National Aeronautics and Space Administration

Workshop on Architecture Issues Associated with Sampling

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Proceedings and Results

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Cover photo: Human-robot interactions during the Arctic Mars Analog Svalbard Expedition (AMASE). The Jet Propulsion Laboratory (JPL) Cliffbot rover hands off a rock sample to Dr Jake Maule in a Mark III lunar prototype spacesuit. The AMASE science lead is Dr Andrew Steele at the Carnegie Institution for Science, Washington D.C. Photograph (C) Kjell Ove Storvik and AMASE. Taken on August 15th 2006, in Svalbard, Norway.

Outline

1.0 Overview

On June 25 and 26, 2007, the Optimizing Science and Exploration Working Group (OSEWG) and the Lunar Exploration Analysis Group (LEAG) conducted the "Workshop on Architecture Issues Associated with Sampling" at the Lunar and Planetary Institute in Houston, TX.

The workshop was planned and timed to respond to ongoing efforts by the OSEWG to ensure the optimization of science in the development of NASA's exploration architecture. The workshop was the first in a series of OSEWG activities designed to engage the broad science and engineering communities in discussions with representatives from NASA's Exploration Systems Mission Directorate (ESMD), Science Mission Directorate (SMD), and Space Operations Mission Directorate (SOMD) on issues affecting science return from the Moon and Mars. The goals of the workshop were 1) to articulate major questions and issues that arise when considering the impact of sample science activities, protocols, and requirements on specific architectural elements, 2) to aid NASA and its partners in the prioritization of follow-on studies, workshops, research programs, and technology development in the area of sampling and curation of extraterrestrial materials, and 3) to respond to the recommendations of the Science Committee of the NASA Advisory Council (NAC) from their Workshop on Science Associated with the Exploration Architecture earlier in the year in Tempe, AZ.

The workshop was a key part of the OSEWG's obligation to advise NASA's mission directorates on scientific exploration requirements while making its findings accessible to the public and to the science and exploration communities interested in participating in the exploration of the Moon and Mars. The agenda was planned to cover the impact of sampling on specific elements of the emerging exploration architecture. The end-to-end process of sampling, from traverse planning to curation, was discussed and some priorities identified as initial guidance for exploration science planning. The workshop deliberations and the ensuing analysis synthesized from the discussions were intended to enable the OSEWG to develop a strategy for prioritizing its goals and milestones for integrating science into the exploration architecture.

The workshop was open to the science and exploration communities and to the public. The workshop served as a venue for these communities to provide input through the OSEWG to NASA and for NASA to communicate the latest in its lunar and Mars architecture plans to the communities for deliberation and discussion. Presentations were given by the OSEWG, LEAG, the Mars Exploration Program Assessment Group (MEPAG), the Curation and

Analysis Planning Team for Extraterrestrial Materials (CAPTEM), the Lunar Architecture Phase 2 Team (LAT 2), and the Constellation Project. The participants in the workshop were also given brief overviews on relevant topics with emphasis on the Apollo experience with a demonstration of Apollo sampling tools, as well as recent advances in technologies such as telerobotics and rovers.

The focus of the workshop, however, was on the group break out discussions. In addition to the OSEWG, LEAG, and NASA representatives, approximately 75 topical experts attended the workshop to participate in the deliberations. Armed with basic concepts and broad expertise and experience, the participants were split into seven small groups and each was assigned a lunar or Mars exploration scenario to frame the discussions. All groups were provided with an identical spreadsheet questionnaire designed to lead them through the process of sampling from end to end in the context of their unique exploration scenario. Groups were asked to move quickly through the questions so that all phases of sampling could be considered and discussions would cover the broad range of topics presented.

The final products of the workshop presented in this report include a list of topics that require further study, some of which were generated in real time by the plenary group after the discussion exercise and some of which were synthesized by analyzing the final summary briefings and completed questionnaire spreadsheets from each group. A summary of the questionnaires and discussions are presented in these proceedings, with analysis highlighting points of agreement and contention within and between the groups.

2.0 Background

2.1 Workshop Sponsors

Optimizing Science and Exploration Working Group (OSEWG)

NASA's Science Mission Directorate (SMD) and the Exploration Systems Mission Directorate (ESMD) jointly created the Outpost Science and Exploration Working Group (OSEWG) in 2007. The word "Outpost" has been changed to "Optimizing" to include in its scope sortie as well as outpost surface exploration science.

The mission of the OSEWG is to engage in mission concept planning and science requirements definition to help inform the development of systems that will optimize exploration and science investigations. This initial focus will be on human and robotic exploration on the Moon. This collaborative leadership and integration body is charged with

- Identifying and communicating science interests/requirements for incorporation into the Constellation architecture and mission planning and

- Prioritizing science requirements and facilitating the assessment and disposition of them for becoming architecture development requirements.

Materials science, physical sciences, and life sciences are included in the scope of the OSEWG charter.

In its first year, several initial objectives were identified for the OSEWG. The objectives can be captured in three interrelated categories: science requirements, surface science scenarios, and analogues. It became clear early in its formulation all categories of OSEWG's objectives are impacted heavily by the problem of sampling and sample return. As its first formal activity, the OSEWG invited the LEAG to co-sponsor a workshop to initiate a broad dialogue on the architecture issues associated with sampling. Members of the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) were asked to assist in the organization of the workshop to ensure appropriate sampling expertise and build on CAPTEM's vast experience.

Lunar Exploration Analysis Group (LEAG)

The LEAG is responsible for analyzing scientific, technical, commercial, and operational issues associated with lunar exploration in response to requests by NASA (www.lpi.usra.edu/leag). The LEAG serves as a community-based, interdisciplinary forum for future exploration and provides analysis in support of lunar exploration objectives and their implications for lunar architecture planning and activity prioritization. It provides findings and analysis to NASA through the NASA Advisory Council (the Council) within which the LEAG Chair is a member of the Planetary Science Subcommittee (PSS).

2.2 Organizing Committee

Kelly Snook, Workshop Chair, Science Mission Directorate, NASA Headquarters
Carlton C. Allen, NASA Johnson Space Center (Astromaterials Curator)
David Beaty, NASA Jet Propulsion Laboratory (Mars Architectural Working Group)
Dean Eppler, NASA Johnson Space Center
Wendell Mendell, NASA Johnson Space Center
Clive Neal, LEAG Chair
Michael Wargo, NASA Headquarters (LEAG)
Geoffrey Yoder, NASA HQ, OSEWG ESMD Co-Chair (at time of workshop)

3.0 Workshop Structure

3.1 Purpose and scope of workshop

The intention of the workshop was to generate detailed dialogue on issues related to sampling in a way that would draw out the most urgent outstanding questions needing to be addressed by NASA. Highly structured discussion exercises were developed prior to the workshop to capture the state of thinking in the various communities of scientists, engineers, managers, and members of the general public on the topic. Because of the short time available and the variety of opinions represented, the workshop was not designed to produce answers, but rather to articulate questions, both old and new.

3.2 Summary of overview presentations and discussion

The first day of the workshop began with a series of talks designed to provide background and perspective to the participants. PowerPoint presentations of the talks are available on the workshop website at http://www.lpi.usra.com/meetings. The invited talks were designed with three objectives in mind: 1) familiarize the discussion groups with current working groups and NASA architecture plans; 2) build on the Apollo experience; and 3) look ahead to promising new technologies that enable science.

The presentations were kicked off by overviews of the history and scope of the various relevant working groups: LEAG (presented by Clive Neal) and OSEWG (presented by Geoff Yoder); Charles Shearer presented CAPTEM and the MEPAG Human Exploration of Mars Science Analysis Group (HEM-SAG) overview was presented by Jennifer Heldmann.

Andy Thomas gave a description of the Lunar Architecture Team Phase II (LAT2) results, including detailed descriptions of the six architectural options:

1. All elements (habitat, rovers, power, etc) delivered with crewed flights (LAT 1)
2. Derivative of LAT 1 except an uncrewed lander can deliver hardware to surface provided all elements must be sized to fit on a crewed lander
3. A single large, fully outfitted and pre-integrated Habitation Element launched and landed on a single uncrewed mission
4. One large lander with integrated surface mobility (mobile lander)

5. Long-range, pressurized rover delivered as early in the sequence as possible (This option was eliminated because the LAT team felt it was captured in each of the other scenarios.)
6. Nuclear power used for the surface power in lieu of solar power

Several talks were presented to explore more deeply some related topics and to continue setting the stage for the afternoon breakout session. Wendell Mendell gave an overview of the Constellation program (http://www.nasa.gov/mission_pages/constellation/main/index.html), discussing the organizational structure of Constellation and NASA's exploration roadmap. Abhi Tripathi talked about the similarities and differences between the Moon and Mars and some of the additional challenges that Mars landing and sample return will entail. Carl Allen and Chip Shearer both discussed the nature and importance of returned samples. Dr. Allen talked about the lessons learned from returned samples of lunar rocks and regolith. Dr. Shearer explained how remote sensing, *in situ* analysis, and returned samples complement and build off of each other.

One of the highlights of the morning session was the opportunity to hear from two Apollo astronauts, Harrison "Jack" Schmitt (Apollo 17) and Capt. John Young (Apollo 16), about their recollections of sample acquisition and handling on the lunar surface and the various tools they were provided on the lunar surface. Judy Alton showed some original Apollo training tools so that the participants could get an opportunity to test out the tools. The Apollo history lesson continued with a discussion of the science backroom and communications during the lunar missions with Gordon Swann. Gary Lofgren also provided a discussion of the curation of the current lunar sample collection and the methods and containers used to obtain those samples.

The final set of talks for the morning session provided updates on some of the equipment and technology being developed for the new architecture. Ron Diftler discussed some of the advances in field robotics, including the K–10, the Athlete, and the Robonaut/Centaur. Mike Gernhardt talked about the FRED (pressurized rover) and other advances in EVA and habitation systems. Terry Fong talked about human-robot interaction and the ways in which robots can be used to improve the efficiency of astronaut EVA time.

3.3 Group assignments

The workshop participants came with a large variety of background knowledge and experiences. They were randomly divided into seven groups for the breakout activities. A list of participants and brief descriptions of their expertise is given in Appendix B, grouped by their original group assignments. It should be noted that the final group composition deviated somewhat from the initial assignments. Each group was given a slightly different set of starting conditions for their exploration scenarios and all were asked to consider three different mission phases; early, buildup, and steady-state.

Group 1 MLM (Mars Long stay, Multiple sites)

- Mars Scenario: 300 day missions to multiple sites
- Moderator Chris McKay

Group 2 LSH1 (Lunar Stationary Habitat 1)

- LAT II Lunar Option: monolithic hab (7 day early, 30 day buildup, 30 steady-state)
- Moderator Wendell Mendell

Group 3 MLS (Mars Long stay, Single site)

- Mars Scenario: Three 300 day stays to single site
- Moderator Jennifer Heldmann

Group 4 LNP (Lunar Nuclear Power)

- LAT II Lunar Option: nuclear power (7 day early, 30 day buildup, 60 steady-state)
- Moderator Eileen Stansbery

Group 5 MSS (Mars Short Stay)

- Mars Scenario: 30 days stays to multiple sites
- Moderator Pan Conrad

Group 6 LSH2 (Lunar Stationary Habitat 2)

- LAT II Lunar Option: monolithic hab (7 day early, 30 day buildup, 30 steady-state)
- Moderator Abhi Tripathi

Group 7 LMH (Lunar Mobile Habitat)

- LAT II Lunar Option: mobile hab (7 day early, 30 day buildup, 60 steady-state)
- Moderator Clive Neal

3.4 Spreadsheet questionnaire genesis

The organizing committee generated a spreadsheet questionnaire to guide discussions and keep them moving. The spreadsheet contained multiple-choice "questions" following a roughly sequential logic through the end-to-end process of sampling. The following issues were specifically addressed. In all cases, participants were instructed to think and respond in the context of science activities and requirements, as opposed to other mission activities and constraints, such as crew health and safety, general logistics, or maintenance.

1. **EVA Planning / Preparation [primary architectures affected: lander/habitat, communications]**
   a. Data Usage—requirements for site surveys, resolution requirements, real time data access requirements
   b. Traverse planning—hypothesis generation, route mapping/planning, sampling strategies, telerobotic path scouting
   c. IVA requirements—Workspace requirements, crew time requirements, use of previously collected samples/data, need for IVA support, decision-making structures

2. **Traversing and EVA [primary architectures affected: mobility, suits, communications/navigation]**
   a. Navigation—Precision requirements, relationships between suits and rovers, data overlays, timecode requirements, position awareness
   b. Communications—2-way audio and video requirements, other communications requirements, real time data access, query, and display, real time data analysis—*in situ* measurements, timecode requirements, telemetry and ephemeris
   c. Traverse flexibility—traverse path change decision-making, traverse ranges—no rover, unpressurized rover, pressurized rover
   d. Robotic field assistance—Command and control, traverse scout display, consumable tracking, crew requirements

3. **Sample and Data Acquisition [primary architectures: suits, mobility, power, communications/navigation]**
   a. Documentation—Navigational precision for sample location, spatial resolution requirements, video resolution requirements, cameras, sample orientation
   b. Communications—2-way audio and video, real time data access/display, real time data analysis, timecode, broadcast telemetry
   c. Sampling—Tools, sample masses, robotic field assistance, telerobotics, sample containment and integrity issues, subsampling, sample acquisition decision-making/discrimination, contamination and planetary protection
   d. Data acquisition—Field instrumentation, sample data handling, crew time constraints, traverse time vs. field site time
   e. Robotic field assistance—command and control, relationship to astronauts

4. **Sample Transport [primary architectures: suits, rovers, habitat/laboratory]**
   a. Human transport—sample handling in suits, environmentally sensitive samples and sample integrity issues
   b. Rover transport—load capacity, preserving sample integrity
   c. Habitat transport/sample pass-through to habitat or lab—glovebox requirements, sample pass-through, sample handling inside lab/habitat

5. **Documentation [primary architectures: suits, rovers, communications/navigation]**
   a. Automated documentation at site—real-time sample/data position and time stamping, data correlation/overlay, real-time data access, real time rover position accuracy requirements, suit position accuracy requirements, instrument pointing accuracy, synchronized time stamping, continuous video broadcast and availability of feed
   b. Subsampling at site—Automated and manual subsampling, initial sample containment issues, environmentally sensitive samples, subsampling strategies
   c. Data usage—All data used/broadcasted/available in real time, type of data stored, data analysis strategies, use of data, robotic return to sites

6. **Sorting and Storage [primary architectures: habitat, lab, mobility, return vehicles, “SHED”]**
   NOTE: A new idea was introduced at this stage: the Sample Handling, Exo-curation, and Documentation (SHED) facility, separate from the habitat. Either unpressurized or pressurized, possibly equipped with tactile, highly capable dedicated virtual-reality telerobotics (e.g., Robonaut) inside performing sample storage, access, sorting, and basic analysis tasks from habitat or ground. It would be designed to conserve EVA time and improve dexterity of sample handling over glovebox or EVA limitations.

a. Sample storage—total collected mass, storage requirements of different types of samples, preserving sample integrity and preventing contamination, crew time and EVA/IVA requirements for sample sorting
b. Subsampling after collection—instrument suite inside habitat/lab/glovebox, access to samples for use inside lab-in-hab, requirements of glovebox, sample handling inside hab, dust issues, sample pass-through requirements
c. Subsampling outside habitat in SHED—instrumentation inside SHED, power requirements, estimated mass of SHED and basic functional requirements

7. Laboratory Analysis [primary architectures: habitat, SHED, laboratory]

a. Minimum analysis capability—tools and instruments, environmental requirements, sample integrity preservation and prevention of contamination
b. Sample pass-through—sealed containers, direct access from outside
c. Advanced analytical capability—extended sample handling and analysis operations in Shed by ground teams, additional equipment in SHED
d. Synergy with *in situ* Resource Utilization (ISRU)—overlapping requirements/needs, waste disposal, cleaning protocols, prevention of contamination, planetary protection

8. Sample Return [primary architectures: ascent vehicles, habitats, SHED, return vehicles]

a. Transport to ascent vehicle—Mass return requirements, robotic mass transfer, robotic mass return separate from crew
b. Planetary protection—Mars forward considerations
9. Curation [primary architectures: habitats, laboratories, SHED, return vehicles]
a. Mass returned per flight—Discussion of CAPTEM report (www.lpi.usra.edu/captem/analysis.shtml), sample return mass requirements, biological samples, curation requirements under Mars/Moon conditions, curation paradigms compared to Apollo
b. Containment and contamination control—container materials, collecting cleanly, cross-contamination in all phases of collection/transport/storage, biologically interesting samples

There were 9 tabs in the spreadsheet questionnaire—one topic per tab. For each of the issues, deliberately vague sentence fragments were presented as questions and three choices (A, B, and C) were given. Groups were encouraged to interpret the questions, choose an answer, and provide comments. They were free and encouraged in all cases to choose (D) and specify their own answers in the space provided. Each question was to be considered in the unique context that each group was given (Mars or Moon, long or short stay, nuclear power or not, etc.). Each question was also to be considered for early in a campaign, midway through a campaign build-up, and in a long-term steady state mode. Groups were also encouraged to devise their own questions if the ones provided seemed inadequate to capture the range of possible issues needing discussion.

