis-lunar Gateway.

However, there is a very risk-adverse culture towards spaceflight when it comes to humans and potentially high-risk experiments. To date, there has never been any surgery or even a sedated astronaut in space. Excluding spaceflight-related deaths, all injuries have been relatively minor. This will pose challenges to testing. Particularly when it comes to fully exploring the limits and characterizing the capabilities of torpor. In addition to evaluating nominal operating conditions, scenarios that involve testing of emergency conditions will need to be conducted. These will include hardware system failures, rates that infection can spreads, rapid rewarming, etc.

12.2.4. Evaluation of Potential Radioprotective Effects

One of the more interesting and potentially significant impacts of torpor may reside in its ability to mitigate and reduce the damaging effects of space radiation. There is a growing body of evidence to support this as a possibility and to establish a plausible medical theory. While numerous extensive experiments and tests could be conducted at the cellular level, with organs, on small animals, etc., the testing of radiation exposure impacts on humans is highly problematic.

While new test facilities are being developed, the general approach for torpor development as it pertains to humans is to not presume any benefits and to conduct testing and collect data between torpor and non-torpor crew members over the natural course of spaceflight missions. Over time, any benefits that are identified and measured will be further leveraged to increase system performance, improve crew health, etc.

13. Summary and Recommendations

This effort resulted in significant refinements to the envisioned approach for implementing the torpor concept for applications in space. The team methodically worked through the various challenges that were identified for the concept and made a number of changes to mitigate any potential issues. As such, we believe a sounder and more practical path forward for the development of 'space torpor' has been established.

From a medical perspective, a number of findings and changes to the original concept were made. Specifically,

- The sentinel protocol proved a reasonable and viable approach for implementing the torpor concept. The total crew time spent in torpor during the transit segment of a Mars mission was generally 70-80%, based on results from the Bio-Simulator tool. The team still envisions ultimately being able to support torpor durations for the crew (and passengers) that last the entirety of the transit phase, this capability will take time to achieve. In the near-term, achieving torpor cycles of 14-21 days can still have a significant positive impact to the mission design, sizing of architecture elements, and overall crew health.

- The transition from crew nutrition and hydration provided via TPN to a liquid enteral solution approach supplied via a PEG tube resulted in eliminating a number of potential medical complications and permits the crew to consume normal (solid) food via oral intake when available and desired.

- The use of cooled ambient air in the habitat as a means of achieving body thermal control (versus a trans nasal catheter device) eliminates a hardware medical system as well as the slightly uncomfortable implementation process for the crew of placing a cannula into their nostrils

- Dexmedetomidine was identified as an excellent candidate for providing the necessary light sedation necessary for the crew during torpor induction.

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

- For the 4-crew habitat system designs, a mass savings of 56% was achieved. These gains were achieved through modifications of a more conservative system, that began with a very detailed NASA EMC reference design

- For the 8-crew habitat system design, a 20% mass savings was realized, however had associated cost penalty of 25% cost increase (or $998M) compared to simply producing two of the 4-crew habitats concepts

Specific results of the architecture design work performed yielded the following:

- SpaceWorks conducted extensive exploration of the design space for numerous exploration missions and examined tens of thousands of architecture designs. In all cases, a torpor-enabled architecture continued to show significant mass savings compared to a traditional, non-torpor architecture design, even after permitting each architecture to be optimized.

- Cost savings of approximately $10B were realized for the crew transit system over a 10-year Mars exploration campaign comprising 3 human missions to Mars and/or its vicinity. While not likely to be a large percentage reduction in the total mission costs once surface elements, ascent/descent stage, etc. are accounted for, the return on investment is very likely to exceed 10x and possibly be 100x.

- Various scenarios were investigated to quantify alternate applications of the mass savings that can be achieved with torpor. It was demonstrated how the crew's radiation exposure levels could be reduced up to 30% with only a small mass penalty from the application of parasitic shielding. This was in comparison to mass increases on the non-torpor habitat that would yield an infeasible architecture design.

- It was determined that the transit time to Mars could be easily reduced by 25%, from 200 days to 150 days, in order to minimize the crew's time in space as well as exposure to the harmful effects of radiation and extended periods of microgravity.

