ARIES

Adaptable Rotating Interplanetary Exploration System

Artificial Gravity Reusable Crewed Deep Space Transport

The University of Illinois at Urbana-Champaign

Illinois Space Society

May 31, 2018

Faculty Advisor: Koki Ho, Ph.D.

Team Lead: Benjamin O'Hearn

Iaroslov Ekimtcov, Megan Geyer, Lucas Hobart, Linyi Hou, Elena Kamis, Adhbuth Reddy Kunta, Connor Latham, Sara Legg, Courtney Leverenz, Rahil Makadia, Josh Pilat, Josh Super, Jasmine Thaweesee

Vehicle Overview

Introduction

The University of Illinois proposes ARIES, the Adaptable Rotating Interplanetary Exploration System, as a solution for an artificial gravity-enabled, reusable deep space transport vehicle. ARIES attempts to merge existing or already developing technologies, such as Bigelow Aerospace's inflatable module designs, with revolutionary new technologies, such as a Hybrid Propulsion Stage (HPS), to offer a cost effective yet innovative system for transporting humans and landers to Mars. The vehicle is composed of two main structures: the HPS and a centrifuge connected by a freely rotating bearing allowing the centrifuge to spin while the HPS remains stationary. Crew will utilize several docking ports, including Common Berthing Mechanisms (CBM) and NASA Docking Systems (NDS), for resupply missions and component staging during assembly. Figure 1 displays the external structures of ARIES.

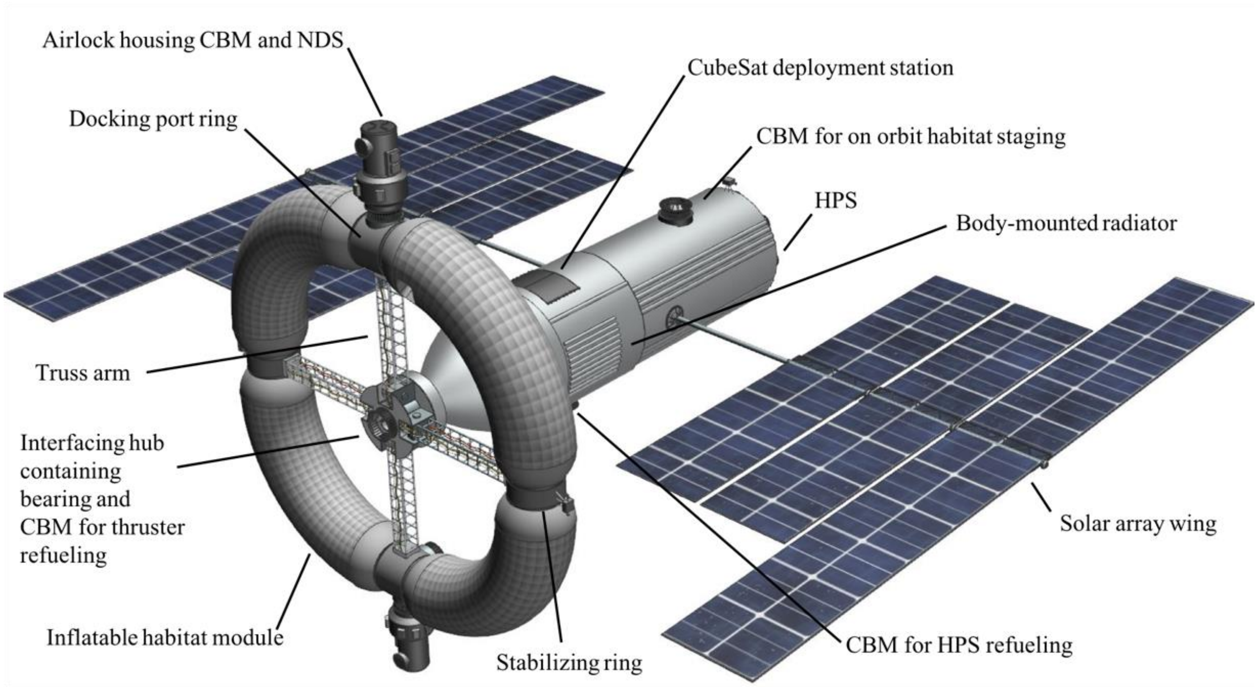

Figure 1: Diagram of ARIES External Structures

Centrifuge

The centrifuge is made up of a ring-shaped Bigelow-derived inflatable habitat and a stabilizing truss assembly that anchors the habitat to the HPS through the bearing. The center hub also contains fuel and oxidizer tanks for the Reaction Control System (RCS) thrusters mounted on the centrifuge. Those thrusters control spin-up and spin-down of the centrifuge, in turn generating artificial gravity within the habitat. The four truss arms are secured to the center hub using joints that offer rotation, enabling the entire assembly to be stored in a completely vertical configuration. Two opposing truss arms are fitted with stabilizing rings that act as forming elements for the inflatable habitat while the two remaining arms are fitted with docking port rings that house docking ports and airlocks. In addition to providing structural support, the trusses also contain cables for power and data transfer as well as propellant lines for the RCS thrusters, necessary for spin-up and spin-down maneuvers of the centrifuge. The habitat structure consists of four inflatable modules connected in a torus-shaped formation. Each module measures 4m outer diameter with a constant wall thickness of .6m.

Hybrid Propulsion Stage

The HPS is derived from the Mars Hybrid Propulsion System documentation, with substantial modifications applied to provide enhanced transportation capabilities for the artificial gravity habitat module. [1] The modified HPS utilizes monomethyl hydrazine (MMH) and nitrogen tetroxide (NTO) for spin-up/spin-down and attitude control with R-1E and Astrium S22-02 engines, hydrazine and NTO for chemical propulsion with R-42DM engines, and xenon for solar electric propulsion (SEP) with X3 engines.

The modified HPS weighs 31.4 metric tons (t) dry and 110.8t fully fueled, with a length of 24.7m and diameter of 7.2m. The upper section houses a passive common berthing mechanism (CBM) and control moment gyroscopes (CMG), as well as power processing units and power management systems for the SEP system. The upper section also contains storage volume to carry CubeSats for science objectives. The lower section of the HPS is outfitted with a pair of solar panels that supply power to both the SEP engines and the habitat. Two passive CBM docking ports are installed for refueling and berthing. Propellant tanks also reside within the lower section of the HPS, while R-42DM and X3 engines are installed at the rear of the HPS. Astrium S22-02 thrusters are installed in clusters on the HPS for attitude control, and R-1E engines are installed on the exterior of the artificial gravity habitat.

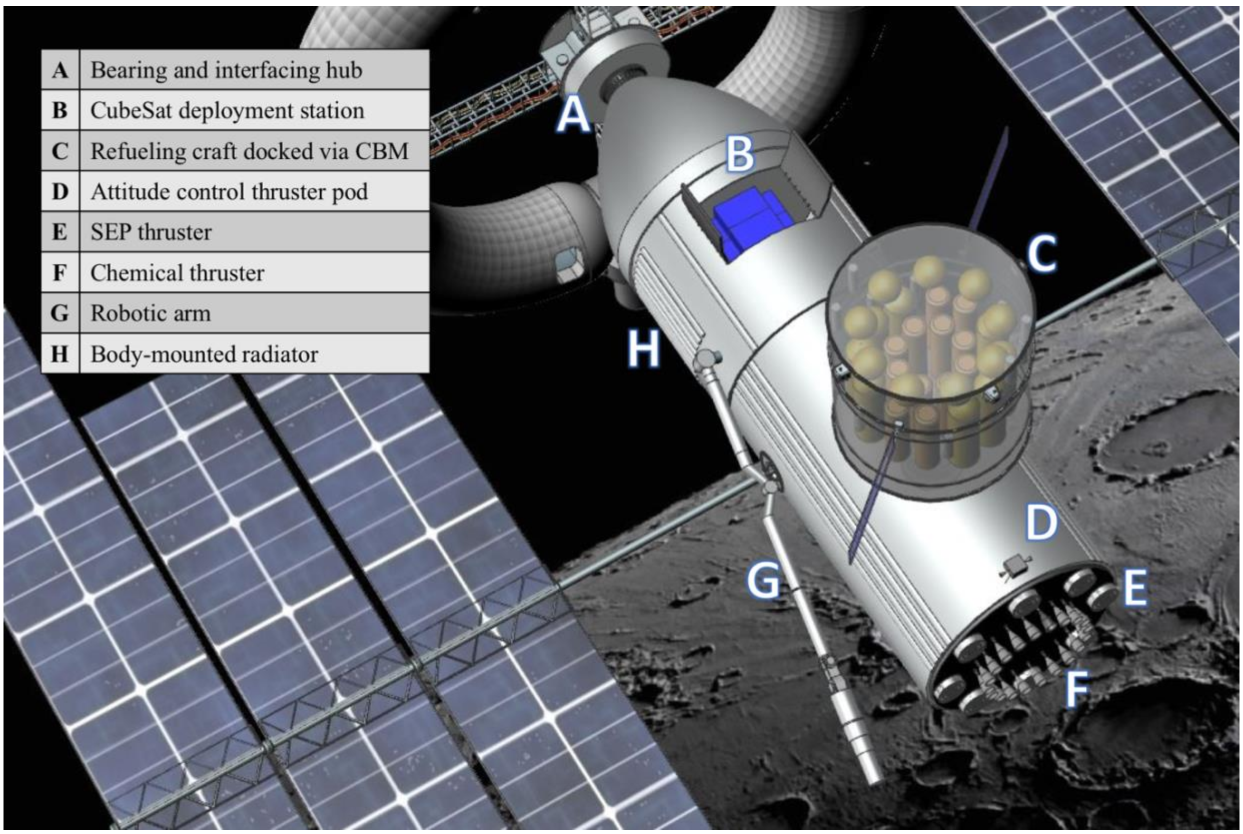

Figure 2: External Structures of the HPS

Concept of Operations

Development and Testing

NASA’s current Deep Space Habitat research program serves as the beginning of the research and development phase of ARIES. An overview of the development stage is presented in Figure 3. In addition, the Bigelow Expandable Activity Module (BEAM) program taking place onboard the International Space

