
# Science Objectives for Human Exploration of Mars Workshop Report

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## Contents

# 1. Executive Summary

The Science Objectives for Human Exploration of Mars Workshop was held in Denver, Colorado on May 4–6, 2022. The workshop was co-sponsored by NASA's Science Mission Directorate and the Exploration Systems Development Mission Directorate to actively engage the planetary science community to determine what planetary science should be done by human crews on the martian surface and how those science objectives can be achieved.

Sessions at the Science Objectives for Human Exploration of Mars Workshop were organized around specific planetary science objectives and mission architecture concepts that were identified during the workshop as the highest priority for human exploration. The intent of this workshop was to synthesize a notional, integrated concept of operations for each scenario to aid in planning and refining the mission architecture for the first human mission to Mars. Results from the Planetary Decadal Survey Report were released xx days before the workshop and were briefed to workshop participants who incorporated the findings in the discussions.

With the Artemis missions, humans will return to the Moon using innovative technologies to explore the lunar surface. We will apply what we learn about exploration architecture, surface infrastructure, and science and exploration operations on and around the Moon to conduct successful missions with the first astronauts to Mars. A human mission to Mars will be a landmark achievement and a golden opportunity to make groundbreaking scientific discoveries on Mars. The potential scope of the science activities and impact of achieving those objectives are extraordinary.

## 1.1. Summary of Findings

- Past workshops and studies have shown that it is important that the science and exploration objectives of the mission should first be identified before key elements of the architecture (landing site, pre-placed robotic assets, crew facilities for surface operations, equipment, and tools) can be appropriately scoped, and both science objectives and architecture should be identified early on so that important development steps can begin. (2.3)

- In addition to a portfolio of common instruments and measurements that would be desired on any human mission, the workshop identified distinct "mission concepts" that are motivated by different sets of high priority science objectives. Each "mission concept" would require very different equipment on the surface and a different style of human and robotic operations. (3.0).
    1. Shallow drilling (<30 m) can be a powerful method to access material protected from the harsh radiation at the surface, and if there is

enough time available, the Technology may allow for multiple drill holes as well as sub-sampling drill cores for sample return (3.1).

2. Deep drilling missions (>30 m) require important precursor work to take place, for example by landed robotic assets, to identify subsurface structures and correctly locate drilling targets (3.2).
3. Mission concepts focused on surface sampling would address high-priority science questions and could be conducted over a wide range of different landing sites (3.3).
4. Atmospheric or geophysical investigations benefit from long-lived stationary equipment, and a human presence would greatly improve selection of deployment location and completion of deployment procedures (3.4).

- Strategically pre-positioned robotic assets can perform a variety of tasks that would enhance the overall science return of the mission, increase our knowledge of contamination of the landing site, and prepare for accommodating future landings (4.1).

- Significant science could be accomplished on a short stay (~30 sol) human mission, and pre-positioned robotic assets will be essential for accomplishing the science mission within the limited human surface mission duration. Robotic assets could serve important roles to ensure the human activities have the highest impact while crew is present on the surface. Pre-positioned robotic assets could also be used to accomplish tasks after the humans have departed (4.2).

- The augmented mass and power capabilities of a human mission allow for more robust and sophisticated robotic assets and equipment that can enhance science return by performing tasks before, during, and after the human mission at the surface (4.5).

- Four key capabilities for robotic assets identified during the workshop were reconnaissance, drilling, long-lived stationary measurements, and sample handling. All were seen as providing substantial benefit toward the science mission while also being technically achievable in the time frame under consideration (5.0).

- In order to effectively prepare for a human mission to Mars, it is of utmost importance to decide early on both the overall science mission concept and the associated architecture needed to achieve science objectives, so that important development steps can begin (6.0).

- Several key capabilities were identified throughout the workshop that would be particularly enabling to the science of human missions to Mars. These key capabilities include: 1) Long-lived surface power; 2) Mobility for crew; 3)

Communication for distributed surface assets; 4) Standard instrument packages; and 5) Technologies for robotic scouting, sampling, long-lived stationary science, and drilling (7.0).

# 2. Workshop Format

The Science Objectives for Human Exploration of Mars Workshop program included an opening plenary session with invited talks, including inspirational remarks from NASA Deputy Administrator Pam Melroy to set the stage for workshop discussions, and was live-streamed to virtual attendees. This opening session was followed by a series of breakout discussions, including a separate virtual-only group discussion to incorporate input from remote workshop participants. Summary reports from each breakout were presented to in-person attendees, and a final plenary discussion with in-person attendees to summarize key findings and next steps closed out the workshop. The workshop adjourned at 12:00 p.m. MDT on May 6.

## 2.1. Workshop Purpose and Goals

Community input and early integration of science into the exploration architectures for the first human missions to Mars are essential to maximizing the science return. The purpose of this workshop was to integrate high-priority science objectives to be addressed by crew on Mars with associated concepts of operations based on realistic human mission architecture scenarios. Furthermore, this workshop was intended to lay out the fundamental groundwork for future discussions of landing site selection. In order to achieve this purpose, the specific tasks of the workshop were to:

- Update and constrain science objectives for humans to address on Mars, to be documented in ESDMD-006 Mars Goal: “Enable science investigations on the surface of Mars, in Mars orbit, and in Mars transit”.
- Identify tools, instruments, and resources needed to address key science objectives.
- Provide early input into the development of future architecture work, to ensure that the chosen architecture enables the achievement of key science objectives for Mars.

## 2.2. Guiding Information to Frame Workshop Discussions

The scientific discoveries achievable by a human crew on the surface of Mars will depend on the basic parameters of the surface deployment architecture. These parameters include the landing site, reconnaissance conducted before arrival, equipment and facilities available for crew to use during

Table 1. Four human mission scenarios discussed during the workshop

| Notional Human Mission Scenarios |
| --- |
| Short-Stay Extra Extravehicular Activity (EVA): In this scenario, a crew of two lands on the surface for a ~30-sol (1 sol = 24.65 hours) surface mission. Science payloads delivered to |

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| the surface are nominally up to 2500 kg*. Up to 45 hours of EVA per crew member are available to conduct scientific investigations. Mass allocation for sample return is nominally 100 kg**. |
| Short-Stay Extra Robots: In this scenario, a crew of two lands on the surface for a ~30-sol surface mission. Science payloads delivered to the surface are nominally up to 2500 kg*, though additional robotic assets may be pre-deployed with sufficient justification. Only 20 hours of EVA per crew member are available to conduct science operations due to increased IVA time to operate robots. Due to limited EVA, science investigations proposed for this scenario should be appropriate for robotic/human-partnered activities. Mass allocation for sample return is nominally 100 kg**. |
| Long-Stay Long Mobility: In this scenario, a crew of four lands on the surface for up to a 300-sol surface mission. Science payloads delivered to the surface are nominally up to 1000 kg*. Multiple EVAs per week are available. Up to 20 hours of EVA time per crew member per week is possible, but the total EVA time for the surface mission will not exceed 400 hours per crew member. The primary living space in this scenario would be a small habitat and a pair of pressurized rovers. These rovers are capable of at least one 100-km traverse over the mission timeline. Mass allocation for sample return is nominally 100 kg**. |
| Long-Stay Fixed Hab: In this scenario, a crew of four lands on the surface for up to a 300-sol surface mission. Science payloads delivered are nominally up to 3000 kg*. Multiple EVAs per week are available. Up to 20 hours of EVA time per crew member per week is possible, but the total EVA time for the surface mission will not exceed 400 hours per crew member. A modest-sized fixed habitat will have space available for shirt-sleeve science investigations (this habitat-based science mass is included in the science allocation). Mass allocation for sample return is nominally 100 kg**. |

* Science allocation includes handheld instruments, rovers, robotic assets, drills, analytical instruments, etc.

** Mass allocation for sample return includes sample containers and any environmental conditioning (e.g., freezers).

surface operations (including robotic assets), and measurement stations that collect data over long durations after the crew departs. In order to appropriately scope these elements and determine how they fit within the overall mission architecture; the science objectives of the mission should first be identified.

Community reports such as the MEPAG Goals document (Appendix A) record the highest priority goals for science on Mars, but not all goals are a high priority for all human mission scenarios. A key goal of this workshop was to identify the highest priority science objectives for four realistic human mission scenarios (see below). These scenarios were derived before the workshop from various NASA Mars Architecture studies over the past 20 years and reflect endmembers that might support different science priorities and, in turn, drive different architecture solutions for achieving those science objectives.

This workshop discussed the highest priority science objectives achievable in these four scenarios of a first human mission to Mars and considered several possible concepts of operation that would enable that science.


Figure 1. Workshop Flow

## 2.3. Plenary Session

The plenary session set the stage for the discussions held in breakout sessions. Opening remarks made by NASA Deputy Administrator Pam Melroy identified science as one of three key pillars for exploration, alongside inspiration and national posture. This underscored the critical importance of defining key science objectives to create a framework for designing an exploration architecture capable of achieving mission success.

The rest of the plenary provided background information to help guide discussions and indicate NASA's intention to use the outputs of this workshop to help guide the definition of high-level objectives for human exploration of Mars, as described by Julie Robinson, as well as to guide upcoming design studies conducted by NASA's Mars Architecture Team, led by Michelle Rucker. Speakers described topics that should be considered in subsequent discussions, including expectations for how much time might be allocated to crew for utilization while on the surface of Mars (Figures 2 and 3 below), what activities crew might be expected to be capable of performing while on the surface (Jeff Somers), and planetary protection guidelines as they stood at the time of the workshop (Elaine Seasly).

