Sustainable Mars Research Agenda

Results of the 1st Sustainable Mars Workshop
Kennedy Space Center Visitor Complex
February 8-9, 2018
When the Apollo astronauts returned from the first landing on the Moon, the President of the United States proclaimed that "as you came down, and we knew it was a success, and it had only been 8 days, just a week, a long week, that this is the greatest week in the history of the world since the Creation." Perhaps that was not entirely hyperbole. But 100 years from now, the history books will devote perhaps a few phrases to the first human landing on the Moon. There will be an entire chapter of that same book devoted to the first human settlement on Mars. I believe that collectively the global spaceflight community is writing the first lines to that chapter today.

At the Aldrin Space Institute we are dedicated to the proposition that there will be a permanent, sustainable, human presence on Mars. Hence, we hosted the first Mars Sustainability Workshop in February 2018 at the Kennedy Space Center. We are certainly not the first to look at permanent habitation of Mars. Many studies have looked at technical habitation systems. However, I think we may be unique in that we take the position that we must begin by understanding the problem from the standpoint of human health and well-being.

The Mars Sustainability workshop was our first step towards developing the research agenda needed to ensure that individuals can remain healthy and productive on Mars for many years, perhaps decades. There is no other way. A productive settlement on Mars will require more people to inhabit the planet than can be reasonably transported during a single flight opportunity. Crew rotations will require that many people remain there across multiple synodic periods. In this first workshop, we brought together leading experts from medical, biological, psychological, sociological, genetic and botanical fields, as well as scientists and engineers, to begin to understand the complexity of this challenge. Many of the experts involved did not come from the traditional space community. We need to reach further outside the confines of aerospace if we are to be successful. Over two days of a structured workshop we learned that the real challenge lies in understanding the interaction of the many problems faced across disciplines. We spent considerable time attempting to discern the connections between problems across disciplines. I believe made considerable progress towards developing a cross disciplinary research agenda. It is only a start. Secondly, I think we learned that many of the most important research issues are going to be the most difficult to resolve. Moreover, there are no easy analogues we can use to research these issues. We will need a combination of literature reviews, analogue research, laboratory research, historical research and computer simulation to be successful as we take the next steps on this research path.

Ultimately, I believe our success in understanding what people need to thrive on Mars will have perhaps greater impact on Earth. Indeed, everything you need to do to live and thrive on Earth, you must do more efficiently, more sustainably on Mars. There will be no greater spin-offs from space than the lessons of sustainability we will learn in preparation for Mars.

The success of this workshop is owed to the participants whose creativity and enthusiasm got us off to a great start. Dr. Peter Eckart and Shawn Shirshekar deserve particular mention for the work they put into preparation for this workshop and preparation of this report. And, of course, I owe the greatest debt of gratitude to my father, Buzz Aldrin for the inspiration that humans can, and indeed must live permanently on Mars.

Dr. Andrew Aldrin
Director, Aldrin Space Institute
Florida Institute of Technology
This Sustainable Mars Research Agenda is based on the inputs of the participants of a Workshop held at the NASA Kennedy Space Center on February 8-9, 2018.

The key outcomes of the Workshop are documented in this report. They constitute the initial draft of a Sustainable Mars Research Agenda. This Agenda is structured along 4 Key Research Areas:

1. Overarching Research Topics
2. Human Physiology & Psychology
3. Mars Crew Activities & Habitats
4. Power Supply & In-situ Resource Utilization (ISRU)
For each of these Research Areas, the Workshop Participants developed and prioritized the Key Questions that need to be addressed and answered to enable a sustained human presence on Mars. The two key objectives of the Sustainable Mars Research Agenda are:

(1) To serve as a framework for the prioritization of research topics.
(2) To shape future activities of the Aldrin Space Institute (ASI) at the Florida Institute of Technology (FIT) in the context of Sustainable Mars.
Establishing a permanent presence on the surface of Mars is an ambitious endeavor with a number of significant challenges and obstacles. Popular transit options to Mars are dependent on orbital trajectories. The Aldrin Cycler is a gravity assisted, reusable, and propulsive cycling spacecraft capable of transporting humans to Mars in approximately five and a half months making it an economically friendly and viable option.

Upon arrival, crews will have to contend with an extreme and somewhat erratic climate, a partial gravitational field, and an extremely thin atmosphere made up primarily of carbon dioxide. Daily water and food requirements will depend on Power sources and In-situ resource utilization (ISRU). Sources of water will include but not be limited to the polar caps, subsurface ice, and the atmosphere.