Station (ISS) offers another pre-existing research project useful for the development of AIRES. To ensure the success of the on-orbit assembly of ARIES, a habitat validation mission is scheduled shortly before the decommissioning of the ISS. A Falcon 9 (F9) will ferry an inflatable habitat module to the ISS where crew will use the Space Station Remote Manipulator System (SSRMS) and extravehicular activity (EVA) to attach and inflate the segment. This mission closely mimics the eventual ARIES construction procedure. In 2024, once the ISS has been officially decommissioned, work will begin to construct a replica of the external structure of ARIES in NASA Johnson Space Center's Neutral Buoyancy Lab (NBL). This replica will replace the current ISS model. It will be used to train astronauts for EVA in microgravity where crew members will assemble and refurbish ARIES during its lifetime. Because ARIES will present the first opportunity for humans to live in artificial gravity, sufficient training will be required to acclimate future crew members to the environment. Crew members will undergo human centrifuge training on Earth to test individual psychological effects of artificial gravity. These tests include being placed in a 5.5m-radius centrifuge while the centrifuge gradually increases its angular velocity from 3 revolutions per minute (rpm) to 7.84rpm to emulate twice Martian gravity. Test subjects' physical and mental responses will be monitored during testing.

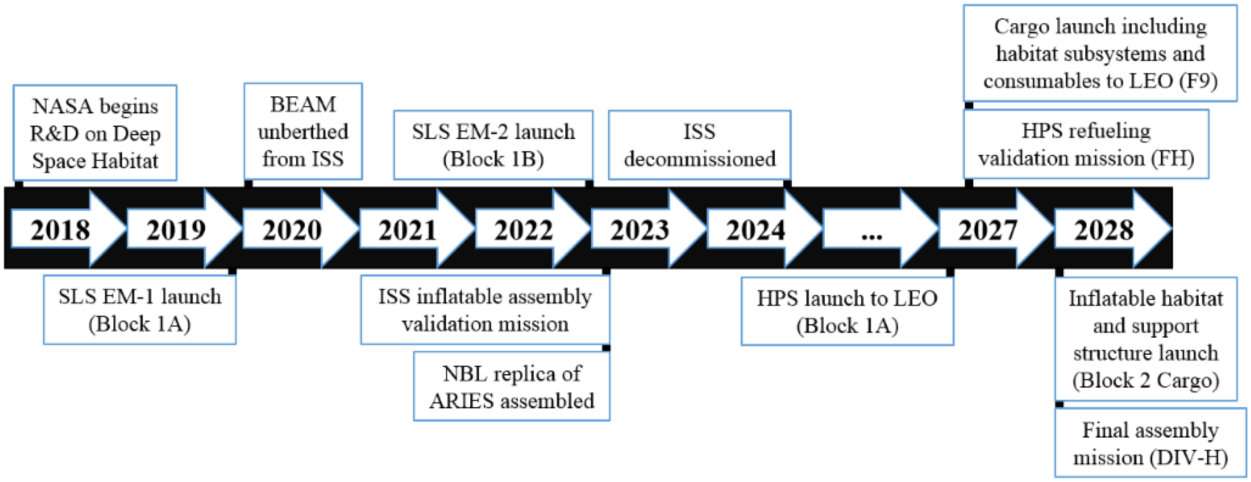

Figure 3: ARIES Research and Development Flowchart (2018-2028)

Assembly and Trans-Lunar Injection

ARIES construction phase begins in early 2027 when the HPS will be inserted into a 400km circular orbit with an inclination of 51.6°. Due to deviations made from the Hybrid Transport Architecture (HTA), the propulsion stage will be delivered via Space Launch System (SLS) Block 1A partially outfitted with 41t of fuel. A validation mission for the refuel tanker detailed in the HTA is planned for late 2027. The refuel tanker will be ferried to the HPS by a Falcon Heavy (FH) carrying additional fuel for the HPS. Approach and docking operations will be tested during this mission. After the initial refuel is deemed successful, five resupply missions will be launched at two-month intervals by F9s carrying Cygnus modules fully loaded with 2100kg of food and 700kg of water into parking orbits while construction on ARIES continues. These modules will contain enough consumables to support a crew of four for an entire 1,100-day Mars mission cycle including a 30% (330 day) safety factor.

The HPS will remain in Low Earth Orbit (LEO) for one year while station-keeping operations and power generation are monitored by ground control. Early in 2028, the full ARIES truss assembly will be mounted onto a canister containing the four inflatable habitat modules (in a partially deflated state) and installed in an SLS Block 2B payload fairing. The modules will house crew-critical subsystems, such as the environmental control and life support system (ECLSS), along with a minimal amount of food and water to sustain a temporary assembly crew. The SLS will deliver the payload to the orbiting HPS where the payload will be berthed to a CBM by the SSRMS. The SSRMS will then un-berth the truss assembly and mount it onto the bearing on the forward end of the HPS. The truss arms will expand, locking in place. The orbiting HPS, habitat canister, and truss assembly will await the construction crew.

Next, a Delta IV Heavy (DIV-H) will launch, carrying an Orion module with 3 crew members, 133kg of food, and 80kg of water. The Orion module will dock with an airlock. Ground control will remotely operate the SSRMS and use it to attach one of the inflatable modules to the same docking ring that is mated to the Orion capsule. The construction crew will then attach the remaining modules to the rings using a combination of EVA and on-orbit control of the SSRMS. The same crew will coordinate the berthing of the five Cygnus modules previously launched in parking orbits and transfer their contents into the habitat. Finally, the crew will place the vehicle in an ultra-low power mode and return to Earth in the Orion capsule.

Upon departure of the construction crew, ARIES will begin a 70-day transfer from LEO to Lunar Distant Retrograde Orbit (LDRO) using SEP, consuming approximately 2,500kg xenon. [2] Simultaneously, three refueling tankers will launch to LDRO via FH to fully refuel the HPS upon its arrival. Another FH, carrying a Crew Dragon accommodating the first Mars crew, will launch in late March 2028 to rendezvous with the HPS and retrieve all three refuel tankers in LDRO. After completing the assembly, the crew will remain in LDRO testing systems operations and acclimating to the vehicle, until their departure in April 2028, marking the completion of ARIES preparation and the beginning of the first Mars mission.

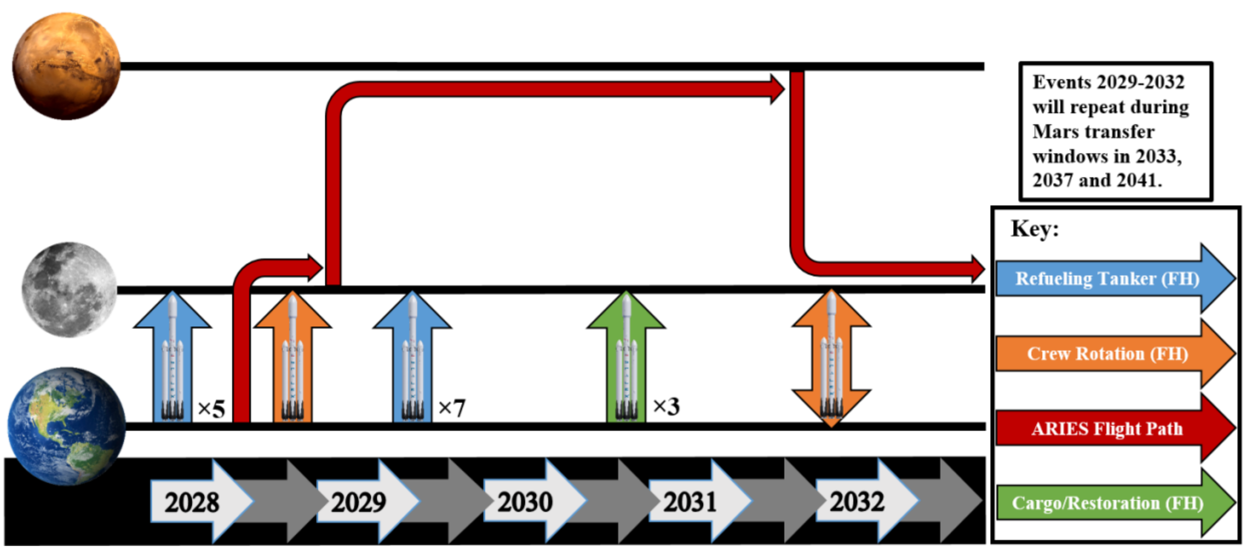

Figure 4: ARIES Launch and Mission Architecture Flowchart (2028-2032)

Conjunction-Class Mission Architecture

After crew rendezvous in April 2028, ARIES will begin its Mars transit from lunar orbit. The vehicle uses its R-42DM chemical engines to initiate a 6-month weak stability boundary transfer to Lunar Distant High Earth Orbit (LDHEO). ARIES then catches two Lunar Gravity Assists (LGA) over 20 days to achieve a departure C3 of 2.00km^2/s^2 on Oct. 18, 2028. A total ΔV of 35m/s is applied. SEP engines are then engaged for 383 days and a 3,301m/s ΔV to achieve a Mars encounter with a periapsis of 236km. On November 26, 2029, ARIES performs a 284m/s capture burn via chemical engines near Mars' periapsis to enter a highly eccentric 5-sol orbit around Mars. Both the interplanetary transfer and Mars orbital insertion maneuvers for the 2028 Mars transfer window are shown in Figure 5.