Relationship to recommendations of the NASA Advisory Council

Prior to this sampling workshop, NASA and the NASA Advisory Council jointly sponsored the Workshop on Science Associated with the Lunar Exploration Architecture, held February 27 to March 2, 2007 in Tempe, Arizona. A final workshop report and thirty-five specific recommendations were generated at the Tempe workshop (http://www.lpi.usra.edu/meetings/LEA/finalReport.pdf), to which NASA responded and is taking action to fulfill. General crosscutting recommendations and others specific to astrophysics, heliophysics, earth science,

Table 1
Relationships of OSEWG workshop discussions to recommendations from the NASA Advisory Council from the Workshop on Science Associated with the Lunar Architecture.

NAC Recommendation	Brief Description of Recommendation	OSEWG Workshop 1 Discussions
C-1	Scientific input to landing sites and operational decisions	
C-2	Evaluation and prioritization of science activities	Discussed
C-3	Architecture should enable highest priority science	Discussed
C-4	Regular reviews of LAT decisions	
C-5	CEV-SIM bay	
C-6	Comparison study for non-polar outpost sites	
C-7	Options for human and robotic sortie missions	Discussed
C-8	Return payload capabilities	Primary
C-9	Sample collection, documentation, containment, curation	Primary
C-10	Roles and capabilities of astronauts	Discussed
C-11	Astronaut exploration training	Discussed
C-12	Improved EVA suits	Discussed
C-13	Integration of orbital data sets	Discussed
C-14	Electromagnetic and charged dust environment	Discussed
C-15	Investigation of time-stratigraphic layers in lunar regolith	Discussed
C-16	Options for large-area lunar surface emplacement	
APS-1	Far side meter wavelength radio environmant	
APS-2	Options for science operations in free space	
APS-3	Use of Constellation heavy lift capability for Astrophysics payloads	
ESS-1	Earth science from the Moon	
ESS-2	Earth view from the outpost	
HPS-1	Develop predictive capability for space weather	
HPS-2	Real-time space weather monitoring	
HPS-3	Provide capability for “drop-off” satellites	
HPS-4	Improved measurements of solar wind composition and flux	Discussed
PPS-1	Contamination control technologies	Discussed
PPS-2	Equipment for planetary protection assays	
PPS-3	Back contamination of sample containers	Discussed
PPS-4	*In situ* investigation of lunar sites for biologically derived or other compounds	Discussed
PPS-5	Planetary protection protocols	Discussed
PPS-6	Advanced life support systems	
PSS-1	Moon as a recorder of impact history of inner solar system…	Discussed
PSS-2	Geophysical network on the lunar surface	Discussed
PSS-3	Mobility on the lunar surface	Primary
PSS-4	Technology development needs	Primary

planetary science, and planetary protection were given. The workshop that is the subject of this report was one of the earliest responses to recommendations on engaging the science community, sampling, curation, analogs, sampling, and sample return mass. Table 1 shows a list of the NAC Tempe recommendations that indicates the areas of most relevance to the OSEWG workshop. Recommendations C-8, C-9, PSS-3, and PSS-4, served as primary motivators for this workshop and were addressed directly in the discussions (labeled as “primary”). Other recommendations, were touched on in some of the discussion questions, but not directly addressed (labeled as “discussed”).

4.0 Results of Breakout Discussion Exercise

Discussions in all seven breakout rooms were lively and participants were fully engaged. A compilation of all answers to the spreadsheet questions is shown in Appendix C. The third column lists options given as possible answers to the questions posed. Those highlighted in red indicate areas of general consensus or wide agreement within and across groups. Participants were encouraged to move quickly through the questions and avoid getting hung up on any particular topic. Not all groups made it through all of the spreadsheet tabs, but most were able to discuss the areas of their primary expertise.

All groups generally followed the train of logic presented in the spreadsheet tabs. In this section, discussions are summarized and points of agreement and contention amongst and between groups are highlighted. Post-workshop analysis examined similarities and differences where appropriate between Moon and Mars discussions, and also between earlier and later stages of campaign build-ups. It was acknowledged repeatedly throughout the two days of discussion that the spreadsheet was a point of departure and contained logic peculiar to the designers of the spreadsheet. Many groups made liberal use of the (d) category of answers and several groups added questions where they deemed appropriate.

There is some intentional overlap between sections, especially in the sections on sample and data acquisition, transport, documentation, and sorting and storage. This was designed to encourage groups to think separately about the constraints of each different step in the sampling process. Results showed that groups answered the same questions differently in different contexts, underscoring the importance of understanding context when developing science requirements.

4.1 Planning

Tab 1 of the spreadsheet was designed to generate discussions on the areas of EVA/IVA planning listed in Section 3.4, especially as they affect the lander, habitat and communications architectures. Important topics identified in this section were data usage, traverse-planning strategies by EVA and ground crews, and IVA activities associated with planning and preparation.

Data Usage

Questions

1. Are precursor site surveys required [none, basic, extensive]?
2. What types of data are needed for traverse planning [photo only, remote sensing, none—Mission Control plans]?
3. What resolution of data is needed for planning purposes [any, ~meter, ~km]?
4. Is real-time data access from the habitat required [instant, daily, none]?
5. Are paper maps and printouts necessary in habitat [yes, no, N/A]?

Responses

The groups were nearly unanimous in their belief that extensive site surveys of the area of interest should be performed at meter resolution or better. High-resolution imaging and multispectral data, as well as mineralogical maps, were particularly desired. Instantaneous, or at least daily, access to orbital/remote sensing data from the habitat was desired, particularly for Mars where it will be important to monitor surface changes. This data will likely be required for safety reasons as well. One surprisingly controversial topic was the use of paper vs. non-paper maps. Several groups had very strong opinions that paper was absolutely necessary because "paper doesn't crash." Others felt that electronic versions would be perfectly adequate and easier to manipulate with gloves on.

Traverse Planning

Questions

1. Which team generates the scientific hypotheses to be tested on traverses [crew, ground, both]?
2. Which team selects the waypoints and plans the routes [crew, ground, both]?
3. Which team develops the sampling strategies [crew, ground, both]?
4. Which team controls the telerobotic scouting prior to traversing [crew, ground, none]?

Responses

The groups generally felt that the best strategy for traverse planning was for the crew and ground to work together. Most participants believed that this relationship would change over time with the ground playing a larger role initially and crews becoming more autonomous during longer stays. Some participants felt strongly that the crew should be given final decision making authority, even in the early stages

Most groups felt that telerobotic scouting prior to EVA would be useful. There was disagreement about whether those scouts should be controlled by the crew or from the ground. True telerobotics on Mars would have to be controlled by the crew; the time-delay is too great for ground control, but ground teams could utilize other types of robotics. Among the lunar groups, some felt quite strongly that remote-controlling robots from the surface is not an efficient use of crew time, particularly during daylight.

IVA Requirements

Questions

1. What type of workspace is required inside the habitat/lander for traverse planning [none, large table, wall screen]?
2. How much crew time is needed for consultations with ground during traverse planning [none, ~15 minutes, ~1 hour]?
3. How much crew time is needed per 8 hour EVA traverse for traverse preparation, gear and instrument readiness **per EVA crew**?
4. How much crew time is needed per 8 hour EVA traverse for traverse preparation, gear and instrument readiness and other support **per IVA crew**?

Responses

All the groups recommended utilizing advanced technologies to replace traditional large-map-on-a-table traverse planning. Some of their suggestions include virtual reality, light tables, and wall screens. One group (MLS) suggested developing new technology to “temporarily project onto a surface that you can write on and erase.”

Most groups suggested allotting about an hour pre-EVA for the crew to consult with the ground and 30 minutes to an hour for other EVA-prep activities. Some groups thought that consultation time with the ground would be reduced with longer stays due to increased crew autonomy (one group, LMH, even felt this could be reduced down to none/automatic in the steady-state case). One of the Mars groups (MSM) encouraged multitasking, saying, “Since communication is not in real time, we need to consider not only the time to transmit and receive, but the time to digest the content. In order to not waste sols, there should be another activity while waiting for completion of the communication.” The groups also recognized that significant time (30 minutes to an hour) would be required for IVA prep in support of EVA. The Mars groups agreed that IVA support for EVA is absolutely necessary, preferably full-time monitoring. The lunar groups were more split on the topic with answers ranging from full-time monitoring to none at all.

It was generally felt that early missions might not need to use data/samples for traverse planning, but that longer missions would require some kind of ability to look at previously collected samples to inform decisions, though not necessarily inside the habitat.

The role of ground support in the decision making structure was heavily scenario dependent. Due largely to the time delay, no Mars scenarios give ground authority, even early on, preferring ground support or full crew autonomy. The lunar groups generally suggested a ground control model for the first 7 day mission, moving towards more autonomy in longer stays (or increased distance). The overall sense was that crews should make decisions in consultation with the ground, but not be denied the opportunity to respond to discovery, particularly in real time. Many groups discussed whether or not the ground would even be able to assert authority over the crews, particularly at Mars and on longer lunar stays. One group (LSH1) suggested that; “[the] crew will listen to the ground if they think they will fly again.”

Planning findings

- When and how a transition to greater crew autonomy would occur was unclear and requires further study.
- Crew time required for traverse planning, data analysis, and other pre/post EVA activities will vary with mission duration and level of crew autonomy. Realistic simulations are necessary to ensure optimization of science.

4.2 Traversing

Tab 2 in the questionnaire focused on issues associated with traversing and execution of extra vehicular activities. Questions relating to navigation, communications, decision-making during traversing, data display and data flow, traverse flexibility and range, and robotic field assistance were discussed.

Traverse Navigation

Questions

1. For navigational purposes (not sampling, measuring, or observing), what precision is required for the rover [~10km, ~1km, ~10m]?
2. For navigational purposes (not sampling, measuring, or observing), what precision is required for suited humans [100's m, 10's m, ≤ 1m]?
3. Where are real-time position mapping and traverse path overlays required [rover, suit, hab]?
4. Where are other real-time data overlays required [rover, suit, hab]?
5. Where is synchronized timecode display required [rover, suit, hab]?
6. Where is automated position and guidance information required [rover, suit, hab]?
7. When is telerobotic scouting necessary [always, sometimes, never]?

Responses

The groups generally concurred that rover navigation precision should be on the order of 10 meters or less. One group (LNP) specified that only obstacle-avoiding navigation at ~100 meters was necessary, but on the other end, another group (MSM) felt that ~1 meter precision was needed. One of the groups (MLS) noted that navigation during Apollo at 100 m was "tough." The groups were more divided on precision for suited humans, with the Mars groups suggesting that sub-meter precision is important, but the lunar groups were comfortable with tens of meters. As in the previous section, there was widespread agreement that the use of telerobotic scouts is sometimes or always useful. One group (LSH1) suggested that it might not be necessary on a first 7 day mission; another (MSM) said, "The default position is to do so as long as it does not create a time resource issue for the crew."

Real time position mapping, data-overlay, and timecode display were desired in the suits, rovers, and habitat. It was generally agreed that all are desired/needed, but there was some disagreement about when and where.

Traverse Communications

Questions

1. Where is 2-way audio communication needed [suit, rover, hab]?
2. Where is 2-way video communication needed [suit, rover, hab]?
3. Where is other 1-way video needed [instrument stations, robotic platforms, none]?
4. Where are real-time data access, query, and display needed [suit, rover, hab]?
5. Where is real-time instrument data analysis for traversing needed [suit, rover, hab]?
6. Where is continuous timecode acquisition needed [suit, rover, instruments].
7. Which elements broadcast telemetry and ephemeris data [suit, rover, instruments]?

Responses

The traverse communication section also revealed tendencies to choose maximum available performance. The questions asked in this section are also highly architecture dependent. The Mars groups, for example, favor more active IVA participation in EVAs and a reduced role for the ground due to the large time delay; this has implications for the types of communication and information needed. It was agreed that 2-way audio was needed between all agents in suits, rovers, and habitats. Video was also desired by most teams, particularly between the rover and habitat. Some felt that while video was important for documentation, real-time was not necessary; it could be stored and transmitted later. Some groups discussed field activities that are already proving their worth, demonstrating in the field that real-time video is a useful feature.

Traverse Flexibility and Range

Note: In this section, groups were instructed to consider these questions from a science perspective only, rather than a safety, engineering, or other logistical standpoint.

Questions

1. Who makes decisions real-time changes in traverse path [crew, ground, none]?
2. If there is no rover, what is the appropriate traverse range (walking) from the suit port [0–1 km, 0–3 km, 0–10 km]?
3. What is an appropriate range for an unpressurized rover for **science** given ~8 hour EVAs (0–1 km, 0–5 km, 0–10 km]?
4. What is an appropriate range for a pressurized rover per trip from the habitat [0–5 km, 0–50 km, 100s km]?

Responses

The groups were unanimous in their belief that the crew should make real-time traverse change decisions, either in conjunction with the ground, or by simply informing the ground. The lunar groups leaned towards joint decisions while the Mars groups expected more EVA crew autonomy.

The questions regarding traverse ranges for suited astronauts, unpressurized rovers, and pressurized rovers were somewhat unclear. For example, the number of available rovers was also not specified, but would clearly impact range requirements. Science requirements for area coverage couple directly with engineering limits on suit and rover range and mobility.

Robotic Field Assistance

Questions

1. Where is the primary command and control for robotic assistance [suit, rover, hab]?
2. Where is the primary display for a traverse scout, if used [suit, rover, hab]?
3. Who requires data for tracking consumables [suit, rover, ground]?
4. How many crew are required to complete all tasks, and how does robotic assistance help or hinder that [2+assist, 2–4+assist, 2 no assist]?

Responses

There was a general feeling among the groups that robotic field assistants could be useful, though that was tempered by concerns about how much time they would consume and whether dealing with them would overburden the field crew or slow them down. Most agreed that robotic assistants should be controllable from suits, rovers, habitats, and/or the ground, and robotic scout information should be viewable in real time. One group (LNP) pointed out that "if you have an assistant you want to be able to control it from wherever you are (including the hab during night)."

Another group (LSH1) noted that even if the robot can be controlled from several locations, it should have "only one boss at a time." The teams were unanimous in feeling that all mission tasks should be accomplishable with at least 2 crew (or up to 4) without robotic assistance in case of robotic failure, even on Mars. There was also a general trend towards more robotic assistance later on during longer stays and with increasing amounts of crew control.

Traversing Findings

- The tendency for groups to prefer the highest level of performance listed may indicate that navigation precision is an area requiring detailed study and field testing rather than relying on opinions to shape surface system performance requirements.
- The traverse communication section also revealed tendencies to choose maximum available performance, which again may indicate that this area needs additional study and/or more specific questions with better-defined terms.
- Field experiments could prove invaluable by providing field tests of proposed traverse communication protocols to determine which communication tools are most effective and what data needs to be transmitted real-time.
- Better-articulated questions and carefully controlled experiments are necessary in follow-on workshops. Studies and field tests are needed to determine appropriate traverse range requirements.

4.3 Sample and Data Acquisition

The sample acquisition section directed attention to issues associated with the automation of documentation *in situ*, communications during sampling, the process and tools for the sampling itself, data acquisition, and again, robotic field assistance.

Documentation

Questions

1. What is the necessary navigational precision for sample location [100s m, ≤ 1 m, ≤ 10 cm]?
2. What is the necessary spatial resolution of instrument data for sample documentation [10s m, ≤ 1 m, ≤ 10 cm]?
3. What is the necessary video resolution for documentation and science purposes [HD quality, TV quality, mpeg quality]?
4. Where are cameras needed [suit head, hand-held, teleoperated]?
5. [Question added by group 7] What sample orientation is best [1°–10°, 10°–20°, 20°–30°]?

Responses

All groups felt that navigational precision for sample documentation should be at least <1 meter resolution and more than half recommended <10 cm. One group (MLS) thought sub-cm resolution would be needed for astrobiology considerations. That group noted, "Apollo had less than 10 cm so we shouldn't go for less." The groups also generally agreed that <10 cm spatial resolution for instrument data was desirable, though the needs would be instrument dependent. One group (MLS again) suggested that sub-cm resolution was needed. That group also noted the need to query such data in real time.

There was a nearly unanimous desire for HD quality video, supporting the paradigm that "more info is better." Specifically, groups felt that high quality video would be good for public engagement and "anomaly resolution and other dynamic issues." Only one group (MLS) said mpeg quality video with high-resolution stills would suffice, but they still recommended that HD be available on request for historic documentation purposes.

In addition to video, multiple still cameras were recommended by nearly all groups: suit-mounted, hand-held, and telerobotic (the more the better was the general sentiment). One group (LNP) pointed out that sometimes a handheld camera can get perspectives that cannot be achieved by a helmet cam, while another (LSH1) suggested a removable mounted chest camera. One group (MLM) also noted a need for hand lens or microscopic imaging capability adding, "Yes, we want it all." It was felt that in another decade, camera and data handling technology will have advanced enough that maximizing the number of high quality imagers will probably not be burdensome to the mission and that this should be the goal. There was some discussion about how much of the video and imagery need to be available in real time and what could be stored for later use and documentation.

Communication

Questions

1. Where is two-way audio needed [suit, rover, hab]?
2. Where is two-way video needed [suit, rover, hab]?
3. Where is other one-way video needed [science stations, robotic platforms, none]?
4. Where are real time data access, query, and display needed [suit, rover, hab]?
5. Where is real-time instrument data analysis for sample collection and subsample decision-making needed [suit, rover, hab]?
6. Where is continuous timecode acquisition needed [suit, rover, instruments]?
7. Which elements need to broadcast telemetry/ephemeris [suit, rover, instruments]?

