

# The International Space Station: Unique In-Space Testbed as Exploration Analog

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Final assembly of the International Space Station (ISS) was completed in 2011. As articulated in the *2011 NASA Strategic Plan*, the Agency's first goal is to extend and sustain human activities across the solar system. Thus, the emerging NASA vision is to launch a bold and ambitious new space initiative to enable human space exploration beyond low-Earth orbit to Lagrange points, the moon, near-Earth asteroids (NEAs), and Mars and its environs. To accomplish this vision, it is necessary to develop and validate innovative exploration technologies and operational concepts. With the extended life of the ISS to 2020 and possibly 2028, NASA has a mandate to maximize the potential of the Nation's newest National Laboratory. Exploration and ISS teams within NASA's Human Exploration and Operations Mission Directorate (HEOMD) have initiated a cooperative effort: the ISS Testbed for Analog Research (ISTAR), a high-fidelity operational analog that complements existing NASA terrestrial laboratory and field testing. To maximize use of the ISS platform to evaluate new exploration technologies, capabilities, and operational concepts to better comprehend and mitigate human spaceflight risks, ISTAR seeks out and encourages investigations dubbed "exploration detailed test objectives" (xDTOs). These xDTOs, building blocks of ISTAR missions, develop and optimize the operations concepts and the use of new technologies that should reduce risks and challenges facing astronauts on long exploration spaceflight voyages. In this paper, we describe (1) the rationale behind ISTAR, (2) a five-year strategic plan, (3) the approach for mission formulation, development, integration, and execution, (4) concepts for near-term missions that implement a phased approach for using ISS as an exploration testbed, and (5) the planned Mars mission simulation using the ISS. This paper<sup>7</sup> will also document several challenges ISTAR must address to execute its missions.

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## I. Introduction

THE International Space Station (ISS) Test Bed for Analog Research (ISTAR) project was begun in the Fall of 2010 at the NASA Johnson Space Center (JSC) as a part of NASA's exploration test and risk mitigation strategy. Strategic Goal 1 of the *2011 NASA Strategic Plan*<sup>1</sup> is to "Extend and sustain human activities across the solar system." Thus, the emerging NASA vision is to launch an ambitious new initiative to enable human space exploration beyond low-Earth orbit to Lagrange points, the moon, near-Earth asteroids (NEAs), and Mars and its environs. To accomplish this vision, it is necessary to develop and validate new and innovative exploration technologies. The *2011 NASA Strategic Plan* sub-goal 1.1 is to "Sustain the operation and full use of the International Space Station (ISS) and expand efforts to utilize the ISS as a National Laboratory for scientific, technological, diplomatic, and educational purposes and for supporting future objectives in human space exploration." With the extended life span of the ISS to 2020 and possibly 2028, NASA wants to maximize the potential of the Nation's newest National Laboratory. One approach to meet the *2011 NASA Strategic Plan* goal is to conduct sustained, full-use operations of the ISS in order to support human exploration objectives.

Exploration and ISS teams within NASA's Human Exploration and Operations Mission Directorate (HEOMD) have initiated a joint cooperative effort: the ISS Testbed for Analog Research (ISTAR), a high-fidelity operational analog that complements existing NASA terrestrial analogs in order to develop and validate innovative exploration technologies and techniques using the ISS platform. ISTAR supports and encourages investigations dubbed "exploration detailed test objectives" (xDTOs) to maximize use of the ISS platform for the evaluation of exploration technologies, capabilities, and operational concepts that mitigate human spaceflight risks.

The goal of ISTAR is to utilize the ISS as a test platform to reduce exploration risks for crewed NEA or Mars missions. The ISS can provide confinement and a micro-g operational environment to simulate the crew experience during long duration transit flights and arrival activities on NEA or Mars missions. ISS pre-flight preparation could simulate exploration mission preparation processes including mission management team functions, flight planning and design, crew training, flight procedure development, and certification of flight readiness. ISTAR's long-term goal is to conduct long-duration ISS Mars Analog missions on-board the ISS, beginning prior to the end of 2015 using technologies and operational tools and concepts developed and tested during earlier ISTAR missions and Earth-based laboratory and field testing. The purpose of these ISS Mars Analog missions is to address key exploration technology and operational concept gaps before conducting human exploration missions beyond low-Earth orbit. Findings from these missions will contribute to the development of a set of design criteria for spaceflight and support systems that enable safe and affordable human exploration missions, in particular to NEAs and Mars.

### A. ISTAR's Objectives

- Identify exploration investigations that require use of the ISS to advance exploration technology and capability needs or buy-down risk,
- Advance preparations for autonomous crew operations supporting NEA or Mars exploration,
- Evaluate and assess new exploration technologies, operations techniques, and methods as they become available,
- Collect lessons-learned and disseminate them to stakeholders and use them to streamline and refine subsequent ISTAR mission processes, and
- Identify effective and affordable ways to send humans beyond low-Earth orbit and enable them to conduct autonomous mission operations.

ISTAR's proposed ISS Mars Analog missions could last six months or longer while exercising Mars exploration mission phases and crew arrival, departure, and landing activities as realistically as possible within ISS operational constraints.

### B. What is an Analog?

Analog missions are remote isolated field tests in locations that are identified based on their physical similarities to the extreme space environments of a target mission. Analog missions exercise multidisciplinary activities that simulate features of human exploration missions in an integrated fashion in order to enable new capabilities for human exploration. Analog missions test robotics, vehicles, habitats, communication systems, in-situ resource utilization, and human performance as it relates to these technologies. Exploration analog missions are conducted to validate architecture concepts, conduct technology demonstrations, and gain a deeper understanding of system-wide technical and operational challenges needed to support crewed missions beyond low-Earth orbit, such as to NEAs or Mars.

### C. Why ISS as a Testbed?

The ISS provides an in-space operational environment that cannot be completely simulated in any of the terrestrial analogs. Its environment is as close to the crewed space exploration environment as is currently possible--providing a unique in-space micro-gravity analog opportunity not available in any of the terrestrial analogs. It is an excellent testbed to simulate crew activities for long-duration flights and crew arrival at a NEA or Mars, and to research (1) the effects of isolation and confinement on flight-crew autonomy, behavior, and interaction with advanced technologies, the ground, and each other, (2) the most beneficial forms of medical and psychological support, (3) the effects of micro-gravity and physical deconditioning on the Mars landing transition, and (4) the effects of the increasing two-way light time on crew planning, interaction with the ground, and anomaly resolution. In contrast to the current mission-control paradigm of real-time crew access to and significant reliance on mission ground control, delayed space-to-ground communications requires an increase in the responsibility of the flight crew for their safety and the safety of the flight vehicle.