Table 2: Workshop Opening Plenary Agenda

| Time (MDT) | Topic | Presenter |
|---|---|---|
| 10:00 a.m. | Opening Remarks | Debra Needham/Jake Bleacher |
| | NASA Moon to Mars Science Objectives | NASA Deputy Administrator Pam Melroy |
| | Overview of Human Exploration and Utilization Planning | Julie Robinson/Jake Bleacher |
| | Decadal Recommendations for Human Exploration at Mars | Jennifer Heldman/John Grunsfeld |
| | Mars Exploration | Michael Meyer |
| | Mars Architecture Overview | Michelle Rucker/Steve Hoffman |

| | | |
|---|---|---|
| | Crew Performance and Operations Considerations | Jeff Somers |
| | Planetary Protection Guidelines | Elaine Seasly |
| 12:00 p.m. | Q&A | |
| | Lunch Break | |
| 1:00 p.m. | Mars Science Objectives for Human Exploration: What's Been Done | Paul Niles |
| | Mars Science Objectives for Human Exploration: Update | Michael Mischna |

The plenary session then turned to a discussion of overarching, high priority science objectives that crew may be uniquely capable of addressing on the surface of Mars. Paul Niles gave an overview of what has been identified as priority science for human exploration of Mars in past workshops, including the Workshop on Science and the Human Exploration of Mars in 2001, Planning for the Scientific Exploration of Mars by Humans report by the Human Exploration of Mars Science Analysis Group in 2008, the Evolvable Mars Campaign 2016 – A Campaign Perspective, and the First Ice Cores from Mars report from the NASA Mars Ice Core Working Group in 2021. Michael Mischna

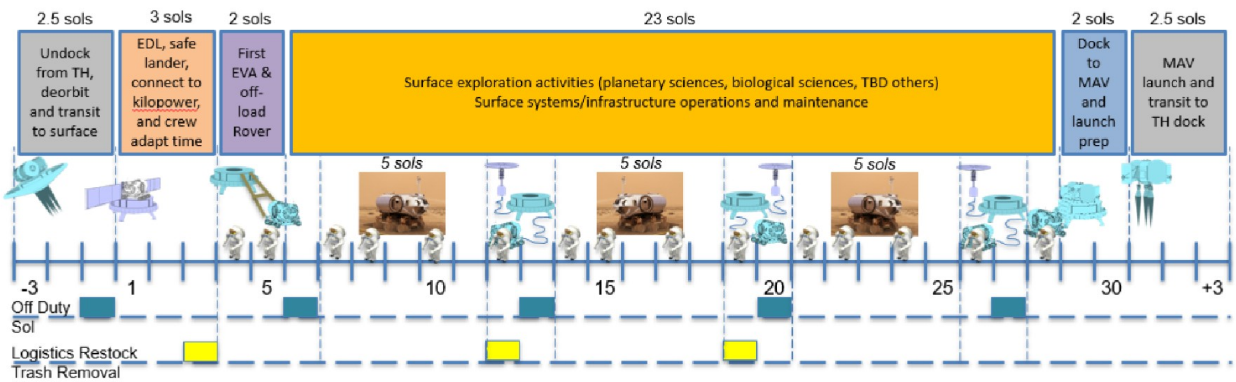


Figure 2: Notional daily surface schedule for a 30-sol Mars surface mission, from Figure 5.1-1 in HEOMD-415, Reference Surface Activities for Crewed Mars Mission Systems and Utilization, NASA Technical Report Document 20220000589 (Jan. 2022).

**Task Time Roll-Up (2 Crew)**

***Total Time on Surface: 30 sols (740 hours)***

*1,480 total crew-hrs*

| Category | Task | Task Hrs | Category Hrs |
|---|---|---|---|
| Mgr's Reserve | | | 39.7 |
| Utilization | *Local EVA Activities* | 17.3 | 263.8 |
| | *Field Exploration EVA* | 101.7 | |
| | *Traverse* | 36.3 | |
| | *IVA Activity* | 108.4 | |
| Morning/Evening Prep-Work | *Morning Prep-Work* | 15.7 | 51.2 |
| | *Evening Prep-Work* | 35.5 | |
| Conferences | *Private Medical Conf. (PMC)* | 15.2 | 51.3 |
| | *Weekly Planning Conf. (WPC)* | 6.7 | |
| | *Daily Planning Conf. (DPC)* | 29.5 | |
| Mission Overhead | *Housekeeping* | 24.0 | 129.7 |
| | *MAV Prep* | 30.2 | |
| | *Safe Lander* | 4.0 | |
| | *EVA Logistics* | 8.8 | |
| | *IVA Logistics* | 2.7 | |
| | *Suit Adjustment* | 16.7 | |
| | *Enter PR* | 16.7 | |
| | *Exit PR* | 25.7 | |
| | *EVA Prep* | 1.0 | |
| | *EVA Support* | - | |
| | *Enter Hab* | - | |
| | *Exit Hab* | - | |
| Off-Duty | | | 60.2 |
| Exercise | *Exercise-Short* | 30.0 | 101.4 |
| | *Exercise-Long* | 71.4 | |
| Personal Activities | *Private Family Conf. (PFC)* | 2.8 | 272.8 |
| | *Pre-Sleep (incl. Meal)* | 120.0 | |
| | *Post-Sleep (incl. Meal)* | 90.0 | |
| | *Midday Meal* | 60.0 | |
| Sleep | | | 510.0 |
| TOTAL Hours | | | 1,480.0 |

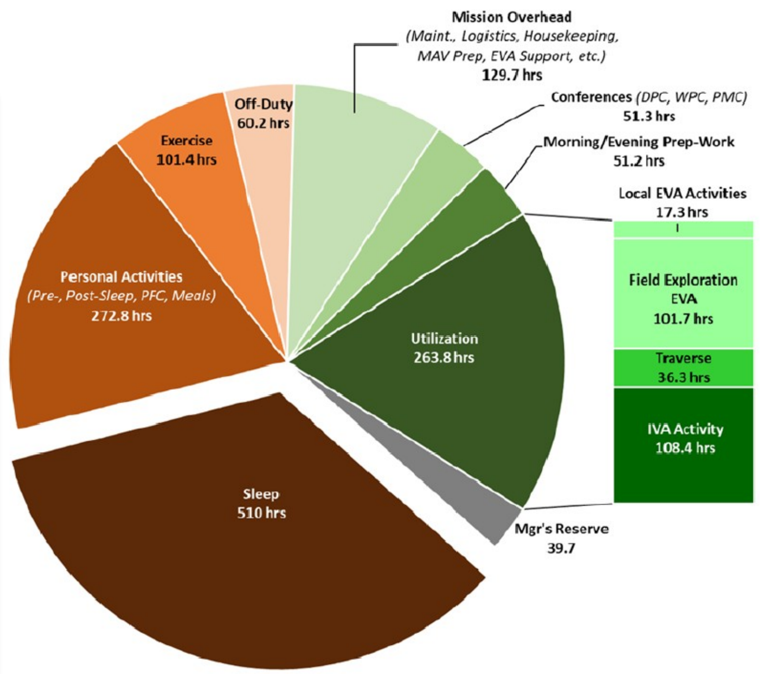


Figure 3: Summary of crew hours used during a notional 30-sol Mars surface mission, as described in Figure 5.7-1 in HEOMD-415, Reference Surface Activities for Crewed Mars Mission Systems and Utilization, NASA Technical Report Document 20220000589 (Jan. 2022).

then provided an update on the Mars Science Objectives for Human Exploration as discussed in the Mars Exploration Program Analysis Group meeting immediately preceding this workshop. This briefing identified the MEPAG highest priority Mars science objectives that could benefit from the involvement of human explorers (Appendix A).

| FINDING |
|---|
| Past workshops and studies have shown that it is important that the science and exploration objectives of the mission should first be identified before key elements of the architecture (landing site, pre-placed robotic assets, crew facilities for surface operations, equipment, and tools) can be appropriately scoped, and both science objectives and architecture should be identified early on so that important development steps can begin. |

The opening plenary closed with a discussion of what science themes should be used to organize the subsequent breakout discussions for the remainder of the workshop. Both in-person and virtual workshop attendees concurred with the themes summarized in Figure 4. These themes were used to organize and guide discussions in the first two breakout sessions of the workshop. There was discussion about why these themes were slightly different from MEPAG Goals document although it was agreed that no new science goals were being introduced. The slightly different organization of the themes in Figure 4 would be useful for structuring workshop discussions.

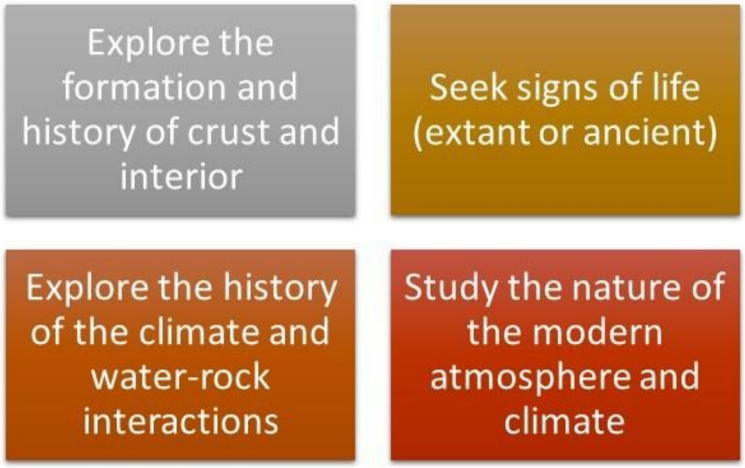


Figure 4. Science Themes used to organize first two breakout sessions

## 2.4. Breakout Sessions #1 and #2

The first two breakout sessions focused on how each science theme could be addressed by different types of human missions to Mars. They formulated ‘mission concepts’ which, for the purposes of this workshop, simply consisted of one or more high-level science objectives specific enough to call for a clear set of landing sites and science equipment. Breakout groups were asked to discuss the following questions for each concept: What are the science objectives and what is their significance? What measurements and equipment are needed? Which activities are most enabled by human presence?

Finally, the breakout sessions discussed how the proposed science investigations would or would not fit into each of the four human mission scenarios presented in Table 1.

