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Generalizable Skills and Knowledge for Exploration Missions

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August 2019

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"The human factor is three quarters of any expedition."
– Roald Amundsen

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The cover illustration, titled, Exploring Mars, is from the BBC/Impossible Films, Ltd., production, *Space Odyssey: Voyage to the Planets*, which was broadcast in November 2004. The "fictional documentary" was written and directed by Joe Ahearne and produced by Christopher Riley, who received the 2005 Sir Arthur Clarke Award for Best TV & Radio Presentation.
http://www.humanmars.net/2015/02/space-odyssey-voyage-to-planets-2004.html#gpluscomments

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EXECUTIVE SUMMARY

This report describes research conducted under Cooperative Agreement 80NSSC18K0042 for the Human Factors and Behavioral Performance Element, Human Research Program, located at the National Aeronautics and Space Administration's (NASA) Johnson Space Center. The research addresses the Risk of Inadequate Mission, Process, and Task Design and the Risk of Performance Errors Due to Training Deficiencies during exploration-class space missions by identifying the tasks that will be conducted by human crew during an expedition to Mars and the abilities, skills, and knowledge that will be required of crew members. By focusing on an expedition to Mars, we have considered the extremes of what is possible for human space exploration during the first half of the 21st Century and accommodated the human requirements for missions to asteroids, Cis-Lunar orbit, and a return to the Moon.

The study uses research methods that were developed to analyze the work performed by a variety of civilian and military occupational specialties and is consistent with Human Factors methods. The work began by developing a comprehensive inventory of 1,125 tasks that are likely to be performed during the 12 phases of the first human expeditions to Mars, from launch to landing 30 months later. Sixty subject matter experts (SMEs) rated expedition tasks in terms of (likely) frequency, difficulty to learn, and importance to mission success; a fourth metric was derived by combining the mean ratings of the three dimensions. Seventy-two SMEs placed the physical, cognitive, and social abilities necessary to perform the tasks in order of importance for specialist domains identified by the task analysis. The research team then identified, 1) Abilities, skills, and knowledge that can be retained and generalized across tasks; 2) Optimum training strategies; and, 3) Implications for crew size and composition. Study results also led to recommendations concerning equipment, habitats, and procedures for exploration-class space missions. The report describes why the study was conducted, describes the research tasks performed and study results, and concludes with a discussion of operational implications and recommendations based on those results. Appendices present details of the procedures used, a complete list of Mars expedition tasks (by mission phase), a list of tasks that are likely to be performed during expeditions to a Cis-Lunar Gateway, and the names of SMEs who contributed to the study.

Note: The full-mission task inventory presented in this report was developed during a comprehensive review of documentation and concepts of operations. It is understood by the study team that the tasks are based on currently-available information and that the tools, equipment, propulsion methods, and/or other aspects of actual human expeditions to Mars might be different from those described here, as a consequence of technological development and evolving Mars Design Reference Missions.

ACRONYMS USED IN THIS REPORT

ANARE	Australian National Antarctic Expeditions
ARC	Ames Research Center
CAT	Critical Abilities and Tasks (method)
CLO	Cis-Lunar Orbit
CMO	Crew Medical Officer
CTE	Cruise to Earth
CTM	Cruise to Mars
DRA	Design Reference Architecture
EA	Earth Approach
EMPIRE	Early Manned Planetary-Interplanetary Roundtrip Expeditions
EOD	Explosive Ordnance Disposal (technicians)
EOR	Earth Orbit Rendezvous
ESD	Earth Surface Descent
ESMD	Exploration Systems Mission Directorate
EVA	Extra-Vehicular Activity
HEOMD	Human Exploration and Operations Mission Directorate
HFE	Human Factors Engineering (Human Factors Psychology, Ergonomics)
HRP	Human Research Program
ICU	Intensive Care Unit
ISS	International Space Station
JAG	Joint Action Group (Planetary)
JSC	Johnson Space Center
LCAC	Landing Craft Air Cushion (US Navy Hovercraft)
LEO	Low Earth Orbit
LOR	Lunar Orbit Rendezvous
LTO	Launch to Orbit
MAV	Mars Ascent Vehicle
MAWG	Mars Architecture Working Group
MCC	Mission Control Center
MDV	Mars Descent Vehicle
MEM	Mars Excursion Module
MEV	Mars Excursion Vehicle
MO	Mars Orbit
MOI	Mars Orbit Injection
MOR	Mars Orbit Rendezvous
MSA	Mars Surface Ascent
MSC	Manned Spaceflight Center (now the Johnson Space Center)
MSD	Mars Surface Descent
MSO	Mars Surface Operations
NACA	National Advisory Committee on Aeronautics
NASA	National Aeronautics and Space Administration
NEEMO	NASA Extreme Environment Mission Operations
NEO	Near Earth Object
PERT	Program Evaluation Review Technique
SEAL	Sea-Air-Land (US Navy commandos)
SME	Subject Matter Expert
SPE	Solar Particle Event
STG	Space Task Group
TEI	Trans-Earth Injection
TMI	Trans-Mars Injection
TROV	Teleoperated Robot Rover
TRW	Thompson Ramo Wooldridge, Inc.
UMPIRE	Unfavorable Manned Planetary-Interplanetary Roundtrip Expeditions

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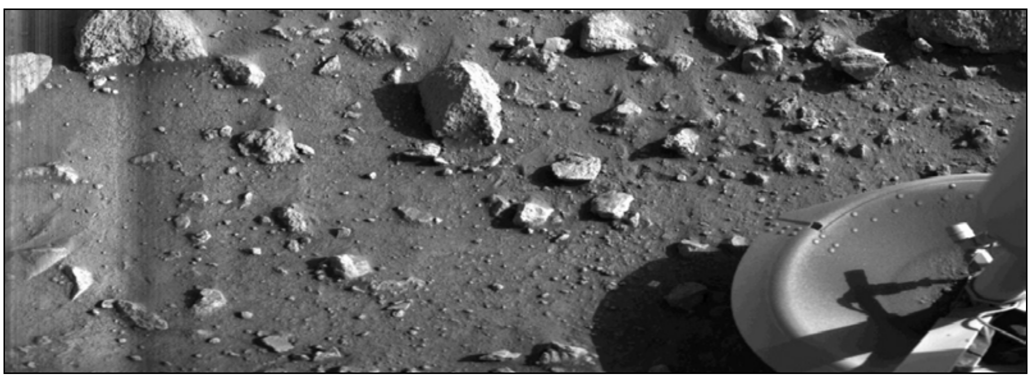


First Photo Taken on Mars, Viking 1, 20 July 1976.

FIGURES, PHOTOGRAPHS, AND TABLES

FIGURES, PHOTOGRAPHS, AND TABLES (CONTINUED)

Images courtesy of the National Aeronautics and Space Administration, 20th Century Fox, BBC/Impossible Films, Ltd., Bonestell LLC, ESA/DLR, and Pat Rawlings; all others are in the public domain.

INTRODUCTION

This report describes research conducted under Cooperative Agreement 80NSSC18K0042 for the Human Factors and Behavioral Performance Element, Human Research Program, NASA's Johnson Space Center (JSC). The research addresses the Risk of Inadequate Mission, Process, and Task Design and the Risk of Performance Errors Due to Training Deficiencies by identifying the work that will be performed during an expedition to Mars and the abilities, skills, and knowledge that will be required of crew members. The study began by developing a comprehensive inventory of 1,125 tasks that are likely to be performed during the 12 phases of the first human expeditions to Mars, from launch to landing 30 months later. Sixty subject matter experts (SMEs) rated expedition tasks in terms of (likely) frequency, difficulty to learn, and importance to mission success; a fourth metric was derived by combining the mean ratings of the three dimensions. Seventy-two SMEs placed the physical, cognitive, and social abilities necessary for performance of the tasks in order of importance for eight specialist domains identified by the task analysis. The research team then identified, 1) Abilities, skills, and knowledge that can be retained and generalized across tasks; 2) Optimum training strategies; and, 3) Implications for crew size and composition, and for the design of equipment, habitats, and procedures to support sustained human performance during exploration-class space missions. The report is presented in four sections. This introduction describes why the study was conducted and provides background information and the historical context of the research. The introduction is followed by a description of the research tasks performed to collect and analyze the data and, in turn, is followed by a section devoted to study results. The report concludes with a discussion of operational implications and recommendations based on those results. Appendices present details of the procedures used, a complete list of Mars expedition tasks (by mission phase), a list of tasks that are likely to be performed during expeditions to a Cis-Lunar Gateway, and the names of SMEs who contributed to the study.

BACKGROUND

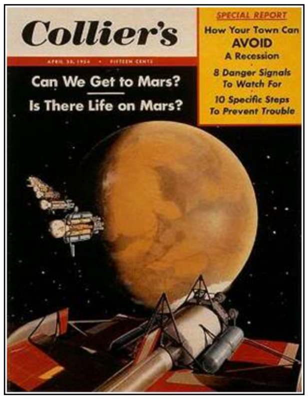
The planets in our solar system are bound to the sun by gravity in elliptical orbits, a discovery that ranks among the most revolutionary in the history of science. Earth and Mars follow orbits that place them in the same relative positions every 26 months and the absolute distances between the two planets follow a 15-year cycle. Optimum launch opportunities to Mars are determined by the lowest possible mass of the spacecraft that must be propelled, because the greater the mass the more fuel is needed, which further increases the mass and cost of the expedition. The mass/energy requirements follow the 26-month cycles within the 15-year cycles. The differences in energy requirements are large and, essentially, define when spacecraft can be launched to intercept Mars.

The mathematics to identify the optimum scenario for an expedition to Mars were known by Wernher von Braun who included the calculations in an appendix to a science fiction story he wrote to counter boredom while serving the US rocket program in 1947-48. The manuscript was unremarkable, but von Braun used the technical appendix as the basis of a lecture at the First Symposium on Spaceflight held at the Hayden Planetarium in New York City in 1951. The appendix was published in a special edition of the German journal *Weltraumfahrt* in 1952 and later that year as a book, titled *Das Marsprojekt*. It was translated into English and published in the United States in 1953.[1]

[1] Wernher von Braun (Translated by Henry J. White). *The Mars Project*. Urbana: University of Illinois Press, 1953.

Von Braun's plan involved 70 crewmembers and a fleet of ten interplanetary ships that would be assembled in low-Earth orbit from parts carried on three-stage rockets; a staggering 950 launches would be required to lift the components, supplies, and fuel out of Earth's gravity well and to support assembly of the fleet in orbit. [2] Seven of the ten interplanetary ships would be made of girders and spheres and lack the streamlining necessary for a planetary landing, but three would have projectile-shaped fuselages equipped with wings to glide through the thin atmosphere of Mars, which was assumed at the time to be ten percent of Earth's. Chemical-fueled rocket engines would fire to leave Earth-orbit and propel the ships on an eight-month cruise and then fire again to slow the fleet for insertion into Mars orbit. One of the winged ships would descend to the surface to land on skis at the north polar ice cap, which is visible through telescopes from Earth. The crew would then make a 4,000-mile (6437 km) mechanized traverse to build a landing strip near the equator for the two remaining winged spacecraft to land on wheels. The wings would be removed and the fuselages elevated to a vertical position in preparation for launch, rendezvous, and return to Earth with the ships remaining in orbit, many months in the future. Von Braun's plan required the least energy (mass/cost) of all launch options, but would subject the crews and equipment to eight-month transits and 16 months on the surface, for a mission duration of nearly three years. Von Braun believed the journey would be possible by the mid-point of the 21st Century.

Exploring Mars by Chesley Bonestell, 1956.



The Mars Project attracted the attention of author, Cornelius Ryan, who served on the editorial staff of *Collier's*, a weekly magazine with a tradition of influencing public opinion and government policy. Ryan commissioned von Braun and other leading space scientists, writers, and astronomical artists to prepare a series of articles based on *The Mars Project*. The series, titled "Man Will Conquer Space Soon!" was published in eight, illustrated installments between March 1952 and April 1954. The primary difference between von Braun's original plan and the one described in the magazine series was the addition of a toroidal space station in Earth orbit to facilitate assembly of the interplanetary ships. The donut-shaped structure became the archetypal space station form in popular culture and the articles propelled von Braun to national prominence and fueled the imagination of post-war America.

Von Braun and Willy Ley quickly published four books that expanded on the topics covered in the *Collier's* series and prepared a revised plan for an expedition to Mars that involved a more reasonable 12 crew members, two ships, and "only" 400 launches of fuel, supplies, and components for assembly in orbit. Walt Disney and producer Ward Kimball were among those inspired by von Braun's plans and hired him and others to help develop three episodes for the popular *Disneyland* television program. "Man in Space" was broadcast in March 1955 to an audience of more than 40 million viewers. President Dwight Eisenhower called Walt Disney the next day to request a copy of the program that could be shown to Pentagon officials.[3] The second episode, "Man and the Moon" aired in December 1955 and, like the previous episode, used documentary footage, on-screen appearances by von Braun and others, and narrated animation to provide remarkably accurate predictions of future events; the programs described the likely effects

[2] Von Braun failed to anticipate developments in automation, hence the need for large crews to operate systems manually and for some crew members to remain in orbit to tend the ships for the return to Earth.
[3] David R. Smith. They're Following Our Script: Walt Disney's Trip to Tomorrowland. *Future*, May, 1978. p. 55.

of weightlessness on humans and introduced the public to a new field of study, called Space Medicine. The third episode in the series, "Mars and Beyond," featured ships with solar-powered ion engines suggested by another German scientist, Ernst Stuhlinger, rather than von Braun's chemical rockets; the program was broadcast on 4 December 1957, two months after the Soviet Union shocked the world with the launch of Sputnik, the first artificial satellite.

Wernher von Braun was confident that all technical obstacles to an expedition to Mars could be overcome, but he looked to the Antarctic experiences of his era for guidance when considering possible behavioral issues for his Mars project:

> I am convinced that we have, or will acquire, the basic knowledge to solve all the physical problems of a flight to mars [sic]. But how about the psychological problems? Can a man retain his sanity while cooped up with many other men in a crowded area, perhaps twice the length of your living room, for more than thirty months? … Little mannerisms—the way a man cracks his knuckles, blows his nose, the way he grins, talks, or gestures—create tension and hatred which could lead to murder. (*Collier's* April 30, 1954 "Can We Get to Mars?" p. 26.)

Such a grim outcome is unlikely, based on more recent space analog and space exploration experience.[4] However, it is important to recall that several expeditions during the heroic and modern periods were jeopardized by the deteriorating mental states of one or more participants. Only the long expeditions of the past come close to the durations currently projected for Mars missions and there is much to learn from those accounts.[5] The accumulating experience concerning both systems and human performance on the International Space Station (ISS) is encouraging, but more research is needed to ensure the reliability of spacecraft and crew personnel during nearly three years of continuous operation.

Von Braun's magazine articles, books, television appearances, and of course Sputnik, led directly to the creation of the National Aeronautics and Space Administration (NASA) in 1958. The agency's initial focus was on matching the Soviet's accomplishments and then shifted to landing humans on the Moon in response to President Kennedy's famous directive. However, Mars remained the ultimate goal of the German-born scientists and others who they influenced. For example, Stuhlinger, who had worked with von Braun during the war and later served as director of the space science lab at the Marshall Space Flight Center, proposed a new approach to Mars in 1962. The plan involved five ships, each with a crew of three astronauts, and paid greater attention to reliability and human factors issues than previous mission plans. In particular, the spacecraft were designed to spin to provide acceleration equal to one-tenth of Earth's gravity to mitigate negative effects of weightlessness on the crew; three of the ships would each carry a 70-ton Mars lander, which provided the triple redundancy that became NASA's standard for ensuring reliability; and all 15 members of the expedition could return to Earth in a single ship if necessary. The most notable consideration in this regard was Stuhlinger's selection of an "opposition class" trajectory, which requires more energy and longer transits to and from Mars than von Braun's conjunction class plan, but a much shorter surface stay and overall mission duration. In other words, an opposition class plan might cost more to implement than a conjunction mission, but it would subject human crew and their equipment to less risk due to shorter exposures. None of the early Mars plans and few of the later ones described tasks that might be performed by crew, other than piloting and vague references to science.

Ernst Stuhlinger's Proposed Ion-Drive Spacecraft, by Mark Wade, 1957.

[4] Peter Suedfeld and G. Daniel Steel. The Environmental Psychology of Capsule Habitats. *Annual Review of Psychology 2000*, *51*: 227-253.

[5] Jack Stuster. *Bold Endeavors: Lessons from Polar and Space Exploration*. Annapolis, Maryland: Naval Institute Press, 1996/2011.

MARS EXPEDITION PLANNING

Thousands of scientists and engineers, including many human factors specialists at NASA and the aerospace contractors, worked on plans for an expedition to Mars throughout the 1960s and early 1970s in hopeful anticipation that a successful Apollo Program would be followed by interplanetary exploration. The Vietnam War and other factors interrupted the plans for human expeditions to Mars, which were replaced by programs that could be funded incrementally and that promised immediate economic benefits. The Space Shuttle's first launch occurred in 1981 and the International Space Station became operational 19 years later with the arrival of the Expedition 1 crew in November 2000.

Interest in exploration beyond Earth orbit has been renewed now that considerable experience has been obtained during nearly two decades of continuous ISS operations. Returning to the Moon as a prelude to a Mars expedition has been suggested, as well as establishing a facility in Cis-Lunar space to support assembly of interplanetary craft and to serve as a "gateway" to exploration-class missions. However, many scientists believe that Near-Earth Objects (NEOs) should be the focus of human exploration, because they fear the consequences of an impact by one of the 1,500 or so NEOs that are discovered each year, some only days before they pass within the orbit of our moon, a near miss, astronomically. The need to learn more about the composition of asteroids and how we might defend our planet from the threat is a compelling reason for NEO missions. It is difficult to argue with the "planetary defense" imperative, but Mars remains the goal for most space exploration enthusiasts, including those at NASA. We can thank, or blame, Wernher von Braun and the other rocket pioneers who set Mars as their goal.

Asteroid Risk to Earth.

The days of describing an interplanetary mission plan with detailed mathematical calculations and a few paragraphs of speculation about the humans who would make the journey are long gone. NASA's procedures for planning human missions are now the epitome of rationality and the roadmap is the mother of all Pert Charts.[6] A recent paper by NASA mission planners describes the process, which begins by defining the purpose of the mission.[7] Identifying risks to human crew and describing the risks in detailed evidence reports are among the first steps in NASA's procedure, which are followed by clarifying the risks; specifying the research gaps to address those risks; preparing and publishing requests for proposals; selecting grant recipients and monitoring progress; and, obtaining deliverables and incorporating results in revised risk evidence reports. These steps are then assessed, within NASA and by outside experts, such as committees of the National Academies of Science and its Institute of Medicine, to identify progress toward retiring risks.

NASA's Human Research Program (HRP) is composed of five topical areas called Elements: Human Factors and Behavioral Performance; Exploration Medical Capability; Human Health Countermeasures; ISS Medical Project; and, Space Radiation. The HRP Elements are responsible, currently, for 32 major risks concerning crew. For example, NASA's Space Human Factors and Habitability Element is responsible for the following risks.

[6] A PERT chart is a project management tool used to schedule, organize, and coordinate project tasks. PERT stands for Program Evaluation Review Technique, a method developed by the US Navy to manage the Polaris submarine missile program in the 1950s. Engineers love PERT charts.

[7] John F. Connolly, Kent B. Joosten, Bret Drake, Steve Hoffman, Tara Polsgrove, Michelle Rucker, Alida Andrews, and Nehemiah Williams. Human Mars Mission Design - The Ultimate Systems Challenge. Conference Paper presented at the 68th International Astronautical Congress (IAC); 25-29 September 2017; Adelaide, Australia.

- Risk of Incompatible Vehicle/Habitat Design.
- Risk of Inadequate Human-Computer Interaction.
- Risk of Inadequate Mission, Process and Task Design.
- Risk of Performance Errors Due to Training Deficiencies.
- Risk of Injury from Dynamic Loads (occupant protection).
- Risk of Inadequate Design of Human and Automation/Robotic Integration.
- Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders.
- Risk of Performance Decrements and Adverse Health Outcomes Resulting from Sleep Loss, Circadian Desynchronization, and Work Overload.
- Risk of Performance and Behavioral Health Decrements Due to Inadequate Cooperation Coordination, Communication, and Psychosocial Adaptation within a Team.

All of the risks listed above and many of the risks comprised by the other four HRP elements have one requirement in common that must be satisfied before proceeding with the process that leads eventually to risk mitigation: The work and other actions to be performed by the human crew must be defined and understood. One of the most salient examples of this requirement is, Risk of Injury and Compromised Performance Due to EVA (Extra-Vehicular Activity) Operations, which is the responsibility of the Human Health Countermeasures element and includes space suit design issues. Two questions are immediately apparent: 1) How can risk be considered without knowing what tasks will be performed while on EVA? and 2) How can the features and capabilities of an EVA suit be designed without knowing what tasks will be performed while wearing it? The manufacturers of gym shorts, running shoes, and yoga pants would never consider designing their garments without first identifying the specific activities they must support. How can EVA suits for Mars exploration be designed without first knowing the tasks that astronauts will perform on the planet's surface? EVA includes the "spacewalks" conducted to install, retrieve, or repair items on the outside of a spacecraft and EVA also is used to refer to actually walking on a planetary surface, as was done on our moon by Apollo astronauts and is expected to be performed on the surface of Mars. It is important to note that the human requirements for space EVA and surface EVA suits are likely to be different, depending on the tasks that will be performed and the environmental conditions of the work.

The primary risks that are addressed by the current research are the Risk of Inadequate Mission, Process and Task Design, and the Risk of Performance Errors Due to Training Deficiencies (the third and fourth items on the list, above). As with EVA suit design or any of the other risks listed, it is impossible to understand the risks or to address mitigations meaningfully without knowing the specific tasks that will likely be performed by crew personnel during all phases of an expedition to Mars. Detailed knowledge of the work that will be performed will enable us to understand the implications of inadequate task design and training deficiencies and to develop mitigations and countermeasures. The best that can be done to prepare for the human exploration of Mars in the absence of detailed task knowledge is to speculate in vague generalities, as has been the practice in the past.

A HUMAN FACTORS APPROACH

Human factors engineering (HFE) emerged as a professional discipline in response to the requirement to improve system performance during World War II. The application of behavioral principles derived from experimental psychology had immediate and dramatic results, such as improved accuracy of bomb sights and reductions in pilot error.[8] Military managers advocated the application of human factors methods after the war and consideration of human factors issues eventually became required in all major military procurements. HFE specialists now apply knowledge concerning human behavior to the design of tools, devices, equipment, vehicles, vessels, inhabited spaces, procedures, processes, and systems com-

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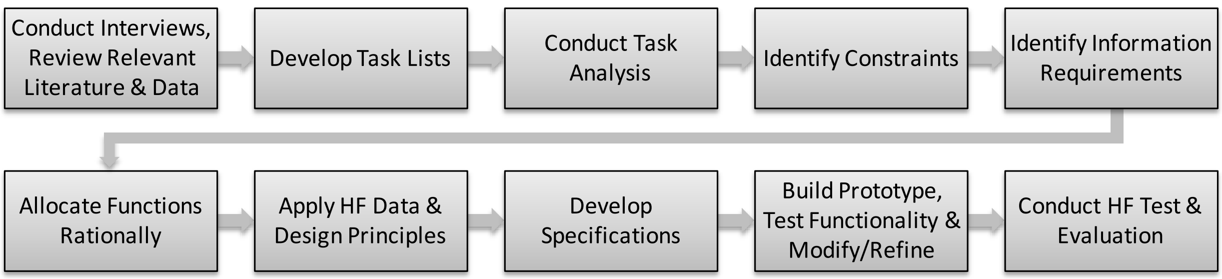
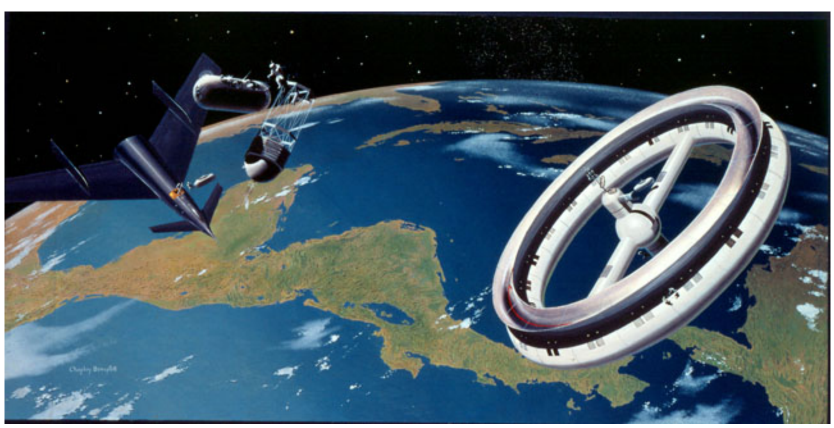
[8] David Meister. *The History of Human Factors and Ergonomics*. Mahwah, NJ: Lawrence Earlbaum Associates, 1999.

posed of these and other elements. That is, the field of human factors engineering is unique because it encompasses the entirety of material culture and, indeed, all human activity. The broad scope of this work is accompanied by enormous responsibility, and for this reason HFE specialists are, first and foremost, advocates for the users, operators, maintainers, and personnel—the “human components” of technological interaction. The discipline has evolved during the past 75 years and extended its influence into nearly all human endeavors, from software development to space exploration.[9]

Human factors specialists benefit from the accumulated experience of their predecessors, a process that fuels all scientific and technical advancement. Human factors experience is expressed in the growing inventory of instrumental techniques for understanding work and performance; in experimentally-derived data concerning human capabilities and limitations; in data-driven design principles; and, in the tradition of serving as advocates for the human component in system operations. Most important, our efforts are guided by a systematic and scientific approach that can be summarized by the following figure.



The sequence of steps illustrated by the figure guides human factors specialists whether they are contributing to the design of a mobile device intended for a single user, or a complex system, such as the control interface of an interplanetary spacecraft with a multi-person crew. Key steps in the sequence are the application of special knowledge (e.g., human factors data and design principles) and the systematic analysis of the tasks that are (or will be) performed by the users. Although NASA has been designing equipment, EVA suits, and space habitats, and preparing plans for the human exploration of Mars since the 1960s, no one has ever actually identified the tasks that would likely be performed during the mission, until now. We are delighted by the challenge and proud to offer a description of our research in the following section of this report and the results and implications of our efforts in subsequent sections.



Space station, ferry rocket and space telescope 1,075 miles above Central America, 1952, by Chesley Bonestell, illustrating Wernher von Braun’s plan described in the *Collier’s* magazine series.

[9] Jack Stuster. (Editor). *The Human Factors and Ergonomics Society: Stories from the First 50 Years.* Santa Monica, CA: Human Factors and Ergonomics Society, 2006.

THE RESEARCH

NASA issued a Research Announcement in June 2014 that solicited proposals to address a range of HRP risks, from bone demineralization to teamwork. Near the end of the announcement was a request for research to identify the Generalizable Skills and Knowledge for Exploration Missions. The statement described a requirement to identify the skills and knowledge that can be retained and generalized across tasks to maximize crew performance during exploration-class missions and to develop methods to mitigate the risk of performance errors due to training deficiencies. The statement did not include a requirement to analyze or even identify specific tasks that might be performed during an exploration-class space mission. However, to human factors specialists, the only way to understand skill and knowledge requirements is to first understand the work; and, the best way to understand work is to conduct a task analysis.[10]

A research team composed of human factors specialists was formed to respond to NASA's solicitation. Although the members of the team have extensive experience in space-related research and development, none could envision an activity more exciting for a human factors professional than conducting the task analysis that would help inform the human exploration of Mars, which we identified as the most ambitious deep space mission likely to be contemplated during the first half of the 21st Century. Our proposal began with a statement expressing sincere delight with NASA's interest in identifying the Generalizable Skills and Knowledge for Exploration Missions. We wrote that it was a good research question, but more important, answering it would first require us to conduct a systematic analysis of the work likely to be performed by the future explorers of Mars; and, the results of that task analysis would be useful to, well, everyone engaged in the design of equipment, procedures, or policies involved in what will surely be one of the boldest human endeavors, ever. Our proposal then described the fundamental role of task analysis in the human factors method and the specific type of task analysis that we had selected as most appropriate to address NASA's risks.

CRITICAL ABILITIES AND TASKS (CAT) METHOD

There are many task analysis methods, but all of them involve the five steps listed below.

1) Formulate at least one research question to be answered by the analysis;
2) Identify tasks and describe them in a systematic format;
3) Collect data about the tasks;
4) Analyze the collected data to develop an understanding of the work and the human requirements, capabilities, and limitations; and,
5) Document the results of the entire effort in a manner that provides information to answer the research question(s).

We next described the Critical Abilities and Tasks (CAT) method to introduce reviewers to the procedures and establish the merits and utility of our proposed approach:

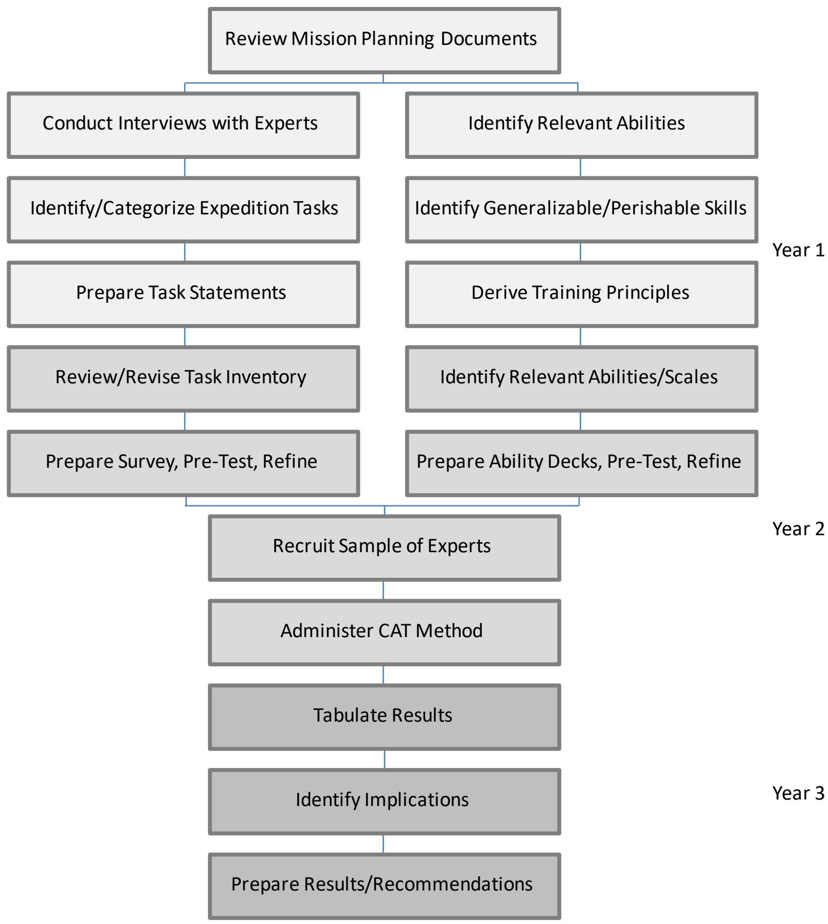
[10] We are aware of the adage that warns, "If your only tool is a hammer, all problems look like nails," but we are convinced that it does not apply in this case, neither in general nor in the specific method selected to address the problem. It is true that engineers could estimate the types of tasks that might be performed during a human expedition to Mars and then design habitats, suits, vehicles, procedures, controls, and displays. That is, it is theoretically possible to base critical design features and policies on educated guesses, as has been the practice for Mars expedition planning in the past. However, it now appears that we might actually launch humans to Mars within the next 20 years, which is "very soon" in aerospace-development time, and ahead of von Braun's estimate. The magnitude of the endeavor and concern for the safety of the explorers (people who are alive at this time) demand that all designs and procedures be based on a comprehensive understanding of the work to be performed.

> [The method] begins by developing a comprehensive inventory of tasks, both actual and expected, with each task statement phrased systematically (beginning with an action verb and followed by the object of the sentence, how the task is performed, and then the reason for the action); for example, *Inspect circuit board visually to detect evidence of electrical short*. A survey instrument is then constructed that asks three questions about each task: 1) How frequently is the task performed? 2) How difficult is it to learn how to perform the task? and 3) How important is the task to mission success? Likert scales with appropriate cognitive anchors are used to record the responses of a sample of job incumbents. The next step in the process is to assemble a list of physical, cognitive, and social abilities with definitions provided by the Fleischman collection, but augmented with job-specific abilities when needed. The sample of job incumbents performs a card-sort exercise to place the relevant abilities in order of importance, first allocating the abilities to one of three categories (More Important, Important, and Less Important), and then in order within each category; the card-sort is engaging and ensures that subjects attend completely to the process. The results of both task and ability exercises are tabulated and descriptive statistics are derived that together provide a comprehensive understanding of the knowledge, skills, and abilities necessary to perform all aspects of a job well. Both the task and ability measures can be performed during the same session with a subject matter expert.

We included example products of the CAT method so reviewers could better imagine what might be the outcome of the proposed research. The proposal also described how the CAT method had been developed to study the work performed by telecommunications technicians and subsequently was applied to identify the skills and abilities of Navy SEALs, EOD technicians, communications specialists, hovercraft crew, and military leaders. We described how we would use our special access to the Astronaut Corps and other space operations personnel to recruit a sample of space exploration professionals, including current and former astronauts, mission planners, technical trainers, and technology experts, to participate as subjects in the task and ability analysis. We described how the key skills and abilities identified by the process will be assessed for perishability, trainability, and generalizability. We then described how we will develop optimum strategies for ensuring that those skills and abilities are possessed by expedition crew members when needed, based on principles derived from an understanding of the relevant literature.

Our introduction to the proposal concluded by stating that we will combine a proven task analytic method with understandings of training issues, space operations, and current plans to produce quantitative data about the skills and abilities necessary to support human space exploration. We wrote that the primary objective of the study is to identify the abilities needed by expedition crew in response to the training risk, but that the results of the analysis will also be useful to the designers of tasks, procedures, software, equipment, vehicles, and habitats, and to those responsible for crew composition.

We introduced our three-year technical approach to the project with the following figure, to assist reviewers of the proposal and later to serve as a guide to the research team. Our technical approach, or work plan, was presented in enumerated steps that we proposed to perform to achieve the study objectives. We were pleased to learn that our proposal was acceptable to NASA and began the work described in this report in September 2015.



Summary of the technical approach.

DESCRIBING WORK

The most common terminology for describing human work provides four levels of description ranging from the most general to the most specific, as summarized below.

A **Job** is a collection of activities that defines the scope of effort assigned to an incumbent. The collection of activities is given a categorical name, such as Boeing 787 Pilot, Explosive Ordinance Disposal (EOD) Technician, or Mk 86 Fire Control (FC) Specialist.

A **Work Component** is defined as a major responsibility that must be assumed by a job incumbent. In a military context, a type of **Mission** can be a work component, such as taking off from an airport for an airline pilot, safing an improvised explosive device for an EOD Technician, or replacing the klystron on the Mk 86 radar for an FC Specialist.

A **Task** refers to an observable, measurable, independent activity that is performed in support of a work component or mission, such as operating the flaps of an aircraft for a pilot, maneuvering a robotic vehicle for an EOD Technician, or shutting down the system for a Mk 86 FC Specialist.

An **Action** refers to an activity element that exists as part of a sequence in which one element is dependent upon another. A task typically is composed of a series of actions, such as making control adjustments for the pilot, EOD Technician, and FC specialist.

TECHNICAL APPROACH

Task and ability analyses are necessary to understand the work performed within a job category. Understanding the environmental and situational constraints, the cognitive and physical requirements, and the information needed to perform tasks allows a human factors specialist to design procedures and equipment that are responsive to each task's requirements and consistent with the capabilities and limitations of human operators. Properly conducted analyses enable the identification of crew size, personnel-selection criteria, training objectives, and design recommendations for equipment and procedures. Descriptions of the research tasks performed during the current study of skills and abilities for exploration-class space missions are presented in the following numbered sections.

Task 1: Review Mission Planning Documents

Human factors specialists usually rely on job descriptions, training documents, written procedures, decision aids, and interviews with job incumbents for information that can be used to develop task statements for analysis. These sources are essential when developing task lists for existing equipment, systems, or processes. Identifying tasks for a new or proposed system requires the analyst to review specifications documents and to simulate operations with mock-ups or perform hands-on operations using prototypes of the system. In contrast to the usual task analysis, a 30-month expedition rather than a "system" is the focus of the current research. Also, no actual equipment has been developed and there are few references in published material to the tasks that might be performed during the expedition. These factors required the research team to interview experts, to review material concerning the human exploration of Mars, and to infer tasks by extrapolating from published and unpublished sources and from analogous jobs and systems.

We had proposed to review a broad range of documents relevant to the human exploration of Mars and began by re-reading von Braun's *Mars Project* and the series of *Colliers* magazine articles, described previously. We then reviewed Mars expedition planning documents, in chronological order of publication, beginning with a study by researchers at the Lewis Research Center and concluding with NASA's most recent Design Reference Architecture, DRA-5, published in 2009.[11] The Lewis study began only one month after Sputnik 1 and a full year before the National Advisory Committee on Aeronautics (NACA) laboratory became part of the new organization, NASA.[12] The purpose of the Lewis study was to explore the feasibility of nuclear-thermal and electric rocket propulsion, which would require less propellant than chemical rockets, thus reducing spacecraft weight, the number of launches to deliver components to Earth-orbit, and the time to assemble an interplanetary ship for transit to Mars. The Lewis researchers were influenced by the discovery of the Van Allen Radiation Belts surrounding Earth by Explorer 1 (the first US satellite) in 1958. They specified an unshielded, two-deck, cylindrical crew compartment that would provide 50 square feet (4.65 square meters) of floor space per crewmember ("between that provided for chief petty officers and commissioned officers on submarines"); the compartment would include a heavily shielded cylindrical "vault" at its center, into which the crew would retreat during passage through the Van Allen belt, during operation of the nuclear rocket, and during periods of solar flares. Sleeping quarters were located in the vault to further reduce crew exposure to cosmic rays. The Lewis team briefed Congress on their results in 1959, but the only other reference to the humans involved was that two of the seven crew members would descend to the planetary surface and, "After a period of exploration these men take off from Mars using chemical-rocket power and effect a rendezvous with the orbit party."[13]

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[11] Bret Drake (Editor). *Human Exploration of Mars Design Reference Architecture 5.0*. NASA/SP–2009–566. Washington, DC: NASA Headquarters (July) 2009. http://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf
[12] Lewis was renamed Glenn Research Center at Lewis Field in 1999.
[13] S. C. Himmel, J. F. Dugan, R. W. Luidens, and R. J. Weber, "A Study of Manned Nuclear-Rocket Missions to Mars," IAS Paper No. 61-49 (paper presented at the 29th Annual Meeting of the Institute of Aerospace Sciences, 23-25 January 1961), p. 2

Von Braun's original Mars mission plan involved assembling the fleet in Earth-orbit, transiting together to Mars, parking the ships in Mars orbit, and then some of the crew descending to the surface in three specialized ships. In contrast, the Stuhlinger and Lewis plans involved descending to the surface of Mars in small excursion vehicles that would detach from the interplanetary ships and return the crew by re-docking after a relatively brief surface stay. This plan, called Mars Orbit Rendezvous (MOR) became the standard mission profile for most Mars expedition planning for both conjunction (long-stay) and opposition (short stay) missions, because it requires far less fuel to land a small spacecraft on a planet than to land a large interplanetary ship.[14] David Portree's excellent history of Mars expedition planning explains the factors that led von Braun and other NASA managers to consider Mars flyby missions as an interim step to actual Mars exploration.[15] To summarize, planners needed more information about Mars before a landing could be made, the Apollo program was consuming NASA resources, and Italian astronomer, Gaetano Crocco, had recently presented a paper showing that a spacecraft could theoretically fire its rockets once to leave Earth-orbit, coast to Mars, and then come within 800,000 miles (1.3 million km) of the planet before using Martian gravity to deflect the ship onto a course for Earth. He estimated that the flyby mission would require less than half the fuel of a MOR mission and take about one year. Crocco calculated that the spacecraft could pass closer to Mars if it maneuvered to swing by Venus on the return trip. These factors resulted in nearly half of Mars mission planning during the 1960s to be focused on piloted flybys, despite criticism by many NASA managers, including Maxime Faget, principal designer of the Mercury capsule, who wrote in 1963 that a piloted Mars flyby would "demand the least [propulsive] energy… but will also have the least scientific value." He suggested, with characteristic prescience, that data gathered during a piloted flyby would be "in many ways no better than those which might be obtained with a properly operating, rather sophisticated unmanned probe."

Piloted Flyby

A piloted flyby of Mars appears from the perspective of the 21st Century to be quaint, a "steampunk" approach to human planetary exploration, necessary perhaps in an era before reconnaissance satellites, digital imagery, and remotely-controlled rovers. It is odd, but serious proposals are still occasionally offered to conduct human flyby missions to Mars, even though all planets in our solar system have been visited by robotic spacecraft and the surface of Mars has been mapped in detail. Why incur the expense and subject humans to the risk for just a flyby of Mars?

NASA's Future Projects Office awarded a series of contracts in 1962 under a program, titled, the Early Manned Planetary-Interplanetary Roundtrip Expeditions (EMPIRE). General Dynamics, Lockheed, and Ford Aeronutronic studied piloted Mars flyby and Mars-orbit missions. One of the objectives of the program was to justify a new large rocket, which encouraged all three contractors to include heavy structures for generating artificial gravity during the transits to and from Mars. For example, in the Aeronutronic design, two cylindrical crew compartments would extend on booms and then rotate to provide artificial gravity. The crew would board a lifting body attached to the interplanetary ship as they approached Earth, undock, and then fire a two-stage retrorocket stack to slow the lifting body to enter Earth's atmosphere while the flyby ship proceeded unoccupied indefinitely. The General Dynamics study was the most elaborate of the three and was presented in nine volumes. The team, led by German rocket pioneer Krafft Ehricke, exceeded the scope of their contract by including a small, Mars lander for two crew members to descend from the orbiter to the surface for a period of seven days.

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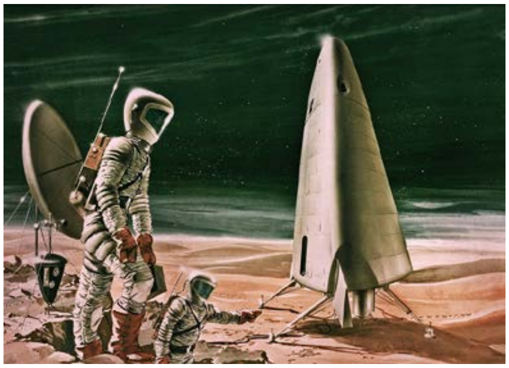
[14] The same approach was selected by NASA in 1962 for the Apollo missions and labeled Lunar Orbit Rendezvous (LOR); a single Saturn rocket launched a command module and landing craft together directly to the Moon without the need for assembly in Earth orbit; the lander undocked from the command module in lunar orbit, descended to the surface, and then re-docked with the command module after a surface stay of a few days.

[15] David S.F. Portree. *Humans to Mars: Fifty Years of Mission Planning, 1950-2000*. Washington, DC: NASA History Division, Monographs in Aerospace History Number 21, 2001.

The Space Task Group (STG) was formed at the Langley Research Center, Virginia, in 1958 to manage Project Mercury. The STG's responsibilities increased in 1961 when President Kennedy announced that NASA would send men to the Moon within the decade, so the group moved to Houston and became the Manned Spacecraft Center (MSC, renamed the Johnson Space Center in 1973). Maxime Faget, MSC's assistant director for research and development, started planning a human expedition to Mars almost immediately. The research resulted in detailed designs for a Mars lander and a mission profile unlike any before or since. Two of the plans were versions of the standard MOR approach, but the third, called the Flyby Rendezvous would achieve weight-reduction benefits of a flyby while also sending a human crew to the surface of Mars. The Flyby-Rendezvous plan would launch an unoccupied flyby craft to Mars 50 to 100 days ahead of a faster, piloted craft with a lander. The crew would reach Mars in 120 days, transfer to the lander as they approached, and then descend to the surface, abandoning their ship to an unoccupied solar orbit. The crew would lift off in their lander 40 days after arriving as the unoccupied ship passed Mars. They would pursue the flyby ship and then dock and board two days after departing the surface. The crew would abandon the flyby ship as they approached Earth and return home in a capsule. The plan avoided the requirement to carry fuel necessary to achieve an orbit around Mars or to slow for Earth return, but it relied on a very capable lander and extraordinary piloting skills.


MSC/Ford Aeronutronic Lander.

One of the MSC plans developed by Ford Aeronutronic involved propulsive braking while the other proposed aerobraking to slow the interplanetary ship sufficiently to achieve a conventional MOR. The planners acknowledged that they lacked reliable data about the atmosphere of Mars and assumed that it would be approximately ten percent of Earth's pressure at sea level. The assumption allowed them to design a 30-ton Mars Excursion Module (MEM) in the shape of a half-cone lifting body to carry three crew members to the surface and to support them for 40 days. During an era when Mars mission planning was almost exclusively devoted to technical issues, developers of the Aeronutronic plan conducted a brief analysis to identify the work that must be performed to satisfy science objectives, which were deemed the highest priority of the mission, especially to determine whether life exists or ever existed on Mars. The analysis found that three, rather than the minimum two crew members would be needed to conduct the biological, geological, and areological research programs, which were summarized in stochastic flow charts. The landing party would be composed of the captain/scientific aide, first officer/geologist, and second officer/biologist, with cross-training and multiple responsibilities. The crew would eject shields covering the MEM windows after landing and then scan the area surrounding their landing site to identify "local hazards," including any "unfriendly life forms." The report noted that "biological evaluation of life forms is essential for the first purely scientific effort to allow pre-contamination studies before man alters the Mars environment." Also, "investigate life forms for possible nutritional value" was listed, hopefully, among the biological tasks to be performed during approximately 16 "man-hours" per day outside the MEM. The plan even specified a 12/12 work-rest cycle to enable all three crew members to be available for working together eight hours per day. The plan provided for a 300-pound armored cassette to ensure safe return of samples in the event of catastrophic failure of the Earth Return Module at the end of the mission. The Aeronutronic plan concluded with cost estimates and a list of requirements, from development of Columbium "hot structures" and altitude-compensating engines, to "verification of man's space operation capability." It was an extraordinary piece of work.[16]

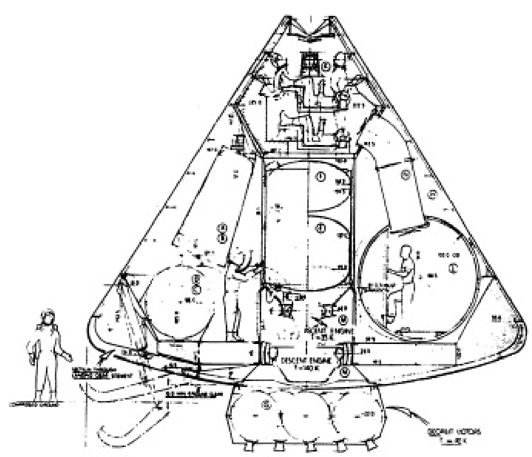
[16] Franklin Dixon, "Summary Presentation: Study of a Manned Mars Excursion Module," *Proceeding of the Symposium on Manned Planetary Missions: 1963/1964 Status*. Huntsville, AL: NASA TM X-53140, 1964, pp. 443-523. https://ntrs.nasa.gov/search.jsp?R=19640017065

We described previously how orbital mechanics determines that minimum energy launch opportunities from Earth to Mars occur every 26 months within a 15-year cycle. Nearly all mission plans assumed a minimum-energy launch opportunity and all of the EMPIRE and MSC plans were opposition-class profiles that involved a maximum of 40 days on the surface of Mars, to minimize exposure of the crew and equipment to risk. The EMPIRE studies showed that the most-fuel-efficient opportunities would occur in 1971 and require increasing amounts of fuel after that until 1977 when the relative positions of the two planets would begin to require less fuel; the next minimum-energy launch opportunities would occur in 1984, 1986, and 1988. NASA's Future Projects Office at the Marshall Spaceflight Center awarded contracts to General Dynamics and Douglas Aircraft in 1964 to study *all* of the profiles for a human mission to Mars during the years 1975-1985 and to identify those of interest; the research program was nicknamed, UMPIRE, for Unfavorable Manned Planetary-Interplanetary Roundtrip Expeditions. The two contractors came to the same conclusion, that the best way to mitigate the cyclic variation in weight (i.e., fuel and cost) to travel to and from Mars is to conduct conjunction-class expeditions using a mission profile of the type originally proposed by von Braun in *Das Marsprojekt*, which increases surface stays to about 500 days, rather than the 30 or 40 days of an opposition-class profile, and nearly doubles total mission duration to 1,000 days.

Conjunction and Opposition

The terms "conjunction class" and "opposition class" refer to the position of Mars relative to Earth during the expedition. In the former, Mars moves behind the Sun as seen from Earth (i.e., it reaches conjunction) halfway through the expedition; in the latter, Mars is opposite the Sun in Earth's skies (i.e., at opposition) at the expedition's halfway point. A 600-day opposition-class expedition (with 30 days on the surface) can require as much as ten times the fuel as a 1,000-day conjunction-class expedition (with 500 days on the surface).[17]

The UMPIRE study conducted by the Douglas Aircraft Company's Missile and Space Systems Division specified a crew of six to make the interplanetary journey using nuclear propulsion. Time on the surface of Mars varied with the type of profile (i.e., a 20-day stay for opposition-class missions and a 300-day stay for conjunction-class missions). The Douglas study concluded that the key to planning expeditions during the unfavorable period is to keep the initial launch mass as low as possible.[18] NASA's Ames Research Center awarded contracts to TRW Space Technology Laboratories and to North American Aviation. TRW's 1964 report focused on Mars stopover missions culminating in a human landing on the planet. It described the mission as a "direct follow on to the Apollo project" and concluded that human participation was essential to the exploration of Mars because the complexities of the mission exceeded the capabilities of robotic spacecraft. Crew sizes for the TRW plan ranged from 3 to 12 with the ideal number being 6 astronauts. North American Aviation's plan described a human landing on Mars with crew size ranging from 3 to 10, with 6 being ideal. The missions were designed to last a total of 700 days, including a stay on or around Mars of 7 to 60 days.



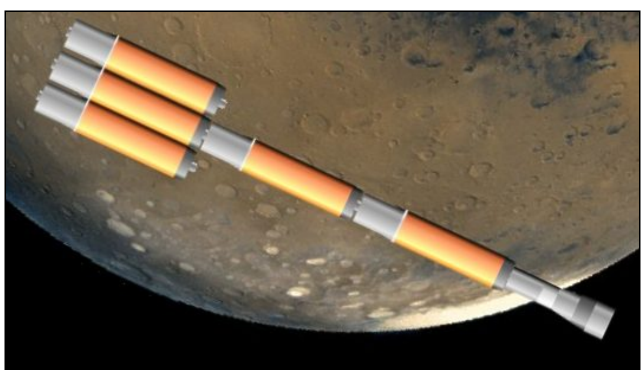
North American Aviation's Mars Lander, 1965.

[17] David S.F. Portree. *Humans to Mars: Fifty Years of Mission Planning, 1950-2000*. Washington, DC: NASA History Division, Monographs in Aerospace History Number 21, 2001.

[18] Howard C. Robins, Jr. and Roberto M. Villarreal. "An Introduction to the NASA Manned Planetary Mission Studies and a Brief Survey of the Study Results." MSC Internal Note No. 65-ET-7. Houston, TX.: NASA MSC, February 1965. In the JSC History Collection, Center Files, Planetary Missions-Silveira Files, Box 1: 1962-1965.

The Mars mission plans of the 1960s contained little information about activities of crew personnel from which we could extract task statements. There were exceptions, such as the Aeronutronic study, which was informed by a cursory task analysis and presented summaries of science programs to be conducted on the surface of Mars. The General Dynamics report stated that scientific objectives were yet to be defined, but discussed crew composition in detail. The General Dynamics plan specified an eight-person crew composed of engineers and scientists, each with specific skills and responsibilities. A commander and a deputy commander were described as mechanical and electrical engineers, respectively; they were responsible for maintaining the ship's structure, mechanical equipment, and electrical systems, in addition to command tasks. Another crewmember, described as a nuclear engineer and physicist, would monitor the nuclear systems and work with the flight surgeon to protect the crew from radiation. Two electronic engineers were specified, one with skills as an astronomer and the other in physics, to handle communications, navigation, and data processing. The planners even specified that one of the three non-command engineers would serve as commander of the landing party, while another team, composed of a physicist/geophysicist and an astronomer/geologist, would conduct scientific observations in space physics, planetology, meteorology, and geophysics. The final member of the crew was to be a physician and biologist.[19]

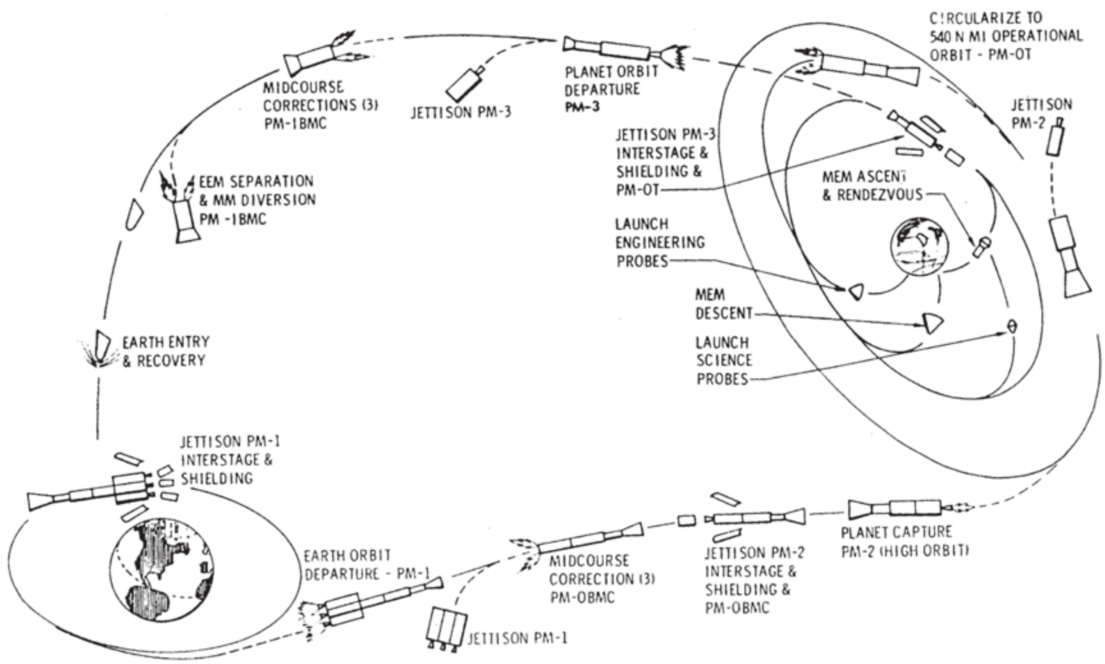
Additional studies that had been underway were published as the decade ended. In particular, the Planetary Joint Action Group (JAG) was composed of representatives from NASA Headquarters and from the three Centers responsible for human spaceflight – the Manned Spaceflight Center in Texas, the Marshall Space Flight Center in Alabama, and the Kennedy Space Center in Florida; specialists from other centers were consulted when their expertise was needed. This team approach was believed to balance the interests of the NASA Centers and thereby foster comprehensive and integrated planning for exploration. The JAG report was published in October 1966, four months before the fire that killed the Apollo 1 crew on the launchpad, which caused program managers to question the technological decisions that had been made in capsule design, and others to question the reasons for space exploration.[20] Formal reviewers of the JAG plan and outside critics further eroded momentum for Mars exploration and when the US Congress was briefed there was little enthusiasm for spending on human planetary missions while the costs of the Vietnam War and dealing with urban unrest were increasing. NASA's budget was cut in 1967 and the final three Apollo missions were cancelled. Boeing published its study of a nuclear-powered expedition to Mars a few months after the JAG report. Boeing's 582-foot long Mars ship would carry a crew of six, a four-deck Mission Module, an Earth Entry Module, and a Mars lander based on the North American design. It was a grand and ambitious plan.



Boeing's Proposed Integrated Manned Interplanetary Spacecraft, using nuclear stages, 1968.

[19] Frederick I. Ordway, III, Mitchell R. Sharpe, and Ronald C. Wakeford. "EMPIRE: Background and Initial Dual Planet Mission Studies," IAA-90-632, Presented to the 41st International Astronautical Congress, 24th Symposium on the History of Astronautics, Dresden, October 11, 1990.

[20] Planetary JAG, Planetary Exploration Utilizing a Manned Flight System, Washington DC: NASA, 1966.



Boeing's Plan for a Nuclear-Powered Expedition to Mars, 1968.

The German and American rocket pioneers were inspired by science fiction writers in their youth and their enthusiasm influenced the next generation of scientists and engineers. Then, the push for human Mars exploration among NASA and contractor personnel during the 1960s was fueled by political and technological aspects of the race to the Moon and by the element of engineering culture that compels practitioners to continue refining a device or system until it has reached its maximum state of development. Motivation to remain employed in the space business also was a factor for individuals and for corporations, and the entire process was facilitated by a series of professional meetings that enabled communication of ideas and contributed to the momentum. It was an exciting time and confidence in the future of technological development led many of those involved to believe that expeditions to Mars would be conducted during the 1980s, if not sooner. That was not to be.

North Vietnam invaded South Vietnam on 30 January 1968, immediately after the Boeing and North American reports were published and three months after the JAG report had met with a chilly reception. The Tet Offensive was repulsed by US and South Vietnamese forces, but presaged increasing costs and was the first of many events during the year that dashed hopes for human expeditions to Mars. President Johnson announced in March that he would not accept nomination at the Democratic Party's convention in Chicago a few months later. Martin Luther King, Jr., was assassinated in April, which was followed by racial violence in many cities. Students occupied buildings at Columbia University during the same month to protest the Vietnam War, which led to demonstrations at universities and colleges throughout the US. Robert Kennedy, brother of the assassinated president who had set the Moon "and the other things" as goals and the Democratic Party's front-runner, was murdered in June. Anti-war protesters encountered a "police riot" during the Democratic National Convention in August. And, Richard Nixon was elected in November, largely because he promised the country a secret plan to end the war. Protests, casualties, and costs continued to increase, which sapped interest in NASA programs among Congress and many voters. Then, in 1970, President Nixon announced that the space shuttle would become NASA's focus, which relegated human Mars exploration to the distant future.[21]

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[21] Annie Platoff. *Eyes on the Red Planet: Human Mars Mission Planning, 1952-1970*. Houston, TX: NASA Johnson Space Center. NASA/CR-2001-208928, July 2001.

No Bucks, No Buck Rogers

The cost of the Vietnam War soared to $25 billion a year in 1967, according to David Portree's history of early Mars expedition planning. It was equivalent to the entire FY 1966 NASA budget every 10 weeks. The cost of the war and of social welfare programs led to Federal budget deficits. Congress was eager to reduce the Johnson Administration's 1968 Federal Budget and NASA was an easy target.[22]

Mars expedition planning did not cease completely when Congress deleted all advanced planning and Mars Voyager funds from NASA's budget.[23] Planning and development of robotic "probes" continued and human missions became the focus of an "underground" movement. Underground may be a stretch, because the advocates of human Mars exploration were primarily respected professors who continued the tradition of mission planning overtly in their classrooms and at high-visibility scientific symposia, most notably the Case for Mars conferences. Enthusiasm among the Mars Underground was fanned by the data returned to Earth from robotic landers (i.e., Mariner, Viking) that offered details concerning atmosphere and topography to replace previous assumptions and to evoke new questions for geologists and biologists. Many NASA personnel and contractors also remained involved throughout the period, which must have seemed like guerilla activity to the agency that discouraged and at times even prohibited work related to the human exploration of Mars.

We read articles about planetary exploration from this period in the proceedings of scientific and engineering symposia, published primarily by the American Astronautical Society, to obtain information about the work that might be performed during a human expedition to Mars. For example, we learned details about the research activities that will be conducted by geologists in a paper by Charles Cockell, Stephen Braham, Bill Clancey, Pascal Lee, and Carlene Lim that had been presented at a symposium in London in 2003.[24] We learned about biological research that will be performed to search for evidence of life on Mars from papers by Chris McKay, presented at the same symposium,[25] and from a paper by Carol Stoker that was included in a previous collection.[26] And, we learned about tasks that will be involved in the growing of food in Martian greenhouses from a paper by a team of students at the University of Colorado, Boulder.[27] Many other similar sources informed our understanding of the work that will be performed *en route* to and from Mars and on the planetary surface.

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[22] David S.F. Portree. *Humans to Mars: Fifty Years of Mission Planning, 1950-2000*. Washington, DC: NASA History Division, Monographs in Aerospace History Number 21, 2001, page 31.

[23] The Voyager Mars Program proposed to land versions of Apollo capsules without crew in 1975, as part of the Apollo Applications Program (AAP), in preparation for a human mission to Mars in the 1980s. The plan was revised when Mariner 4 discovered in 1965 that the Martian atmosphere was much thinner than previously assumed. Congress cut funding for AAP in 1968 and the mission was cancelled in 1971. The Voyager Mars program became the Viking landers, which reached Mars in 1976. The name, "Voyager," was recycled for the Mariner 11 and Mariner 12 probes to the outer planets, which are among the most-visionary space missions ever.

[24] Charles S. Cockell; Stephen Braham; Bill Clancey; Pascal Lee; and Darlene Lim. Exobiological Protocol and Laboratory for the Human Exploration of Mars--Lessons from a Polar Impact Crater. In, *Martian Expedition Planning*, Charles S. Cockell (Ed.), San Diego, CA: American Astronautical Society Volume 107, Science and Technology Series pp.33-52, 2004; Proceedings of the Martian Expedition Planning Symposium of the British Interplanetary Society, London, 24 February 2003.

[25] Christopher P. McKay. Scientific Goals for Martian expeditions. In, *Martian Expedition Planning*, Charles Cockell (Ed.), San Diego, CA: American Astronautical Society Volume 107, Science and Technology Series pp.25-32, (2004).

[26] Carol Stoker. Science Strategy for Human Exploration of Mars. *In Strategies for Mars: A Guide to Human Exploration*. Carol R. Stoker and Carter Emmart (Eds.), San Diego, CA: American Astronautical Society Volume 86, Science and Technology Series pp.537-560, 1996.

[27] Robert Gjestvang. *Mars Deployable Greenhouse Preliminary Design Report*. Boulder: University of Colorado Department of Aerospace Engineering Sciences (March) 2002.

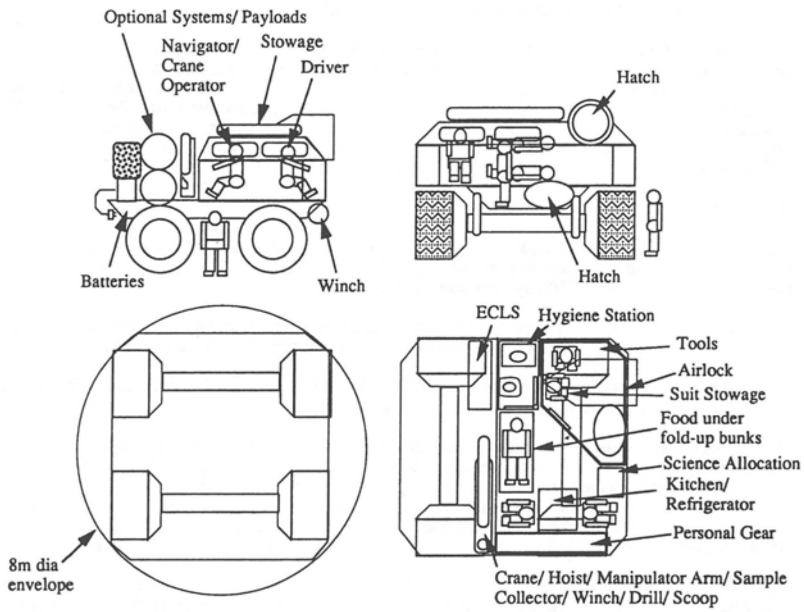
We read books about proposed Mars exploration by science journalists, such as James Oberg[28] and Brian O'Leary.[29] Members of the research team located at the Johnson Space Center obtained several recent unpublished presentations and planning documents, including lists of medical capabilities that have been identified for a Mars expedition and likely activities involving robots and remotely-operated vehicles. We visited websites dedicated to Mars rovers to identify the instruments carried and the types of research conducted robotically. We also read (actually, re-read) a few science fiction stories and viewed key science fiction films (e.g., *2001: A Space Odyssey*, *The Martian*) that had treated space exploration with prescience and/or insight. We extracted tasks while reviewing all of these sources and listed the statements on a spreadsheet.

We then turned our attention to the Mars Design Reference Missions that were developed by NASA after two decades of near "taboo" status of the topic within the agency. The first relevant report to emerge presented the results of the Mars Exploration Study Project that was conducted in response to a strategic planning initiative of the Associate Administrator for Exploration. The purpose of the study was to establish a vision for the human exploration of Mars to help understand the program and technical requirements for a lunar exploration program that was contemplated. The study was to identify commonality between Mars and Moon exploration in order to minimize total costs and avoid dead ends if the programs were to be conducted sequentially. Instead, the study team developed a detailed plan for Mars exploration without consideration of a lunar component. Research results were presented during a two-day workshop at the Ames Research Center (ARC) in May 1993; the report that documents the research is referred to as the ARC report, even though it was published by JSC and the study team was composed of personnel from nearly every NASA center.[30]

The characteristics of the ARC design reference mission that distinguished the plan from previous concepts, include: 1) No low-Earth orbit operations, assembly or fueling; 2) No rendezvous in Mars orbit prior to landing; 3) Short transit times and a long surface stay; 4) A common heavy lift launch vehicle, capable of transporting crew or cargo to space, and delivering required payload with four launches for the first human mission and three launches of cargo and crew for each subsequent opportunity; 5) Exploitation of *in situ* resources from the beginning; and, 6) Availability of abort-to-Mars-surface. More important, unlike previous plans, the ARC study focused equal attention on the "being there" as on the "getting there," which elevated human factors considerations to central design issues and enabled us to identify additional tasks that will likely be performed during long-stay surface operations. For example, a functional analysis showed that the surface objectives could be conducted with as few as five crew members, based on technical skills required. However, loss or incapacitation of one or more personnel might jeopardize mission success. A crew of six was specified for this reason and seven or eight might be required. The plan suggested that crew workloads should be minimized through automation and robotics to allow as much time as possible to conduct science (e.g., automated housekeeping; automated fault-detection and safing). The plan introduced the concept of staging equipment and establishing caches of supplies in advance of a human landing, a practice of polar explorers and now a part of all Mars mission plans. The report also insisted that the habitat be designed specifically for use on the surface, rather than requiring the crew to live in a cramped descent module, as in previous Mars mission plans, an influence of the ARC human factors and architecture participants.

[28] James E. Oberg. *Mission to Mars: Plans and Concepts for the First Manned Landing.* Harrisburg. PA: Stackpole Books, 1982.
[29] Brian O'Leary. *Mars 1999: Exclusive Preview of the US-Soviet Manned Mission*. Harrisburg, PA: Stackpole Books, 1987.
[30] Michael B. Duke and Nancy Ann Budden. *Mars Expedition Study: Workshop II*, NASA Conference Publication 3243. Houston, TX: Lyndon B. Johnson Space Center, 1993.

In addition to the orbital mechanics, propulsion, and descent issues described in previous Mars plans, the ARC Design Reference Mission addressed the extraction, purification, and delivery of consumables that are available on Mars (N_2, O_2, H_2O); life support systems, including an experimental bioregenerative system capable of providing a fraction of the food needed by the crew; surface EVA suits (umbilical, independent, roving) to support maintenance and science tasks; power requirements and supply (primary and backup SP-l00 class nuclear reactor with dynamic conversion, photovoltaics); equipment interfaces; habitability; crew composition and training; communication latency; safety; and, surface mobility (carts and rovers) to support maintenance and research tasks that will be performed by the crew. The ARC report presented a mature plan for the exploration of Mars and contained information relevant to the current task analysis.



Conceptual Design of a Pressurized Rover from the ARC Design Reference Mission Plan, 1993.

Another version of the ARC plan was published in 1997 that elaborated on the original report's discussions of crew requirements and activities. The report included lists of skills that would be required among the Mars mission crew and identified five technical fields: mechanical engineer, electrical and electronics engineer, geologist, life scientist, and physician-psychologist. The report recommended that each field be represented by a specialist, with at least one other crew member cross-trained as a backup; crew members would also be cross-trained for other responsibilities, including command and communications. The report stressed the importance of well-trained personnel to ensure they have the skills to enable real-time, autonomous troubleshooting of maintenance issues and planning of scientific activities in support of mission objectives. The report predicted that maintaining interpersonal relationships and physical and mental conditioning will be primary goals during the cruise to Mars; the focus will be on productivity in a harsh environment while on the surface. It is notable that this report acknowledged a likely international composition of Mars crews, similar to the practice of assembling crews for the International Space Station, with representatives from the United States, Russia, Europe, and Japan, and the possibility that additional countries might be included. The information was presented well and it was accompanied by figures and artists' renderings that contributed to the impression that Mars mission planning had reached a new level.[31]

[31] Stephen J. Hoffman and David I. Kaplan. Editors. *Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team*. NASA Special Publication 6107, Houston, TX: Johnson Space Center (July) 1997.

Four years later, Stephen Hoffman, physicist, mission designer, and an editor of the previously-described report, authored a document, titled, *The Mars Surface Reference Mission: A Description of Human and Robotic Surface Activities*.[32] The purpose of the report was to help the exploration community compare and evaluate approaches to Mars surface operations and to identify and explain system drivers, or significant sources of cost, performance, and risk. The report elaborated on the outline provided by the 1993 ARC study and is unique among the Mars mission literature because it focused exclusively on the human crew and the work they will perform on the planetary surface. Hoffman began by stating the primacy of scientific goals to Mars expedition planning, which was a distinguishing characteristic of the ARC design, and then he offered eight reasons why humans will contribute to achieving those goals, beginning with:

> Humans' unique ability to observe and synoptically integrate their observations is exercised in the discipline called field work. Similar methods are used by geologists, biologists, and paleontologists. This ability comes from a combination of visual acuity and the ability to look at the surface from several perspectives, integrating observations made at different times and different angles to identify subtle differences between materials. A field scientist is able to conduct experiments as needed, such as deploying a field instrument, knocking a corner off of a rock, drilling a core, etc., which improve the ability to recognize rocks. Observations, experiments, and decisions are done rapidly. Finally, humans can use on-the-spot judgment to obtain images of the surface and of materials they sample to document the mission and communicate contextual information. (page xii)

The description of Mars surface operations included in the report was illustrated, helpfully, by images created by space artist, Pat Rawlings, and was presented in the following categories, each of which informed our understanding of the work that will be conducted by human crew during the long-duration surface-stay of a conjunction-class expedition to Mars (i.e., 500 to 600 days).