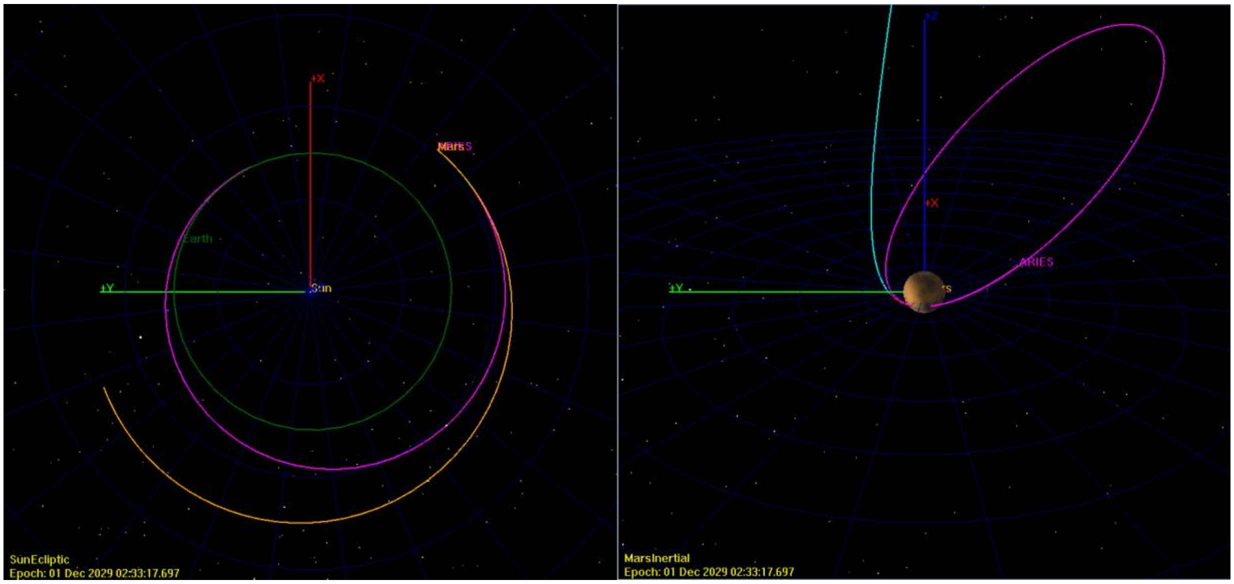

Figure 5: 2028 Mars Transfer Window – Low-Thrust Interplanetary Transfer (Left), Mars Orbital Insertion (Right)

The ARIES crew stays in Mars orbit for 300 days with orbital adjustment and maintenance costs totaling 124m/s. ARIES then performs a trans-Earth injection costing 296m/s ΔV using the chemical thrusters. Following trans-Earth injection, ARIES performs a 2900m/s SEP burn over 360 days, targeting a direct LGA and inserting ARIES into LDHEO in November 2031. Finally, ARIES will initiate another weak stability boundary transfer, using 26m/s chemical and 29m/s SEP to arrive in LDRO in May 2032.

During the first Mars conjunction-class mission, refuel and resupply missions for the next iteration will begin. Eight refuel tankers will reach LDRO between January 2029 and May 3032 to refuel ARIES for its next voyage. Each tanker will ferry 10t of fuel (5.0t xenon, 2.5t hydrazine, 2.5t NTO). In May 2032 a FH will ferry a Crew Dragon to LDRO to dock with ARIES and rotate crew for the next Mars transit. Two additional FH launches will deliver two Cygnus modules each containing 7.0t of food and 2.6t of water to LDRO, fully restocking ARIES and providing additional supplies for the waiting period in LDRO prior to the next Mars transit window. Another FH will deliver new solar arrays to replace the degraded set on the ARIES. This is done via EVA assembly and will restore full power generation. ARIES will be fully operational for its second Mars transit window in March 2033. This schedule will be repeated three additional times between 2033-2036, 2037-2040, and 2041-2044.

Hybrid Propulsion Stage Technical Specifications

Chemical Propulsion Systems

The chemical propulsion systems consist of three different engines used for propulsion, attitude control, and spin-up/spin-down.

The R-42DM engine manufactured by Aerojet Rocketdyne will be the primary chemical propulsion method for ARIES. The engine consumes hydrazine and NTO to produce 890N of thrust with an I_{sp} of 327s. [3] Twenty R-42DM engines will be installed on the HPS to deliver a maximum 17,800N of thrust. The R-42DM was selected for its higher specific impulse as compared to the R-42 engines used in the original Mars HPS design. [1] The number of engines was doubled from the original design to accommodate for the increased mass from the artificial gravity habitat. R-42DM engines will be used for high thrust maneuvers including Mars capture and certain orbital adjustments. As of 2009, the R-42DM was at Technology

Readiness Level (TRL)-6. [3] 38.364t of hydrazine and NTO at a 1:1 ratio will be stored for the R-42DM chemical propulsion system.

Four RCS pods installed at the rear of the HPS will provide attitude control for ARIES. The pods each consist of four clusters of two Astrium S22-02 engines. Each thruster can deliver 22N of thrust at an I_{sp} of 288s and consume MMH+NTO as propellant. [4] RCS thrusters are used to orient ARIES during the mission and are also used for desaturating the CMGs periodically.

Four R-1E engines, manufactured by Aerojet Rocketdyne, will control the spin-up/spin-down cycles of the habitat. Mass and angular velocity constraints made it infeasible to use CMG's or electric motors to spin the habitat, thus it was necessary to install engines. Each R-1E engine produces 110N thrust at an I_{sp} of 280s and consume MMH+NTO as propellant. [3] Two engines will induce a clockwise spin while the other two engines will induce a counterclockwise spin. The low thrust value of R-1E engines retains decent spin-up/spin-down times while reducing mechanical stress on the habitat structure as well as physiological stress on the crew. 772kg of MMH and 443kg of NTO will be allocated for the S22-02 and R-1E engines.

Solar Electric Propulsion System

The SEP system uses the X3 100kW Class Nested Hall Effect Thruster, which consumes xenon gas to produce 2.14N of thrust with a power consumption of 36.4kW and I_{sp} of 2650s. [5] [6] Eight X3 thruster will produce a total of 17.12N of thrust at 291.2kW power consumption. The X3 was selected over the Hall Effect Rocket with Magnetic Shielding (HERMeS) thruster used in the original Mars HPS design. [1] Its greater efficiency allows it to conform to the 750kW power constraint while remaining capable of executing a conjunction-class mission profile. The SEP system will be used for low thrust maneuvers including continuous thrust interplanetary transfers and certain orbital adjustments. Note that the X3 thruster is capable of thrusting at >5N and 100kW, but the above listed value was selected for maximum efficiency. Future iterations of the X3 thruster may enable equal or better efficiency at a higher power level, which would reduce the number of X3 engines required and thus increase payload capacity. 39.374t of xenon gas will be stored for the SEP system.

Power and Thermal Control System

To provide the 325.6kW required for all operations, solar panels on ARIES will need to produce 750kW at beginning-of-life (BOL). The onboard power system will utilize a combination of Spectrolab XTJ Prime Triple Junction Solar Cells and Saft VL48E Li-Ion batteries. [7] [8] [9] Energy transfer efficiencies between the array, battery, and component loads were considered when calculating required array sizing.

This is assuming a 6.77-hour (hr) day and 0.882hr night in a Phobos orbit, 6km above the surface. This will provide 34.42kW to power the habitat and 291.2kW to the propulsion units. Considering the 3-year end-of-life (EOL) efficiency of 26.7%, the required array size is 2,062m^2. The Li-Ion batteries must withstand nearly 3,500 charge/discharge cycles in 3 years, limiting the depth of discharge (DOD) to 70%. [10] The batteries can provide an EOL energy density of 175Wh/kg. The nightly energy draw of 23.89kWh with the limited DOD will require 13 batteries.