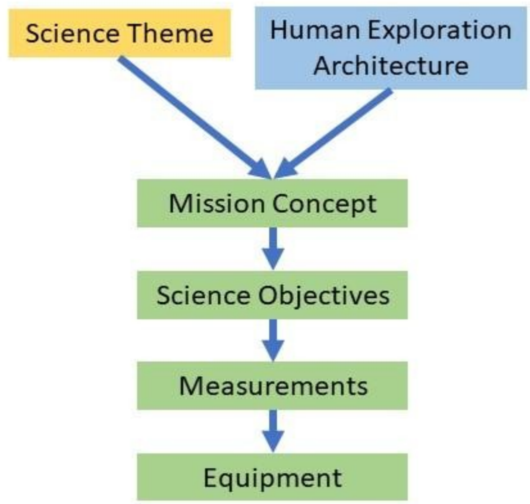


Figure 5. Topics discussed in Breakouts #1 and #2 for each Science Theme.

### 2.5. Breakout Session #3:

The last breakout session was organized according to the surface mission duration. One group focused on all the mission concepts developed for short-stay missions (<30 sols on the surface) and a second group worked on long stay mission concepts (> ~300 sols). The discussions focused on how well these mission durations were suited to accomplishing the high-priority science objectives identified for the mission concept. This included the amount of time needed to complete the essential tasks, the amount and type of EVA needed, and the quantity and type of robotic-human interaction.

| FINDING |
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| In addition to a portfolio of common instruments and measurements that would be desired on any human mission, the workshop identified distinct "mission concepts" that are motivated by different sets of high priority science objectives. Each "mission concept" would require very different equipment on the surface and a different style of human and robotic operations. |

## 3. Science Mission Concepts

Workshop participants in the first two breakout sessions developed a comprehensive list of different 'mission concepts' driven by high-priority science objectives that fall under the Science Themes outlined in Figure 4. These mission concepts frequently accommodated multiple high-priority objectives under more than one theme. It became convenient to organize these based on the overall type of mission and common activities that might occur. These overall groupings are listed in Table 3.

Table 3: Mission Concepts Identified during Workshop Breakout Sessions #1 and #2

| Mission Concept Types |
| --- |
| Shallow Drilling (< 30 m or multiple shorter holes) |
| Deep Drilling (>30 m) |
| Surface Sampling |
| Atmosphere and Geophysics |
| Rugged Terrain |

## 3.1. Shallow Drilling (<30 m or multiple smaller holes)

Shallow drilling was the most popular type of mission concept discussed at the workshop based on notes from the discussions (Table 4). The reason for this is that shallow drilling provides access to the next major scientific frontier, as much of the surface has now been mapped from orbit. Key questions surround the near-subsurface on Mars, where it is expected that materials have been largely protected from modification by surface exposure. The abundance of layered materials on Mars indicate that a shallow drill core could provide valuable insight into the geologic and climatic history of many different landing sites. The radiation and oxidizing environment of the martian surface makes sampling below this harsh environment an important capability for understanding many aspects of the geologic history of Mars. Human explorers and their more capable exploration systems would make shallow drilling operations more efficient and precise and, thus, this type of mission was a focus of the workshop.

| FINDING |
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| Shallow drilling (<30 m) can be a powerful method to access material protected from the harsh radiation at the surface, and if there is enough time available, the Technology may allow for multiple drill holes as well as sub-sampling drill cores for sample return. |

A shallow drilling mission could focus on a smaller, more mobile drill capable of drilling either one medium size hole or multiple smaller holes. In addition, core sampling is another very important capability indicated by this mission type as drill cores would be collected and then packaged to preserve important context and relationships. Another capability discussed in the workshop was onsite analysis of the drill core to enable sub-sampling or volatile analysis so that smaller pieces would be returned and difficult to contain volatile species can be characterized. This could be accomplished using downhole instruments as well as possibly analysis of cores and gases at the surface. One clear distinction was identified in these types of missions where ice is being targeted. Ice-focused missions will require additional equipment for environmental controls during sampling and analysis. Maintaining icy samples at low temperature is acknowledged as an enabler of high-priority science on any mission and targeting ice will require those capabilities. Furthermore, icy and other targets with astrobiological potential are likely to be complicated by planetary protection requirements which will also potentially require modifications to the equipment and procedures. The various shallow drilling concepts are described in Table 4.

Table 4: Shallow Drilling Mission Concepts Hays et. al, 2017 (astrobiology journal)

| Shallow Drilling Mission Concepts | Description |
|---|---|
| Shallow ice | Shallow ice (<10 m deep) is accessible in the latitudes available to a human mission and provides a high priority target for both astrobiology as well as climate history science objectives. Several different types of shallow ice were identified as targets including ground ice, excess ice, remnant glaciers, and polar ice. Furthermore, ice is an ISRU target for human exploration. |
| Salt Deposits | Salt deposits have been identified at various places on the martian surface and shallow drill cores of these deposits can provide key information regarding their formation mechanisms and the regional and global climate of Mars. Further, salts are also key targets for astrobiology as they are excellent biosignature preservation environments. |
| Lake Sediments | There are multiple crater lake deposits on Mars and shallow drilling can sample the materials that are not well exposed at the surface, including deeper material that may better preserve organics and potential biosignatures. |
| Layered Deposits | There are multiple instances of layered deposits on the martian surface, including crater mounds, interior layered deposits, and chaos terrain. Shallow drill cores would provide insight into their origin and history as well as access to potentially preserved astrobiologically-relevant material. |
| Hydrothermal Systems & Spring deposits | Shallow drilling of extinct hydrothermal systems on Mars provides another means for accomplishing high-priority astrobiological science as migrating subsurface hydrothermal fluids within these types of systems can provide habitable environments and preserve a variety of biosignatures. . |

## 3.2. Deep Drilling (>30 m)

There were a group of mission concepts that called for deeper drilling into the martian surface in order to achieve various high priority science objectives (Table 5). As cited in previous reports, deep drilling provides a vertical mobility rather than the horizontal mobility provided by rovers and similarly enables the sampling of a variety of different materials covering a range of geologic ages. These mission concepts would require substantial mass for a large drilling rig capable of drilling and sampling deep in the Mars subsurface. It is assumed that this rig would not be especially mobile and therefore landing site selection would be paramount as the drilling would have to be accomplished nearby. It was noted by workshop participants that our lack of knowledge of subsurface structures over much of the planet is a significant hurdle in being able to pick a landing site, and precursor measurements are a critical enabler for these types of missions. The various deep drilling mission concepts are summarized in Table 5. Similar to shallow drilling concepts, analysis of samples and volatiles on Mars is important due to the larger volume of material being accessed and the overall complexity of the science mission.

| FINDING |
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| Deep drilling missions require important precursor work to take place, for example by landed robotic assets, to identify subsurface structures and correctly locate drilling targets. |

Table 5: Deep Drilling Mission Concepts

| Deep Drilling Mission Concepts | Description |
|---|---|
| Hydrothermal/Serpentinized Crust | Deep crustal hydrothermal environments are a top target for potential habitable environments and sampling extant life (Carrier et al., 2020). Mission would primarily focus on chemical signatures of life and physical structures through borehole analysis and sample return. |
| Noachian-Hesperian Transition | Deep drilling allows for investigation and sampling of stratigraphy that records ancient climate transition protected from surface exposure and modification. Mission would focus on mineralogical, geochemical, organic, and structural analyses across key stratigraphic intervals. |
| Deep Buried Ice | Deep buried ice is being identified at many locations on Mars and at lower latitudes than previously expected. Sampling and analyzing this ice are key for understanding its history, origins, and |

| | |
|---|---|
| | extent. Ice also has an important role in human exploration as an ISRU target. |
| Oceans and Salts | Ancient marine sediments have been hypothesized to exist around the dichotomy boundary – deep drilling could confirm the existence of these sediments and characterize them for the first time. |

## 3.3. Surface Sampling

The second most popular mission concept type based on notes from the discussions can be described as focused on 'surface sampling' (Table 6). These types of missions require surface mobility and basic geologic fieldwork to map the terrain around the landing site and sample/analyze the materials to understand the local and/or regional geologic history. This mission is enabled by extensive previous mapping of Mars from orbit, which has demonstrated that many key layered sequences and other types of deposits are well exposed and accessible. This mission concept could include equipment such as unpressurized rovers, handheld instruments, robotic rovers, helicopters, and basic geologic tools to accomplish the scientific objectives. Furthermore, sampling and sample return is emphasized as a means for enabling terrestrial scientists to perform many more analyses after the conclusion of the mission similar to what has been done on the samples collected during the Apollo missions. The various surface sampling concepts are described in Table 6.

Table 6: Surface Sampling Mission Concepts

| Surface Sampling Mission Concepts | Description |
|---|---|
| Hydrothermal Field Traverse | Hydrothermal deposits at the surface provide important astrobiological and geological targets and a surface sampling campaign can be an effective means for exploring such sites. |
| Hesperian Ice-Magma | Investigation of regions on Mars that show evidence for magma/lava-ice interaction. This provides a potential habitable environment as well as being a location for both volatiles and deep crust investigations. |
| Outflow Channel Deposits | Dedicated mission to an outflow channel and its source region provides an investigation of an important geologic feature on Mars that likely featured long-lived subsurface water as a potential habitable environment. |
| Valley Network Explorer | Valley networks are an important piece of the Mars climate puzzle and understanding |

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|---|---|
| | their history and origins would be key for understanding the history of Mars. |
| Sulfate Deposits | Sulfate minerals have been investigated by multiple rover missions but their origins remain enigmatic. Sample return from layered sulfate deposits can help unlock Mars climate history. In addition, sulfates are potential ISRU targets and their composition and water content require a more comprehensive understanding. |
| Ancient Impact Sampling | Large impact craters on Mars provide an important resource for age dating as well as exposures of deep sections of the martian crust. A surface sampling mission targeting an ancient impact would enable high-priority geochronology science. |
| Megabreccia Explorer | Allows the investigation of the most ancient crust on Mars that could contain even older rocks, trapped gases, and other signatures of the nature of the early atmosphere. |

| FINDING |
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| Mission concepts focused on surface sampling would address high-priority science questions and could be conducted over a wide range of different landing sites. |

## 3.4. Atmosphere and Geophysics

Atmospheric and Geophysical investigations pursue high-priority science objectives that could be enabled by a human exploration mission to the surface of Mars. Many of these investigations could be accomplished as secondary objectives on other types of missions but the workshop participants thought it was important to discuss what missions would look like that are fully dedicated to these types of investigations.