Responses

The most prominent result from this communication section is that all groups answered "all" to nearly all of the questions above. The few exceptions included the Mars groups, who noted that real-time communications between Earth and Mars should not be in the critical decision-making path. Most groups felt that this is a topic that needs more focused, better-defined questions, detailed study, and field experiments.

Tools and Samples

Questions

1. How should the suite of sampling tools compare to Apollo [Apollo-class, some enhancements, high tech]?
2. What is the average mass of samples that will be collected per 8-hour EVA [≤ 5 kg, 5–20 kg, ≥ 50kg]?
3. What level of robotic assistance is needed during sampling [none, some, max]?
4. Select which tasks would be assisted with teleoperated robotics [analysis, lifting, digging].
5. Select which tasks would be assisted with teleoperated robotics [drilling, breaking, carrying].

6. Select which tasks would be assisted with teleoperated robotics [documentation, transport, scouting].
7. Select which tasks would be assisted with teleoperated robotics [scientific reconnaissance, sample collection, instrument deployment].
8. From where should the control of teleoperated robots be located [suit, hab, ground]?
9. When samples are taken, should they be placed in their permanent containers immediately *in situ*, not to be opened again before return (no analysis in rover or hab) [yes, no, depends on sample]?
10. Should samples be subsampled *in situ* rather than later in the rover or hab [yes, no, maybe-depends on sample]?
11. Should samples be stored just temporarily *in situ* for later analysis/sorting/permanent storage [yes, no, depends on sample]?
12. What is the estimated percentage of samples needing further access before return [0%, 0-50%, ≥ 50%]?
13. What percentage of the total sample mass will consist of "environmentally sensitive samples" [0%, 1-5%, 6-20%]?
14. Will rovers and other transport systems require refrigerators, freezers, pressurized compartments, and/or other capabilities for preserving samples [yes, no, depends]?
15. Is advanced scientific judgment and experience required *in situ* for sample collection [yes, no, depends]?
16. Are "back-contamination" planetary protection issues important [yes, no, depends]?
17. Are "forward-contamination" planetary protection issues important [yes, no, depends]?
18. Is assistance from the ground or hab required for sample acquisition and/or subsampling decision-making in the field [yes, no, sometimes]?

Responses

The groups generally felt that "some enhancements" over Apollo-class sampling tools will be required, with significant "high tech" innovations needed for Mars or long-duration lunar stays. Specifically, more complicated instruments were suggested for biologic sampling and it was noted that sub-sampling tools might be particularly useful for decreasing mass of samples. One group (LNP) pointed out that "high-tech" is not always needed with a reminder that, "a hammer and shovel are incredibly useful." All the groups believe that at least 5–20 kg, and the majority felt that more than 50 kg of samples will be collected per 8-hr EVA, although some groups struggled with ideas for how to enable crews to be more selective in the field to reduce the burden of later sorting and analysis.

Sub-sampling capability in the field was deemed important. All teams said either "yes" or "maybe" to the need for subsampling in the field, but it was not clear if everyone was defining sub-sampling in the same way. One group (MLS) commented that they assume some level of high grading at all phases. One strong reason for sub-sampling in field is to split each sample into two: one for potential return to Earth and the other for study in the habitat. Of course, the ability to do this is sample dependent, two splits of a breccia, for example, will likely not sample the same material, basalts on the other hand would be easier to sub-sample.

There was general consensus that >50% of samples collected will have to be accessed again after collection before they are returned to Earth, except in the case of the earliest lunar missions (~7 days). Some felt that the percentage of samples needing to be accessed would increase with stay and distance due to limitations on return mass.

The percentage of environmentally sensitive samples that will be collected is recognized to be heavily dependent on both site (e.g. near a lunar permanently shadowed crater or the Martian polar caps) and assets (e.g. the ability to drill or excavate to depth). One group (LNP) assumed fewer environmentally sensitive samples in initial stages, increasing as assets grow. Others (MLS) thought the opposite would be true; the percentage of sensitive samples would shrink over time, as biological samples would need to be gathered early before the site is contaminated. Several groups recommended that this topic should be included as part of the suggested CAPTEM study on sampling strategies. The groups were split on whether or not refrigerators/freezers should be required on the rovers. Most groups said either yes or it depends, only one said no. Mars groups were more inclined to favor the idea than lunar groups. More than one group suggested that some measures less than active refrigeration may be sufficient, for example, "seal your container early and don't try to keep cold, but later you want to control the environment," or "insulated cool box, not necessarily active refrigeration or freezing." Active refrigeration/ environmental control may be required at the habitat.

It was universally agreed among the participants that geologic training is very important for the crew. Advanced scientific judgment and experience will be required for most sampling, although there is a role for "dumb robotic rake samples" or other sample grabs. One group (MLS) specifically recommended that at least one EVA member should have geologic expertise and background.

There was general agreement that the ground or IVA crew in the habitat will sometimes play a role in sample collection, although one Mars group (MLS) said they recommended no involvement from the ground. The following comment reflects the general sentiment: "Assistance from Hab [or ground] [should be] possible but never required, and may be desired sometimes."

Not surprisingly, planetary protection issues showed a fairly clear Moon/Mars split for both forward and backward contamination with the Mars groups far more concerned about both. It was noted that Mars protocols will vary widely by site. Several groups suggested that it was important for lunar missions to use the Moon as a test bed for planetary protection protocols for Mars.

One group (LMH) added an additional section on contamination prevention. They were curious about what materials can be used for sample containers and tools. Are there other materials that are acceptable apart from Teflon, aluminum, and stainless steel? This group suggested initiating a study into suitable materials for sample containers as well as sampling tools. On Apollo, hydrogen isotope contamination occurred. The group felt that prevention of this breach will be critical for returning polar samples from permanently shaded areas. They suggest using a bag that is "a combination of a zip and heat sealing, with the zip being the barrier between the heat seal and the sample to prevent reaction between the sample and any released gas. Alternatively, it may work to put samples in zip bags and place these in a bigger bag that is zipped and heat sealed."

Data Acquisition

Questions

1. What is the number of non-camera instruments that should be used for gathering scientific data about samples [0, 1–5, 5–10]?
2. How should sample data be handled [streamed real-time, stored, depends]?
3. What is optimal ratio of EVA science time spent using measurement instruments vs. other scientific activities such as making geological observations or sampling [≤ 5%, 5–30%, ≥ 30%]?
4. What is the optimal ratio of time spent at a site of interest vs. time spent traversing to get to the site of interest [≤ 10%, 10–30%, ≥ 30%]?

Responses

There will be many types and sources of data for each sample. The groups were roughly split between 1–5 and 5–10 non-camera instruments to be used for gathering scientific data about samples. Not all of these instruments would need to be operated by crew—some could be automated or teleoperated. There was a general trend towards recommending more instruments/data on Mars, especially for longer stays. There may have been some confusion about the question, with some groups answering strictly for instruments in the field, but others might have included instrument in the Sample Handling, Exo-curation, and Documentation (SHED) facility, lab, etc. One group (LNP) noted that crews "don't have to use every instrument for every sample." It was suggested that it might be interesting for CAPTEM to make list of all possible sources of data for each sample/subsample at the collection site, at the rover, and at the habitat/lab/SHED.

All groups agreed that less than 30% of EVA time at a site should be spent collecting data using instruments vs. making geologic observations, and more than one group wanted to limit instrument usage to <5% of total EVA science time. One group (MLS) suggested, "[The crew] could have certain EVAs focused on *in situ* analysis, and then another EVA for sample collection." That Mars group also noted that crews might want to do more *in situ* analysis so that they don't contaminate biological samples in or near the habitat. Another group (LSH2) suggested that, "human time is best spent thinking, analyzing, and deciding; robots should do menial tasks."

The question on optimal amount of time spent at the site of interest vs. time traversing produced a wide array of answers, probably because the assumptions behind the question were not clear. The MLM group chose to redefine the question to what is the minimum acceptable ratio of time at site vs. time traversing, to which they answered 10%, though in general they recommend keeping it above 30%. The MLS group feels that the answer will evolve over the course of the mission: "Over [a] 500 day mission, early EVAs will be spent exploring, less time at one specific site. Later EVAs will go to more specific sites, revisiting sites, spending more time at the important sites." The LSH2 group noted that; "things can be learned during traverse; it depends on geologic complexity of the sites; give crew maximum flexibility to take advantage of opportunities (don't script every minute)." Finally, the LNP group suggests that the answer "depends on how far you are going; highly variable but generally you [should] drive less time than you spend at a site."

Robotic Field Assistance

Questions

1. [Repeat question] From where should robotic field assistance be controllable [suit, rover, hab]?
2. Should robotic field assistance accompany astronauts [yes, pre-deploy, none]?

Responses

Opinions were split on how big of a role there should be for robotic field assistants. Responses ranged from none to max, though most felt that there was "some" place for them. The concept is still poorly defined at this point, which led to some confusion, interesting discussion, and many comments. A number of groups repeatedly expressed concern that the robots might slow down the crew or become a "nuisance," but many also thought that they could help automate the documentation process and be useful for a number of other "brute force" tasks including lifting, digging, drilling, breaking, and carrying (one group (LMH) noted "we are not sure how much more advanced than [a] little red wagon we need"). One group (LNP) added the more complex tasks of scientific reconnaissance, sample collection, and instrument deployment to the list of possible tasks for robotic assistants. They cautioned, though, that crews should be supervising the assistants and that there is a limit to what robots can do. For example, it is fine for robots to take photos, but the scientific descriptions must be written or recorded by the crew.

In general, the groups favored the idea of pre-deploying robotic scouts. One Mars group noted that scouts might be particularly useful to avoid human contamination; "for biology studies, could send clean robot before humans for 'special regions'." Another group suggested "caching" rovers, sending them out before the EVA team for future rendezvous. It was noted that robotic scouts could also play an important role in entering dangerous terrain ahead of, or in place of, humans. Robotic scouts also have the advantage of nearly unlimited time vs. the very limited human EVA time and they can continue to be utilized between missions. Several groups concluded that the role of robotic field assistants is an area that needs further study.

Acquisition Findings

- It was concluded that the trade between how much of the video and imagery need to be available in real time and what could be stored for later use and documentation needs further study.

- Future workshops and studies involving collaboration between experienced field sample scientists and experts in the areas of command and control, communications, information technology, and data archiving are needed.
- The idea of subsampling in the field probably warrants an independent study by CAPTEM.
- The CAPTEM study on sampling strategies should include discussions of environmentally sensitive samples.
- It was universally agreed among the participants that geologic training is very important for the crew.
- A study is needed to look into suitable materials for sample containers as well as sampling tools.
- CAPTEM should consider making a list of all possible sources of data for each sample/subsample at the collection site, at the rover, and at the habitat/lab/SHED.
- The role of robotic field assistants is an area that needs further study.

4.4 Transport

This section focused on any specific issues associated with transporting samples using humans, rovers, or other means between the collection site and the return vehicle.

Transport of Samples by Humans

Questions

1. What percentage of sample can be handled/transported by hand, touching the astronaut's bare glove [0–5%, 5–50%, ≥ 50%]?
2. [Repeat question] What mass percentage of samples is "environmentally sensitive" [0–5%, 5–15%, ≥ 15%]?
3. What percentage of time will be required for crew to acquire and handle "environmentally sensitive samples" using drilling, telerobotic sampling in Permanently Shadowed Craters, etc., as opposed to acquiring "regular" samples [0–5%, 5–15%, ≥15%]?

Responses

The percentage of samples that groups felt could be picked up by astronauts and handled "bare-glove" ranged from less than 5% to greater than 50%. There was a clear Moon/Mars split here with the Mars groups far more concerned about contamination of biologically interesting samples. One group (MLS) felt that this number might change over time, with crews being more cautious early on, depending on what is found in early investigations. Another group (LMH) noted that this would depend on "the composition of the glove, the type of sample, and the type of investigation." The percentage of "environmentally sensitive" samples showed a similar Moon/Mars split, although the lunar nuclear power group (LNP) anticipated an increase in later missions as they acquired the infrastructure to drill in permanently shadowed craters. The percentage of time spent handling "environmentally sensitive" samples also showed a significant spread, although all the Mars groups anticipated that greater than 15% of crew time would be spent on those samples.

Transport of Samples by Rover

Questions

1. What is the recommended load capacity for a rover carrying collected samples [1–10 kg, 10–40 kg, 40–100 kg]?
2. What is the recommended rover capability for preserving scientific integrity of the samples [refrigeration, pressurization/vacuum, separation from humans]?

Responses

There was general consensus among the groups that the load capacity required for samples on the rover should be 40–100 kg, with at least two groups (LMH, MSM) suggesting greater than 100 kg. One group (LNP) suggested that crews may want to trade this allocated mass on an unpressurized rover with other requirements, but it should never be less than 10 kg. One group (MLM) suggested framing this in the context of how much the crew is expected to pick up during a single EVA and then designing for 3–5 times that amount to enable pressurized rover overnight traverses.

The groups were split on rover requirements for preserving sample integrity. Although all groups agreed that avoiding human contamination was important, there was no consensus on the need for temperature and/or pressure control on the rovers. The groups also clearly recognized that the requirements are highly sample dependent. It was noted that, as standard practice, all samples should be kept in bags or sealed containers to keep them environmentally segregated and to protect them from human out-gassing.

Habitat Transport/Pass-through

Questions

1. Is a glovebox inside the habitat (or lab) needed [yes, no, depends]?
2. Is it necessary to have a direct pass-through from rover to glovebox [yes, no, depends]?
3. What is the percentage of samples that could be handled barehanded by humans inside a lab and returned to Earth with the humans [≥ 40%, 0–40%, 0%]?
4. Should samples ever be removed from their initial containers by humans [yes, no, some]?
5. What percentage of samples can be removed from their initial containers (inside a controlled lab or glovebox) [0%, 0–30%, ≥ 30%]?

Responses

The groups were nearly unanimous in their belief that rocks handled in a human environment with bare hands are contaminated and should not be returned to Earth. The one exception was the MLS group that felt geologic samples could be handled, just not those studied for biologic purposes. One group (LSH2) noted that such "contaminated samples" could be returned "in exceptional circumstances," such as in the case of a unique feature or discovery that was not seen in any other samples.

There was widespread disagreement on the need for a habitat-internal glovebox and/or rover-to-habitat sample pass-through. One group (MSM) suggested a glove box/robotic arm in a contained environment outside of a habitat, but accessible by a non-suit-wearing crewmember. One group (LMH) was adamant that samples should never be brought into the habitat because that would contaminate the samples on both the Moon and Mars and could "contaminate the humans" on Mars. There was a similar range of answers for a glovebox and/or pass-through on the rovers. The MLS group had some interesting insights: "[the crew] can have [the] sample contained and then put [the] container (cleaned) in glovebox, [then] open [the] sample container (as done in terrestrial bio labs). [The] task of sterilizing boxes

is not trivial, [because this process] can [itself] contaminate samples so a drop-box would be useful. Pass-through eliminates steps for returning samples to [the] habitat glovebox. [The rovers] can [be used] to collect initial samples and then test samples in [the] habitat for contamination before [the] first EVA. If traversing long distances in pressurized rover, rover-glovebox pass-through would be useful so [crew] can analyze samples in rover in [the] field. If you ever need the pass-through, might as well keep it for the duration of missions.
Most groups thought it would be necessary for some samples (>30%) to be removed from their original containers for further analysis, high grading, and subsampling. There was a general sentiment that earlier, shorter missions would have a smaller percent of such samples because there would be less need and time for sorting and analysis and, presumably, a higher ratio between samples collected and samples returned to Earth. All agreed that there will be some samples placed in Special Environmental Sample Containers (SESC) that are not touched again until returned to Earth. One group (MSM) noted that doing sample splits in the field eliminates the need to reopen containers destined for Earth return.

Transport Findings

- The concept of a glovebox, whether human tended or equipped with robotic manipulators, is controversial and requires further study.
- Open question—If there are duplicate samples taken in the field, would a glovebox still be needed to analyze the duplicate samples that would not be returned to Earth, or could some samples then be analyzed without a glovebox in the open laboratory air?

4.5 Documentation

The burden that sample documentation imposes on surface system hardware and operations is enormous, and was one of the primary motivators for this workshop. This section of the questionnaire was long and detailed with many questions related to possible automation of tedious documentation processes. Topics discussed included data flow and storage, position accuracy requirements, some repeated audio and video questions, subsampling strategies and automation, and decision-making.

Automated Documentation at Site

All questions in this section pertain to the site where rovers and astronauts are located during EVA.

Questions

1. Are **real-time** sample and data position and time stamping, plotting, correlation, and overlay required [required, desired, not required]?
2. Are **automated** sample and data position and time stamping, plotting, correlation, and overlay required [required, desired, not required]?

3. What is the real-time rover position accuracy upper limit required for sample science documentation [~km scale, ~10 m scale, ~m scale]?
4. What is the real-time suit position accuracy upper limit required for sample science documentation [~km scale, ~10 m scale, ~m scale]?
5. What is the real-time instrument position accuracy upper limit required for sample science documentation [~10 m scale, ≤ 1m, non, time only]?
6. What is the post-processed instrument pointing accuracy/resolution required for sample science documentation [~10 m, ≤ 1 m, ≤ 1 cm]?
7. Is synchronized time stamping on all cameras, instruments, rovers, robotics, etc. needed [yes, no, depends]?
8. Should continuous video documentation be recorded [all samples, general context only, optional]?
9. From where should continuous video be broadcast real-time during EVA [suits, rovers, other]?
10. Where should real-time continuous video feeds be available [suits, rovers, hab/ground]?