The three main power supply options may include pre-staged reactors, geothermal energy, and solar arrays. Other resource utilization options will include Mars regolith, subsurface ice, and atmospheric gases. The crew will have options for food including pre-staged packages and Earth re-supply systems. Artificial ecosystems such as the Bio-regenerative life-support system (BLSS) and growing crops may provide another means of feeding the crew.

### MISSION PARAMETERS & KEY ASSUMPTIONS

To better be able to frame the discussions around priorities for the Sustainable Mars Research Agenda, the Workshop Participants decided to define a discrete set of Mission Parameters and Key Assumptions that are summarized here. These Parameters and Assumptions are ranging from Transportation & Logistics aspects, via environmental, power supply, and resource utilization considerations, all the way to human requirements.

<table>
<thead>
<tr>
<th>Transportation &amp; Logistics</th>
<th>Radiation Environment</th>
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<tbody>
<tr>
<td>Method: Aldrin Cycler</td>
<td>Sources: GCR &amp; SPEs</td>
</tr>
<tr>
<td>Trip Time between Earth and Mars: 100 days</td>
<td>Max dose limit: 1,000 mSv (lifetime)</td>
</tr>
<tr>
<td></td>
<td>Dose per Sol: 67 mSv</td>
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</table>

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Surface Characteristics and Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity: 3.711 m/s², i.e., about 1/3g</td>
<td>Sources of Water: Polar caps, ground ice, glaciers atmosphere, and others</td>
</tr>
<tr>
<td>Composition: CO₂: 95.32%, N: 2.7%</td>
<td>Temperature profile: High of 20 °C (293 K; 68 °F); Low of −153 °C (120 K; −243 °F); Average of −60 °C (−80 °F)</td>
</tr>
</tbody>
</table>

### ISRU & Power Supply Options

- **Power supply options:** Solar: launched/pre-staged, nuclear, and geothermal
- **Materials processing considerations:** Source, energy requirements, equipment mass, and environment
- **Plan growth/food supply considerations:** Soil, Bio-regenerative life-support system (BLSS), pre-staged, and resupply
- **ISRU options:** Solar, regolith, subsurface ice, and atmosphere
Among the major physiological considerations, high levels of radiation exposure and systemic changes in response to microgravity remain major areas of concern. To put things into perspective, the maximum human dose limit in a lifetime is 1,000 mSv. Whereas, the average radiation per one Sol is approximately 0.67 mSv. However, during transit from Earth to Mars (180-day journey) radiation doses could be as 300 mSv, or a total of 600 mSv for the round-trip. Transit to Mars alone, would expose an individual to more than 15 times the annual radiation limit for a nuclear powerplant worker. Mars’ gravity is about 38 percent that of Earth’s surface.

Other physiological risks include changes to the immune system making astronauts susceptible to reactivation of certain latent viruses, as well as fluid redistribution leading to rises in intracranial pressure and possible visual impairment. With respect to the psychological considerations, crew members will have to contend with prolonged group isolation and confinement, as well as possible sensory and sleep deprivation. Isolation and confinement from Earth will also present challenges in communication, with delays expected to exceed 20 minutes. Other psychological considerations include crew cohesion, crew composition, leadership dynamics, and group structure.

### Human Physiology Considerations

<table>
<thead>
<tr>
<th>Daily oxygen requirement:</th>
<th>0.83 kg</th>
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<tr>
<td>Daily water requirement:</td>
<td>3.5 kg for consumption; 25.6 kg for use</td>
</tr>
<tr>
<td>Daily food requirement:</td>
<td>0.62 kg</td>
</tr>
<tr>
<td>Sleep requirement:</td>
<td>6 hours</td>
</tr>
<tr>
<td>Medical needs for systemic changes:</td>
<td>Cardiovascular, musculoskeletal, immune, and more.</td>
</tr>
</tbody>
</table>

### Human Psychology Considerations

<table>
<thead>
<tr>
<th>Isolated</th>
<th>Confined</th>
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<tr>
<td>C</td>
<td>E</td>
</tr>
<tr>
<td>Group delays:</td>
<td>10-20 minutes</td>
</tr>
<tr>
<td>Flat or hierarchy</td>
<td></td>
</tr>
<tr>
<td>Crew composition:</td>
<td>Gender, culture, size and more</td>
</tr>
<tr>
<td>Crew cohesion:</td>
<td>Social and task cohesion</td>
</tr>
<tr>
<td>Leadership dynamics:</td>
<td>Instrumental and supportive leadership; flexible</td>
</tr>
</tbody>
</table>

### Mars Station Characteristics

| Size of Mars crew | 50 members (at steady state) |

Image Credit: Bob Varnas / NASA JPL
Along the 4 Key Areas of Research, and based on the Key Mission Parameters and Assumptions, the Workshop participants developed a set of key findings, specifically the priorities for the Sustainable Mars Research Agenda in the form of Key Questions. These Key Questions were then prioritized along a simple framework with two axes:

- Relative Importance Research Topic to Human Sustainability on Mars
- Relative Availability of Research Data / Material on Research Topic

This approach is, by definition, highly subjective, but given that it involves the inputs of a multi-functional team of some of the best subject matter experts, we believe that it is both pragmatic and the best possible starting point for the further development and prioritization of Sustainable Mars Research Topics.