### D. ISTAR Five-Year Strategic Plan

ISTAR has developed and is implementing a phased approach to use the ISS as an exploration testbed and to provide a realistic exploration experience to flight-crew and ground-control personnel by (1) beginning with short analog missions to test risk-mitigation technologies and operational tools, (2) establishing baselines for crew performance and behavior with and without these technologies and tools, (3) developing countermeasures to the negative effects of the long-duration missions, and (4) testing increasing periods of flight-crew and flight-vehicle autonomy by modifying crew procedures and mission-control operations in response to the increasing light-time communication delays. Figure 1 describes this phased approach.

Phase	Major features of plan
A Evaluate ISS Capabilities [2011-2012]	Primarily current ISS operations and activities. Operational, experimental protocols to protect safety, health, efficiency of ISS crewmembers are evaluated for their applicability to Mars (and NEA) missions.
B Short-Period Simulations [2013-2014]	Discrete Mars-forward activities are inserted, such as intermittent multi-day periods of different degrees of bounded autonomy by the ISS crew, including communications delays typical of Mars missions. Sets of assigned tasks would be accomplished with minimal intervention by the MCC, but few alterations would be made to on-board procedures and MCC monitoring of ISS systems. Impact to non-Mars onboard science operations would be minimized. Flight rules specify threshold at which simulation is broken in case of emergency or system malfunction. Add "exploration" tasks to post-landing timeline.
C Longer-Period Simulations [2014-2015]	More rigorous, longer periods of autonomy would be introduced. Crew procedures, MCC oversight are modified to provide a more realistic experience in autonomous operations to both crew and ground personnel. There would be some impact to onboard non-Mars science operations. Post-landing multi-day exploration analogs would be conducted.
D 6-month Mission and Crew Deconditioning [post 2015]	Transits to Mars (and NEAs) would be simulated as rigorously as feasible in low Earth orbit with existing infrastructure. Progressively increasing communications delays would be introduced, reaching the maximum delay after 6 months to mimic Mars proximity. On-board science operations would be compatible with Mars-like mission parameters. Use of post-landing exploration mission analogs would increase.

Figure 1. ISTAR Five-Year Strategic Plan

### E. Approaches for ISTAR Mission Formulation, Development, and Execution

It is crucial to promote collaboration and synergy where possible by fully engaging the NASA exploration community in strategy development and the execution approach for ISTAR missions. Field-tested lessons-learned from other analogs are integrated into ISTAR planning. Lessons-learned from ISTAR missions will be provided back to exploration-system planners, designers, and operations personnel to refine their processes and enhance their follow-on system development. A mission concept development process was created and includes an integrated product team (IPT) forum to identify and vet exploration mission demonstrations that require use of the unique ISS platform. The IPT is a NASA multi-Center team, with representation from the ISS program, exploration systems,

exploration analogs, the Flight Crew Office, the Human Research Program (HRP), and mission operations and engineering.

Mission planning is closely coordinated with the Human Spaceflight Architecture Team (HAT) to firmly base mission selections on exploration technology and capability needs and to buy-down risks of Mars and NEA design reference missions (DRMs). ISTAR is working with the NASA Headquarters' Strategic Analysis and Integration Division (SAID) that sponsors HAT, the Advanced Exploration Systems Division (AES) that funds AES projects--including the NASA analog missions, and the NASA Office of Chief Technologist (OCT) to establish the best path forward and develop synergistic exploration technologies and operations concepts, and to strategically plan missions that align with ISS increments. ISTAR is partnering with HRP to identify and coordinate ISTAR missions that require approval by the Committee for the Protection of Human Subjects (CPHS) review board. ISTAR also works closely with the ISS Program in mission formulation, planning, integration into ISS, and on-orbit operations.

ISTAR has established a solid working relationship with the AES projects, including the Analog Missions Project, to integrate plans for ISTAR analog testing. As a part of the NASA analog mission family, ISTAR collaborates with Earth-based analogs including the NASA Extreme Environment Mission Operations (NEEMO), Research and Technology Studies (RATS), In-Situ Resource Utilization (ISRU), and the Pavilion Lake Research Project (PLRP) in order to infuse the maturing technologies and operational tools, techniques, and concepts they have developed and the lessons they have learned into ISTAR mission designs.

## II. Advanced Exploration Systems Analog Missions

To prepare for the challenge of deep space exploration missions to the moon, asteroids, Mars, or beyond, NASA conducts "analog" missions here on Earth in remote locations that have physical similarities to extreme space environments. The following describes several of the more important NASA "analog".<sup>2</sup>

### A. NASA Extreme Environment Mission Operations (NEEMO)

NASA's Extreme Environment Mission Operations project (Figure 2), known as NEEMO, utilizes a 45-foot-long, 13-foot-diameter underwater laboratory, named Aquarius, located 62 feet below the surface within the Florida Keys National Marine Sanctuary 3.5 miles off the Key Largo coast. A surface buoy provides laboratory connections for power, life support, and communications. Because of its isolation and real underwater hazards, this laboratory's environment makes it an excellent site for testing space exploration concepts.

NEEMO missions, lasting up to three weeks, provide astronauts the opportunity to simulate living on a spacecraft and executing undersea extravehicular activities (EVA). During these activities they are able to test advanced navigation and communication equipment, extravehicular activity (EVA), integrated human-robotic system interactions, remote science and medical operations, and future exploration vehicles.



Figure 2. An astronaut stands in front of an exploration vehicle mockup during NEEMO field tests.

### B. Research and Technology Studies (RATS)

NASA's Research and Technology Studies (RATS) (Figure 3) analog team evaluates exploration technologies, human-robotic systems, and extravehicular equipment in the high desert near Flagstaff, Arizona. RATS exercises provide information that helps scientists and engineers design, build, and operate equipment for exploration missions, and establish requirements for exploration operations and procedures.

The Arizona desert has a rough, dusty terrain and extreme temperature swings that simulate conditions that may be encountered on planetary, lunar, or asteroid surfaces. Some examples of technologies the RATS team has evaluated include high-fidelity prototype hardware, space-suit equipment, robots,



Figure 3. Two rovers are connected to the Habitat Demonstration Unit during RATS field tests in Arizona.

rovers, habitation modules, exploration vehicles, surface mapping and navigation techniques, and power and communication systems.

RATS objectives are to advance future human exploration capabilities by maturing operational concepts and technologies through integrated demonstrations and to reveal operational lessons-learned and technical deficiencies that enable improvements in system design.