Exercise	Off Duty and Recreation
Training	Initial Surface Operations
Crew Quarters	Life Sciences Experiments
The Field Camp	Preparation for Departure
Sample Analysis	Toxin and Biohazard Assessment
Sample Curation	Wardroom and Food Preparation
Personal Hygiene	Teleoperation of Robotic Vehicles
Exploration Field Work	Inspection, Maintenance, and Repair
General Housekeeping	Autonomous Deployment of System Elements
Surface Transportation	Crew Health/Medical: Routine and Emergency

Nearly every page of the report provided information that allowed us to identify tasks and better understand the conditions of work. For example, the report's descriptions of geologic field work resulted in 30 task statements. And, although the report concerned surface operations, we identified in the following sentences from the report five tasks that will be performed by at least two different crew members at the conclusion of the surface descent phase of a Mars expedition.

> The very first event that will occur after touchdown is to safe the landing vehicle. This will include purging the engines, shutting down the landing systems, and securing the various other systems involved with flight… Determining the crew's physical condition will be the next activity once the vehicle has been placed in a safe mode. (page 15)

[32] Stephen J. Hoffman. *The Mars Surface Reference Mission: A Description of Human and Robotic Surface Activities*. NASA/TP-2001-209371, Houston, TX: Johnson Space Center (December) 2001.

Exobiologist on Mars by Pat Rawlings.
Image Caption of Figure 2.3-1 (page 19) from the 2001 Mars Surface Reference Mission Report: "An EVA crew member examines a rock sample gathered from the base of a vertical wall. The crew will use unpressurized rovers, such as the one seen in the background, to gain access to sites such as these that will likely be beyond walking distance from the landing site."

NASA established the Exploration Systems Mission Directorate (ESMD) in January 2004 to implement the expansion of human capabilities beyond Low-Earth orbit with the goals of answering scientific and philosophical questions while responding to discoveries along the way. The strategy requires developing new technologies and capabilities to enable human exploration of the solar system. ESMD began by conducting a series of studies concerning a return to the Moon, and then NASA Headquarters commissioned The Mars Architecture Working Group (MAWG) in January 2007 to develop the Mars Design Reference Architecture 5.0 (DRA 5.0) to prepare for exploration beyond the Moon. The purpose of DRA-5 was to provide a common framework for planning, technology-development, operational testing, and the integration of multiple agency efforts (e.g., Mars robotic missions, research conducted on the ISS, lunar exploration). The DRA-5 report, published in 2009, describes the systems and operations that could be used during the first three human expeditions to Mars, which would occur on three consecutive trajectory opportunities "sometime within the next several decades."[33]

Together, the 100-page DRA-5 Report and the 400-page Addendum provide a comprehensive plan for the human exploration of Mars, which includes identification of key challenges and gaps in capabilities.[34] The plan specifies a conjunction-class mission profile with rendezvous in either Low-Earth Orbit (LEO) or Cis-Lunar Orbit (CLO) for the crew to board the interplanetary spacecraft. A 180-day transit to Mars is followed by an elliptical parking orbit around the planet; all six crew members then descend to the surface from the interplanetary spacecraft in a Mars Excursion Vehicle (MEV)/Mars Descent Vehicle (MDV) while the interplanetary spacecraft remains untended in Mars Orbit during the crew's 500-day surface stay. Pre-positioned on the surface are a habitat with equipment and consumable supplies; a nuclear-powered electricity-generating plant; teleoperated robot rovers (TROVs) and two pressurized surface rovers; automatically-operating machinery for extracting O_2 and fuel from the Martian atmosphere and subsurface H_2O, and tanks for storing the material produced. Also pre-positioned would be at least one Mars Ascent Vehicle (MAV) for returning the crew to the space ship orbiting the planet after 18 months of surface operations. The first human crew would not launch from Earth unless the automated precursor deliveries of equipment to the surface of Mars were successful.

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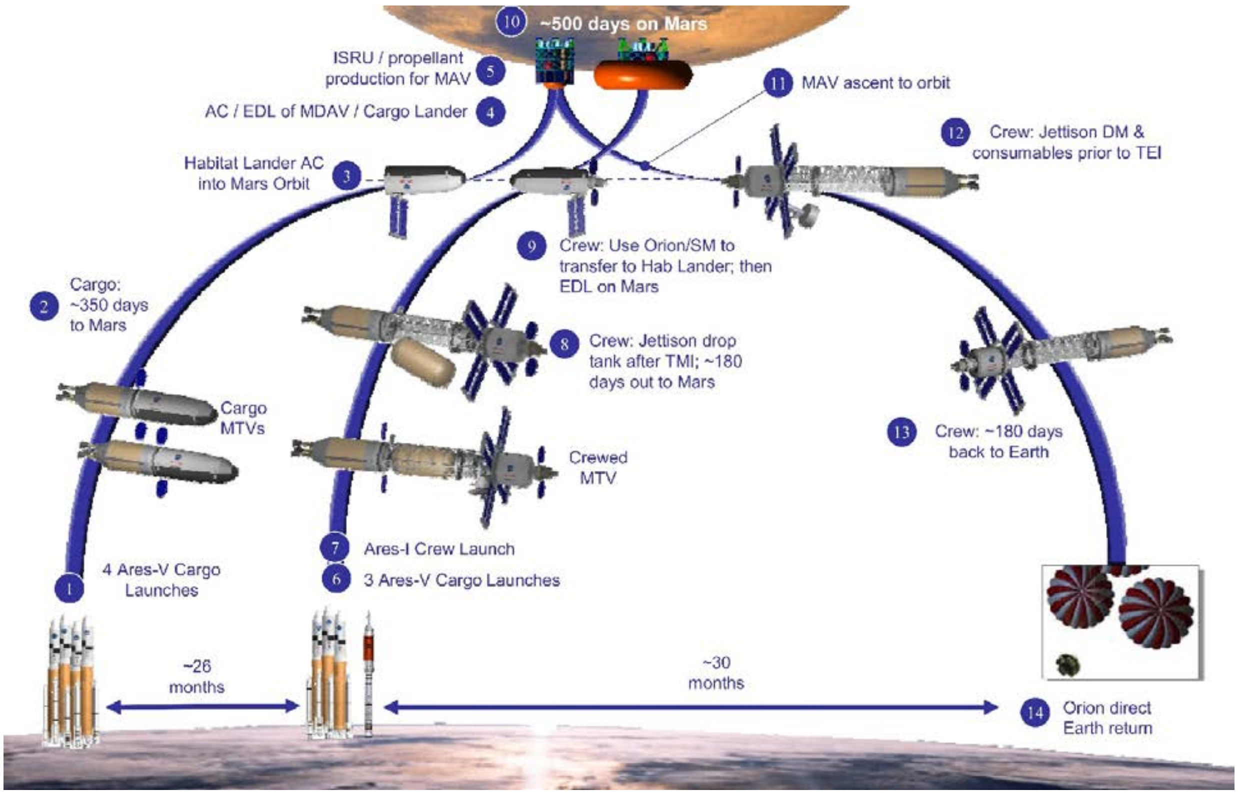
[33] Bret Drake (Editor). *Human Exploration of Mars Design Reference Architecture 5.0*. NASA/SP–2009–566. Washington, DC: NASA Headquarters (July) 2009. http://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf

[34] Bret Drake (Editor). *Human Exploration of Mars Design Reference Architecture 5.0 Addendum*. NASA/SP–2009–566-ADD. Washington, DC: NASA Headquarters (July) 2009. http://www.nasa.gov/pdf/373667main_NASA-SP-2009-566-ADD.pdf

Most of the equipment would remain in cold storage awaiting the crew. However, the power-generating and extraction plants would be assembled and operated remotely; the human mission would launch from Earth only after verification that the propellant and life-support resources needed to survive and return to Earth had been produced. On the return trip, the crew would transfer from the interplanetary ship to an attached Orion-type craft five days before reaching Earth, undock, and then descend to Earth directly in an Apollo-type "skip" trajectory using parachutes and retro-rockets, while the interplanetary ship continues on unoccupied, indefinitely.[35]

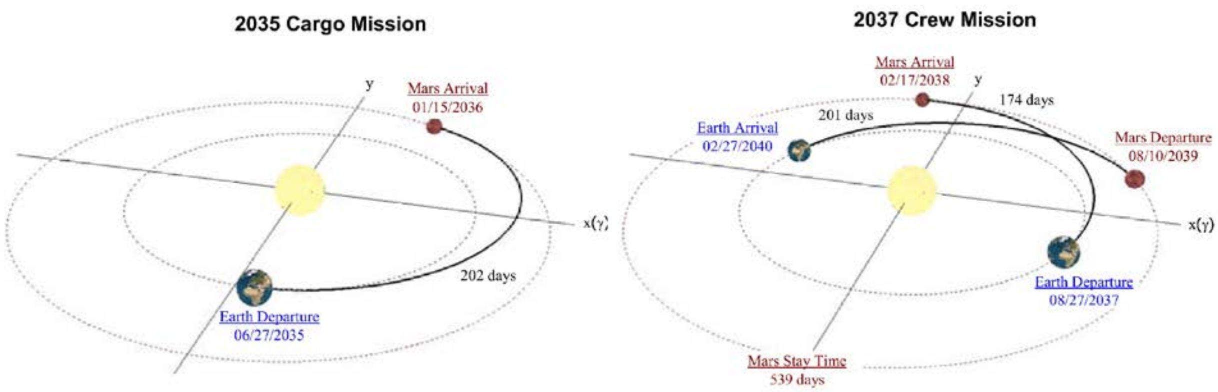


Mars Design Reference Architecture 5.0 Mission Sequence Summary.

The DRA-5 is a further refinement of the Mars Exploration Study Project (i.e., ARC) plan developed by NASA in 1993 and improved in the 1997 and 2001 design reference missions, described previously. DRA-5 retained the previous plans' emphasis on science, including Geology, Geophysics, Aerology, Heliophysics, Biology/Life Sciences, and of course, the search for extant and/or extinct life on the planet. DRA-5 stressed the need for flexible and robust exploration capabilities and identified personal abilities necessary for conducting science on the surface of Mars. The abilities included, speed and efficiency to optimize field work; agility and dexterity to go places that are difficult for robots; and, most important, innate intelligence, ingenuity, and adaptability to evaluate in real-time and improvise to overcome obstacles to acquiring scientific data (i.e., uniquely human capabilities).

The health and performance of human crew are discussed in detail in DRA-5, in addition to the science objectives and research activities. Concerns addressed include, radiation protection, especially from the effects of solar particle events (SPEs); countermeasures to the effects of zero gravity in transit and reduced gravity on the surface of Mars; medical care; life support systems; and, behavioral health, performance, and human factors issues (including personnel selection and habitability).

[35] Direct descent, originally proposed in the 1962 Ford Aeronutronic plan and by Maxime Faget in the 1964 MSC plan, avoids having to carry fuel to and from Mars to slow the interplanetary ship as it approaches Earth. It is a radical but effective method for reducing overall fuel requirements by about one-fourth.



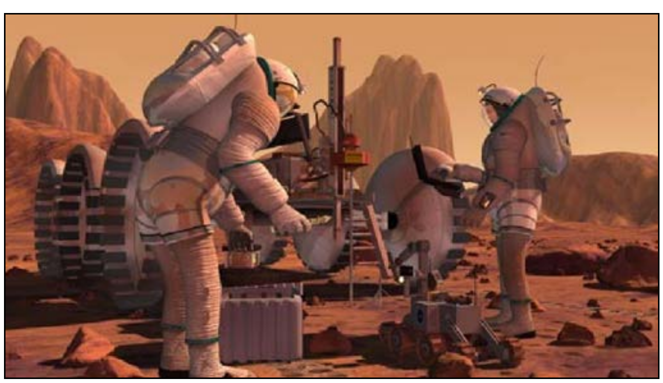
Example DRA-5 Cargo and Crew Trajectories.

Many additional crew tasks were identified while reviewing the DRA-5 Report and Addendum, which also contributed to the current research team's understanding of the work that will likely be performed by the first human explorers of Mars and the conditions under which the tasks will be performed. The DRA-5 report is a monumental achievement of planning that encompasses technical, physical, scientific, engineering, economic, and human components. It offers a comprehensive plan for the human exploration of Mars and presents the current, best ideas of experts within NASA and the agency's support contractors. It was clear to the research team that DRA-5 should provide the primary assumptions to guide our task analysis.

Task 2: Conduct Interviews with Mission Planners and Astronauts

The research team conducted open-ended interviews with a sample of subject matter experts to inquire about the tasks that might be performed during a human expedition to Mars. The sample included, astronauts, mission planners, design engineers, physicians, planetary geologists, EVA suit developers, behavioral scientists, and others involved in space-related research. Tasks identified during the interviews were added to the growing lists. For example, Professor Mike Gaffey of the University of North Dakota, provided background information about the professional requirements for planetary geology and offered several geological research tasks that will be performed by crew members on the surface of Mars, such as:

> Scan surrounding planetary surface, visually through clear visor of surface EVA suit, to identify potential sites for geological research and collection (e.g., contrasting color).
>
> Position drill-bit and operate powered well-drilling equipment, while wearing surface EVA suit, to drill approximately 10-meter hole to sub-surface water level.



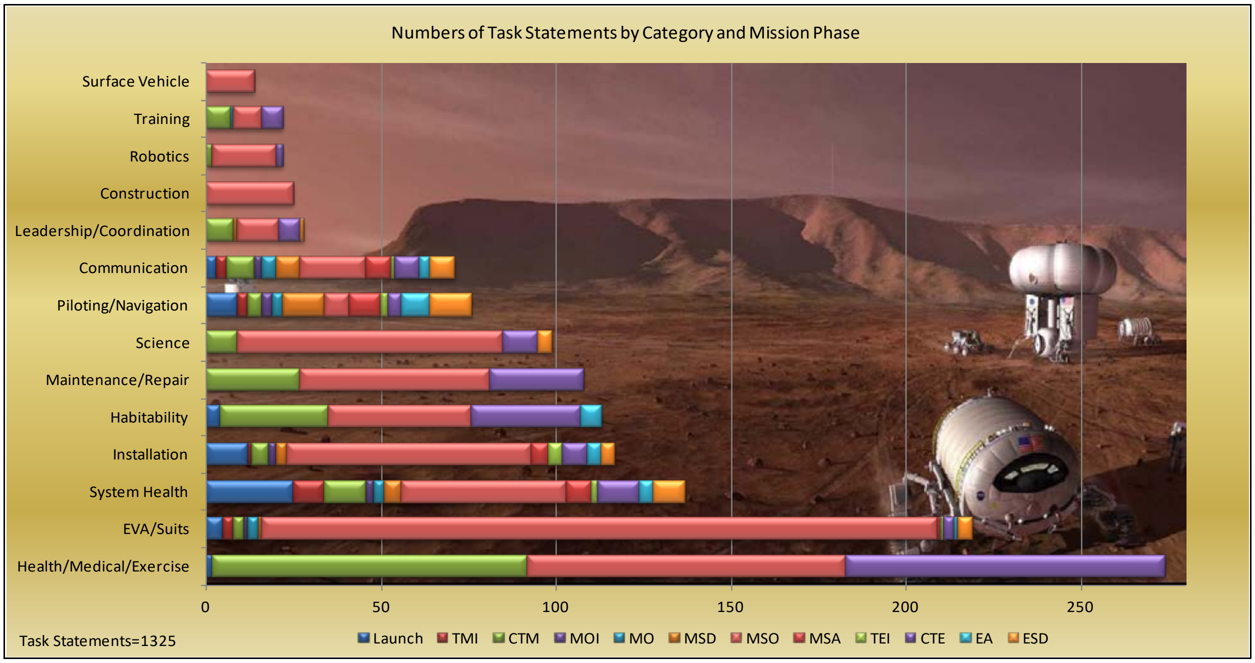
Well-drilling on Mars, from the DRA-5 Report.

Task 3: Identify and Categorize Expedition Tasks

The research team met nearly every week via teleconference to identify gaps in the task lists and then continued to meet to address subsequent steps in the research plan. We decided to divide the mission profile into the 12 phases described in the book by Brian O'Leary that was mentioned previously to help organize the growing inventory of task statements; slight changes were required to adapt O'Leary's assumption of an Earth Orbit Rendezvous (EOR) after the return cruise to be consistent with the Direct Descent method specified in DRA-5. The preliminary lists for the 12 Mars Expedition phases contained a total of 1,125 tasks, as described in the table, below. Mars Surface Operations (MSO) comprises the largest number of tasks, which would be performed during the 18-months the crew remains on the planetary surface. MSO is followed by the Cruise to Mars (CTM) and Cruise to Earth (CTE) phases in numbers of tasks, which would be performed during the six-month transits to and from Mars. Many of the tasks are the same in the two cruise phases, but conditions will be different (i.e., before and after spending approximately 540 days on Mars); they are counted twice for this reason.

Mission Phase	Tasks	Mission Phase	Tasks
Launch to Orbit (LTO)	60	Mars Surface Operations (MSO)	484
Trans-Mars Injection (TMI)	19	Mars Surface Ascent (MSA)	29
Cruise to Mars (CTM)	206	Trans-Earth Injection (TEI)	10
Mars Orbit Injection (MOI)	10	Cruise to Earth (CTE)	204
Mars Orbit (MO)	13	Earth Approach (EA)	26
Mars Surface Descent (MSD)	29	Earth Surface Descent (ESD)	35
		Total	1,125

The 1,125 Mars expedition tasks identified during the review of mission planning documents and interviews were assigned to one or more of 14 categories used by NASA for ISS operations to help characterize the types of work that will be performed from launch to return. The figure below illustrates the number of tasks in each of the 14 NASA/ISS categories by mission phase; 200 of the tasks were assigned to two categories (e.g., Robotics and Construction; Science and EVA). Additional characterizations of the task inventory are presented later in this report.



Task 4: Prepare Task Statements for Review by Key SMEs

Our objective in the current study has been to develop a comprehensive understanding of the human requirements for space exploration in order to identify the specific and generalizable skills and abilities necessary to perform the work under operational conditions. For this reason, it was necessary to include descriptions of all tasks performed by each specialty represented by members of the Mars expedition crew. The Mars mission plans that were reviewed during the current study specified crew sizes ranging from two to 16 (excluding von Braun's 70), with six or eight considered by the planners to be ideal to accomplish all mission objectives and to return to Earth safely. Most of the mission plans also assumed the crew roles to be Commander, Pilot, Medical Officer, Scientist (geologist, biologist), and Engineer (mechanical, electrical, nuclear). Among our goals has been to provide data-driven recommendations for the number of crew members and for their specialties. That is, no assumptions about crew roles were made in our proposal or during the study. Results of the task analysis would lead directly to those recommendations.

Each task statement identified during previous project steps was revised to begin with an action verb, followed by the object of the sentence, and then a description of how and under what conditions the task would be performed; task statements conclude with the reason for the action, in most cases. For example: *Enter control inputs, manually with gloved fingers, to override automatic firing of retro rockets for Mars Surface Descent maneuver if automated system fails.*

The goal is to identify and record four specific elements of each task:

1) What is done? 2) To what is it done? 3) How is it done? 4) Why is it done?

Inspect circuit board, visually, to detect scorching or other evidence of electrical short.

Pound seismometers into rock, manually using slide hammer while wearing surface EVA suit, to deploy sensors.

View ultra-sonic display, visually while manipulating hand-held device manually, to interpret results of ultra-sonic imaging test.

We reviewed the task lists in an iterative process to ensure that task statements were phrased systematically, which would maximize comparability during subsequent data-collection and analysis, and also remove variable syntax as a possible source of experimental bias. The resulting lists of formatted task statements together provide a comprehensive description of the work that will be performed by members of the crew during an expedition to Mars.

Dig loose regolith from around surface rover wheel, manually using shovel while wearing surface EVA suit, to regain traction to proceed, a task performed by Mark Watney (played by Matt Damon) in *The Martian* (2015); image courtesy of 20th Century Fox.

Task 5: Review and Revise the Task Inventory

We prepared an Excel document consisting of 14 tabs. The first tab listed the assumptions of the Mars Expedition, which were based on DRA-5, but included elements derived from other sources:

> A Conjunction Class (approximately 500-day surface stay) mission profile is assumed with outbound Earth Orbit and Mars Orbit Rendezvous (MOR); Earth Orbit Rendezvous in Low-Earth Orbit (LEO) or Cis-Lunar Orbit (CLO) are accommodated by this task inventory. All crew members descend to the surface of Mars from the (interplanetary) spacecraft in a Mars Excursion Vehicle (MEV)/Mars Descent Vehicle (MDV); the (interplanetary) spacecraft remains untended in Mars Orbit. Pre-positioned on the surface are habitats, laboratories, sample storage facilities, and greenhouses (some of which require inflation and siting by the human crew); a nuclear-powered electricity-generating plant; teleoperated robot rovers (TROVs), at least two pressurized surface rovers, excavation/drilling equipment/vehicles; automatically-operating machinery for extracting O_2 and fuel from Martian atmosphere and subsurface H_2O, and tanks for storing the material produced; also pre-positioned is at least one Mars Ascent Vehicle (MAV) for returning the crew to the space ship orbiting the planet (the task inventory also accommodates returning to the orbiting space ship in the same Mars Excursion Vehicle in which the crew arrived). Most of the equipment will remain in cold storage awaiting the crew. However, the power-generating and extraction plants will be set up and placed in operation remotely; the human mission would launch from Earth only after verification that the propellant and life-support resources needed to survive and return to Earth have been produced. On the return, the crew will transfer from the interplanetary ship to an attached Orion-type craft as they approach Earth, undock, and then descend to Earth directly while the interplanetary ship continues on course unoccupied.

The assumptions tab was followed by a tab listing the references from which the tasks were obtained; 12 additional tabs were devoted to each of the 12 mission phases and presented the task statements organized by category and with reference notations.

We conducted a review of the task lists before proceeding to develop a form that could be used by SMEs to rate the tasks in terms of Difficulty, Importance, and (likely) Frequency. We asked a highly-experienced mission planner, a scientist astronaut, and a high-ranking NASA scientist-manager to review the document and then comment on our Mars expedition task lists. The mission planner responded that the lists were comprehensive and recommended a few minor changes to MSO tasks based on the latest, unpublished mission plans (e.g., length of ladder, method for hoisting loads). The scientist manager wrote that the lists were comprehensive and looked like "behind the scenes at *The Martian*," referring to the 2015 feature film that portrayed a human expedition to Mars.[36] The astronaut scientist reported that the lists were comprehensive, but there were too many task statements for SMEs to rate each one in terms of the three dimensions. The research team then performed a few tests and discovered that it would take between four and five hours to rate all 1,125 tasks, which, of course is too long to expect volunteers to devote to our study.

ISS Crew Watching *The Martian*, 1 October 2015.

[36] Andy Weir. *The Martian*. New York: Broadway Books, 2014. Weir's book and Ridley Scott's film with the same title were accurate depictions of an opposition-class (short stay) human expedition to Mars, in the opinions of most mission planning experts, with a few notable exceptions. In particular, [spoiler alert] the Martian atmosphere is too thin for a wind storm to blow down a parabolic antenna, and a gravity-assist maneuver is the first option that NASA scientists would have considered for a rescue mission. NASA cooperated with the filmmakers and the product has been described as the best ever advertisement for careers in science and engineering.

We needed to reduce the burden on SME raters, but we did not want to lose the granularity provided by the detailed task lists. Our solution was to categorize the tasks within each mission phase according to similarity and then compose a statement that summarizes the component tasks. We planned to list the component tasks under the summary statement, but to ask volunteers to rate only the summary statement while considering the component tasks when responding. This process resulted in a total of 158 summary task statements (representing the 1,125 tasks); for example, the 484 Mars Surface Operations tasks were reduced to 55 summary task statements and the 206 Cruise to Mars tasks were reduced to 27 summary statements. A few EVA tasks from the MSO phase are reproduced, below.

Perform surface EVA physical functions on foot during Mars Surface Operations.	
	Carry incapacitated crew mate 20 meters to surface rover, manually while both are wearing surface EVA suits, to prepare for medical treatment.
	Rise from prone position, using arms and legs while wearing surface EVA suit, to recover from fall on flat surface.
	Rise from prone position, using arms and legs while wearing surface EVA suit, to recover from fall in loose regolith.
	Bend over/stoop while wearing surface EVA suit to retrieve hand tool from planet surface.
	Climb 3 meter ladder, manually while wearing surface EVA suit, to access Mars Surface Ascent Vehicle.
	Adjust surface EVA suit controls, manually with gloved fingers, to operate mobile communications with Mars habitat personnel.
	Adjust surface EVA suit controls, manually with gloved fingers, to optimize mobile life support system.
	Carry harvested plant material from greenhouse to surface habitat galley, manually while wearing EVA suit, to prepare for crew consumption.

Example of a Summary Task Statement and Component Tasks from the Master List.

Task 6: Prepare Survey Instrument, Pre-Test, and Refine

The next step was to construct a survey instrument that asked three questions about each mission task: 1) How frequently is the task performed; 2) How difficult is it to learn how to perform the task; and, 3) How important is the task to mission success. A member of our team prepared an Excel file that presented our task lists as a survey instrument that we could send to SMEs, believing that a computer-aided rating form would be more convenient for SMEs than paper forms and would enable automatic scoring, which would eliminate redundant data-entry and transcription errors. The file displayed five radio buttons as a scale with the cognitive anchors "Not at All" and "Very" appearing for each of the three rating dimensions. The task statements that compose each major category could be viewed by clicking on a plus symbol; fields for SMEs to record comments about tasks also were provided.

The form was developed in an iterative process to ensure that it displayed properly on a variety of computers and screens; it was then sent to a small sample of SMEs who were asked to read the instructions, to complete the survey by rating the tasks in all 12 mission phases, and to provide comments about the materials and process. SME comments were used to revise and refine the instrument and procedures. An excerpt from the survey form is reproduced, below, that depicts one summary task statement concerning surface rover maintenance, three component tasks, the three rating scales, and the comments field.

Task #	Task	*How frequently is the task performed?*					*How difficult is it to learn the task?*					*How important is the task to mission success?*				
		Not at all	--	--	--	Very	Not at all	--	--	--	Very	Not at all	--	--	--	Very
25	**Perform surface rover maintenance functions during Mars Surface Operations.**	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	Remove accumulated dust from surface rover windows, manually while wearing surface EVA suit, to maintain optimal visibility.	*Comments?*														
	Conduct troubleshooting, manually/visually using schematics, procedures, and hand tools while wearing surface EVA suit, to identify fault in surface rover.															
	Remove/replace faulty component/connector manually/visually using hand tools and spare parts while wearing surface EVA suit to restore surface rover to operation.															

Excerpt from the Survey Instrument Developed for SMEs to Rate Summary Task Statements.

Task 7: Identify Relevant Physical, Cognitive, and Social Skills/Abilities and Task 8: Identify Generalizable and Perishable Skills

The interactions among human performance capabilities, learning, and the measurement of performance were explored by Edwin Fleishman in a series of scholarly papers, beginning in 1967.[37] His contributions to our understanding of skilled performance were presented in detail in 1984 in a volume that influenced a generation of human factors specialists.[38] Fleishman's taxonomy of human performance includes 52 abilities with each ability accompanied by an operationally-referenced general definition and three levels of specific criterion performance. Each criterion level descriptor has an experimentally-derived mean score on a seven-point Likert scale; the descriptors can serve as concrete (cognitive) anchors when developing survey instruments concerning specific job requirements. A few examples of Fleishman's abilities with descriptors and mean scores are provided (using a seven-point scale): [39]

Fluency of Ideas is the ability to produce ideas about a given topic.	Mean	SD
Name all the possible problems that might occur with a space launch.	6.59	1.02
Think of as many ideas as possible for the name of a new research firm.	3.59	1.38
Name four brands of toothpaste.	1.66	1.26
Information Ordering is the ability to follow rules to arrange things or actions in order.	Mean	SD
Determine the appropriate sequence of checkout procedures for a rocket.	6.75	0.52
Arrange five sentences into a paragraph that makes sense.	3.21	1.26
Put things in numerical order.	1.32	1.16
Manual Dexterity is the ability to make skillful coordinated movements of the hands.	Mean	SD
Perform open heart surgery.	6.75	0.52
Package oranges in crates as rapidly as possible.	4.07	1.39
Tie a necktie.	2.43	0.96

The Fleishman taxonomy was developed to facilitate data-driven understandings of technical performance. Fleishman identified the abilities that compose his taxonomy by conducting a series of interlocking experimental-factor analytic studies that tested hypotheses about the organization of abilities and generalizable skills. Experimental batteries of tasks were administered to several hundreds of subjects iteratively and correlations were calculated and examined.[40] The taxonomy has been used by the principal investigator since 1982 to study a broad range of telecommunications and military specialties, and to support the development of scientifically valid personnel-selection criteria and optimally-effective training. We proposed to select relevant abilities from the Fleishman taxonomy and to augment the list with job-specific abilities that have been identified as relevant to the work that will be performed by future space crews.[41] In particular, space analog research has found that abilities and personal traits that contribute to group solidarity and individual performance during isolation and confinement include: Likeability (affability), Emotional Control, Patience, Tolerance, Confidence, and Teamwork. We proposed that these and any other abilities that might emerge during the research would be included among the generalizable skills and abilities to be rated by SMEs.

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[37] Edwin A. Fleishman. Performance assessment based on an empirically-derived task taxonomy. *Human Factors*, 9, 349-366, 1967.

[38] Edwin Fleishman and Marilyn Quaintance. *Taxonomies of Human Performance: The Description of Human Tasks*. New York: Academic Press, Inc., 1984.

[39] It is instructive, and useful to the current application, that many of Fleishman's ability definitions use spacecraft, aviation, troubleshooting, medical, and communications tasks as the anchor criterion for the highest level of skilled performance.

[40] E.A. Fleishman. Relating individual differences to the dimensions of human tasks. *Ergonomics*, 21(12), 1007-1019, 1978.

[41] L.B. Landon, W.B. Vessey, and J.D. Barrett. *Evidence Report: Risk of Performance and Behavioral Health Decrements due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation Within a Team*. National Aeronautics and Space Association, Houston, TX, 2016.

Task 9: Derive Training Principles from Ability Literature and
Task 10: Identify Relevant Abilities and Scales

Fleishman's original objective was to define the fewest independent ability categories that are the most useful and meaningful in describing performance of the widest variety of tasks. The research team deliberated about which of the Fleishman abilities we could eliminate to remain consistent with Fleishman's objective while at the same time reduce the burden on SMEs recruited to perform the ability ranking component of the task analysis. We concluded that there were so few candidates for exclusion that we should include all 52 abilities, along with the six "job-specific" abilities mentioned previously. We realized that the six items were actually skills or personality characteristics, rather than physical or cognitive abilities, but they might be among the most important personal qualities to successful performance as a member of a space crew. That is, a crew member is a pilot, physician, or scientist for brief and intermittent periods, but he or she will be a member of a small group of humans living and working in close proximity to each other at all times during a 30-month interplanetary expedition. For these reasons, we decided that it is essential to include in our analysis at least the six social skills listed in italics in the following table.

FLEISHMAN ABILITIES AND SIX SOCIAL SKILLS SELECTED FOR THE MARS EXPEDITION ANALYSIS

Oral Comprehension	Multilimb Coordination	Stamina
Written Comprehension	Dynamic Flexibility	Near Vision
Oral Expression	Gross Body Coordination	Far Vision
Written Expression	Gross Body Equilibrium	Visual Color Discrimination
Fluency of Ideas	Response Orientation	Night Vision
Originality	Rate Control	Peripheral Vision
Memorization	Reaction Time	Depth Perception
Problem Sensitivity	Arm-Hand Steadiness	Glare Sensitivity
Mathematical Reasoning	Manual Dexterity	General Hearing
Number Facility	Finger Dexterity	Auditory Attention
Deductive Reasoning	Wrist-Finger Speed	Sound Localization
Inductive Reasoning	Speed of Limb Movement	Speech Hearing
Information Ordering	Selective Attention	Speech Clarity
Category Flexibility	Time Sharing	
Speed of Closure	Static Strength	*Affability*
Flexibility of Closure	Explosive Strength	*Confidence*
Spatial Orientation	Dynamic Strength	*Emotional Control*
Visualization	Trunk Strength	*Patience*
Perceptual Speed	Extent Flexibility	*Teamwork*
Control Precision		*Tolerance*

In addition to the application of Fleishman's data-driven approach, our efforts to identify relevant generalizable and perishable abilities during this project task were informed by a review of the literature concerning the specificity, durability, and generalizability of skills and abilities. The literature concerning abilities and skill acquisition enabled the identification of key training principles. Those principles were applied to identify relevant abilities and scales and later to assess the implications of study results for the optimal design and delivery of training to support sustained human performance during long-duration space exploration. [42]

[42] R.J. Vogel and C.P. Thompson. The specificity and durability of Rajan's memory. In A.F. Healy and L.E. Bourne, Jr. (Eds.). *Learning and Memory of Knowledge and Skills: Durability and Specificity* (pp. 320-342). Thousand Oaks, CA: Sage Publications, 1995.

The Fleishman taxonomy of 52 physical and cognitive abilities, and the five social skills, and one personal characteristic (Confidence) identified as contributors to successful performance during remote duty missions composed our draft list of abilities. That draft list was subjected to another rational review to determine any candidate abilities that should be eliminated as irrelevant to the work expected to be performed during long-duration space expeditions. As part of the rational process, candidate abilities were linked to specific mission tasks in the inventory of work that was developed earlier in the study.

Task 11: Prepare Ability Decks, Pre-Test, Refine

Decks of cards were prepared with the general abilities/skills and their definitions printed on white stock. Three cards bearing the words, More Important, Important, or Less Important were prepared for each deck, as was a cover card for the SME's name, age, and years of relevant experience. Ability decks were produced to accommodate the sample of SMEs recruited to participate in this component of the data collection effort. A complete list of the abilities and skills is provided in Appendix A.

Speed of Closure The ability to combine and organize different pieces of information into one meaningful pattern quickly; the pattern is not known beforehand and the pieces could be visual or auditory.	**Oral comprehension** The ability to understand spoken English words and sentences.	**Teamwork** The ability to routinely subordinate one's own wishes or interests to those of a group to achieve group objectives; the ability to work with others cooperatively and harmoniously.

Examples of Ability Cards.

Task 12: Recruit Sample of Space Operations, Mission Planning, and Training Experts

We prepared a list of 130 astronauts, mission planners, researchers, and other space operations personnel who we believed were sufficiently-informed about the likely work and other conditions of a Mars expedition to participate in the assessment of mission tasks and the general abilities necessary to perform those tasks successfully. We originally proposed to recruit at least 45 participants to perform the ability ranking, 15 each from three categories: 1) Piloting, robotics, rendezvous, docking, and EVA; 2) Science execution and medicine; and, 3) Operations (training, flight control, planning, maintenance). We believed that the three categories represent the major user groups for long duration space expeditions and the target number of participants was based on a recommendation to test at least 15 users when conducting card-sort exercises.[43]

Task 13: Administer CAT Method

Data-collection in the CAT method, which was described at the beginning of this chapter, involves asking SMEs to rate the tasks in terms of the three dimensions and also to rank-order the selected abilities. The same SMEs can contribute to both components of the effort, but it is not always possible or practical to do so. We sent email messages to each of the 130 SMEs on our list asking them to follow an attached set of instructions to complete the rating of summary task statements presented on the (also attached) Excel document. The Excel document had been configured for SMEs to estimate, 1) How frequently is the task (likely to be) performed? 2) How difficult is it to learn how to perform the task? And, 3) How important is the task to mission success? The SMEs were asked to return their completed surveys via email attachment within four weeks. We extended the deadline several times.

While waiting for SMEs to return completed task-rating forms, the four members of the research team reviewed the task lists again and coded the task statements for functional category (e.g., Piloting, Construction, Decision Making, Surface EVA, Geology); coding was performed individually and then

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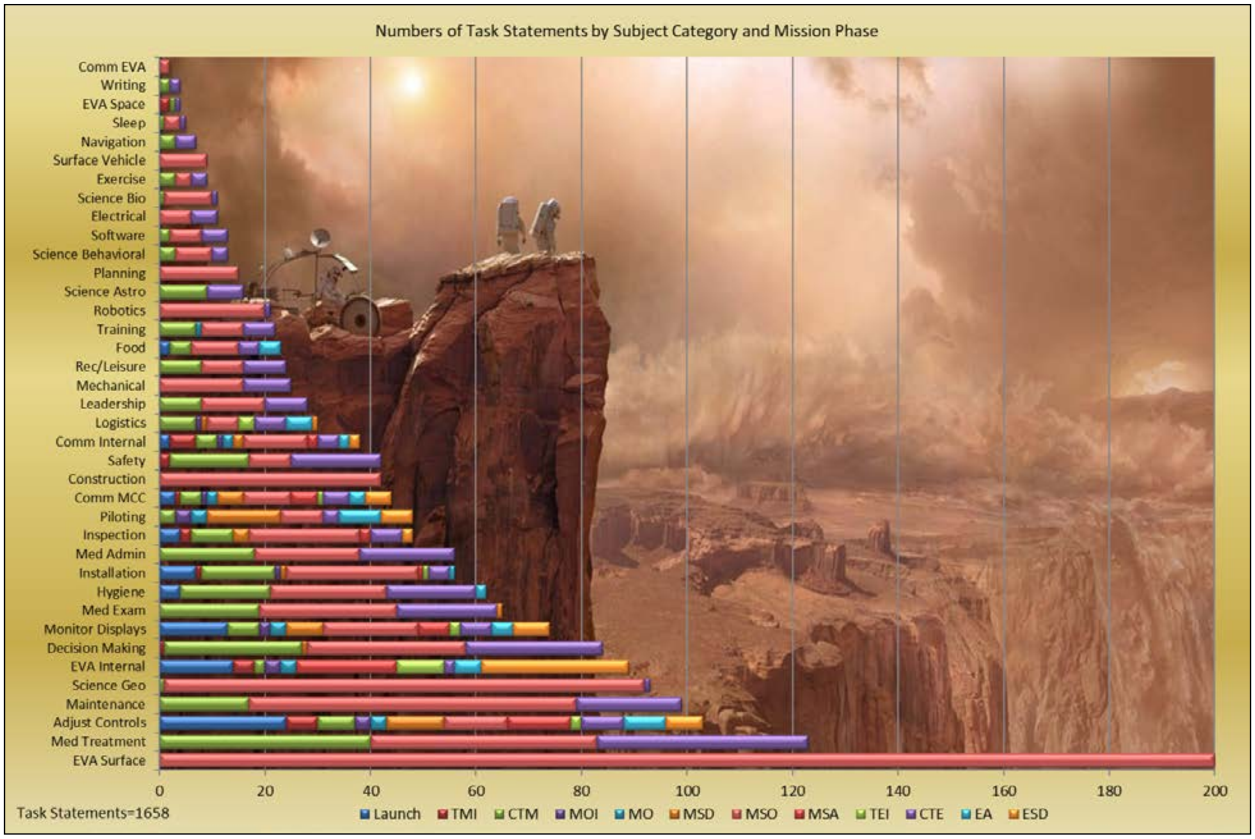
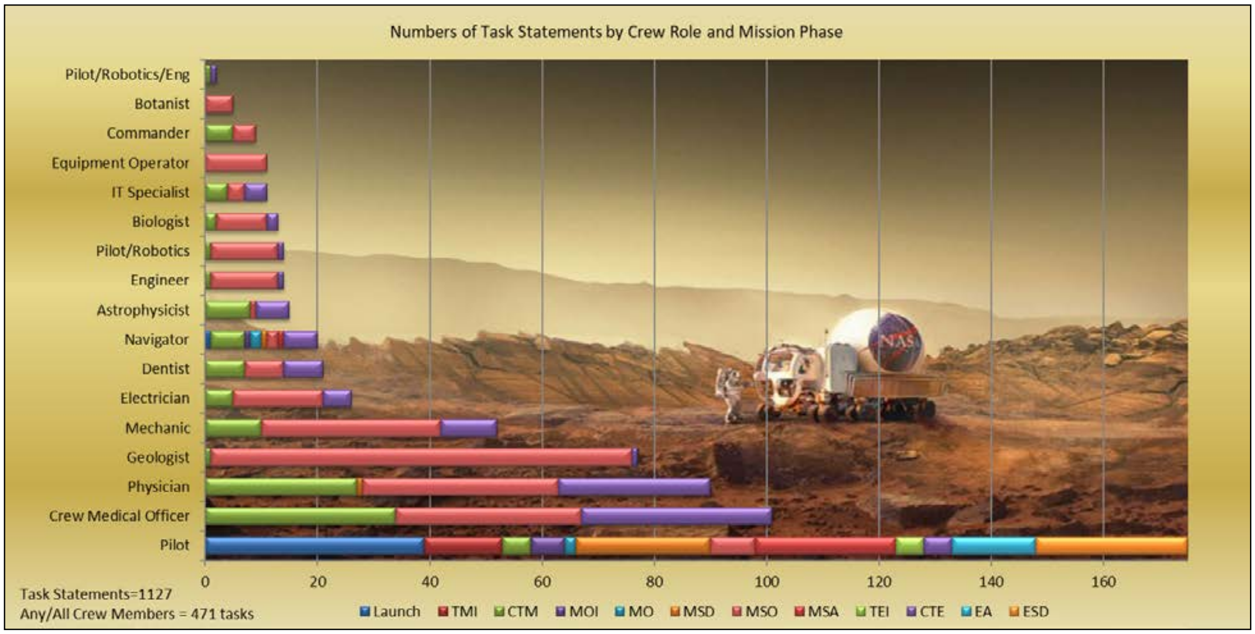
[43] Jakob Nielsen. Card Sorting: How Many Users to Test. Nielsen Norman Group, July 2004. http://www.nngroup.com/articles/card-sorting-how-many-users-to-test/

discussed as a group to arrive at consensus category assignments. This analysis resulted in the 38 categories illustrated by the figure, below. The procedure required including some task statements in more than one category. The analysis was instructive because it allowed us to identify functional sub-categories and better understand the work that will be performed by crew members. For example, the large number of Medical tasks could now be seen as Medical Exams, Medical Treatment, and Administration of Medicine, which is useful to the development of cross-training plans and strategies for offloading medical responsibilities to other crew members, if necessary. We also noted that many of the medical tasks would require a skilled physician, but would be performed only in emergencies. The implications are that an actual physician is required in a Mars expedition crew, but he or she must have other duties to remain engaged throughout the expedition.



The functional categorization led us to also code the task statements by occupational specialty. The research team applied the same modified Delphi technique as in the previous analysis with 17 specialties emerging from the coding-by-consensus process. The results of this analysis are presented in the following figure. We were beginning to understand why von Braun's original Mars mission plan specified a crew of 70, which he later reduced to 12. An objective of our research is to develop personnel-selection and cross-training strategies to enable a crew of five or six, fewer if possible.

Coding the task statements for crew specialty led us to realize that responsibilities that have been assigned to mechanical and electrical engineers in science fiction stories and in the few mission plans that addressed personnel issues would be handled better by mechanics and electricians. That is, it will not be necessary, or even possible, to *design* mechanical and electrical systems during an expedition to Mars, but it will be necessary to *maintain* and *repair* systems. Likely tasks include patching leaks in plumbing and fabricating electrical connectors. Repairing computer hardware and software also emerged as salient responsibilities from the analysis of functional and occupational categories of tasks.



Coding the task statements for occupational specialty allowed us to identify the eight, primary crew roles listed below. We decided that these crew roles, rather than the three domains described previously in Task 12, should be used to focus the ability-ranking procedure on the physical, cognitive, and social abilities necessary for crew members to perform their assigned tasks during the 30-month Mars expedition.

Leader
Biologist
Geologist
Physician
Electrician
Pilot/Navigator
Mechanic/Engineer
Computer Specialist

We prepared detailed instructions for conducting the ability card-ranking, which included background information about the Mars expedition, summaries of the 12 mission phases, example task statements for the eight occupational specialties, and directions for sorting the ability cards. Versions of the instructions were tailored for each role; Appendix B presents the instructions prepared for Geologist. The purpose of preparing the instructions documents was to ensure that all SMEs who were asked to perform the ability card-sort would have the same information before ranking the abilities for their occupational specialty. The research team then began recruiting SMEs from the eight specialties to perform the ability-ranking procedure. We revised our original goal of 15 SMEs for each of the three broad domains mentioned in our proposal to ten SMEs for each of the eight occupational specialties identified by the previous analysis. More than half of the SMEs were recruited from among the ranks of NASA JSC personnel, but the sample also included former astronauts, expert auto mechanics and electricians, military and commercial pilots, physicians and flight surgeons, biologists and astrobiologists, and planetary and engineering geologists. All but a few sessions were administered in person to ensure that SMEs received and understood the mission-relevant information and that study procedures were followed. Comments offered by SMEs during the sessions were recorded in journals to help explain results later.

Task 14-A: Tabulate Results of the Task-Rating Procedure

We received completed task-rating forms from 60 SMEs. The sample included current and former astronauts, flight controllers, flight surgeons, engineers, biologists, geologists, psychologists, physiologists, and human factors specialists. Participants' ratings for the three questions about each of the 158 summary task statements were imported into a pre-formatted spread sheet, the values summed, and mean scores and standard deviations were calculated. The summary task statements were then ranked in descending order of mean scores on each of the three measures (i.e., Frequency, Difficulty, Importance). Mean scores for the three questions about each summary task statement were summed and the resulting metric, labeled "Criticality," was used to rank the task statements in descending order of this combined measure. Results of the task-rating are presented in the following major section of this report.

Task 14-B: Tabulate Results of the Ability-Ranking Procedure

The order of each ability card was recorded in a spreadsheet for each of the 72 SMEs who participated in the card-sorting procedure. The orders of the three category cards also were recorded; the card labeled More Important always was listed as number one in the deck, but the orders assigned to the Important and Less Important category cards varied, depending on each SME's assessment. The ranks assigned to each ability and category card were summed and mean ranks and standard deviations were calculated for each of the eight occupational specialties described previously, and again with data from all eight groups combined. The results were presented as lists of abilities ranked in descending order of importance to successful performance during an expedition to Mars; the mean ranking of category cards divides the lists into abilities that are More Important, Important, and Less Important for each crew/occupational specialty and for all specialties combined. Results of the ability-ranking are presented in the following major section of this report.

Task 15: Identify Implications of Results for Training and Other Issues

We assembled the results of the rating of summary task statements and the associated human abilities and skills: four lists of tasks, one each in descending order of Frequency, Difficulty, Importance, and Criticality; and the lists of abilities also in descending order of salience to exploration-class space missions by the eight crew occupational specialties. We then applied our understanding of training principles and skill-acquisition in a rational process to identify and describe: 1) Clusters of skills that could be used to define the number and roles/specialties of crew members (e.g., leader, pilot, medical specialist, scientist, mechanic); 2) The generalizable skills and abilities necessary for successful performance by each crew role during a Mars expedition; and, 3) The most effective methods for ensuring the crew members possess the requisite skills and knowledge when needed. In addition to the implications of study results to training and generalizable skills and abilities, we identified key implications of task analysis results to the design of spacecraft habitability and ergonomic features, and to the design and presentation of procedures and job aids. We also identified the implications of the ability analysis to personnel selection and crew composition. Together, the four lists of expedition tasks and the nine lists of abilities are a resource that can be used to support future mission planning, research, and development in support of human space exploration.

Task 16: Prepare Recommendations and Report Results

This final report and a Power Point file were prepared to document all project activities and to present study results and implications.

Purpose of the Expedition

Searching for evidence of extinct/extant life and exploring planetary processes have been the explicit purposes of nearly all Mars mission plans reviewed during the current study. A clear statement of the purpose of any endeavor enables organizers to identify goals, which in turn enables analysts to identify the tasks that must be performed by humans and by machines to achieve those goals. Understanding the goals, tasks, and human capabilities and limitations enables the allocation of functions to humans and to machines, and the identification of human and technological requirements. In addition to the instrumental benefits of establishing goals, research concerning expeditions of the past found that the absence of clear objectives and a shared "spirit of the expedition" often resulted in organizational and interpersonal problems.

Institutional Review of the CAT Method

What is commonly known as the Belmont Report was published in 1979 by the National Commission for the Protection of Human Subjects of Biomedical and Behavioral Research. The report specified requirements for the ethical treatment of human subjects in research and was later codified by the US Department of Health and Human Services (45 CFR 46). The law requires that subjects understand any risks associated with their participation in a study and that no harm will come from participation. All research plans must be evaluated and approved by an Institutional Review Board (IRB) before proceeding to recruit subjects for federally-funded research. The Mars expedition task analysis received an exemption from NASA's IRB, because it was found to involve no risk to the SMEs who would rate the tasks or rank the abilities.

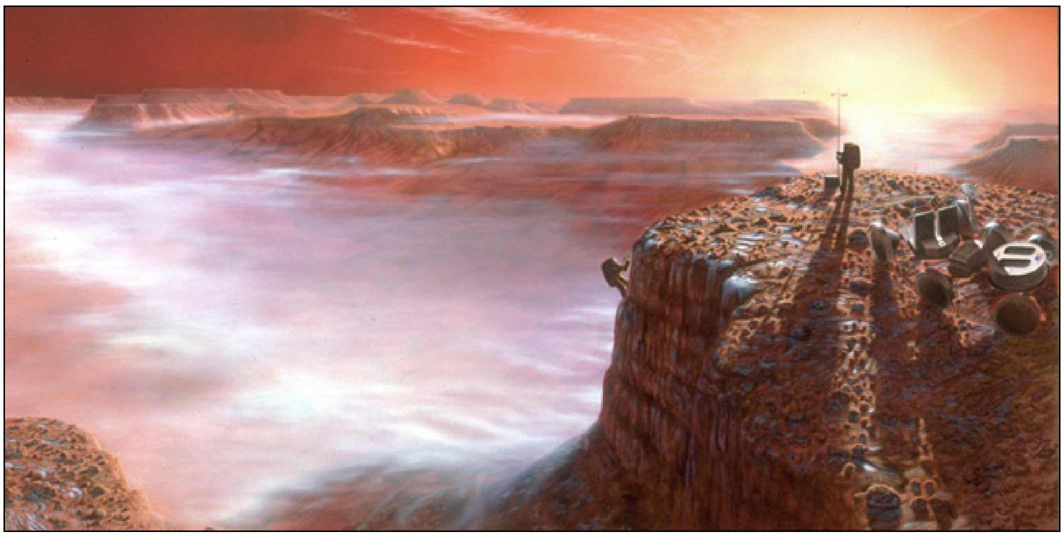
ADVANTAGES OF THE CRITICAL ABILITIES AND TASKS METHOD

- It is flexible.
- It is easy to learn and to conduct.
- It can use existing task statements as a starting point.
- It provides information about each task's importance.
- It provides information about each task's difficulty to learn.
- It provides information about each task's frequency of performance.
- It provides a metric to enable comparisons of each task's overall criticality.
- It identifies the cognitive and physical abilities necessary for task performance.
- Results of the analysis are presented in a manner that facilitates multiple uses.
- The analyst customizes each application by selecting the dimensions to be measured.
- SMEs remain engaged in the card-sorting procedures and demonstrate attention to the task.

DISADVANTAGES OF THE CRITICAL ABILITIES AND TASKS METHOD

- The card-sorting version requires analyst time to supervise each SME.
- The card-sorting version requires preparation of decks of task and ability cards.

The Critical Abilities and Tasks method provides an understanding of work by rating the tasks performed in terms of difficulty, frequency, and importance; a single measure of task criticality is obtained by combining the three metrics. An accompanying procedure requires SMEs to rank relevant abilities adapted from the Fleishman inventory and results in a list of the physical and cognitive abilities in order of importance to successful job performance. The results of both task and ability exercises are tabulated and descriptive statistics are derived that together provide a comprehensive understanding of the knowledge, skills, and abilities necessary to perform all tasks encompassed by a job.



First Light, by Pat Rawlings, 1988.

RESULTS OF THE RESEARCH

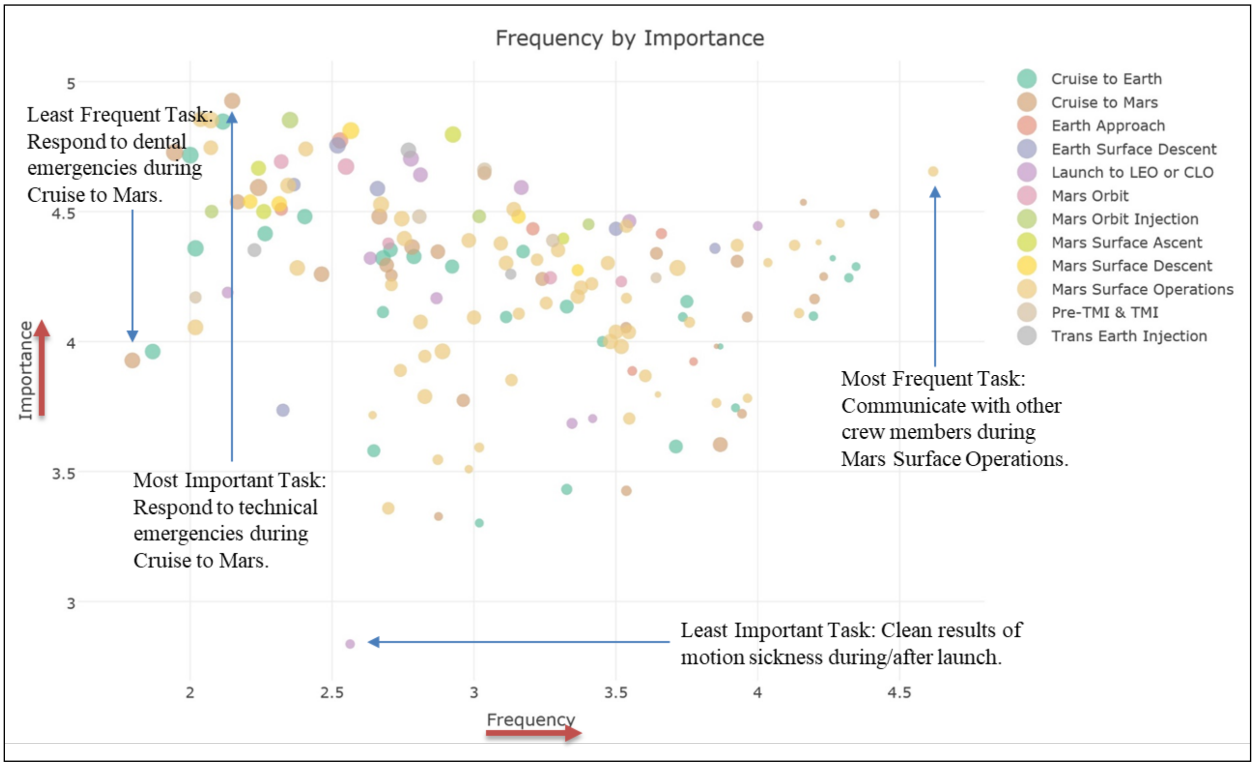
A few analytical results were presented previously while describing research tasks. For example, figures were included in the Research section that illustrated three separate characterizations of the Mars expedition task inventory, using NASA ISS categories, functional categories, and occupational specialties. The latter analysis allowed the research team to the identify eight crew roles, which led us to modify our approach to the ability analysis. This section of the report presents the results of the task-rating and ability-ranking procedures.

RESULTS OF THE TASK-RATING

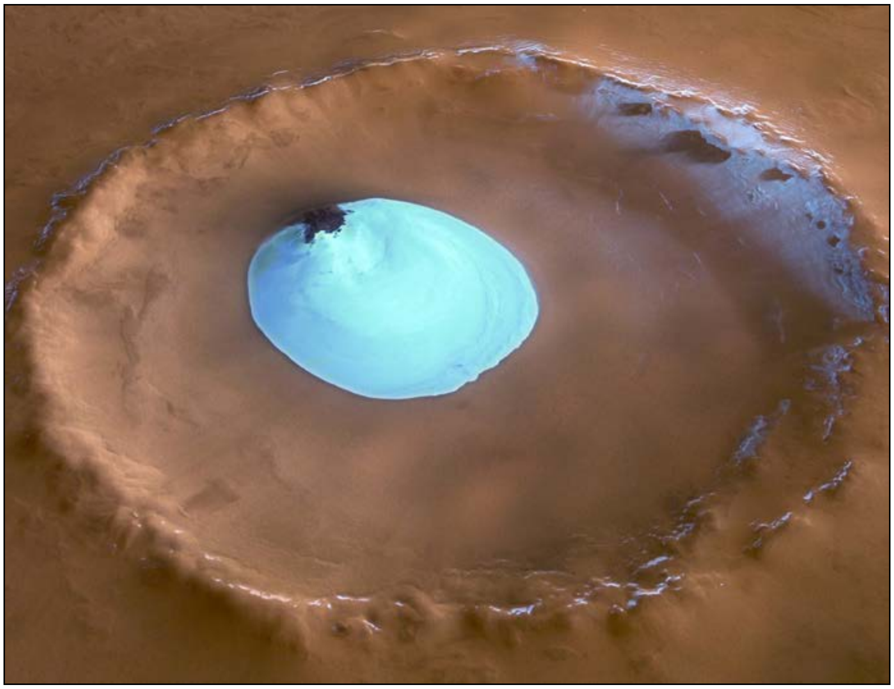
The summary task statements were ranked in descending order of mean scores on each of the three measures (i.e., Frequency, Difficulty to Learn, and Importance). Mean scores for the three questions about each summary task statement were combined to compute a metric, labeled "Criticality," which was used to also rank the task statements in descending order. Some tasks might be frequently performed, but easy to learn or relatively unimportant to mission success. Other tasks might be infrequently performed, but difficult to learn or very important. The three variables are independent. For example, the summary task estimated by the SMEs to be the most frequently performed, *Interact/communicate with other crew members directly during Mars Surface Operations*, was rated 129th in Difficulty, 19th in Importance, and 4th in Criticality. The task estimated to be the most Difficult, *Respond to medical emergencies, following procedures and with equipment provided, during Cruise to Mars*, was rated 156th in Frequency, 13th in Importance, and 24th in Criticality. The task estimated to be the most Important, *Respond to technical emergencies, following procedures and with equipment provided, during Cruise to Mars*, was rated 145th in likely Frequency, 15th in Difficulty, and 29th in Criticality. Similarly, the task that was estimated to be at the top of the Criticality list, *Perform science-related EVA functions during Mars Surface Operations*, was 32nd in Frequency, 16th in Difficulty, and 85th in Importance. Ranking the tasks in terms of each variable and by the combined measure enabled a detailed, quantitative understanding of the work that will be performed during the first human expeditions to Mars.

The task-rating data also were subjected to analyses that allowed us to assess the relationships among the three metrics for each summary task statement. For example, in the scatter diagram on the following page, each dot represents a summary task statement with its location determined by the mean values for Importance and (likely) Frequency of task performance. Color represents mission phase and the size of the dot reflects the mean Difficulty value. Placing a cursor over a dot in the computer-based view evokes a pop-up that displays all three values and the mission phase.

The small, salmon-colored dot on the far right of the scatter diagram represents the task statement, *Interact/communicate with other crew members directly during Mars Surface Operations* (Frequency 4.64, Importance 4.67, Difficulty 2.30). The location of this most-frequent task contributes to our confidence in the method and in the study results, because interacting and communicating with other members of the crew during the 18-months of Mars Surface Operations is expected to be the activity that will be performed most frequently, even more frequently than exercising and preparing meals during the cruise to Mars and on the planetary surface, which are represented by the nearest dots to interacting and communicating while on Mars. The two larger dots on the far left of the diagram represent the task statement, *Respond to dental emergencies, following procedures and with equipment provided during cruise to Mars* and the corresponding statement for the *cruise to Earth*. The sizes of the dots reflect mean Difficulty values of 3.89 and 3.95 and the locations of the dots are determined by mean values of 1.81 and 1.88 for (likely) Frequency and 3.95 and 3.96 for Importance. The locations of these two nearly identical task statements on the diagram provides an additional indication of internal validity for the task-rating procedure; that is, the two cruise-phase dental task statements appear together at the low end of the Frequency scale and dental emergencies are expected to be infrequent during the transit phases of the mission—especially during the cruise to Mars, represented by the dot on the left, because dental examinations are part of pre-launch protocols. The positions and values of these and certain other summary task statements conform to expectations and thereby contribute to our confidence in the data.



The following pages present results of the task-rating, beginning with a discussion of Difficulty to Learn, which is followed by discussions of (likely) task Frequency, Importance, and then Criticality.



Louth Crater, Mars (73°N 103°E), 37km diameter, 2km deep; image by ESA/DLR/FU.

DIFFICULTY TO LEARN

A purpose of the current study is to address NASA's Risk of Performance Errors Due to Training Deficiencies. For this reason, it is appropriate that we focus attention on the tasks that were rated by SMEs as the most Difficult to Learn how to perform. The following table lists the top 32 summary task statements in descending order of the SMEs' ratings on the (5-point) Difficulty to Learn scale.

TOP 32 SUMMARY TASK STATEMENTS RANKED BY DIFFICULTY TO LEARN

	Summary Task Statement	Frequency	Difficulty	Importance	Criticality	Function
1	Respond to medical emergencies, following procedures and with equipment provided, during Cruise to Mars (CTM).	1.948	4.509	4.724	11.181	Medical
2	Conduct Extra-Vehicular Activity (EVA) to perform maintenance or retrieve items from outside the interplanetary space vehicle during Cruise to Mars.	2.246	4.491	4.596	11.333	EVA
3	Perform piloting functions during Mars Surface Descent.	2.589	4.375	4.821	11.786	Piloting
4	Respond to medical emergencies, following procedures and with equipment provided, during Cruise to Earth.	2.000	4.327	4.696	11.024	Medical
5	Perform piloting functions during Earth Descent.	2.545	4.268	4.750	11.563	Piloting
6	Respond to medical emergencies, following procedures and with equipment provided, during Mars Surface Operations (MSO).	2.069	4.263	4.825	11.157	Medical
7	Perform piloting functions during Mars Orbit Injection.	2.386	4.246	4.860	11.491	Piloting
8	Perform piloting functions during Mars Orbit operations	2.556	4.241	4.691	11.487	Piloting
9	Conduct EVA to perform maintenance or retrieve items from outside the interplanetary space vehicle during Cruise to Earth.	2.036	4.196	4.357	10.589	EVA
10	Monitor systems and perform piloting functions during Mars Surface Ascent.	2.912	4.158	4.807	11.877	Piloting
11	Perform piloting functions during Earth Approach.	2.518	4.107	4.786	11.411	Piloting
12	Perform medical diagnoses and evaluations, cognitively, during Cruise to Mars.	2.649	4.055	4.491	11.195	Medical
13	Respond to technical emergencies, following procedures and with equipment provided, during Cruise to Mars.	2.109	4.055	4.818	10.982	Technical
14	Perform medical diagnoses and evaluations, cognitively, during Mars Surface Operations.	2.690	4.053	4.517	11.260	Medical
15	Respond to technical emergencies, following procedures and with equipment provided, during Cruise to Mars.	2.140	4.053	4.930	11.123	Technical
16	Perform science-related EVA functions during Mars Surface Operations.	3.679	4.036	4.286	12.000	EVA
17	Enter control inputs, manually/visually with gloved hand, to pilot Earth Ascent Vehicle (EAV) during launch and cruise to LEO/CLO.	2.772	4.000	4.702	11.474	Piloting
18	Perform medical treatments during Mars Surface Operations.	2.328	3.965	4.586	10.879	Medical
19	Perform science-related EVA functions with heavy equipment during Mars Surface	2.877	3.964	3.946	10.788	EVA
20	Perform medical diagnoses and evaluations, cognitively, during Cruise to Earth	2.696	3.964	4.321	10.981	Medical
21	Respond to dental emergencies, following procedures and with equipment provided, during Cruise to Mars.	1.807	3.947	3.948	9.703	Medical
22	Conduct piloting functions during Cruise to Mars.	2.509	3.930	4.298	10.737	Piloting
23	Respond to dental emergencies during Mars Surface Operations.	2.018	3.929	4.052	9.998	Medical
24	Perform construction-related EVA functions with heavy equipment during MSO.	2.375	3.911	4.286	10.571	EVA
25	Perform post-Mars Descent maneuver functions.	2.333	3.907	4.556	10.796	Piloting
26	Monitor systems and perform piloting functions during Trans Earth Injection.	2.800	3.893	4.732	11.425	Piloting
27	Respond to dental emergencies, following procedures and with equipment provided, during Cruise to Earth.	1.875	3.891	3.964	9.730	Medical
28	Perform tests and examinations, physically, to support medical diagnoses during Cruise to Mars.	2.759	3.877	4.362	10.998	Medical
29	Adjust system controls, manually during buffetted descent, in response to displayed information.	2.673	3.870	4.585	11.128	Piloting
30	Perform medical treatments during Cruise to Earth.	2.273	3.870	4.436	10.579	Medical
31	Perform tests and examinations, physically, to support medical diagnoses during Mars Surface Operations.	2.741	3.860	4.483	11.084	Medical
32	Conduct piloting functions during Cruise to Earth.	2.407	3.852	4.500	10.759	Piloting

Key:	Medical	Piloting	EVA	Technical

The table shows the mean scores for the top 32 summary task statements (the top 20 percent) on the Difficulty to Learn scale and the mean values for Frequency, Importance, and Criticality for those summary task statements. The table includes a column labeled Function that lists the primary category of activity for each summary task statement. Four functional categories are represented in the top 20 percent of the 158 summary task statements when listed in order of Difficulty to Learn. The numbers of summary task statements in each of the four functional categories are shown below.

Functional Category	Number of Summary Task Statements
Medical	13
Piloting	12
EVA	5
Technical	2

The summary task statement rated most-difficult to learn by the SMEs, *Respond to medical emergencies, following procedures and with equipment provided, during Cruise to Mars*, is composed of 15 tasks, including:

Insert catheter in the bladder to drain urine for urine retention.

Insert staples, sutures, or Derma bond to repair skin laceration.

Perform surgery, manually using available instruments, to treat acute appendicitis.

Perform surgery, manually using available instruments, to repair a detached retina.

Perform surgery, manually using available instruments, to repair compound fracture of arm or leg bone.

Administer traction/counter-traction until shoulder slips back in place to relocate a dislocated shoulder.

Insert IV catheter and secure with medical tape to provide intravenous access for medications and fluids.

Insert catheter into pleural space between lung/chest wall, to permit air to escape to perform a needle decompression of a pneumothorax (collapsed lung).

Implement countermeasures (e.g., counseling, software) if symptoms of maladjustment or degraded behavioral health are detected among crew personnel.

The second most-difficult medical summary task statement, rated 4th on the list, comprises an identical set of tasks but during the *Cruise to Earth*. The third most-difficult medical summary task statement, rated 6th by the SMEs, *Respond to medical emergencies, following procedures and with equipment provided, during Mars Surface Operations*, includes most of the medical tasks that might be performed during the cruise phases of the expedition, with some key additions unique to surface operations:

Irrigate eye/perform eye exam to treat chemical exposure to a crewmember's eye.

Minimize eye and skin exposure to toxics to prepare for treating exposed crewmate.

Check for capillary refill/pulses below injury, apply splint, secure with ACE bandage to treat injured extremity.

Administer epinephrine, oxygen, IV antihistamines, cortisone, and beta-agonist, manually, to treat anaphylaxis.

Secure crewmember to flat surface, manually using restraints, to immobilize for treatment of spinal cord trauma.

Remove exposed crewmates soiled clothes, particles/liquid/irrigate with water (flush eye with water) for respiratory exposure/follow Difficulty breathing procedure.

Secure Airway, Breathing, Circulation and perform physiological monitoring (e.g., Vitals and Chem Labs), manually and cognitively, to manage acute radiation syndrome.

Apply physical force and binding/duct tape, manually with the help of another crew member, to restrain a crewmember experiencing a behavioral emergency.

Ten additional summary task statements with medical functions were rated by the SMEs between 12th and 31st in Difficulty to Learn. The tasks that compose those summary statements involve responding to dental emergencies and diagnosing and treating an ill or injured crew member during Mars Surface Operations and during the two cruise phases.

Twelve of the 32 most Difficult to Learn summary task statements involve Piloting and Navigating functions. The highest-rated Piloting summary task statement, *Perform piloting functions during Mars Surface Descent*, was rated 3rd in Difficulty and is composed of nine tasks, including:

Enter control inputs, manually wearing pressure suit/gloves, to configure Mars Excursion Vehicle (MEV)/Mars Descent Vehicle (MDV) computers for Mars Surface Descent maneuver.

Enter control inputs, manually wearing pressure suit/gloves, to detach MEV/MDV from spacecraft.

Enter control inputs, manually wearing pressure suit/gloves, to maneuver MEV/MDV away from spacecraft.

Enter control inputs, manually, to override automatic firing of retro rockets for Mars Surface Descent maneuver if automated system fails.

Adjust parachute, aeroshell, and retro rocket controls in response to system displays to manually override automatic systems, if necessary.

Adjust retro rocket controls, manually during buffeted descent, to maneuver MEV/MDV to correct location near pre-positioned Mars Surface Habitat.

Adjust controls, manually, to shut down retro rocket and other systems after touch down on planetary surface.

Enter control inputs, manually wearing pressure suit/gloves, to activate engine shut down if displays indicate failure of automated shut down after touch down.

Enter control inputs, manually wearing pressure suit/gloves, to activate landing system shut down if displays indicate failure of automated shut down after touch down.

The second most-difficult piloting summary task statement, *Perform piloting functions during Earth Descent*, is 5th on the list and comprises a nearly identical set of tasks as landing on Mars, with a few exceptions. The third and fourth most-difficult piloting summary task statements (7th and 8th on the list) are *Perform piloting functions during Mars Orbit Injection* and *Perform piloting functions during Mars Orbit Operations*, respectively. The fifth and sixth most-difficult piloting summary task statements (10th and 11th on the list) are *Monitor systems/perform piloting functions during Mars Surface Ascent* and *Perform piloting functions during Earth Approach*. Six additional summary task statements with piloting and navigation functions were rated by the SMEs between 17th and 32nd in Difficulty to Learn. The tasks that compose those summary statements, like those listed above, involve monitoring displays, responding to conditions, overriding automated systems when necessary, and adjusting controls during every dynamic phase of the expedition.

Five of the 32 most Difficult to Learn summary task statements involve EVA functions. The highest-rated and second-highest-rated EVA summary task statements, *Conduct Extra-Vehicular Activity (EVA) to perform maintenance or retrieve items from outside the interplanetary space vehicle during Cruise to Mars* and during *Cruise to Earth*, were rated 2nd and 9th in Difficulty to Learn, respectively, and are composed of only three tasks:

Don pressure suit in response to meteor penetration/ hull breech alarm, manually, with crew members helping.

Conduct EVA for maintenance or to retrieve needed supplies/equipment/expertise.

Remove and stow pressure suit following use.

The third most-difficult EVA summary task statement, *Perform science-related EVA functions during Mars Surface Operations (MSO)*, is rated 16th on the list and comprises 61 tasks, including:

Operate magnetometer, manually while wearing surface EVA suit, to record magnetic data.

Identify locations, visually in the field while wearing surface EVA suit, to deploy seismometers.

Collect geological samples, manually using rock pick/sample bags, while wearing surface EVA suit.

Climb crater wall while carrying hand tools and wearing surface EVA suit to conduct geological research.

Extract sedimentary core from drill/package core sample, manually wearing surface EVA suit, for later analysis.

Package geological samples, manually using aseptic equipment while wearing surface EVA suit, to prepare for safe return to Earth.

Dissect rock samples, manually while wearing surface EVA suit and using hand-held power cutting tool, to reveal smooth surface features/stratigraphy.