Table 7: Atmosphere or Geophysics Mission Concepts

| Atmosphere or Geophysics Mission Concepts | Description |
|---|---|
| Dust Properties | Investigations of martian dust properties are important both scientifically and for exploration systems. Key questions about dust flux, wind, electrostatic properties, and column abundance are unanswered. A |

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|---|---|
| | series of ‘scarecrows’ placed across the surface could help understand dust and its behavior over time. Additional dust monitoring stations could help understand electrical and physical properties. |
| Martian Atmosphere Chemistry | Long-term monitoring of the martian atmosphere’s chemical composition isotopic properties, and surface-atmosphere interactions is key for understanding the modern and ancient martian climate. Monitoring stations would be placed in strategic locations to make long term measurements. |
| Radiation Monitoring at Depth | Radiation monitoring at the surface and in the subsurface is important for understanding Mars and the Sun. Human-enabled placement of radiation monitors could provide robust measurements over long periods. |
| Subsurface Sounding | Various geophysics techniques can be utilized to explore the near subsurface at a landing site. This would be strongly synergistic with a drilling mission – and could be used as a forerunner to a dedicated deep drill. Humans enable the operation and deployment of these instruments as well as their mobility across the surface. |
| History and Variability of Crustal Magnetic Fields | A mission to regions of Mars featuring ancient magnetized crustal materials could reveal an enormous amount about the early history of the planet and how it evolved. |
| Geophysical Network | A long lifetime geophysical network measuring heat flow, seismicity, and gravity would provide groundbreaking science and insight into the interior of Mars. |

Mission concepts that focus on atmospheric or geophysical investigations frequently require stationary units that must be long lived and may require complicated deployment procedures, but little active human involvement after the initial set up. The presence of humans enables these deployments, and the robust power infrastructure required by a human mission can be effectively utilized by long-lived measurement stations even after human departure. The concepts discussed for this category are summarized in Table 7.

| FINDING |
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| Atmospheric or geophysical investigations benefit from long-lived stationary equipment, and a human presence would greatly improve selection of deployment location and completion of deployment procedures. |

## 3.5. Rugged Terrain

The presence of humans at the surface enables the exploration of more rugged parts of Mars than could be accomplished via control from Earth. Short time delays and more capable exploration equipment allow for the use of robots that can access hard to reach spots on the martian surface. These mission concepts would require substantial human-robot interaction and cooperation where the presence of both astronauts and robust robotic explorers could synergize the exploration strategies. Mission concepts discussed for this are summarized in Table 8.

Table 8: Rugged Terrain Mission Concepts

| Rugged Terrain Mission Concepts | Description |
| --- | --- |
| Valles Marineris Cliff Explorer | Tethered robots and drones could be used to explore the cliff faces in Valles Marineris that expose a complicated geologic history documenting the growth of Tharsis. Samples collected by these robots can be analyzed and/or triaged for return to Earth by astronauts, who can also help reposition and repair the robots to enable long-term exploration. |
| Lava Tube Explorer | Tethered robots and drones could be used to explore lava tube caves. These are important targets for potential extant life on Mars and are potentially important for future human habitats. |

# 4. Human Mission Architecture Considerations

Any human mission to Mars will be divided into three phases: pre-crew arrival, crew presence, and post-crew departure. There are commonalities for the pre- and post-crew phases that will be very similar for all missions, but the tasks assigned to crew upon their arrival will depend greatly on the landing site, science objectives, and the mission architecture (i.e., what tools and equipment are available for crew use), with most important aspects dependent on whether the mission is short in duration (~30 sols on the surface) or long in duration (300 sols on the surface).

## 4.1. Pre-crew phase

Once pre-crew assets are deployed and their technical health is assessed, early objectives for relevant assets (e.g., rovers, drones) include scouting the site and using input from robotic observations to plan science traverses and activities for upcoming crew missions.  Assets that can be deployed in advance of crew include: power stations, weather towers, drilling systems, science and logistics rovers, tools, support systems, science packages, food, and other supplies as necessary to support the crew once they arrive. Specific assets deployed will depend on the mission type. Nonetheless, for all missions, key activities that could occur are shown in Table 9.

Table 9: Pre-crew Phase activities common to all missions to be done before crews leave Earth

| Activity | Reason |
|---|---|
| Basic surface/subsurface characterization, including physical and chemical properties and general geological/mineralogical/subsurface mapping of the landing site | 1) Physical properties aid in landing and mobility planning<br>2) Ground truth the geology and geography<br>3) Aids planning for equipment, instruments, and traverses. |
| Determine chemical contamination of the landing site from rocket plume and other landing activities and determine its extent | 1)  Identify pristine zones for science<br>2)  Identify landing zone for the crew |
| Look for evidence of Earth life at the site (nucleic acid search, ribosomal RNA search) | 1)  Monitor the pre-, during-, and post-mission presence of Earth life to help determine the degree of terrestrial contamination caused by a human mission and its lifetime on the surface.<br>2)  If Earth life is present before humans arrive then additional care must be taken during search for the presence of Mars life. |
| Look for evidence of extant Mars life at site | 1)  If Mars life is present near the landing site and easily discoverable – additional care must be taken for human mission planning. |
| Weather Monitoring | 1) Human landing safety<br>2) Extend baseline of weather monitoring for science return<br>3) Improved modeling of weathering during human mission |

Pre-positioned robotic assets can be used to identify and characterize where the crew will live and work, what sites they will investigate, and conduct preliminary investigations. The types of robotic capabilities positioned prior to crew arrival include simple landers for weathering monitoring and regolith physical properties, and rovers or helicopters that can be deployed to create detailed maps and investigate the site. Pre-crew arrival activities can include pre-positioning logistics assets like a power station or navigation beacons that would facilitate high-resolution site mapping, site navigation, and aid with guiding the crew vehicle during landing and while crew move about on the surface. Collecting samples and evaluating chemical and mineralogical properties could help with the identification of sites of interest for exploration with crew. Scouting activities could help locating sites for long-lived stationary assets such as weather stations or geophysical networks. Sub-surface scouting would provide information for drilling targets to ensure that drilling activities are successful when the crew arrives. Furthermore, in the event that there is a long interval between the arrival of pre-mission assets and the crew, robotic explorers may be able to conduct scientific investigations further from the landing site than possible once crew arrives, expanding the exploration range to features further afield than will be accessible by crew, especially for shorter duration (~30 sols) missions.

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| Strategically pre-positioned robotic assets can perform a variety of tasks that would enhance the overall science return of the mission, increase our knowledge of contamination of the landing site, and prepare for accommodating future landings. |

In addition to these logistics and science investigation tasks, pre-positioned robotic assets could greatly aid in astrobiological and planetary protection activities. Taking baseline measurements of terrestrial biomarkers is important for eventually characterizing the degree and extent of terrestrial contamination caused by the human mission. Robotic assets in place before the mission can perform important change monitoring to determine how much terrestrial contamination is being introduced by the human crew but also its lifetime on the surface. In the unlikely event that terrestrial biology is present before the crew arrives, it would be important to know this for science planning.

The search for martian life (both extant and past) will no doubt be a major focus of the human mission and workshop participants identified several important factors that must be considered. Presumably a human landing site will be chosen that has a low likelihood of having extant martian life nearby. This likelihood would be determined using data gathered by all of the martian landers since Viking. Ensuring that this likelihood is indeed low is a very important consideration and could be further verified by pre-positioned robotic assets. These assets could also provide ground-truth for the orbital assessments of the landing site and identify any unexpected chemical or mineralogical signatures that might complicate astrobiological investigations.

## 4.2. Short Stay (30-Sol) Crewed Phase

### 4.2.1. Examples of science mission objectives achievable within 30-sol mission

Multiple mission concepts were identified that could fit within a ~30-sol mission timeline. The mission concepts were categorized by how the science would be accomplished because this informed other mission requirements such as the role of robotic assets pre- and post-mission to maximize the utility of the ~30 sols of human presence. The mission concepts were split into four primary categories: scientific questions best answered with drilling (<30 m total drill depth potentially split across multiple drill sites), surface exploration (outcrop science and sample collection), atmospheric measurements, and geophysics. To a large degree, the atmospheric and geophysical investigations are site agnostic, meaning they can be accomplished almost anywhere on the surface of Mars with the primary desire being emplacement of surface assets in appropriate locations with sufficient distance between sites. The 30-sol mission restricts the total distance that can be traveled by crew, requiring a tradeoff between distance between science stations and other science that can be accomplished, though even limited mobility for crew would greatly enhance science return. But these two investigations can be paired with essentially any drilling/surface exploration-focused objective.

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| Significant science could be accomplished on a short stay (~30 sol) human mission, and pre-positioned robotic assets will be essential for accomplishing the science mission within the limited human surface duration. Robotic assets could serve important roles to ensure the human activities have the highest impact while crew is present on the surface. Pre-positioned robotic assets could also be used to accomplish tasks after the humans have departed. |

For drilling, potential science goals include drilling into ice, salt, or hydrothermal deposits to seek signs of extinct or extant life. Shallow drilling into a sedimentary sequence can access layers not exposed in outcrop (Table 4). For surface science, mission concepts include investigating Hesperian ice-magma interactions, sampling throughout an outflow channel, or exploring mega breccia, the oldest exposed rocks on Mars (Table 6). Many surface science and drill concepts are complementary, such as exploring a sedimentary sequence across a climate boundary, that could be done in both mission concepts if an appropriate landing site is selected.