### C. In-Situ Resource Utilization (ISRU) Demonstrations

In-situ resource utilization is a process that harnesses local regolith (surface) or atmospheric resources at an exploration destination (moon, asteroid, or Mars) for use in human and robotic exploration. ISRU demonstrations exercise extraction, separation, and storage of desired exploration commodities (e.g., oxygen, hydrogen, methane, water).

NASA conducts ISRU analog demonstrations (Figure 4) at Mauna Kea in Hawaii in collaboration with partners such as the Pacific International Space Center for Exploration Systems, and the Canadian Space Agency. These demonstrations are used to develop or improve systems and technologies that could be used to look for and extract desired commodities at exploration destinations.

The terrain, rock distribution, soil materials, and permafrost at Mauna Kea provide an ideal setting for testing hardware and operations not available in laboratories or NASA centers.

### D. Pavilion Lake Research Project (PLRP)

The Pavilion Lake Research Project (Figure 5) is an international, multi-disciplinary, science and exploration effort that seeks to explain the origin of the freshwater microbialites that grow in Pavilion and Kelly Lakes in British Columbia, Canada.

NASA conducts this analog mission because it is in a critical science research location that provides a challenging setting to test and develop research and exploration methods for future site surveys and science data collection. Scientists use submersible vehicles and methods of exploration that are similar to how robotic precursor missions would explore near-Earth asteroids. The process refinements for traverse planning and science data collection will help improve techniques for future space exploration missions and scientific research.



**Figure 4. NASA and its international partners test equipment during In-Situ field tests at Mauna Kea volcano in Hawaii.**



**Figure 5. The *Deep Worker* submarine searches for microbialites during field tests at Pavilion Lake in British Columbia, Canada.**

## III. International Space Station<sup>3</sup>

The ISS (Figure 6) is the largest orbiting man-made object. It is composed of about one million pounds of hardware, brought to orbit over the course of a decade. The ISS includes 1) primary structures--the external trusses which serve as the backbone of the station and the pressurized modules that are occupied by the ISS crew, and 2) functional systems made up of replaceable units--systems that provide basic functionality such as life support and electrical power made of modular components that are replaceable by astronauts on orbit.

The ISS was constructed to support three activities: scientific research, technology development, and development of industrial applications. The facilities aboard the ISS allow for ongoing research in microgravity, studies of other aspects of the space environment, tests of new technology, and long-term space operations. The facilities also enable a permanent crew of up to six astronauts to maintain their physical health standards while conducting many different types of research, including experiments in biotechnology,



**Figure 6. The International Space Station**

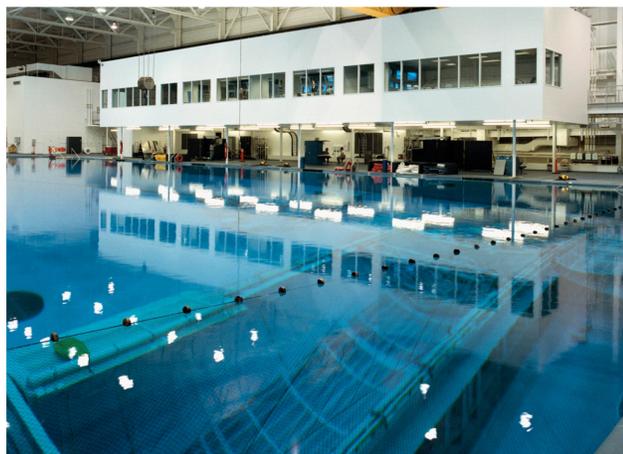
combustion science, fluid physics, and materials science, on behalf of ground-based researchers. Furthermore, the ISS has the capability to support research on materials and other technologies to see how they react in the space environment.

Two ground facilities at the Johnson Space Center in Houston are especially well suited to prepare flight crewmembers and ground controllers for analog operations on the ISS--the Space Station Training Facility (SSTF) (Figure 7) and the Neutral Buoyancy Laboratory (NBL) (Figure 8). The SSTF is a full-scale, high fidelity mockup of the Space Station module cluster. This ISS replica provides interfaces to train flight crewmembers, controllers, and instructors on ISS operations, crew systems, station maintenance, and crew health care. The SSTF is also used to develop and validate operating procedures planned for use on the ISS.

The NBL is an astronaut training facility consisting of the world's largest indoor pool of water, where astronauts perform simulated EVA tasks in preparation for upcoming missions. The NBL contains a full-sized mock-up of the ISS.



**Figure 7. The Space Station Training Facility (SSTF) at the Johnson Space Center**



**Figure 8. The Neutral Buoyancy Laboratory (NBL) at the Johnson Space Center**

#### **IV. Human Spaceflight Architectural Team<sup>4</sup>**

One of ISTAR's important stakeholders is the Human Spaceflight Architecture Team (HAT), a multi-disciplinary, cross-agency study team within NASA Headquarters' HEOMD that conducts strategic analysis cycles to assess integrated development approaches for architectures, systems, mission scenarios, and concepts of operation for human space exploration. During each analysis cycle, HAT iterates and refines design reference mission (DRM) definitions to develop integrated, capability-driven approaches for systems planning to exploration destinations beyond low-Earth orbit.

HAT has generated (Figure 9) a list of risks<sup>5</sup> to the successful accomplishment of crewed exploration missions and a list of mission architecture questions that must be answered before completing design for such missions. ISTAR uses these HAT-generated risks and architectural questions for influencing its mission formulation, development strategy, and mission-evaluation criteria.

#### **V. Human Research Program<sup>6</sup>**

All ISS experiments or activities that involve man-in-the-loop testing, including ISTAR exploration detailed test objectives (xDTOs) that require crew testing as well as planned ISTAR ISS Mars Analog missions, require coordination with and/or approval by NASA's Human Research Program (HRP). HRP, a program managed by the Johnson Space Center's Space Life Sciences Directorate, seeks to perform research necessary to understand and reduce spaceflight human health and performance risks, enable development of human spaceflight medical and human performance standards, and develop and validate technologies that reduce human spaceflight medical risks.

To accomplish these goals, HRP focuses its research on establishing an evidence base on astronaut health and performance for long-duration micro-g missions, on identifying the greatest risks and developing an optimal approach to mitigate those risks, on testing space biomedical technology and medical-care procedures, and on actively collaborating with NASA's international partners on space biomedical research. Figure 10<sup>7</sup> shows HRP's list of human health and performance risks, and its assessment of the criticality of these risks.

ISTAR seeks HRP’s advice, help, and collaboration when developing and executing ISTAR missions because ISTAR will exercise operations concepts that challenge flight crews to work progressively longer periods without direct assistance from ground teams, forcing them to deal with increasingly delayed communications by exercising increasingly autonomous activities. HRP and ISTAR have jointly developed clinical research investigations that assess the impact of communication delay on flight-crew performance. These investigations are being worked through the ISTAR Joint Operations Panel to establish a communication delay protocol and select specific crew tasks and procedures as part of ISTAR Mission 3. See Section VI D (ISTAR Mission 3) below for additional information.