The fourth most-difficult EVA-related summary task statement, *Perform science-related EVA functions with heavy equipment during Mars Surface Operations* (20th in Difficulty to Learn) comprises seven science-related EVA tasks with heavy equipment, including:

Position drill-bit and operate powered well-drilling equipment to drill to sub-surface water level.
Add drill pipe section to stack, manually using hand tools while wearing surface EVA suit, to drill deeper.
Operate rotary/percussion drill to depth of 10m with assistance of crew member while wearing surface EVA suit.
Deploy ice core drilling tool, manually while wearing surface EVA suit, to obtain ice core sample for analysis.
Remove drill pipe section from stack, manually using hand tools while wearing surface EVA suit, to back drill/auger bit out of hole.

The fifth most-difficult EVA-related summary task statement, *Perform construction-related EVA functions with heavy equipment during Mars Surface Operations* (24th in Difficulty to Learn) comprises 12 construction-related EVA tasks with heavy equipment, including:

Operate excavation equipment, while wearing surface EVA suit, to dig and level 1m hole the diameter/dimensions of surface habitat.
Move/deploy surface habitat into excavated hole, using rover/ excavator while wearing surface EVA suit, to prepare habitat for occupancy.
Move regolith using excavator while wearing surface EVA suit to backfill around margins of the habitat base, to prepare habitat for occupancy.

Additional sets of EVA-related construction tasks describe preparing sites and deploying prepositioned sample-storage and green house modules. Backfilling and covering structures with Martian regolith are assumed to be necessary for radiation insulation.

Two of the 32 most Difficult to Learn summary task statements describe crew responses to technical emergencies during the Cruise to Earth and Cruise to Mars phases of the expedition (13th and 15th on list, respectively, but the mean values are essentially the same at 4.055 and 4.053). These summary task statements, *Respond to technical emergencies, following procedures and with equipment provided, during Cruise to Earth* and *during Cruise to Mars*, are composed of the same 15 tasks:

Respond to spacecraft fire alarm.
Respond to spacecraft CO2 alarm.
Respond to spacecraft navigation alarm.
Respond to spacecraft hull breech alarm.
Respond to spacecraft general ECLS failure alarm.
Respond to spacecraft micro-meteorite impact alarm.
Respond to spacecraft toxic substance/outgassing alarm.
Apply patch and adhesive material to meteor penetration site, manually, to close leak.
Remove fire extinguisher from bulkhead bracket and manually carry to source of fire.
Retrieve repair kit from storage and carry to location of meteor penetration or hull breech.
Retrieve and don protective fire-fighting ensemble, manually, to prepare for fire emergency.
Retreat to shielded area of spacecraft with other crew in response to critical radiation event warning.
Remain in shielded area of spacecraft with other members of the crew during critical radiation event.
Point fire extinguisher nozzle at burning material/activate system manually while wearing protective ensemble to suppress fire.
Identify location of meteor penetration/hull breech, visually/aurally, assess severity/determine method(s) to stop loss of pressure.

Implications of the most-Difficult to Learn tasks will be addressed in a subsequent section of this report.

FREQUENCY

The following table lists the top 32 summary task statements (i.e., top 20 percent) in descending order of the SMEs' estimates of the likely Frequency of task performance, again on a 5-point scale.

TOP 32 SUMMARY TASK STATEMENTS RANKED BY (LIKELY) FREQUENCY

	Summary Task Statement	Frequency	Difficulty	Importance	Criticality	Function
1	Interact/communicate with other crew members directly during Mars Surface Operations (MSO).	4.638	2.298	4.672	11.609	Comms
2	Exercise daily using onboard equipment during Cruise to Mars (CTM).	4.390	2.179	4.500	11.068	Exercise
3	Prepare/eat meal, manually, using interplanetary space vehicle food hydration/heating equipment/galley during Cruise to Earth (CTE).	4.345	1.963	4.291	10.599	Habitability
4	Prepare and consume meals in surface habitat during MSO.	4.293	1.982	4.466	10.741	Habitability
5	Exercise daily using onboard equipment during Cruise to Earth.	4.286	2.073	4.232	10.591	Exercise
6	Sleep for approximately 8 hours each 24-hour period during CTE.	4.250	1.545	4.321	10.117	Habitability
7	Prepare/eat meal, manually, using interplanetary space vehicle food hydration/heating equipment/galley during Cruise to Mars.	4.237	1.982	4.254	10.474	Habitability
8	Sleep for approximately 8 hours each 24-hour period during MSO.	4.203	1.483	4.397	10.083	Habitability
9	Use interplanetary space vehicle waste management systems for liquid/solid waste (i.e., toilet/bodily function) during Cruise to Earth.	4.185	2.113	4.093	10.391	Habitability
10	Use interplanetary space vehicle waste management systems for liquid/solid waste (i.e., toilet/bodily function) during Cruise to Mars.	4.172	2.375	4.172	10.720	Habitability
11	Sleep for approximately 8 hours each 24-hour period during CTM.	4.153	1.621	4.542	10.316	Habitability
12	Use surface habitat waste management systems for liquid/solid waste (i.e., toilet/bodily function) during Mars Surface Operations.	4.138	2.281	4.103	10.522	Habitability
13	Conduct communications checks/communicate observations/evaluations to crew/MCC, verbally using communications system during MSO.	4.123	2.500	4.368	10.991	Comms
14	Perform exercise in surface habitat to maintain cardiovascular, muscle, and bone conditioning during Mars Surface Operations.	4.017	2.035	4.322	10.374	Exercise
15	Conduct communications checks/communicate observations/evaluations to crew/MCC verbally using communications system during CTM.	3.982	2.429	4.107	10.518	Comms
16	Conduct communications checks/communicate observations/evaluations to crew/MCC, verbally using comms system, during Launch to Orbit.	3.965	2.158	4.421	10.544	Comms
17	Use surface habitat hygiene systems for cleaning during MSO.	3.948	2.105	3.793	9.847	Habitability
18	Use interplanetary space vehicle hygiene systems for cleaning during CTM.	3.947	2.161	3.719	9.827	Habitability
19	Use interplanetary space vehicle hygiene systems for cleaning during CTE.	3.926	2.000	3.759	9.685	Habitability
20	Perform monitoring functions in surface habitat or modules to ensure crew and system health during Mars Surface Operations.	3.897	3.000	4.386	11.283	Monitoring
21	Monitor systems to ensure proper functioning during Cruise to Mars.	3.897	2.983	4.328	11.207	Monitoring
22	Conduct communications checks/communicate observations/evaluations to crew and MCC personnel during Earth Surface Descent.	3.855	2.473	4.364	10.691	Comms
23	Conduct recreational activities, individually and as a crew, during CTM.	3.828	1.411	3.966	9.204	Habitability
24	Conduct science and planning functions during Cruise to Mars.	3.821	3.625	3.607	11.054	Planning
25	Conduct recreational activities, individually and as a crew, during CTE.	3.821	1.537	3.982	9.341	Habitability
26	Perform surface habitat houskeeping functions during MSO.	3.810	2.158	3.759	9.727	Habitability
27	Prepare/eat meals during Earth Approach.	3.786	1.907	3.945	9.639	Habitability
28	Monitor systems to ensure proper functioning during Cruise to Earth.	3.778	3.074	4.185	11.037	Monitoring
29	Conduct communications checks/communicate observations/evaluations to crew and MCC, verbally using communications system during CTE.	3.768	2.161	4.107	10.036	Comms
30	Perform planning and administrative functions, individually and with other crew members during Mars Surface Operations.	3.754	2.526	4.070	10.351	Planning
31	Conduct science and planning functions during Cruise to Earth.	3.722	3.278	3.593	10.593	Planning
32	Perform science-related EVA functions during Mars Surface Operations.	3.679	4.036	4.286	12.000	EVA

Key:	Habitability	Comms	Exercise	Planning	EVA

The table shows the mean scores for the top 32 summary task statements (top 20 percent) on the Frequency scale and the mean values for Difficulty to Learn, Importance, and Criticality for those summary task statements. As before, this table includes a column labeled Function that lists the primary category of activity for each summary task statement. Six functional categories are represented in the top 20 percent of the 158 summary task statements when listed in order of (likely) Frequency. The numbers of summary task statements in each of the six functional categories are shown below.

Functional Category	**Number of Summary Task Statements**
Habitability	16
Communicating (Comms)	6
Exercise	3
Planning	3
Monitoring	3
EVA	1

The summary task statement rated by the SMEs as likely to be the most-frequently performed during the expedition, *Interact/communicate with other crew members directly during Mars Surface Operations*, is composed of five tasks:

Interact with crew mates, personally, concerning task performance.

Interact with crew mates, personally, concerning non-task-related matters.

Speak with other members of the crew in the surface habitat concerning technical and task-related topics.

Speak with other members of the crew in the surface habitat concerning non-technical/non-task-related topics.

Meet with other members of the crew in the Mars habitat to review research results and plan research activities.

The next communications-related summary task statement in the table, *Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system during Mars Surface Operations*, was estimated by the SMEs to be the 13th most-frequently performed of the 158 summary task statements and is composed of nine tasks:

Prepare group communications, using audio/video equipment, to transmit to MCC.

Operate surface rover communications system to transmit/receive information to/from habitat personnel.

Operate Mars habitat email communications system, manually, to transmit/receive messages to/from MCC.

Operate Mars habitat data link communications system, manually, to transmit/receive messages to/from MCC.

Operate Mars habitat audio/video communications system, manually, to transmit/receive messages to/from MCC.

Transfer digital copies of information from MCC to portable digital device, manually, for later reference.

Print paper copies of information received from MCC, manually using printer, for later reference, if necessary.

Communicate with surface EVA crew members from surface habitat, verbally using radios, to advise and coordinate operations.

Perform interviews and other Public Affairs Office (PAO) events, using communications system, to inform Earth public of progress.

Similar sets of communications tasks (*Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel*) were rated 15th (during Cruise to Mars), 16th (during Launch to Orbit), 22nd (during Earth Surface Descent), and 29th (during Cruise to Earth). Tasks comprised by these summary task statements that are not included in the two most frequent summary statements, and listed above, are:

Operate spacecraft communications system, manually, to transmit message to MCC.

Operate spacecraft communications system, manually, to receive transmission from MCC.

Receive final thrust and duration information from MCC to prepare for Earth Surface Descent.

Communicate status of systems to MCC, verbally, immediately prior to Earth Surface Descent.

Transmit data collected during the Transit of Earth to ground stations immediately following event.

Communicate systems shut down/safing to crew via internal communication system to advise of status.

Communicate systems shut down/safing to MCC via external communication systems to advise of status.

Conduct communications checks with other crew, wearing pressure suit, to prepare for launch to Orbit.

Communicate observations/evaluations to crew/ MCC personnel, verbally using communications system.

Communicate system status, verbally to crew using communications equipment, during Earth Surface Descent.

Communicate system status, verbally in heavy buffeting, to MCC using communications equipment, during Earth Surface Descent.

Communicate successful touch down, verbally/via text, to MCC using external communications equipment to confirm status.

Compose/record electronic/video journal, using keyboard/computer in spacecraft, to create/preserve personal account of experiences.

Conduct physical/cognitive tests in spacecraft to assess fitness for duty (automatically-scheduled/results transmitted to Earth).

The summary task statement, *Exercise daily using onboard equipment during Cruise to Mars*, was estimated by the SMEs to be the 2nd most-frequently performed of the 158 summary task statements. The same statement but during *Cruise to Earth* was estimated to be the 5th most-frequently performed; and, the same statement during *Mars Surface Operations* was estimated to be the 14th most-frequently performed. The three exercise-related summary statements are composed of the same three tasks:

Configure resistive device/perform exercise to maintain cardiovascular conditioning, muscle strength, and bone density.

Mount bicycle ergometer/perform exercise to maintain cardiovascular conditioning, muscle strength, and bone density.

Don harnesses/perform exercise using treadmill to maintain cardiovascular conditioning, muscle strength, and bone density.

Sixteen of the 32 most-frequently performed summary task statements describe habitability functions, the most-frequent of which is, *Prepare/eat meal, manually, using interplanetary space vehicle food hydration/heating equipment/galley during Cruise to Earth*. The summary statement was estimated by the SMEs to be 3rd on the list. The same function (preparing and eating meals) was rated 4th (*during Mars Surface Operations*), 7th (*during Cruise to Mars*), and 27th (*during Earth Approach*). The four food-related summary statements are composed of the same four tasks:

Transfer food packages from deep storage to proximal storage, manually, to prepare galley for crew use.

Activate food hydration/heating equipment, manually, to prepare galley for crew use.

Prepare meal for crew consumption, manually, using spacecraft food hydration/heating equipment.

Eat meal together with other members of the crew in the spacecraft/habitat ward room/galley.

The summary task statement, *Sleep for approximately 8 hours each 24-hour period*, was estimated by the SMEs to be 6th in frequency (*during Cruise to Earth*), 8th (*during Mars Surface Operations*), and 11th (*during Cruise to Mars*). The three sleep-related summary statements are composed of the same two tasks:

Retrieve sleeping bag from storage and attach bag to davits in sleep chamber to prepare for sleep period.

Enter secured sleeping bag and begin sleep period to restore cognitive/physical functioning.

The next most-frequent habitability function, *Use waste management systems for liquid/solid waste (i.e., toilet/bodily function)*, was estimated by the SMEs to be 9th in frequency (*during Cruise to Earth*), 10th (*during Cruise to Mars*), and 12th (*during Mars Surface Operations*). The three toilet-related summary statements are composed of the same two tasks:

Use spacecraft waste management system for liquid waste (i.e., toilet/bodily function).

Use spacecraft waste management system for solid waste (i.e., toilet/bodily function).

The next most-frequent habitability function, *Use hygiene systems for cleaning*, was estimated by the SMEs to be 17th in frequency (*during Mars Surface Operations*), 18th (*during Cruise to Mars*), and 19th (*during Cruise to Earth*). The three hygiene-related summary statements are composed of the same nine tasks:

Brush teeth, manually, to maintain oral hygiene.
Remove soiled garments and don clean clothing.
Insert soiled garments in collection container to dispose.
Operate hygiene system to clean/disinfect hands and body.
Retrieve wet wipes/towel/clothing to clean body after exercise.
Shave, manually using electric razor, to remove beard/hair growth.
Shave, manually using safety razor/soap/water, to remove beard/hair growth.
Cut crewmate's hair, manually using electric razor/scissors, to remove excess growth.
Remove personal garments from surface habitat storage in preparation for changing clothes.

The two remaining habitability-related summary task statements in the top 20 percent, *Conduct recreational activities, individually and as a crew, during Cruise to Mars* and *during Cruise to Earth* were estimated by the SMEs to be 23rd and 25th, respectively, in likely frequency of performance. The two summary statements are composed of the same eight tasks:

Listen to music individually while exercising for recreation.
Listen to music individually during leisure periods for recreation.
Read articles, books, etc., during leisure periods for recreation.
Play chess/board games with other crew members during leisure periods for recreation.
Play chess with MCC personnel and others on Earth during leisure periods for recreation.
Watch video (movies, TV programs, documentaries, etc.) with crew members for recreation.
Watch video (movies, TV programs, documentaries, etc.) individually while exercising for recreation.
Watch video (movies, TV programs, documentaries, etc.) individually during leisure periods for recreation.

Three of the 32 most-frequent summary task statements involve science and planning activities. The statement, *Conduct science and planning functions during Cruise to Mars*, was rated 24th in likely frequency by the SMEs and is composed of 12 tasks:

Conduct life science experiments to occupy cruise time with meaningful activity.
Conduct and record Mars observations using onboard equipment and telescopes.
Conduct and record solar observations using onboard equipment and telescopes.
Conduct and record Earth observations using onboard equipment and telescopes.
Assemble equipment needed to observe/record the Transit of Earth on day 73 after TMI.
Activate equipment, observe/record the eight-hour Transit of Earth on day 73 after TMI.
Conduct and record asteroid/comet observations using onboard equipment and telescopes.
Conduct and record radio astronomy observations using onboard equipment and telescopes.
Conduct and record planetary and stellar observations using onboard equipment and telescopes.
Review geology program objectives/procedures, using onboard resources, to prepare for surface operations.
Review biology program objectives/procedures, using onboard resources, to prepare for surface operations.
Conduct astronomical observations, photography, remote sensing to occupy cruise time with meaningful activity.

A similar set of ten tasks was estimated by the SMEs to be 32nd of the 158 summary task statements in likely frequency, *Conduct science and planning functions during Cruise to Earth*. The science tasks to be performed during the return cruise phase are approximately the same as those to be performed during the cruise to Mars, but the focus of the planning tasks would shift to reviewing objectives, procedures, and data during the return transit to prepare for reporting scientific results.

The third planning-related summary task statement, *Perform planning and administrative functions, individually and with other crew members during Mars Surface Operations,* was estimated by the SMEs to be 30th in likely frequency and is composed of 12 tasks, many of which would be the responsibility of the expedition leader:

Coordinate crew response to meteor penetration, hull breech, fire, ECLS failure, or other emergency.

Review maps/charts/procedures, manually/visually, in Mars habitat to plan construction/installation tasks.

Review maps/charts/procedures, manually/visually, in Mars habitat to plan route for surface sortie/traverse and geological research.

Investigate surroundings visually with help of photographs and surface reconnaissance, to identify permanent location for surface habitat.

Investigate surroundings visually with help of photographs/surface reconnaissance, to identify permanent location for greenhouse, laboratory, and sample storage modules.

Schedule tasks and monitor performance of work to ensure that opportunities and resources are allocated appropriately among crew personnel.

Coordinate surface habitat exercise device availability among crew to ensure access to maintain cardiovascular conditioning, muscle strength, and bone density.

Coordinate surface habitat simulator availability among crew to ensure refresher training for all required skills and functions.

Plan operations/timelines/work assignments (e.g., surface EVA, maintenance of external components) using computer-based tools in consultation with MCC and onboard personnel.

Modify operations plans/timelines/work assignments in response to events using computer-based tools in consultation with MCC and onboard personnel.

Provide feedback about operations plans/timelines/work assignments to expedition leader, personally or in writing, to express concerns/opinions.

Receive feedback about operations plans/timelines/work assignments from crew member, personally or in writing, to improve operations.

Three of the 32 most-frequent summary task statements involve the monitoring of systems. The statement, *Perform monitoring functions in surface habitat or modules to ensure crew and system health during Mars Surface Operations,* was rated 20th in likely frequency by the SMEs and is composed of 12 tasks:

Monitor system displays, visually, to verify normal functioning of telemetry system.

Monitor system displays, visually, to verify normal functioning of power-generation system.

Monitor system displays, visually, to verify normal functioning of surface habitat life support system.

Monitor system displays, visually, to verify normal functioning of surface habitat communication system.

Monitor display, visually from inside the surface habitat, to verify functioning of weather monitoring station.

Monitor habitat atmosphere, visually/manually, by checking displays/comparing values to reference documents.

Monitor radiation-detection systems, visually/aurally, for evidence of Solar Proton and Galactic Cosmic Ray Events.

Monitor display, visually from inside surface habitat, to verify proper functioning of the Radiation Assessment Detector.

Monitor remote-sensing systems, visually from inside the surface habitat, to learn of impending surface weather event (i.e., dust storms).

Monitor atmospheric sampling equipment, remotely from surface habitat, to ensure data are recorded for later analysis and transmission to MCC.

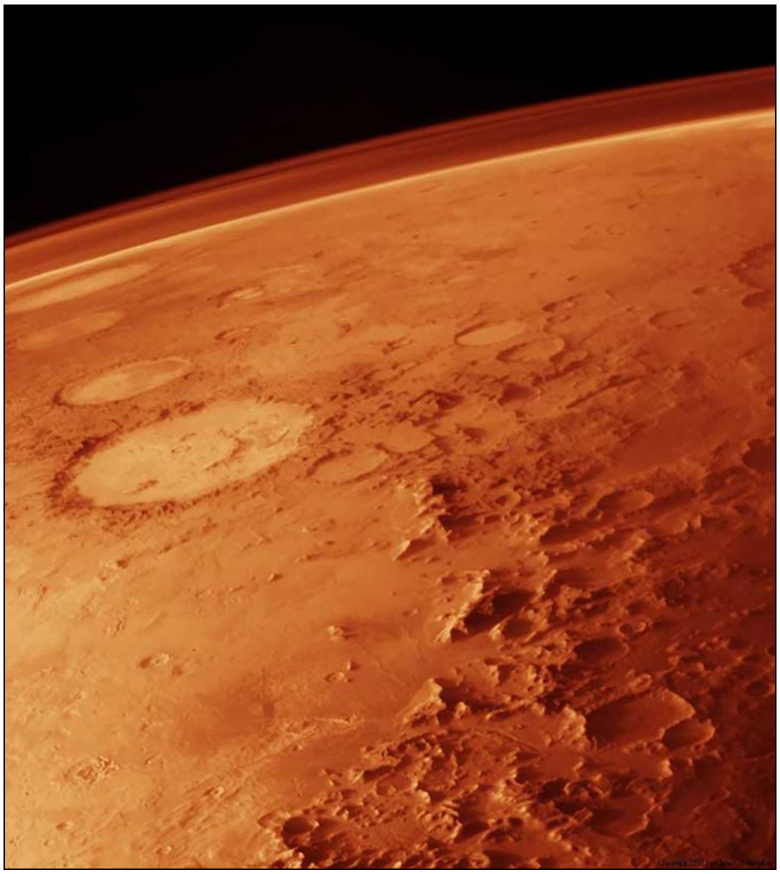
Monitor balloon sensors/transponders, remotely from surface habitat, to ensure data are recorded for later review and transmission to MCC.

Inspect footing/base and structural components of the surface habitat/greenhouse/module, visually, from inside the habitat to ensure integrity.

The two, remaining monitoring-related summary task statements, *Monitor systems to ensure proper functioning during Cruise to Mars* and *during Cruise to Earth* were estimated by the SMEs to be 21st and 28th, respectively, in likely frequency of performance. The two summary statements are composed of the same six tasks:

Monitor system displays, visually, to verify normal functioning of navigation system.
Monitor system displays, visually, to verify normal functioning of life support system.
Monitor system displays, visually, to verify normal functioning of communication system.
Monitor system displays, visually, to verify normal functioning of propulsion/attitude control system.
Monitor spacecraft atmosphere, visually/manually, by checking displays/comparing values to references.
Monitor radiation-detection systems, visually/aurally, for evidence of Solar Proton/Galactic Cosmic Ray Events.

The one EVA-related summary task statement among the top 20 percent in likely frequency, *Perform science-related EVA functions during Mars Surface Operations (MSO),* was estimated by the SMEs to be 32nd on the list and is composed of 61 tasks. This summary statement, rated 16th in Difficulty to Learn and 1st in (overall) Criticality, was described previously and will be discussed again in the section devoted to the combined measure, Criticality. Implications of the most-Frequent tasks will be addressed in the final major section of this report.



Galle Crater (the Happy Face Crater), explored by NASA's *Curiosity* rover beginning in August 2012.
Image captured by Viking 1 in 1975.

IMPORTANCE

The following table lists the top 32 summary task statements (i.e., top 20 percent) in descending order of the SMEs' estimates of the Importance of (correct) task performance, again on a 5-point scale.

TOP 32 SUMMARY TASK STATEMENTS RANKED BY IMPORTANCE

	Summary Task Statement	Frequency	Difficulty	Importance	Criticality	Function
1	Respond to technical emergencies, following procedures and with equipment provided, during Cruise to Mars.	2.140	4.053	4.930	11.123	Technical
2	Perform piloting functions during Mars Orbit Injection.	2.386	4.246	4.860	11.491	Piloting
3	Perform emergency functions in surface habitat or modules during MSO.	2.052	3.810	4.845	10.707	Technical
4	Respond to medical emergencies, following procedures/with equipment provided, during Mars Surface Operations.	2.069	4.263	4.825	11.157	Medical
5	Perform piloting functions during Mars Surface Descent.	2.589	4.375	4.821	11.786	Piloting
6	Respond to technical emergencies, following procedures and with equipment provided, during Cruise to Earth.	2.109	4.055	4.818	10.982	Technical
7	Monitor systems/perform piloting functions during Mars Surface Ascent.	2.912	4.158	4.807	11.877	Piloting
8	Perform piloting functions during Earth Approach.	2.518	4.107	4.786	11.411	Piloting
9	Perform piloting functions during Earth Descent.	2.545	4.268	4.750	11.563	Piloting
10	Prepare for Mars Surface Ascent during Mars Surface Operations.	2.069	3.586	4.741	10.397	Technical
11	Perform initial installation/activation/inspection of surface habitat systems during Mars Surface Operations.	2.386	3.649	4.737	10.772	Technical
12	Monitor systems/perform piloting functions during Trans Earth Injection.	2.800	3.893	4.732	11.425	Piloting
13	Respond to medical emergencies during Cruise to Mars.	1.948	4.509	4.724	11.181	Medical
14	Configure systems for Mars Orbit operations and descent.	2.321	3.625	4.709	10.656	Technical
15	Enter control inputs, manually/visually with gloved hand, to pilot Earth Ascent Vehicle (EAV) during launch and cruise to LEO/CLO.	2.772	4.000	4.702	11.474	Piloting
16	Respond to medical emergencies, following procedures and with equipment provided, during Cruise to Earth.	2.000	4.327	4.696	11.024	Medical
17	Perform piloting functions during Mars Orbit operations	2.556	4.241	4.691	11.487	Piloting
18	Prepare for Mars Surface Ascent maneuver.	2.263	3.737	4.684	10.684	Technical
19	Interact/communicate with other crew members directly during MSO.	4.638	2.298	4.672	11.609	Comms
20	Assess displayed and aural information, cognitively, to determine appropriate course of action during Cruise to Mars.	3.018	3.298	4.649	10.965	Technical
21	Assess displayed information, cognitively, to determine readiness for TMI	3.018	3.571	4.643	11.232	Technical
22	Enter control inputs, manually/visually with gloved hand, to configure and operate Earth Ascent Vehicle (EAV) before and after launch.	2.821	3.614	4.625	11.060	Piloting
23	Prepare for Earth Surface Descent.	2.370	3.200	4.600	10.170	Technical
24	Conduct Extra-Vehicular Activity (EVA) to perform maintenance or retrieve items from outside the interplanetary space vehicle during Cruise to Mars.	2.246	4.491	4.596	11.333	EVA
25	Perform medical treatments during Mars Surface Operations.	2.328	3.965	4.586	10.879	Medical
26	Adjust system controls, manually during buffetted descent, in response to displayed information.	2.673	3.870	4.585	11.128	Piloting
27	Assess displayed information, cognitively, to determine readiness to launch to LEO/CLO.	3.123	3.632	4.579	11.333	Technical
28	Prepare for Mars Surface Descent maneuver.	2.236	3.527	4.564	10.327	Technical
29	Perform post-Mars Descent maneuver functions.	2.333	3.907	4.556	10.796	Piloting
30	Sleep for approximately 8 hours each 24-hour period during CTM.	4.153	1.621	4.542	10.316	Habitability
31	Perform post-Mars Ascent maneuver functions.	2.286	3.772	4.526	10.584	Piloting
32	Perform medical treatments during Cruise to Mars.	2.158	3.786	4.526	10.470	Medical

Key:	Technical	Piloting	Medical	Comms	EVA	Habitability

The table shows the mean scores for the top 32 summary task statements (top 20 percent) on the Importance scale and the mean values for Frequency, Difficulty to Learn, and Criticality for those summary task statements. As before, this table includes a column labeled Function that lists the primary category of activity for each summary task statement. Six functional categories are represented in the top 20 percent of the 158 summary task statements when listed in order of Importance. The numbers of summary task statements in each of the functional categories are shown below.

Functional Category	**Number of Summary Task Statements**
Technical	12
Piloting	12
Medical	5
Communicating (Comms)	1
EVA	1
Habitability	1

Twelve of the most important summary task statements are categorized as technical functions and involve emergency responses, installation and preparation activities, or assessing conditions to determine readiness to proceed. *Respond to technical emergencies, following procedures and with equipment provided, during Cruise to Mars,* was rated by the SMEs to be the most-important of the 158 summary statements; and, responding to technical emergencies *during Cruise to Earth* was rated 6th on the Importance scale. Both summary statements are composed of the same 15 tasks:

Respond to spacecraft fire alarm.
Respond to spacecraft CO2 alarm.
Respond to spacecraft hull breech alarm.
Respond to spacecraft navigation alarm.
Respond to spacecraft general ECLS failure alarm.
Respond to spacecraft micro-meteorite impact alarm.
Respond to spacecraft toxic substance/outgassing alarm.
Remove fire extinguisher from bulkhead bracket and manually carry to source of fire.
Apply patch and adhesive material to meteor penetration site, manually, to close leak.
Retrieve repair kit from storage and carry to location of meteor penetration or hull breech.
Retrieve and don protective fire-fighting ensemble, manually, to prepare for fire emergency.
Retreat to shielded area of spacecraft with crew in response to critical radiation event warning.
Remain in shielded area of spacecraft with other members of the crew during critical radiation event.
Point fire extinguisher nozzle at burning material and activate system manually while wearing protective ensemble to suppress fire.
Identify precise location of meteor penetration/hull breech, visually/aurally, assess severity, and determine method(s) to stop loss of pressure.

One additional emergency-related summary task statement, *Perform emergency functions in surface habitat or modules during Mars Surface Operations*, was rated as the 3rd most-important set of tasks. The tasks are similar to those listed, above, but are limited to responding to module punctures, fires in the habitat or other modules, and radiation events during the crew's 18 months on the surface of Mars.

Six of the most-important technical summary task statements involve work by the crew to prepare for a dynamic maneuver or to install systems or components. For example, the summary task statement, *Prepare for Mars Surface Ascent during Mars Surface Operations*, was rated by the SMEs to be the 10th most-important of the 158 summary statements; it is composed of only three individual tasks:

Connect flexible hose to fittings on the fuel production storage tanks and Mars Excursion Vehicle (MEV)/Mars Ascent Vehicle (MAV), manually while wearing surface EVA suit, to prepare for refueling.

Activate pumps on fuel production system, manually via keyboard input from habitat, to transfer fuel from storage tanks to Mars Excursion Vehicle (MEV)/Mars Ascent Vehicle (MAV).

Enter Mars Excursion Vehicle (MEV)/Mars Ascent Vehicle (MAV), physically while wearing pressure suit, to prepare for launch (Mars Surface Ascent).

The technical summary task statement, *Perform initial installation/activation/inspection of surface habitat systems during Mars Surface Operations*, was rated by the SMEs to be the 11th most-important set of activities and is composed of 11 tasks that must be performed by the crew immediately after entering their surface habitat, which will have been delivered to Mars approximately two years prior to the crew's arrival:

Activate hygiene system in surface habitat to enable hand and body washing.

Activate food heating equipment, manually, to prepare surface habitat galley for crew use.

Deploy surface habitat restraints, interior consoles, and equipment, manually, to prepare for crew use.

Deploy supports/structures, manually, to configure dedicated area of surface habitat for medical procedure.

Activate, program, and adjust surface habitat audio/video capability to enable entertainment during exercise.

Configure habitat system, manually, to enable display of robot remote video on large screen for crew viewing.

Transfer food packages from deep storage to proximal storage in surface habitat, manually, to prepare galley for crew use.

Unstow, deploy, and activate waste management system in surface habitat per procedures, manually, to prepare for use by crew.

Unstow, deploy, and activate surface habitat exercise system per procedures, manually with assistance, to prepare for use by crew.

Activate surface habitat life support system, manually by control inputs/display verification, to switch from temporary onboard system.

Retrieve cosmic radiation dosimeters from storage, manually, and deploy in designated locations in surface habitat to measure cosmic radiation.

The next preparation/installation summary task statement on the most-important list, *Configure systems for Mars Orbit operations and descent*, was rated 14th by the SMEs and is composed of four tasks that must be performed by the crew to prepare the interplanetary ship for 18 months of untended operation in Mars orbit and to transfer to the descent vehicle for their ride to the surface, which is among the most dangerous and technical phases of the mission:

Configure spacecraft computers in preparation for Mars Orbit operations.

Detach from individual crew position, while wearing pressure suit, in preparation for Mars Orbit operations.

Doff pressure suit, manually with the help of one other crew member, in preparation for Mars Orbit operations.

Transfer to Mars Excursion Vehicle (MEM)/Mars Descent Vehicle (MDV), physically while wearing pressure suit, to prepare for descent maneuver.

The fourth most-important preparation/installation summary task statement, *Prepare for Mars Surface Ascent maneuver*, was rated 18th on the Importance scale by the SMEs and is composed of five tasks that must be performed by the crew to enable their launch from the surface of Mars:

Inspect Mars Excursion Vehicle (MEV)/Mars Ascent Vehicle (MAV) to verify that systems are go for ascent.

Don pressure suit, manually with the help of one other crew member, in preparation for Mars Surface Ascent.

Attach to individual crew maneuver position, while wearing pressure suit, in preparation for Mars Surface Ascent.

Enter control inputs, manually, to convert Mars Excursion Vehicle (MEV)/Mars Ascent Vehicle (MAV) from surface mode to ascent mode.

Stow and secure all equipment, manually per load plan, to prepare Mars Excursion Vehicle (MEM)/Mars Ascent Vehicle (MAV) for Mars Surface Ascent maneuver.

The remaining two preparation/installation-related summary task statements on the list, *Prepare for Earth Surface Descent* and *Prepare for Mars Surface Descent maneuver*, were rated by the SMEs as 23rd and 28th in Importance, respectively, and are composed of the same tasks as the previously-described summary statement, with one additional task:

Assess crew members' physical and cognitive abilities, verbally using self-reports and established diagnostics, to determine capacities for descent maneuver.

Three of the most-important technical summary task statements involve the crew assessing the status of systems to determine readiness to proceed. The statement, *Assess displayed and aural information, cognitively, to determine appropriate course of action during Cruise to Mars*, was rated 20th in Importance by the SMEs and is composed of two tasks:

Identify Emergency Alarm (Loss of pressure, Fire, Toxic substance/emission) and develop repair/recovery plan.
Identify Caution/Warning Alarm (e.g., CO2, ECLS, Navigation) and develop repair/recovery plan.

The statement, *Assess displayed information, cognitively, to determine readiness for TMI maneuver*, was rated 21st in Importance by the SMEs and is composed of a single task:

Evaluate alarms and displays, cognitively, to identify any mission-critical anomalies.

And, the statement, *Assess displayed information, cognitively, to determine readiness to launch to LEO/CLO*, is composed of two tasks:

Evaluate displayed/communicated information, cognitively, to assess readiness for orbit operations.
Evaluate alarms/displays, cognitively, to identify mission-critical anomalies during buffeted launch from Earth.

Mission planners assume that piloting functions will be automated and performed manually by a crew member only as a contingency. Twelve of the most important summary task statements are such piloting functions, which would require vigilance, prompt responses to changing conditions, and precise manipulation of controls during dynamic phases of the expedition. *Perform piloting functions during Mars Orbit Insertion,* was rated by the SMEs to be the 2nd most-important and the 7th most difficult of the 158 summary statements; the summary statement comprises three piloting tasks:

Adjust controls (retro rockets, attitude thrusters), manually, to achieve MOI.
Configure spacecraft computers in preparation for aerobraking maneuver to achieve MOI.
Override automatic firing of retro rockets for aerobraking maneuver to achieve MOI if automated system fails.

The summary task statement, *Perform piloting functions during Mars Surface Descent*, was rated 5th most-important and 3rd most-difficult to learn by the SMEs; the nine component tasks of the summary statement were listed previously. Similarly, the summary statement, *Monitor systems and perform piloting functions during Mars Surface Ascent*, was rated 7th in Importance and 10th in Difficulty to Learn; and, *Perform piloting functions during Earth Approach*, was rated 8th on the Importance scale and 11th in Difficulty; the eight component piloting tasks during Earth Approach are:

Enter control inputs to configure EDV computers in preparation for Earth Approach and Descent.
Adjust attitude control thrusters, manually with gloved hand, to change course during Earth Approach.
Adjust thruster controls, manually with gloved hand, to shut down EDV thrusters during Earth Approach.
Enter control inputs, manually with gloved hand, to activate thruster shut down if automated shut down fails.
Adjust thruster controls, manually with gloved hand, to undock EDV/maneuver away from interplanetary ship.
Enter control inputs, manually/gloved hand, to override automatic firing of thrusters if automated system fails.
Adjust attitude control thrusters, manually with gloved hand, to maneuver EDV to achieve correct skip trajectory.
Adjust controls, manually with gloved hand, to shut down attitude control thrusters and other systems to prepare for Earth Surface Descent.

The summary task statement, *Perform piloting functions during Earth Descent*, was rated by the SMEs to be the 9th most-important and the 5th most-difficult of the 158 summary statements; the 11 component piloting tasks were described previously in the discussion of Difficulty to Learn.

The summary statement, *Monitor systems and perform piloting functions during Trans Earth Injection*, was rated as the 12th most-important set of tasks and the 26th most-difficult to learn. The summary statement comprises four piloting tasks that determine the trajectory for the Cruise to Earth:

Enter control inputs to configure spacecraft computers in preparation for thrust maneuver to achieve Trans-Earth Injection.

Enter control inputs to override automatic firing of main engine for thrust maneuver to achieve Trans-Earth Injection, if necessary.

Monitor automatic firing of main engine, visually, for thrust maneuver to achieve Trans-Earth Injection.

Monitor displays and communicate status of systems during thrust maneuver in heavy buffeting to achieve Trans-Earth Injection.

The 15th most-important summary statement, *Enter control inputs, manually/visually with gloved hand, to pilot Earth Ascent Vehicle (EAV) during launch and cruise to LEO/CLO*, was rated by the SMEs to be the 17th most difficult to learn and is composed of ten piloting tasks:

Adjust controls as necessary, manually wearing pressure suit/gloves, during buffeted launch from Earth.

Activate controls, manually wearing pressure suit/gloves, to abort launch in response to evaluation data during buffeted ascent.

Activate controls, manually wearing pressure suit/gloves, to override automated systems/control spacecraft in response to evaluation data during buffeted ascent.

Adjust main engine controls, manually wearing pressure suit/gloves, to maneuver Earth Ascent Vehicle (EAV) to correct location near spacecraft in LEO/CLO.

Adjust main engine controls, manually wearing pressure suit/gloves, to shut down Earth Ascent Vehicle (EAV) main engine en route to spacecraft in LEO/CLO.

Adjust attitude control thrusters, manually wearing pressure suit/gloves, to maneuver Earth Ascent Vehicle (EAV) to spacecraft in LEO/CLO.

Adjust attitude control thrusters, manually wearing pressure suit/gloves, to dock Earth Ascent Vehicle (EAV) to spacecraft in LEO/CLO.

Adjust controls, manually wearing pressure suit/gloves, to shut down attitude control thrusters and other systems after docking with spacecraft in LEO/CLO.

Enter control inputs, manually wearing pressure suit/gloves, to activate engine shut down if displays indicate failure of automated shut down, to ensure safing of Earth Ascent Vehicle after docking.

Activate appropriate controls in response to alarms, manually, while communicating actions to crew and MCC during buffeted launch from Earth.

The next most-important piloting task, *Perform piloting functions during Mars Orbit operations*, was rated 17th on the Importance scale and 8th in Difficulty to Learn. The summary statement comprises two piloting tasks:

Adjust attitude and propulsion controls, manually, in response to navigation/attitude control data, to achieve/maintain proper Mars Orbit.

Adjust attitude and propulsion controls, manually, in response to navigation/attitude control data, to dock with pre-positioned Mars Descent Vehicle.

The summary statement, *Enter control inputs, manually/visually with gloved hand, to configure and operate Earth Ascent Vehicle (EAV) before and after launch*, was rated 22nd in importance by the SMEs and is composed of 11 piloting tasks performed prior to and during launch from Earth to deliver the crew to the interplanetary ship in either Cis-Lunar or Earth-orbit.

Enter control inputs, manually, to align IMU if necessary.

Enter control inputs, manually, to activate ATP/star tracker for cruise to LEO/CLO.

Inspect display, visually wearing suit/helmet, to verify all pyros are armed for ascent.

Enter control inputs, manually/visually with gloved hand, to configure launch displays.

Activate controls, manually while wearing pressure suit/gloves, to configure cabin lighting.

Activate cabin pressure control, manually after visor opening, to prepare for cruise to orbit.

Respond to communications and displays, wearing pressure suit, to prepare for launch from Earth.

Enter control inputs, manually to override automated system, to reconfigure CM/SM heaters if necessary.

Perform controls/switch checklist, visually/manually while wearing pressure suit/gloves, to verify configuration.

Activate controls, manually, to override automated process/initiate/control solar array deployment, if necessary.

Perform ASP/flight crew check, manually while wearing pressure suit/gloves, to ensure hard switches are still in expected configuration after strap in.

The next most-important summary statement, *Adjust system controls, manually during buffeted descent, in response to displayed information*, was rated 26th by the SMEs and is composed of three tasks:

Enter control inputs, manually with gloved hand, to adjust Earth Descent Vehicle (EDV) temperature.

Enter control inputs, manually with gloved hand, to adjust Earth Descent Vehicle (EDV) lighting.

Enter control inputs, manually with gloved hand, to adjust Earth Descent Vehicle (EDV) ECLS.

The summary statement, *Perform post-Mars Descent maneuver functions,* was rated 29th of the 158 summary task statements in Importance and is composed of three tasks:

Enter control inputs, manually wearing pressure suit/gloves, to secure systems after engine shut down.

Enter control inputs, manually, to convert Mars Excursion Vehicle from descent mode to surface mode.

Assess crew members' physical and cognitive abilities, verbally using self-reports and established diagnostics, to determine capacities for immediate work (i.e.., egress).

The last piloting summary task statement in the top 20 percent in Importance, *Perform post-Mars Ascent maneuver functions,* was rated 31st by the SMEs and is composed of three tasks:

Verify automated engine shut down by visually monitoring displays to ensure safing of MAV after docking.

Verify automated docking system by visually monitoring displays to ensure safing of MAV after docking.

Enter control inputs, manually wearing pressure suit/gloves, to secure (other) flight systems after engine shut down to ensure safing of MAV after docking.

Four of the five medical summary task statements that were rated by the SMEs as among the most-important were described previously in the discussion of Difficulty to Learn. The 18 component medical tasks that compose the summary statement, *Respond to medical emergencies, following procedures and with equipment provided, during Mars Surface Operations*, were rated 4th most-important and 6th most-difficult to learn. The 15 tasks that compose the summary statement, *Respond to medical emergencies, following procedures and with equipment provided, during Cruise to Mars*, were rated 13th in Importance and 1st in Difficulty. The same 15 medical emergency tasks performed *during Cruise to Earth* were rated by the SMEs as 16th in Importance and 4th in Difficulty to Learn.

Performing medical treatments was considered by the SMEs to be less important and less difficult to learn than responding to medical emergencies. For example, the summary statement *Perform medical treatments during Mars Surface Operations,* was rated 25th in Importance and 18th in Difficulty; the same 22 component tasks were rated 32nd in Importance *during Cruise to Mars*. Examples are listed below:

Remove sutures with medical scissors to complete repair.

Remove staples using a skin staple remover to complete repair.

Insert catheter in the bladder to drain urine (self-catheterize) for urine retention.

Apply splint, manually, to treat unresolved wrist, elbow, ankle, or knee sprain/strain.

Insert nasal packing and drops, manually per instructions, to stop persistent nose bleeding.

Apply ice (multiple)/administer pain medication as needed, to treat back/shoulder/neck sprain/strain.

Insert staples, sutures, or Derma bond depending on type and location of cut to repair skin laceration.

Drain sinus passageway (with nasal spray) and administer antibiotics, manually, to treat acute sinusitis.

Insert an IV catheter and secure with medical tape to provide intravenous access for medications and fluids.

Administer traction and counter-traction until shoulder slips back in place to relocate a dislocated shoulder.

Administer Lidocaine/Epinephrine with syringed needle, cut with scalpel to drain/treat skin or dental abscess.

Deliver oxygen to respiratory distressed patient by automated ventilation provided in a respiratory support pack.

Operate hand-held ultra-sonic device, manually while visually inspecting display, to locate and then disintegrate renal stone in crew member.

Place PHA QDM on crewmember, deliver oxygen for 2 hours, minimize crewmember's activity and hydrate 1 liter to treat decompression sickness.

Clean fingernail, apply antibiotic ointment, cover with adhesive bandage, manually until a new nail grows, to treat/protect fingernail damage from EVA.

Place Ambu Bag mask over nose and mouth and gently squeeze bag to deliver breaths every 5 to 8 seconds to assist temporary ventilation of compromised patient.

The three remaining summary task statements rated by the SMEs to be among the 32 most-important of the 158 summary statements have been described in previous discussions of Difficulty to Learn and Frequency. The statement, *Interact/communicate with other crew members directly during Mars Surface Operations,* was rated 19th in Importance and 1st in (likely) Frequency. *Sleep for approximately eight hours each 24-hour period, during Cruise to Mars*, was rated 30th in Importance and 11th in Frequency. And, *Conduct EVA to perform maintenance or retrieve items from outside the interplanetary space vehicle during Cruise to Mars*, was rated 24th in Importance and 2nd in Difficulty. Implications of the most-Important tasks will be addressed in the final major section of this report.

CRITICALITY

The top 20 percent of the 158 summary task statements are listed in the following table in descending order of the combined measure, Criticality; the mean values for Frequency, Difficulty to Learn, and Importance also are listed for each statement and the top summary task statement in each dimension is highlighted. A review of the list reveals that eight of the tasks involve primarily piloting, six involve monitoring, five involve medical diagnosis and treatment, four involve science, four are EVA tasks, three involve emergency responses, two involve robots and rovers, and one involves communicating and interacting among the crew while on the surface of Mars, which is likely to be the most-frequently-performed task during the expedition. The list of all 158 summary task statements in order of criticality is presented in Appendix C. The list of 1,125 task statements is presented in Appendix D by mission phase.

The summary task statement with the highest Criticality score, *Perform science-related EVA functions during Mars Surface Operations*, which was described previously, was rated 16th in Difficulty, 32nd in Frequency, and is composed of 61 component tasks, including the following additional examples.

Record field notes, verbally while wearing surface EVA suit, for later transcription.

Operate gravitometer, manually while wearing surface EVA suit, to record gravitational data.

Remove and package ice core sample, manually while wearing surface EVA suit, for later analysis.

Deploy temperature sensors (heat-flow probes) in drill hole manually, while wearing surface EVA suit.

Collect geological samples, manually using Apollo-type rake/sample bags, while wearing surface EVA suit.

Extract regolith core from drill/wrap in plastic, manually while wearing surface EVA suit, for later analysis.

Descend crater wall while carrying hand tools and wearing surface EVA suit to conduct geological research.

Operate seismic testing munitions/equipment, manually while wearing surface EVA suit, record seismic data.

Scan distant planetary surface, visually through clear visor, to identify potential sites for geological research.

Insert geologic samples in glove box, manually while wearing surface EVA suit, to prepare for aseptic analysis.

Pound seismometers into rock, manually using slide hammer while wearing surface EVA suit, to deploy sensors.

Carry sample curation bag into sample storage module, manually while wearing surface EVA suit, to preserve integrity of samples contained.

Attach wire connectors to seismometer and to receiving terminal, manually wearing surface EVA suit, to prepare for recording seismographic data.

Deploy mooring mast with one other crew member, manually using hand tools and wearing surface EVA suit, to prepare for non-rigid airship/ballonet inflation.

TOP 32 SUMMARY TASK STATEMENTS RANKED BY CRITICALITY

	Summary Task Statement	Frequency	Difficulty	Importance	Criticality	Function
1	**Perform science-related EVA functions during Mars Surface Operations (MSO).**	3.679	4.036	4.286	**12.000**	Science EVA
2	Monitor systems/perform piloting functions during Mars Surface Ascent.	2.912	4.158	4.807	11.877	Piloting
3	Perform piloting functions during Mars Surface Descent.	2.589	4.375	4.821	11.786	Piloting
4	**Interact/communicate with crew members directly during MSO.**	**4.638**	2.298	4.672	11.609	Comms
5	Perform piloting functions during Earth Descent.	2.545	4.268	4.750	11.563	Piloting
6	Perform piloting functions during Mars Orbit Injection.	2.386	4.246	4.860	11.491	Piloting
7	Perform piloting functions during Mars Orbit operations	2.556	4.241	4.691	11.487	Piloting
8	Enter control inputs, manually/visually with gloved hand, to pilot Earth Ascent Vehicle (EAV) during launch and cruise to LEO/CLO.	2.772	4.000	4.702	11.474	Piloting
9	Monitor systems/perform piloting functions during Trans Earth Injection.	2.800	3.893	4.732	11.425	Piloting
10	Perform piloting functions during Earth Approach.	2.518	4.107	4.786	11.411	Piloting
11	Assess displayed information, cognitively, to determine readiness to launch to LEO/CLO.	3.123	3.632	4.579	11.333	Piloting
12	Conduct Extra-Vehicular Activity (EVA) to perform maintenance or retrieve items from outside the interplanetary space vehicle during Cruise to Mars.	2.246	4.491	4.596	11.333	EVA
13	Monitor displays/verify configurations before/during launch to LEO/CLO	3.554	3.333	4.439	11.326	Monitoring
14	Monitor systems during Earth Descent.	3.481	3.382	4.436	11.300	Monitoring
15	Perform monitoring functions in surface habitat or modules to ensure crew and system health during Mars Surface Operations.	3.897	3.000	4.386	11.283	Monitoring
16	Enter/exit surface habitat, manually while wearing pressure suit and helmet, during Mars Surface Operations.	3.544	3.246	4.474	11.263	EVA
17	Perform medical diagnoses and evaluations, cognitively, during MSO.	2.690	4.053	4.517	11.260	Medical
18	Perform robot operations-related functions during MSO.	3.527	3.750	3.982	11.259	Robotics
19	Perform geology-related science functions in surface habitat or modules during Mars Surface Operations.	3.491	3.754	4.000	11.245	Science
20	Assess displayed information, cognitively, to determine readiness for TMI.	3.018	3.571	4.643	11.232	Piloting
21	Monitor crew behavioral health/respond to behavioral health issues during Mars Surface Operations.	3.133	3.559	4.517	11.209	Medical
22	Monitor systems to ensure proper functioning during Cruise to Mars.	3.897	2.983	4.328	11.207	Monitoring
23	Perform medical diagnoses/evaluations, cognitively, during Cruise to Mars.	2.649	4.055	4.491	11.195	Medical
24	**Respond to medical emergencies, following procedures and with equipment provided, during Cruise to Mars.**	1.948	**4.509**	4.724	11.181	Medical
25	Perform surface rover piloting/driving functions during MSO.	3.464	3.411	4.304	11.179	Piloting
26	Respond to medical emergencies, following procedures and with equipment provided, during Mars Surface Operations.	2.069	4.263	4.825	11.157	Medical
27	Perform surface EVA physical functions on foot during MSO.	3.298	3.482	4.368	11.149	EVA
28	Adjust system controls, manually during buffeted descent, in response to displayed information.	2.673	3.870	4.585	11.128	Piloting
29	**Respond to technical emergencies, following procedures and with equipment provided, during Cruise to Mars.**	2.140	4.053	**4.930**	11.123	Technical
30	Monitor systems during Mars Surface Descent.	3.148	3.444	4.509	11.102	Piloting
31	Perform tests and examinations, physically, to support medical diagnoses during Mars Surface Operations.	2.741	3.860	4.483	11.084	Medical
32	Perform biology-related science functions in surface habitat or modules during Mars Surface Operations.	3.474	3.579	4.018	11.070	Science

Note: Summary task statements are listed in order of Criticality, the metric derived by combining the mean ratings for Frequency, Difficulty to Learn, and Importance. The top summary task statement in each dimension is highlighted.

What it is about the surface science-related tasks that elevated that summary statement to the top of the Criticality list? The next EVA-related summary task is 12th on the list, *Conduct Extra-Vehicular Activity (EVA) to perform maintenance or retrieve items from outside the interplanetary space vehicle during Cruise to Mars*. This task was estimated to be performed very infrequently, if at all, during the cruise to Mars, and would be in response to a major equipment malfunction. EVAs in space are always difficult and dangerous and are performed only if important to the mission. After this, the next EVA-related summary statement is 16th on the Criticality list, *Enter/exit surface habitat, manually while wearing pressure suit and helmet*, *during Mars Surface Operations*, which is composed of eight tasks from donning an EVA suit to removing dust and doffing the suit upon return. The next EVA statement, *Perform surface EVA physical functions on foot during Mars Surface Operations* was rated 27th in Criticality and is composed of 15 tasks, including:

Measure surface distances using laser rangefinder while wearing surface EVA suit.

Climb 3-meter ladder, manually while wearing surface EVA suit, to access Mars Surface Ascent Vehicle.

Inspect pre-positioned power-generation plant, visually/manually while wearing surface EVA suit, to verify proper functioning.

Carry incapacitated crew mate 20 meters to surface rover, manually while both are wearing surface EVA suits, to prepare for medical treatment.

Respond to puncture of surface EVA suit while wearing the suit on planetary surface, manually by retrieving and attaching temporary fast-patch.

Remove accumulated dust from greenhouse, manually using compressed gas canister while wearing surface EVA suit, to maintain optimal sunlight for plant growth.

The next EVA-related summary task is 44th on the Criticality list, *Perform maintenance, repair, and monitoring functions via surface EVA during Mars Surface Operations*. This statement summarizes 11 tasks, including:

Remove drill bit from drill pipe, manually using hand tolls while wearing surface EVA suit, to restore drill functionality.

Inspect H_2O sublimation system visually/manually, while wearing surface EVA suit, to verify H_2O extraction/storage.

Inspect surface atmosphere mining system visually/manually, while wearing surface EVA suit, to verify O_2/H extraction and storage.

Troubleshoot drill problems, visually/manually/cognitively while wearing surface EVA suit, to determine if equipment is repairable in the field.

A review of the EVA-related summary statements, the component tasks, and their relative orders reveals that the factors that contributed to elevating science-related EVA tasks to the top of the Criticality list are: 1) Science, the reason for going to Mars; and, 2) EVA, which is difficult to perform, dangerous, and only done for important reasons. Similar analyses were conducted to identify contributing factors to other high criticality scores. For example, summary task statements concerning piloting received high scores for Importance; medical tasks were rated high on Difficulty to Learn; and monitoring tasks were elevated by high scores for likely Frequency.

Conducting Geological Field Work on the Surface of Mars.

RESULTS OF THE ABILITY-RANKING

A total of 72 SMEs, representing the technical specialties identified during the task analysis, performed the ability card-sort for their respective roles; six SMEs ranked the abilities for more than one technical specialty and 42 of the SMEs also ranked the abilities for the role of expedition leader. The eight crew specialties/roles are listed, below, with the numbers of SMEs who ranked the abilities.

Crew Role	Number of SMEs	Average Years Experience
Leader	42	15.9
Biologist	12	10.8
Geologist	15	12.4
Physician	11	21.2
Electrician	11	14.6
Pilot/Navigator	10	19.8
Mechanic/Engineer	10	17.7
Computer Specialist	10	17.8

Nine tables were prepared, one for each of the eight crew specialties and one based on all 121 ability rankings. This combined list was derived by calculating the mean rankings of abilities from the means of each crew specialty/role; means were used to calculate the combined measure to eliminate effects of differential sample sizes. The nine tables, or rank-ordered lists, are presented in the following pages; tables derived from calculating mean rankings from all SMEs and from the means of the eight specialties are presented in Appendix E for comparison. Analysis focuses on the top 25 abilities for each of the specialties (i.e., the abilities above the highlighted row in each table). Numbers of SMEs and numbers of abilities in the More Important category for each list are in parentheses.

A review of the rank-ordered ability tables reveals that the expedition Leader is believed by the SMEs to require social skills (Teamwork, Patience, Emotional Control, Tolerance, Affability), but also the abilities to identify and solve problems (Problem Sensitivity, Inductive Reasoning, Deductive Reasoning, Time Sharing, Fluency of Ideas, Originality, Information Ordering, Speed of Closure). The Leader also is expected to be a good listener and a good communicator (Oral Expression, Speech Clarity, Oral Comprehension, Speech Hearing).

The Pilot/Navigator is believed by the pilot SMEs to require technical, fine motor, and other physical abilities (Reaction Time, Control Precision, Rate Control, Multi-Limb Coordination, Manual Dexterity, Near and Far Vision) and situational awareness (Spatial Orientation, Response Orientation, Perceptual Speed, Visualization). The pilot also is expected to possess social skills (Emotional Control, Teamwork) and, to a lesser extent, problem-solving abilities (Time Sharing, Speed of Closure, Information Ordering, Deductive Reasoning). A charter pilot interrupted his ability-ranking to say that social skills are important in his field of aviation, because a crew spends a lot of time together in the air and during layovers; the job would be unpleasant if a crew mate could not get along with others.

Assumption About Piloting Tasks

Piloting tasks will be automated to the extent possible to minimize opportunities for human error resulting from neuro-vestibular effects of micro-gravity transits. The tasks will be performed by crew only if automated systems fail to function as planned. The reliability of automated systems will be established by successful completion of automated missions to deliver cargo and equipment to Mars in advance of the human crew.

The Physician is believed by the physician SMEs to require a combination of problem-solving abilities (Problem Sensitivity, Inductive Reasoning, Deductive Reasoning, Speed of Closure, Originality, Information Ordering, Fluency of Ideas) and social skills (Patience, Teamwork, Affability, Emotional Control, Tolerance). The physician also is expected to possess fine motor abilities (Manual and Finger Dexterity) and to be able to understand others and to speak clearly (Oral Comprehension, Oral Expression), abilities the Physician has in common with the Leader.

Leader (n=42)	Mean	SD
More Important (21)	1.00	0.00
Teamwork	7.17	6.37
Confidence	8.17	6.71
Problem Sensitivity	8.45	5.79
Patience	10.14	7.78
Emotional Control	10.98	7.87
Oral Expression	12.00	6.61
Tolerance	12.10	11.17
Inductive Reasoning	12.48	8.12
Speech Clarity	12.88	7.35
Deductive Reasoning	13.19	6.90
Oral Comprehension	13.71	6.97
Affability	14.71	10.78
Fluency of Ideas	16.98	9.68
Time Sharing	17.26	7.66
Originality	17.60	10.08
Information Ordering	18.86	12.58
Speech Hearing	19.10	10.30
Written Comprehension	19.43	9.80
Written Expression	21.93	11.40
Speed of Closure	23.02	14.24
Category Flexibility	23.60	11.18
Important	24.17	4.05
Visualization	25.07	10.06
Auditory Attention	25.81	9.98
Selective Attention	27.19	12.61
Memorization	27.62	10.72
Perceptual Speed	28.93	11.08
Reaction Time	29.07	13.71
Flexibility of Closure	30.38	14.09
General Hearing	31.00	11.68
Mathematical Reasoning	32.17	9.67
Spatial Orientation	35.12	10.75
Stamina	35.38	13.86
Number Facility	35.57	11.03
Response Orientation	37.05	11.16
Sound Localization	38.76	11.36
Near Vision	39.98	9.92
Less Important	40.81	6.97
Depth Perception	41.88	9.26
Rate Control	42.52	13.79
Control Precision	42.57	11.93
Manual Dexterity	42.83	8.74
Far Vision	42.88	9.92
Gross Body Equilibrium	43.83	10.68
Dynamic Strength	44.33	11.10
Gross Body Coordination	44.33	8.79
Peripheral Vision	44.83	8.95
Multi-Limb Coordination	45.69	8.74
Visual Color Discrimination	45.74	10.62
Finger Dexterity	48.02	8.85
Night Vision	48.02	9.51
Static Strength	48.21	12.41
Arm-Hand Steadiness	49.00	7.79
Trunk Strength	49.43	8.22
Dynamic Flexibility	50.36	8.72
Extent Flexibility	51.00	6.64
Speed of Limb Movement	51.14	8.72
Wrist-Finger Speed	51.38	8.12
Explosive Strength	52.00	10.36
Glare Sensitivity	52.17	8.65

Pilot/Navigator (n=10)	Mean	SD
More Important (18)	1.00	0.00
Reaction Time	10.30	5.01
Control Precision	10.80	11.28
Spatial Orientation	12.10	8.40
Rate Control	15.30	14.23
Time Sharing	16.90	10.70
Confidence	17.00	16.56
Emotional Control	17.50	13.02
Response Orientation	18.30	16.99
Teamwork	19.00	15.65
Speed of Closure	20.50	14.89
Near Vision	20.60	9.45
Perceptual Speed	21.00	12.41
Multi-Limb Coordination	23.00	16.02
Far Vision	23.80	12.08
Visualization	23.80	21.48
Information Ordering	24.40	13.15
Manual Dexterity	24.70	14.57
Deductive Reasoning	25.50	12.93
Important	25.90	5.38
Arm-Hand Steadiness	26.00	17.00
Depth Perception	26.10	13.65
Selective Attention	26.10	18.50
Problem Sensitivity	27.10	10.25
Night Vision	27.90	11.18
Speech Hearing	28.30	17.84
Patience	28.60	15.84
Oral Comprehension	28.70	17.74
Inductive Reasoning	28.80	12.91
Glare Sensitivity	29.10	18.20
Peripheral Vision	29.30	10.86
Speech Clarity	29.80	18.91
Visual Color Discrimination	29.90	16.32
Finger Dexterity	30.80	19.31
Auditory Attention	31.00	10.21
Gross Body Equilibrium	33.80	13.16
Memorization	34.80	14.87
General Hearing	35.10	13.50
Affability	35.20	17.04
Oral Expression	35.40	17.19
Tolerance	35.60	17.75
Stamina	37.40	14.64
Number Facility	37.80	15.55
Wrist-Finger Speed	37.90	20.60
Mathematical Reasoning	38.50	17.48
Dynamic Flexibility	40.60	11.43
Gross Body Coordination	41.70	15.36
Written Comprehension	41.80	15.63
Flexibility of Closure	42.10	15.00
Originality	42.10	13.90
Category Flexibility	42.40	14.94
Extent Flexibility	43.50	9.40
Dynamic Strength	43.60	12.61
Sound Localization	44.30	11.39
Trunk Strength	46.80	6.44
Less Important	47.90	2.81
Speed of Limb Movement	48.30	15.99
Fluency of Ideas	50.20	8.61
Written Expression	50.90	15.77
Static Strength	51.50	10.20
Explosive Strength	52.90	8.35

Physician (n=11)	Mean	SD
More Important (18)	1.00	0.00
Problem Sensitivity	6.00	5.37
Inductive Reasoning	7.55	5.79
Deductive Reasoning	8.09	5.36
Confidence	12.36	12.82
Patience	15.36	8.19
Speed of Closure	15.55	13.91
Teamwork	16.18	10.99
Oral Comprehension	17.82	10.36
Manual Dexterity	17.91	9.24
Finger Dexterity	19.00	11.05
Originality	19.00	13.45
Written Comprehension	20.18	9.38
Affability	20.45	14.24
Emotional Control	20.55	13.16
Information Ordering	20.55	12.96
Fluency of Ideas	21.00	14.89
Selective Attention	21.00	13.39
Oral Expression	22.00	12.25
Important	24.91	7.41
Arm-Hand Steadiness	25.18	10.11
Tolerance	25.36	17.17
Visualization	25.55	15.93
Time Sharing	25.82	12.39
Speech Clarity	26.00	11.72
Flexibility of Closure	26.18	17.84
Speech Hearing	27.00	14.51
Perceptual Speed	27.91	12.64
Spatial Orientation	29.18	14.43
Reaction Time	29.64	18.00
Depth Perception	30.00	11.58
Auditory Attention	31.91	16.56
Written Expression	32.18	15.62
Near Vision	32.36	11.99
Memorization	33.64	16.76
Multi-Limb Coordination	34.27	14.02
Number Facility	34.82	10.21
Control Precision	35.09	17.11
Response Orientation	36.27	15.13
Stamina	36.91	14.70
Mathematical Reasoning	37.36	10.65
General Hearing	37.45	12.07
Gross Body Coordination	38.73	13.96
Wrist-Finger Speed	39.64	18.24
Category Flexibility	41.82	10.10
Gross Body Equilibrium	42.18	12.88
Visual Color Discrimination	42.55	16.84
Peripheral Vision	43.00	13.08
Dynamic Flexibility	44.91	10.45
Dynamic Strength	45.00	10.38
Less Important	45.64	6.50
Rate Control	46.09	9.64
Far Vision	46.45	10.53
Sound Localization	47.36	9.99
Extent Flexibility	47.45	10.27
Static Strength	47.64	7.20
Glare Sensitivity	49.18	15.45
Trunk Strength	51.73	5.93
Speed of Limb Movement	53.64	7.94
Explosive Strength	54.27	4.58
Night Vision	57.18	5.46

Biologist (n=12)	Mean	SD
More Important (21)	1.00	0.00
Inductive Reasoning	9.17	7.54
Confidence	10.00	8.64
Deductive Reasoning	10.67	7.50
Information Ordering	12.25	6.98
Patience	12.42	9.39
Selective Attention	12.58	11.26
Problem Sensitivity	14.00	6.22
Arm-Hand Steadiness	17.75	12.87
Finger Dexterity	17.75	13.10
Originality	18.17	13.53
Written Comprehension	18.50	10.51
Manual Dexterity	18.83	11.99
Near Vision	19.25	12.37
Flexibility of Closure	19.58	12.83
Time Sharing	20.67	9.55
Speed of Closure	21.50	15.54
Fluency of Ideas	22.08	15.19
Written Expression	22.75	10.06
Visual Color Discrimination	23.17	11.58
Mathematical Reasoning	23.92	14.29
Wrist-Finger Speed	24.08	18.47
Important	24.50	5.32
Teamwork	24.50	16.68
Oral Expression	24.75	10.52
Category Flexibility	25.17	11.33
Number Facility	25.42	15.74
Oral Comprehension	25.50	9.31
Control Precision	26.17	17.48
Memorization	26.75	11.93
Visualization	27.25	12.40
Emotional Control	27.58	17.67
Perceptual Speed	29.67	11.65
Speech Clarity	30.17	10.99
Tolerance	33.17	17.68
Affability	33.25	18.70
Depth Perception	34.25	10.54
Reaction Time	34.42	12.82
Rate Control	37.08	14.20
Speech Hearing	41.08	10.74
Glare Sensitivity	41.33	13.73
Multi-Limb Coordination	42.75	14.52
Auditory Attention	42.83	7.98
Spatial Orientation	43.00	11.03
Response Orientation	43.33	9.39
General Hearing	43.58	9.43
Gross Body Coordination	44.67	12.62
Less Important	44.75	4.61
Extent Flexibility	45.75	9.89
Stamina	45.75	11.62
Trunk Strength	45.83	11.26
Dynamic Flexibility	47.83	10.56
Gross Body Equilibrium	47.83	8.39
Peripheral Vision	47.83	10.17
Sound Localization	48.08	11.10
Dynamic Strength	48.67	10.09
Night Vision	48.75	11.48
Speed of Limb Movement	50.42	6.58
Static Strength	51.50	7.82
Far Vision	52.75	7.93
Explosive Strength	58.00	4.09

Geologist (n=15)	Mean	SD
More Important (14)	1.00	0.00
Inductive Reasoning	9.93	7.69
Deductive Reasoning	12.60	11.22
Teamwork	12.80	9.85
Patience	15.80	14.51
Confidence	15.87	10.83
Spatial Orientation	16.80	12.95
Originality	17.33	10.50
Oral Expression	17.47	12.84
Selective Attention	19.07	11.50
Visualization	19.40	15.31
Flexibility of Closure	20.67	20.56
Problem Sensitivity	21.40	17.53
Emotional Control	22.07	17.60
Stamina	22.60	14.11
Important	22.67	6.10
Fluency of Ideas	23.27	17.01
Written Comprehension	23.33	11.00
Affability	23.47	13.85
Far Vision	23.53	13.27
Visual Color Discrimination	24.40	15.39
Speech Clarity	25.67	17.07
Tolerance	25.93	16.72
Speed of Closure	26.13	18.63
Near Vision	26.33	15.50
Oral Comprehension	26.33	12.03
Manual Dexterity	27.07	12.31
Written Expression	27.20	17.91
Information Ordering	27.73	15.90
Gross Body Coordination	28.53	13.93
Gross Body Equilibrium	28.87	11.81
Time Sharing	29.87	15.37
Category Flexibility	30.80	17.42
Dynamic Strength	31.20	13.68
Memorization	31.87	15.50
Depth Perception	33.20	13.01
Finger Dexterity	33.47	15.99
Perceptual Speed	33.47	16.27
Mathematical Reasoning	33.87	10.29
Trunk Strength	33.93	15.21
Arm-Hand Steadiness	36.40	13.12
Extent Flexibility	36.67	14.55
Speech Hearing	36.80	13.22
Static Strength	36.87	11.61
Number Facility	37.60	13.61
Multi-Limb Coordination	39.40	12.37
Control Precision	41.60	9.28
Dynamic Flexibility	41.80	12.70
Less Important	44.67	6.73
Reaction Time	45.40	11.89
Rate Control	46.20	11.45
Glare Sensitivity	46.40	11.73
Explosive Strength	47.33	11.13
General Hearing	48.27	10.24
Response Orientation	48.93	7.14
Wrist-Finger Speed	49.33	9.93
Auditory Attention	49.73	8.53
Speed of Limb Movement	50.53	9.56
Sound Localization	51.40	12.02
Peripheral Vision	53.47	5.84
Night Vision	55.27	8.40

Computer Specialist (n=10)	Mean	SD
More Important (4)	1.00	0.00
Inductive Reasoning	7.10	7.81
Deductive Reasoning	7.80	6.23
Problem Sensitivity	8.80	8.38
Information Ordering	15.50	14.33
Important	18.80	4.08
Mathematical Reasoning	19.10	19.74
Written Comprehension	19.40	18.88
Oral Comprehension	20.20	12.10
Time Sharing	20.70	10.77
Oral Expression	20.80	10.97
Confidence	21.00	14.97
Near Vision	21.10	14.54
Selective Attention	21.20	8.99
Memorization	22.00	16.52
Speed of Closure	22.20	14.62
Originality	23.70	19.66
Speech Clarity	24.00	17.29
Patience	25.30	14.22
Teamwork	25.80	11.75
Finger Dexterity	28.00	14.35
Visualization	28.10	17.03
Fluency of Ideas	28.80	19.22
Perceptual Speed	29.00	20.12
Flexibility of Closure	30.00	21.08
Manual Dexterity	30.10	13.68
Emotional Control	30.50	15.91
Control Precision	30.90	16.39
Number Facility	31.60	18.20
Wrist-Finger Speed	31.90	13.71
Reaction Time	32.00	18.48
Category Flexibility	32.10	17.75
Arm-Hand Steadiness	32.50	10.68
Speech Hearing	32.60	14.55
Response Orientation	32.80	15.70
General Hearing	33.00	12.03
Sound Localization	33.00	15.43
Rate Control	33.30	17.24
Visual Color Discrimination	34.40	17.66
Auditory Attention	34.60	18.82
Multi-Limb Coordination	35.50	16.01
Affability	37.30	12.39
Gross Body Coordination	37.60	13.88
Tolerance	37.80	18.82
Written Expression	38.10	18.73
Extent Flexibility	39.60	9.51
Less Important	39.80	6.65
Depth Perception	41.50	14.85
Dynamic Flexibility	41.60	12.79
Spatial Orientation	42.00	13.12
Night Vision	42.40	12.55
Glare Sensitivity	43.60	15.46
Stamina	43.80	15.33
Gross Body Equilibrium	44.20	11.46
Trunk Strength	44.90	11.10
Peripheral Vision	46.00	12.90
Static Strength	46.30	9.29
Far Vision	46.60	17.48
Speed of Limb Movement	47.10	9.81
Dynamic Strength	47.20	10.22
Explosive Strength	53.30	7.20

Electrician (n=11)	Mean	SD
More Important (15)	1.00	0.00
Inductive Reasoning	9.09	9.05
Problem Sensitivity	10.55	11.06
Confidence	10.64	10.57
Deductive Reasoning	11.45	13.00
Information Ordering	16.18	8.94
Visual Color Discrimination	17.18	14.91
Finger Dexterity	18.09	14.08
Manual Dexterity	18.91	13.20
Originality	19.09	12.68
Selective Attention	20.27	9.58
Mathematical Reasoning	20.82	18.17
Visualization	20.91	15.48
Patience	21.55	10.54
Near Vision	21.73	17.46
Speed of Closure	22.09	15.64
Important	24.36	5.90
Teamwork	24.55	16.64
Arm-Hand Steadiness	25.00	15.06
Night Vision	25.09	14.73
Oral Expression	26.27	16.80
Time Sharing	26.27	16.26
Written Comprehension	26.55	14.86
Number Facility	26.73	13.90
Memorization	26.82	21.33
Flexibility of Closure	28.45	18.88
Perceptual Speed	28.91	12.98
Oral Comprehension	29.00	17.22
General Hearing	29.73	8.79
Reaction Time	29.82	14.95
Speech Clarity	29.91	13.29
Auditory Attention	31.09	9.86
Sound Localization	31.73	10.01
Fluency of Ideas	32.18	13.00
Dynamic Flexibility	32.73	17.15
Control Precision	32.91	14.41
Extent Flexibility	33.36	16.96
Written Expression	33.82	17.31
Affability	34.82	17.73
Category Flexibility	36.36	16.17
Multi-Limb Coordination	36.73	14.04
Emotional Control	37.00	16.80
Speech Hearing	37.09	8.22
Wrist-Finger Speed	37.27	17.78
Response Orientation	38.09	14.02
Gross Body Equilibrium	38.27	15.91
Rate Control	38.73	15.08
Gross Body Coordination	40.09	10.44
Glare Sensitivity	40.73	10.98
Depth Perception	41.09	13.25
Stamina	42.73	14.99
Less Important	43.64	5.99
Spatial Orientation	44.27	11.24
Tolerance	45.00	18.77
Peripheral Vision	46.82	9.56
Dynamic Strength	49.82	8.94
Speed of Limb Movement	50.64	7.47
Far Vision	50.91	5.59
Static Strength	51.09	10.65
Trunk Strength	51.36	12.53
Explosive Strength	58.18	2.93

Mechanic/Engineer (n=10)	Mean	SD
More Important (13)	1.00	0.00
Inductive Reasoning	11.40	8.06
Problem Sensitivity	11.40	14.06
Deductive Reasoning	11.90	8.06
Manual Dexterity	14.00	6.63
Patience	17.70	12.27
Written Comprehension	17.70	14.46
Originality	18.60	13.01
Visualization	19.30	15.53
Mathematical Reasoning	22.20	20.15
Teamwork	22.30	15.69
Confidence	23.00	18.23
Information Ordering	23.80	15.50
Arm-Hand Steadiness	24.00	16.47
Important	24.10	6.24
Rate Control	24.30	19.16
Control Precision	25.90	14.32
Auditory Attention	26.40	18.70
Finger Dexterity	26.50	18.39
Reaction Time	26.50	16.19
Speed of Closure	26.70	14.44
Flexibility of Closure	26.80	17.86
Static Strength	27.60	14.77
Multi-Limb Coordination	28.50	13.63
Dynamic Strength	29.70	15.39
Oral Comprehension	30.00	16.41
General Hearing	30.50	16.90
Gross Body Coordination	30.90	12.27
Tolerance	31.10	19.02
Fluency of Ideas	31.60	18.01
Sound Localization	32.60	20.80
Emotional Control	34.10	21.34
Visual Color Discrimination	34.10	11.45
Speech Hearing	34.30	17.70
Time Sharing	34.40	16.37
Number Facility	34.70	19.33
Oral Expression	34.70	22.24
Response Orientation	34.70	18.74
Spatial Orientation	34.90	12.31
Memorization	35.10	14.10
Near Vision	35.30	20.68
Gross Body Equilibrium	35.50	15.62
Selective Attention	35.70	17.52
Speech Clarity	35.70	17.44
Affability	36.20	15.50
Stamina	36.70	16.10
Explosive Strength	37.20	15.88
Wrist-Finger Speed	37.30	10.72
Perceptual Speed	38.60	9.54
Depth Perception	38.90	11.43
Trunk Strength	39.20	12.25
Dynamic Flexibility	39.40	15.12
Written Expression	40.40	14.35
Category Flexibility	41.20	13.93
Extent Flexibility	42.80	13.81
Night Vision	44.50	12.70
Less Important	46.10	3.73
Peripheral Vision	46.60	15.65
Far Vision	49.30	8.34
Speed of Limb Movement	50.40	9.20
Glare Sensitivity	55.00	8.25

All Specialties Combined	Mean	SD
More Important (12)	1.00	0.00
Inductive Reasoning	11.94	7.04
Deductive Reasoning	12.65	5.55
Problem Sensitivity	13.46	7.22
Confidence	14.75	5.37
Patience	18.36	6.35
Teamwork	19.04	6.60
Information Ordering	19.91	5.21
Originality	21.95	8.38
Speed of Closure	22.21	3.47
Selective Attention	22.89	6.83
Written Comprehension	23.36	7.99
Visualization	23.67	3.44
Important	23.68	2.17
Oral Comprehension	23.91	5.97
Time Sharing	23.99	6.20
Oral Expression	24.17	8.03
Manual Dexterity	24.29	9.19
Emotional Control	25.03	8.82
Speech Clarity	26.77	6.68
Near Vision	27.08	7.84
Finger Dexterity	27.70	10.17
Flexibility of Closure	28.02	6.95
Fluency of Ideas	28.26	10.36
Mathematical Reasoning	28.49	7.83
Affability	29.43	8.60
Arm-Hand Steadiness	29.48	9.68
Reaction Time	29.64	9.72
Perceptual Speed	29.69	4.99
Memorization	29.82	4.72
Control Precision	30.74	10.17
Tolerance	30.76	9.87
Visual Color Discrimination	31.43	9.76
Speech Hearing	32.03	6.99
Spatial Orientation	32.17	12.10
Number Facility	33.03	4.72
Written Expression	33.41	9.73
Auditory Attention	34.17	8.21
Category Flexibility	34.18	7.45
Rate Control	35.44	10.87
Multi-Limb Coordination	35.73	7.36
Depth Perception	35.87	5.90
General Hearing	36.08	6.70
Response Orientation	36.18	8.88
Stamina	37.66	7.19
Gross Body Coordination	38.32	5.89
Wrist-Finger Speed	38.60	8.78
Gross Body Equilibrium	39.31	6.33
Sound Localization	40.90	7.88
Far Vision	42.03	11.72
Dynamic Flexibility	42.40	5.42
Dynamic Strength	42.44	7.71
Extent Flexibility	42.52	5.79
Night Vision	43.64	11.70
Less Important	44.16	2.70
Glare Sensitivity	44.69	8.08
Peripheral Vision	44.73	6.93
Static Strength	45.09	8.53
Trunk Strength	45.40	6.14
Speed of Limb Movement	50.27	1.94
Explosive Strength	51.65	6.78

The Biologist and Geologist selected for an expedition to Mars are believed by the biologist and geologist SMEs to require similar problem-solving abilities (Inductive Reasoning, Deductive Reasoning, Problem Sensitivity, Fluency of Ideas, Originality, Selective Attention, Speed and Flexibility of Closure). The Biologist also requires fine-motor abilities (Arm-Hand Steadiness, Manual Dexterity, Finger Dexterity) and Near Vision, abilities needed for laboratory work. In contrast, the Geologist requires situational awareness (Spatial Orientation, Visualization), Stamina, and Far Vision, abilities needed for geologic field work. SMEs from both disciplines believe that Teamwork and Patience will be required of all scientific personnel.

