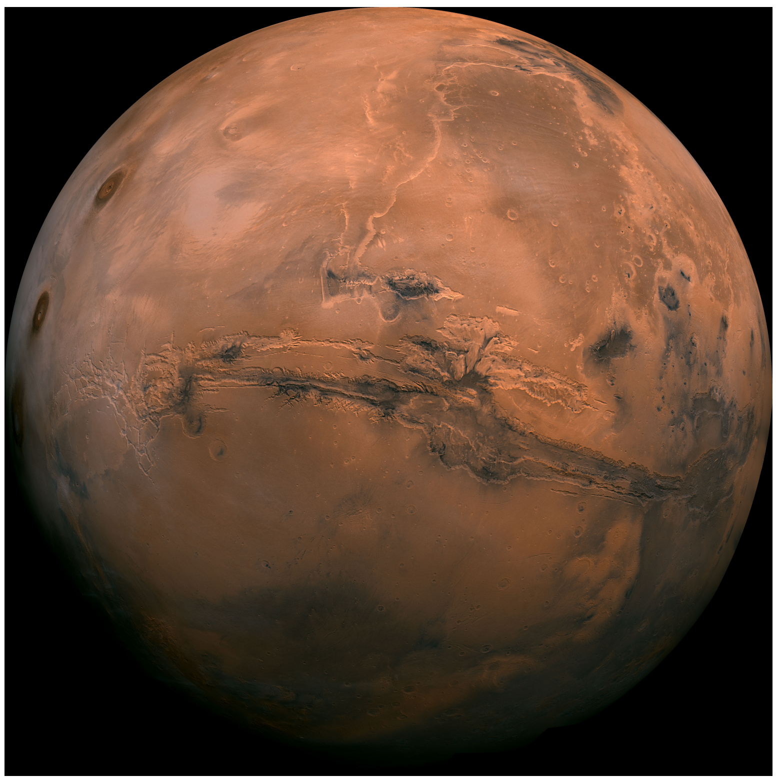
Design Proposal for Crewed Interplanetary Mission

ASEN 3036 Introduction to Human Spaceflight
Spring 2024



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Introduction and Motivation

The following report details a proposal for the Crew Habitat for Interplanetary Program Spacecraft (CHIPS) and Resupply and Logistics for Interplanetary Exploration (RALFIE) modules for a planned National Aeronautics and Space Administration (NASA) interplanetary exploration mission. The proposal includes details regarding the systems, layout, and methods of operation of these modules, as well as general mission design and planning. Additionally, the merits of the selected systems are discussed in detail.

Going to Mars in the near future is a critical milestone for the human race. Despite the disparity seen across the world throughout the latter half of the 20^{th} century, the Space Race, fueled by political tensions and a desire to stay ahead technologically, led to some of the most rapid scientific development in human history. Setting humanity's sights to Mars, especially with the potential of international cooperation (as opposed to the competition seen during the Space Race), will almost certainly lead to another flourishing of scientific thought and technological development. Landing a person on Mars is important to humanity as a next step in exploring the universe; should humanity ever wish to expand off of Earth, an effort needs to be made starting now. Regardless of settling on other worlds, however, humanity must reach Mars for the sake of human perseverance: humanity's innate curiosity and desire to explore leads to pushing ever further outwards. Looking to Mars as the next frontier serves as a uniting goal for humanity to strive for.

For the United States in specific, the goal of reaching Mars is more critical than ever; with a world as divided as it is today, nations around the world are in need of a leader to look up to. In landing humans on another planet and returning them safely, the United States solidifies its role as an international inspiration and leader in science, technology, and human pioneering; this, in turn, bolsters the confidence of its citizens (and those of other nations) and leads to further exploration and scientific developments. Historically, the United States lagged behind the Soviet Union for the majority of the Space Race, with its major first being landing the first human on the Moon (the Soviets accomplished nearly all other milestones before the United States); having a second chance to demonstrate American prowess and capability would also serve as a political bargaining chip and leg up in an increasingly tense global environment. [Voss, 2024]