ID	Exploration Mission RISK	ID	Exploration Mission Architectural Questions
M-EDL	EDL of large Mars payloads	Q1	What is the safest way to approach a small/non-cooperative/non-stable object? (i.e. NEA, satellite)
E-EDL	Earth re-entry at high velocities	Q2	What is the safest and quickest way to anchor to a NEA?
LV	Launch vehicle failures	Q3	What Earth Orbit activities are needed to reduce risk for deep space missions?
Lndr	Lander propulsion systems failure	Q4	What are the impact of the planetary protection requirements on operations and elements?
CSM	Long duration low/zero boiloff cryo-storage and management	Q5	What are the functional/volumetric requirements for habitation and IVA activities in zero and low – g?
CFT	In-space cryogenic fluid transfer	Q6	What is the difference in operational efficiency between crew size? (3 and 4 crew for NEA, 4 and 6 crew for Mars)
ISP	In-space propulsion failures	Q7	What is the most efficient way to communicate under a long >30 sec time delay? Does this change as the time increases?
A-ISP	Reliability verification of advanced in-space propulsion	Q8	What improvements of logistics and packaging can be realized?
Env	Environmental risks: radiation, MMOD, dust, electromagnetic	Q9	What is the most effective trade between level of repair and on-orbit manufacturing?
Dock	Docking/assembly failures	Q10	How do you best reuse/repurpose disposable materials?
Sys	Systems failures: ECLSS, power, avionics, thermal	Q11	What is the most effective means of surface transportation? (NEA, Moon/Mars short distance, Moon/Mars long distance)
EVA	EVA system/suit failure	Q12	Given current robotic capabilities, what level of human/robotic interaction provides the highest level of operational efficiency? (EVA at destination, In-space EVA, IVA, Teleoperations)
Comm	Operations under time delayed communication	Q13	What level of IVA/EVA activities at a destination provides the most benefit?
Aut	Autonomous crew/vehicle operation		
Health	Crew health: behavioral, health care/remote medical, micro-gravity		
SW	Software failure		
Hum	Human error		
ISRU	ISRU equipment failure: propellant, consumables		

Figure 9. Human Spaceflight Architecture Team's (HAT) Exploration Mission Risks and Architectural Questions

## VI. ISTAR Missions

ISTAR’s five-year strategic plan, the exploration community’s exploration risks--in particular those identified by HAT (Figure 9), HRP research objectives that mitigate exploration mission risks such as those in Figure 10, and the rationale for using the ISS as a testbed, all guide the formulation, development, and integration of ISTAR missions into ISS. ISTAR also heeds the following National Research Council (NRC) priorities for key technologies needed to extend and sustain human activities beyond low-Earth orbit<sup>8</sup>:

- Radiation Mitigation for Human Spaceflight,
- Long-Duration Crew Health,
- Environmental Control and Life Support Systems (ECLSS),
- Guidance, Navigation and Control (GN&C),
- (Nuclear) Thermal Propulsion,
- Lightweight and Multifunctional Materials and Structures,
- Fission Power Generation, and
- Entry, Descent and Landing (EDL) Thermal Protection Systems (TPS).

### A. ISTAR Mission Development Process

To aid in formulating its planned missions, ISTAR introduced the term “exploration detailed test objective (xDTO)” to describe the technology and operations-concept building blocks of its missions. ISTAR then developed

a unique review process synchronized with the ISS payload integration template to identify, screen, score, and recommend xDTO candidates for appropriate ISS increments.

<h1 style="margin: 0;">HRP Risks &amp; Criticality</h1>				<b>Human Research Program (HRP) Elements:</b> <ul style="list-style-type: none"> <li>• HHC: Human Health Countermeasures</li> <li>• SHFH: Space Human Factors &amp; Habitation</li> <li>• ExMC: Exploration Medical Capability</li> <li>• BHP: Behavioral Health &amp; Performance</li> <li>• SR: Space Radiation</li> </ul>					
HRP Elem	Risk Title (Short Title)	U: Unacceptable Risk, A: Acceptable Risk, C: Controlled Risk, I: Insufficient Data		Lunar	NEA	Mars			
HHC	Risk of Orthostatic Intolerance During Re-Exposure to Gravity (Short Title: OI)			C	A	A			
HHC	Risk of Early Onset Osteoporosis Due to Spaceflight (Short Title: Osteo)			C	A	A			
HHC	Risk Factor of Inadequate Nutrition (Short Title: Nutrition)			C	A	U			
HHC	Risk of Compromised EVA Performance and Crew Health Due to Inadequate EVA Suit Systems (Short Title: EVA) - <i>Pending Human System Risk Board (HSRB) Risk Management Analysis Tool (RMAT) Approval</i>			A	A	A			
HHC	Risk of Impaired Performance Due to Reduced Muscle Mass, Strength and Endurance (Short Title: Muscle)			A	A	U			
HHC	Risk of Renal Stone Formation (Short Title: Renal)			C	C	C			
HHC	Risk of Bone Fracture (Short Title: Fracture)			C	C	C			
HHC	Risk of Intervertebral Disc Damage (Short Title: IVD)			C	I	I			
HHC	Risk of Cardiac Rhythm Problems (Short Title: Arrhythmia) - <i>Pending HSRB RMAT Approval</i>			C	I	I			
HHC	Risk of Reduced Physical Performance Capabilities Due to Reduced Aerobic Capacity (Short Title: Aerobic)			A	A	U			
HHC	Risk of Crew Adverse Health Event Due to Altered Immune Response (Short Title: Immune)			C	C	I			
HHC	Risk of Impaired Control of Spacecraft, Associated Systems and Immediate Vehicle Egress due to Vestibular / Sensorimotor Alterations Associated with Space Flight (Short Title: Sensorimotor)			C	A	A			
HHC	Risk of Therapeutic Failure Due to Ineffectiveness of Medication (Short Title: Pharm) - <i>Pending HSRB RMAT Approval</i>			C	C	I			
HHC	Risk of Microgravity-Induced Visual Impairment/Intracranial Pressure (Short Title: VIIP) - <i>Pending HSRB RMAT Approval</i>			I	I	I			
HHC	Risk of Injury from Dynamic Loads (Short Title: Occupant Protection)			U	U	I			
SHFH	Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System (Short Title: Food)			C	C	U			
SHFH	Risk of Inadequate Human-Computer Interaction (Short Title: HCI) - <i>Pending HSRB RMAT Approval</i>			C	C	A			
SHFH	Risk of Performance Errors Due to Training Deficiencies (Short Title: Train) - <i>Pending HSRB RMAT Approval</i>			C	C	A			
SHFH	Risk of Inadequate Design of Human and Automation/Robotic Integration (Short Title: HARI) - <i>Pending HSRB RMAT Approval</i>			C	C	A			
SHFH	Risk of Poor Critical Task Design (Short Title: Task) - <i>Pending HSRB RMAT Approval</i>			C	C	A			
SHFH	Risk of Adverse Health Effects of Exposure to Dust and Volatiles During Exploration of Celestial Bodies (Short Title: Dust) - <i>Pending HSRB RMAT Approval</i>			A	I	I			
SHFH	Risk of an Incompatible Vehicle/Habitat Design (Short Title: Hab) - <i>Pending HSRB RMAT Approval</i>			C	C	A			
SHFH	Risk of Adverse Health Effects Due to Alterations in Host-Microorganism Interactions (Short Title: Microhost)			A	I	I			
ExMC	Inability to Adequately Recognize or Treat an Ill or Injured Crew Member (Short Title: ExMC)			A	A	U			
BHP	Risk of Adverse Behavioral Conditions and Psychiatric Disorders (Short Title: Bmed) - Reference RMATs for Risk of Adverse Behavioral Conditions, and Risk of Psychiatric Disorders			C	A	U			
BHP	Risk of Performance Errors Due to Fatigue Resulting from Sleep Loss, Circadian Desynchronization, Extended Wakefulness, and Work Overload (Short Title: Sleep)			C	C	C			
BHP	Risk of Performance Decrements due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation within a Team (Short Title: Team)			C	A	A			
SR	Risk of Radiation Carcinogenesis (Short Title: Cancer)			A	U	U			
SR	Risk of Acute Radiation Syndromes Due to Solar Particle Events (Short Title: ARS)			A	A	A			
SR	Risk of Acute or Late Central Nervous System Effects from Radiation Exposure (Short Title: CNS)			A	I	I			
SR	Risk of Degenerative Tissue or other Health Effects from Radiation Exposure (Short Title: Degen)			A	I	I			