Given the expected constraints on crew EVA/IVA (Intra-Vehicular Activity) time, more study is required to determine how many of these four different categories could be accomplished on any given mission. A large number of potential scientific questions were identified as addressable within a ~30-sol mission (Appendix A), with the understanding that the actual mission would likely focus on one question as the primary mission objective, with a plan to reserve a portion of EVA time to deploy atmospheric/geophysical stations that can continue collecting data long after the crew has departed.

For many of the science investigations considered for the ~30-sol mission concepts, landing at a previously explored site (e.g. Jezero or Gale craters) or a subsequent return to the same initial site would enable more in-depth investigation that would return important science results beyond what has already been discovered by the rovers.

#### 4.2.2. Robotic vs. Human Roles

On short-stay missions, the robotic assets must be pre-placed far enough ahead of the crew to allow sufficient time to complete any critical tasks necessary to lower the risk posed by the short surface duration. These activities could include many of those listed in Table 9. For surface drilling missions, it would be highly valuable to have the robotic assets identify drilling targets and prepare drilling equipment before crew arrival so that science efficiency is maximized during the crew time spent on Mars.

While crew are on the surface, robotic activities could include basic surveying and imaging, astrobiological investigations at contamination-sensitive sites, and sample collection and retrieval. Crew activities could include assessing geologic context and conducting field mapping during EVA traverses, sample selection/prioritization activities, finalizing drill rig deployment and operation, deployment of specialized equipment and sensors that could not be fully deployed robotically (e.g., atmospheric or geophysical stations), and performing basic repairs or resupply of key equipment or instruments that could not be performed robotically.

### 4.3. Long-Stay, Surface Habitat

#### 4.3.1. Examples of science mission objectives achievable within 300-sol mission

A Deep Drilling Mission (>30 m) could best be accomplished within a 300-sol timeline using the Long-Stay Surface Habitat architecture. This mission could be focused on drilling into any one of many different scientifically important sites (e.g., water ice, hydrothermal systems, sedimentology across major transitions, etc.), but would require large pre-placed equipment and needs to allow crew time for troubleshooting problems and examination of drill cores. Deep drilling fits a mission architecture focused on a long-term stay at a single location. The cores from this drilling effort could be analyzed by the human crew on the surface, using the results to guide further drilling and to down-select the best samples for return to Earth. The boreholes themselves could be investigated using tethered robotics and would enable the installation of geophysical instruments (e.g., heat probes, seismometers, etc.) with direct contact to bedrock. This mission architecture would also allow other high-priority science investigations to be conducted simultaneously (e.g., installation and maintenance of atmospheric monitoring stations). The geophysical, atmospheric, and other scientific packages would continue to send data long after the human crew departs due to their close proximity to the power source. Robotic exploration would also continue after the crew has departed. A key objective would be to monitor the spread and lifetime of any chemical or biological contamination caused by the human mission.

### 4.3.2. Robotic vs human roles

For the long-stay mission architectures, the roles of humans and robots are significantly intertwined. The human crew would be primarily responsible for qualitative, real-time decision making and science analysis, while the robotics would be focused on quantitatively enhancing and/or extending the capabilities of the human crew. The core features of the human and robotic roles were the same for all the science mission concepts considered.

Landing site reconnaissance tasks (i.e., hyperspectral imaging, preliminary life detection efforts, etc.) would be mostly delegated to robotic systems, which could be autonomous, operated remotely from Earth, or operated tele-robotically by the human crew. The engineering assessments, geologic interpretations, and selection of scientific samples based on the reconnaissance data would primarily be the responsibility of the human crew. Sample handling and analysis tasks, particularly those involving life detection or contamination assessment, would rely on IVA crew operating tele-robotic analytical assets to reduce the possibility of biological contamination. And finally, robotic systems would provide physical assistance to the human crew, allowing them to explore further, analyze sites longer, and carry larger sample masses than they would be able to on their own.

In some of the more specialized science mission concepts, additional human and/or robotic roles would be required. For example, many science concepts require drilling to significant depths, so the human crew would be required for operating and troubleshooting drilling equipment and operations, which would be much more difficult for robotic systems to do autonomously. In the mission concepts involving ice drilling, the human crew would also be required for real-time analysis of samples that contain volatiles and may have important ephemeral properties that must be observed and analyzed in-situ. For atmospheric-focused mission concepts, humans would enable the assembly and emplacement of atmospheric measurement towers, using the increased down-mass and efficiency of a crewed mission versus what could be done robotically. And finally, in the case of cave exploration, specialized robotics would be required because the operating conditions would be considerably different than other mission concepts (e.g., reduced solar power, three-dimensional navigation, and obstacle avoidance).

## 4.4. Long-Stay, Enhanced Mobility

### 4.4.1. Examples of science mission objectives achievable within 300-sol mission

A Geologic Profiling Mission could be accomplished within a 300-sol timeline using the Long-Stay Enhanced Mobility architecture. This mission could be focused on conducting horizontal profiling across any one of many scientifically important regions (e.g., dichotomy boundary, Noachian-Hesperian transition, outflow channels, potential shorelines), but would require studying the geology and geophysics of the surface across such large features, making it ideal for a mission architecture focused on extended mobility. Networks of geophysical instruments (e.g., seismometers and heat probes) could be deployed across large geographical baselines, with ground penetrating radar studies being conducted continuously along the traverse. Enhanced mobility also allows access to a greater portion of the regional stratigraphy by planning a traverse over a significant change in elevation. This mission architecture could make it more difficult to conduct other high-priority science investigations (e.g., construction of atmospheric monitoring towers), since mission prioritizations would likely favor additional traverse distance over additional time at individual locations. The science packages left behind along the traverse would need reliable independent power sources, since it would not be possible to physically connect them to the base power source. Finally, it should be clarified whether such a mission architecture would require departing from the initial landing location, since profiling across certain regions could be aided or hindered by such a requirement.

### 4.4.2. Robotic vs human roles

The human and robotic roles are essentially the same for all long-stay mission concepts. For enhanced mobility missions, the pre-arrival site reconnaissance has to be extended to cover the expected traverse paths as well as alternate paths. For enhanced mobility missions, any robotics left behind during the traverse would require additional levels of autonomy for their operation. Additional emphasis would also be placed on the robotic systems to physically assist the human crew, since larger sample masses, instrument masses, etc. would need to be mobile.

## 4.5. Post-crew measurements, investigations (All Missions)

All the mission concepts considered had very consistent post-mission requirements, particularly in the case that a significant power source would remain behind to power science instrumentation. A good science outcome is to establish long-lived scientific payloads that operate well beyond the human mission paying dividends on the large investment made in their deployment onto the martian surface. Observations with weather stations over multiple seasonal cycles can distinguish long-term climactic properties from year-to-year variations in weather. Most, if not all, the mission concepts included either drilling or trenching near the landing site, to facilitate science and temperature measurements at multiple depths that characterize the thermal profile of the regolith and measure the heat flux through the crust. Monitoring the thermal profile over long time periods improves the measurements since near-surface temperatures are sensitive to changes in the surface albedo due to landings and other mission activities, as seen in Apollo-era data.  A bore hole would facilitate such thermal measurements at different depths and allow other science objectives to be addressed, such as monitoring radiation and measurements of the lifetime of organic molecules under martian surface conditions. Monitoring a bore hole for gases and organic compounds in a bore hole over multiple seasons and years could help constrain subsurface fluxes. Additionally, passive seismic investigations require observations over long timescales, as signals from many events, which may occur sporadically from multiple locations, improve understanding of subsurface structure and lend insight into whether there are any seasonal or locational trends in seismic activity.

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| The augmented mass and power capabilities of a human mission allow for more robust and sophisticated robotic assets and equipment that can enhance science return by performing tasks before, during, and after the human mission at the surface (4.5). |

Finally, Mars life-detection experiments could benefit from long baseline measurements, possibly observing biomarkers or evidence of biologic activity that might be difficult detect during the limited duration of a human surface mission.

Post crew science for human mission architectures that employ mobile habitats might be impacted by the lack of a centralized power source that would endure for long periods after the conclusion of the human mission. In addition, science instrumentation could be deployed over much greater distances and most packages would not have access to the power source after the crew departs. This might be a potential drawback for this type of architecture with regard to long term science return.

# 5. Technology Issues and Constraints

This section focuses on robotic technology to support human missions to Mars. Given that the Mars architecture includes uncrewed cargo landings that would arrive before humans, as well as assets that could continue to operate after humans leave, the workshop recognized that three timeframes are relevant:

1. What instrumentation and robotic systems, delivered via pre-crew uncrewed cargo landings, are needed to address science objectives before humans arrive?
2. How can robotic systems help maximize crew productivity while humans are there?

3. What can robotic systems accomplish after the crew leaves, potentially over the course of multi-year operations?

Three broad classes of robotic system capability were discussed, with varying potential roles in the three timeframes above: reconnaissance, drilling, and sample handling/analysis. The following subsections discuss how these capabilities could contribute to each of the timeframes listed above.