CHIPS System Descriptions

The CHIPS module is designed to keep a crew alive, healthy, and productive for an extended period of time; as such, each constituent system was chosen carefully as the mass-optimal solution. In particular, regenerative systems are chosen wherever possible; on an extended-duration mission, replenishing consumables is expensive if not impossible, and crew must be able to weather unexpected delays that would be dangerous if all life support were delivered from Earth. Additionally, for such a long-duration mission, regenerative systems require significantly less upmass; carrying all provisions even to Low-Earth Orbit (LEO) would be difficult or impossible, so regenerative systems are necessary to provide for the length of time required to get to Mars. [Voss, 2024]

Water provision is one of the most mass-intensive Environmental Control and Life Support Systems (ECLSS), so optimizing water recovery is critical for a successful mission. The CHIPS module approaches a regenerative water supply mainly through the reclamation of water from condensation and urine. [Gaskill, 2023] The Water Recovery System (WRS) is modeled after that used on the International Space Station (ISS) and operates as follows. Urine is passed through the Urine Processor Assembly (UPA), which uses Vapor Compression Distillation (VCD) to retrieve most of the water from the urine and separate it from a brine product. This brine product is then passed to the Brine Processor Assembly (BPA), which takes the brine produced by the UPA and runs warm, dry air over it to reclaim the remaining water. The water from the VCD and BPA, along with condensation from crew breath and sweat retrieved from the atmosphere, are then passed to the Water Processor Assembly (WPA), which uses a gas separator, filters and filtration beds, and a catalytic oxidation reactor to purify the water. The water is then tested for purity. If it is sufficiently clean, it leaves the WPA and is made available for crew use or stored (often with iodine to prevent microbial growth). If the quality is insufficient, it is passed through the WPA again. Water is also created through the use of fuel cells and as a byproduct from the Sabatier process to reduce carbon dioxide (described later); these water byproducts are similarly treated using the WPA and packaged for crew use. [Carter et al., 2018]

Waste management is a notably difficult challenge due to the sheer uselessness of most waste products. Unfortunately, the principal method of waste disposal currently in use aboard the ISS (dumping for combustion in Earth's atmosphere) is untenable on a long-duration mission to Mars. One possible method to mitigate this issue is a high-temperature reactor being developed by NASA to convert waste (especially biological waste) into gases and a far smaller quantity of solid waste. This reactor, known as the Orbital Syngas Commodity Augmentation Reactor (OSCAR), uses high temperatures to convert trash into a variety of gases (chiefly carbon dioxide, carbon monoxide, water vapor, and methane); these byproducts can then either be repurposed (*i.e.*, methane for fuel, carbon dioxide for use in a Sabatier process, water vapor for reclamation) or vented overboard. [Watson, 2020] Remaining solid waste can be compressed to occupy a smaller total volume and potentially stored until reaching Mars; if possible, this can be disposed of into cislunar space, but this is discouraged due to the risk of collisions on the return trip. [Douglas, 2023] More likely, the remaining (hopefully minimal) solid waste will be stored until it can be returned to Earth or, if necessary, left on the Martian surface.

Fire detection provided by the CHIPS module will be the same as that on the ISS, making use of laser diodes to sense light scattering caused by smoke and other particulates. [Urban et al., 2007] The microgravity environment presents special challenges regarding smoke detection; unlike on Earth, convection does not occur naturally, so smoke will not naturally drift upwards to a ceiling-mounted smoke detector (as there is neither upwards nor a ceiling). Instead, fans are needed to circulate air throughout the spacecraft to ensure that any fire that may occur is detected; additionally, more devices must be installed to provide the same level of detection that would be present on Earth. These devices should primarily be located at junctures of the spacecraft (*i.e.*, where modules connect) and near high risk areas (*i.e.*, areas with a lot of overlapping wiring) to be most effective. The smoke detectors work by detecting forward light scattering caused by airborne particulates. A near-infrared laser beam is deflected off a series of mirrors and back into a sensor; this sensor then measures the difference between the outgoing and incoming beams. The housing containing the mirrors is open to the ambient air to allow for particulates to pass across the beam. Fire suppression on long-term missions is also a significant challenge. Foam-based extinguishers, which work by depriving a flame of oxygen entirely, are ideal, as they do not poison the atmosphere (as a carbon dioxide extinguisher would); however, their byproducts can be difficult to clean off surfaces, and an accidental discharge would be extremely prohibitive to crew productivity. Additionally, on a long-term mission, such consumables would be difficult or impossible to replace; therefore, alternative measures must also be available. Chief among these options is the ability to depressurize and vent a given module of the spacecraft; this would involve moving all crew to a module isolated from the fire, sealing the affected module, and venting the environment within to space. This would entirely extinguish the fire; however, it would be expensive to repressurize the entire module, and so this should only be done if absolutely necessary. [Friedman and Urban, 2000]