Figure 10. NASA's Human Research Program (HRP) Risks and Criticality

For each xDTO candidate, ISTAR documented the candidate's resource requirements (on-orbit crew time, hardware/software development cost and time, payload up-/down-mass and volume, development funding profile, projected earliest readiness date, etc.) using an *xDTO Survey Form*. Proposed xDTO candidates were evaluated by applying a weighting factor (using a scale of 1-3) against the following xDTO selection criteria:

- **ISS as a Testbed:** Is the ISS (or an ISS ground facility) required to test this xDTO candidate? Two points were assigned when ISS was required and no ground facility could be used to test the xDTO candidate, and one point when ISS was not mandatory since an ISS facility (e.g., NBL or SSTF), other facility, or a terrestrial analog could be used to test the candidate. No points were assigned when neither the ISS nor ISS ground facility was required. ISTAR selected this criterion as one of its critical criteria with high value (3-point) weighting factor.
- **Mission Applicability:** What is the applicability of this xDTO candidate to an exploration mission destination? Three points were assigned when a proposed xDTO candidate technology or mitigation method(s) was applicable to a NEA, Mars, and to the ISS as a destination, two points when applicable to both NEA and Mars as destinations, and one point when applicable only to a NEA (or NEA and ISS) or to Mars (or Mars and ISS) as a destination. No points were assigned when a proposed xDTO candidate was applicable to ISS only, to non-NEA/Mars destination(s) only, or to ISS and non-NEA/Mars destination(s) only, since exploration destinations are of high value. ISTAR selected this as another of its critical criteria with a 3-point weighting factor.

- **Safety (Risk) Concern:** Does this xDTO candidate introduce any risk to the ISS vehicle or crew? If so, can the risk be quantified? Three points were assigned when no risks were identified, two points when low risks or no known risks (or only acceptable risks) were identified, or one point when medium risk [or an unacceptable risk(s)] was identified. ISTAR selected this as another of its critical criteria with a 3-point weighting factor.
- **Architecture Relevancy:** Does this xDTO candidate respond to HAT's assessment of Human Space Flight architecture relevance? Three points were assigned when HAT assigned the candidate a high assessed value, two points when HAT assigned a medium assessed value, and one point when HAT assigned a low assessed value. ISTAR selected this as another of its critical criteria with a 3-point weighting factor.
- **Mission-Risk Mitigation:** Does the knowledge gained from this xDTO candidate reduce the risks of a crewed NEA or Mars mission? Three points were assigned to Class 1 xDTO candidates (see listing of ISTAR "classes" immediately below), two points to Class 2 xDTO candidates, and one point to Class 3 candidates. No points were assigned to Class 4 candidates. ISTAR selected this as another of its critical criteria with a 3-point weighting factor. The following describes ISTAR's xDTO candidate classes:
  - Class 1 xDTO candidates intend to provide/improve radiation protection for flight crews (Class 1a), intend to mitigate physiological effects of long-duration micro-gravity (Class 1b), and intend to mitigate psychological effects of long-duration isolation (Class 1c).
  - Class 2 xDTO candidates support development of technology to improve flight-crew life support (including closed loop) and/or habitation systems (Class 2d), support development of technology to improve autonomous systems and avionics (Class 2e); and intend to improve flight-crew productivity during long-duration missions (Class 2f).
  - Class 3 xDTO candidates contribute to supporting flight-crew medical diagnosis and/or acute care (Class 3g), support development of technology to provide or improve automated rendezvous and docking (Class 3h), and intend to improve flight-hardware maintenance/supportability (Class 3i).
  - Class 4 xDTO candidates include those dealing with flight operations, crew clothing or extravehicular-intravehicular suit systems, emergency equipment, experiments/fabrication/facilities, fire detection and control, human systems, materials research, power management, etc. (Class 4j).
- **Potential for Mission-Risk Reduction:** If the proposed xDTO candidate is selected and succeeds, what percent of its associated mission-risk could be mitigated? Three points were assigned if significant (>25%) risk could be mitigated, two points when moderate (>10% but <25%) risk could be mitigated, and one point when only minimal (<10%) risk could be mitigated. ISTAR selected this as the last of its critical criteria with a 3-point weighting factor.
- **Cost:** If development of this xDTO candidate is not fully funded, how much additional funding is required? Four points were assigned when \$0.5M or less is required, three points when \$0.5M-\$1.5M is required, two points when \$1.5M-\$3.5M is required, or one point when more than \$3.5M is required. ISTAR assigned this selection criterion a 2-point weighting factor.
- **Crew Time:** What is the total crew time (hours) needed to support operation of this xDTO candidate? This was assigned three points when 5 or fewer hours are needed, two points when 5-40 hours are needed, or one point when greater than 40 hours are needed. ISTAR assigned this selection criterion a 2-point weighting factor.
- **xDTO Readiness:** What is the progress of any xDTO-candidate hardware/payload-safety certification or safety and mission assurance assessment? Three points were assigned if a candidate had passed its Phase 0/I, II, and III safety reviews to-date, two points if a candidate had passed its Phase 0/I and II safety reviews to-date, and one point if a candidate had passed its Phase 0/I safety review to-date. ISTAR also assigned this selection criterion a 2-point weighting factor.
- **ISS Flight Resource Dependency:** What is anticipated amount of ISS resources (e.g., power, communications, fluid/gas/atmosphere consumables, imagery, tools, crew-aids/provisioning, stowage, attitude/pointing) required to support this xDTO candidate? Three points were assigned when few or no ISS flight resources are required, two points when a moderate amount of resources is required, and one point when a large amount of resources is required. ISTAR assigned this selection criterion a 1-point weighting factor.