The Computer Specialist, Electrician, and Mechanic are all believed by their respective SMEs to be problem-solvers, first and foremost (Inductive Reasoning, Deductive Reasoning, Problem Sensitivity, Information Ordering, Originality, Selective Attention, Visualization, Speed and Flexibility of Closure). All three specialties also are expected to possess mathematical (Mathematical Reasoning) and fine-motor abilities (Finger and Manual Dexterity). The Computer Specialist and Electrician are believed to also require abilities necessary to concentrate attention on a problem (Time Sharing, Selective Attention, Memorization), while the Mechanic is believed to require fine motor abilities (Rate Control, Control Precision), strength (Dynamic and Explosive Strength), and coordination (Multi-Limb Coordination). One of the electrician SMEs mentioned during his session that the list includes social, cognitive, and physical abilities, but olfactory sensitivity is missing; many electricians rely on their sense of smell to detect failing circuits, just as they rely on Near Vision to detect scorching caused by shorts and failed components on circuit boards.

The results of the task-rating and ability-ranking, presented here, were used by the study team to identify social skills and cognitive and physical abilities necessary for eight crew specialty/roles during scientific expeditions to Mars. The next step is to identify the abilities and skills that are common to multiple crew roles, which will enable us to develop recommendations for optimizing personnel-selection and cross-training. The goal of the process is to identify strategies that will allow the fewest number of crew members to perform the expected work safely and to be prepared to perform other, less likely tasks if necessary. Those considerations are addressed in the following section of this report.

Red Storm© by Pat Rawlings, 2000.[44]

Weather influences everything. "To us, instead of being a mere prelude to more serious matters, or the last resort of a feeble intellect, it was the all-engrossing theme."
- Douglas Mawson, Geologist and Antarctic Explorer

[44] The largest dust storm on Mars in more than a decade occurred during preparation of this report. Dust has blocked sunlight from reaching the surface for three months, causing NASA's solar-powered *Opportunity* rover to shut down; the nuclear-powered *Curiosity* rover, located on the opposite side of the planet, continues to function in darkness. https://www.space.com/40952-mars-dust-storm-2018-covers-entire-planet.html

IMPLICATIONS OF RESEARCH RESULTS

Previous major sections of this report have provided background information about exploration-class space missions, described the research conducted by the study team, and presented a summary of research results. The purpose of the current section is to identify and discuss the most salient implications of those research results. Implications are addressed in four categories: Generalizable Skills and Abilities, Personnel Selection and Crew Composition, Training, and Design.

GENERALIZABLE SKILLS AND ABILITIES

We focused primarily on the differences among the crew specialties/roles when presenting results of the ability-ranking in the previous section of this report. However, it also is instructive to identify the abilities that are generalizable across circumstances and crew roles and those that will be required by all crew members during a 30-month expedition to Mars. In particular, the 72 SMEs who ranked the abilities believed that Teamwork and Patience will be necessary for all crew positions to perform their work successfully. All but the Biologist and Mechanic SMEs ranked Emotional Control in the top 25 abilities, missing the cut-off by four and five, respectively. Oral Comprehension was in the top 25 for all specialties, except Electrician and Biologist, but missed the cut-off by only one for both. The importance of interpersonal communications was demonstrated by the rank of Oral Expression in the top 25 for all specialties, except Pilot and Mechanic. Time Sharing ability was in the top 25 for all but the Geologist and Mechanic, missing the cut-off by five and eight ranks, respectively.

One of the surprises revealed by the data is that Written Comprehension was ranked in the top 25 abilities for six of the crew specialties, but not for the Mechanic and the Pilot, missing the cut-off by a substantial 10 and 21 ranks, respectively. It is true that both Mechanics and Pilots perform tasks according to written procedures. However, for both of these specialties task performance is reinforced through training, simulation, and/or repetition, more than the other specialties, which elevates the influence of "muscle-memory" as a contributing factor. Also, for all of the crew specialties, focusing on critical abilities requires that some abilities that are important to the work must be subordinated to others that are even more important. In this regard, Written Comprehension was ranked by the Mechanic and Pilot SMEs within the Important category, despite missing the (arbitrary) cut-off.

Confidence was included among the list of cognitive, physical, and social abilities, even though it is not actually an ability or skill, but rather, a personal characteristic. We included Confidence in our list because it was identified as a trait of successful performers and esteemed leaders during the US Navy's long program of research in Antarctica. Our SMEs confirmed this extrapolation from space analog conditions by ranking Confidence among the most important attributes for all specialties considered in the current study.

The following three tables present results of the ability-ranking. The first table presents (in two pages) the rank-orders of all 52 cognitive and physical abilities, the five social skills, and the one personal characteristic (Confidence) for each of the eight crew specialties/roles; the cells are color-coded for cognitive, physical, and social abilities to facilitate comparisons among the crew specialties. The second table presents the 58 abilities and social skills in alphabetical order with the rank-orders listed for each of the eight crew specialties/roles and for the combined measure, which was derived by summing the mean ranks from all crew specialties. The third table also is a matrix of abilities by crew specialty, but with the abilities listed in the order of the combined measure. Only the rank-orders of the top 15 abilities are listed in the cells of the third table for each crew specialty; 15 is an arbitrary cutoff that represents the most-highly-ranked 25 percent of the Fleishman abilities and our social skills as determined by the SMEs from each crew specialty. The 21 abilities that were not included by the SMEs in any of the crew positions' top 15 were excluded and are listed after the matrix. The 58 abilities/skills ranked by the SMEs are composed of 31 physical abilities (54 percent), 21 cognitive abilities (36 percent), and six social skills (10 percent). The 21 excluded abilities comprise 18 physical abilities (86 percent) and three cognitive abilities (14 percent); all six social skills were among the top 15 for at least one of the eight crew specialties.

	Skill/Ability Rank by Crew Specialty/Role Ranks 1 - 29								
	Leader	**Pilot**	**Physician**	**Biologist**	**Geologist**	**Computer**	**Electrician**	**Mechanic**	**Combined**
1	Teamwork	Reaction Time	Problem Sensitivity	Inductive Reasoning	Inductive Reasoning	Inductive Reasoning	Inductive Reasoning	Inductive Reasoning	Inductive Reasoning
2	Confidence	Control Precision	Inductive Reasoning	Confidence	Deductive Reasoning	Deductive Reasoning	Problem Sensitivity	Problem Sensitivity	Deductive Reasoning
3	Problem Sensitivity	Spatial Orientation	Deductive Reasoning	Deductive Reasoning	Teamwork	Problem Sensitivity	Confidence	Deductive Reasoning	Problem Sensitivity
4	Patience	Rate Control	Confidence	Information Ordering	Patience	Information Ordering	Deductive Reasoning	Manual Dexterity	Confidence
5	Emotional Control	Time Sharing	Patience	Patience	Confidence	Mathematical Reasoning	Information Ordering	Patience	Patience
6	Oral Expression	Confidence	Speed of Closure	Selective Attention	Spatial Orientation	Written Comprehension	Visual Color Discrimination	Written Comprehension	Teamwork
7	Tolerance	Emotional Control	Teamwork	Problem Sensitivity	Originality	Oral Comprehension	Finger Dexterity	Originality	Information Ordering
8	Inductive Reasoning	Response Orientation	Oral Comprehension	Arm-Hand Steadiness	Oral Expression	Time Sharing	Manual Dexterity	Visualization	Originality
9	Speech Clarity	Teamwork	Manual Dexterity	Finger Dexterity	Selective Attention	Oral Expression	Originality	Mathematical Reasoning	Speed of Closure
10	Deductive Reasoning	Speed of Closure	Finger Dexterity	Originality	Visualization	Confidence	Selective Attention	Teamwork	Selective Attention
11	Oral Comprehension	Near Vision	Originality	Written Comprehension	Flexibility of Closure	Near Vision	Mathematical Reasoning	Confidence	Written Comprehension
12	Affability	Perceptual Speed	Written Comprehension	Manual Dexterity	Problem Sensitivity	Selective Attention	Visualization	Information Ordering	Visualization
13	Fluency of Ideas	Multi-Limb Coordination	Affability	Near Vision	Emotional Control	Memorization	Patience	Arm-Hand Steadiness	Oral Comprehension
14	Time Sharing	Far Vision	Emotional Control	Flexibility of Closure	Stamina	Speed of Closure	Near Vision	Rate Control	Time Sharing
15	Originality	Visualization	Information Ordering	Time Sharing	Fluency of Ideas	Originality	Speed of Closure	Control Precision	Oral Expression
16	Information Ordering	Information Ordering	Fluency of Ideas	Speed of Closure	Written Comprehension	Speech Clarity	Teamwork	Auditory Attention	Manual Dexterity
17	Speech Hearing	Manual Dexterity	Selective Attention	Fluency of Ideas	Affability	Patience	Arm-Hand Steadiness	Finger Dexterity	Emotional Control
18	Written Comprehension	Deductive Reasoning	Oral Expression	Written Expression	Far Vision	Teamwork	Night Vision	Reaction Time	Speech Clarity
19	Written Expression	Arm-Hand Steadiness	Arm-Hand Steadiness	Visual Color Discrimination	Visual Color Discrimination	Finger Dexterity	Oral Expression	Speed of Closure	Near Vision
20	Speed of Closure	Depth Perception	Tolerance	Mathematical Reasoning	Speech Clarity	Visualization	Time Sharing	Flexibility of Closure	Finger Dexterity
21	Category Flexibility	Selective Attention	Visualization	Wrist-Finger Speed	Tolerance	Fluency of Ideas	Written Comprehension	Static Strength	Flexibility of Closure
22	Visualization	Problem Sensitivity	Time Sharing	Teamwork	Speed of Closure	Perceptual Speed	Number Facility	Multi-Limb Coordination	Fluency of Ideas
23	Auditory Attention	Night Vision	Speech Clarity	Oral Expression	Near Vision	Flexibility of Closure	Memorization	Dynamic Strength	Mathematical Reasoning
24	Selective Attention	Speech Hearing	Flexibility of Closure	Category Flexibility	Oral Comprehension	Manual Dexterity	Flexibility of Closure	Oral Comprehension	Affability
25	Memorization	Patience	Speech Hearing	Number Facility	Manual Dexterity	Emotional Control	Perceptual Speed	General Hearing	Arm-Hand Steadiness
26	Perceptual Speed	Oral Comprehension	Perceptual Speed	Oral Comprehension	Written Expression	Control Precision	Oral Comprehension	Gross Body Coordination	Reaction Time
27	Reaction Time	Inductive Reasoning	Spatial Orientation	Control Precision	Information Ordering	Number Facility	General Hearing	Tolerance	Perceptual Speed
28	Flexibility of Closure	Glare Sensitivity	Reaction Time	Memorization	Gross Body Coordination	Wrist-Finger Speed	Reaction Time	Fluency of Ideas	Memorization
29	General Hearing	Peripheral Vision	Depth Perception	Visualization	Gross Body Equilibrium	Reaction Time	Speech Clarity	Sound Localization	Control Precision
	Key: Cognitive Abilities=				Social Skills=			Physical Abilities=	

	Skill/Ability Rank by Crew Specialty/Role Ranks 30 - 58								
	Leader	**Pilot**	**Physician**	**Biologist**	**Geologist**	**Computer**	**Electrician**	**Mechanic**	**Combined**
30	Mathematical Reasoning	Speech Clarity	Auditory Attention	Emotional Control	Time Sharing	Category Flexibility	Auditory Attention	Emotional Control	Tolerance
31	Spatial Orientation	Visual Color Discrimination	Written Comprehension	Perceptual Speed	Category Flexibility	Arm-Hand Steadiness	Sound Localization	Visual Color Discrimination	Visual Color Discrimination
32	Stamina	Finger Dexterity	Written Expression	Speech Clarity	Dynamic Strength	Speech Hearing	Fluency of Ideas	Speech Hearing	Speech Hearing
33	Number Facility	Auditory Attention	Memorization	Tolerance	Memorization	Response Orientation	Dynamic Flexibility	Time Sharing	Spatial Orientation
34	Response Orientation	Gross Body Equilibrium	Multi-Limb Coordination	Affability	Depth Perception	General Hearing	Control Precision	Number Facility	Number Facility
35	Sound Localization	Memorization	Number Facility	Depth Perception	Finger Dexterity	Sound Localization	Extent Flexibility	Oral Expression	Written Expression
36	Near Vision	General Hearing	Control Precision	Reaction Time	Perceptual Speed	Rate Control	Written Expression	Response Orientation	Auditory Attention
37	Depth Perception	Affability	Response Orientation	Rate Control	Mathematical Reasoning	Visual Color Discrimination	Affability	Spatial Orientation	Category Flexibility
38	Rate Control	Oral Expression	Stamina	Speech Hearing	Trunk Strength	Auditory Attention	Category Flexibility	Memorization	Rate Control
39	Control Precision	Tolerance	Mathematical Reasoning	Glare Sensitivity	Arm-Hand Steadiness	Multi-Limb Coordination	Multi-Limb Coordination	Near Vision	Multi-Limb Coordination
40	Manual Dexterity	Stamina	General Hearing	Multi-Limb Coordination	Extent Flexibility	Affability	Emotional Control	Gross Body Equilibrium	Depth Perception
41	Far Vision	Number Facility	Gross Body Coordination	Auditory Attention	Speech Hearing	Gross Body Coordination	Speech Hearing	Selective Attention	General Hearing
42	Gross Body Equilibrium	Wrist-Finger Speed	Wrist-Finger Speed	Spatial Orientation	Static Strength	Tolerance	Wrist-Finger Speed	Speech Clarity	Response Orientation
43	Dynamic Strength	Mathematical Reasoning	Category Flexibility	Response Orientation	Number Facility	Written Expression	Response Orientation	Affability	Stamina
44	Gross Body Coordination	Dynamic Flexibility	Gross Body Equilibrium	General Hearing	Multi-Limb Coordination	Extent Flexibility	Gross Body Equilibrium	Stamina	Gross Body Coordination
45	Peripheral Vision	Gross Body Coordination	Visual Color Discrimination	Gross Body Coordination	Control Precision	Depth Perception	Rate Control	Explosive Strength	Wrist-Finger Speed
46	Multi-Limb Coordination	Written Comprehension	Peripheral Vision	Extent Flexibility	Dynamic Flexibility	Dynamic Flexibility	Gross Body Coordination	Wrist-Finger Speed	Gross Body Equilibrium
47	Visual Color Discrimination	Flexibility of Closure	Dynamic Flexibility	Stamina	Reaction Time	Spatial Orientation	Glare Sensitivity	Perceptual Speed	Sound Localization
48	Finger Dexterity	Originality	Dynamic Strength	Trunk Strength	Rate Control	Night Vision	Depth Perception	Depth Perception	Far Vision
49	Night Vision	Category Flexibility	Rate Control	Dynamic Flexibility	Glare Sensitivity	Glare Sensitivity	Stamina	Trunk Strength	Dynamic Flexibility
50	Static Strength	Extent Flexibility	Far Vision	Gross Body Equilibrium	Explosive Strength	Stamina	Spatial Orientation	Dynamic Flexibility	Dynamic Strength
51	Arm-Hand Steadiness	Dynamic Strength	Sound Localization	Peripheral Vision	General Hearing	Gross Body Equilibrium	Tolerance	Written Expression	Extent Flexibility
52	Trunk Strength	Sound Localization	Extent Flexibility	Sound Localization	Response Orientation	Trunk Strength	Peripheral Vision	Category Flexibility	Night Vision
53	Dynamic Flexibility	Trunk Strength	Static Strength	Dynamic Strength	Wrist-Finger Speed	Peripheral Vision	Dynamic Strength	Extent Flexibility	Glare Sensitivity
54	Extent Flexibility	Speed of Limb Movement	Glare Sensitivity	Night Vision	Auditory Attention	Static Strength	Speed of Limb Movement	Night Vision	Peripheral Vision
55	Speed of Limb Movement	Fluency of Ideas	Trunk Strength	Speed of Limb Movement	Sound Localization	Far Vision	Far Vision	Peripheral Vision	Static Strength
56	Wrist-Finger Speed	Written Expression	Speed of Limb Movement	Static Strength	Speed of Limb Movement	Speed of Limb Movement	Static Strength	Far Vision	Trunk Strength
57	Explosive Strength	Static Strength	Explosive Strength	Far Vision	Peripheral Vision	Dynamic Strength	Trunk Strength	Speed of Limb Movement	Speed of Limb Movement
58	Glare Sensitivity	Explosive Strength	Night Vision	Explosive Strength	Night Vision	Explosive Strength	Explosive Strength	Glare Sensitivity	Explosive Strength
	Key: Cognitive Abilities=				Social Skills=			Physical Abilities=	

	Skill/Ability Rank by Crew Specialty/Role in Alphabetical Order								
	Leader	Pilot	Physician	Biologist	Geologist	Computer	Electrician	Mechanic	Combined
Affability	12	37	13	34	17	40	37	43	24
Arm-Hand Steadiness	51	19	19	8	39	31	17	13	25
Auditory Attention	23	33	30	41	54	38	30	16	36
Category Flexibility	21	49	43	24	31	30	38	52	37
Confidence	2	6	4	2	5	10	3	11	4
Control Precision	39	2	36	27	45	26	34	15	29
Deductive Reasoning	10	18	3	3	2	2	4	3	2
Depth Perception	37	20	29	35	34	45	48	48	40
Dynamic Flexibility	53	44	47	49	46	46	33	50	49
Dynamic Strength	43	51	48	53	32	57	53	23	50
Emotional Control	5	7	14	30	13	25	40	30	17
Explosive Strength	57	58	57	58	50	58	58	45	58
Extent Flexibility	54	50	52	46	40	44	35	53	51
Far Vision	41	14	50	57	18	55	55	56	48
Finger Dexterity	48	32	10	9	35	19	7	17	20
Flexibility of Closure	28	47	24	14	11	23	24	20	21
Fluency of Ideas	13	55	16	17	15	21	32	28	22
General Hearing	29	36	40	44	51	34	27	25	41
Glare Sensitivity	58	28	54	39	49	49	47	58	53
Gross Body Coordination	44	45	41	45	28	41	46	26	44
Gross Body Equilibrium	42	34	44	50	29	51	44	40	46
Inductive Reasoning	8	27	2	1	1	1	1	1	1
Information Ordering	16	16	15	4	27	4	5	12	7
Manual Dexterity	40	17	9	12	25	24	8	4	16
Mathematical Reasoning	30	43	39	20	37	5	11	9	23
Memorization	25	35	33	28	33	13	23	38	28
Multi-Limb Coordination	46	13	34	40	44	39	39	22	39
Near Vision	36	11	32	13	23	11	14	39	19
Night Vision	49	23	58	54	58	48	18	54	52
Number Facility	33	41	35	25	43	27	22	34	34
Oral Comprehension	11	26	8	26	24	7	26	24	13
Oral Expression	6	38	18	23	8	9	19	35	15
Originality	15	48	11	10	7	15	9	7	8
Patience	4	25	5	5	4	17	13	5	5
Perceptual Speed	26	12	26	31	36	22	25	47	27
Peripheral Vision	45	29	46	51	57	53	52	55	54
Problem Sensitivity	3	22	1	7	12	3	2	2	3
Rate Control	38	4	49	37	48	36	45	14	38
Reaction Time	27	1	28	36	47	29	28	18	26
Response Orientation	34	8	37	43	52	33	43	36	42
Selective Attention	24	21	17	6	9	12	10	41	10
Sound Localization	35	52	51	52	56	35	31	29	47
Spatial Orientation	31	3	27	42	6	47	50	37	33
Speech Clarity	9	30	23	32	20	16	29	42	18
Speech Hearing	17	24	25	38	41	32	41	32	32
Speed of Closure	20	10	6	16	22	14	15	19	9
Speed of Limb Movement	55	54	56	55	55	56	54	57	57
Stamina	32	40	38	47	14	50	49	44	43
Static Strength	50	57	53	56	42	54	56	21	55
Teamwork	1	9	7	22	3	18	16	10	6
Time Sharing	14	5	22	15	30	8	20	33	14
Tolerance	7	39	20	33	21	42	51	27	30
Trunk Strength	52	53	55	48	38	52	57	49	56
Visual Color Discrimination	47	31	45	19	19	37	6	31	31
Visualization	22	15	21	29	10	20	12	8	12
Wrist-Finger Speed	56	42	42	21	53	28	42	46	45
Written Comprehension	18	46	12	11	16	6	21	6	11
Written Expression	19	56	31	18	26	43	36	51	35

Top 15 Skills/Abilities by Crew Specialty/Role								
	Leader	Pilot/Nav	Physician	Biologist	Geologist	Computer	Electrician	Mechanic
Inductive Reasoning	8		2	1	1	1	1	1
Deductive Reasoning	10		3	3	2	2	4	3
Problem Sensitivity	3		1	7	12	3	2	2
Confidence	2	6	4	2	5	10	3	11
Patience	4		5	5	4		13	5
Teamwork	1	9	7		3			10
Information Ordering			15	4		4	5	12
Originality	15		11	10	7	15	9	7
Speed of Closure		10	6			14	15	
Selective Attention				6	9	12	10	
Written Comprehension			12	11		6		6
Visualization		15			10		12	8
Oral Comprehension	11		8			7		
Time Sharing	14	5		15		8		
Oral Expression	6				8	9		
Manual Dexterity			9	12			8	4
Emotional Control	5	7	14		13			
Speech Clarity	9							
Near Vision		11		13		11	14	
Finger Dexterity			10	9			7	
Flexibility of Closure				14	11			
Fluency of Ideas	13				15			
Mathematical Reasoning						5	11	9
Affability	12		13					
Arm-Hand Steadiness				8				13
Reaction Time		1						
Perceptual Speed		12						
Memorization						13		
Control Precision		2						15
Tolerance	7							
Visual Color Discrimination							6	
Spatial Orientation		3			6			
Rate Control		4						14
Multi-Limb Coordination		13						
Response Orientation		8						
Stamina					14			
Far Vision		14						
Key: Cognitive Abilities=			Social Skills=			Physical Abilities=		

Abilities Not Ranked Among the Top 15 for Any Crew Specialty/Role

Number Facility	Night Vision	Static Strength
Written Expression	Glare Sensitivity	Trunk Strength
Category Flexibility	Peripheral Vision	Dynamic Strength
	Depth Perception	Explosive Strength
	Speech Hearing	Extent Flexibility
	General Hearing	Dynamic Flexibility
	Auditory Attention	Wrist-Finger Speed
	Sound Localization	Gross Body Equilibrium
		Gross Body Coordination
		Speed of Limb Movement

The first of the three tables/matrices is designed to facilitate focusing on crew roles; the second table facilitates focusing on a specific ability to compare the specialties/roles; the third table identifies key abilities and domains across crew roles. Together the three tables/matrices show that four cognitive abilities associated with problem-solving are among the most important abilities to seven of the eight crew specialties/roles: Inductive Reasoning, Deductive Reasoning, Problem Sensitivity, and Originality. Inductive Reasoning is the ability to combine pieces of information to form a general rule or conclusion, such as the cause of seemingly unrelated error messages. In contrast, Deductive Reasoning is the ability to apply a general rule to derive a logical answer or hypothesis, which guides most troubleshooting processes. Problem Sensitivity is the ability to notice when something is wrong, such as interpreting a steadily-decreasing power output as a symptom of imminent system failure. And, Originality is the ability to invent a creative solution to a problem, as Mark Watney did by converting his habitat into a potato farm when he found himself stranded on Mars with a limited food supply (see footnote 36 on page 25). An additional cognitive ability was highly-ranked by five of the SME groups: Information Ordering is the ability to arrange items or actions in a certain order to solve a problem, such as deciding quickly to disconnect the power before attempting to extinguish a fire in an electrical system. All of these cognitive abilities are essential when responding to emergencies.

Problem-solving/cognitive abilities were followed closely by social skills in the SMEs' individual and combined rankings. Confidence, Patience, Teamwork, and Emotional Control were the highest-ranked social skills and Confidence is the only item among the 58 to be ranked in the top 15 by SMEs in all eight crew specialties/roles. SMEs representing all crew specialties included at least one social skill among their top 10.[45] When considering the role of expedition Leader, the SMEs ranked all six social skills among the most important for successful performance (Leader is the only specialty/role to include all six social skills in the top 15).[46] Pilot SMEs were unique among our sample by considering physical, rather than cognitive, abilities to be more important to successful job performance; Reaction Time, Control Precision, Spatial Orientation, and Rate Control are the abilities that enable pilots to survive in an inherently dangerous occupation. However, even the pilot SMEs ranked three of the social skills within their top 15 (i.e., Confidence, Teamwork, and Emotional Control), reflecting a consensus among pilots about the importance of getting along in the cockpit and during long layovers, as mentioned previously.[47]

Manual Dexterity, which is the ability to make coordinated movements of the hands and arms to grasp or move objects quickly and accurately, was the highest-ranked physical ability, overall, and is among the top 15 for Physicians, Biologists, Electricians, and Mechanics. Near Vision was ranked among the top 15 abilities for Pilots, Biologists, Computer Specialists, and Electricians, roles that require reading displays accurately and seeing small objects clearly. Finger Dexterity was ranked among the top 15 abilities by SMEs representing Physicians, Biologists, and Electricians, roles that must make coordinated movements of the fingers to manipulate small objects accurately and quickly. Speech Clarity was the only physical ability ranked by the SMEs in the top 15 for Leaders, due presumably to the need for expedition leaders to convey directions and intentions, personally and via radio, in a manner that is understood by all members of the crew and in all circumstances, despite cultural/linguistic differences, environmental or technical constraints, and/or in emergency situations.

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[45] Empathy and Conscientiousness were suggested as relevant personal qualities that might have been included in our analysis; however, both are psychological constructs and we chose to limit our list of social skills to behaviors identified by previous space analog research. A case could be made for Conscientiousness being the equivalent of Task Proficiency, one of the personal traits of esteemed crew identified by the Navy in Antarctica, but it is reasonable to assume that all personnel selected for an expedition to Mars would be competent in their fields.

[46] The relatively high ranks assigned to the social skills indicate that the SMEs understood the descriptions of likely physical and social conditions during a Mars expedition that were provided as part of the instructions to the card-sort exercise (see Appendix B).

[47] From an aircraft pilot's perspective, a 30-month expedition might be viewed as two six-month flights separated by an 18-month layover with the crew on the surface of Mars.

Personnel-Selection and Crew Composition

The history of exploration is littered with examples of imperfect personnel selection and its consequences, from the friction between sailors and scientists during the *Jeannette* Arctic Expedition in 1880 to the psychosis that emerged among the Seabees who were building in 1956 what later was named McMurdo Station in Antarctica.[48] The Seabees built a room padded with mattresses to muffle their comrade's psychotic ravings, but the prejudices of the *Jeannette's* crew had eroded any solidarity they might have had when they embarked, so they simply fell apart into factions when their ship was beset; few survived the ordeal that followed.[49] It was in response to another highly disruptive psychosis, from which there was no escape, during the Australasian Antarctic Expedition in 1912 that Douglas Mawson wrote, "In no department can a leader spend time more profitably than in the selection of the men who are to accomplish the work."[50]

Psychological issues are outside the scope of the current study, aside from the six social skills that were ranked highly by our SMEs and a few design implications. It is reasonable to assume that candidates for interplanetary crew positions will be screened for psychological problems at least as thoroughly as astronauts are screened now. However, because the best predictor of future performance is past performance, it would be prudent to select candidates who have demonstrated their abilities to adjust to isolated and confined living by having worked at least six months on the ISS, on the Moon, or at some other remote duty location without experiencing behavioral issues. We hope that the managers of future exploration-class space missions recruit technically-qualified crew who also possess the abilities and social skills identified as important by the current study, which include, Confidence, Patience, Teamwork, Emotional Control, Affability, and Tolerance. Additional characteristics that have been identified anecdotally from the expedition literature include: a sense of humor, effective conflict resolution skills, the ability to be easily entertained, and most important, tactfulness in interpersonal relations.

Personal Traits

Willy Ley and Wernher von Braun speculated about the personal traits needed among the crew of a Mars expedition in one of their books that stimulated popular interest in Mars exploration. They wrote that the astronauts selected for the mission must be in good physical condition and "quietly competent, with an outstanding capacity to learn, an exceptional ability of adaptation, and a preference for working in and as a team." They added that crew members must be practical but have good imaginations and a well-developed sense of humor. Also, the crew must be trained to perform tasks outside of their primary fields of expertise to provide backups if other crew members were to become incapacitated or unable to fulfill the duties of their primary specialties/roles.[51]

The number of crew members needed to accomplish mission objectives influences many factors, including the sizes of the ascent and descent vehicles, the size of the interplanetary ship, and the volume of the surface habitat. Crew size also influences the amounts of consumables, other supplies and equipment, and fuel needed to lift the ascent vehicle out of Earth's gravity well, propel the interplanetary ship to Mars and slow it when it arrives, land the descent vehicle on the surface, and propel the interplanetary ship on a trajectory to intercept Earth after the crew has spent 18 months on the surface. The architects of DRA-5 sought to reduce the amount of propellant that must be transported to Mars by extracting fuel for the Mars Ascent Vehicle from resources found on the planet and by abandoning the interplanetary ship as it approaches Earth, allowing the ship to continue on course indefinitely, while landing the crew in a small capsule, as described previously.

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[48] LCDR David Canham, *The Log of the Naval Mobile Construction Battalion (Special)*, unpublished station log, December 1955-March 1957.

[49] Leonard F. Guttridge. *Icebound: The Jeannette Expedition's Quest for the North Pole*. Shrewsbury: Airlife Publishing, 1988.

[50] Douglas Mawson. *The Home of the Blizzard: Being the Story of the Australasian Antarctic Expedition, 1911-1914*. London: Hodder and Stoughton, 1930 (p. 6).

[51] Willy Ley and Wernher von Braun. *The Exploration of Mars.* New York: Viking Press, 1960.

Most Mars expedition plans have assumed a crew size of at least six personnel, but mission planners have considered various ways to reduce the number of crew. For example, the 1993 ARC study determined that mission objectives could be accomplished with five specialists: 1) mechanical engineer; 2) electrical/electronic engineer; 3) geoscientist; 4) life scientist; and, 5) physician/psychologist.[52] The 2001 Mars Surface Reference Mission also identified five crew responsibilities: 1) command; 2) medical; 3) geoscience; 4) bioscience; and, 5) electrical/electronic operations.[53] However, the ARC study concluded that seven or eight crew members would be needed to reduce risk (and assumed a crew of six for planning), and the Mars Surface Reference Mission concluded that six crew members would be needed to accommodate peak workloads and seven or eight crew members would be needed to ensure a safe margin for responding to contingencies. Similarly, the *DRA-5 Addendum* included a strategy by which the identified functional requirements could be satisfied by four, cross-trained crew members:

1) Mission commander & vehicle systems specialist/engineer. Responsible for operations/safety.
2) Medical doctor. Biology background to back up science crew; emergency medical technician (EMT)-level training for all crew members as backup.
3) Geologist/biologist/meteorologist/planetary scientist. A geologist with biology and meteorology training; each crew member also trained in geology.
4) Technical specialist/assistant geologist. An expert at troubleshooting problems and fabricating parts, while also having a substantial geology background.

The DRA-5 plan found that reducing the number of crew members from the usual six to four would reduce vehicle size, pressurized volume, and life support infrastructure substantially, which would further reduce propellant requirements and allow a smaller vehicle for Earth return. However, the plan's authors concluded that four crew members might be operationally sufficient to perform the expected tasks if all goes well, but four would be insufficient to ensure mission success if a single crew member were to become ill or otherwise incapacitated, despite cross-training and attempts to provide redundant capabilities. The DRA-5 plan noted, in particular, that it might be possible for one crew member to possess the inter-disciplinary knowledge and abilities needed to perform all science tasks, but it would be wise to include an additional specialist crew member to increase the probability of completing the expedition's science objectives.[54]

Crew Size

The current study's principal investigator was asked by the US Navy to determine whether the flight deck crew of the Landing Craft Air Cushion could be reduced from three to two, as part of a larger personnel-reduction effort. An experiment was designed in which key mission segments were performed in a full-motion simulator by crews consisting of Craftmaster, Engineer, and Navigator, and the same segments performed by crews with only the Craftmaster and Navigator. We found that the segments conducted by only two flight deck crew members were performed more slowly and produced greater stress and fatigue than those performed by full crews. We also found that while it was possible to operate the hovercraft with only two crew members, operational effectiveness was degraded and crews were forced to abort missions when even the slightest problem or malfunction occurred, due to reduced cognitive resources available with fewer crew members to share the tasks.[55] An undersized crew of a Mars-bound spacecraft or a habitat on the planetary surface would not have the luxury of aborting the mission or returning to a mother ship to make repairs.

[52] Michael B. Duke and Nancy Ann Budden. *Mars Expedition Study: Workshop II*, NASA Conference Publication 3243. Houston, TX: Lyndon B. Johnson Space Center, 1993.
[53] Stephen J. Hoffman. *The Mars Surface Reference Mission: A Description of Human and Robotic Surface Activities*. NASA/TP-2001-209371, Houston, TX: Johnson Space Center (December) 2001.
[54] Bret Drake (Editor). *Human Exploration of Mars Design Reference Architecture 5.0 Addendum*. NASA/SP–2009–566-ADD. Washington, DC: NASA Headquarters (July) 2009.
[55] Jack Stuster. *Salient Human Factors Issues Concerning the Landing Craft Air Cushion (LCAC),* Anacapa Sciences, Inc., Santa Barbara, CA, (July) 2001.

Each crew member increases the overall cost of the endeavor and, for this reason, *decreases* the likelihood of ever sending humans to Mars. It is this imperative that compels us to identify the crew specialties/roles necessary to perform the expected tasks and to develop selection and training strategies that enable safe performance of the work with the fewest crew members possible. Analysis of the tasks for which Mars expedition crew members must be prepared to perform led us to identify the eight specialties/roles, described previously. Four additional roles were suggested by the task analysis, but they were not introduced until now for different reasons. First, a Crew Medical Officer (CMO) is an astronaut who has received at least 40 hours of medical diagnostic and treatment training and one week of field medical training, which includes dental, Emergency Medicine (EM), and Intensive Care Unit (ICU) experience. NASA-STD-3001 requires that the CMO must be an actual physician on missions longer than 210 days, but many non-physician astronauts receive the training and serve as CMOs on ISS missions, which are usually around 180 days.[56] Many of the medical tasks that are likely during a Mars expedition could be performed by non-physician astronauts who have received CMO training. NASA's CMO tradition and standards could ensure sufficient backup to an actual physician for many medical responsibilities.

Second, our research identified several tasks that would ideally be performed by an astronomer or astrophysicist but they are subordinate in importance to the primary scientific goals of a Mars expedition, which are to search for evidence of extant/extinct life and to better understand planetary processes. The astrophysical tasks include conducting observations and measurements from the surface of Mars and during the cruise phases. The surface tasks were described in the DRA-5 Addendum as coronal imaging, ionospheric radiation measuring, and the placing of small laser transponders to enable precision ranging from Earth, similar to what was accomplished during Apollo missions to the Moon. The tasks that would be performed during the cruise phases are primarily observational and would include, most notably, recording the transit of Earth and the Moon across the Sun as they pull ahead of the ship's trajectory; the event would occur approximately 73 days after the Trans-Mars Injection burn that sets the interplanetary spacecraft on its six-month course to the red planet.[57] The 2001 Mars Surface Reference Mission includes allotments of 200 kg for astronomy instruments and 100 kg for telescopes to support astrophysical science objectives during an expedition to Mars.

Planetary Transits

A transit occurs when a planet passes directly between the Sun and the point of view of the observer. During a transit of Venus, observers on Earth see a small black disk move across the face of the Sun, which usually takes several hours (e.g., the transit of 2012 lasted 6 hours and 40 minutes). Transits of Venus are among the rarest predictable astronomical phenomena and occur in pairs of transits eight years apart separated by gaps of 121.5 years and 105.5 years. Transits of Venus have been historically and scientifically important, as they were used to calculate estimates of distances to Venus and the Sun, and the size of the Solar System. Johannes Kepler was the first person to predict a transit of Venus (the 1631 event, predicted in 1627). Most relevant to the current study were the observations made from Tahiti by Captain James Cook, British astronomer Charles Green, British naturalist Joseph Banks, and Swedish naturalist Daniel Solander on 3 June 1769 during Cook's first circumnavigation in HMS *Endeavour*. The 18th Century transits of Venus were the focus of enormous international cooperation and precursors of modern collaborative science. Calculations of the distance to the Sun based on the 1769 transit differ from modern estimates by only eight-tenths of one percent. Astronauts see themselves in the long tradition of exploration and would be enthusiastic participants in a program of astrophysical science during an expedition to Mars.

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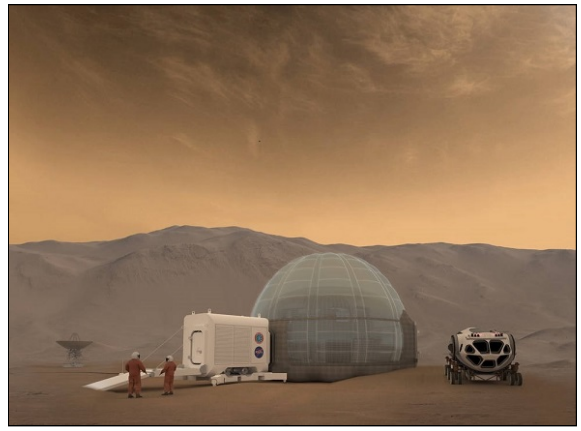
[56] NASA. *Space Flight Human System Standard Volume I: Crew Health*. NASA-STD-3001. Washington, DC: National Aeronautics and Space Administration, 2007.
[57] James E. Oberg. *Mission to Mars: Plans and Concepts for the First Manned Landing.* Harrisburg. PA: Stackpole Books, 1982, page 94.

Third, results of the task analysis also led the research team to consider heavy equipment operator as an additional specialty/role. That is, we believe it will be necessary to excavate crater-like cavities in the Martian surface, perhaps two meters deep, that match the diameters of the cylindrical structures that will have been delivered before the crew arrives. The structures must be dragged into the cavities and then covered with at least one meter of regolith to provide shielding from the various forms of radiation that could affect crew health and performance during their 18-months on the surface of Mars. A vehicle with the capabilities of a conventional backhoe and a competent operator would be required to perform these construction tasks.

Burrowing into north polar ice would provide radiation shielding, but the location is unfavorable (e.g., poor communications, less sunlight, geology). An alternative method would be to pump subsurface water between the layers of an inflatable structure, or dome, which would freeze and provide excellent shielding. The Mars Ice Home, depicted here, was developed by NASA's Langley Research Center in 2016. The concept has several advantages over regolith-shielded designs, but would require complex automated processes to deploy the shell; drill wells; pump, pressurize, and transfer liquid water; and then fill the space between the habitat's inner and outer layers. Designers estimate that it would require more than a year to ready the structure before the crew arrives.[58]



NASA Langley Research Center's Mars Ice Home.

The fourth ancillary crew specialty considered by the research team is botanist, a role made famous by the protagonist of Andy Weir's 2011 novel, *The Martian*. Although it was unclear why a botanist would be included among the crew of an opposition-class, or short-stay, expedition to Mars, Mark Watney's "skill-set" enabled the character to survive by converting the surface habitat into a potato-growing facility after he was left for dead by his crew mates. The current study's mission assumptions include a pre-positioned greenhouse to enable the growing of vegetables during the 18-month surface stay to augment the crew's diet of preserved food and to provide meaningful work during periods of low-tempo operations. Despite the utility of the fictional Watney's special knowledge, the research team concluded that the skills needed to deploy and operate a greenhouse could be developed through training, along with the skills necessary to operate excavation equipment, to serve as a CMO, to record specific astronomical observations, and to perform other duties as backup to a specialist.

Problem-Solving

The problem-solving abilities and personal traits that Andy Weir wrote into his protagonist enabled the character to survive and endeared Mark Watney to readers, including NASA astronauts, managers, engineers, and scientists (see footnote 36 on page 25). They are the same general abilities and social skills that were ranked highly by SMEs during the current study: Inductive and Deductive Reasoning, Problem Sensitivity, Information Ordering, Originality, Confidence, Patience, Emotional Control, and Teamwork.

Our assumptions and inferences about crew composition are subject to change, depending primarily on developments in automation and remote operation. For example, it might be possible to send autonomous vehicles to perform the excavation and construction tasks in advance of the human crew's arrival, which would eliminate the need for a trained equipment operator, reduce the crew's exposure to risk, and provide a safe haven for the crew immediately upon their arrival on the surface of Mars.

[58] https://www.nasa.gov/feature/langley/a-new-home-on-mars-nasa-langley-s-icy-concept-for-living-on-the-red-planet
Also, NASA's 3-D Printed Habitat Design Competition identified five promising concepts for autonomous construction on the surface of Mars. https://www.designboom.com/architecture/nasa-mars-3d-habitat-competition-winners-centennial-challenge-07-30-2018/

Our analyses indicate that the work encompassed by the 1,125-tasks identified during the study could be performed by the eight primary crew specialties/roles listed again, below, this time with the four ancillary roles. We now turn our attention to personnel-selection and cross-training strategies with the goal of providing these key competencies and backups with the fewest number of crew members.

Primary Crew Roles		**Ancillary Crew Roles**
Leader	Mechanic	CMO
Biologist	Electrician	Botanist
Geologist	Pilot/Navigator	Astrophysicist
Physician	Computer Specialist	Equipment Operator

We assume that the personnel-selection process for an expedition to Mars will probably not allow the recruitment of eminent specialists, as in science fiction stories, but rather, individuals will be drawn from existing cadres of space-qualified personnel, almost certainly representing international partners. We will return to this topic later, but in the meantime, the research team identified four hypothetical crew-compositions by a rational process based on results of the task ratings and ability rankings to illustrate the possibilities of assembling and cross-training crews to satisfy operational requirements.

A: Six-Person Crew

Primary Specialties/Roles	**Backup Responsibilities**
Pilot/Navigator (Robotics & Rovers)[59]	Equipment Operator/CMO
Physician/Astrophysicist	Biologist/Geologist
Mechanic/Equipment Operator	Pilot/Navigator/Astrophysicist
Electrician/Computer Specialist	Mechanic/CMO/Botanist
Geologist/Leader	Electrician/Computer Specialist
Biologist/Botanist	Leader/CMO

B: Five-Person Crew

Primary Specialty/Roles	**Backup Responsibilities**
Pilot/Navigator (Robotics & Rovers)	Geologist/Leader/CMO
Physician/Biologist/Astrophysicist	Electrician/Computer Specialist
Mechanic/Equipment Operator	Biologist/CMO/Botanist
Electrician/Computer Specialist	Mechanic/Equipment Operator/CMO
Geologist/Leader/Botanist	Pilot/Navigator/Astrophysicist

C: Five-Person Crew

Primary Specialty/Roles	**Backup Responsibilities**
Pilot/Navigator (Robotics & Rovers)	Geologist/Leader/CMO
Physician/Astrophysicist/Botanist	Pilot/Navigator/Biologist
Mechanic/Equipment Operator	Electrician/Computer Specialist/CMO
Electrician/Computer Specialist	Mechanic/Equipment Operator
Geologist/Biologist/Leader	Botanist/Astrophysicist/CMO

D: Four-Person Crew

Primary Specialty/Roles	**Backup Responsibilities**
Pilot/Navigator/Leader/Astrophysicist	Geologist/Computer Specialist/CMO
Physician/Computer Specialist	Biologist/Mechanic/Electrician/Botanist
Mechanic/Electrician/Equipment Operator	Pilot/Navigator/Astrophysicist/CMO
Geologist/Biologist/Botanist	Equipment Operator/Leader/CMO

Reminder: Fewer crew members reduces mass requirements, but also reduces the availability of backup personnel and increases selection and pre-mission cross-training burdens.

[59] The Pilot/Navigator would have lead responsibility for robotics and rovers during Mars Surface Operations in all four hypothetical crew compositions.

The geologist has been assigned the role of expedition leader in three of the four hypothetical crew compositions. This is because demonstrated experience in a leadership role was found by the US Navy's Antarctic research program to be a characteristic of esteemed leaders.[60] Also, we learned from interviews with planetary geologists that most breakthrough discoveries in geology are made by mature professionals with considerable field experience. These reasons, coupled with the scientific purpose of the mission, suggest that the role of expedition leader might best be performed by a mature geologist with experience leading research teams in the field. Specialties within the discipline, such as Precambrian Biogeology, combine knowledge of geology and biology and offer opportunities to reduce crew size.

We resisted the temptation to assign a formal leadership role to the physician in any of the hypothetical crew compositions, because a physician can perform his or her medical responsibilities far better when independent of the command structure. This arrangement also permits the physician to serve as an informal adviser to the expedition leader, with the capability of providing an alternative opinion or perspective on issues. The task analysis shows that the physician should be skilled at emergency medicine and be capable of performing dental procedures. All four hypothetical crews include one physician, with medical backup provided by three crew members trained to NASA's CMO standard.

Not one of the three most-recent Mars mission plans, the 1993 ARC study, the 2001 Surface Reference Mission, and the 2009 DRA-5, includes a pilot or navigator in recommended crew compositions. The authors of these plans assume, correctly, that most piloting and navigating functions will be performed automatically and/or at the direction of mission control personnel. Although piloting and navigating are definitely candidates for automation, our task inventory includes nearly 200 tasks that might be performed by a pilot/navigator and they are among the highest-ranked actions by our SMEs in Difficulty, Importance, and Criticality. The top 20 percent of summary task statements are presented in a table on page 54 of this report and all 158 summary statements are listed in descending order of criticality in Appendix C. Two tables on the following pages list the numbers of component tasks and the crew specialties/roles that would perform the tasks for the top 50 percent of summary task statements in descending order of their criticality scores. The tables show that 13 of the top 20 summary task statements are the exclusive responsibility of the pilot/navigator:

Rank	Summary Task Statement
2.	*Monitor systems and perform piloting functions during Mars Surface Ascent.*
3.	*Perform piloting functions during Mars Surface Descent.*
5.	*Perform piloting functions during Earth Descent.*
6.	*Perform piloting functions during Mars Orbit Injection.*
7.	*Perform piloting functions during Mars Orbit Operations.*
8.	*Enter control inputs, manually with gloved hand, to pilot EAV during launch to LEO/CLO.*
9.	*Monitor systems and perform piloting functions during Trans Earth Injection.*
10.	*Perform piloting functions during Earth Approach.*
11.	*Assess displayed information, cognitively, to determine readiness to launch to LEO/CLO.*
13.	*Monitor displays and verify configurations before and during launch to LEO/CLO.*
14.	*Monitor systems during Earth Descent.*
18.	*Perform robot operations-related functions during Mars Surface Operations.*
20.	*Assess displayed information, cognitively, to determine readiness for TMI maneuver.*

The 96 component tasks comprised by the 13 summary task statements listed above describe monitoring displays, manipulating controls, and making decisions under nominal operations. The tasks also include interventions that must be made by a pilot or navigator if automated systems fail to function properly or under other contingency situations. All such tasks would be performed during dynamic phases of the mission and all would require immediate action by a skilled pilot. It is for these reasons that pilot/navigator and backups for this critical specialty are included in our recommendations.

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[60] Lawrence A. Palinkas. Psychosocial effects of adjustment in Antarctica - Lessons for long-duration spaceflight. *Journal of Spacecraft and Rockets*, 1990, p. 475.

Top 25 Percent of Summary Task Statements by Criticality and Crew Specialty with Numbers of Component Tasks												
Rank	Phase	Leader	Pilot/Nav	Physician	CMO	Biologist	Geologist	Computer	Electrician	Mechanic	Astrophysicist	All Crew
1	MSO		1				47					13
2	MSA		14									
3	MSD		9									
4	MSO											5
5	ESD		11									
6	MOI		3									
7	MO		2									
8	LTO		11									
9	TEI		4									
10	EA		8									
11	LTO		2									
12	CTM											3
13	LTO		13									
14	ESD		6									
15	MSO									1		11
16	MSO			2								
17	MSO						10				1	
18	MSO			2								
19	MSO		12				1					
20	TMI		1									
21	CTM		2									4
22	CTM			9	6							
23	CTM			2								
24	MSO		1									1
25	MSO			10	4							4
26	MSO											8
27	ESD		3									
28	CTM											15
29	MSD		6									
30	MSO			14	7							
31	MSO					6	2					
32	CTM											3
33	LTO		11									
34	MSO		1				1					6
35	CTM					2	1				8	1
36	CTE											15
37	MSO		4				1					1
38	CTE			9	6							
39	MSO								1			14
40	MSO				1	2						4
Percent of 1 - 40		0.0%	32.1%	12.3%	6.2%	2.6%	16.2%	0.0%	0.3%	0.3%	2.3%	27.8%

Additional implications of the task analysis (and results of other research) to crew-selection and training are: 1) Provide training in Mars geology to all crew members[61]; 2) Ensure that at least two crew members develop proficiency operating the pre-positioned excavation and well-drilling equipment; 3) The pilot and backup have the lead for robot and rover operations, but other crew members also should be trained; 4) Train a member of the crew to lead the observation of the Transit of Earth and Moon during the Cruise to Mars, but conduct the research as a group activity to foster solidarity early in the expedition; and, 5) Require that all crew members and mission control personnel receive training concerning the behavioral effects of isolation and confinement and the need to monitor each other's adjustment to the conditions.

[61] D. Eppler, C. Evans, B. Tewksbury, M. Helper, J. Bleacher, M. Fossum, D. Ross, & A Feustel. Geologic Training for America's Astronauts. *GSA Today*, v. 26, no. 8, 2016. [This paper describes ISS-focused geology training.]

Second 25 Percent of Summary Task Statements by Criticality and Crew Specialty with Numbers of Component Tasks												
Rank	Phase	Leader	Pilot/Nav	Physician	CMO	Biologist	Geologist	Computer	Electrician	Mechanic	Equip Operator Astrophysicist	All Crew
41	CTM			7	8							
42	MSO											9
43	MSO							2	7			
44	MSO						1			9		1
45	CTE		2									4
46	CTE			2								
47	CTM											2
48	MSO								2	8		6
49	CTM		2									5
50	MSO											11
51	MSO			5	12							5
52	CTE			7	8							
53	CTM							1	5	8		
54	MSD											3
55	CTE							1	5	8		
56	TMI		5									
57	MSO										11	1
58	CTM		3									3
59	MOI		2									
60	MSO											6
61	CTE		3									
62	MSO											5
63	CTM		3									
64	EA		4									
65	MSO											4
66	CTM											2
67	TMI		5									
68	CTE		3									3
69	MSO											6
70	ESD		7									5
71	MSA		2									3
72	CTM		3									
73	MO											4
74	CTE		2									4
75	CTE		3									
76	MO		3									
77	CTE											4
78	CTE					2	1				6	1
79	CTE											4
80	MOI		1									3
Percent of 1 - 40		0.0%	32.1%	12.3%	6.2%	2.6%	16.2%	0.0%	0.3%	0.3%	2.3%	27.8%
Percent of 41-80		0.0%	18.7%	7.4%	9.9%	0.7%	0.7%	1.4%	6.7%	11.7%	6.0%	36.7%
Percent of 1 - 80		0.0%	26.3%	10.4%	7.9%	1.8%	10.7%	0.6%	3.0%	5.1%	3.9%	30.2%

The first mention of the expedition leader is not found until the summary task statement ranked 102nd in criticality by the SMEs: *Perform planning and administrative functions, individually and with other crew members, during Mars Surface Operations.* Four examples of the 11 component tasks are listed below. Additional leader tasks occur at summary statements ranked 143rd and 144th of the 158 summary task statements.

Receive feedback about operations plans/timelines/work assignments from crew to improve operations.

Schedule tasks/monitor performance to ensure that resources are allocated appropriately among crew.

Review maps/charts/procedures, manually/visually, to plan construction and installation tasks.

Coordinate crew response to meteor penetration, hull breech, fire, ECLS, or other emergency.

"For scientific leadership give me Scott; for swift and efficient travel, Amundsen; but when you are in a hopeless situation, when there seems no way out, get down on your knees and pray for Shackleton." — *Apsley Cherry-Garrard*[62]

We reviewed published biographies of the 44, active-duty NASA Astronauts (in May 2018) and the biographies of the 12 Astronaut Candidates (assigned in 2017) to test the hypothesis that technically-qualified personnel could be selected from an existing pool of space operations professionals. Astronauts were counted as qualified for a crew role if they had an undergraduate or advanced degree in a directly related field and they were flagged as "maybe" if they had related experience (e.g. robotics operations, EMT, home auto repair). Astronauts were counted as qualified leaders if they had served as commander during ISS or NASA Extreme Environment Mission Operations (NEEMO) missions, or if they had military command experience. Also, an individual could be assigned to more than one role (e.g., a Physician Astronaut). Results of the review are presented in the following two tables.

Numbers of Current Active-Duty Astronauts by Mars Expedition Crew Specialty/Role

Crew Role	Biologist	Computer Specialist	Electrician	Geologist	Mechanical Engineer	Physician	Pilot	Leader
Yes	5	1	6	3	7	5	21	21
Maybe	3				5		9	1

Numbers of Current Astronaut Candidates by Mars Expedition Crew Specialty/Role

Crew Role	Biologist	Computer Specialist	Electrician	Geologist	Mechanical Engineer	Physician	Pilot	Leader
Yes	1	1	2	1	1	2	6	4
Maybe						1		

Results of the review show that it would be possible to fill all primary crew specialties/roles for an expedition to Mars from the current Astronaut Corps, based on minimum technical requirements. It even appears possible that a crew could be assembled from members of the Astronaut Candidate cohort selected in 2017, but with severely-constrained opportunities for qualified backups. The most salient deficiency in both groups appears to be the number of personnel whose biographies indicate proficiency as a computer specialist, which suggests that NASA should consider selecting candidates with IT skills and/or providing training in spacecraft computer systems to astronauts. No assessment can be made of the astronauts' general abilities and social skills from the information available, but the results of this exercise are encouraging. Selecting individuals with the appropriate education and professional experience, and who possess the abilities and skills identified as important by the current study, are critical to assembling a qualified crew for the exploration of Mars. However, development and delivery of pre-mission and refresher training, and the creation of procedures and job-aids will be key to preparing the selected specialists and their backups to perform the expected tasks, and to respond to unplanned events and emergencies, on another planet.

Working the Problem

Canadian Astronaut Chris Hadfield describes NASA's training for troubleshooting as, "Working the problem," which he says, "is NASA-speak for descending one decision tree after another, methodically looking for a solution until you run out of oxygen."[63]

[62] Quoted in Alfred Lansing, *Endurance: Shackleton's Incredible Voyage*. New York: Carroll and Graf Publishers, [1959] 1994.

[63] Chris Hadfield. *An Astronaut's Guide to Life on Earth.* New York: Little, Brown and Company, 2013.

TRAINING

Metaphor is used in all serious fields of inquiry when access to the actual conditions is impossible, either physically or ethically. Engineers and architects build models of bridges, buildings, ships, and airplanes and then subject the models to stresses that simulate real-world conditions. Medical researchers use animal models to test new therapies intended for humans. Economists construct mathematical models to test hypotheses about prices and trade. In the behavioral sciences we look to analogous conditions when access to actual environments is impossible. For example, we studied conditions on Earth that are similar in various ways to what might reasonably be expected of a space station in low-Earth orbit to derive lessons to inform the design and operation of the ISS (e.g., off-shore oil platform workers, crews of long-distance fishing and research vessels, supertanker crews, saturation divers, Antarctic winter-over personnel).[64] Additional research focused on the accounts of previous expeditions and voyages of discovery as metaphors for long-duration space missions.[65] Since the ISS became operational in the year 2000, it has become the most-relevant analog for exploration-class space missions. Unlike previous space analog environments that shared conditions, such as isolation, confinement, and extreme risk, with interplanetary spacecraft, the ISS has the added benefits of being in space and operated by actual space crews. We have learned a lot about the factors that contribute to adjustment and the factors that impede performance in space by studying behavioral issues on the ISS.[66]

Training implications of study results that are derived from previous analog research on Earth and in space are listed below.

- Cross-train crew personnel in multiple specialties. In addition to their primary specialties, all crew members should have major responsibilities in areas outside their primary fields of expertise. This approach could facilitate an equitable distribution of work, provide trained assistance to a designated specialist, ensure a backup if the specialist is incapacitated, and insulate individuals from excessively low workloads if a major responsibility is eliminated by equipment malfunction or another unforeseen factor (e.g., dust storms).
- Cross-training is particularly important for the crew physician because medical experts are vulnerable to underloading in isolated and confined environments (see pages 132-134 in the volume cited in Footnote 65, below, for a discussion of physician-related issues). Our four, hypothetical crew compositions include cross-training for the physician in every backup capacity except expedition leader and CMO, which is the backup to the physician.
- Anticipate and rehearse all actions required in response to emergencies. This policy is already a NASA standard, but the importance of training to human performance and decision-making under extreme stress cannot be overstated. All possible emergencies should be identified, appropriate contingency procedures developed, and training conducted (repeatedly) in the performance of emergency procedures under high-fidelity conditions. It is an established human factors principle that operators revert to expectations and well-trained patterns under stress and conditions of task and information overload.
- Include information in pre-mission training for exploration-class missions concerning the need for crew personnel to learn to be idle without feeling guilty. Most people who are attracted to exciting and unusual work, such as astronauts, are uncomfortable when forced by conditions to remain inactive for long periods (e.g., in response to equipment failures that eliminate research tasks or dust storms that confine crew to the surface habitat).

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[64] Jack Stuster. *Space Station Habitability Recommendations Based on A Systematic Comparative Analysis of Analogous Conditions.* NASA Contractor Report 3943, Moffett Field, CA: NASA Ames Research Center, 1986.
[65] Jack Stuster. *Bold Endeavors: Lessons from Polar and Space Exploration*. Annapolis, Maryland: Naval Institute Press, 1996/2011.
[66] Jack Stuster. *Behavioral Issues Associated with Isolation and Confinement: Review and Analysis of Astronaut Journals, Phase 2 Final Report.* National Aeronautics and Space Administration. NASA/TM-2016-218603, 2016.

The Risk and Management Team of NASA's Human Exploration and Operations Mission Directorate (HEOMD) began research in 2013 to identify lessons from the design, construction, and operation of the ISS that might be applied to future exploration-class space missions. The team conducted audio and video interviews with a broad range of experts, including current and former ISS managers, designers, operators, flight controllers, astronauts, and technical discipline leads. The resulting report presents summaries of key interviews.[67] We discovered the 2014 HEOMD report while contemplating the implications of our study's results and were pleased that ISS lessons learned were consistent with the results of our task and ability analyses; reported lessons support our identification of hands-on experience maintaining mechanical, electrical, and software systems and possession of social skills and cognitive abilities that facilitate troubleshooting as necessary among the crews of exploration-class space missions. A few relevant recommendations from the HEOMD report are listed below. The original quotations have been edited for brevity; page numbers of the HEOMD report are provided for reference.

- A factor for ISS that will definitely be a factor for Deep Space is you need people who have [maintenance] skills, who can repair their washing machine and their car. People who know their way around a toolbox are valuable on the ISS and will be even more useful when we go beyond low earth orbit. (Page 44)
- The imperative of near autonomous operations will require emphasis on selecting and training personnel who are capable of repairing failed systems. A mechanical aptitude, in addition to skills training, is necessary for the crew to be autonomous on exploration-class missions, during which day to day operations are controlled locally with updates and directions sent from mission control. Design philosophy, concept of operations, vehicle and habitat layout, crew selection, crew training, on-site manufacturing, storage, and other considerations must enable the crew's capability to make repairs. (Page 44)
- Crew qualifications and training must include software skills. Troubleshooting and fixing software problems are essential; you need knowledgeable, software-savvy crew members. Also, software must be written with that in mind–to be able to make changes in response to real-time situations. (Page 44)
- Astronauts spend 80 percent of the time performing electrical and mechanical repairs on the ISS, but they receive only 20-25 hours training on these skills during the 2½ years prior to their increment. The crew office has been sending astronauts to immersion style training where they work side by side with certified aviation mechanics performing actual hands-on tasks. They spend a week in the avionics shop and a week in the hydraulics and engine shops. Following that they spend time on the hangar floor maintaining aircraft. These three weeks of training provide more mechanical and electrical experience than they would receive during years of training for an ISS mission. Immersion style training should be considered for skills development, not only for mechanical and electrical skills, but also for language proficiency and other technical areas. (Page 45)
- It is important to consider the time lag between training to operate a payload (e.g., a scientific experiment) and the actual use of the training during a mission. It is not realistic to assume that crew members will remember specific detailed procedures 18 months or longer after the training. When setting up the experiment they will seek out the detailed procedures. The guidance could be in the form of written instructions, pictures, conversations with experimenters on the ground, or from how-to video clips provided by the experimenters. (Page 46)

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[67] David M. Lengyel, NASA HEOMD (Retired) and J Steven Newman, ARES Corporation, Editors, *International Space Station Lessons Learned for Space Exploration*, Human Exploration & Operations Mission Directorate (HEOMD), Houston, TX: NASA Johnson Space Center, September 2014.

- The training organization should develop a library of just-in-time training videos for exploration-class missions. Communication latencies between MCC and the crew will be long during much of the mission, which means that the training products and associated procedures must be very clear, concise, and not subject to misinterpretation. (Page 47)
- When we go away from Earth, to the moon or Mars, we will become more autonomous and more like a classic British expedition sailing about the world for a couple of years. Those explorers had to make decisions on their own and to figure out how to survive with the tools, equipment, and knowledge they possessed. The crews of exploration missions will have more autonomy from mission control than ISS crews have. The operational paradigm of planning every crew activity in detail, as on ISS, should be replaced by a less orchestrated approach. And, you must have a management structure that allows outside the box thinking. (Page 49)
- It is important to understand the operational behavior and culture of international partners. The authority of ground control teams versus crew authority on the ISS is an example; that is, some non-US crew members have had much less authority to call a stop when overworked or when provided with faulty procedures than we are accustomed on the NASA side. It is a mistake to assume that all partners will behave as we do. Training should include instruction about cultural differences among the partners to minimize risk and to facilitate interpersonal and inter-agency relations. (Page 50)
- Exploration missions will require much greater crew autonomy than ISS and will continually test crew flexibility and skill-based knowledge to solve problems. Crew preparation must include extensive pre-mission anomaly response and resolution training and frequent exercises during the mission. (Page 50)
- Many of the first ISS crew members were Space Shuttle-era veterans and were not fully-prepared for missions of six months or more; crew selection became an issue as a result of these incompatibilities. Crew selection and training for exploration-class missions should address personality styles and interpersonal skills. The opportunity for intervention to resolve interpersonal conflict and/or maladjustment during deep space missions will be limited, requiring compatibility to be ensured during crew selection and training. (Page 55)

Seven NASA astronauts spent an average of 140 days on the Russian *Mir* space station between 1995 and 1998 and when they returned they convinced their colleagues that expeditions of three months or more on a space station are qualitatively different from 14-day Space Shuttle missions. Some described Shuttle missions as sprints, compared to the marathons they experienced on *Mir*. The realization that long duration space missions require an expeditionary mind-set and perhaps additional skills and personal qualities than needed for short missions inspired members of the Astronaut Corps to develop a training program in 1999 to prepare future ISS crews for the experience. The Expedition Corps Training Program consisted of team building exercises, simulations, and a two-day seminar designed to sensitize astronauts to behavioral issues and to provide coping strategies and countermeasures to possible problems.[68] Training in cultural differences among international partners was a key component of the seminar. The Expedition Corps Training Program succumbed to efforts to reduce astronauts' pre-mission training burden. However, a recent article about teamwork among space crews mentions that Crew Expeditionary Skills (e.g., leadership/followership, communication, self-care) have been incorporated into astronauts' technical training.[69] This is encouraging, but a dedicated program will be required to prepare crews for living and working together for long periods during exploration-class space missions.