Oxygen is generated chiefly through electrolysis. The system currently in use on the ISS will serve as the basis for the system used in CHIPS, although certain changes to the functionality will need to be made. [Jones, 2016] In the ISS system, water (provided by the WRS described above) is first passed over an ion exchange bed, which removes the iodine added to water to prevent microbial growth. The water is then checked for air bubbles; water with air is sent back to the crew, while the rest goes on to the main Oxygen Generation Assembly (OGA). This system uses electrolysis to break the water into diatomic hydrogen and oxygen. The oxygen is passed through a Hydrogen Sensor On-orbit Replaceable Unit (ORU), which ensures that there is no gaseous hydrogen in the separated oxygen (this would indicate a leak and necessitate immediate shutdown of the system); the hydrogen and water are then provided to the Rotary Separator Accumulator, which separates gaseous hydrogen from remaining liquid water. The liquid water continues the process, while the hydrogen is either discarded of overboard or kept for use (*i.e.*, in the Sabatier process). [Takada et al., 2015] The changes proposed to this system by Takada and others include replacing the Hydrogen Sensor ORU with an H_2-O_2 recombiner, removing the wastewater interface (*i.e.*, allowing water with gas bubbles into the system as it may not make a difference), and removing nitrogen purge equipment (both to save mass). [Jones, 2016]

Atmospheric purification (removal of carbon dioxide) is primarily done through use of zeolites and a Sabatier process. Zeolites are a sponge-like mineral which, when cold, trap carbon dioxide in the porous material; when reheated, the zeolites release the carbon dioxide, making them reusable. The CHIPS atmospheric purification system will use a series of zeolite beds to progressively filter and purify carbon dioxide. [King, 2018] This purified carbon dioxide, rather than being vented overboard, is then passed to a Sabatier reactor. The Sabatier process uses a reaction between carbon dioxide and diatomic hydrogen to generate methane and water as follows:

$$\mathrm{CO_2} + 4\,\mathrm{H_2} \longrightarrow \mathrm{CH_4} + 2\,\mathrm{H_2O}$$

Note that, for this process the work, the carbon dioxide must be highly purified; this is why multiple zeolite beds are necessary. The diatomic hydrogen is provided by the water electrolysis process described above for oxygen regeneration. The water produced can be collected using a centrifuge, condensation, or adsorption; the methane can either be vented overboard or kept as a potential fuel source. [Abney et al., 2011] This combination of water regeneration, oxygen regeneration, and atmospheric purification is essentially closed-loop, an important consideration for a long-duration mission; retrieving and reusing waste products allows for CHIPS to be effective for an entire mission without resupply. High-efficiency particulate arresting (HEPA) filters will be used to remove particulate matter from the air; the lifespan of these filters is far longer than the desired transit time. [Perry, 2005]

Pressure monitoring provided by the CHIPS module is provided by absolute and differential pressure sensors. Both these types of sensors work by detecting deformations in a membrane and converting these deformations to an electric potential; absolute pressure sensors detect the difference between the atmosphere and a sealed vacuum within the device, while differential pressure sensors detect the difference in pressure between two ports on the device. [André et al., 2008] These sensors (in particular the differential pressure sensors) are critical for detecting leaks in a spacecraft; along with airflow monitors, pressure sensors allow for the CHIPS module to detect and warn crew of any potential leaks or dangerous rises in pressure. The total and partial pressures of gasses in the atmosphere are then regulated by venting gasses either into or out of the cabin. Venting out to relieve total pressure is simple and only requires opening a valve to the outside vacuum. Controlling specific partial pressures is more difficult, and is approached by releasing stored gasses (*i.e.*, nitrogen isolated in atmospheric purification, carbon dioxide stored for the Sabatier process, oxygen retrieved from atmosphere revitalization) until the desired partial pressure is reached. The closed-loop processes involving carbon dioxide and oxygen are given above and provide solutions to pressure regulation for these gasses; nitrogen is more difficult and must be carefully regulated so as to not let nitrogen leave the cabin unless absolutely necessary (*i.e.*, it must be kept after it is filtered out in atmospheric purification). Additional nitrogen must be carried up in tanks. [Schaezler and Cook, 2015]