Utilizing the ISTAR IPT forum, ISTAR conducted high-level reviews with stakeholders and management to prioritize and rank xDTO candidates for recommendation to the ISS Program. ISTAR forwarded its recommended list of xDTO candidates, denoting them for flight consideration on specific ISS increments, to the ISS Program's Research Planning Working Group (RPWG) during their ISS utilization planning for an increment period. ISTAR

will monitor the on-orbit execution of its recommended xDTO candidates, conduct post-mission analyses of successfully mitigated exploration mission risk, and collect and disseminate and lessons-learned.

## **B. ISTAR Mission 1**

Ground-based analog missions have found that time delay is an impediment to communication. An in-space operational environment is needed to validate communication delay effects on individual and team performance and behavioral health outcomes. Reduced communication is the first step toward a major cultural shift for mission flight and ground crews in the operation of exploration missions. In contrast to the current mission control paradigm of real-time crew access and significant reliance on ground mission control, delayed communication requires an increase in flight crew responsibility for safety of crew and space vehicle, which may cause initial discomfort for both flight and ground crews. The first ISTAR mission will study countermeasures for communication delays. HRP will sponsor a study on a later mission (planned for ISTAR Mission 3) that will look at the effects of communication delay on crew performance.

Ground-based analog missions have also found that the impact of a communication delay is lessened when autonomous procedures and text messaging are available. The primary purpose of ISTAR Mission 1, planned for ISS Increments 31/32, is to prepare the flight and ground crews for more autonomous flight operations by the execution of autonomous crew procedures and by the engineering evaluation of communication delay countermeasures (text messaging) when voice communication is not being used (but is available). The autonomous crew operations and communication delay countermeasures are separate activities and will be performed at different times so that the variables can be studied independently before the ISTAR Mission 3 test is performed.

- **Crew Procedure Execution** - Communication delays will force the exploration crews and their vehicles to be more autonomous. Crewmembers will not have the ground to rely on for instant assistance, advice, and troubleshooting help while performing procedures. The objective is to prepare the flight and ground crews for more autonomous flight operations (including autonomous crew procedure execution). This will give the procedure authors experience in developing autonomous procedures, understand what extra information the flight crew would need to perform a specific procedure autonomously, and develop methods to train flight crewmembers to perform autonomous execution of procedures. This will give the crew experience in executing procedures without relying on the ground. This may also provide insight into how communication delay might affect not only procedures but also the design, building, and operation of hardware and software for future spacecraft and systems.
- **Communication Delay Countermeasures** - During periods of communication delays that will be simulated in later ISTAR missions, the standard voice communication between the crew and ground is expected to be operationally ineffective. Communication delay scenarios have been simulated on Earth-based analogs and these delays have been found to make space-to-ground voice communication difficult and inefficient. The objective of ISTAR Mission 1 is to explore other methods of space-to-ground communication in order to not sacrifice operational efficiency. As a secondary objective, the results will be compared with the results of RATS, NEEMO, and Pavilion Lake field tests.

Additional exploration-related studies will be performed on ISS during Increment 31/32 but are not sponsored by ISTAR; these include Synchronized Position Hold Engage Reorient Experimental Satellites (SPHERES) free-flyer simulated extravehicular inspection, Robonaut 2 simulated extravehicular routine and emergency operations, and exploration-related HRP studies being performed on ISS. The focus of these experiments will be on gathering lessons-learned for exploration-risk mitigation.

## **C. ISTAR Mission 2**

ISTAR Mission 2, a continuation of ISTAR Mission 1, coincides with ISS Increments 33/34. Lessons-learned during the ISTAR Mission 1 investigation will be incorporated into the ISTAR Mission 2 study. Additional autonomous procedures will be performed, and additional variables or different countermeasures may be added to the communication delay countermeasures study--such as performing the test using more than one crewmember at the same time and/or inserting a time delay. Additional exploration-related studies that will be performed on ISS during these increments that are not sponsored by ISTAR include SPHERES, Robonaut 2, ISS Crew Control of Surface Telerobots, Radiation Environment Monitor, Microbial Growth and Control in Space Suit Assembly (SSA) Gear, and several exploration-related HRP studies. The focus of these experiments will also be on gathering lessons-learned for exploration-risk mitigation.

#### **D. ISTAR Mission 3**

The HRP study of the impact of communication delay on flight crew performance is the primary focus of ISTAR Mission 3. This study, starting in Increment 36, will determine whether the communication delays likely to be experienced on a long-duration mission to an asteroid or to Mars will result in clinically or operationally significant decrements in crew behavior and performance. The test will validate ground test findings and determine and evaluate: 1) risks to flight crew behavioral health and performance, 2) risk of performance decrements due to inadequate cooperation, coordination, communication, and psychosocial adaptation within a team, 3) risk of psychiatric disorders, and 4) risk of adverse behavioral conditions. The crew will use the countermeasures and autonomous procedures developed for ISTAR Missions 1 and 2 in this study.

Additional exploration-related studies that will be performed on ISS during this increment that are not sponsored by ISTAR include ISS Crew Control of Surface Telerobots, Radiation Environment Monitor, Quantification of In-flight Physical Changes—Anthropometry and Neutral Body Posture (NBP), Microbial Growth and Control in Space Suit Assembly (SSA) Gear, and exploration-related HRP studies.