Solar panel degradation over time will significantly reduce the power available for ARIES. A worst-case scenario estimates solar arrays to degrade by 7.0% each year. [11] Thus, ARIES will generate 25% less power at the end of each 4-year mission. This effect will be mitigated by replacing solar arrays in lunar orbit after each mission. The new solar arrays will be delivered to lunar orbit via a FH launch.

ARIES will thermally regulate itself with a variety of subsystems. Taking advantage of the large surface area present on the ring modules, the surface coating will be such that a majority of the radiation from the sun is reflected away, rather than being absorbed as heat, yet the emissivity is maintained at a value that allows the station to radiate heat effectively away. This coating is assumed to be a selective surface similar to that used on the ISS thermal radiator panels. Known as AZ-93, the coating has a solar absorption of only around 0.16 while its emissivity is approximately 0.89. The modules will use this as a way of maintaining the living spaces at conditions that are beneficial for long term travel (21°C in the habitat section). The area that receives this coating is sized based on maintaining that temperature at LEO, neglecting the reflection of sunlight from Earth. In order to maintain this temperature at farther distances, the solar panels can be used in conjunction with heating elements due to the reduced power requirements of the electric propulsion system. Water will be used to shunt heat throughout the habitat. This will also allow for slight radiation shielding effects, similar to Bigelow Aerospace's plan for inflatable habitat modules. [12]

Typical electric power input into the habitat is estimated to be 34.42kW. Since all of this energy is electrical in nature, it can be assumed that nearly all of the energy will turn into heat through the impedances present in the different electrical components. The surface of the habitat will need to radiate away this much heat power at LEO along with solar radiation. Solar heating is the most intense present and is around 1367W/m^2. The maximum radiant thermal input to the ship will occur when the ring faces directly at the sun at some point in LEO orbit, resulting in 241.3m^2 of surface area being exposed. Assuming the values of AZ-93 discussed earlier, the ship could see up to 81.47kW needing to be dissipated. Since the habitat is toroidal in shape, about 75% of the surface is available for radiating thermal energy without sending the waves back into itself assuming specular emission. The area to be treated with this coating is 231.3m^2. This would enable the vehicle to emit the 81.47kW. The rest of the area of ARIES would be coated with a combination of other paints and coverings to balance the solar absorptance and emission of heat from the ship.

The chemical thrust system should not need its own thermal regulation system due to its shorter burn time resulting from high impulse maneuvers and relative internal efficiency of the combustion. The SEP system, however, will require a cooling system during its low-thrust, long-duration burns. Coolant can insulate the HPS bus structure allowing heat to be radiated into space. The X-3 electric engine has a thermal efficiency of 60%. If 40% of the 291.2kW input power to the engines is waste, then 116.48kW needs to be dissipated at steady state operation. Maximum radiant thermal energy to the HPS occurs when it faces side-on with the Sun in LEO. If the structure of the vehicle exposed to the heat generation is allowed to reach 100℃, then 159.1m^2 of HPS surface is required to dissipate the solar radiant energy and the engine heat, assuming the same solar absorption and emissivity rates of AZ-93. The surface coating of the solar panels typically has a high solar absorptivity as well as a high emissivity to aid in the dissipation of waste heat generated due to solar cell inefficiency. These values are typically near .8 for both and will help maintain a low temperature so the solar cells will perform better.

Artificial Gravity System

Crew Effects and Method of Generation

The objective of the artificial gravity system onboard ARIES is twofold: to protect the human body against the effects of microgravity and to offer research opportunities. Because a spinning artificial gravity environment with a small radius and a high angular velocity can induce adverse effects on the human body including vertigo and motion sickness, the size of the centrifuge has been designed with crew comfort in mind. Mass and power constraints also dictated the maximum size of the centrifuge. With a radius of 11m from the axis of rotation to the floor of the habitat and a desired gravitational acceleration of 3.711m/s^2 the centrifuge must spin at 5.55rpm. The 11m radius was chosen because of the resulting rotational speed and head-to-foot gravity gradient coupled with the necessity to minimize the size of the centrifuge. The rotational speed sits comfortably below the generally agreed upon limit of 6rpm—speeds greater than 6rpm have cause motion sickness, but speeds as high as 10rpm have been demonstrated without side effects on humans. [13] Head-to-toe gravity gradient tests have demonstrated that as little as a 20% difference in acceleration can be detected by a human rotating with a radius of less than 10m. [14] Given a tall astronaut of 2m and the radius and rotational speed of the centrifuge, the worst-case gravity gradient experienced by a crew member is 18.2%, again, comfortably below the limit.

RCS thruster pods mounted on each of the two stabilizing rinds control artificial gravity generation. Each pod contains two opposing R-1E thrusters used for spin-up and spin-down. R-1E thrusters were used for attitude control on the Space Shuttle Orbiter and have a low mass, making them an attractive option for ARIES. Each engine produces 110N of thrust. [15] A moment of inertia of 8.32×10^6kg/m^2 was calculated by approximating the entire centrifuge as a solid torus. The actual moment of inertia would likely be less than the approximated valued because of the truss mass concentrated toward the central axis. Given the engine thrust and the centrifuge's rotational speed and radius, the time to complete a spin-up or spin-down maneuver is 32 minutes. This burn time distributed to the two thrusters performing the maneuver along with the mass flow rates of oxidizer and fuel, 0.0256kg/s and 0.0354kg/s, respectively, results in 488.7kg of NTO and 675.8kg of MMH consumed after five spin-up, spin-down cycles. [15] A cycle will occur after leaving and before entering a celestial body's sphere of influence, during Martian orbit, and during Lunar orbit, with one cycle being included for redundancy.

Structural Loading

The mass of the centrifuge coupled with its acceleration during spin-up and spin-down correspond to extreme loading on the structural members, most notably including the truss arms and interfacing hub. Given the mass of the habitat and the rotation speed, the maximum force on each truss arm was calculated to be 82.7kN. Aluminum 6061, a common alloy used in aerospace structures with a yield stress of 276MPa, was chosen to compose the truss arms and interfacing hub. [16] Given the mass of the habitat and each truss arm, and the rotation speed, the maximum force on each joint of the interfacing hub was calculated to be 89.2kN. A finite element analysis (FEA) in ANSYS was performed on the structural members and the maximum stress experienced by each truss arm (11.8MPa) and the interfacing hub (5.68MPa) was determined to be less than the material's yield stress. The results of the FEA are displayed in Figure 6.

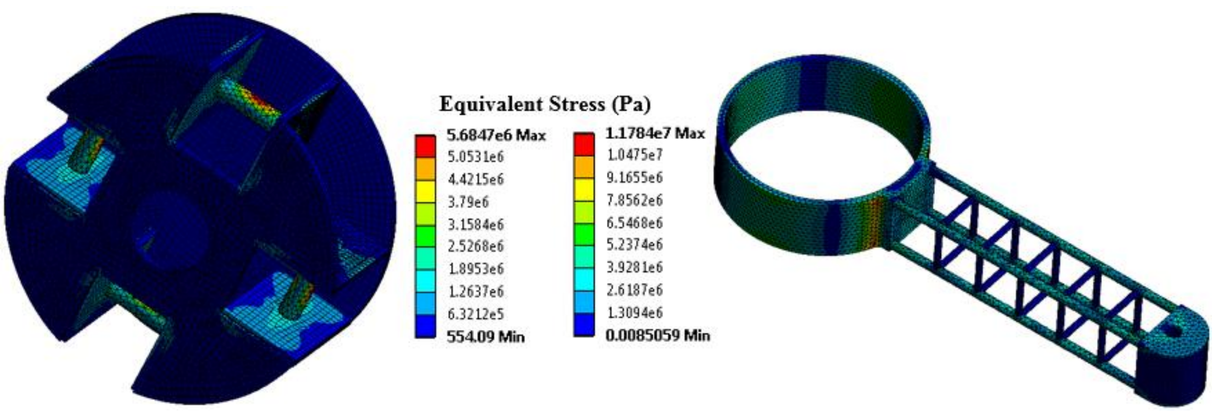

Figure 6: Structural Analysis of Interfacing Hub (Left) and Truss-Stabilizing Ring Assembly (Right)

Habitat

The habitat included with ARIES, though consisting entirely of inflatable modules, has been closely derived from the Mars Transit Habitat. While the form factor of the MTH differs significant from that of the ARIES habitat, the two are very similar in their requirements pertaining to subsystems and crew accommodations, with crew accommodations containing some notable upgrades. Subsystems that function independent of the habitat's size have been preserved while subsystems whose requirements change based on mass or volume of the habitat have been modified. Masses and power consumptions of these subsystems are displayed in Table 1. The total mass and power requirement of the subsystems of the habitat are 94.8t and 18.9kW, respectively.