CHIPS provides temperature and humidity control (THC) in a similar way that these functions would be provided on Earth, albeit with additional difficulties due to microgravity. Temperature and humidity are both controlled through the use of a condensing heat exchanger, which removes water from the atmosphere and in doing so removes heat at the same time. The heat exchanger is coupled to a temperature sensor so as to always keep the crew at a comfortable temperature (within a couple of degrees Fahrenheit of a crew-selected temperature) and works by exposing atmospheric air to a coolant (water in this case) and inducing condensation on the surface. Cabin fans also serve to circulate air within the spacecraft; a lack of gravity results in there being no convection and therefore stagnant air pockets. [Bedard et al., 1998] Besides the risk posed due to possible accumulation of toxic gases (*i.e.*, carbon dioxide) in secluded regions of the spacecraft, a lack of convection necessitates an active cooling and air circulation system. Small fans, installed at various locations throughout the CHIPS and other modules, serve to circulate air to maintain ideal pressure and humidity, as well as help run air over the aforementioned condensing heat exchangers if necessary. Working in tandem, these systems can maintain a comfortable atmosphere entirely renewably.

Gas analysis throughout the spacecraft makes use of the same Major Constituent Analyzers (MCAs) used on the ISS. [Matty et al., 2015] These use a set of air distribution lines and valves to transmit air from a series of locations throughout the spacecraft to the MCAs; the MCAs themselves use mass spectroscopy to determine the composition of the atmosphere within the spacecraft. [Schaezler and Cook, 2015, Matty et al., 2015] The mass spectrometers themselves work by sampling (and if necessary, ionizing) the gas in the cabin; this gas is then sent through an analyzer, which separates the ions by mass-to-charge ratio. The separated ions reach the detector, which uses the separation distances to determine the partial pressures of each constituent atmospheric gas to high accuracy. [Garg and Zubair, 2023]

CHIPS will utilize an Active Thermal Control System (ATCS) similar to that found on the ISS. The CHIPS ATCS will consist of both internal and external thermal control systems. The Internal Active Thermal Control System (IATCS) will use pumped water to reject heat from electronic components inside the spacecraft (avionics, power systems, *etc.*) and transfer it to External Active Thermal Control System (EATCS) via Interface Heat Exchanger (IFHX) units. [Holt and Morrison, 2005] The EATCS, in turn, will take the heat from the IFHX units and transfer it to ammonia coolant lines running through large radiators mounted on the outside of the spacecraft; the heat from the ammonia (used for its low freezing point) is then rejected into space. [Boeing, 2021] Since neither the water nor the ammonia is discarded and the systems for water regeneration are already present, the CHIPS ATCS is entirely regenerative and can function without pause for the entirety of a long-duration mission. Using on-orbit replaceable units in the ATCS systems also allows for easier maintenance.

The CHIPS module will contain an assortment of accommodations and equipment to promote crew health, happiness, and productivity. Chief among these will be exercise devices; to combat bone mass loss and muscle atrophy, astronauts will be required to exercise extensively during the journey to and from Mars. CHIPS will house a treadmill, a resistive exercise device, and a bicycle. The bicycle and treadmill will both use straps to hold the astronauts down and feature vibration dampers to isolate exercise motions from the rest of the cabin. The resistive exercise device will use training bands to allow for emulation of a variety of exercises, chiefly centered around weight-lifting and strength training. The CHIPS module will also house standard hygiene and body care equipment, including a stall with wet wipes to shower, a toilet, razors, nail clippers, and toothpaste. Medical equipment, both emergency and non-emergency, will be stored in the CHIPS module; this will be patterned after the ISS Crew Health Care System (CHeCS) and will include a crew restraint system, life support back, ambulatory support pack, and defibrillator, as well as more mundane items such as an eyewash kit and basic first aid materials. Also included in the kit will be environmental monitors for hazards including radiation, bacterial growth, and sound level. Crew accommodations will also include personal affections such as sleeping pods, mementos from home, and devices with which to contact home. The sleeping pods will be modeled after the ones in use on the ISS, with straps to keep astronauts from drifting during sleep; home contact is a subset of the communications system and is handled as such. Mementos are individual to each astronaut.