### **VII. ISS Mars Analog Mission**

In February 2012 the Associate Administrator for HEOMD at NASA Headquarters challenged ISTAR to perform its first Mars-mission simulation on the ISS before 2016. The main goal of this ISS Mars Analog mission is to address key exploration technology and operational concept gaps before conducting human exploration missions beyond low Earth orbit. Findings from this ISS Mars Analog mission will contribute to the development of a set of design criteria for spaceflight and support systems that enable safe and affordable human exploration missions—in particular to NEAs and Mars. Discussions have begun on possible approaches to meeting this challenge. The following is a description of one possible approach to conducting such a Mars-mission simulation on the ISS:

#### **A. Mission Objectives (Notional)**

- Conduct Mars exploration mission launch, transit, and landing transition phases as realistically as possible within ISS operational constraints,
- Understand the highest risks to human systems during long duration missions and learn how to mitigate them in order to prepare for human exploration missions:
  - Understand what capabilities are required and what tasks/operations should fall under autonomous crew operations for missions to Mars,
  - Gain insight into how best to plan roles and responsibilities between flight and ground for long-duration crewed missions,
  - Understand which are the critical mission preparation processes including exploration mission management team functions, flight design, crew training, flight procedure development, flight software needs, and certification of flight readiness that are unique to long duration missions or mission to Mars,
  - Determine the most efficient way to communicate under a long time delay. Investigate how this changes as the time delay increases incrementally during the “transit” to Mars. (HAT architectural question 7),
  - Investigate risk of adverse behavioral conditions and psychiatric disorders (HRP risk *Bmed*) due to long-term, close-quarters confinement,
  - Identify requirements for needed capabilities for crewed exploration missions,
  - Test and validate DRM architectures and space exploration concepts, and
  - Inform customers and stakeholders of ISS Analog mission results and lessons-learned.
- Collaborate with NASA’s International Partners to develop an integrated strategy for conducting joint exploration missions, including roles and responsibilities and the management model for a Mars mission,
- Work with the International Space Exploration Coordination Group (ISECG) and HAT to ensure that the latest version of the Mars design reference mission is available, and that exploration risks and technology/capability gaps are addressed to the greatest extent possible,
- Demonstrate and validate exploration technologies and operations concepts developed by HEOMD’s Advanced Exploration Systems (AES) Division and NASA’s Office of Chief Technologist (OCT) to the greatest extent possible, and
- Collaborate and synergize with the NASA HQ’s Science Mission Directorate (SMD) to infuse flight proven robotic exploration capabilities and projected science operations to the extent possible.

#### **B. Mission Level 1 Requirements (Notional)**

MR1: The ISS Mars Analog mission shall mitigate the impact to ongoing nominal ISS on-board operations.

MR2: Eighty percent of ISS Mars Analog mission flight-crew activities shall support planned ISS system/experiment activities.

MR3: The ISS Mars Analog mission shall be conducted by three or more flight crewmembers.

MR4: The ISS Mars Analog mission shall be conducted for a minimum of four (TBR) months.

MR5: Participating flight crewmembers shall interact with only each other during 85% of the on-orbit mission phase.

MR6: If four or fewer flight crewmembers participate in the ISS Mars Analog mission, 85% of the on-orbit mission phase time shall be conducted within an ISS habitable volume of 22.5 m<sup>3</sup>/crewmember or less.

MR7: A separate ISS Mars Analog mission ground control team shall control the ISS Mars Analog mission and report activities and simulation progress to the normal ISS ground control team.

MR8: The ISS Mars Analog mission shall be conducted with a communications delay that varies by distance from Earth and corresponds to the delay expected during an Earth-to-Mars transit mission.

MR9: The ISS Mars Analog mission communications delay shall apply to all (TBR) voice, data, and command interaction between the participating ISS Mars Analog mission ground control team and the participating ISS Mars Analog mission flight crew.

MR10: The ISS Mars Analog mission ground control team shall have representation from participating International Partners (IPs).

### **C. Mission Operations Concept (Notional)**

The ISS Mars Analog mission timeline will be based on the latest official design reference architecture for a crewed mission to Mars [currently Design Reference Architecture (DRA) 5.0<sup>9</sup> (Figure 11) created by the NASA Headquarters' Mars Architecture Working Group]. Detailed timeline activities will be based on analogous ISS operations, applicable NASA robotic exploration mission activities, and projected unique human exploration mission tasks with a special emphasis on execution of increased crew autonomous operations.

A separate ISS Mars Analog mission ground control team will control the ISS Mars Analog mission and report activities and simulation progress to the normal ISS ground control team so that the ISS ground control team can maintain overall ISS awareness and control. This will allow the ISS mission control team to monitor both ISS and Mars Analog mission systems and activities to ensure ISS safety, while the ISS Mars Analog mission ground control team controls the progress of Analog operations. Separate mission timelines will be used--the ISS mission timeline that also contains Mars Analog mission activities, and an ISS Mars Analog mission timeline--a filtered version of the ISS mission timeline (TBR)--to govern the activities of the ISS Mars Analog mission.

At a minimum the simulation planning will include the Mars-mission phases of Earth launch/ascent (item 7 in Figure 11), on-orbit (i.e., Mars transit) operations (item 8), Mars entry (represented by Earth entry) (item 9), and Mars-gravity adaptation (represented by Earth-gravity adaptation) on the Mars surface (e.g., the first three weeks of item 10).

### **D. Mission Development Schedule and Simulated Mars-Transit/Arrival Timeline (Notional)**

Figure 12 shows a possible ISS Mars Analog mission development schedule.

Figure 13 shows a timeline of typical crew activities during the launch, transit to and arrival at Mars, and Mars-gravity adaptation periods for a crewed mission to Mars. Where possible, the simulation flight crew will conduct their ISS-experiment and ISS Mars Analog mission activities to simulate the following typical Mars-mission activities:

- Crew launch, low-Earth-orbit (LEO) activities, Mars Transfer Vehicle (MTV) check-out, and Mars-transit injection,
- General housekeeping, food preparation and meals, equipment maintenance and repair, exercise, personal hygiene/time/recreation, and communication with family and friends,
- MTV turns, battery temperature maintenance, MTV attitude maintenance, public affairs activities, and crew just-in-time and refresher training,
- Trajectory correction maneuvers 1-6,
- Subsystem engineering checkout periods 1 and 2, MTV switch to medium-gain antenna, flight software update, and Entry/Descent/Landing (EDL)-parameter update,
- Crew subsystem maintenance and emergency refresher training,
- Crew arrival, orbit, EDL, and surface activities training,
- Crew arrival in Mars orbit, docking with Surface Habitat (SHAB), telerobotics of surface infrastructure, and EDL, and
- Three-weeks of crew adaptation to Mars gravity.