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| Four key capabilities for robotic assets identified during the workshop were reconnaissance, drilling, long-lived stationary measurements, and sample handling. All were seen as providing substantial benefit toward the science mission while also being technically achievable in the time frame under consideration. |

## 5.1. Reconnaissance

### 5.1.1. Pre-crew

Robotic mobility systems could conduct high-resolution surveys to assist in planning potential crew EVA objectives and travel routes prior to crew arrival. Aerial mobility systems are now under development (Bapst et al. 2021) that have goals of being able to carry up to ~ 5 kg of scientific instruments and fly ranges > 100 km/Earth year, with a total system mass < 40 kg. Very lightweight instruments that already exist or are under development for such aircraft include:

- Cameras that enable high-resolution terrain mapping, with spatial scales varying from meters to millimeters per pixel (mass: a few to a few hundred grams).
- Hyperspectral point and imaging spectrometers in wavelengths from visible to thermal infrared (mass: 2 to 3 kg).
- Elemental composition via either an Alpha Particle X-Ray Spectrometer (APXS) or a miniaturized, short-range Laser Induced Breakdown Spectrometer (LIBS) (mass < 3 kg).
- Ground penetrating radar with penetration depth of a few 10’s of meters in basalt, or more in ice, and a vertical resolution of a few 10’s of cm (mass ~ 1 kg).
- A scoop for capturing regolith samples and/or rocks (mass ~ 1 kg).
- A small coring drill with penetration depth of a few centimeters (mass ~ 1 kg).

Such aircraft are enabled by work in progress in highly miniaturized, lightweight, high-performance onboard computing architectures, navigation sensors, batteries, and UHF radios for relay communication to orbit.

Relevant surface mobility systems include free-ranging rovers and tethered rovers capable of rappelling down steep slopes. Recent progress in high-performance mobility actuators and plausible advances in avionics miniaturization, similar to that underway for aerial mobility, could enable 100 to 200 kg rovers to traverse > 100 km between delivery with a cargo lander and crew arrival. Such rovers could carry more payload than an aerial mobility system, including an arm to place instruments against inclined surfaces and/or a more capable drilling/sampling system. At a suitable landing site, a tethered rover or an aerial mobility system could explore along a steep slope prior to crew arrival, potentially including the acquisition of samples, at distances beyond crew range from the landing site.

### 5.1.2. Crewed Period

Robotic reconnaissance could also be useful while the crew is present, though utility of such information would be more broadly useful for a 300-sol duration mission as compared to a ~30-sol duration mission, in which case the pre-crew reconnaissance would be far more important for optimizing crew efficiency while on the surface. Nevertheless, the ability of humans on-site to perceive the large-scale context may enable better targeting of robotic reconnaissance excursions. These might be operated by the crew in orbit while the crew on the surface is otherwise occupied. Robotic vehicles that could also acquire samples from locations inaccessible to the crew might be particularly valuable, and benefit from the combined context assessment capability of the crew and instruments on robotic vehicles.

Crew would also benefit from using highly dexterous analytical equipment that could be operated tele-robotically from within a pressurized facility to analyze ice cores and geologic samples. This capability would mitigate risks of contamination, both of the sample from exposure to the pressurized environment of the habitat and of the crew from exposure to unknown substances in the martian samples. This analytical equipment would be akin to surgical equipment on Earth, with manipulator mechanisms that conduct highly precise operations on small scales and would require integrated cameras and communications capabilities to enable crew to monitor and manipulate the device in real time.

### 5.1.3. Post-crew

Missions to date have shown that robotic mobility systems can successfully operate on the surface of Mars for many years. Coupled with potential advances in the traverse range of robotic mobility systems as discussed earlier, this raises significant possibilities for robotic scientific exploration of the region far beyond reach of the crew after the crew departs. A long-duration robotic mobility system might be designed to make use of sophisticated instruments and the power system left behind by the crew if the robotic systems are designed to return samples to those instruments for automated analysis without the crew present. Post-crew operations of pre-placed assets would maximize the return on investment and enable significant scientific discoveries across the surface of Mars.

## 5.2. Drilling

The very limited crew EVA time available in a short-stay mission implies that as much preparation as possible should be done before the crew arrives, allowing crew time to be focused on activities that cannot be done robotically in advance. These preparation activities could include scouting including subsurface sounding to identify drill targets, deployment of drilling equipment, testing drill function, collecting surface samples. Upon arrival, crew activities could include managing drilling activities, selecting samples for return, packaging previously acquired samples for the return trip, and setting up drilling/sampling equipment that will operate after the crew leaves. Specifics of drilling/sampling equipment needed will depend on science objectives of the mission; this section outlines possibilities to inform further planning and sketches options for employment of this equipment in the three timeframes (pre-/with-/post-crew).

Drilling capabilities developed to date and in development now fall into the following categories, discriminated by depth of penetration:

- <u>Centimeters:</u> rotary-percussive core drills have been flown on rovers that capture cores approximately 1 cm in diameter and 6 cm long. Miniaturized versions of such drills for acquiring slightly smaller cores have mass of ~ 1 kg and may be appropriate for employment on sufficiently heavy rotorcraft.
- <u>A few meters</u>: several single segment and multi-segment drills have been developed for penetration depths of 1 to 2 meters, and slightly deeper depths are conceivable with multi-stem drills. As demonstrated by the Rosalind Franklin rover and lunar rovers in development, such drills can be integrated into rovers that have masses of a few hundred kilograms.
- <u>Up to 10 meters</u>: at this depth, multi-segment drills may become impractical, but coiled tubing drills such as RedWater are a possibility (Zacny et al. 2019), which deploy coiled tubing to line the borehole behind the drill head. Drilling to 10 m and analyzing samples would be a lengthy undertaking (months) and as such, the mission would be more suited for the long-duration, limited mobility mission scenario.
- <u>>10 meters</u>: multiple approaches to wireline drilling are being developed to reach greater depths with much more modest mass than possible with the methods above. The WATSON wireline drill (Eshelman et al. 2019) has already been prototyped and tested to 111 m depth in contexts like drilling in ice, where the risk of borehole collapse is very low. Deep wireline drilling in rock is also under development, but is at lower TRL and faces more challenges. Alternatively, larger coiled tubing drill could be implemented (coiled tubing is used to drill thousands of feet below the ground on Earth). Since a deep drilling mission would take months to years, they are best fit for the long-duration, limited mobility mission scenario.

### 5.2.1. Pre-crew

Drilling centimeters or a few meters via robotic systems is possible with current technology before the crew arrives. Advances in mobility systems, as discussed earlier, could enable such drilling systems to be carried many kilometers from the landing site before crew arrival. To return drilled samples to the base station, the rover could drive back, or the crew could retrieve the samples from the rover, or the rover could be paired with a helicopter that transports samples back to a base station.

Drilling deeper than a few meters before the crew arrives would be attractive. This is conceivable with a coiled tubing drill and may be possible with a wireline drill. Work is required to characterize the current status and maturation roadmap for these methods and their development depends greatly on early decisions being made on which mission concept will be pursued. With the possibility of having several years of operation before the crew arrives, this could allow obtaining samples that could be analyzed by the crew or returned to Earth.

### 5.2.2. With-crew

In addition to retrieving and packaging samples that were acquired before crew arrival, the crew could operate a variety of relatively shallow drilling/sampling devices themselves, in a similar manner to Apollo. There may be scenarios where choosing the exact deployment site for a drill would benefit from crew presence. In this case, a meter-class drill could be deployed by the crew from the crew rover and left in place for a few sols to acquire samples from a few meters of depth. Drilling on the order of 10 meters depth while the crew is present appears to be feasible but more study is required to better understand the time and power requirements of this activity especially if sampling occurs in parallel.

For long-stay missions, drilling to 10s or even 100s of meters with a wireline drill or some hybrid variant that limits downhole mass is an interesting prospect. Alternatively, such drills might be possible as a leave-behind operation for the post-crew phase (see below).

### 5.2.3. Post-crew

The greatest potential benefits for continued operation after the crew departs may lie in the following possibilities:

- Operating relatively shallow drills (centimeter, meter, or 10-meter class) on robotic mobility systems over larger areas, using instrumentation for sample analysis at the base station which is set up with the aid of the crew.
- Much deeper drilling at one or a small number of sites, where the crew participates in setting up the drill(s), initiating drilling, and troubleshooting operations in the early stages of drilling. Crew could also deploy analytical instruments that could take measurements while drilling.

## 5.3. Sample Handling/Analysis

Sample handling begins upon the removal of the sample from its natural environment, and involves transporting, processing, and delivering samples to instrumentation for analysis or preparing them for return to Earth. The sequence of this process depends on the type of sample and on the sample handling technology in use (i.e. in some cases the transporting and processing of the sample may occur coincidentally). Sample processing may involve crushing or cutting a sample, sieving, or isolating particle sizes, heating the sample, or initiating chemical reactions, as required prior to delivery to the instrumentation.

Various techniques can be used depending on the sampling tool and instrument suite. Sample handling technologies are also used to package samples that would be returned with the astronauts. For returned samples, they are likely to be hermetically sealed in individual sample containers. Samples for in-situ analysis or return need to be carefully selected from potentially large volumes of sampled material. Crew provides excellent capabilities in sample selection although new autonomy technologies could help in identifying the most promising samples for analysis or return.

### 5.3.1. Pre-crew

Sample handling and analysis technologies could provide scientific information about the samples, identify areas of interest for exploration when the crew arrives, and assist in selection of desirable samples for return to Earth. Technologies that provide context about where samples are collected from including imaging and remote sensing are key to helping determine scientific value of samples. In addition, measurements of their chemical, mineralogical, and organic properties help further narrow down which samples would provide the greatest impact upon return to Earth. A key example of this would be the Perseverance rover which has performed both scouting and sample collection that could be paired easily with a human mission (Farley et al. 2020).

With guidance from Earth-based operators, samples intended for analysis on Earth could be acquired and packaged for return.  Pre-packaging samples prior to crew arrival could be beneficial to ensure a set of samples free from potential human exposure.

### 5.3.2. With-crew

Crew could acquire samples both by directing robotic systems to acquire the samples and by acquiring them through direct manipulation of the sampling tools. Crew provides the ability to identify drilling locations in real time, deal with instrument faults, and make the processes more efficient overall. Handling for samples acquired during the with-crew phase and intended for in situ analysis might utilize the same sample handling technologies used in the pre-crew phase, but instead be telerobotically operated by crew to reduce time needed for handling procedures. This would reduce risk of contamination of samples by crew and vice versa, while taking advantage of the proximity of crew to enhance efficiency. Samples acquired during the with-crew phase that are intended for analysis on Earth could be prepared and hermetically sealed either robotically, as done for pre-crew samples, or by crew, if completed in situ analyses indicate the sample(s) pose minimal risk to crew.