Command and data handling aboard the spacecraft would utilize a suite of computers housed at a central location (CHIPS) for ease of use. All user-facing programs would be abstracted away from sensor-facing software to allow crew to work with a large variety of input data without requiring extensive training on each instrument. Additionally, all software would be remote-upgradable to allow for ground support crews to make modifications to mission-critical software on relatively short notice. Crew would be able to backup software and data to on-ship physical storage as necessary. Ideally, sensors would interface with crewfacing machines using Universal Serial Bus (USB) ports (or some other uniform package bus) to allow for easy replaceability if a port is damaged; however, the individual sensor connections are dependent on sensor manufacturers and data transfer needs, as some sensors may require more pins than others. [Muri, 2019] Digital processing (especially in regards to optimization and error correction) is sensor-specific as each sensor will need to convert analog signals to digital forms differently; however, common algorithms for signal processing and correction, such as the Fast Fourier Transform (reading meaningful data out of a signal by decomposing it into its constituent frequencies) and low-density parity-checks (correcting radiation-induced bit flips using check bits) are likely to be employed. [Jeon et al., 2010]

Communications with the spacecraft will be done entirely via radio. The CHIPS module will communicate in the government-use S-, X-, and Ka-bands (2-4 GHz, 8-12 GHz, and 27-40 GHz respectively); these frequency bands are preferable to Ultra High Frequency (UHF) bands due to the higher probability of local interference resulting from using UHF bands. Tracking, telemetry, and command in particular will be handled over the S-band. Ku-, K-, and Ka-bands (covering 12-40 GHz) are considered state-of-the-art for larger spacecraft; however, transmitting these high frequencies requires more power and so may be prohibitive on a long duration mission. [NASA, 2024] Historically, lower-frequency ranges have been used for communications (0.1-10 GHz, reflecting frequencies in the Very High Frequency [VHF], UHF, L, S, C, and X bands), with the UHF and S bands being popular choices. [Schmid, 1966] Communications will likely not be directly with Earth, instead using relay satellites to strengthen signals; in this case, the aforementioned Ku-, K-, and Ka-bands are preferred for spacecraft-to-spacecraft communications. [NASA, 2024]

Crew interfaces would be designed with ease of use and learning in mind. Commands would be passed through a digital interface (touchscreen) for accessibility with the option of using physical switches for some functions (especially for maneuvering) if the crew desires. Physical override switches will be provided for critical functions to be used if absolutely necessary; however, these physical switches would be covered to prevent accidental flipping. Switch covers would be simple caps on hinges. The final overall control structure (*i.e.*, positions of switches, labeling scheme, display layouts, etc.) would be designed largely using astronaut feedback during crew training; however, the base structure (on which the astronauts begin to train) would be a multi-panel layout with all physical switches in a board at the bottom. More specialized controls (*i.e.*, for specific sensors) would be located at the relevant locations rather than on the main board to avoid clutter; these would all be physical to reduce system complexity.

RALFIE System Descriptions

Despite the focus on regenerative ECLSS aboard CHIPS, consumable systems aboard RALFIE will provide backups to keep the crew alive for three months in case a main system fails. Consumables have been chosen for their ease of manufacturing, ease of use, relatively low mass in small quantities, and reliability; even in major losses of spacecraft functionality, these systems would most likely operate nominally. [Voss, 2024]

Emergency water provision is a simple matter of storing large quantities of water in tanks. This solution is very mass-prohibitive and is the motivation behind a regenerative water system being included in CHIPS; however, emergency tanks are a feasible solution for the RALFIE module. Additionally, empty tanks could be provided to be filled during transit when the CHIPS system is operating nominally as further backup. [Voss, 2024]

All food would be provided on RALFIE since, as of now, there is no reliable way to grow food in space. This food will be pre-packaged on Earth with all water removed to reduce mass; meals will then be rehydrated by crew during transit. A variety of meals will be provided to ensure that astronauts stay healthy during transit; these include meats, vegetables, and fruits, as well as occasional deserts. [Voss, 2024]