The Key Questions that have been developed and prioritized for the 4 Key Areas of Research are presented in the following sections. An integrated view of the prioritization results across all four Areas of Research shows that the vast majority of Research Topics can be found in the upper right-hand corner of the prioritization framework, i.e., for most Topics we have very limited data, yet they are of critical importance for the planning of a sustained human presence on Mars.

Consequently, the Workshop participants decided that the Sustainable Mars Research Agenda should initially focus on the 12 Highest Priority Questions in the upper right half of upper right Quadrant of the Prioritization Framework.

**OVERARCHING RESEARCH QUESTIONS**

- **O1** Based on which Ground Rules or Assumptions would a permanent presence of humans on Mars be ultimately considered ‘sustainable’, i.e., largely independent from terrestrial supplies?
- **O3** How can we better understand the physiological and psychological long-term impact of the Mars environment on humans and what are the implications on mission and systems design?

**HUMAN PHYSIOLOGY & PSYCHOLOGY RESEARCH QUESTIONS**
- **H1** What will be the effects of Mars Gravity Levels (3/8-g) and Mars Radiation Levels on the human physiology?
- **H2** How can Mars Crew Members be adequately protected from radiation levels on Mars?
- **H3** How can Mars Crew Members be adequately protected from other environmental factors on Mars?

**MARS CREW ACTIVITIES & HABITATS RESEARCH QUESTIONS**
- **C2** Will the habitats and other facilities of the Mars Station be set-up on the Martian Surface or Subsurface?
- **C3** Will the habitats and other facilities of the Mars Station be imported vs. created in-situ vs. a combination of the two options?

**POWER SUPPLY & ISRU RESEARCH QUESTIONS**
- **P1** How much power will be required by the Mars Crew to operate all required systems and facilities?
- **P2** What technology / technologies will be applied to supply the Mars Crew with power?
- **P3** How easy is it to access the resources on Mars?
- **P4** Which in-situ resources may be generated on Mars, using which technologies / types of equipment?
- **P9** How would we grow / produce ‘unconventional’ food on Mars?
The Workshop participants identified and prioritized 9 Overarching Research Questions that are presented in this section. In this context, the term ‘Overarching’ indicates a high level of interdependency between different Research. For example, the level of power availability will strongly drive economic sustainability of a permanent presence of humans on Mars (e.g., by being able to produce and export materials and even goods), as well as the design of habitats (e.g., by being able to provide the facilities and amenities required for long-term stays of humans on Mars).

Based on which Ground Rules or Assumptions would a permanent presence of humans on Mars be ultimately considered ‘sustainable’, i.e., largely independent from terrestrial supplies? (O1)

What technologies and innovations are currently being pursued outside the space sector that could have fundamental positive design implications for ‘Sustainable Mars’ (feasibility, timeline?) (O2)

How can we better understand the physiological and psychological long-term impact of the Mars environment on humans and what are the implications on mission and systems design? (O3)

What are the minimum requirements to make living on Mars ‘sustainable’ for humans (atmosphere, water, food, habitat space / volume, leisure time options)? (O4)

How do we design systems for ‘Sustainable Mars’ for minimum maintenance requirements (minimize spares, minimize crew time spent on maintenance)? (O5)

What conditions would have to be met to achieve a closed loop ‘Sustainable Mars’ facility? (O6)

How can we achieve literally unlimited power availability for ‘Sustainable Mars’ to drive independence and facilitate growth? (O7)

To what extent could the Moon be an ‘enabler’ of Sustainable Mars? (O8)

What would a typical day look like to inhabitants of a ‘Sustainable Mars’? (O9)
The Workshop participants identified and prioritized 10 Research Questions related to Human Physiology and Psychology.

**H1** What will be the effects of Mars Gravity Levels (3/8-g) and Mars Radiation Levels on the human physiology?

**H2** How can Mars Crew Members be adequately protected from radiation levels on Mars?

**H3** How can Mars Crew Members be adequately protected from other environmental factors on Mars?

**H4** What is our current understanding of the psychological challenges of groups of humans living in space or remote locations and what learning can we derive for ‘Sustainable Mars’?