Responses

Synchronized time stamping on all data is strongly recommended. Other automated documentation and data overlays (including instruments, photos, video, audio, etc.) were either desired or required by all groups. The Mars groups tended towards "required" while the lunar groups largely said, "desired." There was some discussion within the groups about how much automation was needed or recommended. Some groups felt that human documentation was sufficient and that automated systems might be intrusive, while others felt automation would save considerable time. One group (MLM) noted that if the system fails, crews would still need the ability to document manually so collection would still be possible. Another group (LNP) noted that continuous audio recording is very good, as is a set of pre-numbered sample bags, like Apollo used.

Most groups felt that, in real-time, the rover position should be known to within about 10 meters for sample science documentation needs. One group (MLS) noted that if the rover is taking samples directly, then higher precision is needed. Another group (LNP) said that precision needs only to be between 10 and 100 m and suggested flagging or using beacons to identify interesting areas to allow crews to find specific locales again.

The lunar groups largely felt that a similar ~10 m accuracy was sufficient for locating a suited crewmember. The Mars groups, however, all suggested that a higher level of accuracy (~1 m) was important for crewmember positioning. It is not obvious why answers were split this way, but it could be due to an increased role of the ground in real-time positioning/vectoring for lunar EVAs vs. Mars. At least one group (LSH2) believed that real-time data wasn't necessary at all; "precise sample position [is] best obtained from photography; real-time suit position [is] not necessary for this."

The groups largely agreed that post-processed position accuracy needed for sample documentation should be at the < 1 cm level, though some felt that the needs here would depend highly on both the instrument and the context with some samples requiring less accuracy than others. The needs for real-time position accuracy will depend upon the level of context required for a particular investigation.

There was good agreement on continuous video recording. Most groups said all samples and sampling should be video recorded. One Mars group (MLS) said video is optional: "[Crews] may want continuous video from rover for operations, also so support team can support [the crew] (also include stereo for further sample context)." There was a unanimous recommendation for real-time continuous video broadcast from the suits and nearly unanimous desire for it on rovers. Most teams recommended video on demand in other locations as well, e.g. in habitat or on ground. There was also a consistent opinion that video inside the suit all the time is undesirable and would be distracting, but could be useful on demand.

Sub-sampling at Site

Questions

1. Can subsampling be automated once samples are identified [yes, no, maybe]?
2. What tools are needed for manual subsampling at site [hammer, hand drill, scoop]?
3. Is the subsampling in the field the final step in subsampling vs. later subsampling in lab or SHED [permanent, temporary, both]?
4. [Repeat question] What is the percentage of samples that are permanently sampled at site, needing no further documentation, subsampling, or analysis prior to return to Earth [0–10%, 10–30%, 30–100%]
5. What types of samples are easily permanently subsampled at the site [drill cores, regolith, rocks]?
6. What types of samples require careful preservation and later subsampling before return [astrobiology samples, volatiles, none]?
7. Does the subsampling strategy require lab-in-hab analysis [yes, no, depends]?

Responses

In this section, subsampling was defined as the splitting or sub-splitting into two or more pieces from the same rock or soil sample for the purpose of distribution to various science teams or for the purpose of fulfilling different sample integrity preservation requirements. The groups were fairly unanimous in understanding that some sub-sampling will be done at the collection site. There was, however, a relatively clear Moon/Mars split for *automated* sub-sampling, with Mars groups more heavily favoring automation. This split might reflect astrobiology sampling requirements and/or more pressure on smart sampling due to the anticipated reduced sample return mass.

There was widespread disagreement about the percentage of samples “permanently sampled” in the field, i.e. those needing no further documentation, sub-sampling, or analysis after collection and prior to return. Percentages ranged from less than 10% to between 30 and 100%. All groups agreed that there would be some samples that would be sealed in containers at the time of collection and not opened again until they were returned to Earth. These types of samples likely will include drill cores and regolith; some groups also felt that rocks may occasionally fall in this category. A number of groups suggested that this percentage was dependent on the return mass allowed and mass of samples collected, as well as the types of samples. There will be less time and need for further analysis and sample triage on short missions, but the percentage is likely to increase as missions become longer and the ratio between mass collected and mass returned grows. One Mars group (MLS), however, suggested the opposite might happen as the “most highly interesting samples” (biologic) may be collected late in their 300-day mission. Another Mars group (MLM) had some interesting comments about collecting biological samples: “Bio specimen collection may be conducted with robotic tools. Need to sterilize tools for bio sampling in between sample collection. Alternative = have rack of pre-sterilized tools in field (equivalent of a box of plastic gloves that are used in the field). One-time use equipment has mass considerations. Likely not disposable but instead return to habitat for re-sterilization.”

One concept that deserves further study is the idea of duplicate sampling. One group (MSM) noted that; “all kinds of investigations might have samples that wouldn’t be touched before return to Earth, but if we have splits, we can keep one pristine and look at its clone.” As noted earlier, duplicate sampling is not feasible for all sample types; breccias, for example, do not lend themselves to this.

Data Usage

Questions

1. [Repeat question] Are data to be used, broadcasted, and available in real-time [yes, no, some]?
2. Where is data primarily stored [rovers/instruments, hab, ground]?
3. Which humans are primarily responsible for data analysis and interpretation to be used in immediate science planning [crew, ground, combination]?
4. Which humans are using the data and making immediate science plans based on data [crew, ground, combination]?
5. Are data used for robotic return to sites of interest if crew time is limited [yes, no]?

Responses

There was a consistent desire for data to be stored both in the habitat and on the ground. Some of the Mars groups recommended additional enhanced data storage capabilities on the rovers. While some groups believed that the ground would be the ultimate storage repository (and also the "great data processor in sky"). At least one group (LSH2) felt that the habitat would be "truly primary"; and transmission to the ground could be "delayed, partial, or both."

There was a general consensus that the crew and ground would jointly use data to prepare immediate science plans, though there were some expectations that the ground would do more work on shorter missions and the crew would have a larger role on longer missions. No teams suggested that data would be recorded only, and therefore, data was assumed to be needed in science planning. The Mars groups pointed out that due to the time delay, crews would have to make decisions on their own during EVA, but the ground would be helpful to plan the next EVA.

The groups generally agreed that a combination of crew and ground would do primary data analysis and interpretation, though again, there were some expectations that the ground would do more work on shorter missions and the crew would have a larger role on longer missions. One group (MLS) noted that the people on the ground have more time and resources to analyze the data, and that, particularly on long-duration missions, the crew must have some science analysis capabilities; "for 500 days on Mars, crews will adjust research directions based on data collected in field." That group also felt that the crew should be publishing in scientific journals while on Mars.

There was also unanimous support for data to be used for robotic return to sites of interest.

Documentation Findings

- The process of documentation and the roles of humans, machines, and automation in the process, will have a large impact on science return and the optimization of surface activities. This is an area rich with topics requiring further study.
- In the plenary discussion after the breakout sessions, it was clear that questions of navigational accuracy for sampling need further refinement and need a solid foundation of field-testing and validation for answers to be meaningful.
- The idea of duplicate sampling deserves further study.

4.6 Sorting/Storage

Sample quantity, high-grading and sub-sampling

Questions

1. What will be the total collected sample mass over each mission [≤ 100kg, 100–300 kg, ≥ 300 kg]?
2. What is the mass percentage of samples that can be stored outside in an open area near the outpost/hab in a "rock garden" [0%, 0–15%, ≥ 15%]?
3. What is the percentage of total collected samples that can be stored in open containers in the SHED facility [0–30%, 30–80%, 100%]
4. What is the mass percentage of total collected samples that must be stored in closed/conditioned containers in SHED or other storage facility [0–10%, 10–25%, ≥ 25%]?
5. What is the mass percentage of samples that must be stored in closed/conditioned containers away from the habitat with no interaction with the lab, hab, or suited/gloved humans [0–5%, 5–25%, ≥ 25%]?
6. What is the mass percentage of samples designated for return that can enter the lab or hab [0–5%, 5–25%, ≥ 25%]?
7. Where should sorting, subsampling, and high-grading take place [Outside the hab (EVA), inside the hab or lab (IVA), or telerobotically in SHED]?

Responses

There was unanimous agreement in believing that far more sample mass would be collected per mission than is likely to be accommodated for return. All groups said that greater than 300 kg of samples would be collected over each mission (except perhaps the earliest 7 day lunar mission). This necessarily implies that some sort of post-EVA sorting and triage will be needed, and some type of "storage" near the habitat will be required.

The groups were split on estimates of crew time required for sorting, sub-sampling, and high-grading per 8-hour EVA, though most groups thought under two hours would be appropriate. One Mars group (MSM) said greater than 6 hours; "it takes a long time to do this task—it might be part of the EVA, it might be other crew, it might be tethered EVA—this one is a red box on the risk matrix." One lunar group's (LSH1) estimates reflected greater pressure on sub-sampling for longer stays due to constraints on sample return mass. Another group (MLS) suggested having external consumables so when the crew returns from their EVA, they could plug into the habitat and still be able to work outside; "so 8 hr EVA could become 10 hours outside of hab." That group also noted that EVA sampling must be organized enough that post-processing documentation is already done, noting, "We don't want to create a backlog of samples that must be sorted/documented/etc. We need an efficient way to keep up with the rate of sample collection."

The groups generally felt that sorting/subsampling/high-grading would occur in multiple modes: EVA-outside, IVA-lab, and Telerobotic SHED. There was one group with a strong dissenting opinion (LMH) that these tasks should be performed in a telerobotic SHED only and that no humans should go near the samples.

Subsampling Inside Habitat (Glovebox Requirements)

Questions

1. Is an instrument suite for sample analysis and subsampling inside habitat needed [required, not required, optional]?
2. How should samples be transferred into glovebox for crew access [robotic directly from outside, hand-carried, closed container through habitat]?

3. What level of instrumentation in the glovebox is needed [basic, elaborate, depends]?
4. Should the glovebox be pressurized and/or temperature controlled [nitrogen purge, cold, vacuum]?
5. [Repeat question] Can any samples be handled inside the habitat outside the glovebox [always, never, sometimes]?
6. How big of a problem is dust control in the lab/hab [big problem, small problem, no problem]?
7. [Repeat question] Is a dedicated sample pass-through directly to the glovebox required [yes, no, N/A]?

Responses

There was general agreement that a substantial percentage of samples (at least 15%) could be stored outside in the open near the outpost/habitat. Many groups specified that samples would need to be in bags to avoid contamination from the habitat and other human activity, but that environmental control wasn't necessary for all samples. One group (LMH) additionally specified that they would need to be out of direct sunlight. Some groups were also concerned about the name of the external storage site; "'rock garden' term implies disorder; organized external storage okay."

Nearly all the groups were surprisingly adamant that any samples brought into the habitat/lab for study would not be considered pristine and no samples that had been in the habitat should be returned to Earth, except in exceptionally rare cases. Only one group (MLS) felt that geologic (not biologically interesting) samples could routinely be brought into the habitat and still be acceptable for return.

One group (LMH) was adamant in their belief that humans should not interact with samples at all, not even in a human-tended glovebox. They preferred a telerobotically-operated gloveless "glovebox," what they termed a "master-slave manipulator box." All of their answers to glovebox questions assumed such a configuration. A second group (LSH2) also did not like the idea of having the glovebox inside the habitat, but felt that it could be accessible from the habitat (through a wall) with either gloves or robotic manipulators. There was, however, much discussion in many of the groups about the degree to which telerobotic manipulation is possible, desirable, and sustainable on lunar and Mars surfaces.

The instrumentation needs/desires for a glovebox were very split, as half of the groups said, "basic," and the other half said, "elaborate." There was a general recognition that the longer the mission, the more elaborate the lab equipment would need to be because triage would become more important.

The Mars groups were quite clear about recommending maintaining Mars ambient conditions in their glovebox facility in terms of both temperature and atmosphere. The two lunar groups that answered were split with one recommending the glovebox utilize a nitrogen atmosphere and the other recommending lunar ambient conditions.

Sample Handling, Exo-curation, and Documentation (SHED) Facility

In this section, a specific concept was introduced for discussion: an unpressurized SHED (possibly using a converted logistics module or other used surface asset) with tactile, highly capable dedicated telerobotics (e.g. Robonaut) inside. Sample storage, access, sorting, and basic analysis tasks could be performed from the ground, the hab, or the field. The SHED would be designed to conserve EVA time, improve dexterity, and minimize contamination in sample handling, sorting, and storage.

Questions

1. Is the SHED an interesting concept [good idea, bad idea, intriguing]?
2. Is an external or separate sample storage and handling facility required [all samples, some samples, no samples]?

3. What instrumentation is needed inside the SHED [saw/polisher, microscopes, SEM]?
4. What is the estimated power required for the SHED [~Watts, ~ kWs, ~ hab]?
5. What is the estimated mass of the SHED infrastructure, not including the module shell (including shelving, sample containers, care and feeding, instrumentation, and 100 kg per robonaut) [~200 kg, ~500–1000 kg, ≥ 1000 kg]?

Responses

All the groups found the SHED idea to be either "good" or "compelling" and worthy of further study. Although most groups liked the idea of a SHED, they were very concerned about samples being stored in "open containers." All agreed that sample contamination and cross-contamination are serious issues. There were many comments that all samples should be individually bagged: "Every sample will have a bag and every sample will stay in its bag or SESC (Special Environmental Sample Container) unless actively being analyzed."

The groups had no clear idea of the mass of such a SHED facility, or the power required for operations. Several suggested the mass would be between 500–1000 kgs for the Moon and possibly greater than 1000 kg for Mars. The size and parameters of a SHED or other storage facility concept needs further study.

Sorting and Storage Findings

- Due to the unanimous agreement that far more sample mass would be collected per mission than can be returned, it is clear that post-EVA sorting and triage will be needed, and some type of "storage" near the habitat will be required.
- The use of gloveboxes or telerobotically operated equipment for sample analysis in or near the habitat is clearly an area that deserves further study.
- All the groups found the Sample Handling, Exocuration, and Documentation (SHED) idea to be either "good" or "compelling", however, the size and parameters of a SHED or other storage facility concept needs further study.
- Some group members expressed very strong feelings against bringing any samples into the habitat.

4.7 Laboratory Analysis

Sample preparation capabilities and minimum analysis capabilities

Questions

1. Where should brushing, scooping, and other sample handling be done [glovebox in hab, SHED, EVA]?
2. Where should sample containers be stored [glovebox, SHED, EVA]?
3. Where are scales needed [glovebox, SHED, EVA]?
4. Where are sieves needed [glovebox, SHED, EVA]?
5. Where is a rock polisher needed [glovebox, SHED, EVA]?
6. Where is a rock saw needed [glovebox, SHED, EVA]?
7. Where is a thin sectioning machine needed [glovebox, SHED, EVA]?
8. Where is a polarizing microscope needed [glovebox, SHED, EVA]?
9. Where is temporary storage needed [glovebox, SHED, EVA]?

10. Where is a portable spectrometer needed [glovebox, SHED, EVA]?
11. Where is a Scanning Electron Microscope needed [glovebox, SHED, EVA]?
12. Where are gloves needed [glovebox, SHED, EVA]?
13. Where is a dust control system needed [glovebox, SHED, EVA]?
14. Where are rock hammers needed [glovebox, SHED, EVA]?

Responses

All groups agreed that **hammers** are very handy on EVA and in the SHED; several even wanted hammers in a habitat glovebox. One question that was not asked was if a rock splitter would be a useful tool inside a glovebox, probably more practical than a hammer.

Almost all the groups indicated the need for a **scale** in the SHED and a habitat (or non-habitat) glovebox and three groups also recommended one on EVA. Two groups made the distinction between having a “balance” in the glovebox and a “scale” in the SHED.

There was unanimous agreement that **sieves** are needed in the SHED. Most groups also recommended sieves in a glovebox and on EVA. Several groups pointed out that sieves will be of different scales in different places, coarse sieving in the field (like the Apollo rake), and fine sieves in the lab.

The groups were split on the need for **rock polishers** or **rock saws**. About a third of the groups saw no need for such tools. Those who did recommend them mostly thought they should be in the SHED, but suggested that such “messy” tools should be in a separate SHED or at least well separated from samples and analytical instruments. Two groups suggested that for EVA, rather than a traditional rock polisher or saw, they would like to have an abrasion tool similar to the RAT (Rock Abrasion Tool) on the Mars rovers.

Results were similar for a **thin sectioning machine** with one group saying it was not needed and another that it was only needed for later, longer missions. If recommended, most groups preferred to put the machine in the SHED, though one group thought it belonged in a glovebox.

It was universally recognized that dust will be a significant problem, particularly given the realities of processing samples—sawing, hammering, drilling, polishing, pouring soils, etc., and steps should be taken to segregate these dust-generating processes from both humans and other samples.

Most groups recommended a **polarizing microscope** in a habitat glovebox. Some also thought it may be useful in the SHED. One group (LMH) noted that a **binocular microscope** would be of more use. Portable **spectrometers** were also generally desired in the habitat, the SHED, and on EVA, though more clarification about what kind of spectrometer(s) was recommended. Groups were more split on the utility and practicality of an **SEM** (Scanning Electron Microscope). Two groups said an SEM was not required, another said it was “not required, but desired if practical.” One group recommended SEMs everywhere, including on EVA. One group (LMH) also discussed the idea of a hand-held **XRF analyzer** for bulk geochemical analyses to be done in the field or in the SHED.

Sample Pass-through

Questions

1. Is it acceptable to pass samples in sealed containers through hab to the glovebox
   [yes, SHED only, non-returned samples only]?
2. [Repeat question] Is a dedicated sample pass-through necessary directly from outside into glovebox
   [required, SHED only, not required]?