Table 1: ARIES Master Equipment List

ARIES System	Mass (kg)	Power (kW)	TRL	ARIES System	Mass (kg)	Power (kW)	TRL
ECLSS				**Thermal**			
COLBERT Treadmill [17]	998	1.5	9	(3) Radiators	2,000	0	8
Exercise Bike [18]	250	0.4	9	**Power**			
ARED [19]	1,000	0.2	9	(2) Solar Array Wing [20]	1,732	0	8
Air Revitalization [21]	652	2.6	9	(13) Battery [22]	15	0	9
Temperature Control	271	2.2	9	**Propulsion/Fluids**			
Fire Control [21]	20	0	9	(10) R-42 DM Thruster [3]	73	0	9
Water Systems [21]	552	0.5	9	(4) R-1E Thruster [3]	8	0	9
Lighting [21]	72	0.3	9	(32) S22-02 Thruster [23]	22	0	6
Shielding [21]	1,461	0	5	(8) X3 Thruster [24]	1,840	291.2	6
Waste Management [21]	184	0	9	RCS Fuel/Oxidizer	76,573	0	9
Structures				HPS Fuel/Oxidizer	1,165	0	9
(4) Inflatable Module	9,373	0	9	**Other Subsystems**			
Truss Assembly	32,796	0	6	C&DH Package [21]	131	1	9
HPS	25,506	0	6	Communication Package [21]	210	0.6	9
(5) CBM [25]	5,175	1.5	9	Radio Transceiver [26]	20	0.2	9
(2) NDS [27]	648	0.5	7	Power Amplifier [28]	6	0.5	9
(2) Quest Airlock [29]	19,847	0.3	9	**Additional Equipment**			
SSRMS [30]	451	0.6	9	Stowed Items [21]	2,476	5.0	9
PDGF [31]	12	0.4	9	Spares and Packaging [21]	4,710	0	9
ADCS				(2) Robonauts	300	0	9
ADCS Sensor Suite [21]	33	0.2	9	Food+30%	10,473	0	9
Star Tracker [32]	3	0.2	9	Water+30%	3,848	0	9
CMGs [33]	28	0.2	9	**Totals**	**204,661**	**310.1**	

Habitat Design Considerations

The ARIES habitat ring was designed to minimize disruptions caused by the artificial gravity system, maximize crew safety, and ensure adaptability for future and alternative missions. Other artificial gravity-capable habitat designs were considered—including a rotating axis with habitat modules on either end and an extendable tether-connected habitat and HPS. While both designs would be smaller in total mass and volume than the centrifuge, they were ultimately discarded primarily due to the complications and disruptions crew would experience because of artificial gravity. The current design enables crew members to easily transfer between habitat modules on foot, with no need for spin-up or spin-down or other special artificial gravity maneuvers. The ring-shaped habitat design also ensures crew members have at least two points of escape from any module in case of airlock failure. Finally, the habitat's size provides an opportunity for many alternative missions such as an artificial gravity-enabled space station in Lunar or Martian orbit, or a transit vehicle carrying up to four crew members comfortably. This adaptability ensures a rich future of space exploration while also promising a high return on investment for the program.

Layout

Each inflatable module measures 4m outer diameter with a 2.8m usable inner diameter. ARIES' four habitat modules will contain storage, research, living quarters, and daily activities. The research quarter will consist of communication stations, vegetation racks, and experimentation areas. The living module will contain hygiene stations, a medical bay, and an exercise area. Exercise equipment will feature ARED devices, COLBERT treadmills, and exercise bikes. These exercise components will be modified to account for artificial gravity. The habitation module will house the galley with all food preparation as well as most food storage. In addition, the habitation module will contain the sleeping quarters. Each astronaut will have their own sleeping quarters that contains the recommended 5.4m^3 usable volume. [34] Crew quarter layout was a key consideration in designing the living quarters. Due to the duration of the mission, hygiene stations will be designed in a communal style, rather than in individual quarters. [35] This allows each crew member to maximize personal living space, which in turn increases quality of life, mood, and performance. Figure 7 and Figure 8 display each module's layout.

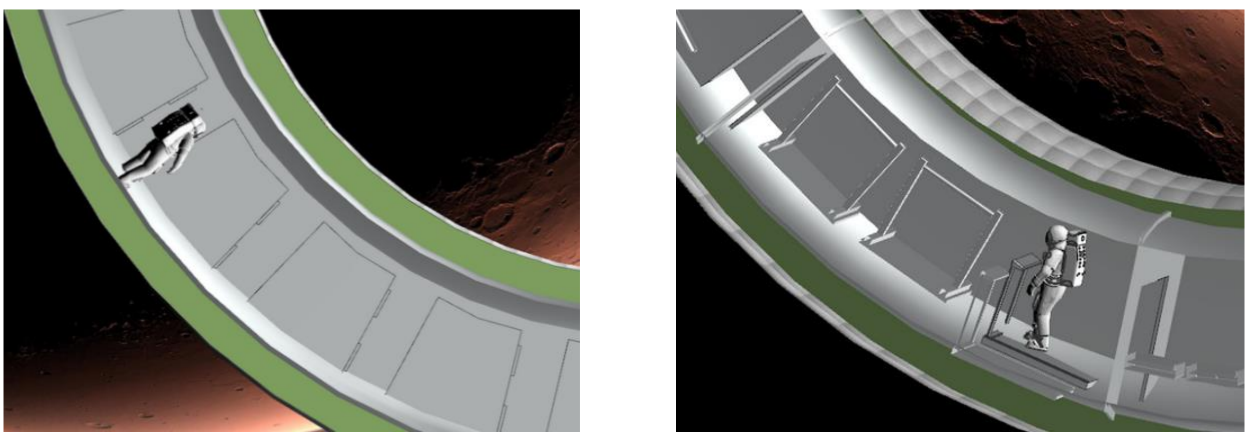

Figure 7: Storage Space (Left) and Living Quarters/Exercise Area (Right)

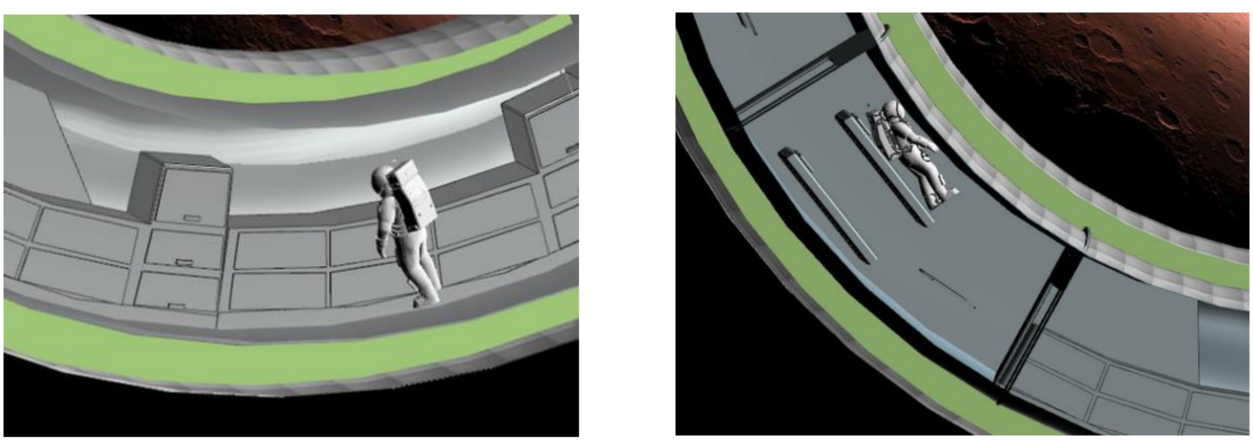

Figure 8: Research Space (Left) and Habitation Quarters/Bedrooms (Right)

Since ARIES will not remain in Earth's magnetic field, the crew will be exposed to high levels of radiation and solar particle events. The exterior walls will provide radiation protection derived from those of the B330. [21] Wall thickness measuring .6m will provide some shelter from radiation exposure. Along with the wall thickness, ARIES will line the habitat with water walls. A 3.5cm thick layer of water reduces the exposure of Solar Particle Event (SPE) radiation by 16%. [36] ARIES will have five 3.5cm thick water walls. To provide crew with extra protection, the habitation quarters will have a minor additional coating of polyethylene. [37] This small coating will keep crew's dose limits provided by NASA of 1.5 Gray-Equivalent (Gy-Eq) for eyes, 3.0 Gy-Eq for skin and 0.5 Gy-Eq for blood forming organs. [38] To assist in protection, the path of transit can be slightly adjusted to avoid major solar particle events. Protecting the habitat from particle debris will be accomplished by micro-meteoroid and orbital debris (MMOD) shielding. ARIES will implement the Al 6061T6 Whipple shield selected for the MTH. [39] Crew members will monitor for particles and can adjust path of transit if deemed necessary. If the habitat is impacted by an MMOD requiring an EVA, ARIES will have two Robonauts perform these tasks. [40] If Robonauts become damaged, EVA suits will be included to perform tasks.

Environmental Control and Life Support System

The life support system on the MTH is based upon scaled ISS hardware as sized using the Advanced Life Support Sizing Analysis Tool (ALSSAT). [21] The tool simulated an 1,100-day crewed mission with an assumption that increased reliability and maintainability can be provided with minimal mass increase from what is currently in use on ISS.