### 5.3.3. Post-crew

Post-crew sample handling and analysis would support robotic sampling systems that are left for long-duration, post-crew operation. Some of these systems would include the robotic systems from the pre-crew phase, and some would be robotic systems deployed by crew.  Sample handling would receive samples, prepare them for analysis, and transfer them to science instruments.

# 6. Outstanding Questions

The workshop highlighted the diversity of mission concepts that could achieve high-priority science, and the range of architectures that would support such discovery. Furthermore, it highlighted the importance of deciding early on both the overall science mission concept and the associated architecture, so that important development steps can begin. There are simply too many open questions needed to be worked in order to effectively prepare for a human mission to Mars if the science and architecture options remain open.

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| In order to effectively prepare for a human mission to Mars, it is of utmost importance to decide early on both the overall science mission concept and the associated architecture needed to achieve science objectives, so that important development steps can begin. |

achieve science objectives, so that important development steps can begin.

## 6.1. Human & Robot Scenarios

The style of human-robot interactions were found to depend on the mission concept such that the roles for humans and robots changed based on the main science objectives or the duration of surface stay. These roles include scouting, sampling, site analysis, instrument deployments, drilling, and sample analysis. Furthermore, depending on the mission concept, these roles can occur in different mission phases (pre-crew, surface mission, and post-crew). The distribution of roles between humans and robots might have substantially different modalities depending on the phase. Technology is at a point where important work can be done developing these human-robot scenarios using analogs, but this work can be easily diluted if the scenarios are not well defined. Early decision making is critical to take advantage of these capabilities; without focus, there is likely not enough time to develop the requirements needed to design these systems effectively.

## 6.2. Drilling Efficiency

While the workshop participants clearly agreed that valuable science could be accomplished in a short-stay (30-sol) mission, several important factors for accomplishing the science objectives were identified. First, substantial preliminary work during the pre-mission phase would need to be done to ensure key scientific objectives could be met. Second, additional testing and development of drilling technologies are needed to understand if they can be utilized effectively during such a short timeframe. Participants repeatedly identified our lack of knowledge about how deeply we could drill and how many holes could be drilled over a given area as major factors in determining whether valuable science could be accomplished with a short-stay mission.

## 6.3. Tradeoffs between Sample Return, In-situ Analysis, and ‘Lab in the Hab’

Another outstanding question that arose several times in the discussions concerned the tradeoffs between sample return, in-situ analysis, and ‘lab in the hab’ analyses. These are three different approaches to doing human exploration of Mars and there was not a clear consensus about which approach would be preferred. It is likely that a particular sampling approach will be best suited to different mission concepts and thus there is no one correct answer. Advantages identified with sample return include the ability to use more sophisticated terrestrial laboratories as well as continuing analyses over time as technologies improve. However, the tradeoff is access to much less material, an increased potential for sample contamination, and an inability to conduct time-sensitive analyses. In situ analysis provides access to potentially the largest amount of material as close to sample collection as possible, however it can be time consuming for an astronaut on EVA and would not provide the most precise data. A ‘lab in the hab’ could potentially produce high quality data without sacrificing EVA time, however lab instruments in the habitat take up valuable space/power, and sample analysis is time consuming, so it may reduce astronaut time for other activities.

## 6.4. Maximizing Science if Limited to 100 kg Sample Return Mass

What should be the approach to utilizing the mass allocation for sample return especially if it is limited to only 100 kg? What is the most efficient use of packing material, and what kinds of sample sizes should be targeted? These are all questions that should be addressed early on to best understand how sample return should be approached and what kind of sub-sampling strategies might be implemented.

## 6.5. Landing Sites

The workshop discussions about mission concepts did not focus on landing sites, but the output of this report sets the stage for future discussions about optimal sites for high-priority human-led science for how (including the mission concepts proposed here) and how they might actually be implemented on the surface according to the characteristics of the candidate site(s). This will help refine landing site constraints originally outlined in the 2015 First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars (HLS2 Workshop Report, Bussey and Hoffman 2016) and will allow researchers to evaluate their proposed sites in more detail. The overall viability and likelihood of a mission concept should be reflected in availability and suitability of landing sites. The knowledge of Mars may not yet be good enough to pursue some mission concepts, and others may be enhanced by the fact that landing sites can be found that address multiple important goals.

## 6.6. Standard Instrument Packages

There are several science objectives and measurements that should be relevant and of high science value regardless of the mission type or destination selected for the human mission. For example, characterizing the local geology and weather dynamics will be feasible and important everywhere on Mars. Achieving these objectives will require a basic suite of instruments that should be developed and included on any human mission to Mars. This suite should include capabilities to perform weather monitoring, geophysics, geochemistry, mineralogy, and baseline astrobiology including life detection. The exact details of this suite should be developed in conjunction with the instruments being developed for lunar exploration.

## 6.7. Planetary Protection

Human exploration of Mars is connected to planetary protection responsibilities and more work is needed and is ongoing in understanding how to address these issues. There remain outstanding questions about how to definitively rule out the presence of life on Mars around the human landing site and how those might impact the overall science strategy of the mission. In addition, there were outstanding questions about characterization of potential terrestrial contamination. If signs of Earth life are absent, shown not to spread, or quickly disappear in the Martian environment, it will be easier to address ongoing concerns around planetary protection. It was noted that planetary protection concerns may vary for missions with objectives related to the search for extant life vs. extinct life.

## 6.8. Communications

The communication infrastructure was identified as a very important aspect for accomplishing science on Mars and the nature of this infrastructure could strongly affect the type of science mission that is implemented. Early decisions and clarity about communication capabilities is needed in order to make science decisions.

### 6.9. Single vs. Sequential Missions

This workshop only considered a single mission without making assumptions about human missions that might follow it. In order to make good science decisions about a human mission to Mars, it is critical to know whether this will be a single mission or part of a larger campaign.

# 7. Next Steps

The results of the workshop discussions lead to a logical set of next steps that might be undertaken to continue the work that was begun here.

First, the objectives identified in this workshop, in conjunction with those identified at the preceding MEPAG meeting, will be used to populate the Mars science objectives in NASA's strategy for human exploration into the Solar System. These objectives are summarized in a document managed by NASA's Exploration Systems Development Mission Directorate, and are used to drive requirements definitions for the architecture that will transport humans further into the Solar System than ever before.

Second, the objectives and instrumentation identified in this workshop will be used to help formulate a strategy for the next sequence of architecture design studies. These studies aim to constrain the technology including mass and timing of delivery of specific exploration assets, for cargo and crewed missions to Mars. These studies help identify what equipment can be delivered when, and what capabilities those assets will provide for achieving mission goals.

Third, there are a number of additional science objectives and associated instrumentation that need to be defined for the biological and human research sciences. Those communities plan to have a dedicated workshop with similar scope in late 2023, once the biological sciences decadal survey has been published. Those objectives will be combined with the objectives from this workshop to help formulate a broader strategy for exploration of Mars.

Finally, there are a number of topics that must be discussed amongst the various science and exploration communities continue refining the strategy for human exploration of Mars. There are numerous opportunities to contemplate, develop, and demonstrate specific capabilities relevant to Mars exploration with crew. Future discussions with the science community may involve what specific technologies and capabilities can be demonstrated in ground analog studies, including Desert Research And Technology Studies (DRATS), Crew Health and Performance Exploration Analog (CHAPEA), Human Exploration Research Analog (HERA), Haughton Mars Project (HMP), NASA Extreme Environment Mission Operations

(NEEMO), and Planetary Science and Technology from Analog Research (PSTAR) programs, as well as on the ISS and even on the lunar surface.  Other future discussions with the science community will focus on the formulation of an exploration roadmap, where detailed strategies will be formulated over a series of missions that may increase in complexity and capability.  And finally, future discussions with the science community will focus on identifying specific locations where the highest priority science objectives from multiple disciplines can be addressed.

| FINDING |
| --- |
| Several key capabilities were identified throughout the workshop that would be particularly enabling to the science of human missions to Mars. These key capabilities include: 1) Long-lived surface power; 2) Mobility for crew; 3) Communication for distributed surface assets; 4) Standard instrument packages; and 5) Technologies for robotic scouting, sampling, long-lived stationary science, and drilling. |

Together, the science, exploration, and commercial communities will forge an exciting path to enable unprecedented discoveries using humans and robots in concert to explore the surface of Mars.

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# 9. Appendix A

In the spring of 2022, the Mars Exploration Program Analysis Group (MEPAG) Goals committee was tasked with assessing how each of the 73 individual science investigations listed in the MEPAG Goals document might benefit from the work of human explorers. Each investigation was classified in one of four categories, indicating the extent to which human involvement would be a positive ('high,' 'medium,' 'low') or negative ('detrimental') contribution. This 'human aided' ranking metric was established in parallel with the existing 'science priority' ranking ('high,' 'medium,' 'low') of the MEPAG Goals document. It was emphasized during this activity that an investigation benefitting from a human explorer did not mean that a human explorer was required to execute that investigation. Several examples of science investigations were highlighted that could be done robotically (at greater cost, time, or effort) but which would be facilitated by human involvement.

Results of the MEPAG analysis are shown in Tables X, X+1, and X+2, corresponding to the three primary science goals of the MEPAG Goals document, Life, Climate and Geology, respectively. Columns of these tables list the MEPAG goals, objectives, sub-objectives and investigations as worded in the Goals document, followed by the existing science priority ranking and the human aided ranking as evaluated by the Goals committee. Those investigations that are identified as of higher science priority and that would benefit most greatly from human involvement are shaded green in the 'Investigation' column.