Responses

The majority of groups responding felt that samples, even in sealed containers, should never be transported inside the habitat to a glovebox. The groups generally preferred a pass-through direct from the outside into a habitat glovebox, except the groups that opposed having a habitat glovebox at all.

Advanced analytical capability

Questions

1. Should there be a capability for extended sample handling and analysis operations using teleoperated robots in the SHED by ground teams [yes, no, depends]?
2. How quickly should additional analytical equipment be supplied to the SHED [quickly, slowly, not at all]?

Responses

All groups said "yes" or "it depends" to the use of extended sample handling and analysis operations using Robonaut (teleoperated robot) in the SHED by ground teams. One Mars group (MLS) noted that while they are there, they recommend the crew to be able to control Robonaut from inside the habitat. The ground can assume control after the crew leaves, but the group notes that; "anything that can be operated from ground after [the] crew leaves should be left in a configuration to allow this dual-mode ops scenario."

Synergy with ISRU

Questions

1. To what extent do science and ISRU needs overlap [none, some, great]?
2. In what ways do they overlap [*in situ* measurements, sample needs, lab equipment needs]?
3. [Added question] How will ISRU waste be disposed of [dump on surface, process further, use for science]?
4. [Added question] What cleaning protocols are required to minimize sample cross-contamination in the sample processing facility [none needed, gas jet, wipe down]?
5. [Added question] What further development of micromanipulators is needed for sample processing and curation, especially at low temperatures?

Responses

The groups generally agreed that science and ISRU needs overlap either "some" or "a great deal" in all ways listed—*in situ* measurements, sample needs and lab equipment. One group (LMP) commented; "a lot of the same instruments and measurements will be needed for characterization of site/materials for science and ISRU. The synergies are such that a purely science mission will have ISRU implications and vice-versa." That group also discussed how ISRU waste would be disposed of—on early missions, it would likely be simply dumped on the surface, but for later missions such waste products could be further processing to extract more material, and possibly used for science.

Laboratory Analysis Findings

- The choices and utility of tools for sample preparation needs further study.
- The choice and utility of *in situ* and habitat/SHED laboratory analysis tools also needs further study.

4.8 Sample Return

Transport to Ascent Vehicle

Questions

1. How is sample mass returned [inside crew return capsule inside containers, attached to outside of crew return vehicle, independent of crew return vehicle]?
2. How is mass transferred to ascent vehicle [robotically from SHED, robotically from hab, humans carrying boxes]?
3. [Added question] Is robotic sample return (separate from crew activities) needed [desired, required, no]?
4. Is Mars sample return to the Moon or another way-station necessary for planetary protection [yes, no, N/A]?

Responses

All the groups concurred with the idea that samples would be transferred to the ascent vehicle by astronauts carrying boxes, although at least one group (MLM) felt that such transfers should ideally be performed robotically. Four of six groups said that samples could be returned inside the crew capsule (in closed containers) while a fifth group had no preference, as long as the samples arrived safely. The sixth group (MSM) suggested the samples should be either attached to the outside of the crew return vehicle or launched independent of crew. Two other groups also suggested that robotic sample return might be preferred. In addition to reducing the design constrains on the crewed return vehicle, an independent sample return vehicle provides for the possibility of early sample return, particularly for long Mars missions, which would allow the ground to perform initial analysis on samples while the crew is still in place and would provide a contingency sample in case the crew doesn't return. One group (MLM) questioned whether planetary protection issues may require that Mars samples need to be returned to the Moon, or space station, or some sort of Mars way-station rather than directly to Earth.

Sample Return Findings
• A trade study is needed for cost/benefit analysis of independent sample return.

4.9 Curation

Mass Returned per Flight

Questions

1. Do you agree with the initial CAPTEM lunar mass return study results [yes, no, N/A]?
2. Is more sample return mass needed for Mars [yes, no, maybe]?
3. Are more samples needed per return flight [yes, no, maybe]?
4. Are more biological or environmentally sensitive samples needed from Mars [yes, no]?
5. [Added question] Is it necessary to curate Mars samples under Mars temperature conditions [yes, no, depends]?
6. [Added question] Is it necessary to curate Mars samples under Mars pressure conditions [yes, no, maybe]?

7. Is it necessary to curate Mars samples under ambient Mars atmosphere conditions [yes, no, depends]?
8. As our paradigm for sampling lunar materials is changing from Apollo, should that for curation also be changed [yes, no, depends]?

Responses

The groups mostly agreed with the CAPTEM study which recommends a minimum return sample mass per flight of 260 kg, but some felt that the CAPTEM estimate for return mass should be taken as a minimum and that the number may evolve for longer stays. As a general rule, groups would like as much mass for returned samples as possible, "and then add 10% more."

There was some diversity in answers about whether sample return mass from Mars should be different than from the Moon. Most felt that the basic idea was the same, but with additional difficulties at Mars due to even more limited mass return fractions. Astrobiological and biochemical samples will also likely be required and need special handling for return. Most groups felt that there would be more environmentally sensitive and biological samples required from Mars, though there was confusion about whether "biological," as it was worded in the questionnaire, referred to "astrobiological" or "medical."

Curation Findings

- The CAPTEM study of a minimum 260 kg return sample mass is a reasonable minimum, though a larger number would be desirable for longer stays.

4.10 Additional comments from individual groups

The majority of new questions posed by the groups fell in the area of sample integrity and the prevention of contamination, underscoring the need for more study in this area.

Questions

1. How will samples be contained—container materials and types?
2. What new protocols need to be developed for clean collecting and prevention of cross-contamination?
3. What would contamination be?
4. Is acidic sample containment necessary for biologically interesting samples?

Responses

Beyond the questions presented in this category, two groups added questions and issues that they feel need to be addressed. The LMH group suggested that Mars samples will need to be transported and curated under Mars temperature conditions and some samples may need to be kept under Mars pressure and atmospheric conditions as well. The group also noted that in addition to meeting the future needs of curation of Mars samples, the current lunar curation paradigm also needs to change along with the exploration paradigm and the curation facilities need to be expanded. "The lunar vault is finite and will need to be expanded if the Apollo model is continued."

The MLM group was concerned about containment and controlling contamination. The group called for clear requirements stating how samples will be contained; i.e. what container materials and types will be used and what clean collecting protocols will be needed. These questions are particularly important for biologically interesting samples and acidic samples. There was also concern about preventing cross contamination during collection and procedures. How can such contamination be avoided, and how can it be identified? The development of sample containers requires further study to ensure that, if possible, containers developed for the Moon could also be used on Mars (i.e. two separate development procedures and costs are not required).

Other Findings

- The development of sample containers requires further study to ensure that, if possible, containers developed for the Moon could also be used on Mars (i.e. two separate development procedures and costs are not required).

5.0 Issues that require further study

Table 2 lists questions synthesized from discussions during the two day workshop and shows the architectural elements that are impacted by sample science or that pose constraints for science. An attempt was not made at the workshop to prioritize the various questions in terms of importance or urgency. However, specific impacts on various architecture elements were discussed. If sample science requirements could be viewed as impacting or being constrained by an architecture element, it is indicated with an x, with red highlighting areas of major impact. Discussions illuminated the need for these listed items to be included as elements of workshops or studies engaging appropriate engineering and scientific communities. Discussions also highlighted the dependence of most issues on the type and location of the mission (outpost vs. sortie, Moon vs. Mars), mission duration and frequency, and the nature of when the mission is occurring in a longer campaign, e.g. whether it is part of the outpost build-up phase or in the steady state of outpost operations. Any further studies on the issues below should explicitly consider these factors. Table 2 is not an exhaustive list of exploration science questions, but is in all cases focused on those issues affected by sampling and curation.

- **Sample Return Mass and Volume:** What are the sample return mass and volume required per flight as a function of mission duration and type/location of mission? These mass and volume requirements affect every system in the architecture and is, therefore, viewed as one of the highest priority science requirements to define, both in terms of importance and urgency.

- **Sample Handling Facility:** Is a separate sample handling facility (SHED) necessary? If so, when? And if so, what are the basic requirements (mass, volume, functionality) of such a facility or capability? What degree of telerobotics is required and acceptable to optimize crew time but minimize risk due to complexity of systems?

The definition of requirements for this facility, if needed, is also a very high priority due to its impact on overall science mission mass, complexity, and quality of samples returned. The nature of this facility both drives and is constrained by all architecture elements because it is a key element in the sample handling trades. It affects capability requirements for the suits, the rovers (especially pressurized rovers, if used), all habitable work mass, volume, and functionality.

- **Mobility:** What are realistic traverse ranges based on science goals and time needed for observations, measurements, and traversing, given different suites of possible mobility systems and spacesuit capabilities? What is the appropriate level of robotic and telerobotic activity and how can human and robotic systems be optimized to reduce cost and risk and maximize science return? Rovers and their capabilities have long been recognized as a core exploration capability, and much iteration will be required between science needs and technological feasibility in defining the masses, volumes, and functional requirements of mobility systems. The importance of small robotic platforms for science is high, as is the capability for remote or autonomous operation of these small platforms for operations when crew are not present or are otherwise occupied.

- **Curation And Sample Integrity:** What are the requirements for curation activities on the Lunar/Martian surfaces, as well as on Earth, to account for reduced fraction of sample return mass to collected mass? What unique capabilities are required to preserve sample integrity? How much sub-sampling and duplicate sampling in the field is necessary to minimize contamination and maximize sample quality? What protocols need to be developed for this? Curation begins at the moment of sample acquisition and therefore impacts and is constrained by every system the samples see between the suited astronaut or rover and Earth. Future missions will see far more challenges than Apollo in optimizing sample acquisition and preserving sample integrity because of increased mission durations, increased desire for more environmentally sensitive samples, and preparation for Mars and its planetary protection constraints.

- **Laboratory, Tools, Eva Suits, And Iva Science Planning:** What sample acquisition and analysis tools and facilities are needed, and when are they needed with respect to other mission priorities? Where are the various tasks best performed? What specific facilities and capabilities are needed for scientific traverse planning, if performed by the crew? Map tables or walls require volume and possibly high bandwidth communications. Gloveboxes require instrumentation and are extremely taxing to work with for long periods of time. Some tasks are not possible inside gloveboxes. The design of tool suites, even for sample acquisition, is driven by the types of samples desired and by the analysis and sample handling crews are required to perform before the samples are returned. Enhanced suit and rover capabilities could reduce the burden of later analysis, and therefore reduce required crew time and resources.

- **Decision-Making:** What are the most appropriate modes of decision-making, authority, and autonomy for flight and ground crews? How might these modes change with mission duration and light time delay? This is one of the most important operational decisions affecting the design of scientific exploration systems. It is also one of the most complex set of trade studies to carry out due to its influence on every system. Increased crew autonomy in planning and decision-making can both increase and decrease mission risk, cost, and complexity. If more decisions are made by the ground, as in a traditional mission control model, the burdens on communication and data systems can be extremely high, especially as mission duration increases and more real-time decisions are required. If more decisions are made by the crew, more sophisticated hardware and software is required on the surface and more crew time will be required for planning, analysis, preparation, and documentation. High communications bandwidth seems to be requirement in all cases, although real-time data requirements change depending on where decision-making is centered.

- **Navigation And Communication:** What are the science requirements for navigation (e.g. precision, accuracy, accessibility) and communication tools (e.g. 2 way audio/video, real time position mapping, data-overlay, timecode display)? How are the science requirements different from general mission requirements for navigation and communications? Should sample data be acquired, processed, and displayed real-time or should it only be stored? How accurately does position and orientation need to be known real time? More attention must be given to the specific constraints and requirements that sample science places on communications and navigation systems. In this area, assumptions are often made, and there is little data upon which to draw for the exploration modes being developed. Navigation and communications requirements for sample science on future lunar and Mars missions will be very different from Apollo and very different from previous robotic missions to the moon and Mars. Field tests are needed in this area to refine and verify any requirements that are developed.

- **Crew Scheduling:** What are the most accurate estimates of time required to perform specific sample science tasks, including traverse planning, navigation to and between sites of interest, observation, *in situ* measurements, sample acquisition, documentation, temporary storage, lab or SHED analysis, sorting, and permanent storage? While it is important for scientists to begin making very accurate estimates of time required for various tasks, it will be necessary to refine these estimates by simulating the protocols under realistic mission constraints with functionally high-fidelity hardware. Such simulations will reduce the risk of overestimating crew performance or underestimating time required for science tasks. Documentation and communications should be included in any realistic simulation.

Summary and Next steps

The Workshop on Architecture Issues Associated with Sampling was designed as a scoping activity to generate and articulate high-priority questions and frame OSEWG's future work. Each question listed in Table 2 could serve as the basis for one or more workshops or detailed study activities, and the OSEWG plans to undertake a series of workshops and studies addressing some of the priority issues. Specifically, CAPTEM, the LEAG, and NASA's Office of Curation will initiate in 2008 a study to review the current state of curation and make specific recommendations for lunar curation, both on the lunar surface and on Earth. This study, funded by the Science Mission Directorate through OSEWG, will address some of the high-priority questions in this report, including the preservation of sample integrity and a refined analysis of return sample mass requirements.

Another activity to be undertaken by the OSEWG in 2008 as a direct result of this workshop is the creation of the Surface Science Scenario Team. This multi-center NASA team is focused on generating detailed lunar surface science scenarios that can be used in lunar architecture studies, surface exploration hardware and software design, communication and navigation system design, and scientific instrument design. This team will generate its initial scenarios in 2008 and will continue to refine and expand these scenarios over the next five years, taking into consideration more of the questions contained in this report in later studies. As a complement to the Surface Science Scenario Team, the OSEWG has created the Analog Missions Team, which will test in the field those scenarios developed by the Surface Science Scenario Team and will inform future calls for relevant NASA science and exploration programs.

In a parallel and coordinated effort, the LEAG will produce in 2008 or early 2009 a Lunar Goals and Objectives document outlining the scientific, exploration, and commercial goals and objectives for the first decade of lunar exploration. The OSEWG will use that document as one of the cornerstones of its future work.

Finally, the OSEWG will create a system to track progress on its goals and on the fulfillment of recommendations made to NASA by the NASA Advisory Council, the National Research Council, the LEAG, CAPTEM, and the international scientific community. The tracking system will be an evolving web-based system that will eventually enable transparency to external communities and efficient prioritization and achievement of milestones. Although the OSEWG is an internal NASA organization, it is necessary for the science and exploration communities to be continually engaged in the evolution of exploration architecture designs to ensure optimum science return and benefit to humanity.

Table 2
Outstanding high-priority science questions and relevance to specific exploration systems.

Outstanding sample science questions	Cargo transport	Crew transfer vehicles	Landers	Habitats	Large Rovers	Small Rovers	Suits	Power	Communications	Ground systems	Glovebox	SHED and/or Storage
What are the **sample return mass and volume** required per flight as a function of mission duration and type/location of mission?	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
What kind of non-habitable space, whether outdoors or in a separate "**SHED**" or "**rock-box**" facility, is required for sample handling, sorting and high-grading, subsampling, curation, and storage? What are its functional requirements and physical characteristics?	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
What are the **science mobility requirements** for both large and small rover platforms, including ranges, slope navagability, automation, tele-operation, power available for science instruments, data storage and handling, and sample storage, handling and analysis?			✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
What unique system capabilities are required to preserve **sample integrity** and ensure optimum returned sample suite, including extraterrestrial surface system and Earth system curation requirements, and transport requirements?		✗	✗	✗	✗						✗	✗
How much **habitable space (volume and surface area)** (dedicated lab or inside hab) is required for traverse planning and laboratory analysis, and when in a series of missions are specific capabilities required?	✗		✗	✗	✗			✗				
What are the IVA functional requirements inside the habitat for **traverse planning**, including map projection and annotation capabilities?		✗	✗	✗	✗				✗			
What are the **IVA** functional requirements and instrument needs for **laboratory analysis**, including dedicated sample pass-through, glovebox requirements, etc.?			✗	✗	✗			✗	✗	✗	✗	✗
What are the **highest priority landing sites** for both outpost and sortie mission sequences?			✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
What are the science requirements for **communication and data systems**, including real time vs recorded or post-processed audio/video communications, data acquisition, archiving, display, and analysis?		✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
What are the sience requirements for **navigation systems**, including absolute and relative navigational precision, real-time position and velocity display, and timecode/location stamping?		✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
What unique requirements do lunar and Mars surface science (as opposed to other operations) put on **spacesuits**?				✗		✗	✗		✗	✗		✗
What are the science requirements for **power systems**, including on the surface and in transit?	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
What kind of **decision-making structure** optimizes science return during traverse and EVA planning, during EVA, and during science analysis/high-grading?			✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
How do science goals, objectives, and protocols change as **mission duration** increases?	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
For **crew scheduling** purposes, what are the most accurate estimates of **time required** to perform specific **sample science tasks**, including traverse planning, navigation to and between sites of interest, observation, in situ measurements, sample acquisition, documentation, temporary storage, lab or SHED analysis, sorting, and permanent storage?	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	