Providing a reliable air filtration system will be crucial for a long duration mission. Therefore, ARIES will use a closed loop air revitalization system with four-bed molecular sieve for CO_2 removal, a Sabatier catalytic conversion of CO_2 with H_2 to water and CH_4, and electrolysis of water for O_2 generation. [41] This system will recover necessary O_2 from CO_2, thus reducing necessary consumables, water and oxygen. [42] The O_2 generation system will function either in continuous or cyclical mode, producing 2.68-9.07kg of O_2 per day or 5.44kg per day, respectively. [17] All gases will be stored in tanks sized for initial inflation, including re-pressurization, six pressurized mating adapter re-pressurizations, EVA support, and contingency. Multiple lithium hydroxide canisters will allow for a 30-day contingency for CO_2 removal. [43]

Maintaining a healthy environment is necessary for a crewed mission. Waste management for long duration transit is a critical operation. ARIES will recycle all liquids using a urine processor and water processor together to purify wastewater for reuse. A low-pressure vacuum distillation process will recover H_2O from urine before entering multiple filtration beds capable of removing solid and gaseous contaminants. Organic contaminants and microorganisms will be removed with a high temperature catalytic reactor while electricidal conductivity sensors will determine the purity of the water. If the water fails to pass, it will re-enter the water processor assembly. [44] An additional source of waste water will come from the washing of crew clothes after 3-5 days of use. Clothing will be sterilized using high heat and an applied cleaning solution inside the showers provided for crew members, which will be both water tight and able to remove steam. Finally, solid waste will also be processed to produce gases including CO, CO_2, CH_4, and H_2. [45] Some of the solid waste may be used as a fertilizer for crops to provide nutrition.

Long durations in space present many health problems for astronauts. Humans spending large amounts of time in space will face many health concerns. It is common for astronauts' bone forming cells to die while remaining healthy bone cells produce fewer minerals for bone regeneration. Muscles also lose strength leading to a decreased ability to burn fat for energy. To prevent this from happening, an ISS-derived exercise suite has been incorporated including a COLBERT Treadmill and an Advanced Resistive Exercise Device. [17] [19] The astronauts will also take regular vitamin supplements to maintain optimal health. In space, it is common for the body fluids to shift directions, flowing to the head. The brain construes the increase in fluid as an increase in overall fluid in the body and works to extract the increased fluid. [46] This may cause changes in the bodies overall health and be harmful over long periods of time. To slow the process in which fluids shift upwards in the body, astronauts will be given adjustable beds intended to be slept upon at an angle. This is chosen with the intention that even throughout rest time periods, the artificial gravity will help keep fluid within the body in its intended location. In addition, sleeping bags will be provided with attachment points to the beds in case of artificial gravity failure.

Sleep loss, circadian desynchronization, and work overload are common issues faced among astronauts. [47] Each of these factors can result in errors that may affect life for crew members, experiments, and the mission. Some methods of prevention include sleep medication, sleep hygiene, and naps. These methods are simple, have minimal cost, and have proven effective on the ISS. [47] Lighting will be adjusted to encourage a natural, 24.2-hr circadian rhythm for the crew. The lights will be dimmed during the "evenings" and brightened in the "mornings". [46] Throughout work hours the lighting will be kept between 200-300 lux. If necessary, during the waking hours 10,000 lux will be used to simulate sunrise and reset circadian rhythms. [46] This will be done by using LED lights in sleep cabins rather than windows, due to the constant sunlight throughout portions of the mission to Mars. [47] In addition, the crew will have access to caffeine to help throughout waking hours. Finally, the sleeping quarter will have sound dampening structures to prevent waking members of the crew if others are working in an adjacent module. [46]

The process of growing crops in space is complex but becoming increasingly necessary as missions extend for longer periods of time. Thus, plants will be grown on ARIES to provide food, O_2, and H_2O; recycle waste; and remove CO_2. [48] Beyond these benefits the plants also offer psychological benefits to the crew as a recreational activity and aesthetics. [49] The system will be composed of a solid substrate due to its ability to provide large specific volumes of water, along with reliability and ease of manufacturing. This system will consist of porous tubes running through the plant roots called Nutrient Delivery Systems (NDS). The NDS delivers water and nutrients to plants without the many fluid-handling problems encountered in microgravity. [50] Other systems including lighting, infrared temperature, humidity, CO_2, ventilation, pressure, anemometers, and O_2 sensors will be present to monitor and encourage proper plant growth. Redundant chambers to contain anomalies, crew accessible ports for re-priming and replacing, and redundant fans and circuitry to ensure airflow will also be added as recommended by the PESTO experiment completed on the ISS. All food grown will be a salad crop like lettuce, radishes, tomatoes, carrots, onions, and cabbage, for their "ready to eat" state. These foods require little to no cooking and are easy to harvest and clean. [50]

Communications

Communication onboard ARIES is derived from the MTH which includes television equipment, Radio Frequency (RF) communications, optical and laser communications, a deep space atomic clock, advanced pointing imaging camera, space security system, and a proximity system for communications functionality. [21] The RF communications structure was based on a combination of X-band and Ka-band systems for deep space communication. These systems of communications have been selected based on the reliability for long duration missions.

Attitude Determination and Control

Because ARIES spends most of its operational lifetime outside of Earth orbit, the attitude determination and control system (ADCS) was designed without consideration for the effects of geopause and Earth-generated gravity gradients. Neglecting those effects eliminates the need for magnetometers and magnetorquers as well as Earth sensors. ARIES will be equipped with star trackers and sun sensors to determine absolute attitude and an inertial measurement unit (IMU) containing rate gyroscopes and accelerometers. To ensure redundancy, five each of the gyroscopes and accelerometers will be installed in the IMU. Attitude control will be handled by the RCS thrusters with minor adjustments being made by

CMGs. Again, five CMGs will be installed onboard to ensure redundancy. RCS thrusters will also be responsible for periodic desaturating of the CMGs.

Command and Data Handling

Command and Data Handling (C&DH) operations in the habitat closely mimic those onboard the MTH. Crew members will each be provided a dedicated C&DH computer used to monitor the vehicle's subsystems, issue commands to those subsystems, and communicate with ground stations. Additionally, data and operations recorders along with video recorders and displays will be installed to ensure ease of communication to ground teams. [21]

Risk Analysis

To prepare and account for all risks pertinent to ARIES, each risk has been categorized based on two main factors, likelihood and consequence. The combination of these two scores assigns a risk level to each item and can be mitigated as seen fit from there. Table 2 displays the risk color code. [51]

Table 2: Risk Matrix Key

Risk Matrix – Key							
Very Likely	*Likelihood*	5					
High		4					
Moderate		3					
Low		2					
Very Low		1					
			1	2	3	4	5
			Consequences				
All decisions based on safety, health, environment, and mission success.			Minimal/No Effect	Low Effect – small injury/small repair/no time lost	Moderate Effect – injury/repair/small loss of time	Significant Effect – permanent injury/repairable damage/large loss of time	Severe Effect – death/ irreversible damage/mission ending

Table 3: ARIES Risk Analysis

Risk	**Likelihood**	**Consequence**	**Level**	**Mitigation**
Exposure to Radiation from EVA	4 – High	4 – Exposure to radiation if repairs necessary outside of Earth's influence		Bring Robonaut attached to outside of module to execute repairs. Prevents radiation exposure for crew while minimizing weight and cost necessary for upgraded suits.
Micro-Meteoroid and Orbital Debris (MMOD) Impact	3 – Moderate	5 - Loss of pressurization or damage to the propulsion stage		Use a Robonaut to complete all repairs from the safety of the module.
Artificial Gravity Spin Up/Down Failure	1 - Very Low	4 - Crew will not be adjusted to Mars		Train crew for zero gravity environments in addition to lower Mars gravity, handholds

		gravity, quality of life lowered		for maneuvering in microgravity, location and hooks available for sleeping bags to be attached to module walls, redundant containment for liquid-based systems.
Propulsion System Failure	2 – Low	5 – Mission Unable to Continue		Multiple engines provide redundancy to prevent total propulsion failure, spare electricity for the SEP system.
Inflation of Habitat Failure	3 – Moderate	4 – Loss of materials and goods within respective habitat, quality of life lowered		Sections will seal individually to allow use of remaining sections, possible manual deployment requiring training, robot used for repairs, supplies will be spread out among each module during inflation to minimize loss.
ECLSS Component Failure	2 – Low	3 – Momentary inability to use part or system		Spares of highest importance will be kept in storage upon inflation, 3D printing available for minor or unavailable parts.
Crew Physical and Mental Health Deterioration	4 – High	4 – Crew members may become unable to perform necessary daily tasks required for survival of crew as a whole		Windows will be available for viewing in the living and research modules, fresh produce will be available for consumption, entertainment including films, books, etc. will be provided, and each crew member will have a designated personal space to themselves, all crew members will be required to pass health tests before launch.
Airlock/Docking Port Failure	2 – Low	3 – Necessary supplies may be momentarily suspended for crew use		All airlocks and docking locations will have a redundant second installation where necessary. Any delays will be small and systems will continue as normal.