**H5** How can the psychological well-being of Mars Crew Members be ensured?

“I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust.”

Gene Cernan, Apollo 17

**H6** What medical services and facilities need to be provided for ‘Sustainable Mars’?

**H7** What is the optimal crew size and makeup (sex, skillset) and how does the optimal makeup change over time as crew size increases?

**H8** How do we ensure optimal health for interrelated systems: nutrition, cardiovascular, immune, endocrine, stress, and behavior/performance?

**H9** What are the factors that optimize crew performance? What are the skillsets of the highest priority?

**H10** What are the organization structures optimal for the Mars colony?
The Workshop participants identified and prioritized 4 Research Questions related to Mars Crew Activities and Habitats.

**C1.** What will the activity profiles of Mars Crew Members look like, esp. what share of Crew Member Time will be ‘productive’ (i.e., used for science, production, and other ‘value adding’ activities, as opposed to maintenance and ‘personal’ time (e.g., sleep, meals, personal hygiene, workout))?  

**C2.** Will the habitats and other facilities of the Mars Station be set-up on the Martian Surface or Subsurface?  

**C3.** Will the habitats and other facilities of the Mars Colony be imported vs. created in-situ vs. a combination of the two options?  

**C4.** What would be the ideal layout of ‘Sustainable Mars’ Colony?
The Workshop participants identified and prioritized 9 Research Questions related to Power Supply and In-Situ Resource Utilization. These are presented in this section.

**P1** How much power will be required by the Mars Crew to operate all required systems and facilities?

**P2** What technology / technologies will be applied to supply the Mars Crew with power?

**P3** How easy is it to access the resources on Mars?

**P4** Which in-situ resources may be generated on Mars, using which technologies / types of equipment?

**P5** Is the use of in-situ resources that are generated on Mars (or imported from the Moon) economically beneficial vs. the supply of consumables from Earth?

**P6** What type of food should we provide / grow on Mars?

**P7** Is plant growth on Mars feasible?

**P8** Are greenhouses on Mars feasible (and sustainable)?

**P9** How would we grow / produce ‘unconventional’ food on Mars?
In the immediate future, the Aldrin Space Institute will focus on two key activities in the context of Sustainable Mars:

1. Conducting and facilitating research addressing the 12 Highest Priority Research Questions
2. Further refining and improving the Research Agenda

Based on the initial Sustainable Mars Research Agenda as presented in this report, we are planning to conduct a 2nd Workshop on Mars Sustainability in the near future. This Workshop will again be by-invitation-only and will again feature a limited number of high-profile subject matter experts. The focus of the 2nd workshop will be to develop Implementation Plans for all 4 Research Areas, i.e., we will define the teams and institution who will lead and conduct research on specific topics, as well as identify ways and sources to obtain the necessary funding.

To be better enabled to answer the above-mentioned Highest Priority Research Questions, and especially to conduct the necessary Trade Studies, the activities of the Aldrin Space Institute with regards to the Sustainable Mars Research Agenda over the coming 24 months are planned as outlined below.

**NEXT STEPS**

**“Sustainable Mars” - Research Agenda**

**Workshop I**
- Build team and brainstorm Research Agenda
- Create Draft Research Agenda (based on results of Workshop I)
- Develop network of Partner Institutions

**Workshop II**
- Review & finalize Research Agenda
- Define teams / Institutions to lead Research
- Develop Concept for Book on Mars Sustainability

**Workshop III**
- Review Research & Further Develop Research Agenda
- Manage the implementation of the Research Agenda
- Develop network of Partner Institutions