Waste management, in the event that the CHIPS system should fail, is simply a manner of storing waste in large bags in RALFIE until it can be disposed of; these large bags, along with bungee cords (or similar) to hold them down, will be sent up with RALFIE for emergency waste storage. [Voss, 2024]

RALFIE will also contain the aforementioned foam fire extinguishers in the event that depressurization and repressurization of a module to extinguish a fire is not a viable option; these will be identical to the ones found in the Russian segments of the ISS and function by spraying a water foam over fires to deprive them of oxygen and prevent them from spreading. The foam will be stored in small, portable, pressurized tanks and be released using a handle attached to a nozzle. [Voss, 2024]

Emergency air provision (both of O_2 and of N_2) will use pressurized gas tanks. These are extremely simple, essentially just being hollow metal shells with a valve at the top, and are relatively lightweight (the required tank thickness depends only on the pressure of the gas contained within). The atmospheric gases can either be provided separately, with oxygen and nitrogen stored in different tanks, or pre-mixed to a desirable composition; both of these are desirable. Pre-mixed tanks can be used to re-pressurize modules if they are vented for fire suppression, while separate tanks can be used if the partial pressure of one particular gas must be adjusted. [Voss, 2024]

RALFIE makes use of lithium hyrdoxide (LiOH) canisters for backup atmospheric purification systems. These systems are extremely simple, utilizing the following chemical reaction to scrub carbon dioxide from the atmosphere:

$$2\,\mathrm{LiOH} + \mathrm{CO_2} \longrightarrow \mathrm{Li_2CO_3} + \mathrm{H_2O}$$

Two kilograms of lithium hydroxide can remove approximately one kilogram of carbon dioxide per day, roughly equivalent to the daily amount generated by one person. The canisters only require that cabin air be passed over them to function. [Voss, 2024]

Personal crew hygiene items are the final remaining consumables to be stored aboard RALFIE. These include razor blades, toothpaste, towels, and clothing, all of which must be discarded after some amount of time. Each crew member will be allocated a set amount of personal items before flight, with durable items (anti-microbial towels and clothing, razors that can be re-sharpened) being preferred. [Voss, 2024]

Conlcusion

A crewed mission to Mars is a daunting task, but nonetheless an essential one for the United States to undertake in its mission to remain a pioneering nation in space exploration and human innovation. The proposed CHIPS and RALFIE modules represent a significant step forward in planning and executing this goal, with human factors considerations an important aspect of the mission. The findings illustrate the importance of regenerative systems for environmental control and life support wherever possible, with lowest-mass systems being the most optimal solutions. Consumable goods, however, are impossible to avoid, so their inclusion must be considered and planned for to allow for a successful mission execution.

CHIPS View (Internal)

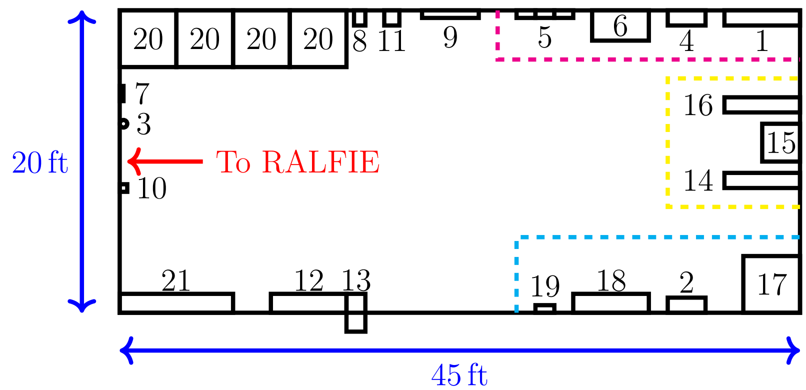

Figure 1: Internal drawing of the CHIPS module. Regions with common functions are outlined and ideally separated by curtains; these include water and atmosphere (magenta), exercise (yellow), and health and hygiene (cyan). The EATCS and radiators are not illustrated as they are external; the EATCS would be connected to the IFHX (13). Empty space in the middle of CHIPS could be utilized as crew meeting/living space during transit.