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Appendix B: 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. SpaceWorks' 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.

The experienced team uses the latest multidisciplinary design techniques and analysis methods 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.

Corporate customers include NASA, the U.S. Air Force, DARPA, traditional aerospace primes and emerging space entrepreneurs and their companies. Since our founding in 2000, SpaceWorks 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.

SpaceWorks 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 was listed as one of the fastest growing businesses in the United States.

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

Appendix C: Study Team Members

DR. JOHN E. BRADFORD, NIAC FELLOW

John E. Bradford is President and Chief Operating Officer (COO) of SpaceWorks Enterprises 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. SpaceWorks' 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. 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, and regularly a guest speaker at science fiction conventions.

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.

MR. BENJAMIN MERREL, AEROSPACE ENGINEER

Mr. Benjamin Merrel is an Aerospace Engineer at SpaceWorks Enterprises, Inc. (SEI). Mr. Merrel serves as a member of SpaceWork's Advanced Concepts Group with an emphasis on hypersonic vehicle design, analysis, and tool development. Prior to joining SpaceWorks, Mr. Merrel interned with the computational fluid dynamics (CFD) groups at both Northrop Grumman and Sage Physics.

Mr. Merrel received his B.S. in Aeronautical and Astronautical Engineering from Purdue University. During his undergraduate tenure, he focused on conceptual design of hypersonic systems as an undergraduate researcher with Michael J. Grant and the Rapid Design of Systems Laboratory (RDSL). His advanced coursework included trajectory optimization, non-equilibrium aerodynamics, and U.S. technology policy. Additionally, Mr. Merrel led a student effort to become the first university team to design and test an orbital launch capability for small satellites.

MR. CALEB WILLIAMS, LEAD ECONOMIC ANALYST

Mr. Caleb Williams is the primary analyst for the SpaceWorks Commercial business unit where he specializes in helping government and commercial clients navigate the new space market landscape. Mr. Williams disciplinary focuses include parametric cost assessment, operations research, market forecasting, competitive intelligence, and corporate strategy. He routinely supports independent cost evaluations for various commercial and government customers, ranging from hypersonic vehicles to NASA flagship-mission proposals. Recent projects include a multi-year effort to model the cost impacts of additively manufactured, modular rocket engines for AFRL, the evaluation of a $3B+ LEO satellite-broadband constellation bid for a major aerospace prime, and an investigation into corporate motivations behind vertical integration activity in the small satellite sector.

Mr. Williams is the lead author for the SpaceWorks Nano/Microsatellite Market Forecast, an annual publication read by 2,500+ professionals each year and his commentary on the commercial space market has been widely featured by media outlets such as WIRED, SpaceNews, Kiplinger, NBC News, Constellations by Kratos, and many others.

In addition to his professional work, Mr. Williams serves as the Associate Conference Chair for the Symposium on Space Innovations in Atlanta, and previously served as the Principal Investigator for the Solar Crafting project in NASA's 3D Printed Habitat Design Challenge.

DR. DOUGLAS TALK, MEDICAL TEAM LIASON

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. KELLY DREW, MEMBER MEDICAL TEAM

Kelly Drew is a Professor of Chemistry and Biochemistry with a research appointment in the Institute of Arctic Biology of the University of Alaska Fairbanks. She has studied hibernation for over 20 years. She received her Ph.D. in neuropharmacology at Albany Medical School with post-doctoral research in neuropharmacology at the Karolinska Institute. Her laboratory discovered that adenosine A1 receptor stimulation drives the onset of hibernation according to a seasonal, higher order process that regulates sensitivity to purinergic signaling. These mechanisms are now being studied in non-hibernating species as novel therapies for stroke and cardiac arrest and potentially for human hibernation. Dr. Drew was one of two Americans to be invited by a group of Scientists working with the European Space Agency on aspects of human hibernation. She was invited to join this group because of her expertise in the pharmacology of hibernation. She has published 60 peer-reviewed papers and been funded since 2000 by NIH, NSF, DOD and DARPA.