**Raise Funds for implementation of “Sustainable Mars” Research Agenda**

Feb 2018 Q1/2019

**Become the Global Center of Excellence on the Development of the Capability to Establish Human Presence on Mars**

**Appendix 1 — Workshop Participants**

<table>
<thead>
<tr>
<th>Topic</th>
<th>Speaker</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WG 1: HUMAN PHYSIOLOGY &amp; PSYCHOLOGY</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human Physiology - Medical Needs</td>
<td>Erik Antonsen</td>
<td>Clinical Assistant Professor of Medicine at Baylor College of Medicine</td>
</tr>
<tr>
<td>Human Physiology - Radiation</td>
<td>Francis A. Cucinotta</td>
<td>Professor of Health Physics at the University of Nevada</td>
</tr>
<tr>
<td>Human Physiology - Radiation II</td>
<td>Huan Giap</td>
<td>Radiation Oncologist Scripps Proton Therapy Center/Clinical Professor at UC San Diego</td>
</tr>
<tr>
<td><strong>WG Lead</strong></td>
<td>Richard Griffith</td>
<td>FIT Professor of ID Psychology and Executive Director of The Institute for Cross Culturala Management</td>
</tr>
<tr>
<td>Mars Environment - Radiation &amp; Atmosphere</td>
<td>Bruce Jakosky</td>
<td>Professor of Geological Sciences &amp; Faculty director, at CU Boulder</td>
</tr>
<tr>
<td><strong>WG Lead</strong></td>
<td>Haifong Jiang</td>
<td>Research Scientist of the Institute for Cross Cultural Management (ICCM) at FIT</td>
</tr>
<tr>
<td>Human Psychology - Isolation Considerations</td>
<td>Nick Kanas</td>
<td>Psychiatrist/Professor of Psychiatry (retired)</td>
</tr>
<tr>
<td>Human Physiology - Circadian Rhythm</td>
<td>Kevin T. Murphy</td>
<td>Radiation Medicine Physician at UC San Diego Health</td>
</tr>
<tr>
<td>Human Physiology - Medical Needs</td>
<td>Roderic Pettigrew</td>
<td>Founding Director of the National Institute of Biomedical Imaging and Bioengineering (NIBIB) at the NIH</td>
</tr>
<tr>
<td>Human Physiology - Physiological Need (Atm/Nutrition/Food)</td>
<td>Jack Stuster</td>
<td>Vice President and Principal Scientist, Anacapo Sciences</td>
</tr>
<tr>
<td>Human Psychology - Team Dynamics / Analogs</td>
<td>Kevin T. Murphy</td>
<td>Neuro-endocrinologist and Medical Director at Barrow Neurological Institute</td>
</tr>
<tr>
<td>Human Physiology - Endocrinopathies in Space</td>
<td></td>
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</tr>
<tr>
<td><strong>WG 2: MARS CREW ACTIVITIES</strong></td>
<td></td>
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</tr>
<tr>
<td><strong>WG Lead</strong></td>
<td>Dan Batchelder</td>
<td>FIT Department Head - Physics and Space Sciences</td>
</tr>
<tr>
<td>Mars Habitat - Habitat Design</td>
<td>Larry Bell</td>
<td>Architect, Professor of Space Architecture at University of Houston</td>
</tr>
<tr>
<td>Mars Habitat - System Requirements</td>
<td>John Connolly</td>
<td>Lead of NASA’s Human Mars Study team</td>
</tr>
<tr>
<td>Mars Habitat - Site Selection</td>
<td>Sydney Do</td>
<td>Systems Engineer in Project Systems Engineering &amp; Formulation Section at NASA Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>Mars Environment - Surface &amp; Surface Materials 1st</td>
<td>Pascal Lee</td>
<td>Planetary Scientist at Seti Institute/Chairman of Mars Institute</td>
</tr>
<tr>
<td>Mars Habitat - Cost &amp; Systems Considerations</td>
<td>John Mankins</td>
<td>Founder and President of Mankins Space Technology</td>
</tr>
<tr>
<td>Moon to Mars - Special lecture</td>
<td>Harrison Schmitt</td>
<td>Apollo 17 Astronaut &amp; Adjunct Professor of Engineering Physics at the University of Wisconsin–Madison</td>
</tr>
</tbody>
</table>
Based on which Ground Rules or Assumptions would a permanent presence of humans on Mars be ultimately considered ‘sustainable’, i.e., largely independent from terrestrial supplies?

→ Trade studies and historical analysis of human expansion will be necessary to select between the following approaches to attaining and increasing the economic viability of the settlement, e.g., based on

○ Indigenous viability, e.g.,
  ■ Property rights and individual wealth creation
  ■ Common ownership and use of all facilities and natural and agricultural resources
  ○ Income producing exports, e.g.,
  ■ Scientific data and Martian samples
  ■ Proprietary scientific, technological or physiological discoveries
  ■ News items and literary documentation of the history of the settlement

What technologies and innovations are currently being pursued outside the space sector that could have fundamental positive design implications for ‘Sustainable Mars’ (feasibility and timeline)?

→ Scan other research initiatives and technology development outside the space community to identify possible ‘game changers’ for ‘Sustainable Mars’, e.g., in the areas of

○ Medical diagnostics / care (esp. genetics)
  ○ Power supply
  ○ Food provision
  ○ Resource utilization
  ○ Biological countermeasures (e.g., drugs)
  ○ Lessons we have derived (or may be deriving) from animal experiments (e.g., using mice)

→ Conduct research on existing knowledge of space environmental factors on long-term space missions and derive recommendations for (1) mission and systems design in the context of ‘Sustainable Mars’ (based on our current understanding) and (2) Future urgent research needs, taking into account, for example

○ Gravity levels
○ Dust environment
○ Crew dynamics in confined space (drawing from terrestrial analogs)
What are the minimum requirements to make living on Mars ‘sustainable’ for humans (atmosphere, water, food, habitat space / volume, leisure time options)?