Interestingly, for no investigation was human presence deemed 'detrimental,' even for those under the 'Life' goal (Table X), where the benefit of human skill outweighed the risk of sample or environmental contamination. It was felt that humans would be able to select better samples for analysis, and perform analysis of time-sensitive samples while still on Mars, reducing the amount of sample degradation that would occur on the journey back to Earth. As discussed above, in this workshop report, humans could deploy instruments more favorably than robots in many circumstances, including deep drilling (>30 m) tools to obtain pristine samples unmodified by exposure to the martian surface environment. Lastly, the simple presence of humans on Mars indicates a more robust mission infrastructure, enabling return of a far greater mass of samples than from prior robotic missions (e.g., ~100 kg vs. 100s g from MSR).

Table A1. MEPAG Goals document investigations for Goal I ('Life') with science priority and human aided rankings.

| | | | Greatest impact Investigations | Science Priority | Human Aided? |
|---|---|---|---|---|---|
| Goal | Objective | Sub-Objective | Investigation | | |
| **Goal I: Determine if Mars ever supported, or still supports, life** | **A. Search for evidence of life in environments that have a high potential for habitability and presevration of biosignatures** | 1. Determine if signatures of life are present in environments affected by liquid water | **1. Chemical signatures of life** | **Higher** | **High** |
| | | | **2. Physical structures of life** | **Higher** | **High** |
| | | | 3. Physiological activity | Medium | High |
| | | 2. Investigate the nature and duration of habitability near the surface and in the deep subsurface | **1. Availability of liquid water** | **Higher** | **High** |
| | | | 2. Constrain energy sources vs depth | Medium | High |
| | | | 3. Characterize environment re: stability of organic bonds | Medium | High |
| | | | 4. Abundance of bioessential elements | Medium | High |
| | | | 5. Overall geologic context | Medium | High |
| | | 3. Assess the preservation potential of biosignatures near the surface and with depth | **1. Preservation of organics compounds vs depth** | **Higher** | **High** |
| | | | **2. Preservation of physical structures** | **Higher** | **High** |
| | | | 3. Preservation of metabolic imprints | Medium | High |
| | **B. Assess the extent of organic, abiotic chemical evolution** | 1. Constrain inventories of carbon (particularly organic molecules) and other biologically important elements over time | **1. Organics on surface/sub-surface vs exposure time** | **Higher** | **High** |
| | | | 2. Atmospheric reservoirs of carbon over time | Higher | Medium |
| | | | 3. Abiotic cycling of bioessential elements | Medium | Medium |
| | | | 4. Bulk carbon in crust and mantle from martian meteorites | Medium | Low |
| | | 2. Constrain the surface, atmosphere and sub-surface processes through which organic molecules could have formed and evolved over martian history | 1. Atmospheric processes that create/transform organics | Higher | Low |
| | | | **2. Ionizing radiation on organics vs depth** | **Higher** | **High** |
| | | | 3. Mineral catalysis role in organic evolution | Medium | Low |
| | | | 4. Hydrothermal/serpentinization driving organic evolution | Medium | Low |

Table A2. MEPAG Goals document investigations for Goal II ('Climate') with science priority and human aided rankings.

| Goal | Objective | Sub-Objective | Greatest impact Investigations<br>Investigation | Science Priority | Human Aided? |
|---|---|---|---|---|---|
| Goal II: Understand the processes and history of climate | A. Characterize the state and controlling processes of the present-day climate of Mars under the current orbital configuration | 1. Characterize the dynamics, thermal structure and distributions of dust, water and carbon dioxide in the lower atmosphere | **1. Dynamics of lower atmosphere, local-global** | **Higher** | **High** |
| | | | 2. Water, CO2 & dust and fluxes between atmospheric reservoirs | Higher | Low |
| | | 2. Constrain the processes by which volatiles and dust exchange between surface and atmospheric reservoirs | **1. Surface-Atmosphere dust and volatile fluxes** | **Higher** | **High** |
| | | | **2. Dust and volatile flux impacts on (sub)surface reservoirs** | **Higher** | **High** |
| | | 3. Characterize the chemistry of the atmosphere and surface. | 1. Vertical profiles of key gas species | Higher | Low |
| | | | 2. Space/time variations of chemically important species/tracers | Medium | Medium |
| | | | 3. Determine importance of heterogeneous- and electro-chemistry | Higher | Medium |
| | | 4. Characterize the state and controlling processes of the upper atmosphere and magnetosphere | 1. Mechanisms of transport from lower to upper atmosphere | Higher | Low |
| | | | 2. neutrals, ions, aerosols in upper atmosphere & magnetosphere | Lower | Low |
| | | | 3. Upper atmosphere state under varying driving conditions | Lower | Low |
| | B. Characterize the history and controlling processes of Mars' climate in the recent past, under different orbital configurations | 1. Determine the climate record of the recent past that is expressed in geomorphic, geological, glaciological, and mineralogical features of the polar regions. | 1. How are polar layers formed | Higher | Medium/High |
| | | | 2. 3D properties of Polar Layered Deposits | Higher | Medium/High |
| | | | 3. Absolute ages of Polar Layered Deposits | Medium | High |
| | | 2. Determine the record of the climate of the recent past that is expressed in geomorphic, geological, glaciological, and | 1. Location structure, composition of ice and volatiles | Medium | Medium/High |
| | | | 2. Volatile reservoir ages/accumulation conditions | Medium | High |
| | | 3. Determine how the chemical composition and mass of the atmosphere changed in the recent past | 1. When & how were buried CO2 S. Pole reservoirs formed? | Medium | Low/Medium |
| | | | 2. Polar Layered Deposits trapped gas composition | Medium | High |
| | C. Characterize Mars' ancient climate and underlying processes | 1. Determine how the chemical composition and mass of the atmosphere have evolved from the ancient past to the present. | **1. How has atmosphere (mass & composition) changed?** | **Higher** | **High** |
| | | | 2. Crustal sinks of atmospheric species | Medium | Medium |
| | | | 3. Gas sources over time (volcanism, alteration, bolides) | Medium | Medium |
| | | | 4. Atmospheric escape rates over geologic time | Medium | Low |
| | | 2. Find and interpret surface records of past climates and factors that affect climate. | **1. Ancient water cycle from geologic record** | **Higher** | **High** |
| | | | 2. Ancient climate via modeling | Higher | Low |

Table A3. MEPAG Goals document investigations for Goal III ('Geology') with science priority and human aided rankings.

| Goal | Objective | Sub-Objective | Greatest impact Investigations<br>Investigation | Science Priority | Human Aided? |
|---|---|---|---|---|---|
| Goal III: Understand the Origin and Evolution of Mars as a Geological System | A. Document the geologic record preseved in the crust and investigate the processes that have created and modified that record. | 1. Identify and characterize past and present water and other volatile reservoirs. | **1. Modern extent of water & hydrous minerals** | **Higher** | **High** |
| | | | **2. Location, timing & extent of ancient water reservoirs** | **Higher** | **High** |
| | | | 3. Structure & age of Polar Layered Deposits, links to climate | Higher | Low |
| | | | 4. 3D ice (H2O & CO2) distribution with time | Medium | Medium |
| | | | 5. Role of volatiles in modern surface processes | Medium | Medium |
| | | 2. Document the geologic record preserved in sediments and sedimentary deposits | **1. Past hydrological cycles in sedimentary & geomorphic record** | **Higher** | **High** |
| | | | **2. Diagenesis/alteration of sediments** | **Higher** | **High** |
| | | | **3. Habitability & biosignature preservation** | **Higher** | **High** |
| | | | 4. Sources & fluxes of aeolian sediments | Low | Low |
| | | | 5. Dust lifting mechanisms | Low | Medium |
| | | 3. Constrain the magnitude, nature, timing, and origin of environmental transitions. | 1. Link local environmental transitions to global evolution | Higher | Medium |
| | | | **2. Age, duration, intermittency of ancient environmental transitions** | **Higher** | **High** |
| | | | 3. Nature & diversity of ancient environments & implications | Medium | High |
| | | | 4. History of Sulfur & Carbon through Mars system | Medium | High |
| | | 4. Determine the nature and timing of construction and modification of the crust | **1. Absolute & relative ages of geologic units** | **Higher** | **High** |
| | | | 2. Link martian meteorites and samples to planet evolution | Medium | Medium |
| | | | 3. Modern surface processes | Low | Medium |
| | | | 4. Impact effects on crust, and cratering rate | Low | Low |
| | | | 5. Surface manifestations of volcanic processes | Low | Medium |
| | | | 6. Petrogenesis of igneous rocks over time | Low | Medium |
| | | | 7. Planet-wide Mars evolution via global/regional mapping | Low | Low |
| | B. Determine the structure, compositio n, and dynamics of the interior and how it has evolved. | 1. Identify and evaluate manifestations of crust-mantle interactions. | **1. Volatiles in the mantle & crust** | **Higher** | **High** |
| | | | 2. Modern tectonics, evidence of past tectonics | Medium | Medium |
| | | 2. Quantitatively constrain the age and processes of accretion, differentiation, and thermal evolution of Mars. | 1. Structure & dynamics of the interior | Higher | Medium |
| | | | 2. Thermal state and internal heat flow | Medium | High |
| | | | 3. Origin & history of magnetic field | Medium | Medium |
| | C. Determin e origin and geologic history of Mars' moons and implicatio ns for the evolution | 1. Constrain the origin of Mars' moons based on the surface and interior characteristics | 1. Properties of the Martian moons | Medium | Low |
| | | | 2. Geologic history of the Martian moons | Medium | Low |
| | | | 3. Interior structure of the Martian moons | Low | Low |
| | | 2. Determine the material and impactor flux within the Mars neighborhood, throughout martian history, as recorded on Mars' | 1. Impactor flux at Mars | Low | Medium |
| | | | 2. Rate of material exchange between Mars & its moons | Low | Low |