1. WRS
2. OSCAR
3. Smoke detector
4. OGA
5. Zeolite beds
6. Sabatier reactor
7. HEPA filter
8. Absolute pressure sensor
9. Heat exchanger (THC)
10. Small fan
11. MCA
12. IATCS
13. IFHX (ATCS)
14. Treadmill
15. Resistive exercise device
16. Bicycle
17. Toilet
18. Hygiene equipment
19. CHeCS
20. Sleeping pods
21. Central computer with control panel

RALFIE and CHIPS View (External)

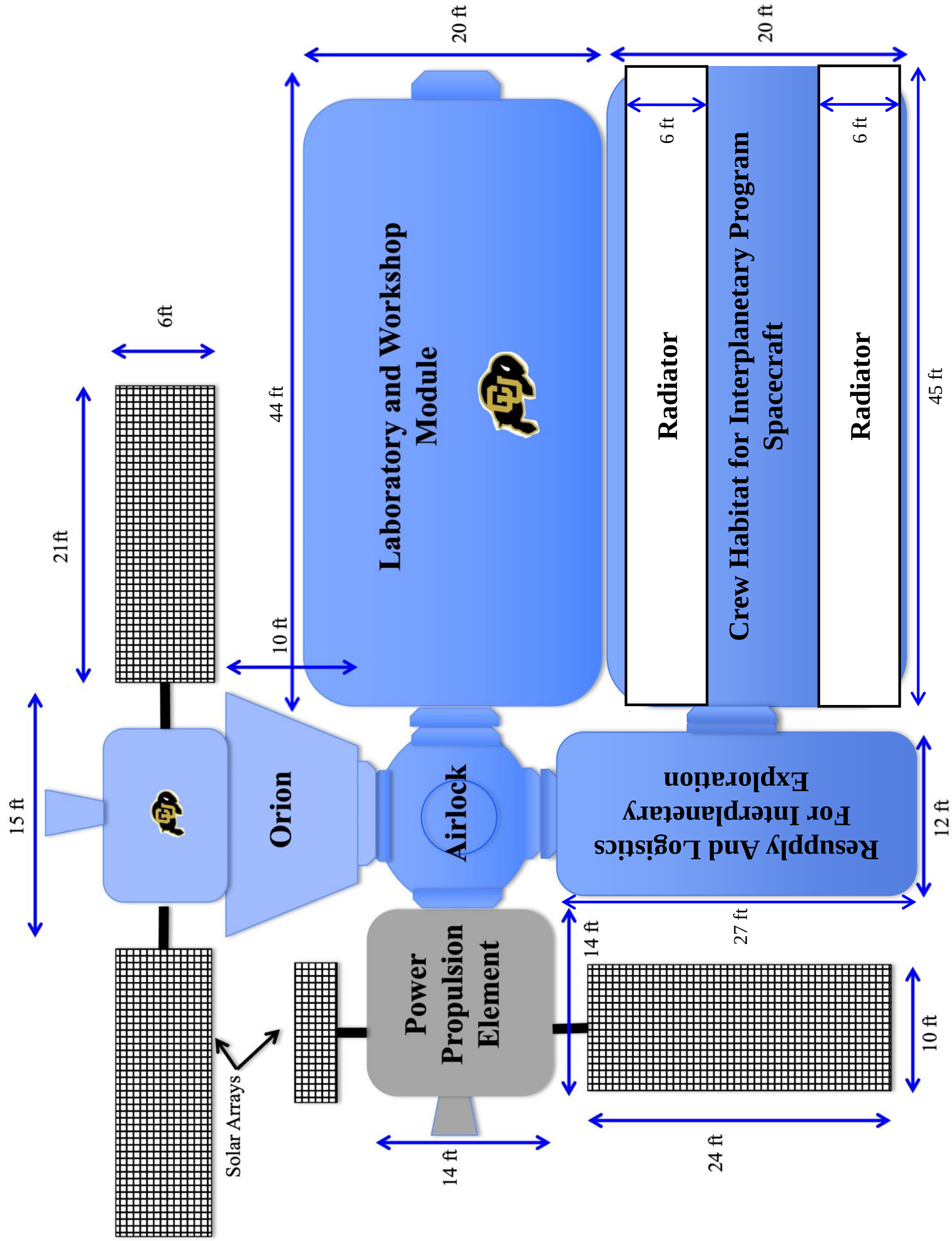

Figure 2: External view of the Mars Transit Vehicle, including RALFIE and CHIPS modules.