- Develop several scenarios and assess resulting implications on, e.g., logistics requirements, power supply needs, and expected physiological and psychological well-being of humans, taking into account, for example,
  - Different stay times (e.g., 2 years vs. 10 years)
  - Varying degrees of in-situ resource utilization (ISRU), i.e., different life support options (e.g., level of food grown in situ vs supplied)
  - Experiences from ISS and terrestrial analogs

How do we design systems for ‘Sustainable Mars’ for minimum maintenance requirements (minimize spares, minimize need for crew time spend on maintenance)?

- Conduct research on existing 3D printing capabilities (and future possibilities) and their potential application in a Sustainable Mars context
- Conduct literature search for fail rates on ISS (what parts fail most? How much time required for maintenance?) and derive recommendations for Sustainable Mars

What conditions would have to be met to achieve a closed loop ‘Sustainable Mars’ facility?

- Conduct research on the key conditions that need to achieve a closed-loop Mars facility, thus minimizing the need to import consumables and systems from Earth, esp. taking into account, e.g.,
  - Life support loop closure
  - Minimizing resupply needs for spares

How can we achieve literally unlimited power availability for ‘Sustainable Mars’ to drive independence and facilitate growth?

- Conduct research on potential options on the availability of unlimited power on Mars to facilitate independence and growth, esp. by not constraining or complicating the design and development of other systems due to limited power availability, taking into account, e.g.,
  - Type of power source (e.g., solar, nuclear)
  - Manufacturing of power systems in situ

To what extent could the Moon be an ‘enabler’ of sustainable Mars?

- (Trade) studies will be necessary to assess to what extent the Moon could be enable of ‘Sustainable Mars’, for example, as a test bed or for the import of resources, e.g.,
  - Habitats and other occupied facilities
    - In-vacuum tests of concepts and hardware
    - Additive manufactured hardware components
  - Physiological Health
    - Verification or non-verification of adaptation to 3/8 gravity
    - Verification of efficacy of anti-radiation damage pharmaceuticals
    - Verification of dust mitigation strategies
    - Verification of Circadian rhythm interruption mitigation strategies
  - Psychological Well-being
    - Evaluation of strategies to promote psychological health
  - Economic Viability
    - Evaluation of a lunar settlement’s approaches and experience related to this issue
  - Power supply
    - Lead-up to sustainment – Fuel cell hydrogen and oxygen

Cannot cycle heat conversion of methane and oxygen supplied from the Moon
- He-3 fusion fuel
- Life support consumables
- Source in period leading up to sustainment
- Possible long-term exporter

What would a typical day look like to inhabitants of a ‘Sustainable Mars’?

- Define the ‘typical day’ of different types of crew members as a model to not only better understand what a crew member day could like, but to use this data to analyze and derive design requirements of habitats, facilities, and systems, as well as assess the psychological aspects of living away from Earth for extended periods of time. Crew time modeling should probably distinguish
  - Work time (‘Productive’ vs. ‘Maintenance’)
  - Group / social interaction time
  - Personal time (e.g., sleep, leisure)

What will be the effects of Mars Gravity Levels (3/8-g) and Mars Radiation Levels on the human physiology?

- (Trade) studies will be necessary to assess the impact of Martian Gravity Levels and Mars Radiation Levels on the human health and, potentially, identify measures to maintain physiological health (Lunar data shows adaptation will be complete; Lunar data also shows possibility of significantly less than complete adaptation Exercise countermeasures? Pharmaceutical countermeasures?)

How can Mars Crew Members be adequately protected from radiation levels on Mars?

- (Trade) studies will be necessary to assess the impact of Martian Radiation Levels on the human health and to identify appropriate radiation protection measures, e.g.,
  - Solar Radiation protection:
    - Water shielding of habitat and rovers vs.
    - Regolith shielding of habitat
    - Pharmaceutical countermeasures
  - Galactic Cosmic Rays protection
    - Thick regolith shielding of habitat
    - Ice or rock caves
    - Magnetic field shielding
    - Pharmaceutical countermeasures

How can Mars Crew Members be adequately protected from other environmental factors on Mars?