✗ impacting or constrained by this architecture element
areas of major impact

Appendices

Appendix A—Workshop Agenda

Monday, June 25,2007		
8:00	Registration and Continental breakfast	
8:15	Welcome, Introduction, Logistics	Steve Mackwell, host
8:20	**Panel**	
	Welcome and Workshop Overview	Geoffrey Yoder
	Lunar Exploration Analysis Group (LEAG) and its Specific Action Teams	Clive Neal
	Curation and Analysis Planning Team for Extraterrestrail Materials (CAPTEM)	Chip Shearer
	MAWG Overview (special focus on MEPAG HEMSAG)—esp. current scenarios	Jennifer Heldmann
9:10	LAT Overview—esp. description of current options, basic architecture elements	Andy Thomas
9:30	Constellation Overview—esp. current plans for surface systems	Wendell Mendell
9:50	Moon and Mars—Physical Challenges, Similarities and Differences	Abhi Tripathi
10:10	What we Learn from Rocks and Regolith	Carl Allen
10:30	*In situ* Analysis and Sample Return: Complementary Components of Scientific Exploration	Chip Shearer
10:50	Apollo Sample Acquisition and Handling on the Lunar Surface—tools, ops	Herrison Schmitt, John Young
11:10	Science Backroom and Communications During Apollo	Gordon Swann, Gene Krantz, Jim Papike
11:30	Sample Handling, Preserving Scientific Integrity, Curation	Gary Lofgren

11:50	Advances in Field Robotics—Robonaut, Centaur, etc.	Ron Diftler (for Rob Ambrose)
12:10	Advances in EVA and Habitation Systmes—FRED	Michael Gernbardt
12:30	Lunch on Site and Presentation on Advances in Navigation/Documentation	Terry Fong
1:10	Goals of workshop, Desired Output, Description of Working Group Questions and Assignments, Grand Visions of Usefulness and Relevance (GVUR)	Kelly Snook
1:55	Break into Groups (by assignment)	
2:00	Working Groups—moderated, split by exploration scenario, same questions	(See list of moderators under group reports on Tuesday)
Tuesday, June 26, 2007		
8:00	Registration and Continental Breakfast	
8:30	Working Groups (continued)	Working Group Moderators
11:00	End Working Group Breakouts—Reconvene in Lecture Hall	
12:30	Lunch on Site	
1:00	Breakout Group Reports and Discussion	Chris McKay, Wendell Mendell, Jennifer Heldmann, Eileen Stansbery, Pan Conrad, Abhi Tripathi. Clive Neal, Jay Falker
2:30	Break	
2:45	Current State of Science in Lunar and Mars Architectures	Laurie Leshin, Wendell Mendell
3:00	Real-Time Results Synthesis and Future Steps	Kelly Snook, Geoffrey Yoder, Clive Neal, Chip Shearer

Appendix B—Registered Workshop Participants

(Note that this list represents the original groupings based on workshop registration, however, not all who registered attended and some attendees switched groups)

Group 1

Group Leader

Last Name	First Name	Degree	Department	Affiliation	Type	Expertise
McKay	Chris	Scientist	NASA, ARC	NASA, ARC	Scientist	Field science
Abel	Phillip	Supervisory Materials Engineer (Branch Chief)	Tribology & Surface Science Branch	NASA, GRC	Physicist	Vacuum technology, tribology, surface science
Bui	Tu-Quynh (T.Q.)	Aerospace Technologist	NASA–JSC	NASA, JSC	Engineer	Mission ops
Cheng	Andrew	Deputy Chief Scientist	SMD	NASA	Scientist	Planetary science
Carrigan	Catherine	Planetary Scientist	Space	JHU/APL	Scientist	Samples, instrument development (mass spec)
Elphic	Richard	Technical Staff Member	Space Science and Applications	Los Alamos National Laboratory	Scientist	Exploration geophysics and instrumentation
Fogel	Robert	Program Scientist	PSD, SMD	NASA HQ	Scientist	Sample curation, sampling, petrology, geochemistry, lunar primitive glasses
Franke	Charles	Enthusiast	Not Applicable	Enthusiast	Enthusiast	Enthusiast
Hyatt	Mark	Project Manager - Dust Management Project	MAC	NASA, GRC	Aerospace Engineer	Dust mitigation technologies
Lavoie	Anthony	Manager	Lunar Programs and Projects Office	NASA, MSFC	SES	Lunar Exploration
Lofgren	Gary	Lunar Curator & Planetary Scientist		NASA, JSC	Scientist	Lunar Sample Curation
Mueller	Robert	Surface Systems Lead Engineer	NASA KSC, KT-C-H1	NASA, KSC	Surface Systems Lead Engineer	Mechanical Engineering, ISRU, Regolith Excavation, Lunar Surface Operations, Support Equipment, Dust
Rask	Jon	Senior Scientist	Space Biosciences Division	NASA, ARC	Scientist	Biology, hardware development, science operations, flight science
Salvatore	Mark	Intern		LPI	Student	Planetary Geology
Treiman	Allan	Sr. Staff Scientist		LPI	Geologist and bon vivant.	Sample collection, curation, analysis.
Williams-Byrd	Julie	Systems Engineer	Space Mission Analysis Branch	NASA, LRC	Electro-optics Engineer	Scientific instrumentation, lidar
Zacny	Kris	Senior Research Scientist		Honeybee Robotics	Scientist/ Engineer	Drilling, sample acquisition

Group 2

Last Name	First Name	Degree	Department	Affiliation	Type	Expertise
Mendell	Wendell	Chief Scientist, Constellation	Constellation	NASA, JSC	Exploration Scientist	Guru of all things lunar
Allen	Carlton	Astromaterials Curator		NASA, JSC	Scientist	Sample curation; space resources
Chamberlin	Sydney	Intern	Astromaterials Research	LPI	Student	Space Radiation, Ionization of Planetary Surfaces, Mathematics
Diftler	Ron	Project Manager	Automation, Robotics and Simulation	NASA, JSC	Mechanical Engineer	Robotics
Gates	Michele	Program Engineer	SOMD	NASA HQ	Engineer	Mission Operations, Science Operations, Systems Engineering
Ignatiev	Alex	Director	Center for Advanced Materials	University of Houston	Scientist	ISRU, Energy, PV
Lawrence	Anneliese	Intern		LPI Intern	Student/Intern	Lunar Samples
Lupisella	Mark	Systems Engineer	Systems Division	NASA, GSFC	Systems Engineer, Scientist	Planetary protection, surface ops
Noble	Sarah	NASA Postdoctoral Fellow	Information Systems Division	NASA, JSC	Scientist	Sample analysis
Saucillo	Rudy	Aerospace Engineer		NASA, LRC	Aerospace Engineer	Lunar Lander Design and Performance
Wargo	Michael	Chief Lunar Scientist for Exploration Systems	ESMD	NASA, HQ	Materials Scientist / Planetary Scientist	Materials processing, ISRU, radiation shielding

Group 3

Last Name	First Name	Degree	Department	Affiliation	Type	Expertise
Heldmann	Jennifer	Planetary Scientist	Space Sciences Division	NASA, ARC	Scientist	Mars science
Allton	Judith	Genesis Solar Wind Curator	Astromaterials Acquisition and Curation	NASA, JSC	Planetary Scientist	Sample curation, sample acquisition tools
Glass	Brian	Group Lead, Deployable Technologies	Information Systems Division	NASA, ARC	Scientist	Robotic planetary drilling and coring automation, human field geology productivity
Jones	Jeff	Exploration Medical Operations Lead	Space Medicine	NASA, JSC	Physician/ Scientist	Medical, Dust toxicity, habitation life support systems
Leshin	Laurie	Director of Sciences and Exploration	Sciences and Exploration Directorate	NASA, GSFC	Scientist, Manager	Sample geochemistry, lunar architecture science
Maule	Jake	Project Scientist, LOCAD-PTS	Geophysical Laboratory	Carnegie Institution of Washington	Scientist	ISS science payload operations, rapid biological analysis
Nute	Robert	Chief Design Integration Office	Operations Division, Mission Operations Directorate	NASA	Engineer	Mission operations
Schmitt	Hariison	Chair		NAC	Geologist, Astronaut	Walking on the moon, collecting moon rocks, exploring
Weinberg	Jonathan	Senior Systems Engineer	Mission Systems, Civil and Operational Space	Ball Aerospace and Technologies Corp.	Systems Engineer	Broad based engineering and materials science, mission design, spacecraft and instrument hardware

Group 4

Group Leader

Last Name	First Name	Degree	Department	Affiliation	Type	Expertise
Stansbery	Eileen	Deputy Director, Astromaterials Research and Exploration	Astromaterials Research and Exploration Science	NASA, JSC	Scientist	Sample curation, contamination
Bell	Mary Sue	Planetary Scientist	Astromaterials Research and Exploration Science	Jacobs, JSC	Geologist	Sample curation, field geology, exploration analogs operations
Chu	Philip	Systems Engineer		Honeybee Robotics Spacecraft Mecha-nism Corporation	Mechanical Engineer	Robotic Sample Manipulation, Robotic Sub-Surface Access Systems
Eppler	Dean	Senior Scientist	Advanced Projects Office, Constellation Program	SAIC-Advanced Projects Office	Scientist, Mission Planner	Geologic field work, EVA operations
Gruener	John	Flight Systems Engineer	Constellation Program Office	NASA Constellation Program Office	Scientist/Engineer	Mission planning
Kennedy	Timothy	Operations Lead	Mission Operations Directorate	NASA, JSC	Engineer	Mission operations
Lewis	Ruthan	Formulation and Advanced Concepts Manager		NASA, GSFC	Engineer, Architect	Flight Systems, Habitation Architecture, Payload Carriers
McKay	David	Chief Scientist for Exploration Science	ARES	NASA, JSC	Scientist	Sample collection and analysis
Papanastas-siou	Dimitri	Senior Research Scientist	Science Division	JPL	Scientist	Isotope cosmochemistry; sample clean processing
Shearer	Chip	Senior Research Scientist III	Institute of Meteoritics	University of New Mexico	Geologist	Sample analysis, cosmochemistry, trace element analysis
Wilcox	Brian	Principal Member of Technical Staff	Electronics and Control	JPL	Engineer	Mobility, Robotics

Group 5

Last Name	First Name	Degree	Department	Affiliation	Type	Expertise
Conrad	Pamela	Research Scientist	Science Division	JPL	Scientist	Habitability and environmental assessment, mineralogy, *in situ* planetary technology
Biswas	Saurav	Scientist	Geosciences and Engineering Division	Southwest Research Institute	Scientist	Geosciences and Engineering
Clark	Pamela	Planetary scientist	Solar System Exploration	CUA at NASA, GSFC	Scientist, Educator, Writer	Lunar geology/geochemistry/geophysics, remote sensing and *in situ* analysis
Feustel	Andrew	Astronaut	Astronaut Office	NASA	Astronaut	Seismology/Rock Physics
Heggy	Essam	Planetary Scientist		LPI	Scientist	Geophysical Exploration Techniques
Klaus	Kurt	Advanced Computing	Information Technology	The Boeing Company	Scientist, Project Management	Planetary Geology, Field Geology, Project Management, Information Architecture
Lindsay	John	Scientist	LPI	LPI	Scientist	Lunar geology, lunar soil, astronaut training
McKay	Gordon	Planetary Scientist	Astromaterials Research Office	NASA, JSC	Scientist	Sample analysis and curation
Plescia	Jeff	Etc	APL	JHU, APL	Scientist	Regolith properties, robotic missions, constellation requirements definition, lunar environmental model
Sims	Michael	Research Scientist		NASA, ARC	Computer Scientist/ Roboticist	Sampling technologies and scientific decisions for sampling
Wilks	Rodney (Rod)	Business Development Manager	Business Development	ATK	Engineer	Launch and Landing Systems

Group 6

Last Name	First Name	Degree	Department	Affiliation	Type	Expertise
Tripathi	Abhi	Aerospace Systems Engineer	JSC-Constellation	NASA, JSC	Aerospace Engineer and Astrobiologist	MAT studies, LAT studies, micropaleontology
Bogard	Donald	Senior scientist	ARES code KR	NASA, JSC	Scientist	Lunar sample science, including regolith and implanted solar particles
Cooke	Douglas	Deputy Associate Administrator	ESMD	NASA HQ	Engineer, Manager	Engineering, testing, Lunar Architectures, Exploration
Hoffman	Stephen	Senior Systems Engineer		SAIC	Aerospace Engineer	Mission planning, surface systems
Kring	David	Planetary Scientist	LPI	LPI	Scientist	Lunar sample analysis and field geology in impact craters
Lindstrom	Marilyn	Program Scientist	Planetary Science Division	NASA HQ	Scientist	Lunar science, sample curation, geochemistry
McLemore	Carole	Project Manager	Exploration Advanced Capabilities Office	NASA, MSFC	Project Manager/ Engineer	Dust and Lunar Simulant Developer
Spudis	Paul	Principal Professional Staff	Planetary Exploration Group	APL	Science	Geology, field study, lunar surface architectures
Yoder	Geoffrey	LAT II Co-Chair	ESMD	NASA HQ	Engineer, Manager	Mission Architectures

Group 7

Last Name	First Name	Degree	Department	Affiliation	Type	Expertise
Neal	Clive	Professor and LEAG Chair	Civil Engine. and Geological Sciences	University of Notre Dame	Scientist	Lunar samples, analyses, curation, etc.
Bussey	Ben	Staff Scientist		JHU, APL	Scientist	Lunar remote sensing
Cooper	Bonnie	Senior Engineer	Robotics and Automation	JSC, Oceaneering Space Systems	Scientist, Engineer	Lunar exploration, resource utilization, surface systems, prospecting science, Apollo science
Fong	Terry	Director, Intelligent Robotics Group		NASA	Roboticist	Planetary rovers, robotic site operations, robotic survey, analog field tests
Horz	Friedrich	Geologist	LZ Technology Inc	ESCG, ARES, JSC	Scientist	Apollo Crew Training; Lunar Surface Processes
Landis	Rob	Flight Controller	Mission Operations Directorate	NASA, JSC	Engineer	Spaceflight operations, planetary surface operations
Lindstrom	David	Discipline Scientist		NASA HQ	Scientist, Manager	Cosmochemistry, sample curation
Meyer	Charles	Planetary scientist	ARES	NASA, JSC	Scientist	Sample science and curation
Rice	Jim	Astrogeologist	School of Earth and Space Exploration	Arizona State University	Mars Scientist	Field geology (Mars Analogs), Mars Exploration Rovers Science Team Member
Toups	Larry	Habitation Focus Element Lead	NASA, JSC	CxPO/Advanced Projects Office	Habitation Systems Engineer	Habitation

Appendix C—Questionnaire Results

EVA Planning/Preparation [primary architectures: hab, comm]

Broad Activity	Issues	Options (d = Other)			Group 2 (Mendell)			Group 4 (Stansbery)			Group 6 (Tripathi)			Group 7 (Neal)			Group 1 (McKay)			Group 3 (Heldmann)			Group 5 (Conrad)		
					Moon/mono hab			Moon/nuclear			Moon/mono hab			Moon/mobile hab			Mars/long stay/ multiple sites			Mars/long stay/ single sites			Mars/short stay/ multiple sites		
		A	B	C	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	1	2	3	Early	Buildup	Steady	Early	Buildup	Steady
Data Usage	Precursor site survey data required	None	Basic	Extensive	C	A	A	C	C	C			C	C	C	C	C	C	C	N/A	N/A	N/A	C	C	maybe C
	Type of data needed for traverse planning	Aerial/ Orbital Photo only	Remote sensing	Non–MCC plans	A	B	C	AB	ABC	C			B				ABC	ABC	ABC	AB	AB	C	AB	AB	AB
	Resolution of data	Any	~kms	~meters	C	C	C	C	C	C			D	C	C	C	C	C	C	C	C	C	C	C	C
	Real time data access from hab	Instant	Daily	none	B	B	A						A	A	B	B	A	A	A	B	B	B	A	A	A
	Paper maps/ printouts?	Yes	No	N/A	B	B	B	C	C	C			D	B	B	B	A	A	A	C	C	C	maybe	maybe	maybe
Traverse Planning	Hypothesis generation	Crew	Ground	Together	B	C	C	B	C	C			C	C	C	A	C	C	C	C	C	C	C	C	C
	Route Mapping/ planning	Crew	Ground	Together	B	C	C	B	C	C			C	C	C	A	C	C	C	C	C	C	C	C	C
	Sampling strategy	Crew	Ground	Together	C	C	C	B	C	C			C	C	C	A	C	C	C	C	C	C	C	C	C
	Telerobotic path scouting prior to EVA	Crew	Ground	None	C	C	C	B	AB	AB			D	B	B	B	A	A	A	ABC	ABC	ABC	Sometimes A & Sometimes B	Sometimes A & Sometimes B	Sometimes A & Sometimes B
IVA Requirements	Workspace for EVA planning	None	Large Table	Wall Screen	A	C	C	BC	BC	BC			D	C	C	C	BC	BC	BC	BC	BC	BC	BC	BC	BC
	Crew time for consul-tations with ground	None -Auto	~15 mins	~1 hr	C	C	C	C	BC	BC			C	C	B	A	C	C	C	C	C	C	As long as it takes		
	Crew time for traverse prep, gear/instrument readiness (per 8 hr EVA per EVA crew) excluding pre-breathe	None -Auto	~30 mins	~1 hr	B	B	B	BC	BC	BC			C	C	C	C	C	C	C	C	C	C	C	C	C
	Crew time for traverse prep, gear/instrument readiness (per 8-hr EVA per IVA support)	None -Auto	~30 mins	~1 hr	C	C	C	BC	BC	BC			C	B	B	A	C	C	C	C	C	C	B	B	B
	Use of previously col-lected samples/data	Data Only	Samples in hab	Not Needed	C	B	B	AB	AB	AB			D	A	A	A	ABC	ABC	ABC	AB	AB	AB			
	Need for IVA support during EVA	Full Time	Part Time Monitor	None	C	C	C	AB	AB	AB			B	C	B	B	A	A	A	A	A	A	Depends, but never C		
	Decisionmaking structure	Ground Authority	Ground Support	Crew Autonomy	A	C	C	A	BC	BC			BC	A	B	BC	B	B	B	BC	BC	BC	B	B	B

Red highlighted areas represent a general consensus among groups.