Concept of Operations and Mission Architecture

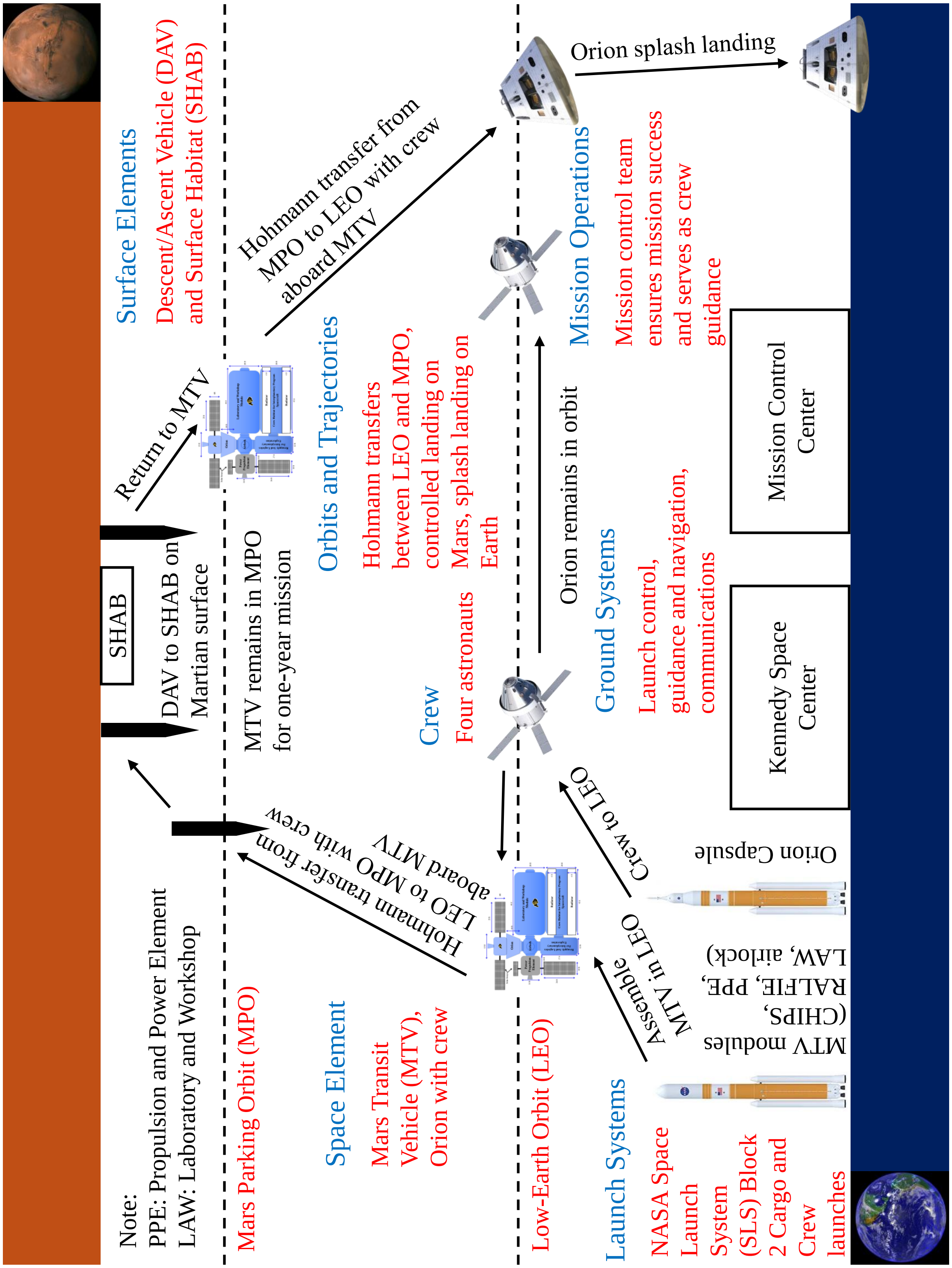

Figure 3: Concept of operations and mission architecture for crewed mission to Mars.

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