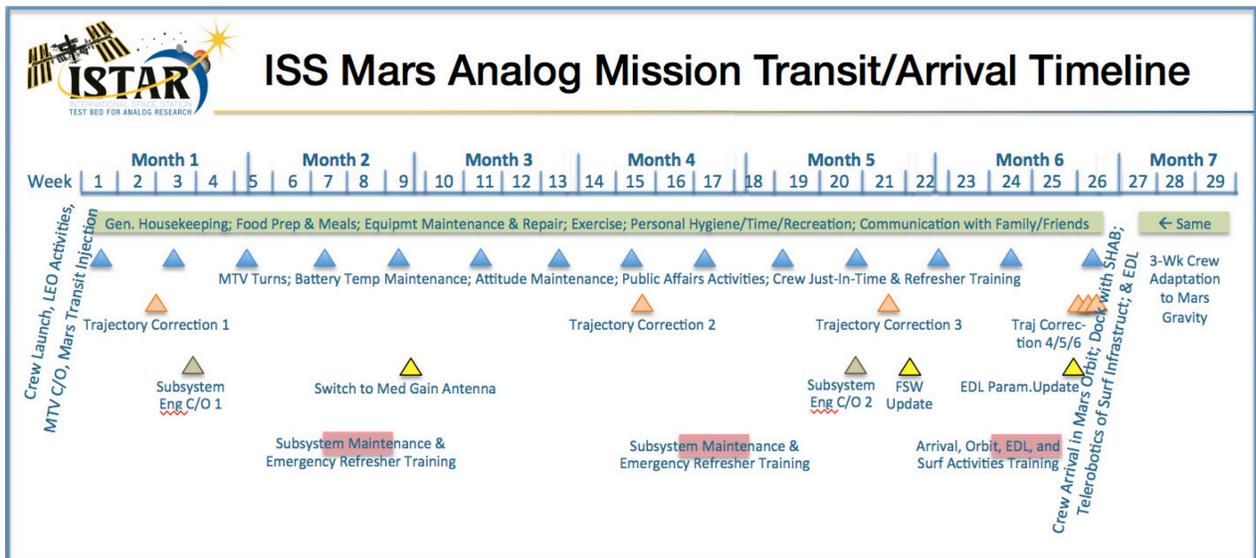


Figure 13. ISS Mars Analog Mission Transit/Arrival Timeline (Notional)

2. **Exploration community buy-ins:** It is absolutely essential to work collaboratively and synergistically with all affected ISS Mars Analog mission planning and implementing organizations (including ISS teams and HRP) and stakeholders (AES and OCT) in the planning of ISTAR missions, including ISS Mars Analog missions. Obtaining adequate support from the involved organizations during mission formulation and planning—competing with their other priorities and with today’s tight budgets—will be a very daunting task. However, it will be critical to maintain their consistent participation via technical interchange meetings and workshops in order to obtain early buy-in and continuing support of ISTAR’s objectives and missions.
3. **Support by the Human Research Program (HRP) and NASA’s Crew Office:** Conducting a Mars Analog mission on the ISS that contributes to understanding and reducing spaceflight human health and performance risks of this exploration mission, and that requires participating flight crewmembers to undergo the simulated rigors of such a mission necessitates a continuing close cooperation with HRP and the Flight Crew Office. Only with their detailed understanding and support can this ISS Mars Analog mission succeed.
4. **Resolution burn-down challenges:** During the formulation process of the ISS Mars Analog mission, adequate resources must be allocated to resolve to-be-determined (TBD) and to-be-resolved (TBR) items to ensure that pre-mission preparation meets planned development timelines and that the simulation will meet planned objectives.

## IX. Conclusion

By its efforts to encourage use of the ISS as a test platform to reduce exploration risks for crewed NEA or Mars missions, ISTAR has made a good first step towards achieving NASA’s goal to “expand efforts to utilize the ISS as a National Laboratory for ... supporting future objectives in human space exploration.” Meeting the objectives of ISTAR Missions 1-3 addresses this goal by contributing towards understanding the challenges and mitigating the risks of conducting crewed exploration missions. The ISTAR ISS Mars Analog mission, if recognized challenges are overcome, would support the development of design criteria for these crewed exploration missions that would enable NASA to meet its strategic goal of “extending and sustaining human activities across the solar system.”

## **Appendix A**

### **Acronym List**

AC	Aero-Capture
AES	Advanced Exploration Systems Division (or Project) (HEOMD)
A-ISP	Advanced In-Space Propulsion
CFT	Cryogenic Fluid Transfer
C/O	Checkout
CPHS	Committee for the Protection of Human Subjects (NASA JSC)
CSM	Cryogenic Storage and Management
DM	Descent Module
DRA	Design Reference Architecture
DRM	Design Reference Mission
EDL	Entry/Descent/Landing (M-Mars; E-Earth)
ENV	Environmental
EVA	Extravehicular Activity
FSW	Flight Software
HAT	Human Spaceflight Architecture Team
HEOMD	Human Exploration and Operations Mission Directorate (NASA HQ)
HQ	Headquarters
HRP	Human Research Program (NASA JSC)
IP	International Partner
IPT	Integrated Product Team
ISECG	International Space Exploration Coordination Group
ISP	In-Space Propulsion
ISRU	In-Situ Resource Utilization
ISS	International Space Station
ISTAR	ISS Testbed for Analog Research
IVA	Intra-Vehicular Activity
JSC	Johnson Space Center (NASA)
LEO	Low-Earth Orbit
LV	Launch Vehicle
MAV	Mars Ascent Vehicle
MCC	Mission Control Center (at JSC)
MDAV	Mars Descent/Ascent Vehicle
MMOD	Micro-Meteoroid Orbital Debris
MTV	Mars Transfer Vehicle
NBL	Neutral Buoyancy Laboratory (JSC)
NBP	Neutral Body Posture
NEA	Near Earth Asteroid
NEEMO	NASA Extreme Environment Mission Operations
NRC	National Research Council
OCT	Office of Chief Technologist (NASA HQ)
PLRP	Pavilion Lake Research Project
RATS	Research and Technology Studies
RPWG	Research Planning Working Group
SAID	Strategic Analysis and Integration Division (NASA HQ)

SM	Service Module
SMD	Science Mission Directorate (NASA HQ)
SPHERES	Synchronized Position Hold Engage Reorient Experimental Satellites
SSA	Space Suit Assembly
SSTF	Space Station Training Facility (JSC)
SHAB	Surface Habitat
SW	Software
TBD	To-be-Determined
TBR	To-be-Resolved
TEI	Trans-Earth Injection
TMI	Trans-Mars Injection
xDTO	Exploration Detailed Test Objective

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