- (Trade) studies will be necessary to assess the impact of other environmental factors on the human health and to identify appropriate protection measures, e.g.,
  - Dust inhalation mitigation:
    - Dust rejection technologies for space suits
    - Dust filtering technologies for habitats, etc.
  - Circadian rhythm interruption:
    - Light and work-cycle management
    - Pharmaceutical intervention
Conduct a study to gather first-hand data from groups who have lived in space / remote locations for extended periods of time and have them help derive learnings / recommendations for ‘Sustainable Mars’ (e.g., by bringing together commanders / team members from ISS crews / stations in Antarctica for a workshop).

How can the Psychological Well-being of Mars Crew Members be ensured?

Trade studies will be necessary to assess the following aspects of crew psychology and, as appropriate, selection between potential approaches to maintain psychological health:

- Quality leadership
  - Leadership selection
  - Population make-up
  - Governance structure
  - Rule of law
- Necessary and useful work and research
  - Exploration
  - Geological, geochemical and biological analysis
  - Physiological research
  - Agricultural research
  - Astrophysics (Earth-Moon-Mars baseline for sensors)
- Maintenance of brain rhythms
- Magnetic resonance intervention
- Circadian rhythm management
- Return to Earth option
- None
- Under options specified in a settler’s contract

What medical services and facilities need to be provided for ‘Sustainable Mars’?

- Conduct studies on what types of medical services and facilities (incl. drugs) and provide recommendations (and rationales) taking into account considerations, such as:
  - Risk of occurrence of specific diseases (and accidents)
  - Availability of trained physicians
  - Medical training of crew members
  - Types and amounts of drugs
  - Types of medical equipment

What is the optimal crew size and makeup (sex, skillset) and how does the optimal makeup change over time as crew size increases?

- Conduct a study of various group sizes living in remote locations for extended periods of time (e.g., Antarctica and analog studies) to determine the optimal number of crew members per mission. Measure levels of cohesion and performance relative to group size. Review previous long-duration spaceflight mission crews (e.g. ISS). Review previous NASA studies comparing all male, all female and 50% mixed gender crews. Review literature on crew composition factors in ICE environments. Analyze how necessity of certain skills evolves with group size proliferation.

How do we ensure optimal health for interrelated systems: nutrition, cardiovascular, immune, endocrine, stress, and behavior/performance?

- Begin by identifying the physiological response of each system under spaceflight conditions (e.g., microgravity, radiation, isolation and confinement, etc.). Review psychological adaptations and changes of previous crews in short duration spaceflight conditions (e.g., ISS) and in analog studies designed to simulate long-duration missions. For example, explore relationship between psychological stress and immunological changes in Antarctica winter-over crews. Determine efficacy of current short duration countermeasures such as:
  - Physical fitness and exercise
  - Radiation shielding
  - Sensory-motor training protocols
  - Bed rest studies
  - Pharmaceuticals
  - Design and technological considerations
  - Virtual reality technology

What are the factors that optimize crew performance? What are the skillsets of the highest priority?

- Begin by identifying all tasks on Mars mission. Trade studies in remote locations will be necessary (e.g., Antarctica and other analogs). Determine which individuals exceed performance standards and explore those specific personality profiles. Use inaugural Mars crew as focus group for future crew considerations.

What are the organization structures optimal for the Mars colony?

- Conduct studies of crews under various management structures (e.g. flat and hierarchical) in remote locations and compare performance levels. Review management structure of previous long-duration spaceflight mission crews (e.g. ISS). Review psychosocial factors of previous NASA analog team studies (e.g., Caves, Hera, and HI-SEAS) such as:
  - Commander leadership type
  - Commander to crew hierarchy (and over time)
  - Crew cohesion (task and social)
  - Crew performance

What will the activity profiles of Mars Crew Members looks like, esp. what share of Crew Member Time will be ‘productive’ (i.e., used for science, production, and other ‘value adding’ activities, as opposed to maintenance and ‘personal’ time (e.g., sleep, meals, personal hygiene, workout))?

- (Trade) studies will be necessary to identify the ‘ideal’ crew composition and activity profiles based on a set of TBD Key Criteria.

Will the habitats and other facilities of the Mars Station be set-up on the Martian Surface or Subsurface?

- Trade studies will be necessary to select between the following approaches to permanent habitats and other occupied facilities on Mars:
  - Surface habitat
  - Subsurface habitat
  - Surface excavation
  - Ice cave excavation
  - Rock cave
Will the habitats and other facilities of the Mars Station be imported vs. created in-situ vs. a combination of the two options?

→ Trade studies will be necessary to select between the following approaches to permanent habitats and other occupied facilities on Mars (example for Surface Habitat):
  - Surface habitat imported in full (from Earth, from Moon)
  - Surface habitat imported in part (from Earth, from Moon) with remainder from Martian resources, including carbon-based composites
  - Frame for surface habitat imported (from Earth, from Moon) with remainder from Martian resources including carbon-based composites
  - Surface habitat entirely from Martian resources including carbon-based composites

What would be the ideal layout of ‘Sustainable Mars’ colony?