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[68] Jack Stuster. *Expedition Astronaut Training Content-Development Project: Lessons from Historic Expeditions*. Prepared for Wyle Laboratories, Inc., and NASA JSC. Santa Barbara, CA: Anacapa Sciences, Inc. August 1999.
[69] Lauren Blackwell Landon, Kelly Slack, and Jamie Barrett. Teamwork and Collaboration in Long-Duration Space Missions: Going to Extremes. *American Psychologist*, Vol 73, No. 4, 563-575, 2018.

DESIGN

We reviewed results of the task analysis to identify descriptions of the expected work that have clear design implications. Many of the implications identified during the review will become apparent to engineers when they begin designing spacecraft and equipment for the first expeditions to Mars. However, we have listed the most salient design implications, below, as part of our systematic approach to task analysis. Implications are presented in eight categories.

EGRESS THE MARS DESCENT VEHICLE (MDV)

It is well-known that astronauts are as weak as kittens when they return from six-months on the ISS, despite having exercised vigorously for more than two hours each day to maintain cardiovascular conditioning, muscle mass, and bone density. They must be helped out of their capsules by ground personnel and placed in reclining chairs from which they wave cautiously to the cameras before being carried to a waiting helicopter. We have watched the process and wondered how a crew could possibly egress their cramped descent vehicle soon after landing on the surface of Mars after the six-month cruise phase and then make their way to the pre-positioned habitat to recover. Veteran astronaut Leroy Chiao wrote about his experiences returning to Earth:

> Even after a ten-to-fourteen-day mission to space, the return is dramatic. Your balance system is turned upside down, and you feel very dizzy. When you stand up for the first time, you feel about five times heavier than you expect. All of this can be unsettling, and nausea is not unusual. After a long-duration flight of six or more months, the symptoms are somewhat more intense. If you've been on a short flight, you feel better after a day or two. But after a long flight, it usually takes a week, or several, before you feel like you're back to normal. All you want to do is lie around, because in that position, you are not dizzy.[70]

Dr. Chiao has identified two concerns: 1) The immediate response to landing, which includes dizziness, headache, pallor, sweating, nausea, and sometimes vomiting; and, 2) Prolonged effects, which include, locomotion and coordination problems, neuro-vestibular disturbances, orthostatic intolerance, and reduced muscle and bone strength. The intensity of both immediate and prolonged effects is generally proportional to the time spent in the absence of gravity, but responses vary. Some astronauts recover quickly, while others require weeks, and that is with assistance provided by ground personnel. Some of the effects might be mitigated by the lower gravity on Mars (i.e., 38 percent of Earth's gravity); that is, astronauts will not feel quite as "heavy" as they feel when they return to Earth, but they almost certainly will experience the other negative effects, especially neuro-vestibular-induced nausea. And, there will be no one waiting on the surface to help the first explorers of Mars egress their MDV and then carry them to their habitat.

DRA-5 included a Mars lander sufficiently large to accommodate the crew for up to 30 days while they adapted to the planet's gravity. We assumed, as a worst-case scenario, that the descent vehicle would be as small as possible (to minimize mass/propellant requirements); that is, the MDV would be suitable only for transporting the crew from their interplanetary ship in orbit to the surface of Mars. The MDV would lack the volume and habitability features that might enable the crew to remain in it until they adapt to Martian gravity (i.e., the crew would be arranged elbow-to-elbow like EVA-suited sardines). Either a more massive MDV must be used, one that is capable of transporting the crew to the surface and supporting them for a week or two until they adapt, or other provisions must be provided to enable egress. In this worst-case scenario, special hand-holds and a device for lowering crew members from the MDV's hatch to the surface (rather than a ladder) would be needed, as would a device, perhaps resembling a "walker," to assist weakened crew to transition from the MDV to their nearby surface habitat after landing. It also would be helpful to direct the pre-positioned surface rovers remotely to retrieve the crew at the landing site and then transport them to the habitat. These design features might be required even if the crew lands in a larger, DRA-5-type MDV and is allowed time to adapt before egressing.

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[70] Leroy Chiao. Return to Earth: An Astronaut's View of Coming Home. *Space.com* 1 March 2016. https://www.space.com/32102-astronaut-perspective-on-long-deployments.html

Landing on Mars

Landing on Mars is difficult, despite the breezy confidence in technological development that has fueled aspirations and all plans for human exploration since von Braun. Sixty percent of spacecraft sent to Mars have failed, for various reasons. The success rate has been improving, due largely to the impressive rover landings orchestrated by scientists and engineers at the Jet Propulsion Laboratory (JPL), but even the largest object JPL has landed on the surface, the Mars Science Laboratory's one-ton *Curiosity* rover, was tiny compared to what will be required to pre-position equipment and supplies, and then two or four years later, to deliver humans to the surface of Mars. The six successful Apollo lunar landings and the spectacular landings on Mars have misled all but the experts into believing that a human expedition would be mostly about the cruises to and from Mars and surviving 18 months on the surface, but several factors have conspired to render the descent to the surface of Mars as the primary technical obstacle to human exploration of the planet. It will be much more difficult to land humans on Mars than it has been to land rovers or was to land astronauts on our Moon. At only one percent of Earth's atmosphere, the Martian atmosphere is too thick to ignore and too thin to be of much help in slowing a spacecraft for landing.

All spacecraft that have returned to Earth arrived at hypersonic speeds and then decelerated to less than Mach 1 at approximately 20 kilometers altitude by plowing through Earth's thick atmosphere and converting nearly all of the kinetic energy into heat, using ablative or ceramic shields. Returning Apollo and Soyuz capsules deployed parachutes to continue the deceleration, while the space shuttle used drag and lift to bleed off the residual energy. Von Braun's winged ships, depicted by Chesley Bonestell on page 2 of this report, were intended to land on Mars using drag and lift, but von Braun and the other early mission architects greatly over-estimated the density of Martian atmosphere (they assumed a density ten percent of Earth's atmosphere). An enormous heat shield would help slow a 40-ton descent vehicle, but the necessary size precludes launching such a large structure from Earth. A parachute also would help, but parachutes can be deployed only at speeds below Mach 2 and to slow a large vehicle in the Martian atmosphere would require a parachute the size of a football stadium; by the time a large vehicle slows to Mach 2 in a Mars descent, there is insufficient time remaining to deploy even a conventional parachute before impact. Air bags, such as those that famously delivered the *Sojourner* rover to the surface of Mars in 1996 also are out, because they would be impractically large and any human inside would be unlikely to survive the g-forces. Retro rockets are the only solution to landing humans on Mars safely, but even this solution is problematic.

The Apollo Moon landings made it appear so easy. However, Mars is more than twice the size of our Moon, as is its gravitational attraction, which increases the amount of fuel needed to slow a vehicle approaching the surface of Mars, compared to one landing on our Moon. Apollo Lunar Landers weighed about 10 tons; a Mars descent vehicle will weigh at least 40 tons, probably more. The amount of fuel needed for retro-rockets to land humans on Mars will be enormous and the fuel must be transported from Earth to Mars orbit to be used in a descent; that fuel will require even more fuel to send it on its way to Mars and an almost equal amount to slow it into a parking orbit when it arrives. The amount of fuel needed to land a crew on Mars is formidable, but it is not the biggest technical challenge. That role belongs to Supersonic Retro-Propulsion, which requires the descent vehicle's rockets to be ignited while plummeting toward Mars at a very high speed. It will be like trying to light a candle in a hurricane, according to DRA-5 mission architect, Stephen Hoffman. A large ship entering the Martian atmosphere will have 90 seconds to decelerate from Mach 5 to Mach 1, fire retro-rockets, reconfigure into a lander, translate to the designated landing site using thrusters, and then touch down gently on the surface. Dr. Hoffman and other experts are optimistic about the prospects of landing humans on Mars, despite the technical challenges.

MEDICAL

The figures on pages 30 and 31 of this report and results of the task analysis summarized by the tables on pages 37 and 47 and in Appendices C and D show that medical tasks are the most numerous of the occupational categories and are among the most difficult to learn and important to mission success. Although many of the medical tasks, such as *Perform surgery, manually using available instruments, to repair a detached retina*, are unlikely, the expedition physician must be prepared with the knowledge, decision-aids, and instruments to perform them. Other medical tasks, such as *Perform surgery, manually using available instruments, to repair a compound fracture of arm or leg bone*, are more likely during an expedition to Mars. The incidence of serious physical injury during a conjunction class mission was estimated, based on Antarctic experience, to be between four and 12 cases among a crew of six, with the most-likely injuries to occur during surface operations and to involve trauma to the hands and feet.[71] Task analysis results and analog experience indicate the need for robust medical capabilities to diagnose and treat physical injuries during an expedition to Mars.[72]

Medical data from Antarctic stations also were used in the study mentioned previously to estimate the probability of behavioral problems occurring during an expedition to Mars (with "serious problem" defined as requiring at least brief hospitalization if on Earth). The estimates ranged from 0.37 to 0.89 cases among a crew of six during a 905-day conjunction-class expedition; the higher estimates are direct extrapolations from Antarctic experience, while the lower estimates reflect adjustments for the comparatively rigorous screening and selection of space crews. These predictions based on analog data suggest that methods will be needed to help individual crew members resolve behavioral issues during their 30-months of living and working together in isolation and confinement. A promising candidate solution for this requirement is the Virtual Space Station, initially conceived by physician, professor, and former NASA payload specialist, Jay Buckey. The Virtual Space Station is a self-guided, multi-media program that addresses psychosocial problems, including depression, interpersonal conflict, and anxiety.[73] The software has been tested successfully in space-analog environments and could be used as part of pre-mission training and for crew members to receive assistance confidentially during an exploration-class space mission.

SCIENCE

The primary purpose of sending humans to Mars is to conduct science. *Perform science-related EVA functions during Mars Surface Operations* was the summary task statement rated highest overall by the SMEs. Examples of this summary statement's 61 component tasks are listed on pages 39 and 53 of this report and all 61 tasks can be found among the 1,125 tasks in Appendix D, along with the component tasks of the seven additional science-related summary task statements, listed below.

Conduct science and planning functions during Cruise to Mars.

Perform science-related EVA functions with heavy equipment during Mars Surface Operations.

Perform geology-related science functions in surface habitat/modules during Mars Surface Operations.

Perform human research-related science functions in surface habitat/modules during Mars Surface Ops.

Perform planning-related science functions in surface habitat/modules during Mars Surface Operations.

Perform biology-related science functions in surface habitat/modules during Mars Surface Operations.

Conduct science and planning functions during Cruise to Earth.

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[71] Jack Stuster. Acceptable Risk: The Human Mission to Mars. *Journal of Cosmology*, 12, pp. 3566-3577, 2010.

[72] Certain medical conditions could be eliminated from possibility during an expedition to Mars by preventive measures. For example, anyone who has experienced an emergency appendectomy would recommend that all crew members have their appendix removed prior to leaving Earth.

[73] AP Anderson, AM Fellows, KA Binsted, MT Hegel, and JC Buckey. Autonomous, Computer-Based Behavioral Health Countermeasure Evaluation at HI-SEAS Mars Analog. *Aerosp Med Hum Perform*. 87(11):912-920, 2016.

Together, the eight science-related summary task statements comprise a total of 121 tasks in the fields of biology, geology, and human research. Science-related tasks represent 11 percent of the total task inventory and 20 percent of the tasks listed for Mars Surface Operations. Most of the science-related tasks will require equipment to perform and have clear design implications. A few examples are listed below, but designers must eventually address the specific equipment requirements of every task.

Example Science-Related Tasks		**Design Implications**
Retrieve geological tools and equipment from storage and carry to surface rover/trailer, manually while wearing surface EVA suit, to prepare for reconnaissance.		Lightweight tools optimized for use with gloved hands; rover trailer.
Collect geological samples, manually using hand auger, while wearing surface EVA suit.		Specialized tools with safety features to prevent suit punctures.
Dissect rock samples, manually while wearing surface EVA suit and using hand-held power cutting tool, to reveal smooth surface features/stratigraphy.		Specialized tools with safety features to prevent suit punctures.
Collect geological samples, manually using Apollo-type scoop (1m handle) and sample bags, while wearing surface EVA suit.		Equipment for collecting and carrying samples.
Inspect geologic samples, visually using hand-held magnifying tool/microscope while wearing surface EVA suit in the field, to conduct preliminary analysis.		Magnifying tool that can be used while wearing surface EVA suit.
Record field notes, verbally while wearing surface EVA suit, to preserve observations for later transcription.		Audio and video recording capability in surface EVA suit.
Scan distant planetary surface, visually through clear visor, to identify potential sites for geological research and collection.		Clear helmet visor to permit seeing contrasting color of strata/rocks.
Deploy and operate ice core drilling tool, manually while wearing surface EVA suit, to obtain ice core sample for analysis.		Easily-transported equipment for operation with gloved hands.
Extract regolith core from drill and package core sample in plastic wrap, manually while wearing surface EVA suit, for later analysis.		Materials for packaging regolith and ice core samples in the field.
Deploy and operate high-vacuum pump and sampling equipment, manually while wearing surface EVA suit, to collect atmospheric data.		Equipment for conducting atmospheric research.
Operate rotary/percussion drill to depth of 10 meters with assistance of one other crew member while wearing surface EVA suit.		Drilling equipment for operation by two with safety features.
Add drill pipe section to stack, manually using hand tools while wearing surface EVA suit, to drill deeper.		Drilling equipment for operation by two with safety features.
Examine sedimentary core sample, using aseptic device/procedures while wearing surface EVA suit, to identify if sample contains biologic or toxic elements.		Science module for geological & biological research with aseptic capability.
Compose/update log of samples, using keyboard in surface habitat/laboratory, to create inventory of material collected to date.		Computer/software for inventory of samples collected.
Inspect Martian water samples, visually using binocular microscope in the surface habitat/laboratory, to conduct analysis/guide additional field research.		Science module for geo/bio research; microscope, spectrometer, glovebox.
Conduct culturing experiment, manually in laboratory module while wearing protective garments, to test sample material for biological content.		Science module for geo/bio research; special equipment and instruments, glovebox.
Conduct wet chemistry experiment, manually in laboratory module while wearing protective garments, to test sample material for biological content.		Science module for geo/bio research; special equipment and instruments, glovebox.
Climb crater wall while carrying hand tools and wearing surface EVA suit to conduct geological research.		Flexible surface EVA suits.

HABITABILITY

Habitability includes the features of a built environment that affect human performance and adjustment. More than 100 habitability tasks are included in our Mars task lists and they were rated by the SMEs to be among the most-frequent tasks to be performed (e.g., preparing and eating meals, sleeping). Humans can endure austere conditions if they must, but optimum performance is facilitated by habitability features such as, 1) Variety and self-selection of food items; 2) A wardroom or galley that enables the crew to eat meals together; 3) Recreation and leisure materials and equipment; and, 4) Private sleep quarters. Designers should consider the provision of habitability features, such as these, to be analogous to overbuilding, a standard method used by engineers to ensure reliability of physical systems (e.g., designing a valve to withstand twice the pressure expected during operation).

Food is the quintessential habitability issue and is well-known to managers of remote-duty facilities as key to individual adjustment to the conditions. Fridtjof Nansen's admonition to explorers to "be especially careful about the food" is echoed by ISS astronauts who wrote in their journals: [74]

> The 9-day cycle of our current menu should be extended. We see too much of the same thing, which would be tedious if we didn't have our bonus food packs to mix things up a bit.
>
> Making the Russian food available to us is a huge addition. The difference in prep techniques and of course recipes between the US and Russia increases our variety immensely. I recommend more than one vendor supply the food for deep space missions; items coming from one vendor are bound to be similar in texture and taste, even across different dishes.

Interplanetary ships and surface habitats must provide areas sufficiently large to allow entire crews to eat meals together and to meet for planning activities. Eating together mitigates sub-group formation and fosters both interpersonal communication and group solidarity. Meeting together for administrative and planning functions is a physical requirement of task performance

Eating dinner in *Skylab Trainer*, 1973.

Eating dinner on the *ISS*, 2015.

The primary leisure activity on the ISS has been Earth-viewing since the station became operational in the year 2000. Earth viewing will not be available to crews soon after the main engine burn that propels the interplanetary ship on a course to intercept Mars six months later. Remotely operated cameras would (at least) enable inspection of the ship's outer hull from inside during the cruise phases. Summary task statements concerning individual and group recreational activities were rated 23rd in Frequency, overall, (for the Cruise to Mars), 25th (during the Cruise to Earth), and 36th (during Mars Surface Operations). SMEs' frequency ratings for recreation and leisure reflect the recognition that the 18 months on the surface will be a period of high-tempo construction and science operations, with fewer opportunities for recreation than during the transits to and from Mars, that is, if all goes well. However, weather conditions,

[74] Jack Stuster. *Behavioral Issues Associated with Isolation and Confinement: Review and Analysis of Astronaut Journals, Phase 2 Final Report.* National Aeronautics & Space Administration. NASA/TM-2016-218603, p. 45, 2016.

equipment failures, and/or injuries to one or more crew members could interrupt operations, delay or cancel scheduled EVAs, and prevent crew from performing work on the planetary surface. For these reasons, it will be necessary to develop plans for conducting meaningful tasks from within the surface habitat (e.g., teleoperation of robotic devices), as well as to provide a variety of recreation and leisure opportunities for crew who might be confined for extended periods.

Living in close proximity to other humans can become stressful. For this reason, everyone who lives and works in an isolated and confined environment for a prolonged period seeks time away from crew mates. Sailors of vessels from the humblest fishing boat to the grandest supertanker periodically seek refuge at the stern or in a compartment below decks; scientists and technicians at Antarctic research stations can be found sitting quietly alone in maintenance huts or in the plant-growing facility; even families that travel together on vacation occasionally seek a few moments away from each other to regain what Ben Weybrew, the principal submarine psychologist of the nuclear age, referred to as, "psychological homeostasis." The private sleep chambers onboard the ISS help satisfy this requirement for astronauts and cosmonauts.

The collection of HEOMD lessons learned, mentioned on page 77 of this report, includes the recommendation to provide private sleep quarters on exploration-class space missions, citing ISS astronauts' positive feedback in debriefings and comments about relying on their private quarters for quality sleep and personal time away from other crew members: "This tiny cubby hole of a world is important to the crew–to be able to decorate it, put up family photos, and obtain some privacy." The authors acknowledge that it will be a challenge for spacecraft designers to include private sleep chambers in the limited habitable space anticipated for exploration-class missions; however, private quarters are considered by the editors of the lessons learned report and by the current study team to be a necessity. An ISS astronaut wrote in his personal journal: "Crew quarters are the answer to anyone's habitat needs. Even though they're small, we can organize them any way we want." Facilities such as the private sleep chambers provided for ISS crew will be required on interplanetary ships and in surface habitats.

Skylab sleep chamber, 1973.

ISS sleep chamber, 2012.

USOS Crew Quarters, 2015.

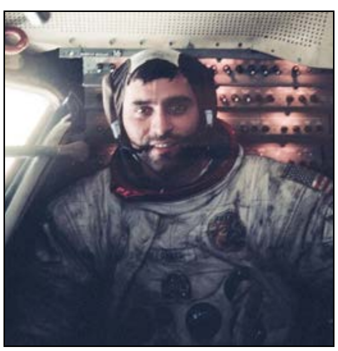
Task Frequency

Half of the top 20 percent of most-frequent summary task statements are habitability tasks: Preparing and eating meals, sleeping, and using hygiene facilities. Six of the most frequent summary statements describe communications among the crew and three are exercise-related tasks. None of the most-frequent tasks was rated among the most difficult to learn and only one made it to the most-important list (i.e., sleep during CTM). Designers might be tempted to devote less attention to the equipment needed for tasks that are easy to learn or relatively unimportant, compared to equipment used to perform critical tasks. However, frequently-performed tasks expose users to the risks of inadequate design (errors, inadvertent acts, frustration) as frequent driving exposes motorists to greater risk of crashing. In other words, sleep chambers, food and hygiene systems, and exercise and comm equipment intended for interplanetary ships and surface habitats must be designed with the same attention to usability as the controls and displays that will be used to pilot a spacecraft during contingencies and to respond to technical emergencies. Frequency has a quality of its own.

SAFETY

Monitoring systems and responding to alarms were rated by the SMEs among the most important tasks to be performed during a Mars expedition; responding to technical emergencies during the Cruise to Mars was rated by the SMEs as the most-important of the 158 summary statements; responding to technical emergencies was 3rd overall during Mars Surface Operations and 6th overall during the Cruise to Earth. The greatest threats to the safety of space crews that might be announced by an alarm are: 1) Fire; 2) Hull puncture followed by rapid decompression; 3) Outgassing, primarily an ammonia leak; and, 4) Solar particle events. All four of the threats have occurred on the ISS, but none with catastrophic consequences, due largely to vigilance, training, sensitive detectors, and automatic alarms. The cost of protection by effective sensor systems is frequent false alarms, which are a source of annoyance to ISS crew. Responding to false alarms interrupts work during the "day" and sleep at "night," but complaints about false alarms are minimal because everyone knows that a fire, hull breech, or ammonia leak could be fatal. An astronaut wrote in his journal, "Another smoke detector alarm today. I was exercising but made sure I checked out the situation. It is good training to react as if it is a real emergency."[75] A few safety-related design implications of task analysis results are listed, below.

- Resist the temptation to disable audible alarms.
- Provide easy access to fire extinguishers in spacecraft and in surface habitats/rovers.
- Provide tethers for connecting crew members together during EVAs over uneven terrain or during dust events.
- Provide ready access to tools and equipment needed to detect and repair hull breeches in spacecraft and in surface habitats.
- Provide an automatic (self-sealing) capability to repair punctures of surface EVA suits, with ready access to materials to make permanent repairs manually in the field.
- Provide shielded areas in the interplanetary ship and in surface habitats to protect crew from solar particle events (e.g., surround sleep chambers with water storage or thick plastic panels; cover surface habitats with regolith).[76]
- Provide a dust removal capability at the entrance to surface habitats to prevent contamination of the interior; a portable method also will be needed to remove dust from suits and boots before entering rovers and the Mars Ascent Vehicle.



Apollo 17 Astronaut Harrison Schmitt (L) was photographed covered in lunar dust following an EVA in 1972. Astronauts (R) are depicted walking from a surface rover to their Mars Ascent Vehicle during a dust storm in the BBC/Impossible Films, Ltd., production, *Space Odyssey: Voyage to the Planets*. Effective management of fugitive dust will be a requirement of human Mars expeditions.

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[75] Jack Stuster. *Behavioral Issues Associated with Isolation and Confinement: Review and Analysis of Astronaut Journals, Final Report.* National Aeronautics & Space Administration. NASA/TM-2016-218603, p. 68, 2016.

[76] Von Braun expressed hope, in the *Collier's* article cited previously that, "by the time an expedition from Earth is ready to take off for Mars, perhaps in the mid-2000s… researchers will have perfected a drug which will enable men to endure radiation for comparatively long periods."

RELIABILITY

A three-year expedition to Mars will test the endurance of both humans and their technology. Approximately ten percent of the 1,125 tasks the crew of a Mars expedition must be prepared to perform involve maintenance and repair, from the spacecraft to the software that will control all systems. Ensuring the reliability of technological components of the enterprise would reduce maintenance workloads and overall risk; it also would increase crew confidence in systems and the probability of mission success. Engineers use four basic design strategies for increasing reliability and reducing the risk and effects of component or system failure:

1) Redundancy. Having two spares for every item needed provides protection against an undetected flaw in a primary item and unexpected damage to the replacement. Triple redundancy has been favored by NASA since the Mercury Program and was a primary strategy of previous explorers. The most notable example was Christopher Columbus, who would not have considered departing Spain with fewer than three hulls and probably would not have returned safely had he done so (his flagship was destroyed on Christmas Day 1492). All serious Mars plans included multiple ships for this reason, that is, until recently; the history of exploration shows that redundancy is a key to survival when venturing outside of FedEx's service area. Spacecraft designers and mission planners should continue the practice of providing redundant ships, systems, and components (in-line spares and replacements) to increase reliability.
2) Overbuilding. Engineers typically design a structure or system component to withstand more than the maximum stress, load, or pressure that is expected. A 150 percent design rule increases the cost of a retaining wall and the weight of a rocket motor, but the strategy also increases the probability that neither item will fail catastrophically. Overbuilding was mentioned previously as a metaphor to encourage engineers and mission planners to consider habitability features as contributing to the reliability of the human components of exploration-class space missions.
3) Graceful degradation. Sudden, catastrophic failure can overwhelm intrinsic precautions and cause a cascade of unexpected negative consequences. Systems should be designed to degrade gradually to allow sufficient time for isolation, replacement, or repair. For example, devices that enable keyless opening of an automobile door are designed to alert users when the tiny battery is failing by requiring closer proximity to the vehicle or repeated button presses to open the car door. This graceful degradation of functionality allows sufficient time to install a replacement battery, rather than stranding the owner inconveniently. The explorers of Mars will also benefit from this design strategy.
4) Maintainability. Systems intended for use in remote environments should be designed to enable repair by human operators and tenders. This strategy includes provisions for accessibility, spare parts, appropriate tools, and procedures and schematics to guide the processes. And duct tape; do not forget the duct tape.

All four of the strategies described here should be employed to increase the reliability of mechanical, electrical, and software components of exploration-class space missions.

European Space Agency Astronaut Samantha Cristoforetti is shown repairing a controller panel on the ISS, a task included in the Mars expedition task lists.

STORAGE

The collection of HEOMD lessons learned includes the observation that the volume available for carrying spare parts during exploration-class space missions will be limited. And, for this reason, crews must have the capability to manufacture replacement parts. The 3-D printing experiment and additive manufacturing currently onboard ISS are steps toward an “in-flight” and on-site manufacturing capability. However, it is essential to move beyond plastic to metallic powder for 3-D printing to be an enabling technology for deep space missions.[77]

Cognizant of Douglas Mawson losing most of his exploration party’s food when a sled was lost in a crevasse during a traverse, the Australian Antarctic Division, in 1948, initiated a policy of distributed storage in all aspects of the Australian National Antarctic Expeditions (ANARE). That is, items of food, fuel, supplies, and equipment are stored throughout remote habitats to avoid the total loss of any material from a localized incident, such as fire. Logisticians and spacecraft and habitat designers should follow the Australian practice of distributed storage to increase the probability that future explorers retain access to the items they need to survive.[78]

Storage and retrieval of items are reported by astronauts in their journals to be major issues on the ISS. In particular, it often requires twice as long to find a specified tool or component than is scheduled to perform the actual task. This inability to promptly locate needed items causes astronauts to fall behind schedule nearly every day and is a leading source of work-related stress for ISS crews. The problem is compounded when astronauts fail to re-stow items carefully in their haste to move on to the next scheduled task, which increases the time that will be required to locate the item when it is needed again. Special attention should be devoted to developing methods for managing the storage of consumables, spare parts, equipment, tools, and other materials for exploration-class space missions. And, crew members should be encouraged to stow and re-stow items with care and to ensure that labels face outward to facilitate finding items when needed. An ISS astronaut wrote in his confidential journal: “It is very important to put things away up here and keep things as neat as you can; this makes future tasks easier and less frustrating.” Another astronaut wrote: “Good organization of items frequently accessed, such as trash receptacles, food, dry goods, tools, etc., is essential and allows you to feel in control of your environment.”

The Leonardo Permanent Multipurpose Module, installed in March 2011, is used for storage on the ISS.

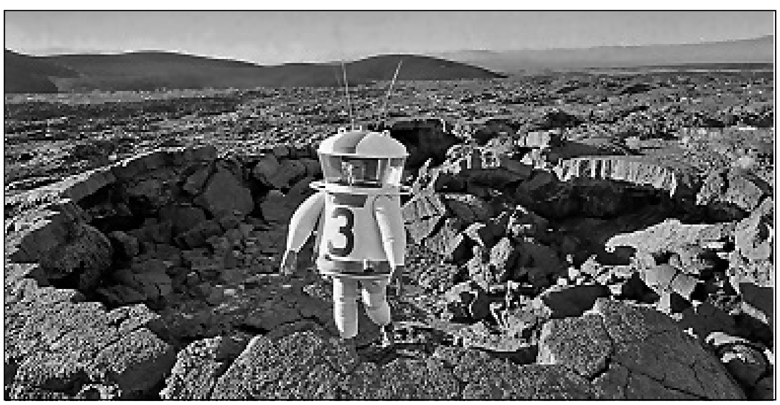
[77] Our task inventory includes 11 3-D printer tasks during the cruise phases and Mars Surface Operations.

[78] Desmond Lugg, personal communication. Dr. Lugg was Field Leader of the International Biomedical Expedition to Antarctica in 1980-1981 and Head of Polar Medicine for the Australian Antarctic Division for 33 years before retiring in 2001; he then served as chief of NASA's Medicine of Extreme Environments office for six years.

CONTROLS AND DISPLAYS

The need to design better controls and displays for ships and aircraft during World War II led to the development of Human Factors Engineering as a scientific discipline. Specifying appropriate “knobs and dials” is fundamental to the field and we are confident that proper attention will be devoted to the design of controls and displays for the EVA suits, rovers, habitats, and spacecraft intended for exploration-class missions. However, we offer a few suggestions based on human factors design principles and results of the task analysis to be consistent with our systematic approach.

- Highlight critical information.
- Integrate displays, where possible.
- Display information that is required and eliminate nonessential information.
- Use familiar elements, metaphors, and qualitative methods to display information.
- Design ascent and descent vehicle (EAV, MDV, MAV, EDV) displays to enable viewing during severe buffeting.
- Design ascent and descent vehicle (EAV, MDV, MAV, EDV) controls to enable precise operation with gloved hands during severe buffeting, if manual override of automated systems becomes necessary.
- Design surface EVA suit displays and controls for viewing and operation while the astronaut is fatigued.
- Design equipment to facilitate crew performance under high-workload and transitional workload conditions.
- Design EVA suits, habitats, and equipment and the associated temperature displays to accommodate the substantial temperature gradients on Mars; that is, the temperature at a standing astronaut’s helmet is approximately 25 degrees Celsius colder (40 degrees Fahrenheit) than at the astronaut’s boots.



Neither this early JPL lunar suit concept, nor a modern gas-pressurized EVA suit, is sufficiently flexible to allow astronauts to perform all anticipated Mars surface tasks; that is, mechanical or hybrid suits must be developed to enable surface exploration. However, numerals as depicted (or color-coding) would be useful features of surface EVA suits. Also, many of the tasks to be performed on Mars are the kinds of tasks that result in serious injury on Earth.

Dangerous Work

The Apollo 13, 15, 16 and 17 missions carried rotary percussion drills that enabled astronauts to place heat probes up to 10 feet (3 meters) below the lunar surface and to collect samples. The drills worked well going in, but pulling them out of the ground was difficult. “I think what happens is, the larger fragments rotate into the flutes, and, because it’s incompressible down there, you can’t move that fragment out of the way without an extraordinary amount of effort. Dave Scott actually wrenched his shoulder doing it on Apollo 15.”

— Apollo Astronaut, Harrison Schmitt (personal communication)

A NOTE ABOUT ASSUMPTIONS, PLANS, AND EXPOSURE TO RISK

The final paragraph of the Executive Summary of this report states that our assumptions about the tasks that are likely to be performed during the first human expeditions to Mars were based on the most-recent mission plan (i.e., DRA-5) and other information available to the research team in 2016, the first year of the study. We acknowledged that the tools, equipment, propulsion methods, and/or other aspects of actual human expeditions to Mars might be different from our assumptions and the tasks described in our report as a consequence of technological development and evolving Mars Design Reference Architectures. Therefore, we were not surprised to learn during the final stages of preparing this report in 2018 that NASA is developing a new mission plan. Details of the plan have not been revealed, but it appears that a difference between our DRA-5-based assumptions and the new plan is that the crew would not abandon the interplanetary ship as it approaches Earth on the return transit and, instead, they would perform a retro burn of the main engine to slow the ship and then maneuver for a rendezvous and docking with a Gateway facility located in Cis-Lunar orbit; the crew would return to Earth in an Orion-type capsule a few days later. It is a major departure from DRA-5's mission profile and would require more mass and propellant than direct descent, but the change is limited to the final two (brief) mission phases and would not affect the applicability of task analysis results materially.

A notable difference between DRA-5 and the new plan (which is based on the notional Evolvable Mars Campaign) is the assumed use of low-thrust propulsion technology for transporting both crew and cargo to Mars and returning crew from Mars. (DRA-5 noted that there were competing propulsion technologies for transit and did not select one as the preferred solution, but did use high-thrust nuclear thermal propulsion to illustrate the end-to-end mission.) Low-thrust propulsion has the advantage of lower propellant usage for the transits but at the cost of longer transit durations. For a representative round trip Mars mission lasting 1000 days, an astronaut crew would experience approximately 350 days in transit to Mars, approximately 300 days on the surface of Mars, and approximately 350 days on the return transit to Earth.

Reducing the time the crew must spend on the surface of Mars from 545 to 300 days would not affect the results of our study and would, in fact, reduce overall exposure to risk for the crew. However, doubling the time the crew must spend in transit to and from Mars (i.e., from six months to almost a year each way) would probably affect the applicability of some study results and, more important, would increase risks to the crew substantially, as described below.

A paper cited previously in this report estimated the incidence of physical injury and the incidence of serious behavioral problems among a crew of six during a 30-month, DRA-5-type expedition to Mars, based on space-analog experience (see Page 81/Footnote 71). A serious behavioral problem was defined as symptoms that normally would require hospitalization on Earth and the assumptions were based on incidence rates experienced at Antarctic research stations (Australian, French, Russian, and US). A table from the paper, reproduced below, shows we should expect 0.893 cases of serious behavioral problems among a crew of six, if we assume a constant rate of 0.06 for the duration of a 30-month DRA-5-type Conjunction Class mission. However, if we assume a different (lower) incidence rate (i.e., 0.02) during surface operations, when confinement would be less of a factor and other stressors might be offset by the novelty of task performance, the number of likely cases drops to 0.534, that is, an approximately 50/50 chance that at least one member of the crew would suffer a serious behavioral problem during the expedition.

		Conjunction Class (DRA-5)				
		Outbound	Surface	Return	Total Days	
	Days	180	545	180	905	Expect In Crew of 6
Risk Factor/Definition	Incidence per 365 days				Behavioral Risk	
Serious Behavioral Problem	0.060	0.030	0.090	0.030	0.149	0.893
Differential	0.020	0.030	0.030	0.030	0.089	0.534

Risk of Serious Behavioral Problem During DRA-5 Mission Profile.

We substituted the durations of the three major mission phases of the new, yet-unnamed DRA for the DRA-5 durations in the figure, below, and found that we should expect 0.789 cases of serious behavioral problems among a crew of six even if we assume the rate during surface operations to be only one-third of the rate during cruise phases (i.e., 48 percent greater than in the DRA-5 profile). The expected incidence if the rate is constant throughout the mission would be 0.986, which when expressed probabilistically is a near certainty that at least one member of the crew would develop a serious behavioral problem during a low-thrust-propulsion expedition with extended transit durations.

	New DRA (in progress)					
		Outbound	Surface	Return	Total Days	
	Days	350	300	350	1000	Expect In Crew of 6
Risk Factor/Definition	Incidence per 365 days				Behavioral Risk	
Serious Behavioral Problem	0.060	0.058	0.049	0.058	0.164	0.986
Differential	0.020	0.058	0.016	0.058	0.132	0.789

Risk of Serious Behavioral Problem During Extended-Duration Cruise Profile.

Doubling transit durations also doubles crew exposure to cosmic radiation and to the risk of experiencing a solar particle event during transit, which could be fatal. In addition, the growing body of evidence from ISS research shows that the negative effects of micro-gravity on humans are cumulative and that mission durations longer than six months are extremely challenging physically and mentally. Astronauts have reported in their confidential journals that they can maintain proficiency and motivation for six months, but nearly all write that they would not want to remain on the ISS longer than that. Most report that three months would be optimal.

Astronaut Scott Kelly helped as Russian rescue force personnel extracted him from the Soyuz capsule after returning from 340 days in space in March 2016; he even had the strength to hold a satellite phone and to punch in the numbers to call his long-time girlfriend at NASA's Johnson Space Center. Two days later he stumbled from his dining table in Houston and made his way to bed where he collapsed in pain, fever, and nausea. "Every part of my body hurts," he wrote later. His legs were swollen and he developed a rash on his back, arms, and legs—everywhere he contacted the bed. He described walking as if he were in quicksand. Kelly had been in space on three previous occasions, including a 159-day ISS expedition, but returning to Earth had never been this difficult, despite having exercised vigorously to counter the negative effects of micro-gravity on his body. Kelly did not recover fully for two months.[79]

We wrote in the Introduction to this report that the work performed by human factors specialists is accompanied by a responsibility to represent the interests of system users, operators, maintainers, and personnel—the "human components" of technological interaction. For this reason, we must state clearly that the physiological and behavioral data derived from ISS and from space-analog experience suggest strongly that transit durations of 12 months to and from Mars would increase risks to the crew and to the overall success of the expedition compared to the six-month transits of a DRA-5 mission. Longer transits, such as the 12 months proposed in the new DRA, would cause substantial exposure to the physiological risks of radiation and micro-gravity, and to the behavioral risks of isolation and confinement.

Imagine

Imagine living in a motor home with five other people for six months. You cannot go outside or even see outside because there are no windows. You have trained with these people for years and know all of their jokes and irritating mannerisms, but there is no escape. When you reach Mars you will live in a small cabin with the same people for 18 months. You may go outside occasionally, but you must wear a space suit. Then, there is a six-month trip home in the motor home. An expedition to Mars would be a lot like this. Now imagine that your motorhome is so slow it will take 12 months to get to Mars and another 12 months to make the drive home after staying nearly one year in the cabin. Spending 300 days in a small habitat and more than 700 days isolated and confined to a small space ship with five other people during transits to and from Mars would be a lot to ask, even of explorers.

[79] Scott Kelly. *Endurance: A Year in Space, a Lifetime of Discovery*. New York: Alfred A. Knopf, 2017.

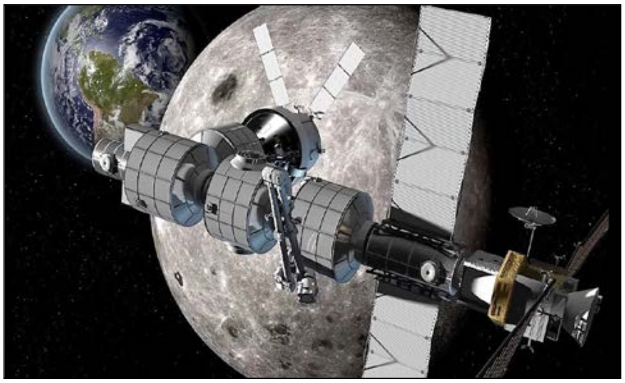
CONCLUSIONS

The primary purpose of the current study has been to identify the skills and abilities needed among the crew of exploration-class space missions. However, it was first necessary to understand the tasks that are likely to be conducted during a representative mission before it was possible to identify the skills and abilities needed to perform the work. Task lists were developed by the research team and reviewed by experts to ensure they accurately reflected what might reasonably be expected of crew during the first few human expeditions to Mars. The 1,125 tasks were then presented in 12 mission phases and rated by 60 SMEs for Difficulty to Learn, Importance, and likely Frequency; SMEs included current and former astronauts, flight controllers, flight surgeons, emergency physicians, engineers, biologists, geologists, psychologists, physiologists, and human factors specialists. Results of this task analysis led us to identify eight crew occupational specialties/roles needed to perform the expected work. Seventy-two SMEs, representing each of the eight specialties, ranked a total of 58 cognitive, physical, and social abilities in order of importance to performing their role during a conjunction-class expedition to Mars. The results of the task and ability analyses presented in this report provide a detailed understanding of the work that is likely to be performed during the first human expeditions to Mars and the abilities that will be needed by the explorers. The research enabled us to identify key implications of study results to Skills and Abilities, Personnel-Selection, Crew Composition, Training, and Design.

By focusing on an expedition to Mars, we have considered the extremes of what is possible for human space exploration during the first half of the 21st Century. A 30-month expedition to Mars is the most technologically and behaviorally challenging mission currently contemplated by NASA. In other words, the tasks that would be performed and the human abilities that would be required to conduct other exploration-class missions are subsets of those required for Mars exploration and are accommodated by our focus on Mars. Other possible exploration-class space missions include:

- Expeditions to asteroids to study their composition; to assess the feasibility of mining; and, most important, to develop methods for protecting Earth from impacts.
- Expeditions to our Moon to establish scientific stations and observatories on the far side; for mining rare elements; and, to test technologies for interplanetary exploration.
- Expeditions to a deep-space facility near our Moon for controlling robotic devices on the surface; for staging human sorties; and eventually for assembling interplanetary ships for the human exploration of Mars.

Expeditions to asteroids are objectively the most compelling of the deep space options if the safety of our planet and the survival of our species are priorities. However, it appears that building a facility at a Lagrange point near the Moon or, more likely, in a Near Rectilinear Halo Orbit, is the most-probable next step. Plans for a facility, currently called Gateway, are under way and, for this reason, we developed task lists to help mission planners prepare for Gateway missions. The task lists were reviewed by NASA engineers to ensure accuracy, but no analyses were performed; the 647 Gateway tasks are presented in nine mission phases as Appendix F of this report.



Proposed Gateway with Orion vehicle docked.

FUTURE RESEARCH

A few examples of additional research identified during the current study that must be conducted to prepare for exploration-class space missions are described, below.

- We developed the Gateway task list, presented in Appendix F, to help planners and designers prepare for missions that are more likely to be conducted in the near future than the human expedition to Mars that served as the focus of this study. The Gateway task list was reviewed by knowledgeable engineers and scientists, but it was not subjected to formal analysis. Research will be required to conduct analyses for Gateway missions as we have analyzed tasks and abilities for the human exploration of Mars. It also will be necessary to develop task lists, conduct analyses, and derive implications for other exploration-class space missions. The Mars and Gateway expedition task lists and the methods documented in this report provide a foundation for conducting those studies.

- It would be helpful to know if it is possible to train the problem-solving abilities estimated to be critical by SMEs for seven of the eight crew occupational specialties/roles identified during the current study. The key abilities, Inductive Reasoning, Deductive Reasoning, Problem Sensitivity, and Originality, are not possessed in equal measure by all people and efforts to develop those abilities have had mixed results. For example, a meta-analysis by Au and colleagues in 2014 found a small, but significant, effect relating working memory training to greater increases in fluid intelligence scores.[80] However, a 2013 meta-analysis by Melby-Lervåg and Hulme failed to find evidence of far-transfer effects of working memory training.[81] And, a meta-analysis by Simons et al., in 2017 concluded that brain training occurs in the same tasks as participants were trained, and in similar tasks, but again, little support was found for far-transfer of the training to general cognitive skills.[82] It is possible to improve an individual's ability to solve problems in a specific domain through training, but there is little evidence that the trained ability is generalizable across domains. It seems likely that it would be possible to learn general problem-solving abilities (i.e., techniques or strategies) in the manner that strength developed by lifting weights can be used to load supplies and the ability to read can be used to follow procedures in a wide range of domains. Research is needed to determine whether general problem-solving abilities and strategies can be trained in the spaceflight domain and then applied successfully in novel, spaceflight-relevant situations.

- The research team composed the four hypothetical crews presented on page 71 of this report to illustrate a process that begins with the occupational specialties/roles identified by the task analysis. This process, in practice, would be augmented by selecting or recruiting candidates with multiple proficiencies or, more likely, by training to develop sufficient knowledge, skills, and abilities in candidates to enable all crew members to serve as backups to other primary crew assignments. Research is needed to refine this process with the goal of assembling crews that possess redundant and complementary sets of skills and abilities.

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[80] J. Au, E. Sheehan, N. Tsai, G.J. Duncan, M. Buschkuehl, and S.M. Jaeggi. Improving fluid intelligence with training on working memory: a meta-analysis. *Psychonomic bulletin & review*, *22*(2), 366-377, 2015.
[81] M. Melby-Lervåg and C. Hulme. Is working memory training effective? A meta-analytic review. *Developmental psychology*, *49*(2), 270, 2013.
[82] D.J. Simons, W.R. Boot, N. Charness, S.E. Gathercole, C.F. Chabris, D.Z Hambrick, and E.A. Stine-Morrow. Do "brain-training" programs work? *Psychological Science in the Public Interest*, *17*(3), 103-186, 2016.

- General schedules and detailed timelines to perform the tasks identified during the current study should be developed for each crew specialty/role. This process will enable analysts to identify periods of high and low workloads for individual crew members and to adjust the schedules iteratively to ensure equitable and sustainable workloads. Analysts could begin with Mars Surface Operations, but all mission phases must be addressed, eventually.

- Knowledge and procedures learned during pre-mission technical training are perishable. ISS astronauts report frequently that they cannot recall ever having been trained on certain tasks, which is attributable to the large number of training sessions and topics astronauts experience while preparing for ISS expeditions, to the high tempo of training, and to the usually long periods between training and actual task performance. Other factors, such as relatively high CO^2 levels on the ISS, fatigue, and the subtle effects of microgravity on cognition contribute to the problem. NASA training experts are aware of the issues and their efforts to develop innovative training methods and job aids to support task performance during exploration-class missions are encouraged.[83]

- Research is needed to support the development of training to prepare crews for the long durations and other special conditions expected for exploration-class space missions. Like the Expedition Corps Training Program developed for the Astronaut Office in 1999 (described on page 78 of this report), the curriculum should include cross-cultural sensitivity training and lessons learned from previous expeditions and from the experiences of ISS astronauts (e.g., trivial issues are exaggerated in isolation and confinement, outside communications are strained, eating meals together facilitates crew solidarity). Knowing what to expect will help crew members of exploration-class space missions adapt to the conditions.

- The many user interfaces and items of equipment mentioned in the task statements identified during the current study will require the attention of engineers and human factors specialists. They will apply design principles and experimentally-derived data to ensure that procedures, controls, displays, and equipment are consistent with human capabilities and limitations under the conditions of use. Everything, from the surgical instruments we hope will never be used, to the food and hygiene systems that will be used daily, must be subjects of systematic research, development, and evaluation.

ACKNOWLEDGMENTS

We are grateful to the many experts who contributed to this study, including Professors James Casler, Michael Gaffey, Pablo de Leon, Susannah Porter, Vadim Rygalov, and Frank Spera who were interviewed about the scientific tasks that astronauts are likely to perform during the first human expeditions to Mars, and to John Charles, Stephen Hoffman, and Don Pettit who reviewed our draft task lists to ensure they were accurate and comprehensive.

We also are grateful to NASA managers Lauren Leveton, Laura Bollweg, Mihriban Whitmore, Brian Gore, Gordon Vos, Jennifer Fogarty, and Tom Williams for finding merit in our original proposal and for supporting our research efforts. We especially appreciate the time devoted to the study by training expert Donna Dempsey and by space operations experts Jay Bucky, Leroy Chiao, Michael Foale, James Kelly, Terry Virts, James Voss, Dafydd Williams and many others. Special thanks to intern Brandin Munson for summarizing research concerning generalizable problem-solving abilities. Finally, our task and ability analyses would not have been possible without the participation of the subject matter experts listed in Appendix G of this report.

[83] Immanuel Barshi and Donna Dempsey. Training for Mars. 9th International Conference on Applied Human Factors and Ergonomics, 21-25 July 2018. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180006491.pdf

Geologist/Astronaut, Harrison Schmitt at Station 6, North Massif during the 3rd Apollo 17 EVA near the Taurus-Littrow landing site in December 1972. Dr. Schmitt instructed the other Apollo astronauts in geological methods, but he was the only actual geologist to explore the moon and he made the most important discoveries.

Lesson Learned: Pilots and Automation

During their descent from lunar orbit on 20 July 1969, Neil Armstrong and Buzz Aldrin noticed that they were passing landmarks on the surface two or three seconds earlier than expected and realized they would land several miles from their target. Soon after reporting this anomaly, the navigation and guidance computer began issuing alarms; it was five minutes into the descent at an altitude of only 6,000 feet (1,800 m) above the surface of the Moon. An engineer at Mission Control determined that the alarms were caused by the computer's inability to keep up with the guidance tasks, but the crew should proceed. When Armstrong looked out the window after the alarm distraction, he saw that the computer had them landing in a boulder-field near a crater. Armstrong immediately took control of the descent, maneuvered the *Eagle* to a safe location, and landed.

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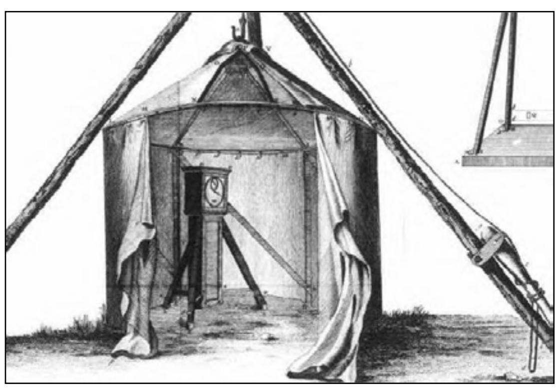


Captain Cook's portable observatory for recording the transit of Venus, by Robert Benard, engraver, from the French edition of James Cook's second voyage, *Voyage dans l'Hémisphère Austral, et autour du Monde, fait sur les Vaisseaux de Roi, l'Aventure, la Résolution, en 1772, 1773, 1774, 1775*. Paris 1778, Public Domain. See page 69.

APPENDIX A: FLEISHMAN ABILITIES + SIX SKILLS DERIVED FROM SPACE ANALOG RESEARCH

Arm-Hand Steadiness
The ability to keep the arm and hand steady while making an arm movement or while holding the arm and hand in one position; the ability does not involve strength or speed.

Auditory Attention
The ability to focus on a single source of auditory information in the presence of other distracting or irrelevant auditory stimuli.

Category Flexibility
The ability to produce many rules so that each rule tells how to group a set of things in a different way, with each different group containing at least two things from the original set of things.

Control Precision
The ability to move controls of a machine or vehicle quickly and repeatedly to exact positions.

Deductive Reasoning
The ability to apply general rules to specific problems to derive logical answers, which includes deciding if an answer makes sense.

Depth Perception
The ability to distinguish which of several objects is most distant from or nearest to the observer, or to judge the distance of an object from the observer.

Dynamic Flexibility
The ability to bend, stretch, twist, or reach out with the body, arms, and/or legs, both quickly and repeatedly.

Dynamic Strength
The ability of muscles to exert force repeatedly or continuously over a long time period; this includes the ability to hold up or move the body's own weight and/or objects repeatedly and represents endurance and the resistance of muscles to fatigue.

Explosive Strength
The ability to use short bursts of muscle force to propel oneself or an object; it requires gathering energy for bursts of muscle effort during a short time period.

Extent Flexibility
The ability to bend, stretch, twist, or reach out with the body, arms, or legs.

Far Vision
The ability to see distant environmental surroundings.

Finger Dexterity
The ability to make skillful, coordinated movements of the fingers of one or both hands, and to grasp, place, or move small objects; the ability involves the degree to which the finger movements can be performed quickly.

Flexibility of Closure
The ability to identify or detect a known pattern (such as a figure, word, or object) that is hidden in other material; that is, to distinguish the disguised pattern from the background material.

Fluency of Ideas
The ability to produce ideas about a given topic.

General Hearing
The ability to detect and to discriminate among sounds that vary over broad ranges of pitch and/or loudness.

Glare Sensitivity
The ability to see objects in the presence of glare or bright ambient light.

Gross Body Coordination
The ability to coordinate movement of the arms, legs, and torso during activity in which the whole body is in motion.

Gross Body Equilibrium
The ability to keep or regain one's body balance or to remain upright when in an unstable position, while changing direction, moving, or standing motionless.

Inductive Reasoning
The ability to combine separate pieces of information, or specific answers to problems, to form general rules or conclusions, which includes thinking of possible reasons why things go together.

Information Ordering
The ability to follow correctly a rule or set of rules to arrange things or actions in a certain order, which could include numbers, letters, words, pictures, procedures, sentences, and mathematical or logical operations.

Manual Dexterity
The ability to make skillful, coordinated movements of one hand, a hand together with its arm, or two hands to grasp, place, move, or assemble objects, such as hand tools or materials; the ability involves the degree to which the arm/hand movements can be performed quickly, but does not include moving machine controls.

Mathematical Reasoning
The ability to understand and organize a problem and then to select a mathematical method or formula to solve the problem, which includes reasoning through mathematical problems to determine appropriate operations to solve problems and understanding or structuring mathematical problems; actual manipulation of numbers is not included in this ability.

Memorization
The ability to remember information, such as words, numbers, pictures, and procedures, either by themselves or with other pieces of information.

Multi-Limb Coordination
The ability to coordinate the movements of two or more limbs (e.g., two arms, two legs, or one leg and one arm), such as in moving equipment or vehicle controls.

Near Vision
The ability to see close environmental surroundings.

Night Vision
The ability to see under low light conditions.

Number Facility
The ability to add, subtract, multiply, and divide quickly and correctly, which can be steps in other operations, such as calculating percentages and square roots.

Oral Comprehension
The ability to understand spoken English words and sentences.

Oral Expression
The ability to use English words or sentences in speaking so others will understand.

Originality
The ability to produce unusual or clever ideas about a given topic or situation; the ability to invent creative solutions to problems or to develop new procedures when standard operating procedures do not apply.

Perceptual Speed
The ability to compare letters, numbers, objects, or patterns quickly and accurately when presented either simultaneously or sequentially.

Peripheral Vision
the ability to see or perceive objects or movement towards the edges of the visual field.

Problem Sensitivity
The ability to tell when something is wrong or is likely to go wrong, which includes identifying the whole problem as well as the elements of the problem.

Rate Control
The ability to adjust an equipment control in response to changes in the speed and/or directions of a continuously moving object or scene; the ability involves timing the adjustments and anticipating the changes, and does not extend to situations in which both speed and direction are perfectly predictable.

Reaction Time
The ability to respond quickly to a signal (sound, light, image) when it appears; this ability is concerned with the speed with which the movement can be started with a hand, foot, or other part of the body.

Response Orientation
The ability to choose between two or more movements quickly and accurately in response to two or more different signals (lights, sounds, images); the speed with which the correct response is made by moving a hand, foot or other part of the body.

Selective Attention
The ability to concentrate on a task, even a boring task, without being distracted.

Sound Localization
The ability to identify the direction from which an auditory stimulus originated relative to the observer.

Spatial Orientation
The ability to determine where you are in relation to the location of some object, or to tell where the object is in relation to you.

Speech Clarity
The ability to communicate orally in a clear fashion understandable to a listener.

Speech Hearing
The ability to learn and understand the speech of another person.

Speed of Closure
The ability to combine and organize different pieces of information into one meaningful pattern quickly; the pattern is not known beforehand and the pieces could be visual or auditory.

Speed of Limb Movement
The ability to make a single movement of the arms or legs; the ability does not involve accuracy, careful control, or coordination of movement.

Stamina
The ability of the lungs and circulatory systems to perform efficiently over long time periods; the ability to exert oneself physically without getting out of breath.

Static Strength
The ability to use muscle force to lift, push, pull, or carry objects; it is the maximum force one can exert for a brief period of time.

Time Sharing
The ability to shift attention back and forth between two or more sources of information.

Trunk Strength
The ability of one's stomach and lower back muscles to support part of the body repeatedly or continuously over time without fatigue.

Visual Color Discrimination
The ability to match or discriminate among colors; the ability includes detecting differences in color purity (saturation) and brightness (brilliance).

Visualization
The ability to imagine how something will look when it is moved or when its parts are moved or rearranged; it requires the forming of mental images of how patterns or objects would appear after certain changes, such as unfolding or rotation.

Wrist-Finger Speed
The ability to make fast, simple, repeated movements of the fingers, hands, and wrists; the ability involves little, if any, accuracy or eye-hand coordination.

Written Comprehension
The ability to understand written words and sentences.

Written Expression
The ability to use English words or sentences in writing so others will understand.

Affability
The ability to get along with others and to speak and behave in a friendly manner.

Confidence
The ability to trust one's own capacity to perform tasks successfully, even under austere or arduous conditions.

Emotional Control
The ability to refrain from expressing anger or other emotional outbursts in words or actions.

Patience
The ability to endure annoyance or adversity with minimal complaint; calm self-possession or forbearance when confronting obstacles.

Teamwork
The ability to routinely subordinate one’s own wishes or interests to those of a group to achieve group objectives; the ability to work with others cooperatively and harmoniously.

Tolerance
The ability to accept cultural differences, personal traits or mannerisms, performance decrements, and similar factors and behaviors in others, without prejudice or effect on one's own behavior.

APPENDIX B: ASSUMPTIONS AND INSTRUCTIONS FOR COMPLETING THE ABILITY CARD-SORT FOR THE MARS EXPEDITION TASK ANALYSIS

The first human expedition to Mars will be conducted during a 30-month period in 12 mission phases. The Mars expedition crew will be more autonomous than current astronauts, with little access to Mission Control and ground support. Therefore, it is important to understand the abilities that must be possessed by the crewmembers. The purpose of this card sorting activity is to consider the most important abilities for a specific crew position to perform the specialized and other tasks to ensure a successful mission. All crewmembers are expected to perform tasks beyond their crew position specialty during every mission phase. Crew positions and mission phases are described following the instructions for estimating the relative importance of abilities that might be required of Mars expedition crew members.

Card Sorting Activity process:

You will be given a set of 58 ability cards. Each card in a set has a different ability and definition printed on one side. Each set also includes a cover card listing a crew position and three category cards labeled: **More Important**, **Important, and Less Important. For the first set of cards, place the category cards on a table with the one labeled Less Important on the left, the card labeled More Important on the right, and the card labeled Important between them. Next:**

1. Allocate each ability card in the set to one of the three categories of importance by placing the cards on the category card that best reflects your judgment of the abilities for the crew position **Geologist**.
   *Please read the definition on each card completely before allocating it to a category. The definitions used in this activity may be different from those you know.
2. When you have finished allocating the ability cards to the Importance categories, order the abilities *within* each category from highest importance to lowest importance, with highest importance on top of each stack.
3. Place the three category cards on top of each card's stack of ability cards.
4. Assemble the three stacks with the Most Important abilities on top, followed by the Important abilities, and then the Less Important abilities. Place the card indicating the crew position on top of the stack and secure the assembled deck of rank-ordered category and ability cards with a rubber band.

General assumptions about crew:

All members of the crew will be healthy and physically-fit (assume NASA standards). Also, all personnel will have received professional training/education corresponding to their assigned crew position (e.g., the physician will be a medical doctor, the geologist will be a planetary geologist, etc.). Every astronaut is expected to perform surface EVAs, habitability and maintenance functions, construction, and science.
Crew positions (One crewmember might fulfill more than one crew positions):

- Leader
- Biologist
- Geologist
- Physician
- Electrician
- Pilot/Navigator
- Mechanic/Engineer
- Computer Specialist

The crew position you will be rating is **Geologist**.

Geologist. The geologist will be responsible for directing the deployment of well-drilling, core sampling, seismographic, and other equipment; for planning and conducting excursions to collect geologic samples; and for the inspection, curation, and analysis of collected cores and samples. The geologist will be assisted by other crew members and will assist other crew members in the performance of their tasks, as needed. All members of the crew will live and work together in isolation and confinement during the 30-month expedition.

Sample tasks:

- Retrieve seismic testing munitions/equipment from storage and carry to surface rover, manually while wearing surface EVA suit, to prepare for geological research.
- Collect geological samples, manually using rock pick (i.e., geologist's hammer) and sample bags, while wearing surface EVA suit.
- Inspect geologic samples, visually using hand-held magnifying tool/microscope while wearing surface EVA suit in the field, to conduct preliminary analysis.
- Deploy and enter sleeping bag in surface rover to enable extended operations on planetary surface.
- Remove fire extinguisher from bracket in surface habitat or module and manually carry to source of fire.

MISSION PHASES

Launch to Low-Earth Orbit or Cis-Lunar Orbit

The first phase of the mission begins with the crew entering the Earth Ascent Vehicle (EAV) on the launch pad and ends with the EAV docking with the interplanetary spacecraft in either Low-Earth Orbit (LEO) or at a Lagrange location near the Moon (i.e., Cis-Lunar, or CLO). The phase would be similar to a journey to the International Space Station (ISS) if the destination were in LEO (24 to 48 hours) and longer if the interplanetary spacecraft were to be waiting in CLO (75 hours). Assume 84 hours (which is slightly longer than the time required for Apollo 11 to reach the Moon for this mission phase.

Pre-Trans Mars Injection and Trans Mars Injection

The second phase of the mission begins with the Mars crew entering the interplanetary spacecraft where they will be greeted by a team of astronauts who have prepared the ship for the journey to Mars and who will return to Earth in either the EAV or a similar space vehicle. This phase ends when the engines are shut down after the burn to achieve the correct course for the cruise to Mars. Assume a duration of four days for this mission phase, which will include final preparations and culminate with the main engine burn of approximately 60 minutes.

Cruise to Mars

The third phase of the mission is the unpowered cruise to Mars, which will take approximately 180 days (i.e., six months). The crew will be busy during this phase exercising and performing training tasks using configurable simulators; some refresher training will be performed, but most of the training will be new (in response to a strategy to transfer much of the pre-launch training burden to the cruise phase).

Mars Orbit Injection

The fourth phase of the mission assumes six days of intermittent preparation as the interplanetary spacecraft approaches Mars and the crew makes final course corrections. This phase ends with 12 hours of high-tempo activity preceding a 60-minute main engine burn to slow the ship, which will be pointed in the opposite direction of travel.

Mars Orbit

The fifth phase of the mission begins as the interplanetary ship approaches and then docks with a pre-positioned Mars Descent Vehicle (MDV), which is located in an elliptical orbit with a 1-Sol (one Martian day) period; the orbit places the spacecraft over the landing site once per Martian day at the same time of day. Assume approximately 48 hours for the rendezvous and docking and another 48 hours for the crew to enter the Mars Descent Vehicle (MDV), configure systems, perform final checks, and communicate with Earth in preparation for descent to the surface of Mars.

Mars Surface Descent

The sixth phase of the mission begins with the crew securing themselves in the Mars Descent Vehicle (MDV) where they will perform final checks before undocking from the interplanetary spacecraft and then initiating the deorbit burn at the highest point of the parking orbit (apoapse). The MDV will descend through half of the parking orbit (about 12 hours) at the end of which is atmospheric entry and the 10 to 20-minute terminal descent burn. Assume approximately 14 hours from ingress in Mars orbit to egress of the MDV following landing, shut-down of MDV systems, and initial communications from the planetary surface.

Mars Surface Operations

The seventh and longest phase of the mission begins with the crew walking from the Mars Descent Vehicle (MDV) to the pre-positioned Mars Habitat following landing, and ends approximately 545 days later when the crew enters the pre-positioned Mars Ascent Vehicle (MAV) to return to Mars orbit and the interplanetary ship. Crew time on the planetary surface will be spent performing construction and maintenance; housekeeping and planning; geological and biological science in the vicinity of the habitat and during mechanized traverses; and communicating among the members of the crew and with Earth (communications response lags with Earth will be approximately 20 minutes).

Mars Surface Ascent

The eighth phase of the mission begins when the crew enters the Mars Ascent Vehicle (MAV) to prepare for launching from the surface of Mars to rendezvous with the interplanetary ship in Mars orbit. Assume approximately 14 hours from ingress to the MAV and shutdown of MAV systems after docking with the interplanetary ship in Mars orbit. A “missed attempt” for rendezvous would add 24 hours to the duration of this mission phase.

Trans-Earth Injection

The ninth phase of the mission begins with the crew preparing the interplanetary ship for the journey home and ends approximately six days later after a main engine burn of 60 minutes has propelled the ship on a course to intercept Earth.

Cruise to Earth

The tenth phase of the mission is the unpowered cruise to Earth, which will take approximately 180 days (i.e., six months). The crew will perform refresher training using onboard computer simulations to prepare for the final phases of the mission; however, most of the crew’s time will be devoted to exercise and to science tasks to provide meaningful work during the cruise.

Earth Approach

The eleventh phase of the mission begins approximately five days before landing with the crew transferring from the interplanetary ship into an attached Orion-type Earth Descent Vehicle (EDV) and undocking. The interplanetary spacecraft continues on it course unoccupied indefinitely while the crew makes final course corrections in cramped conditions onboard the EDV during the five-day approach to Earth.

Earth Surface Descent

The final phase of the mission begins with atmospheric entry, which will involve substantial g-loading and be similar to the “skip” trajectories of Apollo capsule landings. Precision will be required to avoid either intolerable atmospheric friction or skipping off the atmosphere. The duration from first atmospheric interface to landing under parachutes will be 20 to 30 minutes.

CREW POSITIONS

Pilot/Navigator. The Pilot/Navigator will be responsible for operating spacecraft controls and navigation systems during all phases of the expedition, and for operating vehicles and remotely-controlled equipment (e.g. robotic reconnaissance) during Mars Surface Operations. The Pilot/Navigator will be assisted by other crew members and will assist other crew members in the performance of their tasks, as needed. All members of the crew will live and work together in isolation and confinement during the 30-month expedition.

Sample tasks:

- Enter control inputs, manually, to configure Mars Excursion Vehicle computers for Mars Surface Ascent maneuver.
- Deploy and operate robot, remotely on surface, to explore possible sites for field camp to extend EVA range.
- Conduct (training) simulation using surface habitat computer to refresh navigation skills for Mars Surface Ascent.

Physician. The Physician will be responsible for routine and emergency medical and dental treatment throughout the expedition. The physician must be prepared to respond to a broad range of contingencies, most of which are unlikely to occur, but will require prompt attention if they do. The Physician will be assisted by other crew members and will assist other crew members in the performance of their tasks, as needed. All members of the crew will live and work together in isolation and confinement during the 30-month expedition.

Sample tasks:

- Conduct physical/cognitive tests in surface habitat/laboratory to assess fitness for duty (automatically-scheduled/results transmitted to Earth).
- Insert catheter into the pleural space between lung and chest wall, producing a pathway for air to escape to perform a needle decompression of a pneumothorax (collapsed lung).
- Conduct dental examination on crew member, manually/visually, to investigate complaint of tooth/jaw pain.

Biologist. The Biologist will be responsible for human, biological, and life sciences research. The Biologist will be assisted by other crew members and will assist other crew members in the performance of their tasks, as needed. All members of the crew will live and work together in isolation and confinement during the 30-month expedition.

Sample tasks:

- Conduct culturing experiment, manually in laboratory module while wearing protective garments, to test sample material for biological content.
- Operate sample analysis module in the surface habitat/laboratory, manually, to test for presence of hydrogen, oxygen, and nitrogen (associated with life).
- Conduct RNA sequencing experiment, manually in laboratory module while wearing protective garments, to test sample material for biological content.

Mechanic/Engineer. The Mechanic/Engineer will be responsible for the inspection, maintenance, and repair of spacecraft physical systems (e.g., structures, plumbing) during the cruise phases, and for deployment, maintenance, and repair of habitats, auxiliary structures, vehicles, and surface equipment during Mars Surface Operations. The Mechanic/Engineer will be assisted by other crew members and will assist other crew members in the performance of their tasks, as needed. All members of the crew will live and work together in isolation and confinement during the 30-month expedition.

Sample tasks:

- Deploy surface antenna and attach cable connectors to antenna and habitat, manually with one other crew member while wearing surface EVA suits.
- Remove/replace component, manually in surface habitat/laboratory, to repair surface EVA suit.
- Review schematics and other documentation, visually, to isolate plumbing (e.g., cooling, CLSS) fault in spacecraft.

Electrician. The Electrician will be responsible for the inspection, maintenance, and repair of spacecraft, habitat, equipment, and vehicle electrical systems (e.g., wiring, connectors) during all phases of the expedition. The Electrician will be assisted by other crew members and will assist other crew members in the performance of their tasks, as needed. All members of the crew will live and work together in isolation and confinement during the 30-month expedition.

Sample tasks:

- Replace electronic connector on wire/cable in surface habitat, manually, using hand tools and spare parts.
- Review schematics and other documentation, visually, to isolate electronic fault in spacecraft.
- Inspect circuit board, visually, to identify short circuit or loose/missing connection in surface habitat or equipment.

Computer Specialist. The Computer Specialist will be responsible for the inspection, maintenance, and repair of spacecraft, habitat, equipment, and vehicle computer systems (i.e., software) during all phases of the expedition. The Computer Specialist will be assisted by other crew members and will assist other crew members in the performance of their tasks, as needed. All members of the crew will live and work together in isolation and confinement during the 30-month expedition.

Sample tasks:

- Review documentation/enter control inputs, visually/manually, to diagnose software problem.
- Enter control inputs, manually, to load software patch/reload software.
- Program 3-D printer, manually via computer inputs, to fabricate a replacement part for a mechanical system on planet surface.

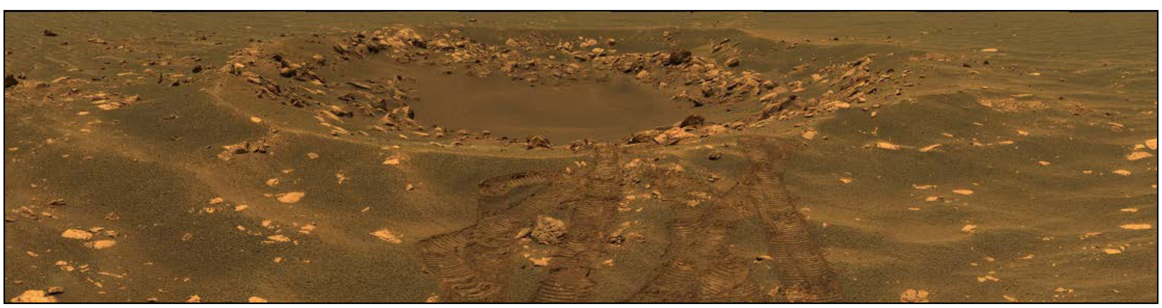
Leader. The expedition Leader will be responsible for coordinating and scheduling crew activities; resolving conflicts; directing responses to emergencies; and facilitating mission objectives. It is likely that the expedition Leader’s role will be combined with one of the other crew positions.

Sample tasks:

- Schedule tasks and monitor performance of work to ensure that opportunities and resources are allocated appropriately among crew personnel.
- Plan operations (e.g., EVA, maintenance of external components) using computer-based records in consultation with MCC and onboard personnel.

Hjalmar Johansen, Fridtjof Nansen, and Sigurd Scott-Hansen view a Solar Eclipse near the *Fram* on 6 April 1894 during the Norwegian Polar Expedition (1893 – 1896).

"Truly, the whole secret lies in arranging things sensibly, and especially in being careful about the food." - *Fridtjof Nansen*



Fram Crater on Mars, named for Fridtjof Nansen's ship.