Business Model

For the duration of 2018-2027 period, the ARIES mission will entail the design and development of improved ECLSS, ADCS, thermal control, communications, structures and power systems, in addition to human rating the FH. The development phase will require a total cost of $1,952.3 million FY2018. The production of ARIES components will require $948.4 million FY2018 in budget allocation, including construction and assembly of the vehicle's replica in the NBL. The production cost of the structural components will total $336.8 million FY2018. These figures return a total development budget for ARIES at $2,901.3 million FY2018 as calculated using NASA Price Cost Estimating Capability software.

Given NASA's historical allocation of 0.5% of the annual federal budget for the past ten years, as well as current federal budget projection data, the team has established a conservative annual NASA budget projection through the end of the 2020s. [52] [53] Further, the Deep Space Exploration budget has been estimated based on historical percentages. Yearly totals of ARIES expenditures sit comfortably below the estimated totals for NASA's DSE budget—even with additional funding required to human-rate FH and expedite the production of SLS Block 2 Cargo to be ready by the 2028 launch. Plotted in Figure 9 are annual totals and category breakdowns for ARIES.

Construction of ARIES in LEO will begin in 2028 and require several subsequent launches, increasing total mission cost to $8,578.5 million FY2018 during assembly. ARIES is scheduled to conduct four roundtrips to Mars in its lifetime, in 2028, 2032, 2036 and 2040 respectively, with fuel and cargo resupply launches to cis-lunar space in between each trip and final return mission in 2044 bringing a total mission cost to $11,575.5 million FY2018.

Years 2027 and 2028 will entail the greatest costs of the entire mission, with SLS launch, cargo and fuel resupply, as well as construction and mission crew launch costs bringing the annual expenditure for 2027 to $1,900 million FY2018 and 2028 to $3,399 million FY2018 respectively. As such, to limit the possibility of overspending annual NASA budget for Deep Space Exploration, costs will be mitigated by organizing a partnership with international space agencies, such as the European Space Agency (ESA) with relevant budget of $2,843 million per year and Roscosmos with a budget of roughly $2,986 million per year. [54] [55] An efficient proposal would include allocating 2 seats on the habitat for international agencies and a 50/50 NASA-International Agencies business model. NASA would accept 50% of the annual expenditure responsibility with ESA and Roscosmos splitting the remaining 50%. Such a strategy will boost international cooperation and decrease NASA's expenditure on the project by $5,787.5 million FY2018, in addition to $198 million in crew launch cost savings for the period 2027-2044. Costs will be further mitigated with contributions gained by providing commercial entities capability for CubeSat and minor experiment delivery into Lunar and/or Martian orbit.

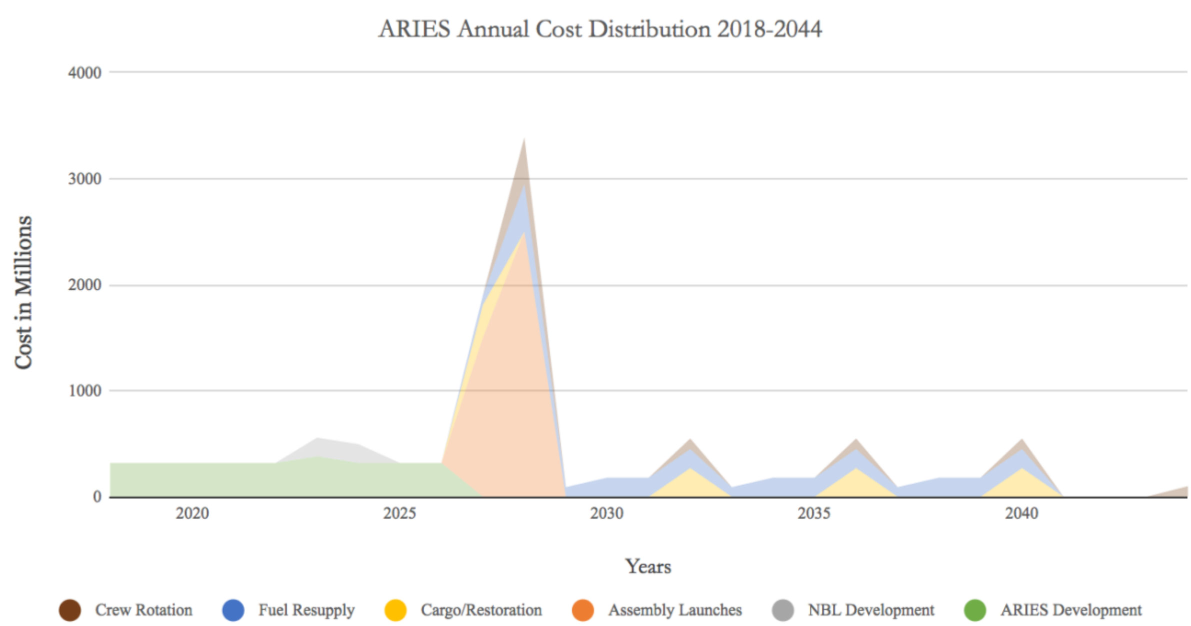

Figure 9: Annual ARIES Budget Breakdown by Category (Millions USD) (2018-2044)

Works Cited

[1] R. G. M. M. Q. Patrick R. Chai, "Mars Hybrid Propulsion System Trajectory Analysis Part I: Crew Missions," August 2015. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160006328.pdf. [Accessed 27 May 2018].

[2] J. F. Herman, "Improved Collocation Methods to Optimize Low-Thrust, Low-Energy Transfers in the Earth-Moon System," 2015. [Online]. Available: https://scholar.colorado.edu/cgi/viewcontent.cgi?article=1117&context=asen_gradetds. [Accessed 27 May 2018].

[3] Aerojet Rocketdyne, "Bipropellant Rocket Engines," 08 June 2009. [Online]. Available: https://www.rocket.com/files/aerojet/documents/Capabilities/PDFs/Bipropellant%20Data%20Sheets.pdf. [Accessed 27 May 2018].

[4] U. Gotzig, "Development of a Low-Cost 22N Thruster," October 2000. [Online]. Available: http://adsbit.harvard.edu/cgi-bin/nph-iarticle_query?bibcode=2000ESASP.465..255G&db_key=AST&page_ind=1&data_type=GIF&type=SCREEN_VIEW&classic=YES. [Accessed 27 May 2028].

[5] R. E. Florenz, "The X3 100-kW Class Nested-Channel Hall Thruster: Motivation, Implementation and Initial Performance," 2014. [Online]. Available: http://pepl.engin.umich.edu/pdf/2014_Florenz_Thesis.pdf. [Accessed 16 January 2018].

[6] B. A. J. H. K. T. W. H. J. H. G. P. Y. P. M. J. B. Scott J. Hall, "High-Power Performance of a 100-kW Class Nested Hall Thruster," 2017. [Online]. Available: https://iepc2017.org/sites/default/files/speaker-papers/high_power_performance_iepc_2017_sjh.pdf. [Accessed 27 May 2018].

[7] Spectrolab - A Boeing Company, "XTJ Prime," [Online]. Available: http://www.spectrolab.com/DataSheets/cells/XTJ_Prime_Data_Sheet_7-28-2016.pdf. [Accessed 29 May 2018].

[8] Saft, "Saft Batteries," Saft, [Online]. Available: https://www.saftbatteries.com/. [Accessed 29 May 2018].

[9] R. G. L. Sadi Carnot, "Rechargeable Li-ion Battery Systems," October 2006. [Online]. Available: http://www.houseofbatteries.com/documents/VES.pdf. [Accessed 29 May 2018].

[10] S. Carnot, "Lithium-ion Battery Life," [Online]. Available: http://sef.solarninovinky.cz/_doc/09_Saft_DOC_%C5%BDivotnost%20Li-Ion%20%C4%8D%C4%BA%C3%A1nk%C5%AF.pdf. [Accessed 29 May 2018].

[11] R. C. Waddel, "Radiation Damage Shielding of Solar Cells on a Synchronous Spacecraft," 01 May 1968. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19680016264.pdf. [Accessed 29 May 2018].

[12] Bigelow Aerospace Division, "Apparatus for Spacecraft Thermal Management," 19 November 2002. [Online]. Available:

https://patentimages.storage.googleapis.com/58/b0/1a/5253bd295ee013/US6481670.pdf. [Accessed 28 May 2018].

[13] T. W. Hall, "Artificial Gravity in Theory and Practice," July 2016. [Online]. Available: http://www.artificial-gravity.com/ICES-2016-194.pdf. [Accessed 11 February 2018].

[14] A. Bukley, W. H. Paloski and G. Clément, "Physics of Artificial Gravity," May 2007. [Online]. Available: https://www.researchgate.net/publication/226552214_Physics_of_Artificial_Gravity. [Accessed 11 February 2018].

[15] M. Wade, "R-1E Engine," [Online]. Available: http://www.astronautix.com/r/r-1eengine.html. [Accessed 20 January 2018].

[16] Aerospace Specification Metals, Inc., "Aluminum 6061-T6 Datasheet," [Online]. Available: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=ma6061t6. [Accessed 28 March 2018].