→ Trade studies regarding layout of surface facilities, taking into account, for example,
  - Surface area requirements for the different habitats / systems
  - Relative location requirements for the different habitats / systems

How much power will be required by the Mars Crew to operate all required systems and facilities?

→ (Trade) studies will be necessary to identify the level of power that will be required by the Mars Crew (different scenarios need to be developed), taking into account all necessary systems and facilities, such as
  - Life support systems
  - Habitat systems
  - Laboratories
  - Surface transportation systems
  - Resource generation / manufacturing facilities (if any)

What technology / technologies will be applied to supply the Mars Crew with power?

→ Trade studies will be necessary to select between the following sources, or combination of sources, of energy, e.g.:
  - Solar Power (PV or SD – Initial plants and fuel imported from Earth)
  - Fuel Cells (Initial plants imported from Earth or through lunar additive manufacturing; Hydrogen and oxygen produced from Martian ice)
  - He-3 fusion (Initial plants and fuel imported from Earth)
  - Hydrocarbon combustion (Carnot cycle heat conversion – Initial plants imported from Earth or through lunar additive manufacturing; methane and oxygen produced from Martian ice and CO2, indigenous hydrocarbons produced from Martian sources (clay-rich areas may have concentrated organic compounds))

How easy is it to access the resources on Mars?

→ Create an overview of Martian resources with an initial assessment of accessibility for utilization
  - Overview on Martian Resources through literature research
  - Assessment of ‘ease of access’ through discussions with, e.g., mining companies and equipment manufacturers (e.g., Caterpillar)

Which in-situ resources may be generated on Mars, using which technologies / types of equipment?

→ (Trade) studies will be necessary to assess the feasibility of generating the following consumables from Martian sources (e.g., soil or atmosphere)
  - Water (e.g., from Martian ice, Martian clay, Martian hydrated minerals, waste recycle)
  - Oxygen (e.g., from Martian ice, Martian ice, Martian CO2, Martian agriculture)
  - Nitrogen (e.g., from Martian nitrates, potential import of solar wind nitrogen from Moon)
  - Food (e.g., Martian agriculture, Import from Moon)
  - Salt (e.g., Martian mineral sources)
  - Nutrients (e.g., waste recycle, Martian mineral sources)

Is the use of in-situ resources that are generated on Mars (or imported from the Moon) economically beneficial vs. the supply of consumables from Earth?

→ Trade studies will be necessary to assess the economic feasibility of ISRU by type of resource (incl. break-even point analyses)

What type of food should we provide / grow on Mars?

→ Conduct research on whether / how a Martian diet should be different from a terrestrial diet and derive what foods should we be growing on Mars, considering, e.g.
  - Physiological and psychological aspects of the human diet
  - Unconventional / ‘new’ food sources (e.g., insects, synthetic proteins)

Is plant growth on Mars feasible?

→ Conduct research on the feasibility of plant growth on Mars (taking into account, for example
  - Growth medium (e.g., plant growth in regolith vs. hydroponics)
  - Lighting considerations (esp. natural sunlight (e.g., solar lighting levels, UV-C) vs. ‘artificial’ lighting
  - Radiation considerations

Are greenhouses on Mars feasible (and sustainable)?

→ Conduct research on what greenhouses on Mars could look like and whether they could be ‘sustainable’ taking into account, for example
  - Greenhouse structural considerations (and plant growth medium)
  - Lighting considerations, esp. ‘transparent’ greenhouses with natural lighting vs. ‘non-transparent’ greenhouses with artificial lighting (that may be potentially in lava tubes)
  - Radiation considerations
  - Other environmental considerations (e.g., dust storms)

How would we grow / produce ‘unconventional’ food on Mars?

→ Conduct research on how ‘unconventional’ food should be grown / produced on Mars and derive the associated resource (e.g., power, water, structures) and maintenance requirement
Appendix 3 — References

1. Transportation and Logistics

2. Human Physiology and Psychology

3. Mars Environment (Atmosphere & Radiation)

Appendix 3 — References

1. Transportation and Logistics

2. Human Physiology and Psychology

3. Mars Environment (Atmosphere & Radiation)
5. Mars Crew and Habitat Design


6. Power Supply and In-situ Resource Utilization (ISRU)


Cooper, M., Perchonok, M., Douglas. G. Initial assessment of the nutritional quality of the space food system over three years of ambient storage. NPJ Microgravity (2017) 3:17; doi:10.1038/s41526-017-0022-z