Traversing And Eva [Primary Architectures: Mobility, Suits, Comm/Nav]

Broad Activity	Issues	Options (d = Other)			Group 2 (Mendell)			Group 4 (Stansbery)			Group 6 (Tripathi)			Group 7 (Neal)			Group 1 (McKay)			Group 3 (Heldmann)			Group 5 (Conrad)		
					Moon/mono hab			Moon/nuclear			Moon/mono hab			Moon/mobile hab			Mars/long stay/ multiple sites			Mars/long stay/ single sites			Mars/short stay/ multiple sites		
		A	B	C	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	1	2	3	Early	Buildup	Steady	Early	Buildup	Steady
Navigation	Precision for rover	~10km	~1km	~10m	C	C	C	100 m	100 m	100 m			C	C	C	C	C	C	C	C	C	C	C	C	C
	Precision for suited human	100's m	10's m	≤ 1m	B	B	B	B	B	B			B	B	B	B	C	C	C	C	C	C	C	C	C
	Real time position mapping overlays?	Rover	Suit	Hab	A	A	AC	ABC	ABC	ABC			A	All	All	All	B	B	B	ABC	ABC	ABC	All	All	All
	Other data overlays?	Rover	Suit	Hab	B	B	B	ABC	ABC	ABC			AB	All	All	All	B	B	B	ABC	ABC	ABC	All	All	All
	Sync'd timecode display	Rover	Suit	Hab	AB	AB	AB	C	C	C			B	All	All	All	B	B	B	ABC	ABC	ABC	All	All	All
	Hertz neverlost guidance—"you are here"—real time	Rover	Suit	Hab	A	A	AC	A	A	A			A	All	All	All	B	B	B	AB	AB	AB			
	Telerobotic scouting	Always	Some-times	Never	C	B	B	B	B	B			B	B	B	B	A	A	A	B	B	B	B	B	B
Communica-tions (traversing)	2-way audio	Suit	Rover	Hab	ABC	ABC	ABC	ABC	ABC	ABC			ABC	All	All	All	ABC	ABC	ABC	ABC	ABC	ABC	All	All	All
	2-way video	Suit	Rover	Hab				ABC	ABC	ABC			BC	All	All	All	ABC	ABC	ABC	N/A	N/A	N/A			
	Other one-way video	Stations	Robotic	None	AB	AB	AB	AB	AB	AB			B	C	AB	AB				AB	AB		AB	AB	AB
	Real time data access, query, and display?	Suit	Rover	Hab	ABC	ABC	ABC	ABC	ABC	ABC			BC	All	All	All	ABC	ABC	ABC	ABC	ABC	ABC	All	All	All
	Real time instrument data analysis for sample collection/ subsample decision-making	Suit	Rover	Hab				N/A					B	All	All	All	ABC	ABC	ABC	ABC	ABC	ABC	All	All	All
	Continuous timecode acquisition	Suit	Rover	instru-ments	ABC	ABC	ABC	ABC	ABC	ABC			ABC	C	C	C	ABC	ABC	ABC	ABC	ABC		All	All	All
	Broadcast telemetry/ ephemeris	Suit	Rover	instru-ments	ABC	ABC	ABC	ABC	ABC	ABC			B				ABC	ABC	ABC						
Traverse flexibility	Traverse path change decisions	Crew	Ground	None	A	A	A	AB	AB	AB			D	AB	AB	A	A	A	A	A	A	A	A	A	A
	No rover - range (dis-tance from suitport)	0-1 km	0-3 km	0-10 km	C	C	C	C	C	C			B				C	C	C	15	15	15	B	B	B
	Unpressurized rover-range	0-1 km	0-5 km	0-10 km	C	C	C	C	C	C			D				C	C	C	15+	15+	15+	>10K	>10K	>10K
	Pressurized rover-range per trip from habitat	0-5 km	0-50 km	100s km	B	C	C	A	B	C			C				C	C	C	C	C	C	B	B	B
Robotic Field Assistance	Command and control	Suit	Rover	Hab	C	AC	AC	ABC	ABC	ABC			ABC				A	A	A	ABC	ABC	ABC	All	All	All
	Traverse scout display	Suit	Rover	Hab	N/A	C	C	ABC	ABC	ABC			BC	C	C	C	A	A	A	C	C	C			
	Consummable tracking	Suit	Rover	Hab/ Ground	AC	ABC	ABC	C	C	C			BC	All	All	All	ABC	ABC	ABC	C	C	C	All	All	All
	All tasks possible with 2-4 humans with/without robotic or teleoperated assistance?	2 + assist	2 to 4 + assist	2 no assist	D	D	D	Teleop from ground	Ground and crew cmd	Teleop from ground, hab, and crew cmd			C				C			C	C	C	C	C	C

Red highlighted areas represent a general consensus among groups.

Sample And Data Acquisition [Primary Architectures: Mobility, Suits, Robotics, Comm]

Broad Activity	Issues	Options (d = Other)			Group 2 (Mendell)			Group 4 (Stansbery)			Group 6 (Tripathi)			Group 7 (Neal)			Group 1 (McKay)			Group 3 (Heldmann)			Group 5 (Conrad)		
					Moon/mono hab			Moon/nuclear			Moon/mono hab			Moon/mobile hab			Mars/long stay/ multiple sites			Mars/long stay/ single sites			Mars/short stay/ multiple sites		
		A	B	C	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	1	2	3	Early	Buildup	Steady	Early	Buildup	Steady
Document-ation	Navigational precision for sample location	100's m	≤ 1 m	≤ 10 cm	B	B	B	BC	BC	BC			B	B	C	C	sub cm	sub cm	sub cm	C	C	C	B	B	B
	Spatial resolution of instrument data	10's m	≤ 1m	≤ 10 cm	C	C	C	C	C	C			C	C	C	C	sub cm	sub cm	sub cm	C	C	C	C	C	C
	Video resolution	HD quality	TV quality		A	A	A	A	A	A			A	A	A	B	sub cm	sub cm	sub cm	C	C	C	A	A	A
	Cameras	Suit head	hand-held		A	A	A	ABC	ABC	ABC			ABC	All	All	All				ABC	ABC	ABC	All	All	All
	Sample Orientation	1–10˚	10–20˚	20–30˚										A	A	A									
Communica-tions (sampling)	2-way audio	Suit	Rover	Hab	ABC	ABC	ABC	ABC	ABC	ABC			ABC	All	All	All	ABC	ABC	ABC	ABC	ABC	ABC			
	2-way video	Suit	Rover	Hab				ABC	ABC	ABC			ABC	All	All	All	ABC	ABC	ABC	N/A	N/A	N/A			
	Other one-way video		Robotic	None	AB	AB	AB	AB	AB	AB			B	AB	AB	AB				hab from suit and rover					
	Real time data access, query, and display?	Suit	Rover	Hab	ABC	ABC	ABC	ABC	ABC	ABC			BC	All	All	All				ABC	ABC	ABC			
	Real time instrument data analysis for sample collection/ subsample decision-making	Suit	Rover	Hab				ABC	ABC	ABC				All	All	All				ABC	ABC	ABC			
	Continuous timecode acquisition	Suit	Rover	Instru-ments	ABC	ABC	ABC	ABC	ABC	ABC				C	C	C				ABC	ABC	ABC			
	Broadcast telemetry/ ephemeris	Suit	Rover	Instru-ments	ABC	ABC	ABC	ABC	ABC	ABC										ABC	ABC	ABC			
Sampling	Sampling tools	Apollo class	Some enhance-ments	High tech	B	B	B	B	C	C			B	B	B	B	C	C	C	BC for bio	BC for bio	BC for bio	B	B	B
	Mass of samples collected per EVA (average over any given mission)	≤ 5 kg	5–20 kg	≥ 50 kg	B	C	C	B	B	B			C	C	C	C	B	B	B	C	C	C			
	Robotic field assistance	None	Some	Max	A	B	B	B	B	B			B				C	C	C	Some	Some	Some	B	B	B
	Telerobotic tasks 1	Analysis	Heavy lifting	Digging	BC	ABC	ABC	ABC	ABC	ABC			AC	BC	BC	BC	ABC	ABC	ABC	ABC	ABC	ABC	All	All	All
	Telerobotic tasks 2	Drilling	Breaking	Carrying	A	ABC	ABC	ABC	ABC	ABC			ABC	All	All	All	ABC	ABC	ABC	ABC	ABC	ABC	All	All	All
	Telerobotic tasks 3	Documen-tation	Transport	Scouting	AB	ABC	ABC	ABC	ABC	ABC			ABC	All	All	All	ABC	ABC	ABC	ABC	ABC	ABC	All	All	All
	Telerobotic tasks 4	Scientific reconnais-sance	Sample collection	instrument deployment				ABC	ABC	ABC															
	Telerobotic control	Suit	Hab	Ground	ABC	ABC	ABC	ABC	ABC	ABC			D	BC	BC	BC	ABC	ABC	ABC	AB	AB	AB	All	All	All
	Store sample perma-nently in field—no need to open again before return?	Yes	No	Depends on sample	C	C	C	C	C	C			C	C	C	C				C	C	C	C	C	C
	Subsample in field	Yes	No	Maybe	C	C	C	A	A	A			A	C	C	C				C	C	C	Yes	Yes	Yes
	Store temporarily for later analysis/sorting?	Yes	No	Depends on sample	C	C	C	AC	AC	AC			C	C	C	C				C	C	C	C	C	C
	Percentage of samples needing further access before return?	0%	0–50%	≥ 50%	A	C	C	C	C	C			C	A	B	C	C	C	C				C	C	C

Broad Activity	Issues	Options (d = Other)			Group 2 (Mendell)			Group 4 (Stansbery)			Group 6 (Tripathi)			Group 7 (Neal)			Group 1 (McKay)			Group 3 (Heldmann)			Group 5 (Conrad)		
					Moon/mono hab			Moon/nuclear			Moon/mono hab			Moon/mobile hab			Mars/long stay/ multiple sites			Mars/long stay/ single sites			Mars/short stay/ multiple sites		
		A	B	C	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	1	2	3	Early	Buildup	Steady	Early	Buildup	Steady
Sampling	Percentage of "environmentally sensitive samples" collected	0%	1–5%	6–20%	B	B	B	B	C	C+			D	BC	BC	BC	B	B	B	A lot	Less	even less	C	C	C
	Rover requires refridgerators/freezers or other capabilities for preserving samples?	Yes	No	Depends	B	B	B	B	C	C			C	A	A	A	A	A	A	C	C	C	Yes	Yes	Yes
	Advanced scientific judgment and experience required for sample collection?	Yes	No	Depends	A	A	A	C	C	C			A	A	A	A	A	A	A	A	A	A	Yes	Yes	Yes
	"Back-contamination" planetary protection issues important?				B	B	B	No	No	No			Yes	B	B	A	A	A	A	A	A	A	Yes	Yes	Yes
	"Forward contamination" issues important?	Yes	No	Highly varialbe	B	B	B	No	No	No			Yes	B	B	A	A	A	A	A	A	A	Yes	Yes	Yes
	Assistance from ground or hab required for sample acquisition/subsampling decisionmaking in field?	Yes	No	Sometimes	C	C	C	C	C	C			C	A	A	C	C	C	C	B	B	B	C	C	C
Data Acquisition	Number of non-camera instruments for gathering scientific data about samples	0	1 to 5	5 to 10	B	B	B	C	C	C			B	B	B	B	C	C	C	B	B	B	C	C	C
	Sample data handling	Real Time	Stored	Depends	AB	AB	AB	C	C	C			AB	A	A	A	C	C	C	C	C	C	C	C	C
	Ratio of time spent on *in situ* sample measurements using instruments (not including human geologic observation) vs. total time at site	≤ 5%	5–30%	≥ 30%	A	B	B	A	A	A			B	AB	AB	AB	B	B	B	b (nominal), c (sometimes)	b (nominal), c (sometimes)	b (nominal), c (sometimes)	B	B	B
	Optimal ratio of time spent at a site of interest vs. time spent traversing	≤ 10%	10–30%	≥ 30%	C	C	C	Can't predict					D				Infinte			A	B	C	B	B	B
Robotic Field Assist	Command and control	Suit	Rover	Hab		ACD	ACD	ABC	ABC	ABC			BC	C	C	C	ABC	ABC	ABC	ABC	ABC	ABC	All	All	All
	Accompany Astronauts?	Yes	Pre-deploy			B	B	AB	AB	AB			ABD	B	B	AC	AB	AB	AB	depends	depends	depends	depends		depends

Red highlighted areas represent a general consensus among groups.

Red Text represents questions the group formulated themselves.

Sample Transport [primary architectures: suits, rovers, hab/lab]

Broad Activity	Issues	Options (d = Other)			Group 2 (Mendell)			Group 4 (Stansbery)			Group 6 (Tripathi)			Group 7 (Neal)			Group 1 (McKay)			Group 3 (Heldmann)			Group 5 (Conrad)		
					Moon/mono hab			Moon/nuclear			Moon/mono hab			Moon/mobile hab			Mars/long stay/ multiple sites			Mars/long stay/ single sites			Mars/short stay/ multiple sites		
		A	B	C	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	1	2	3	Early	Buildup	Steady	Early	Buildup	Steady
Human Transport	Percent of samples that can be handled/ transported "bare glove"	0–5%	5–50%	>50%	C	C	C	C	C	C			B				A	A	A	B	B	BC	A	A	A
	Percent (mass) of "environmentally sensitive" samples	0–5%	5–15%	>15%	A	A	A	A	B	C			B				C	C	C	C	B	A	C		
	Percent (time) handling "environmentally sensitive samples" (drilling, telerobotic sampling in PSCs, etc.)	0–5%	5–15%	>15%	B	B	B	A	A	A			C	A	A	A	C	C	C	C	C	C	C		
Rover Transport	Required load capacity for collected samples (mass)	1–10 kg	10–40kg	40–100kg	B	C	C	C	C	C			C	D	D	D	C	C	C	C	C	C	C		
	Required capabilities for preserving scientific integrity	Refrigeration	Pressurization/ vacuum	Separation from humans	C	C	C	D	D	D			AC	BC	All	All				ABC	ABC	ABC	Depends		
Hab Transport/ Pass-through	Need hab-internal glovebox?	Yes	No	Depends	C	C	C	C	A	A			C	B	B	B	A	A	A	A	A	A	*See Note		
	Rover -> glovebox transport–direct pass-through needed?	Yes	No	Depends	C	C	C	C	C	C			C	B	B	B	A	A	A	A	A	A	Depends		
	Percentage of samples that could be handled bare-handed inside "dirty" lab with humans and returned with humans	≥ 40%	0–40%	0%	C	C	C	C	C	C			C	C	C	C	C	C	C	AB	A	A	C		
	Samples ever removed from initial containers by humans?	Yes	No	Some	B	C	C	C	C	C			C	B	C	C	A	A	A	C	C	C	A		
	Percentage of samples removed from initial containers	0%	0–30%	≥30%	A	B	B	C	C	C			C	A	B	B	C	C	C	BC	C	C	#C- See Note		

Red highlighted areas represent a general consensus among groups.

* How about a glovebox/robotic arm in a contained environment outside of a hab but accessible by a non-suit wearing crew member.