[17] NASA, "CHeCS (Crew Health Care Systems): International Space Station (ISS) Medical Hardware Catalog," 19 August 2009. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110022379.pdf. [Accessed 31 March 2018].

[18] NASA, "NASA - Cycle Ergometer with Vibration Isolation and Stabilization," 10 January 2018. [Online]. Available: https://www.nasa.gov/mission_pages/station/research/experiments/841.html. [Accessed 31 March 2018].

[19] NASA, "NASA - Advanced Resistive Exercise Device," 28 February 2018. [Online]. Available: https://www.nasa.gov/mission_pages/station/research/experiments/1001.html. [Accessed 31 March 2018].

[20] Spectrolab, "Triple Junction Solar Cell," 2008. [Online]. Available: http://www.spectrolab.com/DataSheets/cells/XTJ_Prime_Data_Sheet_7-28-2016.pdf. [Accessed 1 April 2018].

[21] NASA, "Advanced Exploration Systems Mars Transit Habitat Refinement Point of Departure Design," 2016. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170002219.pdf. [Accessed March 2018].

[22] Saft Groupe S.A., "Rechargeable Li-ion Battery systems," October 2006. [Online]. Available: http://www.houseofbatteries.com/documents/VES.pdf. [Accessed 1 April 2018].

[23] U. a. D. E. Gotzig, "Development Status of Astriums New 22N Bipropellant Thruster Family," in *39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, 2003.

[24] University of Michigan, "X3 – Nested Channel Hall Thruster," 2018. [Online]. Available: http://pepl.engin.umich.edu/project/x3-nested-channel-hall-thruster/. [Accessed 1 April 2018].

[25] NASA, "Common Berthing Mechanism to Pressurized Elements Interface Control Document," 25 October 2005. [Online]. Available: https://prod.nais.nasa.gov/eps/eps_data/155430-OTHER-001-009.pdf. [Accessed 1 April 2018].

[26] L3 Telemetry & RF Products, "CXS-1000 MULTI-FUNCTION MINIATURE TRANSCEIVER," [Online]. Available: https://www2.l3t.com/trf/pdf/datasheets/ML642_CXS1000.pdf. [Accessed 17 April 2018].

[27] NASA, "NASA Docking System (NDS) Interface Definitions Document (IDD)," 16 November 2013. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150014481.pdf. [Accessed 1 April 2018].

[28] Teledyne Microwave Solutions, "X-Band GaN SSPA," [Online]. Available: http://www.teledynemicrowave.com/images/gansspa/X-Band%20SSPAs%200116.pdf. [Accessed 17 April 2018].

[29] NASA, "Quest Airlock | NASA," 18 October 2013. [Online]. Available: https://www.nasa.gov/mission_pages/station/structure/elements/quest.html#.Wr_c-C7wb0M. [Accessed 31 March 2018].

[30] NASA, "HSF - The Shuttle," 7 April 2002. [Online]. Available: https://spaceflight.nasa.gov/shuttle/reference/shutref/orbiter/pdrs/. [Accessed 1 April 2018].

[31] NASA, "Systems Analysis and Structural Design of an Unpressurized Cargo Delivery Vehicle," 26 April 2007. [Online]. Available: https://arc.aiaa.org/doi/pdf/10.2514/6.2007-2329. [Accessed 30 March 2018].

[32] Surrey Satellite Technology US LLC, "Rigel-L Star Tracker," [Online]. Available: http://www.sst-us.com/downloads/datasheets/rigel--star-tracker-datasheet_v112.pdf. [Accessed 17 April 2018].

[33] Honeywell Defense & Space, "M50 Control Moment Gyroscope," January 2006. [Online]. Available: https://aerocontent.honeywell.com/aero/common/documents/myaerospacecatalog-documents/M50_Control_Moment_Gyroscope.pdf. [Accessed 17 April 2018].

[34] NASA, "Minimum Acceptable Net Habitable Volume for Long-Duration Exploration Missions," April 2015. [Online]. Available: https://ston.jsc.nasa.gov/collections/trs/_techrep/TM-2015-218564.pdf. [Accessed March 2018].

[35] NASA, "Human Integration Design Handbook (HIDH)," 5 June 2014. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/human_integration_design_handbook_revision_1.pdf. [Accessed March 2018].

[36] M. Flynn, "Water Walls Architecture," 2012. [Online]. Available: https://www.nasa.gov/sites/default/files/files/Flynn_2012_PhI_WaterWalls.pdf. [Accessed May 2018].

[37] L. Narici, M. Casolino and L. D. Fino, "ALTEA Measurements on radiation shielding efficacy," [Online]. Available: http://wrmiss.org/workshops/twentyfirst/Narici_shielding.pdf. [Accessed March 2018].

[38] NASA, "Space Radiation Organ Doses for Astronauts on Past and Future Missions," [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070010704.pdf. [Accessed May 2018].

[39] NASA, "Micrometeoroid and Orbital Debris (MMOD) Shield Ballistic Limit Analysis Program," 2009.

[40] NASA, "Robonaut 2," August 2011. [Online]. Available: https://www.nasa.gov/sites/default/files/files/Robonaut2_508.pdf.

[41] M. Sakurai, A. Shima, Y. Sone, M. Ohnishi, S. Tachihara and T. Ito, "Development of Oxygen Generation Demonstration on JEM (KIBO) for Manned Space Exploration," 13-17 July 2014. [Online]. Available: https://ttu-ir.tdl.org/ttu-ir/bitstream/handle/2346/59644/ICES-2014-125.pdf?sequence=1. [Accessed May 2018].

[42] J. Isobe, P. Henson, A. MacKnight, S. Yates, D. Schuck and D. Winton, "Carbon Dioxide Removal Technologies for U.S. Space Vehicles: Past, Present and Future," 10-14 July 2016. [Online]. Available: https://ttu-ir.tdl.org/ttu-ir/bitstream/handle/2346/67727/ICES_2016_425.pdf?sequence=1. [Accessed May 2018].

[43] ESA, "Environment Control and Life Support System (ECLSS)," [Online]. Available: http://wsn.spaceflight.esa.int/docs/Factsheets/30%20ECLSS%20LR.pdf. [Accessed May 2018].

[44] NASA, "International Space Station - Environmental Control and Life Support Systems," 2008. [Online]. Available: https://www.nasa.gov/centers/marshall/pdf/104840main_eclss.pdf. [Accessed May 2018].

[45] D. L. Linne, B. A. Palaszewski, S. Gokoglu, C. A. Gallo, R. Balasubramaniam and U. G. Hegde, "Wate Managment Options for Long-Duration Space Missions: When to Reject, Reuse, or Recycle," 13-17 January 2014. [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140010284.pdf. [Accessed May 2018].

[46] NASA, "Astronaut Health and Performance," [Online]. Available: https://www.nasa.gov/centers/johnson/pdf/584739main_Wings-ch5d-pgs370-407.pdf. [Accessed March 2018].

[47] Human Research Program - Behavioral Health and Performance Element (NASA), "Risk of Performance Decrements and Adverse Health Outcomes Resulting from Sleep Loss, Circadian Desynchronization, and Work Overload," [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150016964.pdf. [Accessed May 2018].

[48] P. Howard G. Levine, "The Influence of Microgravity on Plants," [Online]. [Accessed May 2018].

[49] D. L. T. Ph.D., "Current Status of NASA Space Biology," 4 October 2014. [Online]. Available: https://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_152360.pdf. [Accessed May 2018].

[50] O. Monje, G. W. Stutte, G. D. Goins, D. M. Porterfield and G. E. Bingham, "Farming in Space: Environmental and Biophysical Concerns," [Online]. Available: http://sciences.ucf.edu/class/wp-content/uploads/sites/58/2017/02/Monje_SpaceFarming_AdvInSpaceRes2002.pdf.

[51] K. D. Moses and W. R. Malone, "Development of Risk Assessment Matrix for NASA Engineering and Safety Center," [Online]. Available: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050123548.pdf.

[52] D. A. Kring, "NASA Budget History," [Online]. Available: https://www.lpi.usra.edu/exploration/multimedia/NASABudgetHistory.pdf. [Accessed March 31 2018].

[53] B. Blom, J. Shakin and C. Williams, "An Update to the Budget and Economic Outlook: 2017 to 2027,"," June 2017. [Online]. Available: https://www.cbo.gov/system/files/115th-congress-2017-2018/reports/52801-june2017outlook.pdf. [Accessed 31 March 2018].

[54] European Space Agency, "Space In Images," 17 January 2018. [Online]. Available: https://www.esa.int/spaceinimages/Images/2018/01/ESA_budget_2018_by_domain. [Accessed 1 April 2018].

[55] ""Roskosmos" has achieved a significant increase from the budget in 2017," 3 November 2016. [Online]. Available: https://iz.ru/news/642588. [Accessed 1 April 2018].

[56] Surrey Satellite Technology Ltd, "2-Axis DMC Sun Sensor," February 2014. [Online]. Available: https://www.sstl.co.uk/getattachment/dadecfcb-e1e0-4ddf-91c6-f046a5441be1/Sun-Sensor. [Accessed 29 May 2018].