APPENDIX C: ALL 158 SUMMARY TASK STATEMENTS RANKED BY CRITICALITY

Rank	Summary Task Statement	Frequency	Difficulty	Importance	Criticality
1	Perform science-related EVA functions during MSO.	3.679	4.036	4.286	12.000
2	Monitor systems and perform piloting functions during Mars Surface Ascent.	2.912	4.158	4.807	11.877
3	Perform piloting functions during MSD.	2.589	4.375	4.821	11.786
4	Interact/communicate with crew members directly during MSO.	4.638	2.298	4.672	11.609
5	Perform piloting functions during Earth Descent.	2.545	4.268	4.750	11.563
6	Perform piloting functions during Mars Orbit Injection.	2.386	4.246	4.860	11.491
7	Perform piloting functions during Mars Orbit.	2.556	4.241	4.691	11.487
8	Enter control inputs, manually/visually with gloved hand, to pilot Earth Ascent Vehicle (EAV) during launch and cruise to LEO/CLO.	2.772	4.000	4.702	11.474
9	Monitor systems/perform piloting functions during TEI.	2.800	3.893	4.732	11.425
10	Perform piloting functions during Earth Approach.	2.518	4.107	4.786	11.411
11	Assess displayed information, cognitively, to determine readiness to launch to LEO/CLO.	3.123	3.632	4.579	11.333
12	Conduct Extra-Vehicular Activity (EVA) to perform maintenance or retrieve items from outside the interplanetary space vehicle during Cruise to Mars.	2.246	4.491	4.596	11.333
13	Monitor displays and verify configurations before and during launch to LEO/CLO	3.554	3.333	4.439	11.326
14	Monitor systems during Earth Descent.	3.481	3.382	4.436	11.300
15	Perform monitoring functions in surface habitat and modules to ensure crew/system health during MSO.	3.897	3.000	4.386	11.283
16	Enter/exit surface habitat, manually while wearing pressure suit and helmet, during MSO.	3.544	3.246	4.474	11.263
17	Perform medical diagnoses and evaluations, cognitively, during Mars Surface Operations.	2.690	4.053	4.517	11.260
18	Perform robot-related functions during MSO.	3.527	3.750	3.982	11.259
19	Perform geology-related science functions in surface habitat or modules during Mars Surface Operations.	3.491	3.754	4.000	11.245
20	Assess displayed information, cognitively, to determine readiness for TMI maneuver.	3.018	3.571	4.643	11.232
21	Monitor crew behavioral health/respond to behavioral health issues during Mars Surface Operations.	3.133	3.559	4.517	11.209
22	Monitor systems to ensure proper functioning during CTM.	3.897	2.983	4.328	11.207
23	Perform medical diagnoses and evaluations, cognitively, during Cruise to Mars.	2.649	4.055	4.491	11.195
24	Respond to medical emergencies, following procedures and with equipment provided, during Cruise to Mars.	1.948	4.509	4.724	11.181
25	Perform surface rover driving functions during MSO.	3.464	3.411	4.304	11.179
26	Respond to medical emergencies, following procedures and with equipment provided, during MSO.	2.069	4.263	4.825	11.157
27	Perform surface EVA physical functions on foot during MSO.	3.298	3.482	4.368	11.149

Rank	Summary Task Statement	Frequency	Difficulty	Importance	Criticality
28	Adjust system controls, manually during buffetted descent, in response to displayed information.	2.673	3.870	4.585	11.128
29	Respond to technical emergencies, following procedures and with equipment provided, during CTM.	2.140	4.053	4.930	11.123
30	Monitor systems during Mars Surface Descent.	3.148	3.444	4.509	11.102
31	Perform tests and examinations, physically, to support medical diagnoses during Mars Surface Operations.	2.741	3.860	4.483	11.084
32	Perform biology-related science functions in surface habitat or modules during Mars Surface Operations.	3.474	3.579	4.018	11.070
33	Exercise daily using onboard equipment during CTM.	4.390	2.179	4.500	11.068
34	Enter control inputs, manually/visually with gloved hand, to configure/operate Earth Ascent Vehicle (EAV) before/after launch.	2.821	3.614	4.625	11.060
35	Perform surface rover operation functions during MSO.	3.364	3.509	4.182	11.055
36	Conduct science and planning functions during CTM.	3.821	3.625	3.607	11.054
37	Monitor systems to ensure proper functioning during CTE.	3.778	3.074	4.185	11.037
38	Perform surface rover navigation functions during MSO.	3.375	3.446	4.214	11.036
39	Respond to medical emergencies, following procedures and with equipment provided, during Cruise to Earth.	2.000	4.327	4.696	11.024
40	Perform human research-related science functions in surface habitat or modules during MSO.	3.534	3.448	4.017	11.000
41	Perform tests and examinations, physically, to support medical diagnoses during Cruise to Mars.	2.759	3.877	4.362	10.998
42	Conduct communications checks and communicate observations/evaluations to crew and MCC personnel, verbally using communications system during MSO.	4.123	2.500	4.368	10.991
43	Perform electronics/computers maintenance/repair functions in surface habitat or modules during MSO.	2.983	3.596	4.404	10.983
44	Perform maintenance/repair/monitoring functions during surface EVA operations during MSO.	3.071	3.589	4.321	10.982
45	Respond to technical emergencies, following procedures and with equipment provided, during CTM.	2.109	4.055	4.818	10.982
46	Perform medical diagnoses and evaluations, cognitively, during Cruise to Earth	2.696	3.964	4.321	10.981
47	Assess displayed and aural information, cognitively, to determine appropriate course of action during CTM.	3.018	3.298	4.649	10.965
48	Perform maintenance/repair functions in surface habitat or modules during Mars Surface Operations.	3.089	3.464	4.393	10.946
49	Conduct training to preserve/learn skills during CTM.	3.661	2.931	4.322	10.914
50	Perform construction-related EVA functions during MSO.	2.768	3.750	4.393	10.911
51	Perform medical treatments during MSO.	2.328	3.965	4.586	10.879
52	Perform tests and examinations, physically, to support medical diagnoses during Cruise to Earth	2.782	3.741	4.327	10.850
53	Conduct maintenance functions during Cruise to Mars.	3.246	3.333	4.246	10.825
54	Perform post-Mars Descent maneuver functions.	2.333	3.907	4.556	10.796
55	Conduct maintenance functions during Cruise to Earth.	3.333	3.296	4.167	10.796

Rank	Summary Task Statement	Frequency	Difficulty	Importance	Criticality
56	Monitor displays and verify configurations before and during Trans Mars Injection (TMI)	3.246	3.175	4.368	10.789
57	Perform science-related EVA functions with heavy equipment during Mars Surface Operations.	2.877	3.964	3.946	10.788
58	Adjust systems to ensure proper functioning during CTM.	2.879	3.534	4.362	10.776
59	Monitor systems during Mars Orbit Injection.	3.018	3.263	4.491	10.772
60	Perform initial installation/activation/inspection of surface habitat systems during MSO.	2.386	3.649	4.737	10.772
61	Conduct piloting functions during Cruise to Earth.	2.407	3.852	4.500	10.759
62	Prepare/eat meals in surface habitat during MSO.	4.293	1.982	4.466	10.741
63	Conduct piloting functions during Cruise to Mars.	2.509	3.930	4.298	10.737
64	Monitor systems during Earth Approach.	3.200	3.109	4.418	10.727
65	Monitor EVA systems during EVA during MSO.	3.411	3.070	4.246	10.727
66	Use interplanetary ship waste management systems for liquid/solid waste during CTM.	4.172	2.375	4.172	10.720
67	Adjust controls/attachments, manually with gloved hands, to configure suit/displays before/during/after launch from LEO/CLO.	2.782	3.473	4.455	10.709
68	Assess displayed and aural information, cognitively, to determine appropriate course of action during CTM.	3.164	3.200	4.345	10.709
69	Perform emergency functions in surface habitat or modules during Mars Surface Operations.	2.052	3.810	4.845	10.707
70	Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel during Earth Surface Descent.	3.855	2.473	4.364	10.691
71	Prepare for Mars Surface Ascent maneuver.	2.263	3.737	4.684	10.684
72	Conduct navigation functions during Cruise to Mars.	2.709	3.636	4.333	10.679
73	Configure systems for Mars Orbit ops and descent.	2.321	3.625	4.709	10.656
74	Adjust systems to ensure proper functioning during CTE.	2.944	3.389	4.315	10.648
75	Conduct navigation functions during Cruise to Earth.	2.698	3.547	4.377	10.623
76	Monitor systems during Mars Orbit operations	3.255	3.089	4.268	10.612
77	Prepare/eat meal, manually, using interplanetary ship food hydration/heating equipment/galley during CTE.	4.345	1.963	4.291	10.599
78	Conduct science and planning functions during CTE.	3.722	3.278	3.593	10.593
79	Exercise daily using onboard equipment during CTE.	4.286	2.073	4.232	10.591
80	Conduct communications checks and communicate observations/evaluations to crew and MCC personnel, verbally using communications system during MOI.	3.400	2.727	4.463	10.590
81	Conduct EVA to perform maintenance or retrieve items from outside the interplanetary ship during CTE.	2.036	4.196	4.357	10.589
82	Perform post-Mars Ascent maneuver functions.	2.286	3.772	4.526	10.584
83	Perform medical treatments during Cruise to Earth.	2.273	3.870	4.436	10.579
84	Perform construction-related EVA functions with heavy equipment during Mars Surface Operations.	2.375	3.911	4.286	10.571
85	Conduct communications checks and communicate observations/evaluations to crew and MCC, verbally using communications system prior to and during EA.	3.673	2.473	4.418	10.564

Rank	Summary Task Statement	Frequency	Difficulty	Importance	Criticality
86	Conduct communications checks and communicate observations/evaluations to crew and MCC, verbally using communications system during launch to LEO/CLO.	3.965	2.158	4.421	10.544
87	Inspect/prepare/ deploy surface rover during MSO.	3.000	3.439	4.105	10.544
88	Use surface habitat waste management systems for liquid/solid waste during MSO.	4.138	2.281	4.103	10.522
89	Conduct communications checks and communicate observations/evaluations to crew and MCC personnel, verbally using communications system during CTM.	3.982	2.429	4.107	10.518
90	Conduct communications checks and communicate observations/evaluations to crew and MCC personnel, verbally using communications system during MSA.	3.368	2.696	4.429	10.493
91	Prepare/eat meal, manually, using interplanetary ship food hydration/heating equipment/galley during CTM.	4.237	1.982	4.254	10.474
92	Perform medical treatments during Cruise to Mars.	2.158	3.786	4.526	10.470
93	Perform surface rover maintenance during MSO.	2.786	3.571	4.089	10.446
94	Conduct communications checks and communicate observations/evaluations to crew and MCC personnel, verbally using communications system during MSD.	3.382	2.745	4.315	10.442
95	Adjust controls in surface habitat or modules to ensure proper functioning of systems during MSO.	3.211	2.895	4.333	10.439
96	Perform pre- and post-EVA inspection and planning tasks during Mars Surface Operations.	3.241	3.018	4.158	10.417
97	Conduct communications checks and communicate observations/evaluations to crew and MCC personnel, verbally using communications system during MSO.	3.527	2.630	4.255	10.411
98	Perform greenhouse/plant growth-related functions in surface module during Mars Surface Operations.	3.589	2.946	3.875	10.411
99	Prepare for Mars Surface Ascent during MSO.	2.069	3.586	4.741	10.397
100	Use interplanetary space vehicle waste management systems for liquid/solid waste (i.e., toilet/bodily function) during CTE.	4.185	2.113	4.093	10.391
101	Perform exercise in surface habitat to maintain cardiovascular/muscle/ bone conditioning during MSO.	4.017	2.035	4.322	10.374
102	Perform planning and administrative functions, individually and with other crew members during MSO.	3.754	2.526	4.070	10.351
103	Conduct communications checks and communicate observations/evaluations to crew and MCC, verbally using communications system during Pre-TMI & TMI.	3.661	2.429	4.250	10.339
104	Prepare for Mars Surface Descent maneuver.	2.236	3.527	4.564	10.327
105	Sleep for approximately eight hours each 24-hour period, during Cruise to Mars.	4.153	1.621	4.542	10.316
106	Perform robot maintenance functions during MSO.	2.818	3.661	3.818	10.297
107	Maintain space craft waste management systems during CTM.	3.542	2.579	4.051	10.172
108	Prepare for Earth Surface Descent.	2.370	3.200	4.600	10.170
109	Perform surface EVA communications during MSO.	3.526	2.439	4.175	10.140

Rank	Summary Task Statement	Frequency	Difficulty	Importance	Criticality
110	Sleep for approximately eight hours each 24-hour period, during Cruise to Earth.	4.250	1.545	4.321	10.117
111	Perform training and skill refreshment in surface habitat during Mars Surface Operations.	3.186	2.810	4.119	10.115
112	Sleep in surface habitat during MSO.	4.203	1.483	4.397	10.083
113	Conduct refresher training during CTE.	3.127	2.815	4.127	10.069
114	Perform administrative/planning-related science functions in surface habitat or modules during MSO.	3.536	2.807	3.702	10.044
115	Conduct communications checks and communicate observations/evaluations to crew and MCC personnel, verbally using communications system during CTE.	3.768	2.161	4.107	10.036
116	Perform suit-related tasks before and after launch.	2.636	3.055	4.321	10.012
117	Respond to dental emergencies during MSO.	2.018	3.929	4.052	9.998
118	Maintain space craft waste management systems during CTE.	3.446	2.509	4.018	9.973
119	Prepare for Earth Approach.	2.327	3.130	4.509	9.966
120	Administer medications during MSO.	2.724	2.947	4.224	9.896
121	Conduct communications checks and communicate observations/evaluations to MCC personnel, verbally using communications system during TEI.	3.123	2.491	4.281	9.895
122	Perform installation/activation/inspection of auxiliary systems during Mars Surface Operations.	2.836	3.089	3.964	9.890
123	Perform surface EVA habitability functions during MSO.	3.143	2.860	3.877	9.880
124	Prepare for Mars Orbit Injection aerobraking maneuver.	2.089	3.263	4.526	9.879
125	Take position and prepare vehicle, manually while wearing pressure suit and helmet, to prepare for launch from Mars Orbit.	2.250	3.246	4.368	9.864
126	Use surface habitat hygiene systems for cleaning during MSO.	3.948	2.105	3.793	9.847
127	Review procedures/checklists to prepare for Mars Orbit Operations and descent.	2.679	2.768	4.393	9.839
128	Use interplanetary space vehicle hygiene systems for cleaning during Cruise to Mars.	3.947	2.161	3.719	9.827
129	Adjust controls, manually with gloved hands, before and after launch to LEO/CLO.	2.821	2.807	4.193	9.821
130	Administer medications during Cruise to Mars.	2.707	2.860	4.241	9.808
131	Conduct installation functions during Cruise to Mars.	2.929	3.089	3.768	9.786
132	Respond to dental emergencies, following procedures and with equipment provided, during Cruise to Earth.	1.875	3.891	3.964	9.730
133	Perform surface habitat housekeeping during MSO.	3.810	2.158	3.759	9.727
134	Respond to dental emergencies, following procedures and with equipment provided, during Cruise to Mars.	1.807	3.947	3.948	9.703
135	Use interplanetary space vehicle hygiene systems for cleaning during Cruise to Earth.	3.926	2.000	3.759	9.685
136	Load/unload surface rover/trailer for MSO.	2.754	3.035	3.877	9.667
137	Prepare/eat meals during Earth Approach.	3.786	1.907	3.945	9.639
138	Use EDV waste management systems for liquid/solid waste during Earth Approach.	3.545	2.164	3.875	9.584

Rank	Summary Task Statement	Frequency	Difficulty	Importance	Criticality
139	Administer medications during Cruise to Earth.	2.691	2.759	4.127	9.577
140	Use Earth Ascent Vehicle (EAV) waste management system for liquid/solid waste.	3.328	2.436	3.702	9.466
141	Conduct recreational activities, individually and as a crew, during Cruise to Earth.	3.821	1.537	3.982	9.341
142	Conduct installation functions during Cruise to Earth.	2.660	3.038	3.615	9.314
143	Perform administrative functions during CTE.	3.352	2.472	3.472	9.295
144	Perform administrative functions during CTM.	3.509	2.333	3.421	9.263
145	Conduct recreational activities, individually and as a crew, during Cruise to Mars.	3.828	1.411	3.966	9.204
146	Prepare/eat meal, manually, using Earth Ascent Vehicle (EAV) food hydration/heating equipment/galley during cruise to CLO.	3.448	2.018	3.719	9.186
147	Perform post-Earth Descent functions.	2.327	3.089	3.750	9.167
148	Perform 3D printer-related functions in surface habitat or modules during Mars Surface Operations.	2.732	2.911	3.393	9.036
149	Perform recreation/leisure activities in the surface habitat during Mars Surface Operations.	3.632	1.554	3.807	8.992
150	Enter vehicle and take position, manually while wearing pressure suit and helmet, to prepare for launch from LEO/CLO.	2.018	2.768	4.196	8.982
151	Enter vehicle/take position, manually while wearing pressure suit/ helmet, to prepare for launch to CLO.	2.125	2.607	4.232	8.964
152	Perform surface rover habitability/logistics functions during MSO.	2.897	2.404	3.569	8.869
153	Use surface rover waste management systems for liquid/solid waste during MSO.	3.035	2.232	3.596	8.864
154	Prepare/eat meals in surface rover during MSO.	3.017	1.912	3.534	8.464
155	Conduct inventories and update records during CTE.	3.000	1.982	3.339	8.321
156	Sleep in surface rover during Mars Surface Operations.	2.661	1.873	3.732	8.266
157	Conduct inventories and update records during CTM.	2.864	1.965	3.345	8.174
158	Use emergency materials to contain/clean results of motion sickness during/after launch.	2.552	2.103	2.845	7.500

Egress by Paul Hudson.

Appendix D: All 1,125 Mars Expedition Tasks by Mission Phase

Phase 1: Launch to LEO or CLO (LTO)

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

- Conduct communications checks with other crew, wearing pressure suit, to prepare for launch from Earth.
- Conduct communications checks with ground personnel, wearing pressure suit, to prepare for launch from Earth.
- Communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Enter vehicle and take position, manually while wearing pressure suit and helmet, to prepare for launch from Earth.

- Enter vehicle via diving board and ingress/egress straps, manually while wearing pressure suit and helmet, to prepare for launch from Earth.
- Conduct final predeparture inspections of storage and equipment, visually, prior to launch from Earth.
- Move (translate) to crew seat, wearing pressure suit, to prepare for launch from Earth.

Adjust controls, manually with gloved hands, before and after launch.

- Adjust control, manually with gloved hand, to reconfigure ECLS/change cabin temperature.
- Press edge key/button and F1 panel switch, manually with gloved hand, to activate LCG Pump.
- Press edge key/button with gloved hand to cycle to fresh PSA swing bed.
- Press edge key/button, with gloved hand, to activate Air Revitalization System (ARS)/Suit Mode.

Perform suit-related tasks before and after launch.

- Secure seat restraints, wearing pressure suit/gloves, to prepare for launch from Earth.
- Attach umbilicals (GSE air) to suit, manually while wearing pressure suit/gloves, to prepare for launch from Earth.
- Secure umbilicals with URDs, manually while wearing pressure suit/gloves, to prevent damage during launch.
- Install emergency O2 bottles on crew leg, manually, with help of support personnel.
- Connect to AIU, manually while wearing pressure suit/gloves, to prepare for launch from Earth.
- Conduct final suit leak check, manually with help of support personnel, to verify suit integrity.
- Release flail restraints and harness, manually, to prepare for removing pressure suit and helmet.
- Remove pressure suit/helmet, manually, to prepare for cruise to orbit.

Use Earth Ascent Vehicle (EAV) waste management system for liquid/solid waste (i.e., toilet/bodily function).

- Use Earth Ascent Vehicle (EAV) waste management system for liquid waste (i.e., toilet/bodily function).
- Use Earth Ascent Vehicle (EAV) waste management system for solid waste (i.e., toilet/bodily function).

Use emergency materials to contain/clean results of motion sickness during/after launch.

- Access and open emesis bag located in pressure suit/seat pocket, manually with gloved hand, to prepare for barfing.
- Access disposable towel located in seat pocket, manually with gloved hand, to prepare for cleaning barf from face/helmet/visor.

Prepare/eat meal, manually, using Earth Ascent Vehicle (EAV) food hydration/heating equipment/galley during cruise to LEO/CLO.

- Prepare meal for crew consumption, manually, using Earth Ascent Vehicle (EAV) food hydration/heating equipment.
- Eat/drink meal in Earth Ascent Vehicle (EAV) during cruise to LEO/CLO.

Enter control inputs, manually/visually with gloved hand, to configure and operate Earth Ascent Vehicle (EAV) before and after launch.

- Perform controls/switch checklist, visually/manually while wearing pressure suit/gloves, to verify proper configuration.
- Perform ASP/flight crew check, manually while wearing pressure suit/gloves, to ensure hard switches are still in expected configuration after strap in.
- Inspect display, visually wearing suit/helmet, to verify all pyros are armed for ascent.
- Enter control inputs, manually/visually with gloved hand, to configure launch displays.

Enter control inputs, manually, to activate ATP/star tracker for cruise to LEO/CLO.
Enter control inputs, manually, to align IMU if necessary.
Enter control inputs, manually to override automated system, to reconfigure CM/SM heaters if necessary.
Activate controls, manually while wearing pressure suit/gloves, to configure cabin lighting.
Activate cabin pressure control, manually after visor opening, to prepare for cruise to orbit.
Respond to communications and displays, wearing pressure suit, to prepare for launch from Earth.
Activate controls, manually, to override automated process to initiate/control solar array deployment sequence, if necessary.

Monitor displays and verify configurations before and during launch to LEO/CLO

Observe crew position displays and activate controls, wearing pressure suit, to prepare for launch from Earth.
Monitor audio communications and displays, wearing pressure suit/helmet, to prepare for launch from Earth.
Monitor displays, visually while wearing pressure suit/helmet, to verify system configuration formats and eProc.
Monitor displays, visually, to assess solar array deployment status.
Monitor/control external video camera, visually/manually, to verify solar array deployment.
Monitor display, visually, to verify solar array power generation/battery charging.
Monitor displays/communicate values, visually/verbally, to evaluate system and crew readiness for orbit operations.
Monitor engine performance displays, visually wearing pressure suit/helmet, to ensure proper functioning during buffeted ascent.
Monitor displays, visually wearing pressure suit/helmet, to verify LAS jettison during buffeted ascent.
Monitor displays, visually wearing pressure suit/helmet, to verify MECO during buffeted ascent.
Monitor displays, visually wearing pressure suit/helmet, to verify core stage separation during buffeted ascent.
Monitor audio communications and displays, wearing pressure suit/helmet, during buffeted launch from Earth.
Monitor displays, visually, to verify star tracker configuration/status.

Assess displayed information, cognitively, to determine readiness to launch to LEO/CLO.

Evaluate displayed/communicated information, cognitively, to assess readiness for orbit operations.
Evaluate alarms and displays, cognitively, to identify any mission-critical anomalies during buffeted launch from Earth.

Enter control inputs, manually/visually with gloved hand, to pilot Earth Ascent Vehicle (EAV) during launch and cruise to LEO/CLO.

Adjust controls as necessary, manually wearing pressure suit/gloves, during buffeted launch from Earth.
Activate controls, manually wearing pressure suit/gloves, to abort launch in response to evaluation data during buffeted ascent.
Activate controls, manually wearing pressure suit/gloves, to override automated systems/control spacecraft in response to evaluation data during buffeted ascent.
Adjust main engine controls, manually wearing pressure suit/gloves, to maneuver Earth Ascent Vehicle (EAV) to correct location near spacecraft in LEO/CLO.
Adjust main engine controls, manually wearing pressure suit/gloves, to shut down Earth Ascent Vehicle (EAV) main engine near spacecraft in LEO/CLO.
Adjust attitude control thrusters, manually wearing pressure suit/gloves, to dock Earth Ascent Vehicle (EAV) to spacecraft in LEO/CLO.
Adjust attitude control thrusters, manually wearing pressure suit/gloves, to maneuver Earth Ascent Vehicle (EAV) to spacecraft in LEO/CLO.
Adjust controls, manually wearing pressure suit/gloves, to shut down attitude control thrusters and other systems after docking with spacecraft in LEO/CLO.
Enter control inputs, manually wearing pressure suit/gloves, to activate engine shut down if auto shut down fails, to ensure safing of EAV after docking.
Activate appropriate controls in response to alarms, manually, while communicating actions to crew and MCC during buffeted launch from Earth.

Phase 2: Pre-Trans-Mars Injection (TMI) & TMI

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Conduct communications checks with other crew, wearing pressure suit, to prepare for departing LEO/CLO.

Conduct communications checks with ground personnel, wearing pressure suit, to prepare for departing LEO/CLO.

Communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Enter vehicle and take position, manually while wearing pressure suit and helmet, to prepare for launch from LEO/CLO.

Open spacecraft hatch, wearing pressure suit, to prepare for entering prior to departing LEO/CLO.

Enter spacecraft hatch, wearing pressure suit, to prepare for departing LEO/CLO (i.e., Trans-Mars Injection).

Move (translate) to crew seat, wearing pressure suit, to prepare for departing LEO/CLO.

Secure seat restraints and umbilicals, wearing pressure suit, to prepare for departing LEO/CLO.

Conduct final predeparture inspections of storage and equipment, visually, prior to departing LEO/CLO.

Monitor displays and verify configurations before and during Trans Mars Injection (TMI)

Observe crew position displays and activate controls, wearing pressure suit/gloves, to prepare for departing LEO/CLO.

Monitor communications, aurally while wearing pressure suit/helmet, to prepare for departing LEO/CLO.

Monitor displays, visually while wearing pressure suit/helmet, to prepare for departing LEO/CLO.

Monitor communications, aurally wearing pressure suit/helmet, during departure burn from LEO/CLO.

Monitor displays, visually wearing pressure suit/helmet, during departure burn from LEO/CLO.

Assess displayed information, cognitively, to determine readiness for TMI maneuver.

Evaluate alarms and displays, cognitively, to identify any mission-critical anomalies.

Adjust controls/attachments, manually with gloved hands, to configure suit and displays before, during, and after launch from LEO/CLO.

Activate appropriate controls in response to alarms, manually wearing pressure suit/gloves, while communicating actions to crew and MCC.

Respond to communications and displays, wearing pressure suit, to prepare for departing LEO/CLO.

Adjust controls as necessary, wearing pressure suit/gloves, during departure burn from LEO/CLO.

Activate controls, manually wearing pressure suit/gloves, to abort TMI in response to evaluation data.

Activate controls, manually wearing pressure suit/gloves, to override automated systems/control spacecraft in response to evaluation data.

Phase 3: Cruise to Mars (CTM)

Conduct communications checks/communicate observations/evaluations to other crew and MCC personnel, verbally using comm system during Cruise to Mars.

Operate communications system, manually, to receive transmission from MCC.

Operate communications system, manually, to transmit message to MCC.

Speak with other members of the crew concerning technical and task-related topics.

Speak with other members of the crew concerning non-technical and non-task-related topics.

Perform interviews and Public Affairs Office (PAO) events, using communications system, to inform Earth public of progress.

Transmit data collected during the Transit of Earth to ground stations immediately following event.

Interact with crew mates, personally, concerning task performance.

Interact with crew mates, personally, concerning non-task-related matters.

Compose/record electronic/video journal, using keyboard/computer in spacecraft, to create/preserve personal account of experiences.

Conduct physical/cognitive tests in spacecraft to assess fitness for duty (automatically-scheduled/results transmitted to Earth).

Conduct EVA to perform maintenance or retrieve items from outside the interplanetary space vehicle during Cruise to Mars.

Don pressure suit in response to meteor penetration or hull breech alarm, manually, with crew members helping each other.

Conduct EVA for maintenance or to retrieve needed supplies/equipment/expertise.

Remove and stow pressure suit following departure burn from LEO/CLO (i.e., Trans-Mars Injection).

Use interplanetary space vehicle waste management systems for liquid/solid waste (i.e., toilet/bodily function) during Cruise to Mars.

Use spacecraft waste management system for liquid waste (i.e., toilet/bodily function).

Use spacecraft waste management system for solid waste (i.e., toilet/bodily function).

Use interplanetary space vehicle hygiene systems for cleaning during Cruise to Mars.

Activate hygiene system to enable hand and body washing.

Shave face, manually using safety razor/soap/water, to remove beard growth.

Shave face, manually using electric razor, to remove beard growth.

Cut hair, manually using clippers/scissors/comb/vacuum tube, to remove excess hair growth.

Operate hygiene system to clean/disinfect hands and body.

Operate hygiene system to clean/brush teeth.

Retrieve wet wipes, towel, and clothing to clean body after exercise in preparation for study and work-related tasks.

Remove personal garments from storage in preparation for changing clothes.

Doff (remove) soiled garments and don clean clothing.

Insert soiled garments in collection container to dispose.

Maintain spacecraft waste management systems during Cruise to Mars.

Remove and replace bio collection container from waste management system, manually, to ensure continuity of operation.

Discard packaging waste in trash compactor, manually, to clear galley.

Operate trash compactor, manually, to increase space for additional packaging waste.

Remove compacted packaging waste from trash compactor, manually, and transport to onboard storage.

Insert new sanitary liner in trash compactor, manually, to prepare for additional use.

Prepare/eat meal, manually, using interplanetary space vehicle food hydration/heating equipment/galley during cruise to Mars during Cruise to Mars.

Transfer food packages from deep storage to proximal storage, manually, to prepare galley for crew use.

Activate food hydration/heating equipment, manually, to prepare galley for crew use.

Prepare meal for crew consumption, manually, using spacecraft food hydration/heating equipment.

Eat meal together with other members of the crew in the spacecraft ward room/galley.

Conduct recreational activities, individually and as a crew, during Cruise to Mars.

Read articles, books, etc., during leisure periods for recreation.

Listen to music individually during leisure periods for recreation.

Listen to music individually while exercising for recreation.

Watch video (movies, TV programs, documentaries, etc.) individually while exercising for recreation.

Watch video (movies, TV programs, documentaries, etc.) individually during leisure periods for recreation.

Watch video (movies, TV programs, documentaries, etc.) together with other crew members during leisure periods for recreation.

Play chess and other board games together with other crew members during leisure periods for recreation.

Play chess with MCC personnel and others on Earth during leisure periods for recreation.

Sleep during cruise phase for approximately eight hours each 24-hour period, during Cruise to Mars.

Retrieve sleeping bag from storage and attach bag to davits in sleep chamber to prepare for sleep period.

Enter secured sleeping bag and begin sleep period to restore cognitive/physical functioning.

Conduct inventories and update records during Cruise to Mars.

Conduct and maintain inventories of consumable supplies, visually/manually (e.g., food, water, O2), to update records.

Conduct and maintain inventories of spare parts and materials, visually/manually, to update records.

Exercise daily using onboard equipment during Cruise to Mars.

Configure resistive device and perform exercise to maintain cardiovascular conditioning, muscle strength, and bone density.

Mount bicycle ergometer and perform exercise to maintain cardiovascular conditioning, muscle strength, and bone density.

Don harnesses and perform exercise using treadmill to maintain cardiovascular conditioning, muscle strength, and bone density.

Assess displayed and aural information, cognitively, to determine appropriate course of action during Cruise to Mars.

Identify Emergency Alarm (i.e., Loss of pressure, Fire, Toxic substance/emission) and develop repair/recovery plan.

Identify Caution/Warning Alarm (e.g., CO2, ECLS, Navigation) and develop repair/recovery plan.

Respond to technical emergencies, following procedures and with equipment provided, during Cruise to Mars.

Retreat to shielded area of spacecraft with other members of the crew in response to critical radiation event warning.

Remain in shielded area of spacecraft with other members of the crew during critical radiation event.

Respond to spacecraft fire alarm.

Respond to spacecraft micro-meteorite impact alarm.

Identify precise location of meteor penetration/hull breech, visually/aurally, assess severity, and determine method(s) to stop loss of pressure.

Retrieve repair kit from storage and carry to location of meteor penetration or hull breech.

Apply patch and adhesive material to meteor penetration site, manually, to close leak.

Retrieve and don protective fire-fighting ensemble, manually, to prepare for fire emergency.

Remove fire extinguisher from bulkhead bracket and manually carry to source of fire.

Point fire extinguisher nozzle at burning material and activate system manually while wearing protective ensemble to suppress fire.

Respond to spacecraft hull breech alarm.

Respond to spacecraft toxic substance/outgassing alarm.

Respond to spacecraft CO2 alarm.

Respond to spacecraft general ECLS failure alarm.

Respond to spacecraft navigation alarm.

Respond to dental emergencies, following procedures and with equipment provided, during Cruise to Mars.

Conduct dental examination on crew member, manually/visually, to investigate complaint of tooth/jaw pain.

Interpret results of dental examination, cognitively with MCC consultation, to identify source of apparent tooth/jaw pain.

Prepare dental adhesive, fit, apply adhesive, and replace crown.

Administer pain medicine (Eugenol), manually as needed, to treat a crewmember's fractured tooth showing exposed pulp.

Apply direct pressure and hold until bleeding stops to treat loss of tooth of a crewmember.

Administer medication and if pain severe perform dental nerve block to treat crewmember's dental pain.

Apply temporary tooth filling and smooth excess (instruct patient to limit solid food consumption on affected side of mouth for 12-24 hours) to repair dental filling.

Perform medical diagnoses and evaluations, cognitively, during Cruise to Mars.

Diagnose medical condition, cognitively and verbally through interviews with conscious ill or injured crewmember and physical exam.

Evaluate unresolved sleep disorder, cognitively per procedures, to diagnose problem and identify treatment/intervention.

Perform tests and examinations, physically, to support medical diagnoses during Cruise to Mars.

Collect vitals from injured/ill crew (e.g. temp, pulse, oxygen saturation, respiration rate, blood pressure) with tools in kit, reassess as treatments/meds are administered.

Use medical software along with vitals/test results to help diagnosis condition of conscious or unconscious injured/ill crewmember.

Take image of the back of the eye, manually using a retinal camera (fundus exam), to test for visual impairment and/or increased intracranial pressure (VIIP).

Perform decompression sickness examination with the aid of an electronic form to determine if treatment is needed.

Collect Electrocardiogram (ECG) wave properties data with ECG hardware and leads placed on the patient for analysis of heart rate and variability.

Perform initial evaluation/treatment of chest pain by administering Aspirin, delivering oxygen with respiratory equipment, collecting vitals/ECG, and listening to lungs.

Check for capillary refill and pulses below injury location, apply splint, secure with ACE bandage to treat injured extremity (e.g., leg, arm).

Measure pulse and respiratory rate, administer oxygen and inhaled Albuterol, perform chest exam, and obtain blood pressure to treat difficulty breathing.

Obtain vital signs and photo-document rash, injury or other ailments to perform periodic health evaluation of a crewmember.

Test near and far visual acuity, visual field, contrast sensitivity, and potential cornea abrasions using a Panoptic tool to examine eyes.

Apply blood pressure device and monitor to assess patient's blood pressure.

Examine patient, manually/cognitively, to diagnose lower extremity stress fracture; proscribe reducing weight-bearing activities (exercise in micro/walking in partial).

Collect sample via swab and perform culture, manually, to test for bacterial infection.

Collect samples of blood/urine/saliva, manually, to prepare for lab tests.

Conduct lab tests (e.g., CBC, chemical panels, strep throat), manually on collected samples, to help diagnose medical problem.

Respond to medical emergencies, following procedures and with equipment provided, during Cruise to Mars.

Clear airway obstruction of choking/conscious crew by abdominal thrusts from behind patient with fist below ribcage pulling inward and upward until object clears.

Treat patient who becomes unconscious from choking by attempting to clear foreign object manually/pinch nose/apply breaths and begin CPR.

Perform CPR on unconscious /not breathing crewmember and determine if additional actions are needed as apart of Advanced Cardiac Life support.

Perform defibrillation on unconscious electrically isolated crewmember using AED to restore heartbeat.

Insert catheter in the bladder to drain urine (self-catheterize) for urine retention.

Administer traction and counter-traction until finger slips back in place to relocate a dislocated finger.

Administer traction and counter-traction until shoulder slips back in place to relocate a dislocated shoulder

Insert staples, sutures, or Derma bond depending on type and location of cut to repair skin laceration.

Insert catheter into pleural space between lung/chest wall, producing a pathway for air to escape to perform a needle decompression of a pneumothorax (collapsed lung).

Insert an IV catheter and secure with medical tape to provide intravenous access for medications and fluids.

Attach prepared fluid set to an inserted IV catheter tp administer IV fluids and medications.

Perform surgery, manually using available instruments, to repair a detached retina.

Perform surgery, manually using available instruments, to repair a compound fracture of arm or leg bone.

Perform surgery, manually using available instruments, to treat acute appendicitis.

Implement countermeasures (e.g., counseling, software) if symptoms of maladjustment or degraded behavioral health are detected among crew personnel.

Administer medications during Cruise to Mars.

Administer medications or an intramuscular shot (e.g. Epipen) to treat an allergic reaction.

Administer medication to suppress seizure/avoid loss of consciousness and uncontrolled muscle contractions.

Administer intramuscular shot, take vitals, and administer oxygen as needed to protect patient from injury from seizure.

Administer medications (e.g., antibiotics, antidiarrheal, antihistamine, decongestants, lubricants, pain relievers, sleep, steroids, stimulants and stool softeners) for conditions.

Administer hydrocodone and acetaminophen (Vicodin HP) and notify CMO to treat pain.

Administer Lidocaine or Epinephrine with a syringed needle, then create opening with scalpel to drain, to treat skin or dental abscess.

Apply a thin layer of Mupirocin (Bactroban) ointment and bandage affected areas to treat burned skin.

Deliver medication to the lungs with inhaler by patient closing lips around inhaler, inhaling slowly, holding breath for 10 secs/removing inhaler from mouth and exhaling.

Apply medical drops into the ear canal to treat ear pain caused by blockage (i.e., Barotrauma) that is not alleviated by yawning or chewing.

Administer antibiotics, manually per instructions, to treat ear infection.

Administer antibiotic ointments/drops, manually per instructions, to treat eye irritations/abrasions/infections.

Administer appropriate antibiotic (oral or IV) to treat confirmed bacterial infection.

Administer epinephrine, oxygen, IV antihistamines and cortisone, and beta-agonist (e.g., Albuterol), manually, to treat anaphylaxis.

Administer sedative, manually via syringe, to treat crewmember experiencing a behavioral emergency.

Administer anti-inflammatory drugs, manually, to immobilized crewmember to treat spinal cord trauma.

Administer IV antibiotics, manually, to treat sepsis (administer vasopressor medication if blood pressure remains low).

Perform medical treatments during Cruise to Mars.

Irrigate eye and perform eye exam to treat chemical exposure to a crewmember's eye.

Minimize eye and skin exposure to toxics to prepare for treating exposed crewmate.

Remove exposed crewmates soiled clothes, particles/liquid and irrigate with water (flush eye with water) for respiratory exposure/follow Difficulty breathing procedure.

Place PHA QDM on crewmember, deliver oxygen for 2 hours, hydrate 1 liter per hour for 2 hours or as tolerated to treat decompression sickness.

Remove staples using a skin staple remover to complete repair.

Remove sutures with medical scissors to complete repair.

Insert Oral Airway device halfway into mouth and rotate 180 degrees before inserting until it is flush against the lips to aid ventilation of unconscious patient.

Place Ambu Bag mask over nose and mouth and gently squeeze bag to deliver breaths every 5 to 8 seconds to assist temporary ventilation of a compromised patient.

Deliver oxygen to a respiratory distressed patient by automated ventilation provided in a respiratory support pack.

Pinch fleshy part of nose, manually, for 10 minutes to stop nose bleeding.

Insert nasal packing and drops, manually per instructions, to stop persistent nose bleeding.

Remove wax from ear, manually using curette/medical drops, to treat ear pain.

Clean fingernail, apply antibiotic ointment, cover with adhesive bandage, manually until a new nail grows, to treat/protect fingernail damage from EVA.

Apply ice (multiple sessions) and administer pain medication as needed, manually, to treat back/shoulder/neck sprain/strain.

Apply ice/cold pack and compress with bandage, manually, to treat wrist, elbow, ankle, or knee sprain/strain.

Apply splint, manually, to treat unresolved wrist, elbow, ankle, or knee sprain/strain.

Drain sinus passageway (with nasal spray) and administer antibiotics, manually, to treat acute sinusitis.

Secure Airway, Breathing, Circulation (ABCs)/perform physiological monitoring (e.g., Vitals and Chem Labs), manually and cognitively, to manage acute radiation syndrome.

Apply physical force and binding/duct tape, manually with the help of another crew member, to restrain a crewmember experiencing a behavioral emergency.

Perform a reduction maneuver gently and slowly, manually with the assistance on another crewmember, to realign a dislocated elbow.

Secure crewmember to a flat surface, manually using restraints, to immobilize for treatment of suspected spinal cord trauma.

Apply cast, splint, or brace to extremity (e.g., arm, leg), manually, to immobilize simple fracture.

Perform administrative functions during Cruise to Mars.

Coordinate exercise device availability among crew to ensure access to maintain cardiovascular conditioning, muscle strength, and bone density.
Coordinate simulator availability among crew to ensure refresher training for all required skills and functions.
Coordinate crew response to meteor penetration, hull breech, fire, ECLS, or other emergency.
Monitor individual behavioral health by speaking with each crew member with the goal of identifying symptoms of maladjustment.
Schedule tasks and monitor performance of work to ensure that opportunities and resources are allocated appropriately among crew personnel.
Plan operations (e.g., EVA, maintenance of external components) using computer-based records in consultation with MCC and onboard personnel.

Conduct science and planning functions during Cruise to Mars.

Review expedition geology program objectives and procedures, using onboard resources, to prepare for surface operations.
Review expedition biology program objectives and procedures, using onboard resources, to prepare for surface operations.
Assemble equipment needed to observe and record the Transit of Earth that will occur on day 73 after TMI.
Conduct astronomical observations, photography, and remote sensing to occupy cruise time with meaningful activity.
Conduct life science experiments to occupy cruise time with meaningful activity.
Activate equipment, observe, and record the eight-hour Transit of Earth on day 73 after TMI.
Conduct and record solar observations using onboard equipment and telescopes.
Conduct and record planetary and stellar observations using onboard equipment and telescopes.
Conduct and record radio astronomy observations using onboard equipment and telescopes.
Conduct and record Mars observations using onboard equipment and telescopes.
Conduct and record asteroid/comet observations using onboard equipment and telescopes.
Conduct and record Earth observations using onboard equipment and telescopes.

Conduct installation functions during Cruise to Mars.

Enter control inputs, manually, to configure spacecraft computer to support training simulation and task preparation.
Deploy supports/structures, manually, to configure dedicated area of spacecraft for medical procedure.
Modify pressure suit to adjust length of torso segment in response to spine elongation in zero gravity.
Enter control inputs, manually, to load software patch/reload software.
Program 3-D printer, manually via computer inputs, to fabricate a replacement part for a mechanical system onboard spacecraft.
Operate 3-D printer, manually via computer inputs, to fabricate a replacement part for a mechanical system onboard spacecraft.
Remove and trim object fabricated by 3-D printer, manually using hand tools, to prepare replacement part for a mechanical system onboard spacecraft.

Conduct maintenance functions during Cruise to Mars.

Review schematics and other documentation, visually, to isolate electronic fault in spacecraft.
Review schematics and other documentation, visually, to isolate plumbing (e.g., cooling, CLSS) fault in spacecraft.
Insert test equipment probes in electronic components, manually, and observe displays, visually, to isolate electronic fault in spacecraft.
Inspect circuit board, visually, to identify short circuit or loose/missing connection in spacecraft.
Inspect circuit board, visually, to identify scorching that might indicate degraded/faulty/failed electronic component in spacecraft.
Review documentation/enter control inputs, visually/manually, to diagnose software problem.
Inspect plumbing (e.g., cooling, CLSS), visually and with hand tools, to identify source of plumbing fault in spacecraft.
Remove and replace plumbing component (e.g., section, valve), using hand tools and schematics, to restore system functionality in spacecraft.
Retrieve spare parts/materials (e.g., valve, duct tape) from storage and move to work site in spacecraft, manually, to prepare for troubleshooting/repair.
Cut pipe, manually using hand saw, to remove damaged section of spacecraft plumbing.

Insert new section of pipe and attach in place, manually, using electric soldering tool, flux, and solder to repair spacecraft plumbing.
Remove 1 meter of duct tape from roll, manually, to temporarily repare leaking hose/fitting.
Wrap 1 meter of duct tape around hydraulic hose/fitting, manually, to temporarily repair leak.
Replace electronic connector on wire/cable, manually, using hand tools and spare parts.

Conduct navigation functions during Cruise to Mars.

Use sextant and star charts to estimate spacecraft position and course to compare to computerized navigation system.
Use sextant and star charts to estimate spacecraft position and course if computerized navigation system fails.
Convert results of manual navigation fix to propulsion changes necessary to achieve MOI, using tables and other calculation references.

Conduct piloting functions during Cruise to Mars.

Operate propulsion controls, manually, to maneuver space ship in preparation for ship-to-ship EVA.
Deploy and operate robot, remotely during cruise phase, to inspect external features of spacecraft.
Deploy and operate robot, remotely during cruise phase, to repair external features of spacecraft.

Monitor systems to ensure proper functioning during Cruise to Mars.

Monitor system displays, visually, to verify normal functioning of *life support system*.
Monitor system displays, visually, to verify normal functioning of *navigation system*.
Monitor system displays, visually, to verify normal functioning of *propulsion/attitude control syste*m.
Monitor system displays, visually, to verify normal functioning of *communication system*.
Monitor radiation-detection systems, visually/aurally, for evidence of Solar Proton and Galactic Cosmic Ray Events (SPE/GCR).
Monitor spacecraft atmosphere, visually/manually, by checking displays and comparing values to reference documents.

Adjust systems to ensure proper functioning during Cruise to Mars.

Adjust controls, manually per procedures, to maintain normal functioning of *life support system*.
Adjust controls, manually per procedures, to maintain normal functioning of *navigation system*.
Adjust controls, manually per procedures, to maintain normal functioning of *propulsion/attitude control system*.
Adjust propulsion/attitude control system controls, manually, to maintain proper course to Mars Orbit Injection (MOI).
Adjust controls, manually per procedures, to maintain normal functioning of *communication system*.
Adjust spacecraft atmosphere, manually, by making computer input commands in response to displays and reference documents.

Conduct primary and refresher training to learn/preserve skills during Cruise to Mars.

Review procedures for emergency mission abort (periodically during first third of cruise phase).
Review emergency procedures for various possibilities (fire, micro-meteorite impact, hull breech, outgassing, ECLS failure, etc.).
Conduct (training) simulation using spacecraft computer to refresh piloting skills for Mars Orbit Injection.
Conduct (training) simulation using spacecraft computer to refresh navigation skills for Mars Orbit Injection.
Conduct (training) simulation using spacecraft computer to refresh communication skills for Mars Orbit Injection.
Conduct primary training using digital media and spacecraft computer to learn information and skills that were not included in pre-mission training.
Read procedures and technical information to prepare for conducting tasks during cruise, MOI, and descent to planet.

PHASE 4: MARS ORBIT INJECTION (MOI)

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Receive final course-correction information from MCC to prepare for aerobraking maneuver to achieve MOI.
Communicate status of systems during aerobraking maneuver and aerocapture in heavy buffeting to achieve MOI.

Prepare for Mars Orbit Insertion aerobraking maneuver.

Don pressure suit, manually with the help of one other crew member, in preparation for aerobraking maneuver to achieve MOI.

Stow and secure all equipment, manually per load plan, to prepare spacecraft for aerobraking maneuver to achieve MOI.

Attach to individual crew maneuver position, while wearing pressure suit, in preparation for aerobraking maneuver to achieve MOI.

Monitor systems during Mars Orbit Insertion.

Monitor automatic firing of retro rockets, visually, for aerobraking maneuver to achieve MOI.

Monitor displays during aerobraking maneuver and aerocapture in heavy buffeting to achieve MOI.

Perform piloting functions during Mars Orbit Insertion.

Configure spacecraft computers in preparation for aerobraking maneuver to achieve MOI.

Override automatic firing of retro rockets for aerobraking maneuver to achieve MOI if automated system fails.

Adjust controls (retro rockets, attitude thrusters), manually, to achieve MOI.

Phase 5: Mars Orbit (MO)

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Communicate status of spacecraft and systems to crew, verbally using communications equipment, to advise of conditions.

Communicate status of spacecraft and systems to MCC, verbally using communications equipment, to advise of conditions.

Communicate status of systems to MCC, verbally/manually (text) during Mars Orbit operations to advise of conditions.

Review procedures/checklists to prepare for Mars Orbit Operations and descent.

Review checklists, visually/verbally, with other crew members to verify that all procedures have been completed to secure for Mars Orbit operations.

Conduct final preparation/training tasks to prepare for Mars Surface Descent.

Configure systems for Mars Orbit operations and descent.

Configure spacecraft computers in preparation for Mars Orbit operations.

Detach from individual crew maneuver position, while wearing pressure suit, in preparation for Mars Orbit operations.

Doff pressure suit, manually with the help of one other crew member, in preparation for Mars Orbit operations.

Transfer to Mars Excursion Vehicle (MEM)/Mars Descent Vehicle (MDV), physically while wearing pressure suit, to prepare for descent maneuver.

Monitor systems during Mars Orbit operations

View displays, visually, to verify aerobraking maneuver has achieved MOI.

Inspect spacecraft displays and equipment, visually/manually, to identify any apparent damage from aerobraking maneuver.

Monitor system displays, visually, to ensure nominal functioning during Mars Orbit operations.

Perform piloting functions during Mars Orbit operations

Adjust attitude and propulsion controls, manually, in response to navigation/attitude control data, to achieve/maintain proper Mars Orbit.

Adjust attitude and propulsion controls, manually, in response to navigation/attitude control data, to dock with pre-positioned Mars Descent Vehicle.

Phase 6: Mars Surface Descent (MSD)

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Receive final thrust and duration information from MCC to prepare for Mars Surface Descent maneuver.

Communicate status of systems during Mars Surface Descent maneuver in heavy buffeting to depart Mars Orbit for surface.

Communicate system status, verbally to crew members using internal communications equipment, during controlled descent.

Communicate system status, verbally to MCC using external communications equipment, during controlled descent.

Communicate successful touch down, verbally and via text, to MCC using external communications equipment to confirm status.
Communicate systems shut down and safing to crew via internal communication system to advise of status.
Communicate systems shut down and safing to MCC via external communication systems to advise of status.

Prepare for Mars Surface Descent maneuver.

Stow/secure all equipment, manually per load plan, to prepare Mars Excursion Vehicle (MEV)/Mars Descent Vehicle (MDV) for Mars Surface Descent maneuver.
Don pressure suit, manually with the help of one other crew member, in preparation for Mars Surface Descent maneuver.
Attach to individual crew maneuver position (i.e., seat), while wearing pressure suit, in preparation for Mars Surface Descent maneuver.
Inspect Mars Excursion Vehicle (MEV)/Mars Descent Vehicle (MDV) to verify that systems are go for descent maneuver.

Monitor systems during Mars Surface Descent.

Monitor automatic firing of Mars Excursion Vehicle (MEV)/Mars Descent Vehicle (MDV) retro rockets, visually, for Mars Surface Descent maneuver.
Monitor displays during Mars Surface Descent maneuver in heavy buffeting to depart Mars Orbit for surface.
View displays for parachute, aeroshell, and retro rocket to verify correct functionality at appropriate times to ensure controlled descent to surface.
View displays, visually during buffeted descent, to assess proximity and verify touch down on planetary surface.
Verify automated engine shut down by visually monitoring displays to ensure safing of Mars Excursion Vehicle after touch down.
Verify automated landing system shut down by visually monitoring displays to ensure safing of Mars Excursion Vehicle after touch down.

Perform piloting functions during Mars Surface Descent.

Enter control inputs, manually wearing pressure suit/gloves, to configure Mars Excursion Vehicle computers for Mars Surface Descent maneuver.
Enter control inputs, manually wearing pressure suit/gloves, to detach Mars Excursion Vehicle (MEV)/Mars Descent Vehicle (MDV) from spacecraft.
Enter control inputs, manually wearing pressure suit/gloves, to maneuver Mars Excursion Vehicle (MEV)/Mars Descent Vehicle (MDV) away from spacecraft.
Enter control inputs, manually, to override automatic firing of retro rockets for Mars Surface Descent maneuver if automated system fails.
Adjust parachute, aeroshell, and retro rocket controls in response to system displays to manually override automatic systems, if necessary.
Adjust retro rocket controls, manually during buffeted descent, to maneuver MEV/MDV to correct location near pre-positioned Mars Surface Habitat.
Adjust controls, manually, to shut down retro rocket and other systems after touch down on planetary surface.
Enter control inputs, manually wearing pressure suit/gloves, to activate engine shut down if displays indicate failure of automated shut down after touch down.
Enter control inputs, manually wearing pressure suit/gloves, to activate landing system shut down if displays indicate failure of automated shut down after touch down.

Perform post-Mars Descent maneuver functions.

Enter control inputs, manually wearing pressure suit/gloves, to secure (other) flight systems after engine shut down.
Enter control inputs, manually, to convert Mars Excursion Vehicle (MEV)/Mars Descent Vehicle (MDV) from descent mode to surface mode.
Assess crew members' physical and cognitive abilities, verbally using self-reports and established diagnostics, to determine capacities for immediate work.
Egress Mars Excursion Vehicle (MEV)/Mars Descent Vehicle (MDV), physically while wearing pressure suit, to prepare for transitioning to surface habitat.

PHASE 7: MARS SURFACE OPERATIONS (MSO)

Conduct communications checks/communicate observations/evaluations to other crew and MCC, verbally using communications system during MSO.

Communicate with surface EVA crew members from surface habitat, verbally using radios, to advise and coordinate operations.
Operate surface rover communications system to transmit/receive information to/from habitat personnel.
Operate Mars habitat audio/video communications system, manually, to transmit/receive messages to/from MCC.
Operate Mars habitat email communications system, manually, to transmit/receive messages to/from MCC.
Operate Mars habitat data link communications system, manually, to transmit/receive messages to/from MCC.
Transfer digital copies of information received from MCC to portable digital device, manually, for later reference.

Print paper copies of information received from MCC, using available printer manually, for later reference, if necessary.
Prepare group communications, using audio/video equipment, to transmit to MCC.
Perform interviews and other Public Affairs Office (PAO) events, using communications system, to inform Earth public of progress.

Interact/communicate with other crew members directly during Mars Surface Operations.

Meet with other members of the crew in the Mars habitat to review research results and plan additional research activities.
Interact with crew mates, personally, concerning task performance.
Interact with crew mates, personally, concerning non-task-related matters.
Speak with other members of the crew in the surface habitat concerning technical and task-related topics.
Speak with other members of the crew in the surface habitat concerning non-technical and non-task-related topics.

Enter/exit surface habitat, manually while wearing pressure suit and helmet, during Mars Surface Operations.

Enter pre-positioned Mars habitat, on foot via airlock while wearing surface EVA suit, to prepare activation of surface habitat systems.
Assemble and don surface EVA suit in Mars habitat with help of one other crew member.
Enter airlock from surface habitat, on foot while wearing surface EVA suit, in preparation for exiting to planetary surface.
Exit surface habitat airlock, on foot while wearing surface EVA suit.
Remove dust from suit and equipment before entering surface habitat following surface EVA to minimize contamination of airlock interior.
Blow accumulated dust from surface EVA suit, using compressed gas and vacuum, while wearing surface EVA suit in airlock, to decontaminate before entering habitat.
Enter surface habitat from airlock, on foot, while wearing surface EVA suit.
Attach tether to surface EVA suit and to other crew member's suit and/or rover, manually while wearing suit in dust storm, for safety when visibility conditions warrant.

Perform initial installation/activation/inspection of surface habitat systems during Mars Surface Operations.

Activate surface habitat life support system, manually by control inputs and display verification, to switch from temporary onboard system.
Unstow, deploy, and activate waste management system in surface habitat per procedures, manually, to prepare for use by crew.
Activate hygiene system in surface habitat to enable hand and body washing.
Activate food heating equipment, manually, to prepare surface habitat galley for crew use.
Deploy surface habitat restraints, interior consoles, and equipment, manually, to prepare for crew use.
Unstow, deploy, and activate surface habitat exercise system per procedures, manually with assistance, to prepare for use by crew.
Activate, program, and adjust surface habitat audio/video capability to enable entertainment during exercise.
Deploy supports/structures, manually, to configure dedicated area of surface habitat for medical procedure.
Transfer food packages from deep storage to proximal storage in surface habitat, manually, to prepare galley for crew use.
Retrieve cosmic radiation dosimeters from storage, manually, and deploy in designated locations in surface habitat to measure cosmic radiation.
Configure habitat system, manually, to enable display of robot remote video on large screen for general crew viewing.

Use surface habitat waste management systems for liquid/solid waste (i.e., toilet/bodily function) during Mars Surface Operations.

Use waste management system in surface habitat to eliminate liquid waste.
Use waste management system in surface habitat to eliminate solid waste.

Use surface habitat hygiene systems for cleaning during Mars Surface Operations.

Operate hygiene system in surface habitat to clean/disinfect hands and body.
Shave face, manually using safety razor/soap/water, to remove beard growth.
Shave face, manually using electric razor, to remove beard growth.
Remove personal garments from surface habitat storage in preparation for changing clothes.
Remove soiled garments and don clean clothing in surface habitat.

Insert soiled garments in surface habitat collection container to dispose.
Cut hair, manually using electric razor, to remove excess growth.
Brush teeth, manually, to maintain oral hygiene.

Prepare and consume meals in surface habitat during Mars Surface Operations.

Prepare meal for crew consumption, manually, using surface habitat food heating equipment.
Prepare drink for crew consumption, manually, using surface habitat liquid dispensing system
Prepare/retrieve snack for crew consumption, manually, using surface habitat food system
Eat meal together with other members of the crew in the surface habitat ward room/galley.

Perform surface habitat housekeeping functions during Mars Surface Operations.

Conduct routine housekeeping/cleaning, manually using cloths, liquids, and vacuum, to maintain hygiene of surface habitat.
Conduct routine replenishment of stores, manually, to maintain functionality of surface habitat.
Remove and replace bio collection container from waste management system in surface habitat, manually, to ensure continuity of operation.
Discard packaging waste in surface habitat trash compactor, manually, to clear galley.
Operate surface habitat trash compactor, manually, to increase space for additional packaging waste.
Remove compacted packaging waste from surface habitat trash compactor and transport to dedicated trash storage, manually.
Insert new sanitary liner in surface habitat trash compactor, manually, to prepare for additional use.
Retrieve wet wipes, towel, and clothing from surface habitat storage to clean body after exercise in preparation for work-related tasks.

Perform recreation/leisure activities in the surface habitat during Mars Surface Operations.

Read articles, books, etc., in the surface habitat during leisure periods for recreation.
Listen to music individually in the surface habitat during leisure periods for recreation.
Listen to music individually in the surface habitat while exercising for recreation.
Watch video (movies, TV programs, documentaries, etc.) individually in the surface habitat while exercising for recreation.
Watch video (movies, TV programs, documentaries, etc.) individually in the surface habitat during leisure periods for recreation.
Watch video (movies, TV programs, documentaries, etc.) together with other crew members in the surface habitat during leisure periods for recreation.
Play chess and other board games together with other crew members in the surface habitat during leisure periods for recreation.
Play chess with MCC personnel and others on Earth while in the surface habitat during leisure periods for recreation.

Perform exercise in surface habitat to maintain cardiovascular, muscle, and bone conditioning during Mars Surface Operations.

Mount surface habitat bicycle ergometer and perform exercise to maintain cardiovascular conditioning, muscle strength, and bone density.
Don harnesses and perform exercise using surface habitat treadmill to maintain cardiovascular conditioning, muscle strength, and bone density.
Configure surface habitat resistive device and perform exercise to maintain cardiovascular conditioning, muscle strength, and bone density.

Sleep in surface habitat during Mars Surface Operations.

Enter sleeping compartment in surface habitat and begin sleep period to restore cognitive/physical functioning.

Sleep in surface rover during Mars Surface Operations.

Deploy and enter sleeping bag in surface rover to enable extended operations on planetary surface.
Sleep in surface rover to enable extended operations on planetary surface (e.g., 3 sols during drilling operations).

Use surface rover waste management systems for liquid/solid waste (i.e., toilet/bodily function) during Mars Surface Operations.

Use waste management system in surface rover for liquid waste.
Use waste management system in surface rover for solid waste.

Prepare and consume meals in surface rover during Mars Surface Operations.

Prepare meal for crew consumption, manually, using (pressurized) surface rover food dispensing equipment to enable extended operations on planetary surface.
Eat food/drink fluids in (pressurized) surface rover to enable extended operations on planetary surface.

Perform surface rover habitability/logistics functions during Mars Surface Operations.

Retrieve food/supplies from storage and stow in surface rover, manually while wearing surface EVA suit, to replenish consumables for additional operations.
Remove/replace human waste storage containers from surface rover, manually while wearing surface EVA suit when necessary, to prepare for additional operations.

Perform installation/activation/inspection of auxiliary systems during Mars Surface Operations.

Remove restraints from greenhouse equipment, manually while wearing protective gloves, to prepare greenhouse for operation.
Remove growing medium from storage and place in designated locations, manually while wearing protective gloves, to prepare for greenhouse operation.
Connect plumbing fixtures/pipes to H2O/fertilizer circulation system, manually while wearing protective gloves, to prepare greenhouse for operation.
Insert seeds in growing medium, manually while wearing protective gloves, to prepare greenhouse for operation.
Deploy sample curation console and partition/materials in sample storage module, manually, to enable curation/processing of key samples for Earth return.

Perform planning and administrative functions, individually and with other crew members during Mars Surface Operations.

Provide feedback about operations plans/timelines/work assignments to expedition leader, personally or in writing, to express concerns/opinions.
Receive feedback about operations plans/timelines/work assignments to expedition crew member, personally or in writing, to improve operations.
Review maps/charts/procedures, manually/visually, in Mars habitat to plan construction/installation tasks.
Review maps/charts/procedures, manually/visually, in Mars habitat to plan route for surface sortie/traverse and geological research.
Investigate surroundings visually with help of photographs and surface reconnaissance, to identify permanent location for surface habitat.
Investigate surroundings visually with help of photographs/surface reconnaissance, to identify permanent location for greenhouse, laboratory, sample storage modules.
Coordinate crew response to meteor penetration, hull breech, fire, ECLS, or other emergency.
Schedule tasks and monitor performance of work to ensure that opportunities and resources are allocated appropriately among crew personnel.
Coordinate surface habitat exercise device availability among crew to ensure access to maintain cardiovascular conditioning, muscle strength, and bone density.
Coordinate surface habitat simulator availability among crew to ensure refresher training for all required skills and functions.
Plan operations/timelines/work assignments (e.g., surface EVA, maintenance) using computer-based tools in consultation with MCC and onboard personnel.
Modify operations plans/timelines/work assignments in response to events using computer-based tools in consultation with MCC and onboard personnel.

Perform pre- and post-EVA inspection and planning tasks during Mars Surface Operations.

Conduct pre-EVA briefing/meeting with other crew and MCC personnel to plan EVA.
Conduct post-EVA briefing/meeting with other crew and MCC personnel to discuss previous EVA.
Conduct pre-EVA inspection/inventory of equipment, manually/visually, to ensure proper functioning.
Conduct post-EVA inspection/inventory of equipment, manually/visually, to ensure proper functioning.

Perform surface EVA physical functions on foot during Mars Surface Operations.

Carry incapacitated crew mate 20 meters to surface rover, manually while both are wearing surface EVA suits, to prepare for medical treatment.
Rise from prone position, using arms and legs while wearing surface EVA suit, to recover from fall on flat surface.
Rise from prone position, using arms and legs while wearing surface EVA suit, to recover from fall in loose regolith.
Bend over/stoop while wearing surface EVA suit to retrieve hand tool from planet surface.
Climb 3 meter ladder, manually while wearing surface EVA suit, to access Mars Surface Ascent Vehicle.
Adjust surface EVA suit controls, manually with gloved fingers, to operate mobile communications with Mars habitat personnel.
Adjust surface EVA suit controls, manually with gloved fingers, to optimize mobile life support system.
Adjust surface EVA suit controls, manually with gloved fingers, to operate mobile situation awareness data displays.
Carry harvested plant material from greenhouse to surface habitat galley, manually while wearing EVA suit, to prepare for crew consumption

Remove accumulated dust from greenhouse, manually using compressed gas canister while wearing surface EVA suit, to maintain optimal sunlight for plant growth.
Respond to puncture of surface EVA suit while wearing the suit on planetary surface, manually by retrieving and attaching temporary fast-patch.
Carry air filters from surface habitat air circulation system to planetary surface, manually while wearing surface EVA suit, to prepare for filter cleaning.
Blow accumulated dust from air filters, using portable compressed gas device while wearing surface EVA suit, to clean filter for reuse in habitat.
Measure surface distances using laser rangefinder while wearing surface EVA suit.
Inspect pre-positioned power-generation plant, visually/manually while wearing surface EVA suit, to verify proper functioning.

Monitor EVA systems during EVA during Mars Surface Operations.

Monitor surface EVA suit displays (e.g., time, radiation dosimeter, consumables), visually/cognitively, while wearing surface EVA suit to ensure safe operation.
Monitor surface EVA suit parameters (e.g., time, radiation dosimeter, consumables remaining), remotely from inside surface habitat, to ensure safe operation.
View display, visually while wearing surface EVA suit, to verify proper functioning of the Radiation Assessment Detector (RAD).
View display, visually while wearing surface EVA suit, to verify proper functioning of the weather monitoring station.
Monitor atmospheric sampling equipment, manually while wearing surface EVA suit, to ensure that data are recorded for later analysis and transmission to MCC.

Perform surface EVA communications functions during Mars Surface Operations.

Communicate with other crew members in the field, verbally while wearing surface EVA suit, to coordinate/advise actions.
Communicate with other crew members in the surface habitat, verbally while wearing surface EVA suit in the field, to coordinate/advise actions.

Perform surface EVA habitability functions during Mars Surface Operations.

Eat food while wearing surface EVA suit to enable uninterrupted operations on planetary surface.
Drink liquid while wearing surface EVA suit to enable uninterrupted operations on planetary surface.
Eliminate solid and liquid waste while wearing surface EVA suit, if necessary, to enable uninterrupted operations on planetary surface.

Inspect/prepare/ deploy surface rover during Mars Surface Operations.

Deploy surface rover vehicle, manually/visually while wearing surface EVA suit, to prepare for use.
Deploy surface rover trailer, manually/visually while wearing surface EVA suit, to prepare for use.
Inspect surface rover vehicle, manually/visually while wearing surface EVA suit, to verify functionality.
Inspect surface rover trailer, manually/visually while wearing surface EVA suit, to verify functionality.
Connect rover trailer to surface rover trailer hitch, manually while wearing surface EVA suit with the help of one other crew member, to prepare for use.
Connect umbilical from rover to surface EVA suit, manually while wearing EVA suit, to provide auxiliary life support.
Connect umbilical from rover to crew mate's surface EVA suit, manually while wearing EVA suit, to provide auxiliary life support.
Connect rover towing cable to surface rover trailer hitches, manually with the help of one other crew member while wearing surface EVA suit, to prepare for towing.

Load/unload surface rover/trailer for Mars Surface Operations.

Lift sample container, manually using Apollo-style block and tackle, to load container into Mars Surface Ascent Vehicle.
Remove food containers from pre-positioned lander and carry, manually while wearing surface EVA suit, to transfer provisions to surface habitat.
Retrieve nuclear power system/shield from storage/load onto rover trailer, manually using block/tackle while wearing surface EVA suit, for transporting to installation site.
Operate surface rover and trailer to a distance 1 km from habitat, manually while wearing surface EVA suit, to prepare for installing nuclear power reactor.
Remove nuclear power reactor and shield from rover trailer, manually using block/tackle while wearing surface EVA suit, to install system for power generation.
Retrieve power cable spool from storage/load onto rover trailer, manually while wearing surface EVA suit, to prepare for applying power to surface habitat.
Deploy power cable from rover trailer during traverse to reactor site, using spool device while wearing surface EVA suit, to switch from battery to external power source.
Retrieve inflatable structure from storage and load on rover trailer, manually, with two other crew members, while wearing surface EVA suit.
Retrieve well-drilling equipment from storage (pre-positioned) and attach to surface rover, manually while wearing surface EVA suit.
Retrieve H_2O sublimation equipment from storage (pre-positioned) and attach to surface rover, manually while wearing surface EVA suit, to prepare for H_2O extraction.

Perform surface rover maintenance functions during Mars Surface Operations.

Remove accumulated dust from surface rover windows, manually while wearing surface EVA suit, to maintain optimal visibility.

Conduct troubleshooting, manually/visually using schematics, procedures, and hand tools while wearing surface EVA suit, to identify fault in surface rover.

Remove/replace faulty component/connector manually/visually using hand tools and spare parts while wearing surface EVA suit to restore surface rover to operation.

Perform surface rover navigation functions during Mars Surface Operations.

Exit surface rover during pause in reconnaissance/traverse wearing surface EVA suit to perform navigation tasks.

Observe route markers/beacons, visually while operating surface rover and wearing surface EVA suit, to navigate route.

Review maps/charts/procedures, manually/visually, in surface rover to verify/alter/report route for surface sortie/traverse and geological research.

Operate surface rover navigation system to select/guide route during reconnaissance/traverse.

Operate surface rover (backup) dead-reckoning system to estimate position of rover on planetary surface.

Conduct preliminary reconnaissance of surroundings, visually, with one other crew member using rover vehicle.

Perform surface rover piloting/driving functions during Mars Surface Operations.

Operate surface rover vehicle on planetary surface, manually while wearing surface EVA suit.

Conduct expeditionary traverse of at least one Sol, with one other crew member using rover vehicle.

Perform surface rover operation functions during Mars Surface Operations.

Exit surface rover during pause in reconnaissance/traverse wearing surface EVA suit to perform geological tasks.

Enter Mars surface rover with one other crew member while wearing surface EVA suits to prepare for traverse.

Dig loose regolith from around surface rover wheel, manually using shovel while wearing surface EVA suit, to regain traction to proceed.

Deploy and attach battery cables to surface rover, manually while wearing surface EVA suit, to prepare for recharging rover batteries.

Deploy and attach battery cables from surface rover to habitat power connectors, manually while wearing surface EVA suit, to recharge rover batteries.

Move well-drilling rig to identified location, using surface rover while wearing surface EVA suit, to prepare for drilling H2O well.

Move H2O sublimation equipment to well location, using surface rover while wearing surface EVA suit, to prepare for H2O extraction

Operate surface rover with failed surface rover attached by towing cable to return failed rover to vicinity of Mars habitat for repair.

Perform construction-related EVA functions during Mars Surface Operations.

Pound stakes through habitat eyelets into planetary surface, manually using sliding hammer, to secure habitat to excavated foundation hole.

Pound stakes through sample storage module eyelets into planetary surface, manually using sliding hammer, to secure module to excavated foundation hole.

Retrieve solar panels/transformer from storage and carry to designated location near surface habitat, with two other crew members while wearing surface EVA suit.

Pound stakes through greenhouse module eyelets into planetary surface, manually using sliding hammer, to secure module to excavated foundation hole.