DR. ALEJANDRO RABINSTEIN, MEMBER MEDICAL TEAM

Alejandro Rabinstein is a highly trained Neurocritical Care specialist with over 20 years of experience in the medical field. He has a deep interest in the therapeutic uses of induced hypothermia. He has pursued research on therapeutic hypothermia after cardiac arrest in the clinical setting and is involved in the design of experimental studies for the development of novel techniques to induce hypothermia. In 2008, Dr. Rabinstein received the Teacher of the Year Award for the Department of Neurology from the Mayo Fellows' Association. He continues to work with the Mayo Clinic as a Professor of Clinical Neurology, the Medical Director of the Neuroscience ICU, and serves as the Director of the Fellowship Program in Neurocritical Care.

An accomplished writer, Dr. Rabinstein's expertise is well known and sought after in the medical community. He has authored or co-authored six books, 23 editorials, and has had more than 250 peer-reviewed articles published. He has also contributed to websites and written reviews of various letters, books, and periodicals. Dr. Rabinstein is an active member of numerous groups and societies, including the American Academy of Neurology and the Neurocritical Care Society.

Dr. Rabinstein earned his medical degree in 1993 from Universidad Nacional de Cordoba in Argentina. He continued his studies in both Argentina and the United States becoming first a Resident in Internal Medicine, followed by a Resident in Neurology, and finally rounding off his studies by acquiring Fellowship status in Critical Care Neurology from the Mayo Clinic in 2002.

As a Neurocritical Care Specialist with training in Internal Medicine, Critical Care and Neurology, Dr. Rabinstein is deeply interested in therapeutic uses of induced hypothermia. With his training, he is well prepared to study the physiological changes encountered when hypothermia is induced and to understand the neuroprotective mechanisms of this intervention. He has pursued research on therapeutic hypothermia after cardiac arrest in the clinical setting and is involved in the design of experimental studies for the development of novel techniques to induce hypothermia.

DR. MATTHEW KUMAR, MEMBER MEDICAL TEAM

Mathew Kumar brings over 25 years of experience in every aspect of therapeutic hypothermia (TH), from protecting the vital organs during cardiopulmonary bypass to deep hypothermic circulatory arrest for the surgical correction of arteriovenous malformations of the brain. After several years in clinical practice, he returned to basic research with a solid understanding of the utility and limitations of hypothermia in the current patient care environment and a clear understanding of what is necessary to safely extend the viable duration of therapeutic hypothermia beyond 1 or 2 weeks. The Mayo Clinic has an over 100-year history of fostering scientific research and medical innovations. The institution is committed to providing time, materials, and the personnel necessary for investigators to succeed. Its research laboratories, hospitals, and graduate schools provide the intellectual environment and resources required to accomplish the goals of the proposed study.

DR. LEROY CHIAO, MEMBER MEDICAL TEAM

Leroy Chiao is a former NASA astronaut and International Space Station commander. He works in business and consulting. Chiao also holds appointments at Rice University and the Baylor College of Medicine and is the special advisor for human spaceflight to the Space Foundation. He has worked extensively in both government and commercial space programs and has held leadership positions in commercial ventures and NASA. Chiao has extensive experience as a NASA Astronaut and prior to that, as a Research Engineer. Dr. Chiao is a fellow of the Explorers Club, and a member of the International Academy of Astronautics and the Committee of 100. Chiao also serves in various capacities to further space education.

Dr. Chiao left NASA in 2005 following a fifteen-year career with the agency. A veteran of four space missions, Dr. Chiao most recently served as Commander and NASA Science Officer of Expedition 10 aboard the International Space Station. He has logged over 229 days in space - over 36 hours of which were spent in Extra-Vehicular Activity (EVA, or spacewalks). From June–September 2009, he served as a member of the White House appointed Review of U.S. Human Spaceflight Plans Committee, and currently serves on the NASA Advisory Council.

Dr. Chiao studied Chemical Engineering, earning a Bachelor of Science degree from the University of California at Berkeley in 1983. He continued his studies at the University of California at Santa Barbara, earning his Master of Science and Doctor of Philosophy degrees in 1985 and 1987. Prior to joining NASA in 1990, he worked as a Research Engineer at Hexcel Corp. and then at the Lawrence Livermore National Lab.

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