\# If we are doing sample splits in the field, it would be half—otherwise it would be nearly all of the samples

Documentation [primary architectures: suits, rovers, comm/nav, hab/lab]

Broad Activity	Issues	Options (d = Other)			Group 2 (Mendell)			Group 4 (Stansbery)			Group 6 (Tripathi)			Group 7 (Neal)			Group 1 (McKay)			Group 3 (Heldmann)			Group 5 (Conrad)		
					Moon/mono hab			Moon/nuclear			Moon/mono hab			Moon/mobile hab			Mars/long stay/ multiple sites			Mars/long stay/ single sites			Mars/short stay/ multiple sites		
		A	B	C	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	1	2	3	Early	Buildup	Steady	Early	Buildup	Steady
Automated documentation at site	Real-time sample/ data position/time stamping, plotting, correlation, overlay	Required	Desired	Not Required	B	B	B	B	B	B			BC	A	A	A	A	A	A	A	A	A	A		
	Automated sample/ data position/time stamping, plotting, correlation, overlay	Required	Desired	Not Required	B	B	B						B	A	A	A	A	A	A	B	B	B	A		
	Sample data available real time to?	Suits	Rover	Hab	ABD	ABD	ABD	C	C	C			C	All	All	All	ABC	ABC	ABC	ABC	ABC	ABC	All		
	Real-time rover position accuracy required for sample science documentation	~ km	~ 10m	≤ 1m	B	B	B	B	B	B			B	B	B	B	B	B	B	B	B	B	C		
	Real-time suit position accuracy required for sample science documentation	~ km	~ 10m	≤ 1m	B	B	B	B	B	B			D	B	B	B	C	C	C	C	C	C	C		
	Real-time instrument pointing accuracy/ resolution required for sample science documentation	~ 10m	≤ 1m	None, time only	C	C	C	D	D	D			B	D	D	D	≤ 1 cm	≤ 1 cm	≤ 1 cm	B	B	B	B		
	Post-processed instrument pointing accuracy/resolution required for sample science documentation	~ 10m	≤ 1m	≤ 1 cm	C	C	C	D	D	D			D	D	D	D	C	C	C	C	C	C	C		
	Syncronized time stamping on all cameras, instruments, rovers, robotics, etc?	Yes	No	Depends	A	A	A	A	A	A			A	A	A	A	A	A	A	A	A	A	A		
	Continuous video documentation (recording)	All samples	General context only	Optional	A	A	A	A	A	A			B	A	A	A	A	A	A	C	C	C	A		
	Real-time continuous video broadcast from	Suits	Rovers	Other	A	AB	AB	ABC	ABC	ABC			AB	All	All	All	ABC	ABC	ABC	AB	AB	AB	All		
	Real-time continuous video feed available to	Suits	Rovers	Hab/ ground	C	C	C	ABC	ABC	ABC			C	All	All	All	ABC	ABC	ABC	a, b (on call), c	a, b (on call), c	a, b (on call), c	BC		
Subsampling at site (subsample = two or more roughly identical or representational versions of the same sample that can later be treated differently for different uses)	Automated subsampling?	Yes	No	Maybe	B	B	B	B	B	B			C	B	B	B	C	C	C	C	C	C	C		
	Manual subsampling at site	Hammer	Hand Drill	Scoop	AC	AC	AC	ABC	ABC	ABC			ABC	All	All	All	All	All	All	ABC	ABC	ABC	All		
	Permanent or temporary sampling in field?	Perm	Temp	Both	C	C	C	D	D	D							C	C	C	C	C	C	C		
	Percentages of samples permanently sampled at site (need no further documentation, subsampling, or analysis prior to return)	0–10%	10–30%	30–100%	C	B	B	D	D	D			ABC				A	A	A	A	A	AB	C		
	Type of samples easily permanently sampled at site	Drill cores	Regolith	Rocks	AB	AB	AB	D	D	D			ABC				A	A	A	ABC	ABC	ABC	All		
	Type of samples requiring careful preservation and later subsampling before return	Astro-bio	Volatiles	none	AB	AB	AB	AB	AB	AB			C				AB	AB	AB	AB	AB	AB	AB		
	Subsampling strategy requires lab-in-hab analysis?	Yes	No	Depends	C	C	C	C	A	A			C	B	B	B	C	C	C	C	C	C	C		

Documentation (Continued)

Broad Activity	Issues	Options (d = Other)			Group 2 (Mendell)			Group 4 (Stansbery)			Group 6 (Tripathi)			Group 7 (Neal)			Group 1 (McKay)			Group 3 (Heldmann)			Group 5 (Conrad)		
					Moon/mono hab			Moon/nuclear			Moon/mono hab			Moon/mobile hab			Mars/long stay/ multiple sites			Mars/long stay/ single sites			Mars/short stay/ multiple sites		
		A	B	C	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	1	2	3	Early	Buildup	Steady	Early	Buildup	Steady
Data usage	All data used/ broadcasted/available real time?	Yes	No	Some	C	C	C	A	A	A			C	C	C	C	A	A	A	C	C	C	A		
	Primary data stored	On rovers/ instru-ments	Hab	Ground	BC	BC	BC	C	BC	BC			BC	BC	BC	BC	All	All	All	ABC	ABC	ABC	BC		
	Primary humans doing data analysis and interpretation	Crew	Ground	Combo	B	C	C	C	C	C			C	C	C	A	C	C	C	C	C	C	C		
	data used to plan immediate science plans?	Crew	Ground	Record only	B	AB	AB	AB	AB	AB			AB	AB	AB	AB	A	A	A	AB	AB	AB	AB		
	Data used for robotic return to sites of interest?	Yes	No		B	A	A	A	A	A			A	A	A	A	A	A	A	A	A	A	A		

Red highlighted areas represent a general consensus among groups.

Sample High-Grading [primary architectures: SHED, rock garden, lab]

Broad Activity	Issues	Options (d = Other)			Group 2 (Mendell)			Group 4 (Stansbery)			Group 6 (Tripathi)			Group 7 (Neal)			Group 1 (McKay)			Group 3 (Heldmann)			Group 5 (Conrad)		
					Moon/mono hab			Moon/nuclear			Moon/mono hab			Moon/mobile hab			Mars/long stay/ multiple sites			Mars/long stay/ single sites			Mars/short stay/ multiple sites		
		A	B	C	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	1	2	3	Early	Buildup	Steady	Early	Buildup	Steady
Sample storage	Total collected sample mass over each mission	≤100kg	100–300kg	≥300kg	B	C	C						C	C	C	C	C	C	C	C	C	C	C		
	Mass percentage of samples that can be stored outside in open near outpost/hab (rock garden)	0%	0–15%	≥ 15%	C	C	B						C	D	D	D	C	C	C	C	C	C	C		
	Mass percentage of total collected samples that can be stored in open containers in SHED (Sample Handling and Early Discrimination) facility	0–30%	30–80%	100%	B	B	B						D	B	B	B	0–10%	0–10%	0–10%	B	B	B	None		
	Mass percentage of total collected samples that must be stored in closed/con-ditioned containers in SHED facility	0–10%	10–25%	≥ 25%	C	C	C						D	B	B	B	A	A	A	AB	AB	AB	All and see above		
	Mass percentage of total collected samples that must be confined to SHED only, no interaction with lab-in-hab	0–5%	5–25%	≥ 25%	C	C	C						A	A	A	A	C	C	C	A	A	A	C		
	Mass percentage of samples designated for return that can enter lab-in-hab	0–5%	5–25%	≥ 25%	A	A	A						D	A	A	A	A	A	A	C	C	C	None		
	Crew time required for sorting/subsam-pling/high-grading per 8-hour EVA (person-hours)	≤ 2 hrs	2–6 hrs	≥ 6 hrs	A	B	C						AB	A	A	AB	A	A	A	A	A	A	C		
	Crew mode for sorting/subsampling/ high-grading	EVA–outside	IVA–lab	Tele-robotic –SHED	BC	BC	BC						ABC	C	C	C	ABC	ABC	ABC	ABC	ABC	ABC	All		
Subsampling inside hab (subsample = two or more roughly identical or representational versions of the same sample that can later be treated differently for different uses)	Instrument suite for sample analysis inside hab?	Required	Not Required	Optional	A	A	A						A	B	B	B	A	A	A						
	Access to samples for use inside lab-in-hab	Robotic	Hand carried	Closed container thru hab	C	C	C						BD	D	D	D	C	C	C				AC		
	Instruments in glovebox?	Basic	Elaborate	Depends	A	A	A						B	A	C	B	B	B	B				Depends		
	Glovebox pressur-ized? Temperature controlled?	Nitrogen purge	Cold	Vacuum	A	A	A						D	D	D	D/Depends on sample							Mars Ambient		
	Any samples handled in hab outside glovebox?	Always	Never	Some-times	C	C	C						C	B	B	B	B	B	B				C		
	Dust control in lab/hab	Big Problem	Small Problem	No Problem	A	A	A						D	C	B	A	A	A	A				A		
	Dedicated sample pass-through directly to glovebox required?	Yes	No	N/A	B	B	B						A	A	A	A	A	A	A				A		

Sample High-Grading (Continued)

Broad Activity	Issues	Options (d = Other)			Group 2 (Mendell)			Group 4 (Stansbery)			Group 6 (Tripathi)			Group 7 (Neal)			Group 1 (McKay)			Group 3 (Heldmann)			Group 5 (Conrad)		
					Moon/mono hab			Moon/nuclear			Moon/mono hab			Moon/mobile hab			Mars/long stay/ multiple sites			Mars/long stay/ single sites			Mars/short stay/ multiple sites		
		A	B	C	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	1	2	3	Early	Buildup	Steady	Early	Buildup	Steady
Subsampling outside hab (subsample = two or more roughly identical or representational versions of the same sample that can later be treated differently for different uses)	Concept - unpressurized SHED (converted logistics module) with tactile highly capable dedicated virtual-reality telerobotics (eg robonaut) inside. Sample storage, access, sorting, and basic analysis capabilities from hab or ground. Designed to conserve	Good Idea	Bad Idea	Intriguing	C	A	A						C	AC	AC	AC	A	A	A				A		
	External/separate sample storage and handling facility required?	All Samples	Some Samples	No Samples	B	B	B						D	A	A	A	Most	Most	Most				All		
	Instrumentation inside SHED	Saw/ polisher	Micro-scopes	SEM	B	AB	AB						D	All	All	All							Separate Places		
	Power required	~ Watts	~ kW's	~ hab	B	B	B						A	A	A	A	B	B	B				B		
	Estimated mass of SHED infrastructure, not including module shell (incl. shelving, sample containers, care and feeding, instrumentation, and 100 kg per robonaut)	~ 200 kg	500–1000 kg	≥ 1000 kg	A	B	B						D	A	B	B	C	C	C				B (200-500)		

Red highlighted areas represent a general consensus among groups.

Laboratory Analysis [primary architectures: habs, SHED, rock garden, lab]

Broad Activity	Issues	Options (d = Other)			Group 2 (Mendell)			Group 4 (Stansbery)			Group 6 (Tripathi)			Group 7 (Neal)			Group 1 (McKay)			Group 3 (Heldmann)			Group 5 (Conrad)		
					Moon/mono hab			Moon/nuclear			Moon/mono hab			Moon/mobile hab			Mars/long stay/ multiple sites			Mars/long stay/ single sites			Mars/short stay/ multiple sites		
		A	B	C	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	1	2	3	Early	Buildup	Steady	Early	Buildup	Steady
Minimum analysis capability	Brushes, scoops, sample handling	Glovebox in hab	SHED	EVA	ABC	ABC	ABC						C	C	BC	BC	ABC	ABC	ABC	ABC	ABC	ABC	All		
	Sample containers/ holders	Glovebox in hab	SHED	EVA	ABC	ABC	ABC						ABC	C	BC	BC	ABC	ABC	ABC	ABC	ABC	ABC	All		
	Scale	Glovebox in hab	SHED	EVA	BC	BC	BC						AB	C	BC	BC	ABC	ABC	ABC	mass scale in hab	mass scale in hab	mass scale in hab	AB		
	Sieve	Glovebox in hab	SHED	EVA	AB	AB	AB						ABC	C (rake)	BC	BC	ABC	ABC	ABC	ABC	ABC	ABC	BC		
	Rock Polisher	Glovebox in hab	SHED	EVA	N/A	B	AB						D	N/A	N/A	N/A	ABC	ABC	ABC	AB	AB	AB	*B See Note		
	Rock saw	Glovebox in hab	SHED	EVA	N/A	B	AB						D	D	D	D	B	B	B	AB	AB	AB	B same as above and possibly C as well.		
	Thin sectioning machine	Glovebox in hab	SHED	EVA	N/A	N/A	AB						AB	N/A	N/A	N/A	A	A	A	AB	AB	AB	*See Note		
	Polarizing microscope	Glovebox in hab	SHED	EVA	N/A	N/A	AB						AB	D	D	D	A	A	A	A	A	A	A		
	Temporary storage	Glovebox in hab	SHED	EVA	B	B	B						AB	C	BC	BC	ABC	ABC	ABC	ABC	ABC	ABC	B		
	Portable Spectrometer	Glovebox in hab	SHED	EVA	C	BC	BC						ABC				ABC	ABC	ABC	ABC	ABC	ABC	All		
	SEM	Glovebox in hab	SHED	EVA	N/A	N/A	N/A						D	N/A	B	B	ABC	ABC	ABC	A	A	A	Glove box or other dust free area		
	Gloves	Glovebox in hab	SHED	EVA	AC	AC	AC						D	Always	Always	Always	ABC	ABC	ABC	ABC	ABC	ABC	All		
	Dust control system	Glovebox in hab	SHED	EVA	AC	AC	AC						D	All	All	All	ABC	ABC	ABC	ABC	ABC	ABC	All		
	Rock hammer	Glovebox in hab	SHED	EVA	BC	BC	BC						ABC	C	BC	BC	ABC	ABC	ABC	ABC	ABC	ABC	BC		
Sample pass-through	Sealed containers transported inside hab to glovebox?	OK	SHED	Non-returned samples	A	A	A						D				No	No	No	A	A	A	Never inside hab		
	Direct from outside pass-through into hab glovebox	Required	SHED	Not required	C	C	C						A				A	A	A	A	A	A	Yes, and it may be through the shed		

Red highlighted areas represent a general consensus among groups.

Red Text represents questions the group formulated themselves.

* Messy activities may need a different SHED than analytical activities that should also take place in a protected environment.

Laboratory Analysis (Continued)

Broad Activity	Issues	Options (d = Other)			Group 2 (Mendell)			Group 4 (Stansbery)			Group 6 (Tripathi)			Group 7 (Neal)			Group 1 (McKay)			Group 3 (Heldmann)			Group 5 (Conrad)		
					Moon/mono hab			Moon/nuclear			Moon/mono hab			Moon/mobile hab			Mars/long stay/ multiple sites			Mars/long stay/ single sites			Mars/short stay/ multiple sites		
		A	B	C	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	1	2	3	Early	Buildup	Steady	Early	Buildup	Steady
Advanced analytical capability	Extended sample handling and analysis operations using Robonaut in SHED by ground teams?	Yes	No	Depends	B	A	A						C	A	A	C	C	C	C	A	A	A	A		
	Additional analytical equipment supplied to SHED	Quickly	Slowly	No	B	B	B						D	C	B	B	A	A	A				A		
Synergy with ISRU?	To what extent do science and ISRU needs overlap?	None	Some	Great	B	B	B						B	B	C	C	B	B	B	C	C	C	B		
	In what ways do they overlap?	*In situ* measure-ments	Sample needs	Lab equip-ment needs	ABC	ABC	ABC						ABC	AB	All	All	A	A	A	ABC	ABC	ABC	All		
	How will ISRU waste be disposed of?	Dump on surface	Process further (extract more material)	Use for science??										A	All	All									
	What cleaning protocols are required to minimize sample cross contamination in the mast-slave processing box?	None needed	Gas jet	Wipe down										A	B	B									
	Further development of micro-manipulators for sample processing and curation is needed, especially at low temperatures.																								

Red highlighted areas represent a general consensus among groups.

Red Text represents questions the group formulated themselves.

Sample Return [primary architectures: ascent vehicle, habs, SHED, rock garden, lab, mobility]

Broad Activity	Issues	Options (d = Other)			Group 2 (Mendell)			Group 4 (Stansbery)			Group 6 (Tripathi)			Group 7 (Neal)			Group 1 (McKay)			Group 3 (Heldmann)			Group 5 (Conrad)		
					Moon/mono hab			Moon/nuclear			Moon/mono hab			Moon/mobile hab			Mars/long stay/ multiple sites			Mars/long stay/ single sites			Mars/short stay/ multiple sites		
		A	B	C	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	1	2	3	Early	Buildup	Steady	Early	Buildup	Steady
Transport to Ascent vehicle	Mass returned in what way?	Inside crew return capsule (inside containers)	Attached to outside of crew return	In-depend-ent of crew return	A	A	A						D	A	A	A				AC	AC	AC	B or C		
	Mass transferred to ascent vehicle	Roboti-cally from SHED	Roboti-cally from hab	Humans carrying boxes	C	C	C						C	C	C	C				C	C	C	A or C		
	Is robotic sample return (separate from crew activities) needed?	Desired	Required	No										C	A	A									
Plenatary Protection	Does this imply that Mars sample return to the Moon or station or a Mars way-station is necessary?																								

Red highlighted areas represent a general consensus among groups.

Red Text represents questions the group formulated themselves.

Curation [primary architectures: return vehicle, sample containers]

Broad Activity	Issues	Options (d = Other)			Group 2 (Mendell)			Group 4 (Stansbery)			Group 6 (Tripathi)			Group 7 (Neal)			Group 1 (McKay)			Group 3 (Heldmann)			Group 5 (Conrad)		
					Moon/mono hab			Moon/nuclear			Moon/mono hab			Moon/mobile hab			Mars/long stay/ multiple sites			Mars/long stay/ single sites			Mars/short stay/ multiple sites		
		A	B	C	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	Early	Buildup	Steady	1	2	3	Early	Buildup	Steady	Early	Buildup	Steady
Mass returned per flight	Agree with CAPTEM (lunar) study results?	Yes	No		A	A	A				C	C	D	A	C	C	A	A	A				B		
	Mars different?	Yes	No		B	B	B						A	A	A	A	B	B	B	A	A	A	A		
	Need more samples per return flight?	Yes	No	Just some types	A	A	A						A!				B	B	B	A	A	A	A		
	Need more biological samples from Mars?	Yes	No	Maybe	A	A	A						A!				C	C	C	A	A	A	C		
	Do you need to curate Mars samples under Mars temperature conditions?	Yes	No	Depends												A									
	Do you need to curate Mars samples under Mars pressure conditions?	Yes	No	Depends												C									
	Do you need to curate Mars samples under ambient Mars atmo-sphere conditions?	Yes	No	Depends												C									
	As our paradygm for sampling lunar materials is changing from Apollo, should that for curation also be changed?	Yes	No	Depends										B	C	AC									
New curation issues																									
Contain-ment and controlling contamina-tion	How will samples be contained - container materials/types																								
	Clean collecting																								
	Preventing cross contamination during collection and procedures																								
	What would the contamination be?																								
	Acidic sample containment																								
	Biologically interest-ing samples																								

Red highlighted areas represent a general consensus among groups.

Red Text represents questions the group formulated themselves.

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