Connect pwr cables to connectors on power distribution bus/surface habitat, manually while wearing surface EVA suit, to switch from battery to external power source.

Activate controls, manually while wearing surface EVA suit, to switch from MEV/habitat battery to external power source.

Connect cables/plumbing from pre-positioned thermal control system to MEV/surface habitat, manually while wearing surface EVA suit, to enable heat radiation.

Activate controls, manually while wearing surface EVA suit, to initiate pre-positioned thermal control system.

Retrieve surface antenna, supports, and cables from storage and manually carry to designated location near habitat while wearing surface EVA suit.

Deploy surface antenna and attach cable connectors to antenna and habitat, manually with one other crew member while wearing surface EVA suits.

Adjust antenna, using hand tools and mobile data display while wearing surface EVA suit, to optimize communications between habitat and Earth stations.

Deploy and secure solar panels, manually using hand tools with two other crew members while wearing surface EVA suits.

Attach cables to solar panels, transformer, and surface habitat, manually with two other crew members while wearing surface EVA suit, to enable charging of batteries.

Adjust solar-tracking mechanism on solar panel system, manually while wearing surface EVA suit, to achieve optimal solar cell performance.

Attach cables to solar panels, transformer, and greenhouse, manually with two other crew members while wearing surface EVA suit, to provide power to greenhouse.

Retrieve Radiation Assessment Detector (RAD) from storage, manually while wearing surface EVA suit, and deploy in vicinity of surface habitat.
Connect power cable connectors from Radiation Assessment Detector (RAD) to power source, manually while wearing surface EVA suit, to activate system.
Retrieve weather monitoring equipment/station from storage, manually while wearing surface EVA suit, and carry to suitable location near surface habitat.
Connect power cable connectors from weather monitoring station to power source, manually while wearing surface EVA suit, to activate system.
Deploy inflatable structure, manually, with two other crew members, while wearing surface EVA suit.
Deploy surface atmosphere mining system manually with one other crew member, while wearing surface EVA suit, to begin O2/H extraction/storage.
Inspect vicinity of surface habitat, visually with the aid of photos and maps, to identify appropriate location to drill H2O well.
Install H2O sublimation system manually with one other crew member, while wearing surface EVA suit, to begin H2O extraction/storage.
Connect power cable connectors from H2O sublimation system to power source, manually while wearing surface EVA suit, with the help of one other crew member.
Remove accumulated dust from solar panels, manually while wearing surface EVA suit, to maintain optimal solar cell performance.

Perform construction-related EVA functions with heavy equipment during Mars Surface Operations.

Retrieve excavation equipment from storage (pre-positioned) and move to appropriate location, while wearing surface EVA suit, to prepare for digging habitat foundation.
Operate excavation equipment, while wearing surface EVA suit, to dig and level one meter hole the diameter/dimensions of surface habitat.
Move/deploy surface habitat into excavated hole, using rover and excavator while wearing surface EVA suit, to prepare habitat for occupancy.
Move regolith using excavator while wearing surface EVA suit to backfill around margins of the habitat base, to prepare habitat for occupancy.
Operate excavation equipment, while wearing surface EVA suit, to dig and level one meter hole the diameter/dimensions of sample storage module.
Move/deploy sample storage module into excavated hole, using rover and excavator while wearing surface EVA suit, to prepare module for receiving geologic samples.
Move regolith using excavator while wearing surface EVA suit to backfill around margins of the sample storage module base, to prepare for use.
Move excavation equipment to appropriate location, while wearing surface EVA suit, to prepare for digging greenhouse foundation.
Operate excavation equipment, while wearing surface EVA suit, to dig and level one meter hole the diameter/dimensions of greenhouse module.
Move/deploy greenhouse into excavated hole, using rover and excavator while wearing surface EVA suit, to prepare module for growing plants.
Move regolith using excavator while wearing surface EVA suit to backfill around margins of the greenhouse base, to prepare for use
Move excavation equipment to appropriate location, while wearing surface EVA suit, to prepare for digging sample storage foundation.

Perform maintenance/repair/monitoring functions during surface EVA operations during Mars Surface Operations.

Troubleshoot drill problems, visually/manually/cognitively while wearing surface EVA suit, to determine if equipment is repairable in the field.
Remove drill bit from drill pipe, manually using hand tolls while wearing surface EVA suit, to restore drill functionality
Remove auger bit from drill pipe, manually using hand tolls while wearing surface EVA suit, to restore drill functionality
Monitor temperature sensor remote display, visually, to verify successful deployment and recording of data.
Inspect surface atmosphere mining system visually/manually, while wearing surface EVA suit, to verify O2/H extraction and storage.
Inspect H2O sublimation system visually/manually, while wearing surface EVA suit, to verify H2O extraction/storage.
Inspect footing/base/structural components of surface habitat/greenhouse/module, visually, from outside the habitat while wearing surface EVA suit to ensure integrity.
Inspect fuel "cache" (fuel storage tanks), visually while wearing surface EVA suit, to verify that pre-positioned fuel production has been stored for later use.
Inspect hoses from fuel production plant to fuel storage tanks, visually while wearing surface EVA suit, to ensure there is no leakage.
Inspect fuel storage tanks, visually while wearing surface EVA suit, to ensure there is no leakage.
Inspect pre-positioned fuel production plant, visually/manually while wearing surface EVA suit, to verify proper functioning.

Perform science-related EVA functions during Mars Surface Operations.

Retrieve geological tools and equipment from storage and carry to surface rover/trailer, manually while wearing surface EVA suit, to prepare for reconnaissance.
Retrieve magnetometer from storage and carry to surface rover, manually while wearing surface EVA suit, to prepare for geological research.
Remove magnetometer from rover trailer and deploy, manually while wearing surface EVA suit, to prepare for recording magnetic data.

Retrieve gravitometer from storage and carry to surface rover, manually while wearing surface EVA suit, to prepare for geological research.
Remove gravitometer from rover trailer and deploy, manually while wearing surface EVA suit, to prepare for recording gravitational data.
Retrieve seismic testing munitions/equipment from storage and carry to surface rover, manually while wearing surface EVA suit, to prepare for geological research.
Remove seismic testing munitions/equipment from rover trailer and deploy, to prepare for recording seismic data.
Pound seismometers into rock, manually using slide hammer while wearing surface EVA suit, to deploy sensors.
Attach wire connectors to seismometer and to receiving terminal, manually wearing surface EVA suit, to prepare for recording seismographic data.
Retrieve cosmic radiation dosimeters from storage/deploy in vicinity surface habitat manually using digging tool while wearing surface EVA suit, to measure radiation.
Retrieve cosmic radiation dosimeters from storage/deploy in vicinity geological research manually using digging tool while wearing surface EVA suit, to measure radiation.
Remove cosmic radiation dosimeter from deployed site, manually while wearing surface EVA suit/carry to surface rover or habitat/laboratory for analysis/data recording.
Retrieve weather balloon and portable hydrogen tank from storage and carry to surface rover, manually while wearing surface EVA suit, to prepare for geological survey.
Remove weather balloon and portable hydrogen tanks from rover trailer, fill balloon, attach remote sensors/transponders, and deploy balloon to conduct survey.
Remove rotary/percussion drill from rover, wearing surface EVA suit, and transport (10m) to drilling site with assistance of one other crew member.
Deploy temperature sensors (heat-flow probes) in drill hole manually, while wearing surface EVA suit.
Deploy route markers (3 meter stakes, flags/beacons) at intervals, manually using post-pounder and/or sledge while wearing surface EVA suit, to indicate route.
Retrieve non-rigid airship/ballonet, gondola, mast, portable hydrogen tank from storage, manually with two other crew members, while wearing surface EVA suit.
Deploy mooring mast with one other crew member, manually using hand tools and wearing surface EVA suit, to prepare for non-rigid airship/ballonet inflation.
Attach fitting to portable hydrogen tank/ballonet, fill ballonet with hydrogen, attach gondola, manually with two other crew members, while wearing surface EVA suit.
Load supplies and equipment into ballonet gondola, manually with two other crew members, in preparation for aerial research/reconnaissance mission.
Operate magnetometer, manually while wearing surface EVA suit, to record magnetic data.
Operate gravitometer, manually while wearing surface EVA suit, to record gravitational data.
Operate seismic testing munitions/equipment, manually while wearing surface EVA suit, record seismic data.
Identify locations, visually in the field (i.e., rock) while wearing surface EVA suit, to deploy seismometers for seismological research.
Retrieve geological tools and equipment from surface rover/trailer, manually while wearing surface EVA suit, to prepare for geological research
Record field notes, verbally while wearing surface EVA suit, to preserve observations for later transcription.
Extract regolith core from drill and package core sample in plastic wrap, manually while wearing surface EVA suit, for later analysis.
Examine regolith core sample, visually while wearing surface EVA suit, to verify sample and conduct preliminary assessment.
Examine regolith core sample, using aseptic device/procedures while wearing surface EVA suit, to identify if sample contains biologic or toxic elements.
Extract sedimentary core from drill and package core sample in plastic wrap, manually while wearing surface EVA suit, for later analysis.
Examine sedimentary core sample, visually while wearing surface EVA suit, to verify sample and conduct preliminary assessment.
Examine sedimentary core sample, using aseptic device/procedures while wearing surface EVA suit, to identify if sample contains biologic or toxic elements.
Walk on planetary surface while carrying hand tools and wearing surface EVA suit to conduct geological research.
Climb crater wall while carrying hand tools and wearing surface EVA suit to conduct geological research.
Descend crater wall while carrying hand tools and wearing surface EVA suit to conduct geological research.
Descend gully while carrying hand tools and wearing surface EVA suit to conduct geological research.
Climb gully while carrying hand tools and wearing surface EVA suit to conduct geological research.
Scan immediate vicinity of planetary surface, visually through clear visor, to identify potential sites for geological research and collection (e.g., contrasting color).
Scan distant planetary surface, visually through clear visor, to identify potential sites for geological research and collection (e.g., contrasting color).
Scan surrounding planetary surface, visually through clear visor, to identify potential sites for geological research and collection (e.g., contrasting color).
Collect geological samples, manually using rock pick (i.e., geologist's hammer) and sample bags, while wearing surface EVA suit.

Collect geological samples, manually using Apollo-type rake (1m handle) and sample bags, while wearing surface EVA suit.
Collect geological samples, manually using Apollo-type scoop (1m handle) and sample bags, while wearing surface EVA suit.
Collect geological samples, manually using hand auger, while wearing surface EVA suit.
Label collection bags with location coordinates, manually with Sharpie-type marker while wearing surface EVA suit, to record origins of geological samples.
Insert rock/dust/regolith samples in labeled bag, while wearing surface EVA suit, for later analysis/storage/transport to Earth.
Insert labeled bags into curation collection bag, manually while wearing surface EVA suit, for transport to sample storage module.
Carry sample curation bag into sample storage module, manually while wearing surface EVA suit to preserve integrity of samples contained.
Record contents of curation bag in sample log, manually using dedicated keyboard while wearing surface EVA suit, to update inventory of samples collected
Dissect rock samples, manually while wearing surface EVA suit and using hand-held power cutting tool, to reveal smooth surface features/stratigraphy.
Operate camera to record still and video images of planetary surface/surroundings, while wearing surface EVA suit.
Operate camera to record still and video images of geological specimens/phenomena while wearing surface EVA suit.
Change lenses on camera while wearing surface EVA suit in the field.
Insert geologic samples in glove box, manually while wearing surface EVA suit, to prepare for aseptic analysis.
Inspect geologic samples, visually using hand-held magnifying tool/microscope while wearing surface EVA suit in the field, to conduct preliminary analysis.
Package geological samples, manually using aseptic equipment while wearing surface EVA suit, to prepare samples for safe return to Earth.
Remove and package ice core sample, manually while wearing surface EVA suit, for later analysis.
Enter ballonet gondola with one other crew member, manually while wearing surface EVA suit, to prepare for launch.
Launch and operate non-rigid airship/ballonet with one other crew member while wearing surface EVA suit to conduct aerial research/reconnaissance mission.
Recover non-rigid airship/ballonet with two other crew members while wearing surface EVA suit and attach lines to mooring mast after research/reconnaissance mission.

Perform science-related EVA functions with heavy equipment during Mars Surface Operations.

Retrieve high-vacuum pump/sampling equip from storage while wearing surface EVA suit/manually carry to vicinity of habitat to prepare for atmospheric sampling.
Deploy and operate high-vacuum pump and sampling equipment, manually while wearing surface EVA suit, to collect atmospheric data.
Operate rotary/percussion drill to depth of 10 meters with assistance of one other crew member while wearing surface EVA suit.
Add drill pipe section to stack, manually using hand tools while wearing surface EVA suit, to drill deeper.
Remove drill pipe section from stack, manually using hand tools while wearing surface EVA suit, to back drill/auger bit out of hole.
Position drill-bit and operate powered well-drilling equipment to drill approximately 10-meter hole to sub-surface water level.
Deploy and operate ice core drilling tool, manually while wearing surface EVA suit, to obtain ice core sample for analysis.

Perform geology-related science functions in surface habitat or modules during Mars Surface Operations.

Examine regolith core sample, visually in surface habitat/laboratory, to conduct assessment.
Examine sedimentary core sample, visually in surface habitat/laboratory, to conduct assessment.
Dissect rock samples, manually using hand-held power cutting tool in surface laboratory, to reveal smooth surface features/stratigraphy.
Evaluate geological data collected/analyzed, with aid of references and consultation, to plan further collection activities based on results.
Conduct astronomical observations, photography, and remote sensing in the surface habitat.
Analyze geological specimens and photographs, visually/cognitively, to develop hypotheses to guide additional field work.
Inspect geologic samples in glove box, manually/visually using hand tools/microscopes in surface laboratory, to perform aseptic analysis.
Inspect geologic samples, visually using magnifying tool/microscope in the surface habitat/laboratory, to conduct analysis/guide additional field research.
Inspect geologic samples, visually using binocular microscope in the surface habitat/laboratory, to conduct analysis/guide additional field research.
Inspect geologic samples, visually using spectrometer in the surface habitat/laboratory, to conduct analysis/guide additional field research.
Inspect ice core samples, visually using spectrometer in the surface habitat/laboratory, to conduct analysis/guide additional field research.

Perform human research-related science functions in surface habitat or modules during Mars Surface Operations.

Complete mood inventory questionnaires for later transmission to TSC for analysis.

Collect saliva samples, label, and preserve, manually, for later analysis.

Collect blood samples, label, and preserve, manually, for later analysis.

Record confidential audio/visual journal entries for later transmission to TSC for analysis and archiving.

Conduct life science experiments involving crew members, manually using various instruments in the surface habitat, to generate data.

Record/report results of life science investigations/procedures, manually using keyboard, to document activity.

Compose/record electronic/video journal, using keyboard/computer in surface habitat/laboratory, to create/preserve personal account of experiences.

Perform administrative/planning-related science functions in surface habitat or modules during Mars Surface Operations.

Identify locations visually from photographs and charts in the surface habitat to deploy seismometers for seismological research.

Transcribe audio field notes, using keyboard in surface habitat/laboratory, for later review/analysis/traverse route-planning.

Compose/update log of samples, using keyboard in surface habitat/laboratory, to create inventory of material collected to date.

Compose report concerning geological research, using keyboard in surface habitat/laboratory, to document activity/results.

Annotate aerial photograph, manually on computer indicating habitat, antennae, equipment, etc., to create interactive map of Mars base for planning and safety.

Perform biology-related science functions in surface habitat or modules during Mars Surface Operations.

Record digital image of geologic/biologic sample, manually using binocular microscope camera, for later reference/analysis.

Place geologic sample, manually, in the sample analysis module (i.e., "Easy Bake Oven") in the surface habitat/laboratory to prepare for analyzing sample.

Operate sample analysis module in the surface habitat/laboratory, manually, to test for presence of hydrogen, oxygen, and nitrogen (associated with life).

Inspect Martian water samples, visually using binocular microscope in the surface habitat/laboratory, to conduct analysis/guide additional field research.

Inspect Martian water samples, visually using spectrometer in the surface habitat/laboratory, to conduct analysis to guide additional field research.

Conduct culturing experiment, manually in laboratory module while wearing protective garments, to test sample material for biological content.

Conduct wet chemistry experiment, manually in laboratory module while wearing protective garments, to test sample material for biological content.

Conduct RNA sequencing experiment, manually in laboratory module while wearing protective garments, to test sample material for biological content.

Perform robot operations-related functions during Mars Surface Operations.

Deploy and operate robot, remotely on planetary surface, to inspect external features of habitat and external equipment/structures.

Operate rover, remotely on surface, to explore in vicinity of habitat.

Operate rover, remotely on surface, to explore areas in vicinity of field camp.

Operate robot, remotely on surface, to assemble/construct/ system elements to prepare field camp for humans.

Operate robot, remotely on surface, to deploy/position offloaded system elements to prepare field camp for humans.

Deploy and operate robot, remotely on surface, to explore possible sites for field camp to extend EVA range.

Deploy and operate robot, remotely on surface, to deliver/offload assets/equipment/materials to prepare field camp for humans.

Retrieve geological samples from robot, manually, and place in surface laboratory/storage facility for later analysis/transport to Earth.

Deploy and operate robot, remotely on planetary surface, to repair/maintain external equipment/structures (e.g., to blow dust from solar panels).

Deploy and operate robot, remotely on surface, to clean up potentially contaminating fluid spill on Mars surface (e.g., propellant, ammonia, human waste).

Deploy and operate robot, remotely on surface, to reconnoiter route/site for future traverse/research.

Deploy and operate robot, remotely on surface, to collect, bag, and return geological samples to surface habitat/laboratory.

Deploy and operate robot, remotely on surface, to test geological samples for biologic/toxic elements.

Perform robot maintenance-related functions during Mars Surface Operations.

Retrieve robot from storage, manually while wearing surface EVA suit, to prepare for use.

Troubleshoot robot problems, visually/manually/cognitively while wearing surface EVA suit, to determine if equipment is repairable in the field.
Inspect robot, visually/manually while wearing surface EVA suit, to prepare for use.
Identify and replace components (line replaceable units, wheels, etc.), manually per procedures, in surface habitat/laboratory to restore surface robot functionality.
Inspect hoses from fuel production plant to fuel storage tanks, remotely using surface robot vehicle, to ensure there is no leakage.
Inspect fuel storage tanks, remotely using surface robot vehicle, to ensure there is no leakage.
Inspect pre-positioned fuel production plant, remotely using surface robot vehicle, to verify proper functioning.

Respond to dental emergencies during Mars Surface Operations.

Conduct dental examination on crew member, manually/visually, to investigate complaint of tooth/jaw pain.
Interpret results of dental examination, cognitively with MCC consultation, to identify source of apparent tooth/jaw pain.
Apply temporary tooth filling and smooth excess (instruct patient to limit solid food consumption on affected side of mouth for 12-24 hours) to repair dental filling.
Prepare dental adhesive, fit, apply adhesive, and replace crown.
Administer pain medicine (Eugenol), manually as needed, to treat a crewmember's fractured tooth showing exposed pulp.
Apply direct pressure and hold until bleeding stops to treat loss of tooth of a crewmember.
Administer medication and if pain severe perform dental nerve block to treat crewmember's dental pain.

Perform medical diagnoses and evaluations, cognitively, during Mars Surface Operations.

Diagnose medical condition, cognitively and verbally through interviews with conscious ill or injured crewmember and physical exam.
Evaluate unresolved sleep disorder, cognitively per procedures, to diagnose problem and identify treatment/intervention.

Perform tests and examinations, physically, to support medical diagnoses during Mars Surface Operations.

Apply hand-held ultra-sonic device to naked crew member skin, manually using gel, to obtain image of internal organs/bones for diagnosis.
View ultra-sonic display, visually while manipulating hand-held device manually, and interpret results of ultra-sonic imaging test.
Use medical software along with vitals/test results to help diagnosis condition of conscious or unconscious injured/ill crewmember.
Operate hand-held ultra-sonic device, manually while visually inspecting display, to assess/measure bone demineralization of crew member.
Record/report results of ultra-sonic investigations/procedures, manually using keyboard, to document activity.
Conduct physical/cognitive tests in surface habitat/laboratory to assess fitness for duty (automatically-scheduled/results transmitted to Earth).
Collect vitals from injured/ill crew (e.g. temp, pulse, oxygen saturation, respiration rate, blood pressure) with tools in kit, reassess as treatments/meds are administered.
Perform decompression sickness examination with the aid of an electronic form to determine if treatment is needed.
Collect Electrocardiogram (ECG) wave properties data with ECG hardware and leads placed on the patient for analysis of heart rate and variability.
Perform initial evaluation/treatment of chest pain by administering Aspirin/delivering oxygen with respiratory equip/collecting vitals/ECG, and listening to lung sounds.
Measure pulse and respiratory rate, administer oxygen and inhaled Albuterol, perform chest exam, and obtain blood pressure to treat difficulty breathing.
Obtain vital signs and photo-document rash, injury or other ailments to perform periodic health evaluation of a crewmember.
Examine eye using a Panoptic tool to test near and far visual acuity, visual field, contrast sensitivity, and potential cornea abrasions.
Apply blood pressure device and monitor to assess patient's blood pressure.
Collect sample via swab and perform culture, manually, to test for bacterial infection.
Take image of the back of the eye, manually using a retinal camera (fundus exam), to test for visual impairment and/or increased intracranial pressure (VIIP).
Examine patient, manually/cognitively, to diagnose lower extremity stress fracture; proscribe reducing weight-bearing activities for up to 12 weeks.
Examine skin, visually, to detect evidence of radiation-induced skin cancer.
Examine stool samples, visually using microscope, to detect evidence of radiation-induced cancer.
Collect samples of blood/urine/saliva, manually, to prepare for lab tests.
Conduct lab tests (e.g., CBC, chemical panels, strep throat), manually on collected samples, to help diagnose medical problem.

Respond to medical emergencies, following procedures and with equipment provided, during Mars Surface Operations.

Clear airway obstruction of choking conscious crewmember by performing abdominal thrusts with fist below ribcage pulling sharply inward and upward until object clears.

Treat patient who becomes unconscious from choking by attempting to clear foreign object manually/ pinch nose/apply breaths and begin CPR.

Perform CPR on unconscious /not breathing crewmember and determine if additional actions are needed as apart of Advanced Cardiac Life support.

Perform defibrillation on unconscious electrically isolated crewmember using AED to restore heartbeat.

Irrigate eye and perform eye exam to treat chemical exposure to a crewmember's eye.

Minimize eye and skin exposure to toxics to prepare for treating exposed crewmate.

Remove exposed crewmates soiled clothes, particles/liquid and irrigate with water (flush eye with water) for respiratory exposure follow Difficulty breathing procedure.

Check for capillary refill and pulses below injury location, apply splint, secure with ACE bandage to treat injured extremity (e.g., leg, arm).

Insert catheter into pleural space between lung/chest wall, producing a pathway for air to escape to perform a needle decompression of a pneumothorax (collapsed lung).

Secure Airway/Breathing/Circulation (ABCs)/perform physiological monitoring (e.g., Vitals and Chem Labs), manually/cognitively, to manage acute radiation syndrome.

Administer epinephrine, oxygen, IV antihistamines and cortisone, and beta-agonist (e.g., Albuterol), manually, to treat anaphylaxis.

Apply physical force and binding/duct tape, manually with the help of another crew member, to restrain a crewmember experiencing a behavioral emergency.

Secure crewmember to a flat surface, manually using restraints, to immobilize for treatment of suspected spinal cord trauma.

Administer anti-inflammatory drugs, manually, to immobilized crewmember to treat spinal cord trauma.

Perform surgery, manually using available instruments, to repair a detached retina.

Apply cast, splint, or brace to extremity (e.g., arm, leg), manually, to immobilize simple fracture.

Perform surgery, manually using available instruments, to repair a compound fracture of arm or leg bone.

Perform surgery, manually using available instruments, to treat acute appendicitis.

Administer medications during Mars Surface Operations.

Administer medication to suppress seizure/avoid loss of consciousness and uncontrolled muscle contractions.

Administer intramuscular shot, take vitals, and administer oxygen as needed to protect patient from injury from seizure.

Administer meds (e.g., antibiotics, antidiarrheal, antihistamine, decongestants, lubricants, pain relievers, sleep, steroids, stimulants and stool softeners) for conditions.

Administer hydrocodone and acetaminophen (Vicodin HP) and notify CMO to treat pain.

Administer medications or an intramuscular shot (e.g. Epipen) to treat an allergic reaction.

Apply ointment, bandages, and latex barrier gloves to hands to treat blisters from surface EVA work.

Apply ointment, bandages, and latex barrier covering to feet to treat blisters from surface EVA work.

Apply ointment and bandages to pressure points on body to treat abrasions from surface EVA work.

Apply a thin layer of Mupirocin (Bactroban) ointment and bandage affected areas to treat burned skin.

Deliver meds to lungs with inhaler by patient closing lips around the inhaler, inhaling slowly, holding breath for 10 seconds and removing inhaler from mouth and exhaling.

Attach prepared fluid set to an inserted IV catheter to administer IV fluids and medications.

Apply medical drops into the ear canal to treat ear pain caused by blockage (i.e., Barotrauma) that is not alleviated by yawning or chewing.

Administer antibiotics, manually per instructions, to treat ear infection.

Administer antibiotic ointments/drops, manually per instructions, to treat eye irritations/abrasions/infections.

Administer appropriate antibiotic (oral or IV) to treat confirmed bacterial infection.

Administer pill (TBD) to treat acute radiation syndrome.

Administer sedative, manually via syringe, to treat crewmember experiencing a behavioral emergency.

Administer IV antibiotics, manually, to treat sepsis (administer vasopressor medication if blood pressure remains low).

Perform medical treatments during Mars Surface Operations.

Insert catheter in the bladder to drain urine (self-catheterize) for urine retention.

Operate hand-held ultra-sonic device, manually while visually inspecting display, to locate and then disintegrate renal stone in crew member.

Place PHA QDM on ill crew/deliver oxygen for 2 hours, hydrate 1 liter per hour for 2 hours (administer IV fluids if unable to drink) to treat decompression sickness.

Administer traction and counter-traction until finger slips back in place to relocate a dislocated finger.

Administer traction and counter-traction until shoulder slips back in place to relocate a dislocated shoulder

Insert staples, sutures, or Derma bond depending on type and location of cut to repair skin laceration.

Administer Lidocaine or Epinephrine with a syringed needle, then create opening with scalpel to drain, to treat skin or dental abscess.

Remove staples using a skin staple remover to complete repair.

Remove sutures with medical scissors to complete repair.

Insert Oral Airway device halfway into mouth and rotate 180 degrees before inserting until it is flush against the lips to aid ventilation of unconscious patient.

Place Ambu Bag mask over nose and mouth and gently squeeze bag to deliver breaths every 5 to 8 seconds to assist temporary ventilation of a compromised patient.

Deliver oxygen to a respiratory distressed patient by automated ventilation provided in a respiratory support pack.

Insert an IV catheter and secure with medical tape to provide intravenous access for medications and fluids.

Pinch fleshy part of nose, manually, for 10 minutes to stop nose bleeding.

Insert nasal packing and drops, manually per instructions, to stop persistent nose bleeding.

Remove wax from ear, manually using curette/medical drops, to treat ear pain.

Clean fingernail, apply antibiotic ointment, cover with adhesive bandage, manually until a new nail grows, to treat/protect fingernail damage from EVA.

Apply ice (multiple sessions) and administer pain medication as needed, manually, to treat back/shoulder/neck sprain/strain.

Apply ice/cold pack and compress with bandage, manually, to treat wrist, elbow, ankle, or knee sprain/strain.

Apply splint, manually, to treat unresolved wrist, elbow, ankle, or knee sprain/strain.

Drain sinus passageway (with nasal spray) and administer antibiotics, manually, to treat acute sinusitis.

Perform a reduction maneuver gently and slowly, manually with the assistance on another crewmember, to realign a dislocated elbow.

Monitor crew behavioral health/respond to behavioral health issues during Mars Surface Operations.

Monitor individual behavioral health by speaking with each crew member with the goal of identifying symptoms of maladjustment.

Implement countermeasures (e.g., counseling, software) if symptoms of maladjustment or degraded behavioral health are detected among crew personnel.

Perform greenhouse/plant growth-related functions in surface module during Mars Surface Operations.

Adjust growing medium mixture, manually to augment automated system, manually via keyboard, when necessary to optimize plant growth.

Adjust/move plant containers/plumbing/reflectors, manually while wearing protective gloves, when necessary to optimize plant growth.

Remove plant material, manually using hand tools while wearing protective gloves, to harvest plants/vegetables for crew consumption.

Monitor plant growth, remotely via video feed to surface habitat, to verify/measure proper functioning of greenhouse.

Monitor plant growth, visually in person, to verify/measure proper functioning of greenhouse.

Perform maintenance/repair functions in surface habitat or modules during Mars Surface Operations.

Repair tear/puncture in surface EVA suit by manually turning suit inside out, cleaning fabric with alcohol, applying adhesive and patch, clamping firmly/allowing to dry.

Modify surface EVA suit, manually in surface habitat/laboratory, to adjust length of torso segment in response to spine elongation in reduced gravity.

Troubleshoot surface EVA suit, manually in surface habitat/laboratory, to identify problem.

Remove/replace component, manually in surface habitat/laboratory, to repair surface EVA suit.

Repair tear/puncture of surface habitat/module, manually by cleaning fabric, scoring surface with tool, applying adhesive/patch, clamping firmly, allowing to dry.

Repair broken hand tool, manually in surface habitat, using repair kit/materials, to restore functionality for later use.

Review schematics and other documentation, visually, to isolate plumbing (e.g., cooling, CLSS) fault in spacecraft.
Review schematics and other documentation, visually, to isolate plumbing (e.g., cooling, CLSS) fault in surface habitat or equipment.
Inspect plumbing (e.g., cooling, CLSS), visually and with hand tools, to identify source of plumbing fault in surface habitat or equipment.
Remove and replace plumbing component (e.g., section, valve), using hand tools and schematics, to restore system functionality in surface habitat or equipment.
Retrieve spare parts/materials (e.g., valve, duct tape) from storage/move to work site on surface, manually while wearing surface EVA suit, for troubleshooting/repair.
Remove 1 meter of duct tape from roll on rover, manually while wearing surface EVA suit, to temporarily repair leaking hydraulic hose/fitting.
Wrap 1 meter of duct tape around hydraulic hose/fitting on rover (or other equipment), manually while wearing surface EVA suit, to temporarily repair leak.
Retrieve spare parts/materials (e.g., valve, duct tape) from storage and move to work site in surface habitat, manually, to prepare for troubleshooting/repair.
Cut pipe, manually while wearing surface EVA suit and using hand saw, to remove damaged section of space habitat/equipment plumbing.
Insert section of pipe and attach in place, manually while wearing surface EVA suit and using electric soldering tool, flux, and solder to repair habitat/equipment plumbing.
Remove/replace filters in surface habitat, manually, to ensure safe removal of dust from breathable air.

Perform electronics/computers maintenance/repair functions in surface habitat or modules during Mars Surface Operations.

Review schematics and other documentation, visually, to isolate electronic fault in surface habitat or equipment.
Insert test equipment probes in electronic components, manually, and observe displays, visually, to isolate electronic fault in surface habitat or equipment.
Inspect circuit board, visually, to identify short circuit or loose/missing connection in surface habitat or equipment.
Inspect circuit board, visually, to identify scorching that might indicate degraded/faulty/failed electronic component in surface habitat or equipment.
Inspect circuit board, visually, while wearing surface EVA suit to help isolate source of electronic equipment trouble in the field.
Review documentation/enter control inputs, visually/manually, to diagnose software problem.
Enter control inputs, manually, to load software patch/reload software.
Replace electronic connector on wire/cable in surface habitat, manually, using hand tools and spare parts.
Replace electronic connector on wire/cable, manually while wearing surface EVA suit, using hand tools and spare parts.

Perform emergency functions in surface habitat or modules during Mars Surface Operations.

Respond to puncture of surface habitat/greenhouse/module, manually by retrieving and attaching temporary fast-patch.
Retrieve and don protective fire-fighting ensemble, manually, to prepare for fire emergency in surface habitat or module.
Remove fire extinguisher from bracket in surface habitat or module and manually carry to source of fire.
Point fire extinguisher nozzle at burning material and activate system manually while wearing protective ensemble to suppress fire.
Retreat to shielded area of surface habitat with other members of the crew in response to critical radiation event warning.
Remain in shielded area of surface habitat with other members of the crew during critical radiation event.

Perform 3D printer-related functions in surface habitat or modules during Mars Surface Operations.

Program 3-D printer, manually via computer inputs, to fabricate a replacement part for a mechanical system on planet surface.
Operate 3-D printer, manually via computer inputs, to fabricate a replacement part for a mechanical system on planet surface.
Remove and trim object fabricated by 3-D printer, manually using hand tools, to prepare replacement part for a mechanical system on planet surface.
Disassemble 3-D printer, manually using hand tools, to perform routine maintenance/cleaning.
Disassemble 3-D printer, manually using hand tools, to diagnose fault/restore functionality.

Perform monitoring functions in surface habitat or modules to ensure crew and system health during Mars Surface Operations.

Monitor display, visually from inside surface habitat, to verify proper functioning of the Radiation Assessment Detector (RAD).
Monitor display, visually from inside the surface habitat, to verify proper functioning of the weather monitoring station.
Monitor remote-sensing systems, visually from inside the surface habitat, to learn of impending surface weather event (i.e., dust storms).
Monitor atmospheric sampling equipment, remotely from surface habitat, to ensure that data are recorded for later analysis and transmission to MCC.

Monitor balloon sensors/transponders, remotely from surface habitat, to ensure that data are recorded for later review and transmission to MCC.
Monitor radiation-detection systems, visually/aurally, for evidence of Solar Proton and Galactic Cosmic Ray Events (SPE/GCR).
Monitor system displays, visually, to verify normal functioning of power-generation system.
Monitor system displays, visually, to verify normal functioning of *surface habitat life support system*.
Monitor system displays, visually, to verify normal functioning of *telemetry system*.
Monitor system displays, visually, to verify normal functioning of surface habitat *communication system*.
Monitor habitat atmosphere, visually/manually, by checking displays and comparing values to reference documents.
Inspect the footing/base and structural components of the surface habitat/greenhouse/module, visually, from inside the habitat to ensure integrity.

Adjust controls in surface habitat or modules to ensure proper functioning of systems during Mars Surface Operations.

Adjust controls, manually per procedures, to maintain normal functioning of power-generation system.
Adjust controls, manually per procedures, to maintain normal functioning of surface habitat *life support system*.
Adjust controls, manually per procedures, to maintain normal functioning of *telemetry system*.
Adjust controls, manually per procedures, to maintain normal functioning of surface habitat *communication system*.
Adjust controls, manually per procedures, to maintain optimum habitat atmosphere (temperature, CO2, etc.).

Perform training and skill refreshment in surface habitat during Mars Surface Operations.

Review procedures for emergency mission abort on planetary surface to refresh training.
Review emergency procedures for contingencies (fire, micro-meteorite impact, hull breech, outgassing, ECLS failure, etc.) while on surface to refresh training.
Configure surface habitat computer to support training simulation and task preparation.
Conduct (training) simulation using surface habitat computer to refresh piloting skills for Mars Surface Ascent.
Conduct (training) simulation using surface habitat computer to refresh navigation skills for Mars Surface Ascent.
Conduct (training) simulation using surface habitat computer to refresh communication skills for Mars Surface Ascent.
Read procedures and technical information to prepare for conducting tasks during Mars Surface Ascent.
Conduct final preparation/training tasks to prepare for Mars Surface Ascent.

Prepare for Mars Surface Ascent during Mars Surface Operations.

Connect hose to fittings on fuel storage tanks and Mars Excursion Vehicle (MEV)/Mars Ascent Vehicle (MAV), manually while wearing surface EVA suit, for refueling.
Activate pumps on fuel production system, manually via keyboard input from habitat, to transfer fuel from storage tanks to MEV/MAV.
Enter Mars Excursion Vehicle (MEV)/Mars Ascent Vehicle (MAV), physically while wearing pressure suit, to prepare for launch (Mars Surface Ascent maneuver).

PHASE 8: MARS SURFACE ASCENT (MSA)

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Receive final thrust and duration information from MCC to prepare for Mars Surface Ascent maneuver.
Communicate status of systems during Mars Surface Ascent maneuver in heavy buffeting to depart surface for Mars Orbit.
Communicate system status, verbally to crew members using internal communications equipment, during controlled ascent.
Communicate system status, verbally to MCC using external communications equipment, during controlled ascent.
Communicate successful docking with spacecraft in Mars Orbit, verbally and via text, to MCC using external communications equipment to confirm status.
Communicate systems shut down and safing to crew via internal communication system to advise of status.
Communicate systems shut down and safing to MCC via external communication systems to advise of status.

Prepare for Mars Surface Ascent maneuver.

Inspect Mars Excursion Vehicle (MEV)/Mars Ascent Vehicle (MAV) to verify that systems are go for ascent maneuver.

Don pressure suit, manually with the help of one other crew member, in preparation for Mars Surface Ascent maneuver.

Enter control inputs, manually, to convert Mars Excursion Vehicle (MEV)/Mars Ascent Vehicle (MAV) from surface mode to ascent mode.

Stow and secure all equipment, manually per load plan, to prepare Mars Excursion Vehicle (MEM)/Mars Ascent Vehicle (MAV) for Mars Surface Ascent maneuver.

Attach to individual crew maneuver position, while wearing pressure suit, in preparation for Mars Surface Ascent maneuver.

Monitor systems and perform piloting functions during Mars Surface Ascent.

Enter control inputs, manually, to configure Mars Excursion Vehicle computers for Mars Surface Ascent maneuver.

Enter control inputs, manually wearing pressure suit/gloves, to override auto firing of MEM/MAV main engine if automated system fails.

Enter control inputs, manually wearing pressure suit/gloves, to override automatic systems in response to system displays, if necessary.

Enter main engine control inputs, manually wearing pressure suit/gloves during buffeted ascent, to maneuver MEV to location near spacecraft in Mars Orbit.

Enter control inputs, manually wearing pressure suit/gloves, to shut down MEM/MAV main engine near spacecraft in Mars Orbit.

Adjust attitude control thrusters, manually wearing pressure suit/gloves, to dock Mars Excursion Vehicle MEM/MAV to spacecraft in Mars Orbit.

Adjust attitude control thrusters, manually wearing pressure suit/gloves, to maneuver MEM/MAV to spacecraft in Mars Orbit.

Adjust controls, manually wearing pressure suit/gloves, to shut down attitude control thrusters and other systems after docking with spacecraft in Mars Orbit.

Enter control inputs, manually, to activate engine shut down if displays indicate failure of automated shut down, to ensure safing of Mars Ascent Vehicle after docking.

Activate docking system shut down manually by control inputs if displays indicate failure of automated shut down, to ensure safing of MAV after docking.

Monitor automatic firing of Mars Excursion Vehicle (MEM)/Mars Ascent Vehicle (MAV) main engine, visually, for Mars Surface Ascent maneuver.

Monitor displays during Mars Surface Ascent maneuver, visually in heavy buffeting wearing pressure suit, to depart surface for Mars Orbit.

Monitor system displays, visually in heavy buffeting wearing pressure suit, to verify correct functionality at appropriate times during ascent to Mars Orbit.

Monitor system displays, visually wearing pressure suit, to assess proximity and verify docking with spacecraft in Mars Orbit.

Perform post-Mars Ascent maneuver functions.

Enter control inputs, manually wearing pressure suit/gloves, to secure (other) flight systems after engine shut down to ensure safing of MAV after docking.

Verify automated engine shut down by visually monitoring displays to ensure safing of Mars Ascent Vehicle after docking.

Verify automated docking system shut down by visually monitoring displays to ensure safing of Mars Ascent Vehicle after docking.

Phase 9: Trans-Earth Injection (TEI)

Conduct communications checks and communicate observations/evaluations to MCC personnel, verbally using communications system.

Receive final thrust and duration information from MCC to prepare for initiating Trans-Earth Injection (TEI).

Take position and prepare vehicle, manually while wearing pressure suit and helmet, to prepare for launch from Mars Orbit.

Don pressure suit, manually with the help of one other crew member, in preparation for thrust maneuver to achieve Trans-Earth Injection.

Transfer equipment and samples, manually, from Mars Excursion Vehicle (MEV)/Mars Ascent Vehicle (MAV) to spacecraft, in preparation for TEI.

Stow and secure all equipment, manually per load plan, to prepare spacecraft for thrust maneuver to achieve Trans-Earth Injection.

Stow and secure all samples collected on the surface, manually per load plan, to prepare spacecraft for thrust maneuver to achieve Trans-Earth Injection.

Attach to individual crew maneuver position, while wearing pressure suit, in preparation for thrust maneuver to achieve Trans-Earth Injection.

Monitor systems and perform piloting functions during Trans Earth Injection.

Enter control inputs to configure spacecraft computers in preparation for thrust maneuver to achieve Trans-Earth Injection.

Enter control inputs to override automatic firing of main engine for thrust maneuver to achieve Trans-Earth Injection, if necessary.

Monitor automatic firing of main engine, visually, for thrust maneuver to achieve Trans-Earth Injection.

Monitor displays and communicate status of systems during thrust maneuver in heavy buffeting to achieve Trans-Earth Injection.

PHASE 10: CRUISE TO EARTH (CTE)

Conduct communications checks/communicate observations/evaluations to other crew and MCC personnel, verbally using communications system during Cruise to Earth.

Operate communications system, manually, to receive transmission from MCC.

Operate communications system, manually, to transmit message to MCC.

Speak with other members of the crew concerning technical and task-related topics.

Speak with other members of the crew concerning non-technical and non-task-related topics.

Perform interviews and Public Affairs Office (PAO) events, using communications system, to inform Earth public of progress.

Transmit data collected during the Transit of Earth to ground stations immediately following event.

Interact with crew mates, personally, concerning task performance.

Interact with crew mates, personally, concerning non-task-related matters.

Compose/record electronic/video journal, using keyboard/computer in spacecraft, to create/preserve personal account of experiences.

Conduct physical/cognitive tests in spacecraft to assess fitness for duty (automatically-scheduled/results transmitted to Earth).

Conduct EVA to perform maintenance or retrieve items from outside the interplanetary space vehicle during Cruise to Earth.

Don pressure suit in response to meteor penetration or hull breech alarm, manually, with crew members helping each other.

Conduct EVA for maintenance or to retrieve needed supplies/equipment/expertise.

Remove and stow pressure suit following departure burn (i.e., Trans-Earth Injection).

Use interplanetary space vehicle waste management systems for liquid/solid waste (i.e., toilet/bodily function) during Cruise to Earth.

Use spacecraft waste management system for liquid waste (i.e., toilet/bodily function).

Use spacecraft waste management system for solid waste (i.e., toilet/bodily function).

Use interplanetary space vehicle hygiene systems for cleaning during Cruise to Earth.

Activate hygiene system to enable hand and body washing.

Shave face, manually using safety razor/soap/water, to remove beard growth.

Shave face, manually using electric razor, to remove beard growth.

Cut hair, manually using clippers/scissors/comb/vacuum tube, to remove excess hair growth.

Operate hygiene system to clean/disinfect hands and body.

Operate hygiene system to clean/brush teeth.

Retrieve wet wipes, towel, and clothing to clean body after exercise in preparation for study and work-related tasks.

Remove personal garments from storage in preparation for changing clothes.

Doff (remove) soiled garments and don clean clothing.

Insert soiled garments in collection container to dispose.

Maintain spacecraft waste management systems during Cruise to Earth.

Remove and replace bio collection container from waste management system, manually, to ensure continuity of operation.

Discard packaging waste in trash compactor, manually, to clear galley.

Operate trash compactor, manually, to increase space for additional packaging waste.

Remove compacted packaging waste from trash compactor, manually, and transport to onboard storage.

Insert new sanitary liner in trash compactor, manually, to prepare for additional use.

Prepare/eat meal, manually, using interplanetary space vehicle food hydration/heating equipment/galley during cruise to Earth.

Transfer food packages from deep storage to proximal storage, manually, to prepare galley for crew use.

Activate food hydration/heating equipment, manually, to prepare galley for crew use.

Prepare meal for crew consumption, manually, using spacecraft food hydration/heating equipment.
Eat meal together with other members of the crew in the spacecraft ward room/galley.

Conduct recreational activities, individually and as a crew, during Cruise to Earth.

Read articles, books, etc., during leisure periods for recreation.
Listen to music individually during leisure periods for recreation.
Listen to music individually while exercising for recreation.
Watch video (movies, TV programs, documentaries, etc.) individually while exercising for recreation.
Watch video (movies, TV programs, documentaries, etc.) individually during leisure periods for recreation.
Watch video (movies, TV programs, documentaries, etc.) together with other crew members during leisure periods for recreation.
Play chess and other board games together with other crew members during leisure periods for recreation.
Play chess with MCC personnel and others on Earth during leisure periods for recreation.

Sleep during cruise phase for approximately eight hours each 24-hour period, during Cruise to Earth.

Retrieve sleeping bag from storage and attach bag to bulkhead davits to prepare for sleep period.
Enter secured sleeping bag and begin sleep period to restore cognitive/physical functioning.

Conduct inventories and update records during Cruise to Earth.

Conduct and maintain inventories of consumable supplies, visually/manually (e.g., food, water, O_2), to update records.
Conduct and maintain inventories of spare parts and materials, visually/manually, to update records.

Exercise daily using onboard equipment during Cruise to Earth.

Configure resistive device and perform exercise to maintain cardiovascular conditioning, muscle strength, and bone density.
Mount bicycle ergometer and perform exercise to maintain cardiovascular conditioning, muscle strength, and bone density.
Don harnesses and perform exercise using treadmill to maintain cardiovascular conditioning, muscle strength, and bone density.

Assess displayed and aural information, cognitively, to determine appropriate course of action during Cruise to Earth.

Identify Emergency Alarm (i.e., Loss of pressure, Fire, Toxic substance/emission) and develop repair/recovery plan.
Identify Caution/Warning Alarm (e.g., CO_2, ECLS, Navigation) and develop repair/recovery plan.

Respond to technical emergencies, following procedures and with equipment provided, during Cruise to Earth.

Retreat to shielded area of spacecraft with other members of the crew in response to critical radiation event warning.
Remain in shielded area of spacecraft with other members of the crew during critical radiation event.
Respond to spacecraft fire alarm.
Respond to spacecraft micro-meteorite impact alarm.
Identify precise location of meteor penetration/hull breech, visually/aurally, assess severity, and determine method(s) to stop loss of pressure.
Retrieve repair kit from storage and carry to location of meteor penetration or hull breech.
Apply patch and adhesive material to meteor penetration site, manually, to close leak.
Retrieve and don protective fire-fighting ensemble, manually, to prepare for fire emergency.
Remove fire extinguisher from bulkhead bracket and manually carry to source of fire.
Point fire extinguisher nozzle at burning material and activate system manually while wearing protective ensemble to suppress fire.
Respond to spacecraft hull breech alarm.
Respond to spacecraft toxic substance/outgassing alarm.
Respond to spacecraft CO_2 alarm.
Respond to spacecraft general ECLS failure alarm.

Respond to spacecraft navigation alarm.

Respond to dental emergencies, following procedures and with equipment provided, during Cruise to Earth.

Conduct dental examination on crew member, manually/visually, to investigate complaint of tooth/jaw pain.

Interpret results of dental examination, cognitively with MCC consultation, to identify source of apparent tooth/jaw pain.

Prepare dental adhesive, fit, apply adhesive, and replace crown.

Administer pain medicine (Eugenol), manually as needed, to treat a crewmember's fractured tooth showing exposed pulp.

Apply direct pressure and hold until bleeding stops to treat loss of tooth of a crewmember.

Administer medication and if pain severe perform dental nerve block to treat crewmember's dental pain.

Apply temporary tooth filling and smooth excess (instruct patient to limit solid food consumption on affected side of mouth for 12-24 hours) to repair dental filling.

Perform medical diagnoses and evaluations, cognitively, during Cruise to Earth

Diagnose medical condition, cognitively and verbally through interviews with conscious ill or injured crewmember and physical exam.

Evaluate unresolved sleep disorder, cognitively per procedures, to diagnose problem and identify treatment/intervention.

Perform tests and examinations, physically, to support medical diagnoses during Cruise to Earth

Collect vitals from injured/ill crew (e.g. temp, pulse, oxygen saturation, respiration rate, blood pressure) with tools in kit, reassess as treatments/meds are administered.

Use medical software along with vitals/test results to help diagnosis condition of conscious or unconscious injured/ill crewmember.

Take image of the back of the eye, manually using a retinal camera (fundus exam), to test for visual impairment and/or increased intracranial pressure (VIIP).

Perform decompression sickness examination with the aid of an electronic form to determine if treatment is needed.

Collect Electrocardiogram (ECG) wave properties data with ECG hardware and leads placed on the patient for analysis of heart rate and variability.

Perform evaluation/treatment of chest pain by administering Aspirin, delivering oxygen with respiratory equipment, collecting vitals/ECG, and listening to lung sounds.

Check for capillary refill and pulses below injury location, apply splint, secure with ACE bandage to treat injured extremity (e.g., leg, arm).

Measure pulse and respiratory rate, administer oxygen and inhaled Albuterol, perform chest exam, and obtain blood pressure to treat difficulty breathing.

Obtain vital signs and photo-document rash, injury or other ailments to perform periodic health evaluation of a crewmember.

Test near and far visual acuity, visual field, contrast sensitivity, and potential cornea abrasions using a Panoptic tool to examine eyes.

Apply blood pressure device and monitor to assess patient's blood pressure.

Examine patient, manually/cognitively, to diagnose lower extremity stress fracture; proscribe reducing weight-bearing activities for up to 12 weeks.

Collect sample via swab and perform culture, manually, to test for bacterial infection.

Collect samples of blood/urine/saliva, manually, to prepare for lab tests.

Conduct lab tests (e.g., CBC, chemical panels, strep throat), manually on collected samples, to help diagnose medical problem.

Respond to medical emergencies, following procedures and with equipment provided, during Cruise to Earth.

Clear airway obstruction of choking crewmember by performing abdominal thrusts with fist below ribcage pulling sharply inward and upward until object clears.

Treat patient who becomes unconscious from choking by attempting to clear foreign object manually/pinch nose/apply breaths and begin CPR.

Perform CPR on unconscious /not breathing crewmember and determine if additional actions are needed as apart of Advanced Cardiac Life support.

Perform defibrillation on unconscious electrically isolated crewmember using AED to restore heartbeat.

Insert catheter in the bladder to drain urine (self-catheterize) for urine retention.

Administer traction and counter-traction until finger slips back in place to relocate a dislocated finger.

Administer traction and counter-traction until shoulder slips back in place to relocate a dislocated shoulder

Insert staples, sutures, or Derma bond depending on type and location of cut to repair skin laceration.

Insert catheter into pleural space between lung/chest wall, producing a pathway for air to escape to perform needle decompression of a pneumothorax (collapsed lung).

Insert an IV catheter and secure with medical tape to provide intravenous access for medications and fluids.

Attach prepared fluid set to an inserted IV catheter to administer IV fluids and medications.
Perform surgery, manually using available instruments, to repair a detached retina.
Perform surgery, manually using available instruments, to repair a compound fracture of arm or leg bone.
Perform surgery, manually using available instruments, to treat acute appendicitis.
Implement countermeasures (e.g., counseling, software) if symptoms of maladjustment or degraded behavioral health are detected among crew personnel.

Administer medications during Cruise to Earth.

Administer medications or an intramuscular shot (e.g. Epipen) to treat an allergic reaction.
Administer medication to suppress seizure/avoid loss of consciousness and uncontrolled muscle contractions.
Administer intramuscular shot, take vitals, and administer oxygen as needed to protect patient from injury from seizure.
Administer meds (e.g., antibiotics, antidiarrheal, antihistamine, decongestants, lubricants, pain relievers, sleep, steroids, stimulants and stool softeners) for conditions.
Administer hydrocodone and acetaminophen (Vicodin HP) and notify CMO to treat pain.
Administer Lidocaine or Epinephrine with a syringed needle, then create opening with scalpel to drain, to treat skin or dental abscess.
Apply a thin layer of Mupirocin (Bactroban) ointment and bandage affected areas to treat burned skin.
Deliver meds to lungs with inhaler by closing lips around the inhaler/inhaling slowly, holding breath for 10 seconds and removing inhaler from mouth and exhaling.
Apply medical drops into the ear canal to treat ear pain caused by blockage (i.e., Barotrauma) that is not alleviated by yawning or chewing.
Administer antibiotics, manually per instructions, to treat ear infection.
Administer antibiotic ointments/drops, manually per instructions, to treat eye irritations/abrasions/infections.
Administer appropriate antibiotic (oral or IV) to treat confirmed bacterial infection.
Administer epinephrine, oxygen, IV antihistamines and cortisone, and beta-agonist (e.g., Albuterol), manually, to treat anaphylaxis.
Administer sedative, manually via syringe, to treat crewmember experiencing a behavioral emergency.
Administer anti-inflammatory drugs, manually, to immobilized crewmember to treat spinal cord trauma.
Administer IV antibiotics, manually, to treat sepsis (administer vasopressor medication if blood pressure remains low).

Perform medical treatments during Cruise to Earth.

Irrigate eye and perform eye exam to treat chemical exposure to a crewmember's eye.
Minimize eye and skin exposure to toxics to prepare for treating exposed crewmate.
Remove exposed crewmates soiled clothes, particles/liquid and irrigate with water (flush eye with water) for respiratory exposure/follow Difficulty breathing procedure.
Place PHA QDM on crewmember/deliver oxygen for 2 hours, hydrate 1 liter per hour for 2 hours to treat decompression sickness.
Remove staples using a skin staple remover to complete repair.
Remove sutures with medical scissors to complete repair.
Insert Oral Airway device halfway into mouth and rotate 180 degrees before inserting until it is flush against the lips to aid ventilation of unconscious patient.
Place Ambu Bag mask over nose and mouth and gently squeeze bag to deliver breaths every 5 to 8 seconds to assist temporary ventilation of a compromised patient.
Deliver oxygen to a respiratory distressed patient by automated ventilation provided in a respiratory support pack.
Pinch fleshy part of nose, manually, for 10 minutes to stop nose bleeding.
Insert nasal packing and drops, manually per instructions, to stop persistent nose bleeding.
Remove wax from ear, manually using curette/medical drops, to treat ear pain.
Clean fingernail, apply antibiotic ointment, cover with adhesive bandage, manually until a new nail grows, to treat/protect fingernail damage from EVA.
Apply ice (multiple sessions) and administer pain medication as needed, manually, to treat back/shoulder/neck sprain/strain.
Apply ice/cold pack and compress with bandage, manually, to treat wrist, elbow, ankle, or knee sprain/strain.
Apply splint, manually, to treat unresolved wrist, elbow, ankle, or knee sprain/strain.

Drain sinus passageway (with nasal spray) and administer antibiotics, manually, to treat acute sinusitis.

Secure Airway, Breathing, Circulation (ABCs)/perform physiological monitoring (e.g., Vitals and Chem Labs), manually and cognitively, to manage acute radiation syndrome.

Apply physical force and binding/duct tape, manually with the help of another crew member, to restrain a crewmember experiencing a behavioral emergency.

Perform a reduction maneuver gently and slowly, manually with the assistance on another crewmember, to realign a dislocated elbow.

Secure crewmember to a flat surface, manually using restraints, to immobilize for treatment of suspected spinal cord trauma.

Apply cast, splint, or brace to extremity (e.g., arm, leg), manually, to immobilize simple fracture.

Perform administrative functions during Cruise to Earth.

Coordinate exercise device availability among crew to ensure access to maintain cardiovascular conditioning, muscle strength, and bone density.

Coordinate simulator availability among crew to ensure refresher training for all required skills and functions.

Coordinate crew response to meteor penetration, hull breech, fire, ECLS, or other emergency.

Monitor individual behavioral health by speaking with each crew member with the goal of identifying symptoms of maladjustment.

Schedule tasks and monitor performance of work to ensure that opportunities and resources are allocated appropriately among crew personnel.

Plan operations (e.g., EVA, maintenance of external components) using computer-based records in consultation with MCC and onboard personnel.

Conduct science and planning functions during Cruise to Earth.

Review expedition geology program objectives and procedures, using onboard resources, to prepare for reporting results.

Review expedition biology program objectives and procedures, using onboard resources, to prepare for reporting results.

Conduct astronomical observations, photography, and remote sensing to occupy cruise time with meaningful activity.

Conduct life science experiments to occupy cruise time with meaningful activity.

Conduct and record solar observations using onboard equipment and telescopes.

Conduct and record planetary and stellar observations using onboard equipment and telescopes.

Conduct and record radio astronomy observations using onboard equipment and telescopes.

Conduct and record Mars observations using onboard equipment and telescopes.

Conduct and record asteroid/comet observations using onboard equipment and telescopes.

Conduct and record Earth observations using onboard equipment and telescopes.

Conduct installation functions during Cruise to Earth.

Enter control inputs, manually, to configure spacecraft computer to support training simulation and task preparation.

Deploy supports/structures, manually, to configure dedicated area of spacecraft for medical procedure.

Modify pressure suit to adjust length of torso segment in response to spine elongation in zero gravity.

Enter control inputs, manually, to load software patch/reload software.

Program 3-D printer, manually via computer inputs, to fabricate a replacement part for a mechanical system onboard spacecraft.

Operate 3-D printer, manually via computer inputs, to fabricate a replacement part for a mechanical system onboard spacecraft.

Remove and trim object fabricated by 3-D printer, manually using hand tools, to prepare replacement part for a mechanical system onboard spacecraft.

Conduct maintenance functions during Cruise to Earth.

Review schematics and other documentation, visually, to isolate electronic fault in spacecraft.

Review schematics and other documentation, visually, to isolate plumbing (e.g., cooling, CLSS) fault in spacecraft.

Insert test equipment probes in electronic components, manually, and observe displays, visually, to isolate electronic fault in spacecraft.

Inspect circuit board, visually, to identify short circuit or loose/missing connection in spacecraft.

Inspect circuit board, visually, to identify scorching that might indicate degraded/faulty/failed electronic component in spacecraft.

Review documentation/enter control inputs, visually/manually, to diagnose software problem.
Inspect plumbing (e.g., cooling, CLSS), visually and with hand tools, to identify source of plumbing fault in spacecraft.
Remove and replace plumbing component (e.g., section, valve), using hand tools and schematics, to restore system functionality in spacecraft.
Retrieve spare parts/materials (e.g., valve, duct tape) from storage and move to work site in spacecraft, manually, to prepare for troubleshooting/repair.
Cut pipe, manually using hand saw, to remove damaged section of spacecraft plumbing.
Insert new section of pipe and attach in place, manually, using electric soldering tool, flux, and solder to repair spacecraft plumbing.
Remove 1 meter of duct tape from roll, manually, to temporarily repair leaking hose/fitting.
Wrap 1 meter of duct tape around hydraulic hose/fitting, manually, to temporarily repair leak.
Replace electronic connector on wire/cable, manually, using hand tools and spare parts.

Conduct navigation functions during Cruise to Earth.

Use sextant and star charts to estimate spacecraft position and course to compare to computerized navigation system.
Use sextant and star charts to estimate spacecraft position and course if computerized navigation system fails.
Convert results of manual navigation fix to propulsion changes necessary to achieve EOI, using tables and other calculation references.

Conduct piloting functions during Cruise to Earth.

Operate propulsion controls, manually, to maneuver space ship in preparation for ship-to-ship EVA.
Deploy and operate robot, remotely during cruise phase, to inspect external features of spacecraft.
Deploy and operate robot, remotely during cruise phase, to repair external features of spacecraft.

Monitor systems to ensure proper functioning during Cruise to Earth.

Monitor system displays, visually, to verify normal functioning of *life support system*.
Monitor system displays, visually, to verify normal functioning of *navigation system*.
Monitor system displays, visually, to verify normal functioning of *propulsion/attitude control syste*m.
Monitor system displays, visually, to verify normal functioning of *communication system*.
Monitor radiation-detection systems, visually/aurally, for evidence of Solar Proton and Galactic Cosmic Ray Events (SPE/GCR).
Monitor spacecraft atmosphere, visually/manually, by checking displays and comparing values to reference documents.

Adjust systems to ensure proper functioning during Cruise to Earth.

Adjust controls, manually per procedures, to maintain normal functioning of *life support system*.
Adjust controls, manually per procedures, to maintain normal functioning of *navigation system*.
Adjust controls, manually per procedures, to maintain normal functioning of *propulsion/attitude control system*.
Adjust propulsion/attitude control system controls, manually, to maintain proper course to Earth Orbit Injection (EOI).
Adjust controls, manually per procedures, to maintain normal functioning of *communication system*.
Adjust spacecraft atmosphere, manually, by making computer input commands in response to displays and reference documents.

Conduct refresher training to preserve skills during Cruise to Earth.

Review procedures for emergency mission abort (periodically during first third of cruise phase).
Review emergency procedures for various possibilities (fire, micro-meteorite impact, hull breech, outgassing, ECLS failure, etc.).
Conduct (training) simulation using spacecraft computer to refresh piloting skills for Earth Approach and Descent.
Conduct (training) simulation using spacecraft computer to refresh navigation skills for Earth Approach and Descent.
Conduct (training) simulation using spacecraft computer to refresh communication skills for Earth Approach and Descent.
Read procedures and technical information to prepare for conducting tasks during cruise, Earth Approach, and Descent.

Phase 11: Earth Approach (EA)

Conduct communications checks/communicate observations/evaluations to other crew and MCC, verbally using comm system prior to and during Earth Approach.

Receive final course-correction information from MCC to prepare for entering Earth Descent Vehicle (EDV), undocking, and skip trajectory.

Communicate status of systems during checkout and undocking of Earth Descent Vehicle (EDV).

Communicate status of systems from EDV during Earth Approach.

Prepare for Earth Approach.

Don pressure suit, manually with the help of one other crew member, in preparation for entering Earth Descent Vehicle (EDV).

Open hatch, manually, to access Earth Descent Vehicle (EDV) from (interplanetary) spacecraft.

Transfer cargo/personal/storage media items, manually, from interplanetary ship to Earth Descent Vehicle (EDV) to prepare for delivery to Earth surface.

Stow and secure all equipment, manually per load plan, to prepare EDV for Earth Approach and Earth Surface Descent.

Attach to individual crew maneuver position, while wearing pressure suit, in preparation for undocking the EDV from the interplanetary ship.

Monitor systems during Earth Approach.

Monitor automatic firing of retro rockets, visually, for undocking the EDV to achieve Earth Approach.

Monitor displays, visually, during undocking and maneuvering EDV away from interplanetary ship to prepare for Earth Approach and Descent.

Monitor displays, visually, during Earth Approach to prepare for Earth Surface Descent.

Monitor displays, visually using exterior video camera, to verify undocking of Earth Descent Vehicle (EDV).

Perform piloting functions during Earth Approach.

Enter control inputs to configure EDV computers in preparation for Earth Approach and Descent.

Enter control inputs, manually with gloved hand, to override automatic firing of maneuver thrusters if automated system fails.

Adjust thruster controls, manually with gloved hand, to undock EDV and maneuver away from interplanetary ship.

Adjust thruster controls, manually with gloved hand, to shut down EDV thrusters during Earth Approach.

Adjust attitude control thrusters, manually with gloved hand, to change course during Earth Approach.

Adjust attitude control thrusters, manually with gloved hand, to maneuver EDV to achieve correct skip trajectory.

Adjust controls, manually with gloved hand, to shut down attitude control thrusters and other systems in preparation for Earth Surface Descent.

Enter control inputs, manually with gloved hand, to activate thruster shut down if displays indicate failure of automated shut down.

Use EDV waste management systems for liquid/solid waste (i.e., toilet/bodily function) during Earth Approach.

Use EDV waste management system for liquid waste (i.e., toilet/bodily function).

Use EDV waste management system for solid waste (i.e., toilet/bodily function).

Prepare/eat meals during Earth Approach.

Remove food packages from storage, manually, to prepare meals during Earth Approach.

Remove drink packages from storage, manually, to prepare enable crew hydration during Earth Approach.

Distribute food and drink packages, manually, during Earth Approach.

Eat meal together with other members of the crew during Earth Approach.

Phase 12: Earth Surface Descent (ESD)

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel during Earth Surface Descent.

Receive final thrust and duration information from MCC to prepare for Earth Surface Descent.

Communicate status of systems to MCC, verbally, immediately prior to Earth Surface Descent.

Communicate system status, verbally to crew members using internal communications equipment, during Earth Surface Descent.

Communicate system status, verbally in heavy buffeting, to MCC using external communications equipment, during Earth Surface Descent.
Communicate successful touch down, verbally and via text, to MCC using external communications equipment to confirm status.
Communicate systems shut down and safing to crew via internal communication system to advise of status.
Communicate systems shut down and safing to MCC via external communication systems to advise of status.

Prepare for Earth Surface Descent.

Don pressure suit, manually with the help of one other crew member, in preparation for Earth Surface Descent.
Stow and secure all equipment, manually per load plan, to prepare Earth Descent Vehicle (EDV) for Earth Surface Descent.
Attach to individual crew maneuver position, while wearing pressure suit, in preparation for Earth Surface Descent.
Assess crew members' physical and cognitive abilities, verbally using self-reports and established diagnostics, to determine capacities for Earth descent.
Inspect Earth Descent Vehicle (EDV), visually, to verify that systems are go for descent maneuver.

Monitor systems during Earth Descent.

Monitor automatic firing of Earth Descent Vehicle (EDV) retro rockets, visually, for Earth Surface Descent.
Monitor displays, visually in heavy buffeting, during Earth Surface Descent.
Monitor displays, visually, for parachute and retro rocket to verify correct functionality at appropriate times during Earth Surface Descent.
Monitor displays, visually during buffeted descent, to assess proximity and verify touch down on Earth surface.
Secure (other) flight systems, manually by control inputs, to ensure safing of EDV after touch down.
Monitor displays, visually, to verify system functionality.

Adjust system controls, manually during buffeted descent, in response to displayed information.

Enter control inputs, manually with gloved hand, to adjust Earth Descent Vehicle (EDV) temperature.
Enter control inputs, manually with gloved hand, to adjust Earth Descent Vehicle (EDV) lighting.
Enter control inputs, manually with gloved hand, to adjust Earth Descent Vehicle (EDV) ECLS.

Perform piloting functions during Earth Descent.

Enter control inputs, manually with gloved hand, to configure Earth Descent Vehicle (EDV) computers, for Earth Surface Descent.
Enter control inputs, manually with gloved hand, to adjust EDV pitch and yaw during Earth Surface Descent.
Enter control inputs, manually with gloved hand, to maneuver Earth Descent Vehicle (EDV) during Earth Surface Descent.
Enter control inputs, manually with gloved hand, to override automatic firing of retro rockets during Earth Surface Descent if automated system fails.
Enter control inputs, manually with gloved hand, to adjust/override automatic systems in response to system displays, if necessary.
Adjust retro rocket controls, manually with gloved hand during buffeted descent, to maneuver EDV to correct landing location, if necessary.
Adjust controls, manually with gloved hand, to shut down retro rocket and other systems after touch down on Earth surface.
Verify automated engine shut down by visually monitoring displays to ensure safing of Earth Descent Vehicle (EDV) after touch down.
Enter control inputs, manually with gloved hand, to activate engine shut down if automated shut down fails, to ensure safing of Earth Descent Vehicle (EDV).
Verify automated landing system shut down by visually monitoring displays to ensure safing of Earth Descent Vehicle (EDV) after touch down.
Activate landing system shut down manually by control inputs if displays indicate failure of automated shut down, to ensure safing of EDV after touch down.

Perform post-Earth Descent functions.

Detach restraints and umbilicles from pressure suit, manually after landing, to prepare for egressing Earth Descent Vehicle (EDV).
Remove helmet, manually after landing, to prepare for egressing Earth Descent Vehicle (EDV).

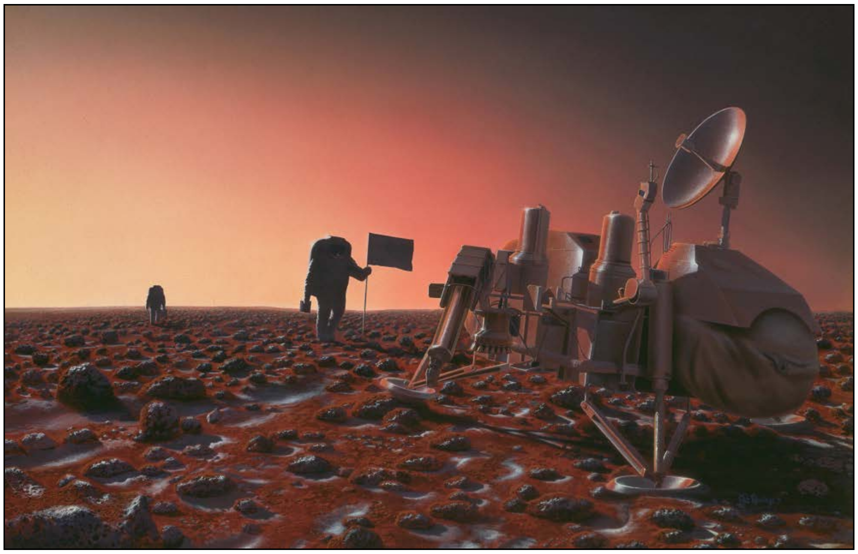
Mars Expedition

Summary Task Statements: 158; Tasks: 1125; Mission Phases: 12

APPENDIX E: TWO CALCULATIONS OF COMBINED ABILITY RANKINGS

All Specialties Combined	Mean	SD
More Important (12)	1.00	0.00
Inductive Reasoning	11.94	7.04
Deductive Reasoning	12.65	5.55
Problem Sensitivity	13.46	7.22
Confidence	14.75	5.37
Patience	18.36	6.35
Teamwork	19.04	6.60
Information Ordering	19.91	5.21
Originality	21.95	8.38
Speed of Closure	22.21	3.47
Selective Attention	22.89	6.83
Written Comprehension	23.36	7.99
Visualization	23.67	3.44
Important	23.68	2.17
Oral Comprehension	23.91	5.97
Time Sharing	23.99	6.20
Oral Expression	24.17	8.03
Manual Dexterity	24.29	9.19
Emotional Control	25.03	8.82
Speech Clarity	26.77	6.68
Near Vision	27.08	7.84
Finger Dexterity	27.70	10.17
Flexibility of Closure	28.02	6.95
Fluency of Ideas	28.26	10.36
Mathematical Reasoning	28.49	7.83
Affability	29.43	8.60
Arm-Hand Steadiness	29.48	9.68
Reaction Time	29.64	9.72
Perceptual Speed	29.69	4.99
Memorization	29.82	4.72
Control Precision	30.74	10.17
Tolerance	30.76	9.87
Visual Color Discrimination	31.43	9.76
Speech Hearing	32.03	6.99
Spatial Orientation	32.17	12.10
Number Facility	33.03	4.72
Written Expression	33.41	9.73
Auditory Attention	34.17	8.21
Category Flexibility	34.18	7.45
Rate Control	35.44	10.87
Multi-Limb Coordination	35.73	7.36
Depth Perception	35.87	5.90
General Hearing	36.08	6.70
Response Orientation	36.18	8.88
Stamina	37.66	7.19
Gross Body Coordination	38.32	5.89
Wrist-Finger Speed	38.60	8.78
Gross Body Equilibrium	39.31	6.33
Sound Localization	40.90	7.88
Far Vision	42.03	11.72
Dynamic Flexibility	42.40	5.42
Dynamic Strength	42.44	7.71
Extent Flexibility	42.52	5.79
Night Vision	43.64	11.70
Less Important	44.16	2.70
Glare Sensitivity	44.69	8.08
Peripheral Vision	44.73	6.93
Static Strength	45.09	8.53
Trunk Strength	45.40	6.14
Speed of Limb Movement	50.27	1.94
Explosive Strength	51.65	6.78

All SMEs Combined (121)	Mean	SD
More Important (16)	1.00	0.00
Inductive Reasoning	11.89	9.78
Problem Sensitivity	12.39	11.42
Deductive Reasoning	12.71	9.55
Confidence	12.93	12.12
Teamwork	15.75	13.62
Patience	15.98	12.26
Information Ordering	19.80	13.23
Originality	20.50	13.93
Oral Expression	20.69	14.68
Emotional Control	21.30	16.60
Oral Comprehension	21.33	13.13
Written Comprehension	22.24	13.57
Time Sharing	22.43	12.72
Speed of Closure	22.52	14.99
Speech Clarity	23.12	15.04
Selective Attention	23.66	13.89
Important	23.79	5.41
Visualization	23.92	14.14
Fluency of Ideas	24.94	16.27
Affability	25.32	16.58
Tolerance	25.74	19.04
Flexibility of Closure	28.19	17.19
Speech Hearing	28.96	14.83
Manual Dexterity	29.12	15.19
Memorization	29.28	14.43
Mathematical Reasoning	29.62	14.94
Perceptual Speed	29.62	13.29
Written Expression	29.93	16.69
Reaction Time	30.22	15.94
Near Vision	30.33	15.45
Category Flexibility	31.17	15.18
Spatial Orientation	32.57	15.11
Auditory Attention	32.70	14.40
Finger Dexterity	33.00	17.73
Number Facility	33.73	14.07
Control Precision	34.30	16.24
Arm-Hand Steadiness	34.66	16.37
Visual Color Discrimination	34.76	16.70
General Hearing	35.32	13.10
Stamina	36.60	15.24
Response Orientation	37.07	14.55
Depth Perception	37.31	12.41
Rate Control	37.90	16.51
Multi-Limb Coordination	38.63	14.13
Gross Body Coordination	39.63	12.86
Gross Body Equilibrium	40.23	13.10
Sound Localization	40.87	13.89
Far Vision	41.78	14.43
Wrist-Finger Speed	42.18	16.06
Dynamic Strength	42.66	12.98
Less Important	43.31	6.47
Dynamic Flexibility	44.51	12.60
Extent Flexibility	44.54	12.10
Peripheral Vision	45.17	11.56
Night Vision	45.32	14.06
Static Strength	45.75	12.92
Trunk Strength	46.10	11.54
Glare Sensitivity	46.69	13.65
Speed of Limb Movement	50.55	9.26
Explosive Strength	51.74	10.58



Visiting Viking (AKA *Return to Utopia*), by Pat Rawlings, 1991.
The artist wrote: “The Viking 2 Mars lander sparkles with an early morning frost as visitors from another planet carefully approach over the rock-strewn plain. The lander, which arrived at the *Utopia Planitia* site in 1976, is now covered with a thin layer of Martian dust.”

APPENDIX F: GATEWAY TASKS BY MISSION PHASE

Phase 1: Launch to Low-Earth Orbit (LEO)

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Conduct communications checks with other crew, wearing pressure suit, to prepare for launch from Earth.

Conduct communications checks with ground personnel, wearing pressure suit, to prepare for launch from Earth.

Communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Enter vehicle and take position, manually while wearing pressure suit and helmet, to prepare for launch from Earth.

Enter vehicle via diving board and ingress/egress straps, manually while wearing pressure suit and helmet, to prepare for launch from Earth.

Conduct final predeparture inspections of storage and equipment, visually, prior to launch from Earth.

Move (translate) to crew seat, wearing pressure suit, to prepare for launch from Earth.

Adjust controls, manually with gloved hands, before and after launch.

Adjust control, manually with gloved hand, to reconfigure ECLS/change cabin temperature.

Press edge key/button and F1 panel switch, manually with gloved hand, to activate LCG Pump.

Press edge key/button with gloved hand to cycle to fresh PSA swing bed.

Press edge key/button, with gloved hand, to activate Air Revitalization System (ARS)/Suit Mode.

Perform suit-related tasks with help of support personnel before launch.

Secure seat restraints, wearing pressure suit/gloves, to prepare for launch from Earth.

Attach umbilicals (GSE air) to suit, manually while wearing pressure suit/gloves, to prepare for launch from Earth.

Secure umbilicals with URDs, manually while wearing pressure suit/gloves, to prevent damage during launch.

Install emergency O2 bottles on crew leg, manually, to prepare for launch from Earth.

Connect to Audio Interface Unit, manually while wearing pressure suit/gloves, to prepare for launch from Earth.

Conduct final suit leak check, manually, to verify suit integrity.

Use emergency materials to contain/clean results of motion sickness during/after launch.

Access and open emesis bag, manually with gloved hand, to prepare for vomiting.

Access disposable towel, manually with gloved hand, to prepare for cleaning vomit from face/helmet/visor.

Enter control inputs, manually/visually with gloved hand, to configure and operate Orion before and after launch.

Perform controls/switch checklist, visually/manually while wearing pressure suit/gloves, to verify proper configuration.

Perform Acquisition Strategy Plan (ASP)/flight crew check, manually while wearing pressure suit/gloves, to ensure hard switches are still in expected configuration after strap in.

Inspect display, visually wearing suit/helmet, to verify all pyros are armed for ascent.

Enter control inputs, manually/visually with gloved hand, to configure launch displays.

Enter control inputs, manually, to activate Acquisition Tracking and Pointing/star tracker for launch to Earth Orbit.

Enter control inputs, manually, to align Inertial Measurement Unit (IMU) if necessary.

Enter control inputs, manually to override automated system, to reconfigure CM/SM heaters if necessary.

Activate controls, manually while wearing pressure suit/gloves, to configure cabin lighting.

Activate cabin pressure control, manually after visor opening, to prepare for orbit operations.
Respond to communications and displays, wearing pressure suit, to prepare for launch from Earth.
Activate controls, manually, to override automated process to initiate/control solar array deployment sequence, if necessary.

Monitor displays and verify configurations before and during launch.

Observe crew position displays and activate controls, wearing pressure suit, to prepare for launch from Earth.
Monitor audio communications and displays, wearing pressure suit/helmet, to prepare for launch from Earth.
Monitor displays, visually while wearing pressure suit/helmet, to verify system configuration formats and eProc.
Monitor displays/communicate values, visually/verbally, to evaluate system and crew readiness for orbit operations.
Monitor engine performance displays, visually wearing pressure suit/helmet, to ensure proper functioning during buffeted ascent.
Monitor displays, visually wearing pressure suit/helmet, to verify LAS jettison during buffeted ascent.
Monitor displays, visually wearing pressure suit/helmet, to verify MECO during buffeted ascent.
Monitor displays, visually wearing pressure suit/helmet, to verify core stage separation during buffeted ascent.
Monitor audio communications and displays, wearing pressure suit/helmet, during buffeted launch from Earth.
Monitor displays, visually, to verify star tracker configuration/status.

Assess displayed information, cognitively, to determine readiness to launch.

Evaluate displayed/communicated information, cognitively, to assess readiness for Earth Orbit operations.
Evaluate alarms and displays, cognitively, to identify any mission-critical anomalies during buffeted launch from Earth.

Enter control inputs, manually/visually with gloved hand, to pilot Orion during launch and transit.

Adjust controls as necessary, manually wearing pressure suit/gloves, during buffeted launch from Earth.
Activate controls, manually wearing pressure suit/gloves, to abort launch in response to evaluation data during buffeted ascent.
Activate controls, manually wearing pressure suit/gloves, to override automated systems/control spacecraft in response to evaluation data during buffeted ascent.
Adjust main engine controls, manually wearing pressure suit/gloves, to maneuver Orion to correct location in Earth Orbit.
Adjust main engine controls, manually wearing pressure suit/gloves, to shut down Orion main engine in Earth Orbit.
Activate appropriate controls in response to alarms, manually, while communicating actions to crew/MCC during buffeted ascent from Earth.

Phase 2: Low-Earth Orbit (LEO)

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Conduct communications checks with other crew, wearing pressure suit after launch/ascent.
Conduct communications checks with ground personnel, wearing pressure suit, to prepare for transit to Gateway.
Communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Inspect vehicle, visually/manually while wearing pressure suit and helmet, after launch/ascent.

Move (translate) to/from crew seat, wearing pressure suit, to inspect the vehicle systems after entering Low Earth Orbit.
Conduct post-launch inspections of storage and equipment, visually, after entering Low Earth Orbit.

Adjust controls, manually with gloved hands, before and after launch.

Adjust control, manually with gloved hand, to reconfigure ECLS/change cabin temperature.

Press edge key/button and F1 panel switch, manually with gloved hand, to activate LCG Pump.
Press edge key/button with gloved hand to cycle to fresh PSA swing bed.
Press edge key/button, with gloved hand, to activate Air Revitalization System (ARS)/Suit Mode.

Perform suit-related tasks during Low Earth Orbit operations.

Doff helmet/gloves after launch.
Temporarily stow helmet/gloves after launch.

Use emergency materials to contain/clean results of motion sickness.

Access and open emesis bag, manually, to prepare for vomiting.
Access disposable towel, manually, to prepare for cleaning vomit from face/helmet/visor.

Enter control inputs, manually/visually, to configure and operate Orion during Low Earth Orbit operations.

Perform controls/switch checklist, visually/manually, to verify proper configuration.
Perform ASP/flight crew check, manually while wearing pressure suit/gloves, to ensure hard switches are still in expected configuration after launch.
Enter control inputs, manually/visually, to configure displays.
Enter control inputs, manually, to activate Acquisition Tracking and Pointing/star tracker for transit to High Earth Orbit.
Enter control inputs, manually, to align Inertial Measurement Unit (IMU) if necessary.
Enter control inputs, manually to override automated system, to reconfigure CM/SM heaters if necessary.
Activate controls, manually, to configure cabin lighting.
Activate cabin pressure control, manually, to prepare for transit to High Earth Orbit.
Respond to communications and displays to prepare for transit to High Earth Orbit.
Activate controls, manually, to override automated process to initiate/control solar array deployment sequence, if necessary.

Monitor displays and verify configurations before and during Earth Orbit operations.

Observe crew position displays and activate controls to prepare for transit to High Earth Orbit.
Monitor audio communications and displays, to prepare for transit to High Earth Orbit.
Monitor displays, visually, to verify system configuration formats and eProc.
Monitor displays/communicate values, visually/verbally, to evaluate system and crew readiness for High Earth Orbit operations.
Monitor engine performance displays, visually, to ensure proper functioning during Earth Orbit operations.
Monitor audio communications and displays during Earth Orbit operations.
Monitor displays, visually, to verify star tracker configuration/status.

Assess displayed information, cognitively, to determine system readiness to depart Low Earth Orbit.

Evaluate displayed/communicated information, cognitively, to assess readiness for orbit operations and departure from Earth Orbit.
Evaluate alarms and displays, cognitively, to identify any mission-critical anomalies during Earth Orbit operations.

Perform suit-related tasks during Low Earth Orbit operations.

Retrieve temporarily stowed helmet/gloves to prepare for High Earth Orbit burn.
Don helmet/gloves after launch to prepare for High Earth Orbit burn.

Enter control inputs, manually/visually with gloved hand, to pilot Orion during Low Earth Orbit operations.

Adjust controls as necessary, manually wearing pressure suit/gloves, during Earth Orbit operations.

Activate controls, manually wearing pressure suit/gloves, to abort departure in response to evaluation data during Earth Orbit operations.

Activate controls, manually wearing pressure suit/gloves, to override automated systems/control spacecraft in response to evaluation data during Earth Orbit operations.

Adjust main engine controls, manually wearing pressure suit/gloves, to maneuver Orion to correct location in Earth Orbit.

Adjust main engine controls, manually wearing pressure suit/gloves, to shut down Orion main engine in Earth Orbit.

Activate appropriate controls in response to alarms, manually, while communicating actions to crew/MCC during departure from Earth Orbit.

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Conduct communications checks with other crew, wearing pressure suit, to prepare for transit to Gateway.

Conduct communications checks with ground personnel, wearing pressure suit, to prepare for transit to Gateway.

Communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Inspect/prepare vehicle, visually/manually while wearing pressure suit and helmet, to prepare for launch from Earth Orbit to Gateway.

Conduct final predeparture inspections of storage and equipment, visually, prior to launch from Earth.

Move (translate) to/from crew seat, wearing pressure suit, to prepare for departure burn from Earth Orbit.

Adjust controls, manually with gloved hands, before and after launch.

Adjust control, manually with gloved hand, to reconfigure ECLS/change cabin temperature.

Press edge key/button and F1 panel switch, manually with gloved hand, to activate LCG Pump.

Press edge key/button with gloved hand to cycle to fresh PSA swing bed.

Press edge key/button, with gloved hand, to activate Air Revitalization System (ARS)/Suit Mode.

Inspect/prepare vehicle, visully/manually while wearing pressure suit/helmet, to prepare for burn from Low Earth Orbit to High Earth Orbit.

Conduct final inspections of storage and equipment, visually, prior to burn to High Earth Orbit.

Move (translate) to/from crew seat, wearing pressure suit, to prepare for departure burn from Earth Orbit.

Phase 3: High Earth Orbit

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Conduct communications checks with other crew, wearing pressure suit, to prepare for transit to Gateway.

Conduct communications checks with ground personnel, wearing pressure suit, to prepare for transit to Gateway.

Communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Perform suit-related tasks during Earth Orbit operations.

Doff suit/helmet/gloves after insertion burn from Low Earth Orbit.

Stow suit/helmet/gloves after insertion burn from Low Earth Orbit.

Inspect/prepare vehicle, visually/manually while wearing pressure suit and helmet, to prepare for launch from Earth Orbit to Gateway.

Conduct post-burn inspections of storage and equipment, visually, after entering High Earth Orbit.

Adjust controls after entering High Earth Orbit.

Adjust control, manually, to reconfigure ECLS/change cabin temperature.

Press edge key/button and F1 panel switch, manually, to activate LCG Pump.

Press edge key/button to cycle to fresh PSA swing bed.

Press edge key/button to activate Air Revitalization System (ARS)/Suit Mode.

Use emergency materials to contain/clean results of motion sickness during/after launch.

- Access and open emesis bag, manually, to prepare for vomiting.
- Access disposable towel, manually, to prepare for cleaning vomit from face/equipment.

Enter control inputs, manually/visually, to configure and operate Orion during Earth Orbit operations.

- Perform controls/switch checklist, visually/manually, to verify proper configuration.
- Perform ASP/flight crew check, manually while wearing pressure suit/gloves, to ensure hard switches are still in expected configuration after launch.
- Enter control inputs, manually/visually, to configure launch displays.
- Enter control inputs, manually, to activate Acquisition Tracking and Pointing/star tracker for transit to CLO.
- Enter control inputs, manually, to align Inertial Measurement Unit (IMU) if necessary.
- Enter control inputs, manually to override automated system, to reconfigure CM/SM heaters if necessary.
- Activate controls, manually while wearing pressure suit/gloves, to configure cabin lighting.
- Activate cabin pressure control, manually after visor opening, to prepare for transit to CLO.
- Respond to communications and displays, wearing pressure suit, to prepare for transit to CLO.
- Activate controls, manually, to override automated process to initiate/control solar array deployment sequence, if necessary.

Prepare/eat meal, manually, using Orion food hydration/heating equipment/galley during Earth Orbit Operations.

- Transfer food packages from deep storage to proximal storage, manually, to prepare for crew use.
- Prepare meal for crew consumption, manually, using Orion food hydration/heating equipment.
- Eat/drink meal in Orion during Earth Orbit Operations.

Sleep during cruise phase for approximately eight hours each 24-hour period, during Transit to CLO/Gateway.

- Retrieve sleeping bag from storage to prepare for sleep period.
- Enter secured sleeping bag and begin sleep period to restore cognitive/physical functioning.

Use space vehicle waste management systems for liquid/solid waste (i.e., toilet/bodily function) during Transit to CLO/Gateway.

- Use spacecraft waste management system for liquid waste (i.e., toilet/bodily function).
- Use spacecraft waste management system for solid waste (i.e., toilet/bodily function).

Use interplanetary space vehicle hygiene systems for cleaning during Transit to CLO/Gateway.

- Retrieve wet wipes, towel, and clothing to clean body after exercise in preparation for study and work-related tasks.
- Remove personal garments from storage in preparation for changing clothes.
- Doff (remove) soiled garments and don clean clothing.
- Insert soiled garments in collection container to dispose.

Monitor displays and verify configurations before and during Earth Orbit operations.

- Observe crew position displays and activate controls, wearing pressure suit, to prepare for transit to CLO.
- Monitor audio communications and displays, wearing pressure suit/helmet, to prepare for transit to CLO.
- Monitor displays, visually while wearing pressure suit/helmet, to verify system configuration formats and eProc.
- Monitor displays, visually, to assess solar array deployment status.
- Monitor/control external video camera, visually/manually, to verify solar array deployment.
- Monitor display, visually, to verify solar array power generation/battery charging.

Monitor displays/communicate values, visually/verbally, to evaluate system and crew readiness for Earth Orbit operations.
Monitor engine performance displays, visually wearing pressure suit/helmet, to ensure proper functioning during Earth Orbit operations.
Monitor audio communications and displays, wearing pressure suit/helmet, during Earth Orbit operations.
Monitor displays, visually, to verify star tracker configuration/status.

Assess displayed information, cognitively, to determine system readiness to depart Earth Orbit.

Evaluate displayed/communicated information, cognitively, to assess readiness for orbit operations and departure from Earth Orbit.
Evaluate alarms and displays, cognitively, to identify any mission-critical anomalies during Earth Orbit operations.
Activate controls, manually, to override automated process to initiate/control solar array retraction sequence, prior to burn, if necessary.
Monitor displays, visually, to assess solar array detraction status.
Monitor/control external video camera, visually/manually, to verify solar array detraction.

Enter control inputs, manually/visually with gloved hand, to pilot Orion during Earth Orbit operations.

Adjust controls as necessary, manually wearing pressure suit/gloves, during Earth Orbit operations.
Activate controls, manually wearing pressure suit/gloves, to abort departure in response to evaluation data during Earth Orbit operations.
Activate controls, manually wearing pressure suit/gloves, to override automated systems/control spacecraft in response to evaluation data during Earth Orbit operations.
Adjust main engine controls, manually wearing pressure suit/gloves, to maneuver Orion to correct location in Earth Orbit.
Adjust main engine controls, manually wearing pressure suit/gloves, to shut down Orion main engine in Earth Orbit.
Activate appropriate controls in response to alarms, manually, while communicating actions to crew/MCC during departure from Earth Orbit.

Phase 4: Transit to CLO/Gateway

Monitor displays and verify configurations before and during transit to CLO/Gateway.

Observe crew position displays and activate controls, wearing pressure suit/gloves, to prepare for departing Earth Orbit.
Monitor communications, aurally while wearing pressure suit/helmet, to prepare for departing Earth Orbit.
Monitor displays, visually while wearing pressure suit/helmet, to prepare for departing Earth Orbit.
Monitor communications, aurally wearing pressure suit/helmet, during departure burn from Earth Orbit.
Monitor displays, visually wearing pressure suit/helmet, during departure burn from Earth Orbit.

Assess displayed information, cognitively, to determine readiness for transit to CLO/Gateway maneuver.

Evaluate alarms and displays, cognitively, to identify any mission-critical anomalies.

Adjust controls/attachments, manually with gloved hands, to configure suit/displays before, during, after departure from Earth Orbit.

Activate appropriate controls in response to alarms, manually wearing pressure suit/gloves, while communicating actions to crew and MCC.
Respond to communications and displays, wearing pressure suit, to prepare for departing Earth Orbit.
Adjust controls as necessary, wearing pressure suit/gloves, during departure burn from Earth Orbit.
Activate controls, manually wearing pressure suit/gloves, to abort departure burn in response to evaluation data.
Activate controls, manually wearing pressure suit/gloves, to override automated systems/control spacecraft in response to evaluation data.

Perform suit-related tasks during Transit operations.

Doff suit/gloves after insertion burn from High Earth Orbit.
Stow suit/gloves after insertion burn from High Earth Orbit.

Adjust controls/attachments, manually to configure suit and displays before, during, and after departure from Earth Orbit.

Activate controls, manually, to override automated process to initiate/control solar array deployment sequence, if necessary.

Monitor displays, visually, to assess solar array deployment status.

Monitor/control external video camera, visually/manually, to verify solar array deployment.

Monitor display, visually, to verify solar array power generation/battery charging.

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system during transit to CLO/Gateway.

Operate communications system, manually, to receive transmission from MCC.

Operate communications system, manually, to transmit message to MCC.

Speak with other members of the crew concerning technical and task-related topics.

Speak with other members of the crew concerning non-technical and non-task-related topics.

Perform interviews and Public Affairs Office (PAO) events, using communications system, to inform Earth public of progress.

Transmit data collected during the transit to CLO/Gateway to ground stations immediately following event.

Interact with crew mates, personally, concerning task performance.

Interact with crew mates, personally, concerning non-task-related matters.

Compose/record electronic/video journal, using keyboard/computer in spacecraft, to create/preserve personal account of experiences.

Conduct physical/cognitive tests in spacecraft to assess fitness for duty (automatically-scheduled/results transmitted to Earth).

Use space vehicle waste management systems for liquid/solid waste (i.e., toilet/bodily function) during Transit to CLO/Gateway.

Use spacecraft waste management system for liquid waste (i.e., toilet/bodily function).

Use spacecraft waste management system for solid waste (i.e., toilet/bodily function).

Use space vehicle hygiene systems for cleaning during Transit to CLO/Gateway.

Retrieve wet wipes, towel, and clothing to clean body after exercise in preparation for study and work-related tasks.

Remove personal garments from storage in preparation for changing clothes.

Doff (remove) soiled garments and don clean clothing.

Insert soiled garments in collection container to dispose.

Maintain spacecraft waste management systems during Transit to CLO/Gateway.

Remove and replace bio collection container from waste management system, manually, to ensure continuity of operation.

Discard packaging waste in trash compactor, manually, to clear galley.

Operate trash compactor, manually, to increase space for additional packaging waste.

Remove compacted packaging waste from trash compactor, manually, and transport to onboard storage.

Insert new sanitary liner in trash compactor, manually, to prepare for additional use.

Prepare/eat meal, manually, using spacecraft food hydration/heating equipment during Transit to CLO/Gateway.

Transfer food packages from deep storage to proximal storage, manually, to prepare for crew use.

Activate food hydration/heating equipment, manually, to prepare for crew use.

Prepare meal for crew consumption, manually, using spacecraft food hydration/heating equipment.

Eat meal together with other members of the crew.

Conduct recreational activities, individually and as a crew, during Transit to CLO/Gateway.

Read articles, books, etc., during leisure periods for recreation.

Listen to music individually during leisure periods for recreation.

Listen to music individually while exercising for recreation.

Watch video (movies, TV programs, documentaries, etc.) individually while exercising for recreation.

Watch video (movies, TV programs, documentaries, etc.) individually during leisure periods for recreation.

Watch video (movies, TV programs, documentaries, etc.) together with other crew members during leisure periods for recreation.

Play chess and other board games together with other crew members during leisure periods for recreation.

Play chess with MCC personnel and others on Earth during leisure periods for recreation.

Sleep during cruise phase for approximately eight hours each 24-hour period, during Transit to CLO/Gateway.

Retrieve sleeping bag from storage to prepare for sleep period.

Enter secured sleeping bag and begin sleep period to restore cognitive/physical functioning.

Exercise daily using onboard equipment during transit.

Deploy exercise device to maintain cardiovascular conditioning, muscle strength, and bone density.

Configure exercise device and perform exercise to maintain cardiovascular conditioning, muscle strength, and bone density.

Assess displayed and aural information, cognitively, to determine appropriate course of action during Transit to CLO/Gateway.

Identify Emergency Alarm (i.e., Loss of pressure, Fire, Toxic substance/emission) and develop repair/recovery plan.

Identify Caution/Warning Alarm (e.g., CO2, ECLS, Navigation) and develop repair/recovery plan.

Respond to technical emergencies, following procedures and with equipment provided, during Transit to CLO/Gateway.

Retreat to shielded area of spacecraft with other members of the crew in response to critical radiation event warning.

Remain in shielded area of spacecraft with other members of the crew during critical radiation event.

Respond to spacecraft fire alarm.

Respond to spacecraft micro-meteorite impact alarm.

Identify precise location of meteor penetration/hull breech, visually/aurally, assess severity/determine method(s) to stop loss of pressure.

Retrieve repair kit from storage and carry to location of meteor penetration or hull breech.

Apply patch and adhesive material to meteor penetration site, manually, to close leak.

Retrieve and don protective fire-fighting ensemble, manually, to prepare for fire emergency.

Remove fire extinguisher from bulkhead bracket and manually carry to source of fire.

Point fire extinguisher nozzle at burning material and activate system manually while wearing protective ensemble to suppress fire.

Respond to spacecraft hull breech alarm.

Respond to spacecraft toxic substance/outgassing alarm.

Respond to spacecraft CO2 alarm.

Respond to spacecraft general ECLS failure alarm.

Respond to spacecraft navigation alarm.

Perform medical tasks during CLO- Gateway operations.

Perform medical (including dental) diagnoses and evaluations, cognitively, during transit operations.

- Perform tests and examinations, physically, to support medical diagnoses, during transit operations.
- Respond to medical emergencies, following procedures and with equipment provided, during transit operations.
- Administer medications during transit operations.
- Perform medical treatments during transit operations.

Perform administrative functions during Transit to CLO/Gateway.

- Coordinate exercise device availability among crew to ensure access to maintain cardiovascular conditioning, muscle strength, and bone density.
- Coordinate simulator availability among crew to ensure refresher training for all required skills and functions.
- Coordinate crew response to meteor penetration, hull breech, fire, ECLS, or other emergency.
- Monitor individual behavioral health by speaking with each crew member with the goal of identifying symptoms of maladjustment.
- Schedule tasks and monitor performance of work to ensure that opportunities and resources are allocated appropriately among crew personnel.
- Plan operations (e.g., EVA, maintenance of external components) using computer-based records in consultation with MCC and onboard personnel.

Conduct science and planning functions during transit.

- Conduct astronomical observations, photography, and remote sensing to document transit phase.
- Conduct and record solar observations using onboard equipment and telescopes.
- Conduct and record Earth observations using onboard equipment and telescopes.

Conduct maintenance functions during Transit to CLO/Gateway.

- Review schematics and other documentation, visually, to isolate electronic fault in spacecraft.
- Review schematics and other documentation, visually, to isolate plumbing (e.g., cooling, CLSS) fault in spacecraft.
- Insert test equipment probes in electronic components, manually, and observe displays, visually, to isolate electronic fault in spacecraft.
- Inspect circuit board, visually, to identify short circuit or loose/missing connection in spacecraft.
- Inspect circuit board, visually, to identify scorching that might indicate degraded/faulty/failed electronic component in spacecraft.
- Review documentation/enter control inputs, visually/manually, to diagnose software problem.
- Inspect plumbing (e.g., cooling, CLSS), visually and with hand tools, to identify source of plumbing fault in spacecraft.
- Remove/replace plumbing component (e.g., section, valve), using hand tools and schematics, to restore system functionality in spacecraft.
- Retrieve spare parts/materials (e.g., valve, duct tape) from storage and move to work site in spacecraft, manually, to prepare for troubleshooting/repair.
- Remove 1 meter of duct tape from roll, manually, to temporarily repair leaking hose/fitting.
- Wrap 1 meter of duct tape around hydraulic hose/fitting, manually, to temporarily repair leak.
- Replace electronic connector on wire/cable, manually, using hand tools and spare parts.

Monitor displays and verify configurations before rendezvous.

- Activate controls, manually, to override automated process to initiate/control solar array retraction sequence, prior to burn, if necessary.
- Monitor displays, visually, to assess solar array retraction status.
- Monitor/control external video camera, visually/manually, to verify solar array retraction.

Conduct navigation functions during Transit to CLO/Gateway.

- Use sextant and star charts to estimate spacecraft position and course to compare to computerized navigation system.
- Use sextant and star charts to estimate spacecraft position and course if computerized navigation system fails.
- Convert results of manual navigation fix to propulsion changes necessary to achieve CLO, using tables and other calculation references.

Conduct piloting functions during transit.

Operate propulsion controls, manually, to maneuver space ship in preparation for ship-to-ship EVA.

Deploy and operate robot, remotely during transit to CLO, to inspect external features of spacecraft.

Deploy and operate robot, remotely during cruise phase, to repair external features of spacecraft.

Adjust controls as necessary, manually wearing pressure suit/gloves, during transit to CLO.

Activate controls, manually wearing pressure suit/gloves, to abort departure to CLO in response to evaluation data.

Activate controls, manually wearing pressure suit/gloves, to override automated systems/control in response to evaluation data during transit to CLO.

Adjust main engine/thruster controls, manually wearing pressure suit/gloves, to maneuver Orion during transit to CLO.

Adjust main engine controls, manually wearing pressure suit/gloves, to shut down Orion main engine in Earth Orbit.

Activate appropriate controls in response to alarms, manually, while communicating actions to crew/MCC during buffeted transit.

Monitor systems to ensure proper functioning during Transit to CLO/Gateway.

Monitor system displays, visually, to verify normal functioning of *life support system*.

Monitor system displays, visually, to verify normal functioning of *navigation system*.

Monitor system displays, visually, to verify normal functioning of *propulsion/attitude control system.*

Monitor system displays, visually, to verify normal functioning of *communication system.*

Monitor radiation-detection systems, visually/aurally, for evidence of Solar Proton and Galactic Cosmic Ray Events (SPE/GCR).

Monitor spacecraft atmosphere, visually/manually, by checking displays and comparing values to reference documents.

Adjust systems to ensure proper functioning during Transit to CLO/Gateway.

Adjust controls, manually per procedures, to maintain normal functioning of *life support system.*

Adjust controls, manually per procedures, to maintain normal functioning of *navigation system.*

Adjust controls, manually per procedures, to maintain normal functioning of *propulsion/attitude control system.*

Adjust propulsion/attitude control system controls, manually, to maintain proper course to Gateway module rendezvous and docking.

Adjust controls, manually per procedures, to maintain normal functioning of *communication system.*

Adjust spacecraft atmosphere, manually, by making computer input commands in response to displays and reference documents.

Conduct primary and refresher training to learn/preserve skills during Transit to CLO/Gateway.

Review procedures for emergency mission abort (periodically during transit).

Review emergency procedures for various possibilities (fire, micro-meteorite impact, hull breech, outgassing, ECLS failure, etc.).

Conduct (training) simulation using spacecraft computer to refresh piloting skills for Gateway module rendezvous and docking.

Conduct (training) simulation using spacecraft computer to refresh navigation skills for Gateway module rendezvous and docking.

Conduct (training) simulation using spacecraft computer to refresh communication skills for Gateway module rendezvous and docking.

Conduct primary training using digital media/spacecraft computer to learn information and skills not included in pre-mission training.

Read procedures and technical information to prepare for Gateway module rendezvous and docking and Cis-Lunar orbit.

Perform suit-related tasks to prepare for rendezvous and docking.

Retrieve temporarily stowed helmet/gloves to prepare for rendezvous and docking.

Don suits/helmet/gloves to prepare for rendezvous and docking.

Phase 5: Rendezvous & Docking at Gateway

Enter control inputs, manually/visually with gloved hand, to pilot Orion during rendezvous and docking.

Adjust attitude control thrusters, manually wearing pressure suit/gloves, to dock Orion to Deep Space Gateway module.

Adjust attitude control thrusters, manually wearing pressure suit/gloves, to maneuver Orion to Gateway module.

Adjust controls, manually wearing pressure suit/gloves, to shut down attitude control thrusters and other systems after docking with Gateway module in CLO.

Enter control inputs, manually wearing pressure suit/gloves, to activate engine shut down if displays indicate failure of automated shut down, to ensure safing of Orion after docking.

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Receive final thrust and duration information from MCC to prepare for Gateway approach maneuver.

Communicate status of systems, verbally, during rendezvous and docking.

Communicate system status, verbally to crew members using internal communications equipment, during controlled Gateway rendezvous and docking.

Communicate system status, verbally to MCC using external communications equipment, during Gateway rendezvous and docking.

Communicate successful docking with Gateway, verbally and via text, to MCC using external communications equipment to confirm status.

Communicate systems shut down and safing to crew via internal communication system to advise of status.

Communicate systems shut down and safing to MCC via external communication systems to advise of status.

Monitor displays and verify configurations before and during rendezvous and docking

Observe crew position displays and activate controls, wearing pressure suit, during rendezvous and docking.

Monitor audio communications and displays, wearing pressure suit/helmet, during rendezvous and docking.

Monitor displays, visually while wearing pressure suit/helmet, to verify system configuration formats/eProc during rendezvous and docking.

Monitor displays/communicate values, visually/verbally, to evaluate system and crew readiness for rendezvous and docking.

Monitor engine performance displays, visually wearing pressure suit/helmet, to ensure proper functioning during rendezvous and docking.

Monitor displays, visually, to verify star tracker configuration/status.

Assess displayed information, cognitively, to determine readiness to dock to the Gateway module.

Evaluate displayed/communicated information, cognitively, to assess readiness for rendezvous and docking.

Evaluate alarms and displays, cognitively, to identify any mission-critical anomalies during rendezvous and docking.

Phase 6: Gateway / Cis-Lunar Orbit Operations

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Communicate status of spacecraft and systems to crew, verbally using communications equipment, to advise of conditions.

Communicate status of spacecraft and systems to MCC, verbally using communications equipment, to advise of conditions.

Communicate status of systems to MCC, verbally/manually (text) during Cis-Lunar orbit operations to advise of conditions.

Review procedures/checklists to prepare for Cis-Lunar orbit operations.

Review checklists, visually/verbally, with other crew members to verify that all procedures have been completed to secure for Cis-Lunar orbit operations.

Configure systems for Cis-Lunar orbit operations.

Configure spacecraft computers in preparation for Cis-Lunar orbit operations.

Detach from individual crew maneuver position, while wearing pressure suit, in preparation for Cis-Lunar orbit operations.

Doff pressure suit, manually with the help of one other crew member, in preparation for Cis-Lunar orbit operations.

Monitor systems during Cis-Lunar orbit operations.

View displays, visually, to verify aerobraking maneuver has achieved Cis-Lunar orbit.

Inspect spacecraft displays and equipment, visually/manually, to identify any apparent damage from rendezvous and docking maneuvers.

Monitor system displays, visually, to ensure nominal functioning during Cis-Lunar orbit operations.

Activate controls, manually, to override automated process to initiate/control solar array deployment sequence, if necessary.

Monitor displays, visually, to assess solar array deployment status.

Monitor/control external video camera, visually/manually, to verify solar array deployment.

Monitor display, visually, to verify solar array power generation/battery charging.

Perform piloting functions during Cis-Lunar orbit operations.

Adjust attitude/propulsion controls, manually, in response to navigation/attitude control data, to achieve/maintain proper Cis-Lunar orbit.

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system during cislunar orbit operations.

Operate communications system, manually, to receive transmission from MCC.

Operate communications system, manually, to transmit message to MCC.

Speak with other members of the crew concerning technical and task-related topics.

Speak with other members of the crew concerning non-technical and non-task-related topics.

Perform interviews and Public Affairs Office (PAO) events, using communications system, to inform Earth public of progress.

Transmit data collected during the Transit from Earth to ground stations immediately following event.

Interact with crew mates, personally, concerning task performance.

Interact with crew mates, personally, concerning non-task-related matters.

Compose/record electronic/video journal, using keyboard/computer in spacecraft, to create/preserve personal account of experiences.

Conduct physical/cognitive tests in spacecraft to assess fitness for duty (automatically-scheduled/results transmitted to Earth).

Conduct EVA to perform maintenance or retrieve items from outside the Gateway habitat during Cis-Lunar orbit operations.

Don pressure suit in response to meteor penetration or hull breech alarm, manually, with crew members helping each other.

Conduct EVA for maintenance or to retrieve needed supplies/equipment/expertise.

Conduct EVA to install equipment outside of the Gateway module.

Remove and stow pressure suit following EVA.

Launch robotic lunar vehicles.

Use Gateway waste management systems for liquid/solid waste (i.e., toilet/bodily function) during Cis-Lunar orbit operations.

Use Gateway waste management system for liquid waste (i.e., toilet/bodily function).

Use Gateway waste management system for solid waste (i.e., toilet/bodily function).

Use Gateway hygiene systems for cleaning during Cis-Lunar orbit operations.

Activate hygiene system to enable hand and body washing.

Shave face, manually using safety razor/soap/water, to remove beard growth.

Shave face, manually using electric razor, to remove beard growth.

Cut hair, manually using clippers/scissors/comb/vacuum tube, to remove excess hair growth.

- Operate hygiene system to clean/disinfect hands and body.
- Retrieve wet wipes, towel, and clothing to clean body after exercise in preparation for study and work-related tasks.
- Remove personal garments from storage in preparation for changing clothes.
- Doff (remove) soiled garments and don clean clothing.
- Insert soiled garments in collection container to dispose.

Maintain Gateway waste management systems during Cis-Lunar orbit operations.

- Remove and replace bio collection container from waste management system, manually, to ensure continuity of operation.
- Discard packaging waste in trash compactor, manually, to clear galley.
- Operate trash compactor, manually, to increase space for additional packaging waste.
- Remove compacted packaging waste from trash compactor, manually, and transport to onboard storage.
- Insert new sanitary liner in trash compactor, manually, to prepare for additional use.

Prepare/eat meal, manually, using Gateway vehicle food hydration/heating equipment/galley during Cis-Lunar orbit operations.

- Transfer food packages from deep storage to proximal storage, manually, to prepare galley for crew use.
- Activate food hydration/heating equipment, manually, to prepare galley for crew use.
- Prepare meal for crew consumption, manually, using spacecraft food hydration/heating equipment.
- Eat meal together with other members of the crew in the spacecraft ward room/galley.

Conduct recreational activities, individually and as a crew, during Cis-Lunar orbit operations.

- Read articles, books, etc., during leisure periods for recreation.
- Listen to music individually during leisure periods for recreation.
- Listen to music individually while exercising for recreation.
- Watch video (movies, TV programs, documentaries, etc.) individually while exercising for recreation.
- Watch video (movies, TV programs, documentaries, etc.) individually during leisure periods for recreation.
- Watch video (movies, TV programs, documentaries, etc.) together with other crew members during leisure periods for recreation.
- Play chess and other board games together with other crew members during leisure periods for recreation.
- Play chess with MCC personnel and others on Earth during leisure periods for recreation.

Sleep for approximately eight hours each 24-hour period, during Cis-Lunar orbit operations.

- Retrieve sleeping bag from storage and attach bag to davits in sleep chamber to prepare for sleep period.
- Enter secured sleeping bag and begin sleep period to restore cognitive/physical functioning.

Conduct inventories and update records during Cis-Lunar orbit operations.

- Conduct and maintain inventories of consumable supplies, visually/manually (e.g., food, water, O2), to update records.
- Conduct and maintain inventories of spare parts and materials, visually/manually, to update records.

Exercise daily using onboard equipment during Cis-Lunar orbit operations.

- Deploy exercise device to maintain cardiovascular conditioning, muscle strength, and bone density.
- Configure exercise device and perform exercise to maintain cardiovascular conditioning, muscle strength, and bone density.

Assess displayed and aural information, cognitively, to determine appropriate course of action during Cis-Lunar orbit operations.

Identify Emergency Alarm (i.e., Loss of pressure, Fire, Toxic substance/emission) and develop repair/recovery plan.

Identify Caution/Warning Alarm (e.g., CO_2, ECLS, Navigation) and develop repair/recovery plan.

Respond to technical emergencies, following procedures and with equipment provided, during Cis-Lunar orbit operations.

Retreat to shielded area of Gateway/spacecraft with other members of the crew in response to critical radiation event warning.

Remain in shielded area of Gateway/spacecraft with other members of the crew during critical radiation event.

Respond to Gateway/spacecraft fire alarm.

Respond to Gateway/spacecraft micro-meteorite impact alarm.

Identify precise location of meteor penetration/hull breech, visually/aurally, assess severity/determine method(s) to stop loss of pressure.

Retrieve repair kit from storage and carry to location of meteor penetration or hull breech.

Apply patch and adhesive material to meteor penetration site, manually, to close leak.

Retrieve and don protective fire-fighting ensemble, manually, to prepare for fire emergency.

Remove fire extinguisher from bulkhead bracket and manually carry to source of fire.

Point fire extinguisher nozzle at burning material and activate system manually while wearing protective ensemble to suppress fire.

Respond to Gateway/spacecraft hull breech alarm.

Respond to Gateway/spacecraft toxic substance/outgassing alarm.

Respond to Gateway/spacecraft CO_2 alarm.

Respond to Gateway/spacecraft general ECLS failure alarm.

Respond to Gateway/spacecraft navigation alarm.

Perform medical tasks during Gateway operations.

Perform medical (including dental) diagnoses and evaluations, cognitively, during Cis-Lunar orbit operations.

Perform tests and examinations, physically, to support medical diagnoses during Cis-Lunar orbit operations.

Respond to medical emergencies, following procedures and with equipment provided, during Cis-Lunar orbit operations.

Administer medications during Cis-Lunar orbit operations.

Perform medical treatments during Cis-Lunar orbit operations.

Perform administrative functions during Cis-Lunar orbit operations.

Coordinate exercise device availability among crew to ensure access to maintain cardiovascular conditioning, muscle strength, and bone density.

Coordinate simulator availability among crew to ensure refresher training for all required skills and functions.

Coordinate crew response to meteor penetration, hull breech, fire, ECLS, or other emergency.

Monitor individual behavioral health by speaking with each crew member with the goal of identifying symptoms of maladjustment.

Schedule tasks/monitor performance of work to ensure opportunities and resources are allocated appropriately among crew personnel.

Plan operations (e.g., EVA, maintenance of external components) using computer-based records in consultation with MCC and onboard personnel.

Conduct science during Cis-Lunar orbit operations.

Assemble equipment needed to observe and record the Cis-Lunar phase of the mission.

Conduct astronomical observations, photography, and remote sensing to document experience.

Conduct and record life science experiments using onboard equipment and samples.

Conduct and record solar observations using onboard equipment and telescopes.
Conduct and record planetary and stellar observations using onboard equipment and telescopes.
Conduct and record radio astronomy observations using onboard equipment and telescopes.
Conduct and record Moon observations using onboard equipment and telescopes.
Conduct and record asteroid/comet observations using onboard equipment and telescopes.
Conduct and record Earth observations using onboard equipment and telescopes.

Conduct installation functions during Cis-Lunar orbit operations.

Enter control inputs, manually, to configure spacecraft computer to support training simulation and task preparation.
Deploy supports/structures, manually, to configure dedicated area of spacecraft for medical procedure.
Modify pressure suit to adjust length of torso segment in response to spine elongation in zero gravity.
Enter control inputs, manually, to load software patch/reload software.
Program/operate 3-D printer, manually via computer inputs, to fabricate a replacement part for a mechanical system onboard spacecraft.

Conduct maintenance functions during Cis-Lunar orbit operations.

Review schematics and other documentation, visually, to isolate electronic fault in spacecraft.
Review schematics and other documentation, visually, to isolate plumbing (e.g., cooling, CLSS) fault in spacecraft.
Insert test equipment probes in electronic components, manually, and observe displays, visually, to isolate electronic fault in spacecraft.
Inspect circuit board, visually, to identify short circuit or loose/missing connection in spacecraft.
Inspect circuit board, visually, to identify scorching that might indicate degraded/faulty/failed electronic component in spacecraft.
Review documentation/enter control inputs, visually/manually, to diagnose software problem.
Inspect plumbing (e.g., cooling, CLSS), visually and with hand tools, to identify source of plumbing fault in spacecraft.
Remove/replace plumbing component (e.g., section, valve), using hand tools and schematics, to restore system functionality in spacecraft.
Retrieve spare parts/materials (e.g., valve, duct tape) from storage and move to work site in spacecraft, manually, to prepare for troubleshooting/repair.
Cut pipe, manually using hand saw, to remove damaged section of spacecraft plumbing.
Insert new section of pipe and attach in place, manually, using electric soldering tool, flux, and solder to repair spacecraft plumbing.
Remove 1 meter of duct tape from roll, manually, to temporarily repair leaking hose/fitting.
Wrap 1 meter of duct tape around hydraulic hose/fitting, manually, to temporarily repair leak.
Replace electronic connector on wire/cable, manually, using hand tools and spare parts.

Conduct navigation functions during Cis-Lunar orbit operations.

Use sextant and star charts to estimate spacecraft position and course to compare to computerized navigation system.
Use sextant and star charts to estimate spacecraft position and course if computerized navigation system fails.
Convert results of manual navigation fix to propulsion changes necessary, using tables and other calculation references.

Conduct piloting functions during Cis-Lunar orbit operations.

Operate propulsion controls, manually, to maneuver Gateway to proper orbit.
Deploy and operate robot, remotely during CLO operations, to inspect external features of Gateway/spacecraft.
Deploy and operate robot, remotely during CLO operations, to repair external features of Gateway/spacecraft.

Monitor systems to ensure proper functioning during Cis-Lunar orbit operations.

Monitor system displays, visually, to verify normal functioning of *life support system.*

Monitor system displays, visually, to verify normal functioning of *navigation system.*

Monitor system displays, visually, to verify normal functioning of *propulsion/attitude control system.*

Monitor system displays, visually, to verify normal functioning of *communication system.*

Monitor radiation-detection systems, visually/aurally, for evidence of Solar Proton and Galactic Cosmic Ray Events (SPE/GCR).

Monitor spacecraft atmosphere, visually/manually, by checking displays and comparing values to reference documents.

Adjust systems to ensure proper functioning during Cis-Lunar orbit operations.

Adjust controls, manually per procedures, to maintain normal functioning of *life support system.*

Adjust controls, manually per procedures, to maintain normal functioning of *navigation system.*

Adjust controls, manually per procedures, to maintain normal functioning of *propulsion/attitude control system.*

Adjust controls, manually per procedures, to maintain normal functioning of *communication system.*

Conduct primary and refresher training to learn/preserve skills during Cis-Lunar orbit operations.

Review procedures for emergency mission abort (periodically during Cis-Lunar orbit).

Review emergency procedures for various possibilities (fire, micro-meteorite impact, hull breech, outgassing, ECLS failure, etc.).

Conduct (training) simulation using spacecraft computer to refresh piloting skills for return to Earth.

Conduct (training) simulation using spacecraft computer to refresh navigation skills for return to Earth.

Conduct (training) simulation using spacecraft computer to refresh communication skills for return to Earth.

Conduct primary training using digital media/spacecraft computer to learn information/skills that were not included in pre-mission training.

Read procedures and technical information to prepare for undocking and return to Earth.

Configure Cis-Lunar Modules to prepare for long duration dormancy.

Set up Comm/Nav system fault management to maintain scheduled frequency of commands issued from Earth to the vehicle(s) at a rate consistent with normal operations expectations during dormancy.

Set up Instrument, Engineering, and Science Telemetry to provide downlinks and video during dormancy.

Set up Vehicle Navigation, Location and Position orientation capability during dormancy.

Set up Internetworking through the standardization of LANs, WANs, and Internet Protocols (Vehicle to ground and vehicle to vehicle).

Set up ECLSS monitoring, autonomous recalibrations, preventative and corrective maintenance, on-orbit data analysis, and safing operations for dormancy.

Set up Fire Safety systems including continuous monitoring of system states, periodic circulation and monitoring of the cabin atmosphere.

Set up fire suppression system (fixed or robotic TBD) for dormancy.

Set up Propulsion monitoring of peassurant leakage, propellant leakage, propellent boil-off.

Configure health monitoring and checking of main propulsion prior to reactivation.

Set up continuous Structures system monitoring (diagnosis & prognosis) and evaluation of structural integrity, residual strength, and life critical elements.

Set up Thermal monitoring system for monitoring, preventative and corrective maintenance during dormancy.

Configure Robotic operations for monitoring, preventative and corrective maintenance of systems during dormancy.

Perform suit-related tasks to prepare for undocking.

Retrieve temporarily stowed helmet/gloves to prepare for descent.

Don suits/helmet/gloves to prepare for undocking.

Phase 7: Undocking from Gateway

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system prior to and during Earth Approach.

Receive final course-correction information from MCC to prepare for entering Orion, undocking, and skip trajectory.

Communicate status of systems during checkout and undocking of Orion.

Communicate status of systems from Orion during Earth Approach.

Monitor systems during undocking from Gateway module.

Monitor automatic firing of thrusters, visually, after undocking the Orion to achieve transit course to Earth.

Monitor displays, visually, during undocking and maneuvering Orion away from interplanetary ship to prepare for transit to Earth.

Monitor displays, visually using exterior video camera, to verify undocking of Orion.

Enter control inputs, manually/visually with gloved hand, to maneuver Orion during undocking from Gateway.

Adjust attitude control thrusters, manually wearing pressure suit/gloves, to undock Orion from Gateway module.

Adjust attitude control thrusters, manually wearing pressure suit/gloves, to maneuver Orion away from Gateway module.

Adjust controls, manually wearing pressure suit/gloves, to shut down attitude control thrusters and other systems after undocking from Gateway module.

Enter control inputs, manually wearing pressure suit/gloves, to activate thruster shut down if displays indicate failure of automated shut down, to ensure safing of Orion after undocking.

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system.

Receive final thrust and duration information from MCC to prepare for Earth transit maneuver.

Communicate status of systems during Gateway undocking maneuver to prepare for transit to Earth.

Communicate system status, verbally to crew members during Gateway undocking using internal communications equipment.

Communicate system status, verbally to MCC during Gateway undocking using external communications equipment.

Communicate successful undocking from Gateway, verbally and via text, to MCC using external communications equipment to confirm status.

Communicate systems shut down and safing to crew via internal communication system to advise of status.

Communicate systems shut down and safing to MCC via external communication systems to advise of status.

Monitor displays and verify configurations before and during undocking from Gateway module.

Observe crew position displays and activate controls, wearing pressure suit, to prepare for undocking.

Monitor audio communications and displays, wearing pressure suit/helmet, to prepare for undocking.

Monitor displays, visually while wearing pressure suit/helmet, to verify system configuration formats and eProc.

Monitor displays/communicate values, visually/verbally, to evaluate system and crew readiness for for undocking from Gateway.

Monitor engine performance displays, visually wearing pressure suit/helmet, to ensure proper functioning during undocking.

Monitor audio communications and displays, wearing pressure suit/helmet, during undocking.

Monitor displays, visually, to verify star tracker configuration/status.

Assess displayed information, cognitively, to determine readiness to undock from the Gateway module.

Evaluate displayed/communicated information, cognitively, to assess readiness for undocking and transit to Earth.

Evaluate alarms and displays, cognitively, to identify any mission-critical anomalies during undocking.

Phase 8: Transit to Earth

Monitor displays and verify configurations before and during Transit to Earth.

Observe crew position displays and activate controls, wearing pressure suit/gloves, to prepare for transit to Earth.

Monitor communications, aurally while wearing pressure suit/helmet, to prepare for transit to Earth.

Monitor displays, visually while wearing pressure suit/helmet, to prepare for transit to Earth.

Monitor communications, aurally wearing pressure suit/helmet, during departure burn from near Gateway in CLO.

Monitor displays, visually wearing pressure suit/helmet, during departure burn from near Gateway in CLO.

Assess displayed information, cognitively, to determine readiness for departure burn from near Gateway in CLO.

Evaluate alarms and displays, cognitively, to identify any mission-critical anomalies.

Adjust controls/attachments, manually with gloved hands, to configure suit and displays before, during, and after Transit to Earth.

Activate appropriate controls in response to alarms, manually wearing pressure suit/gloves, while communicating actions to crew and MCC.

Respond to communications and displays, wearing pressure suit, to prepare for transit to Earth.

Adjust controls as necessary, wearing pressure suit/gloves, during departure burn from CLO.

Activate controls, manually wearing pressure suit/gloves, to abort transit to Earth in response to evaluation data.

Activate controls, manually wearing pressure suit/gloves, to override automated systems/control spacecraft in response to evaluation data.

Perform suit-related tasks during Transit operations.

Doff pressure suit/helmet/gloves after undocking from Gateway.

Stow suit/helmet/gloves after undocking from Gateway.

Prepare/eat meal, manually, using Orion food hydration/heating equipment/galley during Transit to Earth.

Prepare meal for crew consumption, manually, using Orion food hydration/heating equipment during transit to Earth.

Eat/drink meal in Orion during transit to Earth.

Conduct communications checks and communicate observations/evaluations to other crew and MCC personnel, verbally using communications system during Transit to Earth.

Operate communications system, manually, to receive transmission from MCC.

Operate communications system, manually, to transmit message to MCC.

Speak with other members of the crew concerning technical and task-related topics.

Speak with other members of the crew concerning non-technical and non-task-related topics.

Perform interviews and Public Affairs Office (PAO) events, using communications system, to inform Earth public of progress.

Transmit data collected during the Transit to Earth to ground stations immediately following events.

Interact with crew mates, personally, concerning task performance.

Interact with crew mates, personally, concerning non-task-related matters.

Compose/record electronic/video journal, using keyboard/computer in spacecraft, to create/preserve personal account of experiences.

Conduct physical/cognitive tests in spacecraft to assess fitness for duty (automatically-scheduled/results transmitted to Earth).

Use space vehicle waste management systems for liquid/solid waste (i.e., toilet/bodily function) during Transit to Earth.

Use spacecraft waste management system for liquid waste (i.e., toilet/bodily function).

Use spacecraft waste management system for solid waste (i.e., toilet/bodily function).

Use space vehicle hygiene systems for cleaning during Transit to Earth.

Retrieve wet wipes, towel, and clothing to clean body after exercise in preparation for study and work-related tasks.

Remove personal garments from storage in preparation for changing clothes.

Doff (remove) soiled garments and don clean clothing.

Insert soiled garments in collection container to dispose.

Maintain spacecraft waste management systems during Transit to Earth.

Remove and replace bio collection container from waste management system, manually, to ensure continuity of operation.

Discard packaging waste in trash compactor, manually, to clear galley.

Operate trash compactor, manually, to increase space for additional packaging waste.

Remove compacted packaging waste from trash compactor, manually, and transport to onboard storage.

Insert new sanitary liner in trash compactor, manually, to prepare for additional use.

Prepare/eat meal, manually, using spacecraft food hydration/heating equipment during Transit to Earth.

Transfer food packages from deep storage to proximal storage, manually, to prepare for crew use.

Activate food hydration/heating equipment, manually, to prepare for crew use.

Prepare meal for crew consumption, manually, using spacecraft food hydration/heating equipment.

Eat meal together with other members of the crew.

Conduct recreational activities, individually and as a crew, during Transit to Earth.

Read articles, books, etc., during leisure periods for recreation.

Listen to music individually during leisure periods for recreation.

Listen to music individually while exercising for recreation.

Watch video (movies, TV programs, documentaries, etc.) individually while exercising for recreation.

Watch video (movies, TV programs, documentaries, etc.) individually during leisure periods for recreation.

Watch video (movies, TV programs, documentaries, etc.) together with other crew members during leisure periods for recreation.

Play chess and other board games together with other crew members during leisure periods for recreation.

Play chess with MCC personnel and others on Earth during leisure periods for recreation.

Sleep for approximately eight hours each 24-hour period during Transit to Earth.

Retrieve sleeping bag from storage to prepare for sleep period.

Enter secured sleeping bag and begin sleep period to restore cognitive/physical functioning.

Exercise daily using onboard equipment during Transit to Earth.

Deploy exercise device to maintain cardiovascular conditioning, muscle strength, and bone density.

Configure exercise device and perform exercise to maintain cardiovascular conditioning, muscle strength, and bone density.

Assess displayed and aural information, cognitively, to determine appropriate course of action during Transit to Earth.

Identify Emergency Alarm (i.e., Loss of pressure, Fire, Toxic substance/emission) and develop repair/recovery plan.

Identify Caution/Warning Alarm (e.g., CO2, ECLS, Navigation) and develop repair/recovery plan.

Respond to technical emergencies, following procedures and with equipment provided, during Transit to Earth.

Retreat to shielded area of spacecraft with other members of the crew in response to critical radiation event warning.

Remain in shielded area of spacecraft with other members of the crew during critical radiation event.

Respond to spacecraft fire alarm.

Respond to spacecraft micro-meteorite impact alarm.

Identify precise location of meteor penetration/hull breech, visually/aurally, assess severity, determine method(s) to stop loss of pressure.

Retrieve repair kit from storage and carry to location of meteor penetration or hull breech.

Apply patch and adhesive material to meteor penetration site, manually, to close leak.

Retrieve and don protective fire-fighting ensemble, manually, to prepare for fire emergency.

Remove fire extinguisher from bulkhead bracket and manually carry to source of fire.

Point fire extinguisher nozzle at burning material and activate system manually while wearing protective ensemble to suppress fire.

Respond to spacecraft hull breech alarm.

Respond to spacecraft toxic substance/outgassing alarm.

Respond to spacecraft CO2 alarm.

Respond to spacecraft general ECLS failure alarm.

Respond to spacecraft navigation alarm.

Perform medical tasks during Transit to Earth.

Perform medical (including dental) diagnoses and evaluations, cognitively, during Transit to Earth.

Perform tests and examinations, physically, to support medical diagnoses during Transit to Earth.

Respond to medical emergencies, following procedures and with equipment provided, during Transit to Earth.

Administer medications during Transit to Earth.

Perform medical treatments during Transit to Earth.

Perform administrative functions during Transit to Earth.

Coordinate exercise device availability among crew to ensure access to maintain cardiovascular conditioning, muscle strength, bone density.

Coordinate simulator availability among crew to ensure refresher training for all required skills and functions.

Coordinate crew response to meteor penetration, hull breech, fire, ECLS, or other emergency.

Monitor individual behavioral health by speaking with each crew member with the goal of identifying symptoms of maladjustment.

Schedule tasks/monitor performance of work to ensure opportunities and resources are allocated appropriately among crew personnel.

Plan operations (e.g., EVA, maintenance) using computer-based records in consultation with MCC and onboard personnel.

Conduct science and planning functions during Transit to Earth.

Conduct astronomical observations, photography, and remote sensing to document transit phase.

Conduct and record solar observations using onboard equipment and telescopes.

Conduct and record Earth observations using onboard equipment and telescopes.

Conduct maintenance functions during Transit to Earth.

Review schematics and other documentation, visually, to isolate electronic fault in spacecraft.

Review schematics and other documentation, visually, to isolate plumbing (e.g., cooling, CLSS) fault in spacecraft.

Insert test equipment probes in electronic components, manually, and observe displays, visually, to isolate electronic fault in spacecraft.

Inspect circuit board, visually, to identify short circuit or loose/missing connection in spacecraft.

Inspect circuit board, visually, to identify scorching that might indicate degraded/faulty/failed electronic component in spacecraft.

Review documentation/enter control inputs, visually/manually, to diagnose software problem.

Inspect plumbing (e.g., cooling, CLSS), visually and with hand tools, to identify source of plumbing fault in spacecraft.

Remove and replace plumbing component (e.g., section, valve), using hand tools/schematics, to restore system functionality in spacecraft.

Retrieve spare parts/materials (e.g., valve, duct tape) from storage and move to work site in spacecraft, manually, to prepare for troubleshooting/repare.

Remove 1 meter of duct tape from roll, manually, to temporarily repare leaking hose/fitting.

Wrap 1 meter of duct tape around hydraulic hose/fitting, manually, to temporarily repair leak.

Replace electronic connector on wire/cable, manually, using hand tools and spare parts.

Conduct navigation functions during Transit to Earth.

Use sextant and star charts to estimate spacecraft position and course to compare to computerized navigation system.

Use sextant and star charts to estimate spacecraft position and course if computerized navigation system fails.

Convert results of manual navigation fix to propulsion changes necessary to achieve MOI, using tables and other calculation references.

Conduct piloting functions during Transit to Earth.

Operate propulsion controls, manually, to maneuver spacecraft during transit to Earth.

Deploy and operate robot, remotely during transit to Earth, to inspect external features of spacecraft.

Deploy and operate robot, remotely during transit to Earth, to repair external features of spacecraft.

Monitor systems to ensure proper functioning during Transit to Earth.

Monitor system displays, visually, to verify normal functioning of *life support system.*

Monitor system displays, visually, to verify normal functioning of *navigation system.*

Monitor system displays, visually, to verify normal functioning of *propulsion/attitude control system.*

Monitor system displays, visually, to verify normal functioning of *communication system.*

Monitor radiation-detection systems, visually/aurally, for evidence of Solar Proton and Galactic Cosmic Ray Events (SPE/GCR).

Monitor spacecraft atmosphere, visually/manually, by checking displays and comparing values to reference documents.

Adjust systems to ensure proper functioning during Transit to Earth.

Adjust controls, manually per procedures, to maintain normal functioning of *life support system.*

Adjust controls, manually per procedures, to maintain normal functioning of *navigation system.*

Adjust controls, manually per procedures, to maintain normal functioning of *propulsion/attitude control system.*

Adjust propulsion/attitude control system controls, manually, to maintain proper course to return to Earth.

Adjust controls, manually per procedures, to maintain normal functioning of *communication system.*

Adjust spacecraft atmosphere, manually, by making computer input commands in response to displays and reference documents.

Conduct primary and refresher training to learn/preserve skills during Transit to Earth.

Review procedures for emergency mission abort (periodically during transit to Earth).

Review emergency procedures for various possibilities (fire, micro-meteorite impact, hull breech, outgassing, ECLS failure, etc.).

Conduct (training) simulation using spacecraft computer to refresh piloting skills for Earth Descent and Landing.

Conduct (training) simulation using spacecraft computer to refresh navigation skills for Earth Descent and Landing.

Conduct (training) simulation using spacecraft computer to refresh communication skills for Earth Descent and Landing.

Read procedures and technical information to prepare for Earth Descent and Landing.

Perform suit-related tasks during Transit to Earth to prepare for Descent.

Retrieve temporarily stowed helmet/gloves to prepare for descent.

Don helmet/gloves after launch to prepare for descent.

Phase 9: Earth Descent & Landing

Conduct communications checks/communicate observations/evaluations to other crew/MCC personnel during Earth Descent/Landing.

Receive final thrust and duration information from MCC to prepare for Earth Descent and Landing.

Communicate status of systems to MCC, verbally, immediately prior to Earth Descent and Landing.

Communicate system status, verbally to crew members using internal communications equipment, during Earth Descent and Landing.

Communicate system status, verbally in heavy buffeting, to MCC using external communications equipment, during Earth Descent/Landing.

Communicate successful touch down, verbally and via text, to MCC using external communications equipment to confirm status.

Communicate systems shut down and safing to crew via internal communication system to advise of status.

Communicate systems shut down and safing to MCC via external communication systems to advise of status.

Prepare for Earth Descent and Landing.

Don pressure suit, manually with the help of one other crew member, in preparation for Earth Descent and Landing.

Stow and secure all equipment, manually per load plan, to prepare Orion for Earth Descent and Landing.

Attach to individual crew maneuver position, while wearing pressure suit, in preparation for Earth Descent and Landing.

Assess crew members' physical and cognitive abilities, verbally using self-reports/established diagnostics, to determine readiness for Earth Descent/ Landing.

Inspect Orion, visually, to verify that systems are go for Earth Descent and Landing.

Monitor systems during Earth Descent and Landing.

Monitor automatic firing of Orion retro rockets, visually, for Earth Descent and Landing.

Monitor displays, visually in heavy buffeting, during Earth Descent and Landing.

Monitor displays, visually, for parachute/retro rocket to verify correct functioning at appropriate times during Earth Descent and Landing.

Monitor displays, visually during buffeted descent, to assess proximity and verify touch down on Earth surface.

Secure (other) flight systems, manually by control inputs, to ensure safing of Orion after touch down.

Monitor displays, visually, to verify system functionality.

Adjust system controls, manually during buffeted descent, in response to displayed information.

Enter control inputs, manually with gloved hand, to adjust Orion temperature.

Enter control inputs, manually with gloved hand, to adjust Orion lighting.

Enter control inputs, manually with gloved hand, to adjust Orion ECLS.

Perform piloting functions during Earth Descent and Landing.

Enter control inputs, manually with gloved hand, to configure Orion computers, for Earth Descent and Landing.

Enter control inputs, manually with gloved hand, to adjust Orion pitch and yaw during Earth Descent and Landing.

Enter control inputs, manually with gloved hand, to maneuver Orion during Earth Descent and Landing.

Enter control inputs, manually with gloved hand, to override automatic firing of retro rockets during Earth Descent and Landing if automated system fails.

Enter control inputs, manually with gloved hand, to adjust/override automatic systems in response to system displays, if necessary, during Earth Descent and Landing.

Adjust retro rocket controls, manually with gloved hand during buffeted descent, to maneuver Orion to correct landing location, if necessary.

Adjust controls, manually with gloved hand, to shut down retro rocket and other systems after touch down on Earth surface.

Verify automated engine shut down by visually monitoring displays to ensure safing of Orion after touch down.

Enter control inputs, manually with gloved hand, to activate engine shut down if displays indicate failure of automated shut down, to ensure safing of Orion.

Verify automated landing system shut down by visually monitoring displays to ensure safing of Orion after touch down.

Activate landing system shut down manually by control inputs if displays indicate failure of automated shut down, to ensure safing of Orion after touch down.

Perform post-Earth Descent and Landing functions.

Detach restraints and umbilicles from pressure suit, manually after landing, to prepare for egressing Orion.

Remove helmet, manually after landing, to prepare for egressing Orion.

Maneuver to hatch, manually while wearing pressure suit, to prepare for egressing Orion after landing.

Egress the Orion after landing.

Gateway Mission

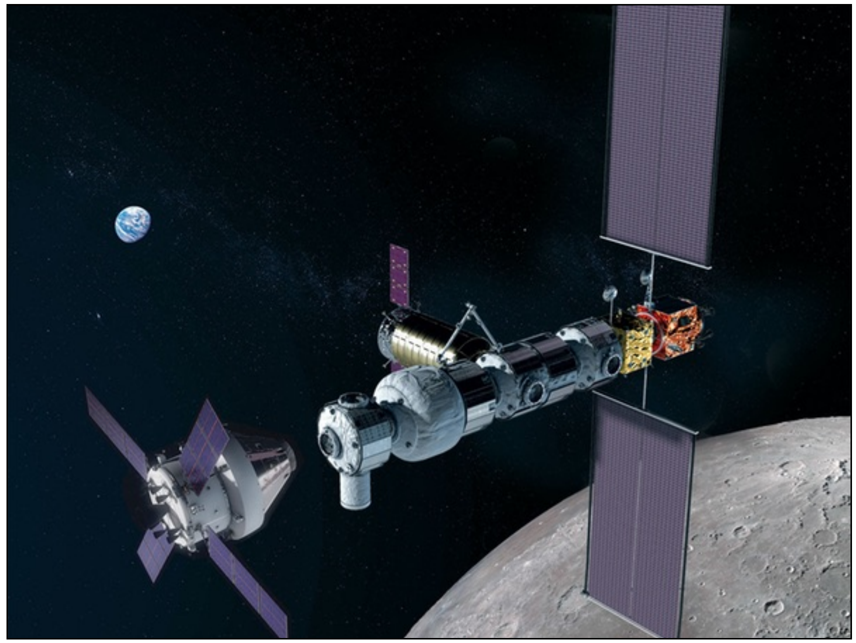
Summary Task Statements: 132

Tasks: 647

Phases: 9

GATEWAY MISSION ASSUMPTIONS

A crew of four astronauts will launch from Earth in an Orion vehicle. The crew will spend time in two Earth orbits (low and high) before continuing their journey to Cis-Lunar orbit, where they will dock to the Gateway module/habitat. Following approximately 30 days in Cis-Lunar orbit, the crew will use their Orion vehicle to return to Earth. During their mission, the crew is expected to perform robotic teleoperation and to operate in semi-autonomous conditions. An airlock for EVA during the Cis-Lunar orbit phase is expected. Prior to departing from the Cis-Lunar module/habitat, the crew will prepare it for dormancy. Health/medical capabilities are expected to be less than those for a Mars expedition, but are not yet defined.



Proposed Gateway with Orion approaching.

Appendix G: Subject Matter Experts Who Rated Tasks / Ranked Abilities

Alida Andrews
Erik Antonsen
Doug Archer
Ron Archer
Diana Arias

Mathias Basner
Tina Beard
Katerina Bezrukova
Richard Boetter
Lynn Boley
Grace Boothe
Jay Bucky
Eric Bunker

Holly Cagle
James Casler
Christian Castro
Leroy Chiao
Natacha Chough
Jon Clark
Toni Clark
Zail Coffman
Malcolm Cohen
Marc Cohen
Jan Connolly
Vince Cross

Pablo de Leon
Donna Dempsey
Anneliese DeVyldere
David Dinges
Jonathan Dory
Christine Dubbert
Chris Dunagan
Brandon Dunbar

Duane Eldridge
Rich Ellenberger
Elizabeth Erickson
Cindy Evans

Alan Fox
Jeremy Frank
Matt Frechette
Michelle Frieling

Steve Gonzalez
Terry Guess

Christopher Haas
Melinda Hailey
David Ham
Tanner Hamilton
Robert Hienz
Stephen Hoffman
Ulyana Nadia Horodyskyj
Forrest Horton
Kenneth Hudson
Emma Hwang

Rod Jones

Jeffrey Keaton
James Kelly
Kriss Kennedy
Elizabeth Klerman
Andrei Kolomenski

Lauren Landon
Arion Larsen
Karen Lawrence
Lauren Leveton
Ben Levine
Chuck Lewis
Robert Linton
Chip Litaker
Bill Lytle

Dan Masys
Sean McCloat
Jane McCourt
Dennis McDaniels
Chris McKay
Shannon Melton
Tina Melton
Jennifer Mindock
Brett Montoya
Richard Morency

Ashok Narayanamoorthi
Travis Nelson
Steve Norton

Bill Ogden
Kristine Ohnesorge
Sophie Orr
Cherie Oubre

James Patterini
Lynn Pickett
Noah Polek-Davis
Susannah Porter
Terry Price

Elizabeth Rampe
Terry Rector
Aaron Regberg
Royce Renfrew
David Reyes
Jen Rochlis
Pete Roma
Pierre Romo
Vadim Rygalov

Lynn Saile
Jason Schneiderman
Calvin Seaman
Mark Shelhamer
Marc Shepanek
Nick Shields
Shayan Shirshekar
Frank Spera
Alexander Stahn
Jerri Stephenson
Carol Stoker
Tiffany Swamer

Kamel Takla
Mark Taylor
Sherry Thaxton
Moriah Thompson
David Tomko
Tinh Trinh

Michelle Urbina
Debra Underwood

Edward Van Cise
Michael Van Wie
Terry Virts
James Voss

Samuel Wald
Antonius Widjokongko
Dafydd Williams
Thomas Williams
Daniel Wisniewski

Kelsey Young

Mars Seen from Demos Its Farther Moon, by Chesley Bonestell, 1956

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